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Miniaturised Electromagnetic Generators for Portable Applications

A Thesis Presented to the National University of Ireland, Galway
In Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

By

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Declaration

This thesis has not been submitted before, in whole or in part, to this or any other University for any degree and is, except where otherwise stated, the original work of the author.

Signed_______________________

Damien John Carroll
This thesis is dedicated to those that never give up, my wonderful family, and in particular my parents and fantastic wife.
“Scientists investigate that which already is, Engineers create that which has never been”

Albert Einstein

“Engineers like to solve problems. If there are no problems handily available, they will create their own problems”

Scott Adams

“The story of civilization is, in a sense, the story of engineering - that long and arduous struggle to make the forces of nature work for man's good”

L. Sprague de Camp

“Engineering is a great profession. There is the satisfaction of watching a figment of the imagination emerge through the aid of science to a plan on paper. Then it moves to realisation in stone or metal or energy. Then it brings homes to men or women. Then it elevates the standard of living and adds to the comforts of life. This is the engineer's high privilege”

Herbert Hoover

“The ideal engineer is a composite ... He is not a scientist, he is not a mathematician, he is not a sociologist or a writer; but he may use the knowledge and techniques of any or all of these disciplines in solving engineering problems”

N. W. Dougherty

“The engineer's first problem in any design situation is to discover what the problem really is”

Unknown

“The human foot is a masterpiece of engineering and a work of art”

Leonardo da Vinci
Abstract

With the advent of wearable electronics, the demands on power sources for portable electronic equipment are ever-increasing. Requirements include increased functionality and decreased size, with power sources (e.g. batteries) providing at least the same lifetime as the device. In this project, the possibility of unobtrusively capturing some of the energy expended by a person while walking / running and converting it into electrical energy is investigated. The development of such alternative or complementary power sources would significantly reduce the demands on conventional power sources. Modelling and analysis of an electromagnetic generator designed for harvesting power produced during walking is presented. The generator is designed to be inconspicuous to the user by embedding it within the thickness of a normal shoe sole, and by applying a passive generation principle which requires minimal additional force over that normally exerted by the user during walking. In this way, a portion of the power used in walking is harvested for potential use in powering portable electronic devices. The main outcome of the work is specification and comparison of the power levels available from the electromagnetic generators designed for integration into shoes. Circuit models are applied to predict maximum voltage and power levels produced during walking. Analytical and Finite Element Analysis (FEA) models are applied to design the generator winding and core structures. Furthermore, analysis of different geometrical and material properties is applied to identify the conditions for optimised generator designs. The nature of the generator output necessitated the development of AC/DC conversion methods which are modelled to predict the maximum DC power available within the given structure. DC power levels of up to 10 mW are demonstrated within a volume of $15 \times 15 \times 100$ mm$^3$ at a walking speed of 2 steps per second. At least two of these volumes can be easily accommodated within a standard shoe heel to provide up to 40 mW of DC power per user, with higher power levels achieved for faster walking or running speeds. A microprocessor/transceiver system integrated into the shoe is demonstrated to identify the possible commercial use of such generator designs.
Acknowledgements

Firstly, I’d like to thank my supervisor Dr. Maeve Duffy, for whom this is the only part of this thesis that hasn’t been carefully reviewed. Maeve you gave me the opportunity to pursue this PhD and also advance my career through teaching and self-directed research, a sincere thank you for your enduring patience and belief and for never giving up on me. Thank you also Professor Gerald Hurley for allowing me to gain a wealth of experience in the Power Electronics Research Centre. Special thanks also to Miles and Martin for all the help ye offered throughout my PhD, and of course the odd game of soccer.

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To my fellow lab mates past and present, too many to mention individually but thank you all for the advice & help. Life outside the lab is very important to keep you sane through the years and I’m blessed to have a great group of friends who’ll be as happy as me that this thesis is finished. Where would I be without my amazing family? To my siblings; brothers Chris, Ronan, Darren, Giles & Mike, sisters Nathalie, Sabrina, Maureen, Cara & Sharon not forgetting my niece Clodhna and nephews Aodan, Kaylum, Cathal and Ruadhan, thanks is just never going to be enough, I could never have finished without your support and love.

And finally the three people that have stood by me the most! To my parents Michael & Theresa you have always encouraged me in everything I do, been proud no matter what and always taught me to believe in myself. Your love and support has brought me this far and I will never be able to thank you both enough for everything. Last but not least my amazing wife Shelly, we were both a bit crazy to start PhDs but I would never have finished without you. Thanks for keeping me sane, proof reading and for your love any encouragement throughout.
1. Chapter 1 - Introduction

1.1 Context

The increasing use of portable electronic devices for communication, entertainment, sports and healthcare applications has created a significant challenge in relation to their requirement for sustainable power. Today the rate at which the functionality of these portable electronic devices is increasing is far outpacing the rate that battery technologies can be improved. Current handheld electronics can take photographs, make phone calls, play music, play videos, surf the web, connect via Bluetooth radio and even identify a user’s location in the world. Each of these attractive features is draining mA of current from the battery power source and once all the battery energy is consumed a second power source, mainly the AC mains available in every home and office, is required to replenish the battery. Ultimately, this translates into limited battery life-time and the associated inconvenience of recharging batteries.

Energy harvesting is the process in which energy is captured from a system’s environment and converted into usable electric power. Human energy harvesting solutions have been developed to address portable battery issues and a range of different operating principles have been applied to convert kinetic energy into useful levels of electrical energy [1], [2], [3]. A range of generator structures have been investigated previously for integration into various personal accessories; e.g. Baedekers’s pen harvester [4] and Granstrom’s backpack generator [5]. Previous body integrated generator structures proposed in the literature include those based on pneumatic [6], piezoelectric [7], [8] and electromagnetic [9] principles of operation. Power levels from mW to the 1 W ranges have been achieved with such generator designs. While usable power has been achieved with these designs, no efficient optimum unobtrusive body worn generator solution exists to date. Thus the design of an optimised wearable power generator to generate electrical energy during walking is investigated in this research.
1.2 Issues

The human energy harvesting solutions that have been developed to date are capable of generating useful power levels, however these also have a range of issues including; size, weight, reliability, etc. Pneumatic generators require fluid or air flow to excite other energy conversion technologies to provide electrical energy and these tend to be large bulky designs [6]. Piezoelectric generators provide typically high peak voltage and low power from the foot, while electromagnetic generators provide higher power with less available voltage. To date many of the piezoelectric and electromagnetic generator designs that achieve usable power levels are difficult to integrate onto the human body unobtrusively. While relatively high power levels (100mW to 1W) have been reported for electromagnetic generators, their operation involves significant interference with the user’s normal gait. The piezoelectric generator design (integrated into a shoe sole) that provides maximum human generated power requires significant force experienced by the user during the human gait cycle [8]. Many electromagnetic generator designs converting foot pressure require levers extended from the foot in order to excite the generator [9], [10]. Several other designs apply resonant generators to the shoe heel but the unobtrusiveness of these designs has yet to be verified [11], [12] and there are concerns with regard to the reliability of the mechanical components applied. A detailed review of wearable power generator structures for harvesting energy from the body during walking is included in Chapter 2.

One of the main limitations of all energy harvesting methods is the need to efficiently convert the generated AC power into usable DC power. Microscale electromagnetic and piezoelectric generators have a major obstacle to overcome as the generated voltage is in the mV range and thus require very efficient AC/DC conversion techniques in order to produce usable DC power [2], [13]. Much of the current research has combined AC/DC with DC/DC conversion to form a single stage converter to achieve this increased efficiency [14], [15]. The predicted performance of these conversion methods are accomplished based on the peak voltage and frequency of a continuous electromagnetic generated AC voltage, which is most often produced by a resonating vibrational source.

Due to the intermittent excitation of human worn generator systems it is difficult to predict the DC output for a given generator while walking using typical
conversion circuits. Predicting the DC performance of the generator designed in this research is more complicated due to the location and excitation frequency of the human body. During operation there are large periods of zero induced voltage produced by the generator in-between steps, rather than a continuously generated voltage which is available from resonant generator structures. Thus the DC performance of the generator is difficult to predict due to the discontinuous nature of the supply voltage.

Peak power levels from mW [10] range to the 1 W [16] ranges have been achieved with previous generator designs. However, when compared to the power requirements of portable electronic devices (1-6 Watts) these generated power levels are low and so human energy harvesting cannot to date suitably replace battery power.

1.3 Statement of Objectives

The aim of this work is to provide an energy harvesting solution that meets the following specifications; the generator structures are unobtrusive (unlike previous designs); the user doesn’t need to apply any significant additional force over that normally applied during walking (the gait isn’t changed to cause the movement or excitation of the generator design). To that end one of the main objectives of this work is the design of a generator where the user isn’t required to carry any bags or backpacks to house the generator structure, as it must be integrated onto the user’s clothes or footwear. A further objective is that the generators don’t involve complicated mechanical components and therefore reliability issues are assuaged. The main technologies of interest are electromagnetic and piezoelectric designs as these have the most attractive attributes for unobtrusive integration onto the human body. To provide a wider scope of generator design a further objective of this work is the design of two separate generator structures with different operating principles that are located where the maximum human mechanical power is available. It is expected that for the generator to be integrated with a structure that is unobtrusive to the user it should have a volume of <50 cm$^3$. Thus both generators designed in this work have a volume within these limits. In a bid to address these limitations, the possibility of redefining the generator structure specifically for integration into the clothes or shoes is identified, so that power can be harvested from both generators passively from users without impacting on or disrupting their normal gait. Given that existing
analytical models are based largely on resonant generator principles, which do not apply on the human body, another objective of this work is to provide analytical models to predict the AC performance of both generators structures. These models are developed so that a wide range of generator dimensions can be investigated without the need to build generator structures. However, these models are verified with measurements from one of each generator design integrated onto the body. By analysing the performance of both generator structures under similar conditions the most efficient design is identified and the objective is to maximise the available AC power from this chosen structure. To do this generator parameter analysis is carried out and an optimum design procedure is identified.

Another objective of this work is that the power generated will at least match the power requirements of the RFID application demonstrated by Paradiso [8] using a piezoelectric generator. Thus, a target power level of between 10 mW and 100 mW is identified for a demonstrator unobtrusive body worn generator. As some demonstrator applications are capable of operating with voltages as low as 1 V the target DC voltage level of this work is $\geq 1V$. One of the main outputs of this research is the development of analytical models that provide an accurate prediction of generator DC performance for a number of conversion circuits, based on the discontinuous nature of the generated AC voltage. Although the conversion circuits themselves are not novel the models developed for such source voltages are, due to the nature of the generated AC source voltage from the human body. For validation these DC models are also compared with measured results. The end goal is that for a given set of available generator dimensions and parameters the optimum performance of the generator design can be predicted. In this way the optimum AC performance of the generator structure is predicted using the guidelines achieved while the optimum DC performance for the given structure and source voltage is predicted using the conversion models developed. These models have the capability of being applied to generator structures in other power harvesting environments that suffer from non-continuous excitation frequencies where much larger AC peak voltages may be available. The final objective is to demonstrate the generator power with a commercial product that requires between 10mW and 100mW to validate this work.
Chapter 1: Introduction

1.4 Thesis Contributions

Chapter 2 investigates the human gait cycle and identifies the optimum body location for the generators. Initially the human gait is analysed in terms of movement for optimum generator excitation. Also, the location of maximum mechanical power from the body during a normal gait cycle is identified [17]. The areas of most interest on the body are the upper body, the legs and finally the feet. By investigating the generator designs that convert all body movements at these different locations around the body during walking, a suitable technology and generator structure is identified to convert the foot motion. A range of human energy harvesting generator designs that have been developed to date is also investigated with particular interest in electromagnetic and piezoelectric technologies. A review of the power requirements of suitable applications is also carried out with a suitable generator demonstrator application identified for the generator designed in this work. The low power AC/DC conversion methods that have been developed for energy harvesting are also discussed in this chapter.

A typical generator will have a fixed housing such as a stator and moving object such as a rotor to achieve the generated electrical energy. In this work the excitation forces developed at the location of the body where the generators are integrated are identified in Chapter 3. The mechanical structures of both designs are also investigated. This accomplishes a prediction of generator “stator” and “rotor” excitation, direction of movement and velocity for both designs. The principle of operation of both generator structures is presented, along with mechanical and electrical models used to predict their performances. Suitable generator materials are chosen for both generators in order to maximise generated voltage and power. A user software interface is also created to allow any user to input values of the generator variables that are limited by the generator volume. This software analytical model accurately predicts the AC performance of the chosen generator designs. A means of optimising both generator structures based on “rotor” movement is also investigated. The performance of both structures is compared under similar conditions and the optimum generator design is then identified.

While two basic structures are initially considered for the normal gait cycle, initial testing under the same conditions identifies which design provides the power levels that are required by this work; i.e. 10mW to 100mW. Due to the passive nature
of energy conversion in the proposed basic structures, generated power levels are relatively low (<10mW). Therefore the generator design with the best prospects for further power is optimised to achieve the maximum possible power that can be harvested. The optimum generator design established in Chapter 3 is then enhanced in Chapter 4. For this purpose, novel analysis of a wide range of generator parameters is provided, where the effects of several geometrical and material properties are illustrated for normalised generator dimensions. This optimisation provides guidelines to improve the power available from generator with a similar structure with any dimensions, but specifically where different body sizes are involved. Similar analysis can be applied to other generator structures based on the same principle for use in other power harvesting environments, where larger structures and therefore higher power levels may be achieved. Supporting measurement results are also presented to demonstrate the accuracy of the design guidelines developed in Chapter 4. Three of the optimum generator structures that are predicted to produce maximum AC power are built and the performance of these generators integrated onto the body will then be compared to the AC analytical models. The effect of the integrated generator on the human body is also investigated.

The generator structure that produces maximum AC power is then combined with an optimum AC/DC circuit so that maximum DC power can be achieved. The DC power is investigated in terms of both constant and pulsed DC power and the optimum method is identified in Chapter 5. The constant and pulsed DC power models for each of the AC/DC circuits considered are derived and a final model based on peak AC voltage, conversion voltage loss, capacitance, rotor frequency, walking frequency, load resistance, etc. is identified for each circuit. Optimisation of DC power is also described by evaluating the influence of wire diameter and walking speed on the generated DC voltage. While the generated voltage is expected be >1V and large enough to overcome a normal diode drop, the discontinuous nature of the source makes it difficult to provide a usable DC voltage without a large output capacitor. Thus a suitable output capacitor is also identified for a body worn generator structure.

Measurements are then taken from the optimum built structure with a number of AC/DC circuits. The measured constant and pulsed DC power performance of the optimum generator design is investigated in Chapter 6. The results are produced while walking on a treadmill at various fixed speeds and maximum power is identified
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based on a range of load resistances for a number of power conversion circuits. The steady state voltage that is achieved with each circuit and the charge time for this range of resistive loads is identified. Based on the models developed in Chapter 5 a comparison between the measured and predicted generator DC performances is investigated over a range of walking speeds in Chapter 6 to verify the model accuracy, but also to identify the optimum AC/DC circuit for this application. For the generator design to be successful the measured and predicted power must achieve the target power of >10mW while the measured DC voltage must achieve the target of >1V. By comparing the power requirements of suitable demonstrator loads with the power levels achieved by the designed human energy harvesting generator in this work, the effectiveness of energy harvesting of the design can be quantified. A suitable demonstrator load is selected and its operation is demonstrated during a normal gait cycle. Finally a demonstrator system is designed and integrated in Chapter 6 and the performance is investigated whereby the optimum generator alone will supply the required power.
Chapter 2 - Literature Review

2.1 Introduction

Energy harvesting (also known as power harvesting or energy scavenging) is the process in which energy is captured from a system’s environment and converted into usable electric power [18]. Energy harvesting allows electronics to operate where there is no conventional power source, eliminating the need to run wires or make frequent visits to the electronic device to replace batteries. As the miniaturisation and complexity of electronic devices is being developed at a rapid pace, the interest and investment in energy harvesting techniques for smaller scale power has also intensified. A recent major market research report [19] on low power energy harvesting has been published by iRAP Inc. [20], which predicts that the energy harvesting market will increase by 73.6 % from $79.5 million in 2009 to $1,254 million in 2014. The focus of this thesis is on energy harvesting techniques on the human body for portable applications.

In 1996, T. Starner began an investigation into utilising energy expended by the human body during normal everyday activities to power portable electronic devices, which had begun to be developed [17]. The purpose of this investigation was to analyse all aspects of human power generation including breath, blood pressure, body heat, finger and limb motion. Since then many researchers have developed generators that aim to produce electrical power from these human power sources. For example Paradiso and Shenck’s foot pressure generator [8], Hayashida’s foot pressure generator [10], a backpack generator from Rome et al [21], Li and Donelen’s knee generator [22], Elmes’s backpack generator [23] and Saha’s human vibration generator [24] are all successfully designed power harvesting generators which are excited by human motion during walking, corresponding to generated power levels of 8.4mW, 5W, 7.4W, 1W, 58.1mW and 2.46mW respectively. These and other similar generators will be discussed in more detail in section 2.3.

While the range of human energy harvesters is vast, this thesis is only concerned with the generators that harvest from human motion during walking. Based on the requirements set out in the introduction this chapter aims to analyse the human gait cycle and identify the optimum location for human harvesting generators. As the...
focus of this work is the design of an electromagnetic generator or its leading competitor (piezoelectric) a number of previous generator designs that convert human walking using these technologies are identified for comparison in section 2.3. Based on this analysis the optimum technology is then identified. Section 2.2 identifies the principles of operation of both technologies and how both technologies have been developed to generate electrical power from the human motions experienced during walking. Although a number of other energy harvesting technologies are available, including hydraulic and pneumatic systems [25] and electroactive polymers [26], [27], these are outside the scope of this thesis due to the large volumes associated with the generator structures [3]. Sections on piezoelectric and electromagnetic generators are divided further in terms of the various positions around the body where they are located. These include: the upper body; where center of mass motion and human vibrations are converted, the leg; where leg joint rotation is converted and finally the foot itself; where foot swing and foot pressure are converted. This analysis will provide a good indication on how competitive the generators which will be designed in this work are in terms of generated power and generator volume.

An energy harvesting system generally includes the electrical power generator and circuitry to charge an energy storage cell and to manage the power so that it provides a regulated voltage for some particular application. As the work described in this thesis is focused on a generator that harnesses the energy from human walking, this chapter will also investigate the conversion circuits and applications that are associated with this subject in section 2.4. The range of AC/DC conversion techniques for power harvesting sources is described in the context of low voltage generators as it is one of the main focuses of this thesis.

Finally current methods of powering commercial portable electronics are highlighted in section 2.5.1, while the power requirements of these portable electronic devices are identified in section 2.5.2. A range of human excited energy harvesting structures and technologies are investigated and a suitable demonstrator portable electronic system that can realistically be powered by the human powered generator designed in this work is then identified.
2.2 Energy Harvesting Technologies

2.2.1 Piezoelectric Energy Conversion

Piezoelectric materials are one of the most commonly used technologies in human power harvesting research. The piezoelectric effect occurs when certain materials subjected to mechanical strain experience an electrical polarization which is proportional to the applied strain, and vice versa when the same material is subjected to an electric field. A piezoelectric module is represented in Figure 2.1 and shows the three Cartesian axes as well as the shear around the three axes where the piezoelectric effect occurs [3].

![Figure 2.1: Basic Piezoelectric Module Structure [3], [28]](image)

Electrical parameters are in the 1, 2 and 3 directions whereas mechanical parameters include also the shear about the three axes (4, 5 and 6). Piezoelectric materials are generally employed in mode 33 or 31 in energy harvesting as the direction of polarisation for these materials is in the thickness direction (3). If in mode 33 a mechanical stress is applied to direction 3 the resulting electrical field also takes place in that direction (Parallel Compression Generators). In mode 31 a mechanical stress applied to direction 1 results in an electrical field in direction 3. Hence pulling the piezo material along the 1 axis develops a voltage across the 3 axis [28] (Transversal Tension Generators).

Piezoelectric materials can be excited by compression or bending with each method generating electrical energy. There are two bending materials (unimorphs and bimorphs) that can be implemented as piezoelectric generators in the shoe due to their structure, size and electromechanical efficiency; Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride (PVDF), with maximum electromechanical efficiency of
approximately 50% available from PZT material (in parallel mode) [29]. Table 2.1 describes the main properties of these materials.

### Table 2.1: PVDF and PZT Properties [17]

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>PVDF</th>
<th>PZT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>1.78</td>
<td>7.6</td>
</tr>
<tr>
<td>Relative Permittivity</td>
<td>ε/ε₀</td>
<td>12</td>
<td>1700</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>10⁶ N/m</td>
<td>0.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Piezoelectric Constant</td>
<td>10⁻¹² C/N</td>
<td>d₁₃=20</td>
<td>d₃₃=180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d₁₅=30</td>
<td>d₅₃=360</td>
</tr>
<tr>
<td>Coupling Constant</td>
<td>CV/Nm</td>
<td>0.11</td>
<td>k₁₃=0.35, k₅₃=0.69</td>
</tr>
</tbody>
</table>

The coupling constant shown in Table 2.1 is the efficiency with which a material converts mechanical energy to electrical energy. Although PVDF materials are more suitable for embedding in the shoe sole, their conversion efficiencies are almost one order of magnitude smaller than that of the PZT. From the coupling constants in Table 2.1 the most efficient energy conversion is found from compressing the PZT in mode 33 (d₃₃). But due to the rather large elastic modulus for PZT (4.9x10¹⁰ N/m²) it would take an undesirably large force to compress the material even a small distance [3]. This is due to the relationship; \( \Delta H = F H / A Y \) where \( F \) is force, \( H \) is the unloaded height, \( A \) is the area over which the force is applied, and \( Y \) is the elastic modulus. However, bending a piezoelectric material and taking advantage of its mode 31 conversion is much easier and PVDF material is very flexible and is also easy to shape, stable over time and does not depolarise when very high alternating fields are applied.

### Table 2.2: Mode 31 and Mode 33 Properties [28]

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<thead>
<tr>
<th></th>
<th>Mode 31</th>
<th>Mode 33</th>
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</thead>
<tbody>
<tr>
<td>( V_o )</td>
<td>( g_{31}(F/L/W) )</td>
<td>( g_{33}(F/WL)H )</td>
</tr>
<tr>
<td>( q )</td>
<td>( d_{31}(F/L/H) )</td>
<td>( d_{33}F_3 )</td>
</tr>
</tbody>
</table>

Table 2.2 describes the properties of the mode 31 and mode 33 of the piezoelectric materials where voltage, \( V_o \), and charge, \( q \), are obtained in the plane perpendicular to direction 3 by applying a mechanical stress in direction 1, mode 31, and in direction 3, mode 33. \( g \) is the piezo stress constant, \( d \) the piezo strain constant, \( F \) the force, \( L, H \) and \( W \) are the longitude, thickness and width of the piezoelectric
film respectively. Properties and dimensions of PVDF make it appropriate to obtain a higher mechanical to electrical efficiency by bending. In a thin PVDF film the ratio L/H is on the order of 1000, while \( d_{31} = 23 \times 10^{-12} \, m/V \) and \( d_{33} = 33 \times 10^{-12} \, m/V \). If it is considered that \( F_1 = F_3 \), \( V_o \) and q for the mode 31 will be on the order of 700 times greater than \( V_o \) and q for the mode 33, as can be seen from Table 2.2. Therefore, for the same mechanical energy input, more electrical energy output is obtained in mode 31 than in mode 33 when PVDF piezoelectric films are employed. However, for PZT mode 33 is usually a better solution than mode 31 since thickness is less than length and width of the piezoelectric material.

Piezoelectric generators are similar to electromagnetic in that additional circuitry is required to rectify the output power from the unsteady high impedance source to a stable low impedance supply. Although when compared to the electromagnetic harvesting systems piezoelectric systems provide better voltage levels and higher power densities. This will be seen in examples of both systems in section 2.4.

### 2.2.2 Electromagnetic Energy Conversion

Electromagnetic induction is the production of an electric current across a conductor moving through a magnetic field [30]. Electromotive force (EMF) produced around a closed conductor path (closed circuit) is proportional to the rate of change of the magnetic flux through any surface bounded by that path. This applies whether the field itself changes in strength or the conductor is moved through it. Described as Faraday’s law it is described mathematically as:

\[
\mathcal{E} = -N \frac{d\Phi_B}{dt}
\]

for the case of a coil of wire (as the conductor), composed of \( N \) turns; \( \mathcal{E} \) is the electromotive force and \( \Phi_B \) is the magnetic flux. In electromagnetic energy harvesting systems either the coil or magnets can be allowed to move, while the other remains fixed. It is generally designed so that the magnets are moving while the coil remains fixed, and in the case of a vibrational design the magnet can act as an inertial mass. If the induced voltage is too small to be usable it must therefore be increased by increasing the number of turns in the coil or introducing a transformer or increasing the permanent magnetic field, all of which are dependent on the volume constraints of a generator system.
2.2.2.1 Magnet Technologies

The magnet is a vital component of the electromagnetic generator. Potentially appropriate magnets for the electromagnetic shoe generator were assessed in terms of shape, size and strength. A hysteresis loop shown in Figure 2.2 identifies the relationship between the induced magnetic flux density (B) and the magnetizing force (H) of a magnetic material and is often referred to as the B-H loop.

![Figure 2.2: Hysteresis or B–H loop of Magnetic Material [31]](image)

Important properties for energy harvesting include the residual flux density (Br, identified by b and e in Figure 2.2) which is the maximum magnetic flux density that remains in a material when the magnetizing force is zero in a closed magnetic circuit. The Maximum Energy Product (BHmax) is measured in MegaGauss Oersted (MGOe) and identifies the quality due to the size and shape of a magnet. Coercivity (Hc) is a measurement of a magnet’s resistance to demagnetization giving the measurement of external magnetic field strength required to magnetise, demagnetise or re-magnetise a material (measured in Gauss or Tesla and identified by points c and f on the hysteresis curve in Figure 2.2) [31]. By considering these properties with all commercially available magnets (Samarium Cobalt, Alnico, Ferrite (Ceramic)) it was identified that the NdFeB was the most suitable magnetic material to be integrated in this work due to the high Br and Hc values achieved. The properties of some of these materials are summarised in Table 2.3. NdFeB (Neodymium-Iron-Boron) materials are the most powerful “Rare Earth” permanent magnet compositions known. They are capable of the highest B, Br, and BHmax of any other magnetic formulation and also carry a very high Hc as presented in Table 2.3. However they are hard to machine, brittle and are
sensitive to both corrosion and high temperatures. Their main advantage lies within the expected power generation, as NdFeB magnets can achieve 4-5 times the power output to that of ceramic magnets and to date this material provides the maximum energy per unit volume of any other commercially available magnetic material [31].

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</thead>
<tbody>
<tr>
<td>5 Cast (Alnico)</td>
<td>12,500</td>
<td>640</td>
<td>640</td>
<td>5.5</td>
<td>540</td>
<td>540</td>
<td>0.253</td>
</tr>
<tr>
<td>6 Cast (Alnico)</td>
<td>10,500</td>
<td>780</td>
<td>800</td>
<td>3.9</td>
<td>540</td>
<td>540</td>
<td>0.250</td>
</tr>
<tr>
<td>2 Sintered (Alnico)</td>
<td>6,600</td>
<td>550</td>
<td>550</td>
<td>1.4</td>
<td>540</td>
<td>540</td>
<td>0.300</td>
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<tr>
<td>5 Sintered (Alnico)</td>
<td>10,800</td>
<td>600</td>
<td>600</td>
<td>3.8</td>
<td>540</td>
<td>540</td>
<td>0.300</td>
</tr>
<tr>
<td>B15S (SmCo)</td>
<td>7,950</td>
<td>6,100</td>
<td>10,500</td>
<td>14</td>
<td>-0.04</td>
<td>150</td>
<td>0.300</td>
</tr>
<tr>
<td>22 (SmCo)</td>
<td>9,850</td>
<td>8,750</td>
<td>12,000</td>
<td>22</td>
<td>-0.03</td>
<td>250</td>
<td>0.300</td>
</tr>
<tr>
<td>27H (SmCo)</td>
<td>11,000</td>
<td>10,300</td>
<td>26,000</td>
<td>28</td>
<td>-0.03</td>
<td>350</td>
<td>0.300</td>
</tr>
<tr>
<td>28 (SmCo)</td>
<td>10,700</td>
<td>10,300</td>
<td>18,000</td>
<td>28</td>
<td>-0.03</td>
<td>350</td>
<td>0.300</td>
</tr>
<tr>
<td>32H (SmCo)</td>
<td>11,600</td>
<td>9,500</td>
<td>14,000</td>
<td>31</td>
<td>-0.03</td>
<td>350</td>
<td>0.300</td>
</tr>
<tr>
<td>4SB (NdFeB)</td>
<td>3,460</td>
<td>3,460</td>
<td>9,600</td>
<td>3</td>
<td>-0.10</td>
<td>150</td>
<td>0.217</td>
</tr>
<tr>
<td>28 (NdFeB)</td>
<td>10,800</td>
<td>10,100</td>
<td>17,000</td>
<td>28</td>
<td>-0.11</td>
<td>150</td>
<td>0.271</td>
</tr>
<tr>
<td>30H (NdFeB)</td>
<td>11,200</td>
<td>10,700</td>
<td>17,000</td>
<td>30</td>
<td>-0.11</td>
<td>150</td>
<td>0.271</td>
</tr>
<tr>
<td>35 (NdFeB)</td>
<td>12,300</td>
<td>11,300</td>
<td>14,000</td>
<td>35</td>
<td>-0.11</td>
<td>150</td>
<td>0.271</td>
</tr>
<tr>
<td>42H (NdFeB)</td>
<td>13,300</td>
<td>12,700</td>
<td>17,000</td>
<td>43</td>
<td>-0.10</td>
<td>120</td>
<td>0.271</td>
</tr>
<tr>
<td>48 (NdFeB)</td>
<td>14,100</td>
<td>12,900</td>
<td>13,500</td>
<td>48</td>
<td>-0.12</td>
<td>80</td>
<td>0.271</td>
</tr>
</tbody>
</table>

2.3 Wearable Energy Harvesting Systems

The available human power predicted by Starner [17] identifies the varying mechanical power levels available at different parts of the body for various activities using simplified calculations and attributes of an average human body (e.g. mass of 68 Kg). Each result was calculated using theoretical formulae, thus the values presented are optimistic, but they do give a good indication of the upper limit of available power from different methods of energy harvesting from the human body i.e. ranging from 6.9 mW from finger motion to 67 W from walking. With this fairly large window of human power available, it might be possible to harvest some of this energy to power some mobile electronic device without affecting the human body’s normal everyday actions which is the main aim in human power harvesting. The widest range of power harvesting devices and technologies which have been developed to date relate to walking.
Chapter 2: Literature Review

The power predicted by Starner [17] may be achieved by converting the energy consumed by the body during everyday actions unobtrusively or intentionally [3], [17]. Intentional power conversion is not new as torches [33], phone chargers [34], [35], [36] and wind-up radios [37], [38] have been on the market for years utilising human energy. Outside of the electromagnetic designs described in the following sections (2.3.2 to 2.3.4) a number of linear type electromagnetic generators have been developed for intentional human energy harvesting. These include the linear electromagnetic generator designed by Steve Vetroino of Applied Innovative Tech [39] which was the first magnetic force flashlight called “NightStar” that is capable of 20 minutes of light after 30 seconds of intentional shaking. This device weighs about 150 g with a volume \( > 100 \text{ cm}^3 \) and is capable of 200 mW with a steady shake at its mechanical resonance (200 cycles/min) [33]. Jung et al [40] have also designed a permanent magnet linear generator similar to the “Nightstar” and it is also excited by deliberate hand shaking but on this occasion can be applied to various loads such as lanterns, mobile phones, mp3 players. The design consists of a cylindrical shaped apparatus with several radially magnetized magnets and circular coils. However with the given structure and dimensions of both designs the power has not been optimised. McCarthy et al [41] have derived a toolbox, which is designed to evaluate and optimise the performance of these air-core linear generators by providing an analytical method to modify magnet geometries and coil structures. This has been shown to increase the generated output energy by 18% when compared to an off-the-shelf design. The toolbox developed by McCarthy is based on specially developed finite element analysis (FEA) which can be achieved more simplistically with commercial software (tools) such as Ansoft Maxwell [42]. The model is also based on a single coil and single magnet structures so the scope for optimisation is limited.

In terms of unobtrusive power much research has been carried out in the areas of body heat [17], [3] and human breathing [43] using thermoelectric [44], [45], [46], electromagnetic [47] and electrostatic generators [2], [48], [49] respectively. A number of reviews have been carried out which describe these and other power harvesting generators that have been integrated around the body. While some of the work presented in these reviews is not directly relevant to this thesis; the power, voltage and volume results are summarised later in Table 2.5 to Table 2.10 to identify how the generators designed in this work compare. These reviews include: Starner and Paradiso [3], Harb [13], Mateu and Moll [50], Reinmann [51], Jia et al [52],...
Romero et al [53] and Cook-Chennault et al [54]. This large range of reviews identifies the large interest in the human energy harvesting field.

### 2.3.1 Walking Power Analysis

![The Gait Cycle](image)

**Figure 2.3:** The Gait Cycle [55]

The simplest model of the human gait can be described as an inverted pendulum (pendulum with its mass above its pivot point) where one leg is swung from one position to the next while the other foot remains in contact with the ground during the transition from one inverted pendulum to the next [56], [57], [58]. A typical gait cycle is the time from when the heel of one leg strikes the ground to the time at which the same heel contacts the ground again [59]. The gait cycle of each leg is divided into the stance phase and the swing phase, where the stance phase is the period of time that the foot is in contact with the ground from heel strike to toe off, while the swing phase is the period of time in which the foot is off the ground and moving forward. During walking the stance phase comprises of approximately 60% of the gait cycle while the swing phase takes up the remaining 40%. This proportion of swing to stance phases alters with increasing speeds of walking or running [60]. The stance phase can be divided into three sub-phases: from heel strike to foot flat (initial contact period), from foot flat to heel off (mid-stance period) and from heel off to toe off (propulsive period) as illustrated in Figure 2.3. The swing phase is the time while the foot is in the air from the toe-off to heel strike. Similarly this swing phase can be divided into three sub-phases: acceleration, mid-swing and deceleration [55], [61] as shown in Figure 2.3.

The power available from the body during this human gait cycle can be extracted using a number of methods and over a range of locations on the body; i.e.
where a number of joints are rotating, where the center of mass of the body is displaced, where legs are swung forwards and backwards and where pressure is applied at the foot. Besides the estimated 67 W (based on foot pressure) predicted by Starner [17] a number of other studies have been carried out to estimate the amount of power that might be available from these various movements the body undergoes while performing the human gait cycle.

During walking, the center of mass of the human body experiences a motion similar to a sine wave with an amplitude of 2.5 cm. Thus, any object being carried by the human body will experience the same movement creating an exchange of energy between both bodies. Through all the activities the human body undergoes, the movement of the legs is one of the most energy consuming. The force the human body’s weight exerts is projected through the legs and thus the force created by the legs is greater than any other part of the body. While a person is walking, they cause 30% more force to be applied to the balls of their feet than provided by their own body weight [17].

The human body can also use mechanical energy for conversion to electrical power by the use of a proof mass attached to the body suffering the same accelerations as the body experiences during walking. Von Buren [62] evaluated the kinetic energy provided by human physical activities such as walking as a source for inertial micro-generators by using acceleration measurements taken on different locations on the human body while subjects were walking on the treadmill. Results identified that four times more energy can be scavenged by these inertial generators when placed on the lower limbs, when compared to the upper body. This is due to more abrupt acceleration changes on the lower limbs than the upper limbs during the normal human gait [53], [63].

Table 2.4 summarises the power levels predicted from a range of studies that predict the mechanical force available from the various walking body movements at a typical walking speed of two steps per second. It is clear from Table 2.4 that maximum power is predicted in the foot during the swing phase of the gait. Leg joint rotation and foot pressure also provide attractive power levels.
Table 2.4: Estimated Power during Gait Cycle

<table>
<thead>
<tr>
<th>Body Movement</th>
<th>Authors</th>
<th>Theory/Assumptions</th>
<th>Walking Speed</th>
<th>Estimated Energy</th>
<th>Theoretical Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Mass Motion</td>
<td>Winter [64]</td>
<td>sine wave with an amplitude of 2.5 cm</td>
<td>2.8 km/hr to 26.6 km/hr</td>
<td>20 J to 150 J</td>
<td></td>
</tr>
<tr>
<td>Center of Mass Motion</td>
<td>Willems et al [65]</td>
<td>- carrying a 20 Kg load - 0.98 m leg length - leg range of motion of 30°</td>
<td>1 m/s</td>
<td>1 W</td>
<td></td>
</tr>
<tr>
<td>Center of Mass Motion</td>
<td>Niu [66], [11]</td>
<td>-50% conversion efficiency -0.2 kg mass</td>
<td>1 m/s</td>
<td>1 W</td>
<td>-100 mW</td>
</tr>
<tr>
<td>Human Vibrations</td>
<td>Moll and Rubio [57]</td>
<td>-60s periods - using accelerometer sensors</td>
<td>constant speed of 4 km/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Vibrations</td>
<td>Von Buren et al [62], [67]</td>
<td>-Walking on the treadmill -most body locations - ankle and knee locations</td>
<td>1 m/s</td>
<td>&gt; 0.5 mW/cm³</td>
<td>&gt; 10 mW/cm³</td>
</tr>
<tr>
<td>Human Vibrations</td>
<td>Romero et al [68]</td>
<td>-68 kg man - half this power is being used in moving the legs [3]</td>
<td>2 steps per second</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Joint Rotation</td>
<td>Morton [69]</td>
<td>-68 kg man - half this power is being used in moving the legs [3]</td>
<td>2 steps per second</td>
<td>324 W</td>
<td></td>
</tr>
<tr>
<td>Human Joint Rotation</td>
<td>Gordon and Robertson [70]</td>
<td>- during the swing phase - mechanical power is maintained at the ankle joint</td>
<td>2 steps per second</td>
<td>5 W</td>
<td></td>
</tr>
<tr>
<td>Human Joint Rotation</td>
<td>Donelan et al [58], [71], Niu [66],</td>
<td>- leading leg performs negative work to redirect the center of mass velocity</td>
<td>1.25 m/s</td>
<td></td>
<td>140 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- simultaneously the trailing leg performs positive work to replace this lost energy</td>
<td></td>
<td>1.07 to 34.9 J/step at various joints</td>
<td>2.1 to 69.8 W</td>
</tr>
<tr>
<td>Foot Pressure</td>
<td>Winter [72]</td>
<td>- mechanical powers at the ankle - number of human subjects - during the push off the foot from the ground.</td>
<td>natural, slow and fast walking speeds</td>
<td>2 to 4.6 W/Kg</td>
<td></td>
</tr>
<tr>
<td>Foot Pressure</td>
<td>Moll [7]</td>
<td>- 80 Kg person - 1.2 m leg - 20 degree gait</td>
<td>1.3 m/s</td>
<td></td>
<td>79 W</td>
</tr>
<tr>
<td>Foot Pressure</td>
<td>Niu et al [66], Shorten [73]</td>
<td>- force in a linear 4mm displacement - 80 Kg user - work was only carried out during compression - during a heel strike</td>
<td>1 Hz (i.e. two step per second)</td>
<td>0.4 to 1.0 J/step</td>
<td>2 W</td>
</tr>
<tr>
<td>Foot Pressure</td>
<td>Starner [17]</td>
<td></td>
<td>1 Hz</td>
<td>67 W</td>
<td></td>
</tr>
<tr>
<td>Foot Swing</td>
<td>Donelan [71]</td>
<td></td>
<td>1 Hz</td>
<td>2 – 4.5 W/kg</td>
<td>400 W</td>
</tr>
</tbody>
</table>
2.3.2 Upper Body Based Systems

By far the lowest amount of mechanical power available from the body while walking is achieved from human vibrations according to the data presented in Table 2.4. Nonetheless, a wide range of electromagnetic and piezoelectric generators have been designed to convert the vibrations experienced by the human body during walking. Typically these generators have been located on the upper body even though four times more power is available on the lower limbs according to Von Buren [67]. The earliest human vibration energy conversion designs have been integrated into watches [3], [74] incorporating electromagnetic technologies. Yeatman [75] investigated the potential power from such electromagnetic devices that exploit rotating proof masses which are excited by linear or rotational motion. He identified that with excitation by linear source motion, the ultimate power levels for rotational and linear internal motion are similar, so the choice between them will depend mainly on practical constraints in particular applications.

Seiko’s Automatic Generating System (AGS) [76] electromagnetic design has been developed by a number of researchers [77], [78], [79] to convert human vibrations, and although the generator volumes are small (<10cm$^3$) the power generated is typically low ($\leq$1mW). The original AGS system utilises an oscillating weight connected to a small permanent magnet generator and produces a worn average power of 5 $\mu$W and is capable of up to 1 mW when forcibly shaken. As these generator designs have typically complicated mechanical coupling components they are outside the scope of this thesis but the power, voltage and volume achieved with a number of such designs are highlighted in Table 2.5 to Table 2.10 for comparison.

According to the mechanical power data in Table 2.4, besides the leg and the foot the center of mass motion is predicted to provide the next best mechanical power during walking. To investigate the power levels achieved to date as a comparison a number of generators utilising this excitation force were reviewed. Conversion of the center of mass displacement using piezoelectric materials has been achieved using a number of novel energy harvesting backpacks that generate electrical energy from the differential forces between the wearer and the backpack. Feenstra et al [80] developed a mechanically amplified piezoelectric stack actuator optimised to replace the strap buckle of a backpack generating 176 mW of average power, while Granstrom et al [5] expanded this concept further by replacing the entire strap of a backpack with a
piezoelectric polymer (PVDF) that generates 45.6 mW of power. In both cases ([80] and [5]) power generated is low considering the user is required to carry extra load in the form of a loaded backpack to achieve this generated power.

The human center of mass displacement has also been investigated for a number of electromagnetic generator designs. Niu and Chapman [11] designed a linear permanent magnet motion harvester fixed initially to an unloaded backpack (<1kg) based on fixed magnets with coils fixed to a spring moving linearly through an air gap. Similarly Elmes et al [16] have incorporated an energy harvesting backpack with a linear generator fixed to the backpack frame, but on this occasion a permanent magnet (PM) shaft connected to a suspended load frame moves linearly through the generator frame (with coils wrapped around it) shown in (Figure 2.4 (b)). Finally Rome et al [21] have developed a different type of electromagnetic generator where a dc motor is excited by the center of mass motion, as shown in (Figure 2.4 (a)). While Niu’s design generates a typical open circuit voltage of ~20V (50-80 mW of power which is increased to 95 mW when slider is oscillating [81]) with a slow walking speed of 0.75 m/s, Elmes’s design provided measured results provided 1 W of electrical power at a walking frequency of 1.5 Hz. Driving the 25:1 geared DC generator up to 5000 rpm on Rome’s design generates up to 5.6 W to 7.4 W of electrical power. However all three designs require heavy weights of 4 kg, 11.33 kg and 38 kg respectively in the backpacks. When compared to the piezoelectric strap generators ([5] and [80]) the power generated by Niu’s design is much smaller even though a backpack is also required. Although all designs produce an attractive amount

Figure 2.4 (a): Backpack Generator [21] (b) Linear Backpack Generator [23]
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of power the structure of the generators required is bulky (volume >>100cm$^3$) before any backpack is attached and the combination would cause a considerable load on the user. These backpack generator designs require the user to attach the generator frame and backpacks on the back before any power is generated thus could fall into the category of intentional generated power.

![Figure 2.5 (a): Backpack Generator [24] (b) nPowerpeg [82]](image)

On a much smaller scale a number of other designs have also been developed to harness the center of mass motion of the human body. Saha et al [24] have designed a linear electromagnetic generator [Figure 2.5 (a)] that converts the human center of mass motion by vibrating a magnet suspended in air using a magnetic spring. Commercially the “nPower Personal Energy Generator (PEG)” [82] is available which is a mass spring system tuned for excitation frequencies experienced on a backpack, in a briefcase or in a purse carried by a person walking or running [Figure 2.5 (b)]. It operates using the same principles to that of Saha’s vertical linear design where a vibrating magnet is passed through a center coil but in this case a mechanical spring is used. While Saha’s design produces only 0.3 mW to 0.95 mW while walking (or 1.86 mW to 2.86 mW while running slowly) in a 12.5 cm$^3$ volume, the PEG is capable of charging an on board 2000 mAh Li-ion battery (capable of 5V, 500mA) in a large 562 cm$^3$ volume. However both designs have to be in the vertical position before any power is generated and even though volume is small (in the case of Saha’s design) they cannot be integrated onto the upper body easily and instead both require a backpack to produce energy.
2.3.3 **Leg Based Systems**

According to the data presented in Table 2.4 up to 324 W of mechanical power is available from the joint rotation on the legs during the human gait cycle. This is of interest here as the mechanical power from this body motion is predicted to be one of the largest and any generators designed here would compete in terms of power with those integrated at the foot. The rotation of these leg joints during the gait cycle can utilise piezoelectric materials [83], although it is much more difficult to exploit this technology unobtrusively in these areas given their nature. In terms of electromagnetic joint rotation converters, Donelan et al [84] and Li et al [85] designed and developed a knee-mounted biomechanical energy harvester (Figure 2.6). The generator system is mounted on a customized orthopedic knee brace and contains a permanent magnet generator and a gear train that converts low velocity and high torque movement at the knee into high velocity and low torque for the generator. Using this generative braking harvesting system a peak power of 20 W was achieved corresponding to an average power of 4.8 ± 0.8 W. Although the power achieved is attractive, this design comes with the undesirable requirement of the user strapping this considerable generator volume (>100cm³) to the knee before any power is generated.

![Figure 2.6: Knee Mounted Biomechanical Energy Harvester [22]](image)

One linear electromagnetic vibrational generator design is interesting due to the optimisation method used. Von Buren and Troster [86] have optimized a linear air-cored tubular electromagnetic generator (presented in Figure 2.7) to power body-worn sensor nodes. The design includes axially magnetized disc shaped permanent...
magnets separated by soft magnetic spacers, an iron-less stator with several coils and a flexible translator bearing. The mechanical resonance frequency and load resistance were optimised to achieve maximum output power, based on acceleration data from various locations on body [62]. Optimised designs in a 0.25 cm³ generator volume were identified, composed of between 6 and 9 magnets and 6 to 10 coils. A prototype generator consisting of six magnets and five coils in a 0.50 cm³ volume provided an average power of 0.35 µW when the generator was mounted below the person’s knee. The outer generator structure of 30.4 cm³ required to provide the linear motion significantly increases the volume of the generator and this reduces the mechanical efficiency of the device.

![Linear Vibration-Driven Electromagnetic Micro-Power Generator](image)

**Figure 2.7:** Linear Vibration-Driven Electromagnetic Micro-Power Generator [86]

### 2.3.4 Foot Based Systems

The area of most interest in this work is generators developed to convert the mechanical power available at the foot during walking. The generator designs described in this section identify how successful this area has been given the large power available at this location, as well as the opportunity to integrate such designs in a shoe.

#### 2.3.4.1 Piezoelectric Generators

Harvesting foot pressure during the human gait using piezoelectric materials can be viewed as the most sensible approach and one of the first projects that investigated how the energy dissipated in the shoe could be tapped for usable electric
power was carried out in MIT [8], [9] using this technology. MIT investigated two actions of the foot as potential parasitic power sources; striking of the heel against the ground and the bending of the sole. The work focused on a displacement of < 1 cm (13 W of calculated power) which is the distance a normal padded sports shoe deforms [73]. Kymissis et al [9] investigated and compared two types of piezoelectric generator designs, one to harness the heel strike energy (Thunder PZT) and the second to harness the energy bending of the sole (PVDF (polyvinylidenefluoride) as the foot leaves the ground. The PDVF stave with a total source capacitance of 330 nF is laminated in a bimorph design with 28 micron sheets (10 x 8 cm² area) of PVDF around a 1 mm plastic substrate, linked with a stretched hexagon electrode pattern and laminated in two 8-layer stacks on each side of the substrate. While the PZT unimorph was a modified strip (180 nF capacitance) integrated in 7 x 7 cm² area and bonded to a curved piece of 7 x 9.5 cm² spring steel with a 7 mm range of motion. The PZT unimorph and PVDF bimorph stave were tested in the heel of a size 11½ (US) Nike Air running shoe as shown in Figure 2.8.

![Figure 2.8: PZT unimorph and PVDF “Stave” Laminate Foil bimorph Inserted in Shoe [8]](image)

At a relatively fast walking pace of around 2 Hz from an average 68kg weight person, voltage peaks of about ±60 V are produced by the PVDF stave with a 7 mm range of motion in the 3-1 mode. While the PZT unimorph with a 7 mm deflection also in 3-1 mode measured significantly larger results approaching 150 V, corresponding to peak power levels of 20 mW and 80 mW for the PVDF and PZT respectively. Corresponding average powers however are poor due to the high load resistance required given the source capacitance nature of the materials and the low walking frequency. The PVDF is capable of only 1.1 mW while the PZT averages at just under twice that at 1.8 mW. Further development of these materials achieved a
similar peak power level but an improvement in average power was recorded across the gait as it increased to 1.3 mW and 8.4 mW for the PVDF and PZT respectively [87].

While the generated peak voltages are large the corresponding power is low in both cases due to a 250 kΩ load required for maximum power. When compared to electromagnetic designs, much lower load resistances (<100 Ω) provide maximum power. This work is also interesting due to the fact that power is only generated while the foot is in contact with the ground during each step (stance phase of gait) so there are large periods of zero induced voltage. These periods of zero induced power result in low average power levels. For such a large area the power produced by the PVDF material is low even though there is no significant obtrusion on the user. While the PZT provides larger average power there is significant obtrusion on the user to deflect the material 7 mm, which is not an attractive feature of the design. Both of the piezoelectric designs encapsulate a much larger area than planned for the generators designed in this work.

Further work has been carried out by a number of researchers to improve the performance of piezoelectric materials embedded in the shoe sole. Wang [88] investigated a range of PVDF and PZT piezoelectric materials with various dimensions in the shoe sole and demonstrated a power of up to 5.04 mW with a certain PVDF material, which is more than twice that achieved by Kymissis’s investigation [8]. Fourie [89] developed a horseshoe shaped rubber frame to house two polycarbonate plates, fifteen elongated rectangular PVDF unimorph strips bonded to cyanoacrylate, standing vertically and connected electrically in parallel which is then slotted into the heel of a running shoe. At a walking frequency of 1 Hz the generator induces a peak voltage of 21 V corresponding to 0.06 mW of power when connected to an optimum load of 470 kΩ. Considering that this generator consumes the total heel area (~43 cm³ volume) of a shoe the generated average power is low. Finally Mateu et al [90] have designed two piezoelectric films connected in parallel (total capacitance of 22nF) excited in 3-1 mode inside each shoe’s total area corresponding to load resistance of 500kΩ to achieve maximum power. Initial results from the generated voltage waveform resulted in peak power of 18 µW which is low given the large area consumed by the generator. Even though it can be envisaged that piezoelectric shoe inserts should be a suitable means of harvesting the mechanical energy dissipated during the normal gait cycle (particularly the stance phase), the
power results presented in this section are poor (<10mW) considering such a large area of the shoe sole has been utilised by all the designs discussed.

2.3.4.2 Electromagnetic Generators

Using pistons, cams and flywheel mechanisms pressure exerted at the heel can be also converted into electrical energy using electromagnetic generators. However the added mechanical friction due to stroke to rotary conversion causes efficiency to be reduced. Starner and Paradiso [3] discussed how the energy dissipated during walking could be recovered using rotary and spring systems, without creating an extra load on the user. Such a system was designed by Jim Gilbert from the University of Hull for Trevor Baylis’s walk in the Namibian Desert [91]; using an off the shelf dynamo in the heel of a boot, which was spun with the energy stored in a spring each time the heel hit the ground, inducing a small amount of current when the spring energy was transferred to the generator. They encountered a problem of transferring the generated power from the shoe generator so instead charged a battery on shoe and transferred it to a phone when it was needed.

Figure 2.9 (a): Hand Crank Flashlight on Heel [8] (b) Rotary Magnetic Generator [10]

Another method of extracting power from the heel strike was investigated at MIT Media lab by coupling the downward force to a standard electromagnetic generator [8]. In this way a hand crank driven flashlight was attached to the side of the shoe and the generator was cranked by a lever that was extended under the heel of the shoe and depressed by each downward step as shown in Figure 2.9 (a). When the electromagnetic generator was excited at a normal walking frequency it converted a 3 cm deflection during the heel strike which produced a peak power of 1 Watts corresponding to an average power level of 250 mW. This rotary generator is capable of powering a wide range of applications and was demonstrated powering a common
transistor radio. In a bid to improve this energy conversion method a further variation of this design using a rotary arm and an electromagnetic generator [10] was investigated as illustrated in Figure 2.9 (b). The design consists of two dc motors ran as generators which are rotated due to the deflection of the rotary arm. The arm would be compressed by 3.2 cm during each step and so the converted rotary motion needs to be stepped up by a gearbox (a gear ratio of 1:42 was used). With a moderate walking pace where the generator heel hits the ground once per second an average voltage of 4.2 V is reported, with a corresponding peak power level of 1.61 W and 58.1 mW average power.

These three electromagnetic designs are similar as they all require a rotary arm extended from the shoe to achieve rotary motion of the embedded generator. This of course is not ideal as a rotary arm extending out from a person’s shoe will cause considerable discomfort during the normal gait cycle as well as being dangerous. All designs also include complex mechanical systems and coupling which may not be suited to the harsh environment of the shoe sole. Although the power generated is often high (1W and 58.1 mW) it is poor when compared to the linear electromagnetic generators (>1W) described in section 2.3.2 designed for the center of mass motion, which according to the data presented in Table 2.4 has less human mechanical power available.

![Figure 2.10 (a): Opposing Magnetic Plate Generator [92], (b) PM Magnetic Machine with Spring [66]](image)

A number of other electromagnetic generators have been developed to convert the linear heel strike during the stance phase of the human gait. Watanabe et al [92] designed a heel generator consisting of an iron case, two permanent magnetic plates
that face each other with two coils arranged between them Figure 2.10 (a). Another electromagnetic design similar to Watanabe’s opposing magnet generator has been achieved using a spring rather than the repulsion force between magnets. Niu et al [66] built a system to use the heel strike in the form of a PM linear generator where a spring was incorporated to store the mechanical energy as illustrated in Figure 2.10 (b). Watanabe reported poor AC voltage of less than 200 mV Pk-Pk, while Niu achieved a useable voltage level of 3.5 V (corresponding to 4 W) from a 1 cm deflection by an 80 Kg (800 N) person at a 1 Hz walking speed. Watanabe identified no magnetic material for the magnetic plates and no consideration was given for how these strong magnet plates would affect the user. Niu also provided no further analysis especially on how the force required to push the rather large spring together affected the gait cycle. Although both generators are designed for integration into the shoe heel no specific dimensions were given, and with Niu’s design it can be assumed for the structure to achieve a 1 cm linear motion it would have to be at least 2 cm in height which would not be acceptable for shoe integration.

![Figure 2.10](image)

Figure 2.10 (a): Soldier Power Regeneration Kit (SPaRK) [93], (b) Horizontal Foot Motion Generator [12]

A Soldier Power Regeneration Kit (SPaRK) [93] has been developed by the U.S. Army that converts the 6 Joules of energy expended on the stance foot during the 20% and 40% stages of the gait cycle. The design of the generator mounted in parallel to a combat boot, incorporates a nylon cord that pulls a ball-screw (and a spring) that rotates a motor as the leg rolls over the ankle of the stance foot during the swing phase of the gait (shown in Figure 2.11 (a)). Average power levels of 2.5 W and 3.5 W have been generated at walking speeds of 4.8 km/hr and 6.4 km/hr respectively. This obtrusive design is focused more for a soldier’s boot rather than an everyday walking/running shoe, and is attached to the outside of the boot all the way up the
back of the heel to well above the ankle. Again power levels are attractive but the
design is big and bulky and includes complex mechanical couplings which are not
ideal at the back of the foot.

In terms of a low volume design Romero et al [94] exploited an axial flux
generator, which is also based on the Seiko AGS mechanism to convert oscillations
produced by body motions at the ankle. The $2 \text{ cm}^3$ generator structure produced 117
$\mu$W of power when placed laterally on the ankle while walking on a treadmill at 3
mph (1.34 m/s) [95]. This low volume makes it suitable for integration into the shoe,
however the power generated is particularly low for such a high mechanical powered
area. A number of resonant linear electromagnetic designs have been investigated to
sliding coil generator worn on the outside of the shoe. Zeng et al [12] (Figure 2.11
(b)) and Stamenkovic et al [96] have proposed flat type linear permanent magnetic
generators to convert the human horizontal foot motion to electrical power. Both
designs consist of a double sided stator linear machine, with a moving translator with
opposing magnetised polarity permanent magnets and soft magnetic spacers fixed to
an end wall with a spring. Niu and Chapman’s design is capable of producing an open
circuit voltage of 27 V with an average power of 80 mW and although no actual
dimensions were provided, it can be expected that the volume of the generator is not
suitable for integration into the shoe. Even though voltage and power levels are
attractive it is required that the generator is strapped to the outside of the shoe which
is not an unobtrusive design. Zeng and Stamenkovic’s designs predict resonant
movement of the magnets that correspond to 8.5 mW/cm$^3$ and 59.05 mW (in a 10 cm$^3$
volume) respectively. Both these designs include attractive power results but no
physical generator system has been achieved to date. Furthermore no analysis on how
the magnet would be excited during the normal gait was introduced or how the
magnet would oscillate during the various phases of the gait cycle, or if the spring
would be effective in the shoe sole environment.

### 2.3.5 Human Power Summary

Based on the reviews that are available on human energy harvesting, as well as
the generators that have been described in this chapter, a clear picture of the actual
electrical power available from the body can be achieved. Power levels available from
sources such as body heat, and body movements based on piezoelectric,
electromagnetic and electrostatic generators are presented. The power levels achieved are compared in Table 2.5 to Table 2.10, which summarise the performance of all the human energy harvesting work that has been identified in terms of location on the body, power generated, voltage, generator volume, etc. The generator designed in this work will attempt to compete with the technologies discussed as an alternative useful power source from the body. The main goal of the generators designed in this work is to generate a usable power (10 mW to 100 mW) in a small volume (<50 cm$^3$) that is unobtrusive to the user, something a large number of the generators presented in the following tables fail to do.

**Table 2.5: Body Heat and Breathing Human Power**

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Freq</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermolife [3]</td>
<td>Body Heat</td>
<td>1.5 – 3.0 V</td>
<td>40 µW</td>
<td>0.5 cm$^2$</td>
<td>-</td>
<td>5°C</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>eTEG [3]</td>
<td>Body Heat</td>
<td>-</td>
<td>16 – 36.5 mW</td>
<td>-</td>
<td>-</td>
<td>10 K</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Tashiro [43]</td>
<td>Breathing</td>
<td>-</td>
<td>36 µW</td>
<td>-</td>
<td>6 Hz</td>
<td>180 bpm</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Leonov [46]</td>
<td>Body Heat</td>
<td>-</td>
<td>62 µW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Leonov [46]</td>
<td>Body Heat</td>
<td>-</td>
<td>2.8 mW</td>
<td>76.8 cm$^3$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>LPTG [50]</td>
<td>Body Heat</td>
<td>4.0 V</td>
<td>20 µW</td>
<td>-</td>
<td>-</td>
<td>20 K</td>
<td>15 µW/cm$^2$</td>
</tr>
<tr>
<td>7</td>
<td>ZnO Nanowire [52]</td>
<td>Breathing</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.7 – 11 mW/cm$^2$</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Flipsen [53]</td>
<td>Body Heat</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1°C</td>
<td>13 µW/cm$^2$</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Review [54]</td>
<td>Body Heat</td>
<td>0.25 – 2.3 V</td>
<td>1 µW - 184 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>Carasco [97]</td>
<td>Body Heat</td>
<td>-</td>
<td>1.5 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Yang [98]</td>
<td>Body Heat</td>
<td>-</td>
<td>1 – 2 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Lossec [99]</td>
<td>Body Heat</td>
<td>-</td>
<td>-</td>
<td>1.4 m/s</td>
<td>-</td>
<td>7 – 30 µW/cm$^2$</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Huang [100]</td>
<td>Body Heat</td>
<td>-</td>
<td>40 - 520 µW</td>
<td>-</td>
<td>-</td>
<td>3 – 15°C</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>NanoRibbons [101]</td>
<td>Breathing</td>
<td>-</td>
<td>0.01 µW</td>
<td>1 cm$^2$</td>
<td>32 Hz</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 2.6: Center of Mass Motion Human Power**

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Freq</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Galstrom [5]</td>
<td>Center of Mass</td>
<td>-</td>
<td>45.6 mW</td>
<td>-</td>
<td>-</td>
<td>100 lbs. Load</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Niu [11]</td>
<td>Center of Mass</td>
<td>20 V</td>
<td>50 – 80 mW</td>
<td>-</td>
<td>-</td>
<td>1 kg Load</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>Elmes [16]</td>
<td>Center of Mass</td>
<td>-</td>
<td>0.86 – 21.15 W</td>
<td>-</td>
<td>1.5 Hz</td>
<td>1.7 cm Amp 11.3 kg Load</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>Rome [21]</td>
<td>Center of Mass</td>
<td>-</td>
<td>5.6 – 7.4 W</td>
<td>-</td>
<td>4 – 6.4 km/hr</td>
<td>4.5 cm Amp 38 kg Load</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>Kim [53]</td>
<td>Center of Mass</td>
<td>18 – 198 mV</td>
<td>-</td>
<td>-</td>
<td>0.5 – 8 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>Arakawa [53]</td>
<td>Center of Mass</td>
<td>-</td>
<td>6 µW</td>
<td>-</td>
<td>10 Hz</td>
<td>1 mm Amp</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>Amirtharajah [54]</td>
<td>Center of Mass</td>
<td>-</td>
<td>400 µW</td>
<td>-</td>
<td>2 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>Feenstra [80]</td>
<td>Center of Mass</td>
<td>-</td>
<td>176 – 400 mW</td>
<td>-</td>
<td>2.75 Hz</td>
<td>50 lbs. Load</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Niu [81]</td>
<td>Center of Mass</td>
<td>-</td>
<td>95 mW</td>
<td>105 cm$^3$</td>
<td>0.75 m/s</td>
<td>4 kg Load</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>Khaligh [102]</td>
<td>Center of Mass</td>
<td>-</td>
<td>6 + 37 mW</td>
<td>49 cm$^3$</td>
<td>2 Hz</td>
<td>3 cm Amp</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>Farmer [103]</td>
<td>Center of Mass</td>
<td>3 V</td>
<td>-</td>
<td>482.6 cm$^3$</td>
<td>1-2 Hz</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
## Chapter 2: Literature Review

### Table 2.7: Vibrational Human Power

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Saha [24]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>0.3 – 2.86 mW</td>
<td>50 cm$^3$</td>
<td>2 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>Nasiri [47]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>1 mW</td>
<td>1.7 in$^3$</td>
<td>0.3 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>Najafi [53]</td>
<td>Human Vibrations</td>
<td>6 mV</td>
<td>120 nW - 3.97 µW</td>
<td>500 µW</td>
<td>1 – 10 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>Miao [54]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>80 µW</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>Cavallier [53]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>62 nW – 0.5 µW</td>
<td>6 Hz</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>31</td>
<td>AGS [76]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>5 µW – 1 mW</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>32</td>
<td>Wang [77]</td>
<td>Human Vibrations</td>
<td>3 V</td>
<td>15 mW</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
<td>Najafi [53]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>15 – 170 µW</td>
<td>1 – 2 Hz</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>Von Buren [86]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>0.35 µW</td>
<td>0.5 cm$^3$</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>Romero [94]</td>
<td>Human Vibrations</td>
<td>59.4 mV</td>
<td>3.9 µW</td>
<td>1.5 cm$^3$</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>36</td>
<td>Romero [95]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>117 µW</td>
<td>2 cm$^3$</td>
<td>1.34 m/s</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>37</td>
<td>Naruse [104]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>40 µW</td>
<td>9 cm$^3$</td>
<td>2 Hz</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>38</td>
<td>Dallago [105]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>6 mW</td>
<td>10 Hz</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>39</td>
<td>Arnold [106]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>-</td>
<td>1.5 – 4 cm$^3$</td>
<td></td>
<td>-</td>
<td>0.5 mW/cm$^3$</td>
</tr>
<tr>
<td>40</td>
<td>Minazara [107]</td>
<td>Human Vibrations</td>
<td>-</td>
<td>3.5 mW</td>
<td>12.5 Hz</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2.8: Human Body Pressure Power

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>Yaglioglu [6]</td>
<td>Body Pressure</td>
<td>-</td>
<td>3 W</td>
<td>3 cm$^3$</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>42</td>
<td>Kymissis [9]</td>
<td>Body Pressure</td>
<td>1.8 Vrms</td>
<td>250 mW</td>
<td></td>
<td>3 cm</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>43</td>
<td>Kymissis [9]</td>
<td>Body Pressure</td>
<td>-</td>
<td>1 – 2 mW</td>
<td>2 Hz</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>44</td>
<td>Hayashida</td>
<td>Body Pressure</td>
<td>4.2 V</td>
<td>58.1 mW</td>
<td>166.46 cm$^3$</td>
<td>3.2 cm</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>SRI [26]</td>
<td>Body Pressure</td>
<td>-</td>
<td>800 mW – 1 W</td>
<td>2 step/s</td>
<td>3 mm/mms</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>46</td>
<td>Enocean [50]</td>
<td>Body Pressure</td>
<td>3.3 V</td>
<td>6.9 – 19 mW</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>47</td>
<td>Antaki [53]</td>
<td>Body Pressure</td>
<td>-</td>
<td>150 – 700 mW</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>48</td>
<td>Niu [66]</td>
<td>Body Pressure</td>
<td>3.5 V</td>
<td>4 W</td>
<td>1 Hz</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>49</td>
<td>Shenck [87]</td>
<td>Body Pressure</td>
<td>-</td>
<td>1.3 – 8.4 mW</td>
<td>2 Hz</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>Wang [88]</td>
<td>Body Pressure</td>
<td>-</td>
<td>5.94 mW</td>
<td>2 Hz</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>51</td>
<td>Fourse [89]</td>
<td>Body Pressure</td>
<td>21 V</td>
<td>0.06 mW</td>
<td>1 Hz</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>52</td>
<td>Wantabe [92]</td>
<td>Body Pressure</td>
<td>200 mV pk-pk</td>
<td>-</td>
<td>2.4 cm$^3$</td>
<td>5 mm/mms</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>53</td>
<td>Wang [108]</td>
<td>Body Pressure</td>
<td>12 – 16.5 V</td>
<td>2.45 – 4.63 mJ</td>
<td>0.15 – 0.45</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>54</td>
<td>Continum Control [109]</td>
<td>Body Pressure</td>
<td>-</td>
<td>3.7 – 12.3 mW 55 – 180 mW</td>
<td>1.6 cm$^3$ 2.4 cm$^3$</td>
<td>1 Hz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>55</td>
<td>Rahim [110]</td>
<td>Body Pressure</td>
<td>0.3 -2 V</td>
<td>-</td>
<td>1 step/s</td>
<td>200 - 600 N</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2.9: Arm Swing Human Power

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>Niu [11]</td>
<td>Arm Swing</td>
<td>7 V</td>
<td>10 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>Nightstar [33]</td>
<td>Arm Swing</td>
<td>-</td>
<td>200 mW</td>
<td>-</td>
<td>&gt;10 Hz</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>Renaud [53]</td>
<td>Arm Swing</td>
<td>-</td>
<td>40 µW</td>
<td>&lt; 1 cm³</td>
<td>1 Hz</td>
<td>10 cm Amp</td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>Renaud [53]</td>
<td>Arm Swing</td>
<td>-</td>
<td>47 – 600 µW</td>
<td>14 cm³</td>
<td>10 Hz</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Li [111]</td>
<td>Arm Swing</td>
<td>-</td>
<td>0.3 µW</td>
<td>-</td>
<td>6.5 Hz</td>
<td>42 mm Amp</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.10: Leg Motion Human Power

<table>
<thead>
<tr>
<th>No.</th>
<th>Research</th>
<th>Body Source</th>
<th>Generated Voltage</th>
<th>Generated Power</th>
<th>Volume/Area</th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>Niu [11]</td>
<td>Leg Motion</td>
<td>27 V</td>
<td>80 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>Zeng [12]</td>
<td>Leg Motion</td>
<td>-</td>
<td>-</td>
<td>116.48 cm³</td>
<td>1.75 Hz</td>
<td>40.9 cm Amp</td>
<td>8.5 mW/cm³</td>
</tr>
<tr>
<td>63</td>
<td>Platt [53]</td>
<td>Leg Motion</td>
<td>2.7 V</td>
<td>50 – 225 µW, 0.85 – 4.8 mW</td>
<td>1.2 cm³</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>Lewandowski [63]</td>
<td>Leg Motion</td>
<td>-</td>
<td>8 – 690 µW</td>
<td>0.25 cm³</td>
<td>1 Hz</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Pozzi [83]</td>
<td>Leg Motion</td>
<td>-</td>
<td>5 – 7 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>Donelan [84]</td>
<td>Leg Motion</td>
<td>-</td>
<td>~ 4.8 W</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>SParK [93]</td>
<td>Leg Motion</td>
<td>-</td>
<td>2.5 – 3.5 W, 9.2 W</td>
<td>-</td>
<td>4.8 km/hr</td>
<td>6.4 km/hr</td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>Stamenkovic [96]</td>
<td>Leg Motion</td>
<td>-</td>
<td>53.79 – 59.05 mW</td>
<td>10 cm³</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>Turri [112]</td>
<td>Leg Motion</td>
<td>-</td>
<td>849.4 µW – 2.5 mW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

2.4 AC/DC Conversion Circuitry

Due to the intermittent and spontaneous nature of energy harvesting sources, they cannot provide an unlimited supply of energy, and so any device that is intended to utilise this harvested power must be designed so that its demands are capable of being met. At the heart of energy harvesting technologies described in the previous sections is the generated AC voltage. This AC voltage must be converted into a stable DC voltage so that it can be used in some application, be it charging a battery or powering of a sensor. The bridge rectifier is a common source of AC/DC conversion but with generated voltages produced by energy harvesting sources often being lower than the forward barrier voltage of a diode (0.3V to 0.7V), this may not be possible. Much of the work presented up to this point has exploited these simple AC/DC conversion methods as the focus was mainly on the generation aspect of the technology.

The concept of synchronous rectification was introduced to reduce power losses produced by the diodes in DC/DC regulators. These power losses are reduced by
replacing the diodes with MOSFETs with a low on resistance. Similarly this technology can also be exploited to reduce the power loss created by the diodes in AC/DC circuits, thus increasing the conversion efficiency, which is critical for these low voltage energy harvesters. The following paragraphs will discuss all the AC/DC conversion methods that have been developed to date for electromagnetic conversion to achieve a usable DC power from electromagnetic energy harvesting technologies.

The electromagnetic damping force that achieves maximum energy conversion can be altered by the resistance of the load connected to the coil. To reduce the effect of diode voltage drops in conversion circuitry the voltage source voltage must be much greater than 1 V in order to achieve a usable DC output voltage. For an electromagnetic generator to achieve high voltage a large coil length or large number of coil turns is required (2.1). However, this leads to problems of higher self-inductance (related to the square of the number of turns); longer time period to achieve maximum current and high resistive losses [14].

The problem with walking as a source of energy is the voltage waveform tends to be of a discontinuous pulsed nature, having bursts of AC pulses followed by often significant periods of no voltage unless the generator is capable of resonating. The most obvious method of utilising this energy source effectively is by storing the converted energy in devices such as capacitors, inductors and/or batteries. The converted power is then available when demanded. One of the main objectives in this work is to develop analytic models that enable identification of conditions for maximum output power for different AC/DC conversion circuits with typical wearable generator voltage waveforms applied. Not much research has considered the case where there are large periods of zero induced voltage into the AC/DC conversion circuit. Ottman et al [113] developed an analytical model to predict the AC/DC performance of a piezoelectric transducer through a full bridge rectifier. As the models are based on a piezoelectric source the source capacitance of the piezoelectric element is significant in the models, which is not the case with electromagnetic generators. The models were also based on a continuous generator voltage source and so did not have to implement long periods of non-zero voltage. The final results predicted that peak output power is proportional to the output voltage, source piezoelectric current and source capacitance. This design was further developed by Ottman et al [114] to also model the performance of a DC/DC converter where the optimum duty cycle to produce maximum DC power was predicted.
One method of converting low level (<1V) electromagnetic source voltages is to combine the AC/DC conversion and DC/DC conversion into a single circuit. Mitcheson et al [14] proposed that both the positive and negative half cycles of the generated voltage (195 mV) are separately processed by two synchronous rectification boost converter circuits (operating in discontinuous conduction mode [DCM]). This proposed design has yet to be demonstrated and is also based on a constant voltage supply with no zero voltage periods at the source. A number of similar converter topologies operating in DCM have also been designed by Dawri et al [15], [115] and Dayal et al [116], [117] for direct AC/DC conversion for low voltage AC generators (Figure 2.12) with a 400 mV source voltage using a single inductor and a bidirectional switch (achieved with two MOSFETs). While these designs attempt to improve the conversion efficiencies (~50% with an output power of 50 mW and output voltage of 3.3 V in the case of Mitcheson’s design and ~60% with an output power of 54.5 mW and output voltage of 3.3 V for Dawri’s) the models developed to predict the performance of these circuits are based on a constant sinusoidal source voltage with source frequencies of up to 100 Hz. Although these designs are effective for a low voltage source <1V the constant 100 Hz sinusoidal source allows DC/DC conversion to be implemented effectively as much lower output capacitance is required at the AC/DC output than with pulsed voltages produced during walking.

If diodes are not used most full wave rectifier circuits using synchronous rectification and CMOS technology are achieved with a number of MOSFET’s and the control circuitry to switch these transistors on or off. To improve conversion efficiency a number of circuits have been developed to achieve passive full wave rectification using low on resistance CMOS transistors where the gate signals of the
MOSFETs are connected to the source voltage. To overcome the problem of no control over the current flow in the circuit Peters et al [118], Rao and Arnold [119] have implemented a second stage with an active diode (Figure 2.13) to stop current that can flow back if the output voltage is higher than the input. However, both designs are based on continuous sinusoidal source voltage levels of 0.5 V [120] to 1V or higher (1.25 V to 3.75 V) with source resonant frequencies of 20 Hz (Rao) and 170 Hz (Peters), corresponding to power efficiencies of 82.4 % and >95% respectively. Once more the design requires a constant sinusoidal source voltage and a source excitation frequency not achievable during a normal gait to be provided for the conversion to be effective. In all cases no models have been presented to predict the performance the circuits, but it can be expected that these could be achieved easily due to the source voltage used.

![Figure 2.13: Passive and Active Rectifier [118]](image)

The problem of large source impedances (required to achieve >1V output voltages) of energy harvesting transducers is one that can restrict maximum power output when different loads are attached. The aim of energy harvesting design is to establish maximum power output for every attached load and this can mainly be achieved with proper impedance matching. A number of AC/DC conversion designs have implemented intelligence to provide maximum output power no matter what load is attached to the low source voltage generator. Maurath and Manoli [121] developed an adaptive interface inserted between an AC/DC MOS rectifier and output DC buffer or active diode [122]. A maximum power point tracking (MPPT) algorithm for a full wave rectifier and cascaded boost buck converter circuit combination has been optimised by Zeng et al [12] to deliver maximum harvested DC energy from the unconventional electromagnetic low frequency foot generator presented earlier. Elmes [16] has combined a boost converter operating in continuous conduction mode (CCM)
with digital control, a MPPT algorithm and a full wave rectifier for a < 2 Hz AC source generated from a backpack generator [23]. Niu et al [81] have also combined a full wave rectifier with a boost converter circuit that was controlled with an impedance matching circuit, which controlled the input current to the boost converter. These MPPT methods have been demonstrated to provide improved conversion efficiencies over the entire load resistance range with > 90% for a 168 Hz source [121], 80% for a 1.75 Hz source [12], > 95% for a < 2Hz [16] and 80-85 % for 6 V to 10 V source voltages [81]. Although these MPPT conversion designs are promising they are based on constant high frequency/low voltage sources or constant high voltage/low frequency sources, which is difficult to achieve with human power harvesting. Once more the performance of these conversion designs would be much more difficult to predict or achieve with a generator source voltage with large zero voltage periods.

A number of regular AC/DC conversion rectifier circuits implementing synchronous rectification to reduce diode voltage drops, have also been developed for human energy harvesting designs. Niu et al [11] utilised both voltage doubler and voltage tripler rectifiers incorporating synchronous rectification (using comparators and MOSFETs) for the linear electromagnetic generators described in section 2.3.4. Shuo et al [123], [124] have also implemented a synchronous rectification method on a voltage doubler circuit with a comparator (560 nW). While Saha et al [125] have implemented synchronous rectification with analogue switches and low power consumption comparators (0.5 µW). Shuo [123] achieved conversion efficiencies of 74% – 92% for 100mV to 1V source amplitudes while Saha [125] achieved conversion efficiencies of 80 – 85% for 230 mV (260 µW at 14 Hz resonant frequency) and 350mV (17.5 µW at 53 Hz resonant frequency) source amplitudes. The main drawback of these designs is that an external power source was provided for the comparators (and analogue switches) so they cannot be classified as a self-sufficient energy harvesting design. Analytical models were developed by Saha [125] to predict the performance of the circuit and these compared well to measured results. These models were again based on the electromagnetic energy harvesters which have a continuous sinusoidal source voltage with frequencies of 14 to 53 Hz.

One option available to low source frequency energy harvesting designers is to charge a supercapacitor with the rectified generator voltage, which can then provide a constant DC source for the various load applications. Wang et al [126] have applied a
Schottky rectifier with a Single-Ended Primary Inductor Converter (SEPIC) to achieve DC power from a backpack generator [21]. Due to the low 2 Hz frequency and discontinuous nature of the generator source, a bank of six 2.5 F supercapacitors is used to store the generated DC energy, where frequency and capacitance are related by \( f = \frac{V_o}{(R_{\text{load}} \times \Delta V \times C)} \). The problem with this type of design is the charging time constant associated with these large capacitance supercapacitors, meaning that a usable DC voltage would not be available to the load application for a certain amount of time especially when low generator currents are involved. Olivo et al [127] have developed a clever design to overcome this problem by using a switched capacitor technology as an intermediary between the supercapacitor and a lower capacitance output capacitor to reduce time for a usable DC voltage to be available for the load application.

Clearly there is much interest in methods of efficiently converting low voltage and low frequency source voltages from energy harvesters. However, while each design is novel and efficient, they mainly do not consider the intermittent nature of the source especially for walking, thus analytical models to predict circuit performance are easier to achieve. Table 2.11 compares all the AC/DC conversion methods discussed in this section 2.4. The source frequency and conversion method are of most interest.
Table 2.11: Low Voltage AC-DC Conversion Circuit Performance – Electromagnetic

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Source Frequency</th>
<th>AC Voltage</th>
<th>AC Power</th>
<th>Conversion Method</th>
<th>DC Voltage</th>
<th>DC Power</th>
<th>Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic [14]</td>
<td></td>
<td>195 mV</td>
<td></td>
<td>Dual Boost Converter</td>
<td>3.3 V</td>
<td>50 mW</td>
<td>-</td>
</tr>
<tr>
<td>Electromagnetic [15], [115]</td>
<td>100 Hz</td>
<td>400 mV</td>
<td></td>
<td>Direct AC/DC using Buck/Boost Converter</td>
<td>3.3 V</td>
<td>-</td>
<td>- 60 %</td>
</tr>
<tr>
<td>Electromagnetic [116]</td>
<td>108 Hz</td>
<td>400 mV</td>
<td>17 %</td>
<td>Direct AC/DC using Boost Converter with Control Circuitry</td>
<td>3.3 V</td>
<td>10 mW</td>
<td>55 %</td>
</tr>
<tr>
<td>Electromagnetic [117]</td>
<td>100 Hz</td>
<td>400 mV</td>
<td></td>
<td>Direct AC/DC using Buck/Boost Converter</td>
<td>3.3 V</td>
<td>-</td>
<td>61 %</td>
</tr>
<tr>
<td>Electromagnetic [118]</td>
<td>170 Hz</td>
<td>1.25 – 3.75 V</td>
<td>162 µW</td>
<td>Passive Full Bridge and Active Rectifier</td>
<td>2.0 V</td>
<td>154 µW</td>
<td>95 %</td>
</tr>
<tr>
<td>Electromagnetic [120]</td>
<td>3 kHz</td>
<td>350 - 500 mV</td>
<td>21.1 µW</td>
<td>Passive Full Bridge and Active Rectifier</td>
<td>-</td>
<td>19 µW</td>
<td>90 %</td>
</tr>
<tr>
<td>Electromagnetic [121]</td>
<td>168 Hz</td>
<td>1.5 V</td>
<td>221 µW</td>
<td>Rectifier with Load Matching Detector &amp; Interface</td>
<td>2.4 – 2.6 V</td>
<td>210 µW</td>
<td>90 – 95 %</td>
</tr>
<tr>
<td>Electromagnetic [122]</td>
<td>125 kHz</td>
<td>2.0 – 3.0 V</td>
<td></td>
<td>Passive Full Bridge and Active Rectifier with Load Matching Detector &amp; Interface</td>
<td>2.0 – 2.5 V</td>
<td>-</td>
<td>80 %</td>
</tr>
<tr>
<td>Function Generator [119]</td>
<td>20 Hz</td>
<td>1 V</td>
<td>0.425 mW</td>
<td>Full Bridge Rectifier with Synchronous Rectification</td>
<td>-</td>
<td>0.350 mW</td>
<td>82.4 %</td>
</tr>
<tr>
<td>Function Generator [123]</td>
<td>20 Hz</td>
<td>1 V</td>
<td>0.652 mW</td>
<td>Voltage Doubler with Synchronous Rectification</td>
<td>-</td>
<td>0.6 mW</td>
<td>92 %</td>
</tr>
<tr>
<td>Electromagnetic [126]</td>
<td>2 Hz</td>
<td>20.31 W – 20.32 W</td>
<td>Full Bridge Rectifier with SEPIC Converter</td>
<td>5 V &amp; 15 V</td>
<td>16.14 W</td>
<td>17.90 W</td>
<td>79.46 % - 88.09 %</td>
</tr>
<tr>
<td>Electromagnetic [125]</td>
<td>14 Hz &amp; 53 Hz</td>
<td>230 mV &amp; 350 mV</td>
<td>262.5 µW &amp; 18.2 µW</td>
<td>Voltage Multiplier Circuit</td>
<td>450 mV &amp; 1.2 V</td>
<td>210 µW &amp; 15.5 µW</td>
<td>79 – 85 %</td>
</tr>
<tr>
<td>Electromagnetic [127]</td>
<td>0.5 Hz</td>
<td>1.6 V – 3.3 V</td>
<td></td>
<td>Rectifier with Supercapacitor and Switched Capacitor</td>
<td>2.4 V</td>
<td>26 mW</td>
<td>-</td>
</tr>
<tr>
<td>Electromagnetic [12]</td>
<td>1.75 Hz</td>
<td>1.4 V</td>
<td>1 W</td>
<td>Full Bridge Rectifier with Buck Boost Converter with MPPT</td>
<td>3.7 V</td>
<td>0.83 W</td>
<td>80 %</td>
</tr>
<tr>
<td>Electromagnetic [11]</td>
<td>2.5 Hz</td>
<td>7 V – 27 V</td>
<td>30 mW – 330 mW</td>
<td>Voltage Doubler and Tripler with Synchronous Rectification</td>
<td>12 V</td>
<td>10 mW – 90 mW</td>
<td>27 % - 33 %</td>
</tr>
<tr>
<td>Electromagnetic [81]</td>
<td>0.75 – 1.8 m/s</td>
<td>6 V – 10 V</td>
<td>112.5 mW – 423.5 mW</td>
<td>Full Bridge Rectifier with Boost Converter with Input Current Control</td>
<td>7.5 V</td>
<td>90 mW – 360 mW</td>
<td>80 % - 85 %</td>
</tr>
</tbody>
</table>

2.5 State-of-art Portable Power Systems

2.5.1 Portable Power Sources

For now, electrochemical batteries (secondary or rechargeable) are generally considered as the main power source for portable electronic systems and wireless sensor networks due to their portability, modularity and practicality. The Iphone for instance is supplied by a lithium-ion 3.7 V battery (with energy densities of up to 620
Wh/L) which is capable of delivering many hours of performance depending on the numbers of applications being used [128].

![Figure 2.14: Energy Gap of Mobile Device (2010) [129]](image)

However, while a variety of choice of mobile phone/mp3 player/digital camera designs and technologies are available to consumers today, the slow changing battery technology offers little or no choice on how each device may be powered. Battery energy density (measured in Wh/Kg or Wh/L or gravimetric energy density) has obviously one of the most important roles in mobile computing yet it follows one of the poorest trends in this field as shown in Figure 2.14. Ajith [130] recently described how battery technology has been scaling at a rate of 2 times every 10 years while the semiconductor technology is scaling twice every 18 months [129]. This is a similar trend to that seen by Paradiso and Starner [131], [3] nearly ten years previously. While the lithium-ion secondary battery technology currently provides maximum energy density (250 -620 Wh/L), new technologies currently being developed (including lithium-polymer [132], lithium-air [133] and lithium-sulphur [134]), aim to provide 3 – 10 times the energy density available from the lithium-ion technology.

The demand for primary and secondary batteries will continue to rise over the next number years as everyday new portable electronic devices are being developed with more and more power hungry electronics. Thus alternative power sources are currently becoming a heavily researched area. Paradiso and Starner [3], Saez [28], Cook-Chennault [54] and Roundy [135] have all discussed alternative technologies to secondary macro-scale batteries. These include ultra-capacitors, microscale batteries
[136], [137], radioactive power sources [138], [139], micro-heat engines [140], [141], and microfuel cells [142], [143] all of which are still at a development stage. Fuel cells are the most attractive alternative to batteries as hydrocarbon fuel cells have a much higher energy density. Methanol has an energy density of 17.6 KJ/cm³ which is about 6 times that of a lithium battery and is a very attractive and promising source of power. The challenge lies in fitting the chemistry, fuel, plumbing and ventilation into a space the size of a matchbox [144]. The purpose of the work presented in this thesis is to replace these energy sources and storage devices as much as possible, or to supplement them by charging while the human body is active.

2.5.2 Portable Power Requirements

Nowadays there is a demand for portable electronic devices to be capable of complex and sophisticated performances with an intensive number of operations per unit time, but at the same time with reduced power consumption. Portable electronic devices have become a critical part of modern life and communication. Laptops have high power consumption of the order of 10 – 40 W and no harvesting technique demonstrated to date would be able to replace this type of power demand. Devices such as mobile phones, mp3 players, and PDA’s, although not as power hungry as laptops still require power levels that are outside the current scope of a portable power harvester. The overall power consumption of personal handheld electronic devices depends on the device itself as well as the operation being carried out, but typically power is required in the Watt [52] or high mW range which would typically be outside the scope of a human energy harvester. The Iphone for example has many applications such as Bluetooth, Wi-Fi, Video, Mp3, Phone, and etc. all with different power requirements. In the future however it is envisaged that the power requirements of these devices will reduce to levels which can be addressed by harvesting methods.

Power harvesting design is dependent on the power consumption of the portable device the harvester is intended to power, as the size of the harvesting device required may be not be realistic in terms of portable power. Hahn and Reichl [145] described three categories of portable devices; (i) the wearable computer main unit such as a notebook, (ii) small devices which are distributed around the human body and (iii) active tags that are situated around the user’s environment which enable situated and ubiquitous computing. This review focuses mainly on the first two
situations where devices are either carried by a person or integrated into their clothing or accessories.

### Table 2.12: Power Requirements of Power Electronic Devices Available Today

<table>
<thead>
<tr>
<th>Devices</th>
<th>Voltage requirements</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop while Idle (iMac) [146]</td>
<td>16-19V</td>
<td>94 W</td>
</tr>
<tr>
<td>iMac Laptop while active –Max CPU [146]</td>
<td>16-19V</td>
<td>241 W</td>
</tr>
<tr>
<td>MP3 Walkman (Sony) [147]</td>
<td>1.5V-3V</td>
<td>60 mW up to 1.25W</td>
</tr>
<tr>
<td>Mobile phone during a call (Nokia) [148], [149]</td>
<td>3.6V</td>
<td>up to 2W</td>
</tr>
<tr>
<td>Mobile phone sleeping (Nokia) [148]</td>
<td>3.6V</td>
<td>80mW</td>
</tr>
<tr>
<td>Mobile phone used as MP3 player (Nokia) [148]</td>
<td>3.6V</td>
<td>310mW</td>
</tr>
<tr>
<td>Ipod Touch/ Iphone Processor [128], [150]</td>
<td>3.7V</td>
<td>180 mW</td>
</tr>
<tr>
<td>Ipod Touch/ Iphone (Average) [128], [151], [152]</td>
<td>3.7V</td>
<td>3 – 5.7 Watts</td>
</tr>
<tr>
<td>GPS (S-911 Lapisc) [153]</td>
<td>4.2</td>
<td>420 mW</td>
</tr>
<tr>
<td>PDA (palm) [154]</td>
<td>3.7V</td>
<td>40 mW – 2 W</td>
</tr>
<tr>
<td>Digital Camera [155]</td>
<td>3.7 V</td>
<td>555 mW to 3.3 W</td>
</tr>
</tbody>
</table>

Table 2.12 describes the power requirements of some of the main portable electronic devices available today. Ideally the generator designed in this work would be capable of powering these devices. However, each of the different processes involved in operating all devices requires a minimum power level which is generally higher than that produced by available wearable generators. At the lower scale a PDA for instance requires in the region of 100 mW during a memory intensive operation, but during sleep mode only 20 mW is required which is more achievable for typical energy harvesting sources. Given the relatively high power requirements of the above applications, a more suitable application for utilising human energy harvesting would be a human wireless sensor network where harvested power could be applied to individual microprocessors, sensors and transceivers.

Hanson et al [156] described how non-invasive body area sensor networks (BASNs) provide novel applications in healthcare, fitness and entertainment. Yeatman [157] has broken up a human sensor network into the sensing elements, signal conditioning, data storage, data transmission versus the available power and demonstrated how each stage of the sensor network might utilise the available power from different power harvesting technologies. Mitcheson et al [2] identified that for a biosensor application the power consumption could be <10 µW which could be easily achieved with energy harvesting. A typical BASN interface is achieved using an
energy source, one or more sensors, a mixed-signal processor and a communication transceiver. The power consumption of low power embedded processors can range from 0.93 mW to 1.4 mW when running at a frequency of 0.75 MHz [52] and even at a 1 V supply transmitters can now run with an average power consumption of < 10 mW [158]. Mathuna [159] identified power requirements of pressure, displacement and acceleration sensors for biomedical applications to be between 1 and 35 mW. More recently Stojcev et al [160] have presented the power requirements of the current crop of microprocessors (5.4 µW to 60 mW), radio transmitters (1.8 mA to 37 mA) and sensor nodes (0.09 mW to 9 mW). All of which identifies that a sensor network powered by energy harvesting techniques is now possible.

Table 2.13: Generator Demonstrator Possibilities

<table>
<thead>
<tr>
<th>Devices</th>
<th>Voltage</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedometer [161], [162]</td>
<td>1.5 V - 2.5 V</td>
<td>0.2 mW</td>
</tr>
<tr>
<td>Temperature sensor [163]</td>
<td>2.25 V – 3.6 V</td>
<td>160 µW</td>
</tr>
<tr>
<td>Pressure Sensor [164]</td>
<td>3.3 V – 5 V</td>
<td>11.6 mW</td>
</tr>
<tr>
<td>Blood Pressure sensor [165]</td>
<td>3 V</td>
<td>0.5 mW</td>
</tr>
<tr>
<td>Accelerometer [166]</td>
<td>2 V – 3.4 V</td>
<td>94 – 160 µW</td>
</tr>
<tr>
<td>Microcontroller (MSP430) in active mode</td>
<td>1.8 V - 3.6 V Typ: 2.2 V</td>
<td>352 µW 1.54 µW</td>
</tr>
<tr>
<td>in Low Power Mode (from TI) [167]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital clock [168]</td>
<td>1.3 V</td>
<td>13 mW</td>
</tr>
<tr>
<td>μprocessor (Freescale) (active) (Standby)</td>
<td>1.8 to 3.6 V</td>
<td>180 mW 0.25 mW</td>
</tr>
<tr>
<td>[169]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flash Microcontroller [170]</td>
<td>2 V</td>
<td>350 µW</td>
</tr>
<tr>
<td>LED [171],[172], [173]</td>
<td>1.6 – 5 V</td>
<td>8.6 - 100 mW</td>
</tr>
<tr>
<td>Small radio FM(Philips) [174]</td>
<td>1.5 V – 3 V</td>
<td>40 mW up to 0.5 W</td>
</tr>
</tbody>
</table>

Due to these lower voltage and power requirements of microprocessors and sensors, the power levels provided by power harvesting from the body does have the potential for powering some commercial applications; these are summarised in Table 2.13. These devices could realistically be powered by human generators as both the voltage and power level requirements have been demonstrated in one form or another.

If the power (upper and lower) and voltage requirements of the applications described in Table 2.12 and Table 2.13 are compared to the human harvesting generator power that have been designed to date, a clear picture is achieved as demonstrated in Figure 2.15. The high power requirements (>100 mW) of the portable electronic devices presented in Table 2.12 are difficult to achieve with power
harvesting methods. Although three of the human generators presented here do produce suitable power levels (>100mW), it is identified in section 2.3 that this power was achieved with obtrusive generator designs (>100 cm³) such as backpack and knee brace generators. The goal of this work is the design of an unobtrusive generator that can generate usable power levels that match the power requirements in the highlighted area in Figure 2.15 (devices listed in Table 2.13). A number of generators already in the literature do achieve these power levels as seen in Figure 2.15 but once more this is mainly at the expense of a large generator volume. For this work to be successful the generator should achieve the required power and voltage levels (highlighted in Figure 2.15) but with an unobtrusive volume of <50 cm³ and also be comparable or better than the previously designed generators that fit in this area.

![Figure 2.15: Power Requirements vs. Harvested Power](image)

2.5.2.1 Shoe Integrated Generator Applications

In terms of a suitable final application a wireless sensor demonstrator system may be applied in the shoe sole that could be applied for gait analysis or for a fitness application. Previously Benbasat et al [175] and Morris and Paradiso [176] developed a shoe-mounted gait analysis system called the wireless shoe sensor stack. The system consists of piezoelectric sensors embedded in the shoe sole where power is supplied via a typical 9 V battery converted to 5 V and 3 V using a regulation board. The requirement for such a system can range from developmental maturation, fall detection to recovery from a stroke. A similar such shoe sensor system for monitoring the condition of the feet was patented by Brown [177] but on this occasion the
Chapter 2: Literature Review

sensors, microprocessor and power source were all embedded in the shoe sole. Zemel and O’Donnell [178] developed a “Pediatric Dynamometer” [179] embedded in the soles of children’s shoes to investigate weight bearing activity and how it impacts on bones.

In terms of a fitness application something similar to the Adidas® [180] which incorporates a microprocessor system embedded within the shoe sole may be possible. It uses a sensor, a microprocessor and a motorised cable system (all powered by a battery) to automatically adjust the shoe’s cushioning. The sensor measures the compression on the sole and detects whether the shoe is too soft or firm, that information is sent to the microprocessor which in turn tells the cable to adjust the heel cushion while the shoe is in the air. A further end application would be comparable to a concept that exists commercially where Nike® [181] and the Apple Ipod® [182] have come together to create a pedometer transceiver system called the “Nike + iPod Sport Kit” [183]. The system operates by placing the sensor (with a transmitter) powered by a battery into a built-in pocket beneath the insole of the Nike shoe and attaching the receiver to the iPod. When the user walks the pedometer functionality is displayed on the LCD screen of the iPod, recording the number of steps, calories burnt, distance travelled and average speed.

2.6 Conclusions

This chapter accomplishes a number of the objectives set out in the introduction of this thesis. The mechanical power developed by the body during walking is reviewed and found to be an attractive human energy source with vibrations, center of mass motion, joint rotation, foot pressure and foot swing motions all available. Maximum mechanical power is predicted during joint rotation and at the foot during both the swing and stance phases of the gait cycle. To date only one generator has been successful in converting the large energy available at the knee during the gait cycle. This is achieved however with a large $80 \text{ cm}^3$ electromagnetic design that is not unobtrusive to the user. Thus analysis has identified that the maximum potential for harvesting of energy around the human body occurs in the feet during walking or running, and therefore this work focuses on the design of generators integrated into the shoe. Based on this analysis it is proposed that the two generator structures to be
designed in this work should convert both phases of the gait cycle; one to convert the stance phase and the other to convert the swing phase.

Even though the mechanical power available from human center of mass (CoM) motion is predicted to be less than that available at the foot, a number of generator designs have been successful in achieving significant power levels, much higher than designs located at the foot. Many of these CoM designs however require large backpack frames and heavily loaded backpacks to achieve the generated power levels. Most of these CoM designs incorporate electromagnetic technologies and as such require volumes >100cm³ as shown in Figure 2.16, which has a significant impact on the user.

![Figure 2.16: Generator Power Vs. Volume](image)

In all body locations; electromagnetic and piezoelectric generator designs are the most developed in terms of human energy harvesting, especially at the foot. Piezoelectric can be viewed as the most realistic in terms of converting the human foot pressure (given the nature of the materials), but a number of attempts have failed to achieve significant power levels. Electromagnetic generator designs located at the foot have been more successful in generating more electrical power than the piezoelectric generators. However, these electromagnetic designs tend to be bulky (volume >100cm³) and obtrusive to the user and so cause a significant hindrance to the user to achieve these power levels. Figure 2.16 compares the generated power
achieved by the generators discussed in this chapter and the generator volumes required to achieve these levels. The electromagnetic generators are highlighted in red, the piezoelectric generators highlighted in blue, while a small number of the other generator technologies are highlighted in green. Vibrational electromagnetic generator designs have much smaller volumes and can be integrated onto the user more efficiently. However, the usable power is significantly reduced when converting normal human vibrations associated with walking. The piezoelectric designs although more integrable (especially into the shoe sole) provide much less power. For the generators designed in this work to be successful the power levels would need to compare with the electromagnetic levels while the volume would need to match the piezoelectric designs.

The aim of Figure 2.17 is to demonstrate how the volumes of some of these generator structures compare to a standard man with a height of 5’10”. A scale of 15 cm = 5’10” has been used for both the human and generator structures. While the generator volumes are presented in cubes rather than as their actual structures the volume shown are a true representation of the size when compared to a 5’10” tall man. The CoM generator designs are represented by the volume of generator alone without considering the volume of the backpack. Clearly the generator designs developed to date that provide attractive power levels cannot be integrated onto the user unobtrusively especially those located at the foot. Both generator structures designed in this work would ideally have to be integrable into the shoe sole of a size 10 sports shoe with dimensions of 28x7x3 cm³ available. Although a more unobtrusive approach would be to fix the generator location to the heel of the shoe sole, which provides only 10x7x3 cm³ of available space. This approach would achieve a generator volume of <50cm³ which is an objective of this work as it has not been accomplished to date. Size 10 is also chosen due to the testability provided by the author. The generator designs will provide methods of optimising for all sizes of shoe. The designed generators need to be integrated unobtrusively into this area without adding significant extra weight or strain on the user that would impact the normal gait cycle as seen with the previous generators described in this chapter.
Figure 2.17: Scaled Man vs. Scaled Generator Volumes (Picture courtesy of www.fallingpixel.com)

Figure 2.18 compares the generated power achieved by the generators discussed in this chapter and the generator corresponding voltages. Again the different technologies are colour coded as in Figure 2.16. Given the nature of the piezoelectric materials the piezoelectric generator designs generate much higher voltage levels when compared to the electromagnetic generators. But as can be seen from Figure 2.16 the corresponding power levels are significantly less. This is because of the large resistance required (kΩ range) to achieve maximum power due to the source capacitance nature of the materials.
Based on the power, volume and voltage achieved by the generators investigated in this chapter, the electromagnetic technology is chosen as the technology upon which both generators designed in this work will be based. To date no electromagnetic generator design has been integrated into the shoe sole successfully. Some of the most successful electromagnetic generator structures have been linear in nature and one such design is chosen in this work to convert the foot swing phase energy. Although the linear structure is not new, the novelty lies in integrating it into the shoe sole which has not been attempted previously. The second generator designed in this work to convert foot pressure (stance phase) will also be linear in nature and will attempt to be integrated into shoe sole without the requirement of a lever. While a number of researchers have exploited accelerometer data to predict excitation forces available on the body for vibration type generators, none have utilised this technology to predict the forces acting on a linear type generator embedded into the shoe sole. One design has presented an opposing electromagnetic type structure but no significant results were provided and so the stance phase linear electromagnetic generator developed in this work is therefore also a novel concept.

Electromagnetic generator designs tend to generate much less voltage and this poses a problem when converting to DC voltage. In order to achieve a usable DC voltage the number of coil turns need to be increased corresponding to much higher source impedance. A number of AC/DC conversion designs incorporating
synchronous rectification have been successful in reducing the conversion losses, thus the generated source voltage and corresponding source impedance can be reduced. However the problem lies in the startup of these designs as well as providing power to turn on the MOSFET gates of these circuits. The majority of AC/DC conversion circuits that are discussed in this chapter are all based on a continuous sinusoidal electromagnetic source. They do not consider the periods where no excitation of the generator is achieved. Thus it is easier to predict the performance of these AC/DC circuits. One of the goals of this work is to predict the performance of AC/DC conversion circuits that have a source voltage with periods of zero induced voltage, something that hasn’t been achieved to date. A successful electromagnetic design should generate enough voltage (>1V) with the least amount of turns possible while the conversion circuit applied to convert this voltage to DC, dropping the least amount of voltage possible.

Another aim of this chapter is to identify portable electronic devices or systems that may be powered by this technology. The limited advances in battery technology pose a significant problem for the portable electronic devices industry today and the need for alternative power sources is clear. However, from this review it is also clear that portable electronic devices such as mobile phones or digital cameras cannot be powered by human harvesting methods alone, especially those that are designed to be unobtrusive to the user. Due to the location of the foot where the designed power source will be applied a number of suitable demonstrator loads are investigated. Power is difficult to extract from the foot unobtrusively and so an on shoe application is required. Such applications include; a sensor system to aid in gait analysis or a fitness application that analyses the user’s performance. A more realistic approach would be to design a novel self-powered pedometer system with power requirements between 10 mW to 100 mW and this is identified as the application that is to be powered by the generator designed in this work as it is a power level more achievable by unobtrusive generator designs.
3. **Chapter 3 - Shoe Integrated Electromagnetic Generator Design**

3.1 **Introduction**

The conclusions from Chapter 2 identified that the maximum energy available from harvesting from the human body is while walking or running. Based on the objectives of this work this chapter will aim to; design two unobtrusive electromagnetic generators to be integrated into the shoe sole that convert the energy generated while walking into usable electrical energy, identify the excitation forces that will be applied to them, investigate both their mechanical and electromagnetic models and derive analytical models to predict their electrical performance. An opposing magnet structure is developed to convert the stance phase of the gait cycle while a sliding magnet structure is developed to convert the swing phase of the gait cycle. The opposing magnet structure has been identified in a previous design [92] but no proper characterisation and optimisation for a shoe sole integration has been achieved. The linear type electromagnetic generator developed in this chapter is similar in principle to previous energy harvesters [16], [39] but in this work the proposed structure is a micro-scale design for integration in a shoe where higher power levels can be harvested without deliberate effort from the user. Unobtrusive integration into the shoe sole of an electromagnetic generator design has not been achieved to date and this chapter outlines the design procedure to achieve this for both designs.

As the energy dissipated during walking or running is the power source for these generators, accelerometer measurements are investigated initially in order to identify the excitation forces that may be applied to electromagnetic generator structures incorporated into the shoe. As both generator structures have not been embedded in a shoe sole previously no such excitation force investigation has been carried out to date. The mechanical mass-spring-damper model is also investigated to predict the motion of the moving magnet mass. An optimum magnet material and associated structure is identified in order to achieve the maximum flux linkage results for the generator designs.

Both electromagnetic generator designs are described in section 3.2 in terms of structure, operation, design and Finite Element Analysis (FEA). A detailed
electromagnetic model for the generator is developed to address the inter-relation between magnetic flux distribution, coil length, and coil resistance. Analytical models are explored through the design of a software user interface where generator variables selected by the user are applied to predict the open circuit voltage output from the chosen generator design. These models are developed to enable prediction of the performance of both generator structures for a given fixed available area. A novel method for predicting the optimum generator coil length is also derived in section 3.3. Prototype structures for both generators are analysed and built based on the same magnets, walking excitation frequency and number of coils. Measurements from both structures are analysed in section 3.4 to identify the power achieved and to demonstrate which of the two structures provides maximum power at the foot unobtrusively. These measurements also allow verification of the analytical models that have been developed.

3.2 Generator Principles of Operation

Several generator structures may be considered, whereby voltage is induced in response to relative motion produced between magnet and coil structures during walking. The sliding magnet generator (SMG) presented in Figure 3.1 (a) is designed to convert the swing phase of the gait cycle while the opposing magnet generator (OMG) presented in Figure 3.1 (b) is designed to convert the stance phase of the gait cycle [184]. The basic structure of the SMG is illustrated in Figure 3.1 (a); it consists of a disk magnet which is free to slide up and down through a cylindrical coil similar
Chapter 3: Shoe Integrated Electromagnetic Generator Design

to those described in [4] and [39]; i.e. there are no springs or other fixtures used to connect between the magnet and the coil or former. In this case, when the coil is fixed horizontally in the shoe sole as shown in Figure 3.1 (a), the pendulum motion of the foot during walking maintains bidirectional movement of the magnet through the coil during the swing phase of the gait cycle (when the foot is off the ground). It should be noted that so long as the magnet mass, m, is much lower (at least 100 times less) than the mass of the foot, M, continuous movement of the magnet is sustained by forces exerted normally by the foot during walking, and there is no significant or deliberate effort needed from the user as in the case of [39]. The application of springs to form a resonant structure as discussed in [4] & [185] was not considered, because the structure is intended to harvest power for a range of walking speeds, which will vary from time to time and from person to person. Saha [24] previously showed that with only one fixed opposing magnet on the end of his design the displacement of the center magnet could be increased, which identified that by reducing the effect of the spring and increasing the magnet displacement in the system, power can be increased. The linear generator designed in this work also utilises this principle where maximum magnet displacement is achieved at the expense of no mechanical spring in order to maximise generated power.

To convert the mechanical power available during the stance phase of the gait cycle (when the foot is on the ground), the OMG illustrated in Figure 3.1 (b) was investigated. The OMG maximises the vertical movement of the foot, specifically when the heel is in contact with the ground. This generator consists of 2 magnets, one of which is fixed to the inside of the shoe sole, while the other is free to move vertically up and down parallel to the fixed magnet through a coil. The 2 magnets are oriented so that their forces repel one another. Therefore, during a typical gait cycle the magnets are pushed together by the force of the wearer taking a step during the stance phase, while the repulsive force acts to separate the magnets between steps during the swing phase. As before, voltage is induced in the coil due to the changing magnetic flux.

The opposing generator is similar to Saha’s [24] design; however Saha’s vertical tube generator which contains a center permanent magnet suspended in air due to the repulsive force between it and two further magnets fixed at either ends with the same polarization. In this way the center magnet is repelled by both ends allowing it to move up and down freely. This OMG concept has also been investigated
previously in the heel area [92] with two opposing magnetic plates, one fixed and one moving due to heel pressure and magnetic opposing forces. However, that design includes an iron core which would significantly increase the weight of the generator while the OMG in this work consists of only magnets and coils in a much lighter structure. Similarly, the extent of the magnetic field in that design is large enough that the magnets may interact with other ferromagnetic materials in the environment external to the shoe and as highlighted in Chapter 2 no proper consideration was given to this.

Several smaller magnets are used in this work, whose fields are limited to the thickness of the shoe sole. While this approach is more active in that the user needs to apply a force against the opposing magnets, the optimum design requires that this opposing force is not felt by the user and should be no more than experienced when deflecting a regular shoe sole. Thus, the scope for magnet movement in the shoe is limited if the normal gait of the user is to be maintained.

As both generator structures are designed to convert the energy generated during the human gait unobtrusively, magnet movement in each structure would ideally take advantage of the pulses of movement seen in the foot during the different stages of each step. In the case of the SMG the swing motion of the human foot forces magnets to slide through a long generator structure placed along the length of the heel of the shoe sole. While foot forces during the stance or pressure phase (from heel-strike to toe-off) causes opposing magnets to be forced together. The analysis in section 3.2.1 identifies accelerations experienced by the foot during each step in the gait. Based on measured values of acceleration, the force experienced by each generator magnet can be estimated and a model of how both generator structures perform mechanically based on foot movement can be achieved. A mechanical model of the magnet inside the generator structure is also described.

3.2.1 Foot Excitation Forces

3.2.1.1 Sliding Magnet Generator

Prediction of the exact force acting on the magnet versus time during walking is difficult because the force exerted by the user varies hugely with walking speed and style. In order to assess the two main phases of foot movement in more detail an accelerometer and data-logger [186] were used to measure the forces encountered at
Chapter 3: Shoe Integrated Electromagnetic Generator Design

the heel of the foot during normal activities. Therefore, measurements performed using an accelerometer attached (using strong tape) to the outer heel of a shoe were applied to predict the magnet motion. As force \( F = ma \), by identifying the acceleration or number of \( g \) (\( g = 9.8 \text{ ms}^{-2} \)) acting on a certain location of the foot the excitation force and direction of force can be identified using an accelerometer. Two individual accelerometers from Analog Devices were used with ranges of +/-10g [187] and +/-18g [188]. Results of horizontally and vertically directed acceleration measured at the heel of the foot using the +/-10g accelerometer are presented in Figure 3.2 for 3 steps. These were produced by attaching the accelerometer at the centre to the outer side of the shoe heel.

Vertical acceleration has a constant offset of –g, indicating when the foot is at rest. The offset in horizontal acceleration in Figure 3.2 may be explained by a non-zero orientation of the sensor with respect to gravity. The time instants of foot action are marked in Figure 3.2 (a) to clarify how acceleration varies during foot motion. In both vertical and horizontal results, it is observed that the g-force is lower during lift-off (against gravity) indicated by TO (Toe-off) in Figure 3.2 (a), than when the foot is returning after stepping indicated by HS (Heel-Strike) in Figure 3.2 (a), where forces of over 4 g are apparent.

(a)

![Graph showing vertical and horizontal acceleration](image)
forces exerted for a walking rate of 1.5 steps per second. Positive components of magnet of the SMG during the foot swing. Results in Figure 3.2 (a) are typical g-

The horizontal acceleration results indicate the forces that are applied to the magnet of the SMG during the foot swing. Results in Figure 3.2 (a) are typical g-forces exerted for a walking rate of 1.5 steps per second. Positive components of horizontal and vertical acceleration are defined relative to the shoe as indicated. Note that since an accelerometer measures the force acting on a reference mass that is free to move within a package that is fixed to the body under test, the g-acceleration shown in Figure 3.2 (a) may be taken as the actuating forces applied to the magnet. In
this case, measured g-acceleration includes the combination of user applied forces
during walking and gravity. The forces applied to the SMG structure require further
analysis. Consider all the inertial forces applied at the start of a step from heel-off as
indicated in Figure 3.2 (a) where it is assumed that the magnet is positioned towards
the front of the heel. This is verified in photographs 1 and 2 in Figure 3.2 (b), where
the magnet can be seen at the position indicated (by the red arrow) inside a transparent
plastic tube attached to the outer side of the shoe.

In Figure 3.2 (a), is seen that after an initial forward force (+ve acceleration)
associated with lifting the heel (HO = Heel-off) in Figure 3.2 (a)) from the ground,
there is a net backward horizontal acceleration (-ve acceleration with respect to the
shoe) of between 1 – 2 g measured as the foot is lifted against gravity after toe-off
(TO). For a coil with an unconnected magnet inside, the corresponding horizontal
forces acting on the magnet are shown in Figure 3.2 (c). These include the actuating
inertia force as measured by the accelerometer, \(-F_{hm}\), (minus to follow the reference
directions defined in Figure 3.2 (a)) and friction, \(F_{fr1}\), which depends on the reaction
force between the magnet and the coil former acting in the vertical direction, and can
be taken as minus the measured component of the vertical force, \(F_{vm}\), in Figure 3.2
(a). Initially, the magnet remains in contact with the generator structure, but as the
foot is lifted after heel-off (HO), \(-F_{vm}\) decreases thereby also causing reduced friction,
\(F_{fr1}\). Taking \(-F_{vm}\) at an average of 0.5mg (kg·ms\(^{-2}\)) during this phase and a coefficient
of static friction, \(\mu_s\), of 0.4 for metal–plastic, frictional force, \(F_{fr}\), is estimated by:

\[
F_{fr} = \mu_s F_{vm} = 0.5\mu_s mg \tag{3.1}
\]

reducing to 0.2mg (kg·ms\(^{-2}\)) for a magnet mass, \(m\). When compared with a backward
actuating force of greater than 1mg (kg·ms\(^{-2}\)), it is clear that the magnet will be
propelled backwards relative to the coil. This is evident in photographs 3 and 4 in
Figure 3.2 (b). Magnet motion continues until it reaches the stop end of the coil
former, with which it impacts. Estimated results of velocity are included in Figure 3.2
(a) where the net negative acceleration, \(-F_{hm} + 0.4F_{vm}\), was integrated with respect to
time from the instant when \(-F_{hm} > 0.4F_{vm}\). The velocity was reset to 0 once the
magnet travelled 100 mm, indicating that the magnet impacted with the stop end of
the coil former.
In a similar manner, forward motion of the magnet can be explained by forces exerted during the swing phase of the foot forward, when the horizontal force acting at the heel, measured in Figure 3.2 (a) is of the order of 2 – 3 g. Corresponding horizontal forces acting on the magnet are the same as described above; i.e. \( F_{hm} \) as measured by the accelerometer and friction, \( F_{fr2} \), as shown in Figure 3.2 (d), with a reaction force \(-F_{vm}\) acting in the vertical direction. During this phase, it is seen that as \( F_{hm} \) increases, so too does \(-F_{vm}\) and estimation of the corresponding frictional force, \( F_{fr2} \), indicates that it is large enough to prevent magnet motion. (Using \( \mu_s = 0.4 \) as before, with \(-F_{vm}\) taken as \( 2mg \) \((\text{kg} \cdot \text{ms}^{-2})\), maximum frictional force is estimated as \( 0.8mg \) \((\text{kg} \cdot \text{ms}^{-2})\) vs. \( F_{hm} \sim 1g \)). However, it is found that just before heel strike, when \( F_{hm} \) is increasing towards a maximum, \(-F_{vm}\) and as a result friction, \( F_{fr2} \), both decrease as the heel lifts before striking. Taking \(-F_{vm} = 0.5mg \) \((\text{kg} \cdot \text{ms}^{-2})\) and \( \mu_s = 0.4 \), \( F_{fr2} \) is again estimated as \( 0.2mg \) \((\text{kg} \cdot \text{ms}^{-2})\) acting against \( F_{hm} \) of over \( 2g \) and therefore the magnet slips forward through the coil towards the toe end of the shoe, where it remains until after the toe-off phase of the next step. Estimated magnet velocity in Figure 3.2 (a) is slightly higher during this phase due to higher actuating force, and this is confirmed by measurements of induced voltage presented in Chapter 4.

In a generator structure with an attached load, once the magnet starts moving a current is induced in the coil, and an electromagnetic force, \( F_{em} \), will act against the motion of the magnet. However, it is shown in section 3.3.1.1.1 that the magnitude of this force is of the order of 12.4 mN which is much lower than the forces acting to produce magnet motion in either direction, and therefore it does not significantly impact on the magnet motion. Furthermore, it may be deduced that the associated electromagnetic reaction force imposed by the moving magnet on the user (through the coil) is negligible when compared with the user applied forces of several g acting on the mass of the foot and shoe. Further work presented in Chapter 4 investigates the generator effects on user gait by comparing accelerometer measurements with and without the generator attached.

Acceleration was also measured while running. On this occasion the 18 g accelerometer was utilised, with +10 to −4 g of acceleration measured in the horizontal direction and +4 to −6 g in the vertical direction. Figure 3.3 (a) and (b) illustrate both the horizontal and vertical accelerations experienced by the accelerometer during these running measurements. Much larger acceleration results can be seen in both the horizontal and vertical directions. However the generator
designs will focus on the lower acceleration achieved at the heel during walking in order to identify what can be generated through normal everyday use. The increased generator power (compared to that of walking power) that can be achieved during running is identified by measurements in Chapter 4.

![Graphs of horizontal and vertical accelerations](image)

Figure 3.3: (a) Horizontal acceleration and (b) Vertical acceleration of heel when running.

### 3.2.1.2 Opposing Magnet Generator

Based on the vertical acceleration results presented in Figure 3.2 it is clear that maximum vertical force that may be applied to the opposing magnet structure is achieved during the heel strike (HS). However, these acceleration results are not capable of identifying the force applied underneath the heel of the shoe sole during the stance phase. A range of studies have been carried out [189], [190] that have identified the pressure applied at the heel during a normal gait cycle. While all have
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identified a mean heel pressure of > 200 kPa (1 Pa = N/m² or kg/ms²) a study using a BioFoot® sensor [191] measured a mean heel pressure of 253 kPa based on 30 subjects with a mean weight of 68 kg. As pressure is calculated based on force and area \( (p=F/A) \), the force applied during a heel strike is estimated to be 1771 N (kg·m/s²) based on a heel area of length 100mm and width 70 mm. For a user with a weight of 68kg (average weight) this corresponds to an acceleration of \( \sim 26 \text{ m/s}^2 \) or \( \sim 2.66 \text{ g} \), which is less than the acceleration measured for the SMG. Clearly for the opposing magnet structure to be effective the opposing magnetic force between the magnets must be \( << 1771 \text{ N} \) so that the normal gait is not affected.

3.2.2 Mechanical Models

3.2.2.1 Sliding Magnet Generator

\[ l_{m} \]
\[ l_{gen} \]
\[ d_{oc} \]
\[ d_{oc} \]

Vibration generators are often modeled as mass-spring-damper systems with optimization applied to ensure operation at a resonant frequency. While the applied forces are periodic in this case, they are not typically sinusoidal for walking speeds as seen in Figure 3.2. During running, there is closer agreement between the periods of applied force and the step as seen in Figure 3.3 and therefore the scope for resonant operation is considered. With this structure the coil remains fixed while the magnets move in response to the acceleration of the foot during walking. Since it is more difficult to force the movement of the coil, it is more realistic for the magnets of mass
m, to move. For the purpose of this analysis the generator structure is assumed to be a cylindrical volume, i.e. \( y = z = d_{oc} \), as shown in Figure 3.4 where \( d_{oc} \) is the maximum outer dimension (maximum coil diameter). Only the magnet and coil dimensions are considered for this volume as the housing is the coil former, which is inside the coil, and the spring (air in this case) allows the required movement of the magnet mass at the frequency the structure accelerates during walking.

The available mechanical energy depends on the level of acceleration the magnet is subjected to in the shoe heel during walking but the maximum displacement is constrained by the volume of the generator. The peak displacement \( x_p \), in this case is given by the external dimension \( l_{gen} \) (length of the generator), and the dimension of the magnet \( l_m \) [192]. For the sliding magnet structure if a single magnet is considered then mechanical energy is maximised either by a thin magnet with a large displacement or a thicker magnet with a small displacement. In this case the magnet is displaced from one end of the generator to the other during the acceleration the structure experiences during walking, thus the peak displacement is calculated from:

\[ x_p = l_{gen} - l_m. \]

If the generator structure is described as a typical mass (m) – spring (k) – damper \( D_p \) system [49], the basic equation to describe the motion of the mass (magnet) relative to the housing (coil) when driven by a force is given by [192]:

\[
m \frac{d^2x}{dt^2} + D_p \frac{dx}{dt} + kx = F_o \sin \omega t - F_{em}
\]

(3.2)

where \( x \) is the relative movement between the magnet and the coil, \( D_p \) is the parasitic damping (which represents loss mechanisms such as air damping, squeeze film effects, thermoelastic damping, and friction in the clamping), and \( F_{em} \) is the electromagnetic force due to the force between the current in the coil and the magnet, \( F_o \) is the driving force which is given by mass times the acceleration \( a \), \( \omega \) in this case is the frequency of the applied force, which in this case is the force applied by the foot. The spring constant \( k \), is due to air as there is no physical attachment to the magnet mass and it can be calculated by [193]:

\[
k = \frac{\mu_p S}{l}
\]

(3.3)
where \( \gamma \) is the adiabatic gas constant, \( S \) is the cross-sectional area (of the magnet), \( P_a \) is the atmospheric pressure and \( l \) is the length of the air column which is equal to the peak magnet displacement \( x_p \) for this structure. Based on the prototype generator parameters (described in section 3.2.3) a spring constant \( k \) value of \(~124 \text{ N/m}\) is estimated. Solution to (3.2) for magnet (mass) displacement can be expressed as [192]:

\[
x(t) = \frac{F_o}{\sqrt{(k - m\omega^2)^2 + (D_p + D_{em})^2 \omega^2}}
\]

where \( D_{em} \) is the electromagnetic damping and \( D_p \) is the parasitic damping. The electromagnetic damping represents the mechanism by which the electrical power is extracted from the system, i.e. the current flowing in the coil. The average electrical power from the generator structure can then be expressed as:

\[
P_{avg} = \frac{D_{em} F_o^2 \omega^2}{2 \sqrt{(k - m\omega^2)^2 + (D_p + D_{em})^2 \omega^2}}
\]

The electromagnetic damping force is proportional to magnet velocity and is expressed as [192]:

\[
F_{em} = \left( N \frac{d\phi}{dx} \right)^2 \frac{1}{R_c + R_l + j\omega L} \frac{dx}{dt} = D_{em} \frac{dx}{dt}
\]

where \( N \) is the number of coil turns, \( d\phi/dx \) is the average flux linkage per turn for the coil, \( R_c \) is the coil resistance, \( L_c \) is the coil inductance and \( R_l \) is the load resistance. Coil resistance and coil inductance depend on the number of turns in the coil.

If the generator structure is designed to operate at resonance it is found that the maximum electrical power occurs when, \( D_{em} = D_p \). Therefore the objective of such a generator design should be to achieve this optimum electromagnetic damping, i.e. it should aim to make electromagnetic damping equal to the parasitic damping. If electromagnetic damping is very low compared to parasitic damping (\( D_p >> D_{em} \)), then the displacement is determined by the range of motion provided by the generator structure. In this case the load power is simply obtained from the voltage division between load resistance and coil resistance and the maximum power will be transferred to the load when the load and coil impedance are equal [194].
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From (3.4) and (3.5), it is found that the generator has a mechanical resonant frequency \( \omega_n = \sqrt{\frac{k}{m}} \) and it is generally required to have the frequency of the driving force \( \omega \) equal to \( \omega_n \) to maximise displacement. Magnet mass can be calculated based on the density of the magnetic material and the volume, \( V \), of the magnet being used \( (m = \rho V) \). Thus, the resonant frequency of this generator structure is calculated from:

\[
\omega_n = \sqrt{\frac{k}{\rho \pi r^2 x_{mass}}}
\]  

(3.7)

A summary of magnet properties; spring constant and resonant frequency is presented in Table 3.1, based on the chosen magnet (described in section 3.2.3.1). Using (3.3) and (3.7), a resonant frequency of \(~17\) Hz is predicted in the generator air column for the SMG. Thus if the proposed SMG structure is to achieve mechanical resonance (with \( \omega \) equal to \( \omega_n \)) then the frequency (\( \omega \)) of the applied force from the foot would have to cause the magnet to move once every \(~60\) ms, corresponding to \(17\) steps/s. As the frequency of the driving force is fixed by the walking frequency of the user this cannot be achieved with this generator design. This generator structure is designed to be excited by a range of human foot frequencies it is not tuned to a particular frequency and so mechanical resonance will not be achieved.

<table>
<thead>
<tr>
<th>Generator Parameter</th>
<th>Calculated Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet Radius ( r_m )</td>
<td>0.005 m</td>
</tr>
<tr>
<td>Magnet Length ( l_m )</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Peak Displacement or l ( x_p )</td>
<td>0.09 m</td>
</tr>
<tr>
<td>N30H Magnet Density ( \rho )</td>
<td>7500 kg/m³</td>
</tr>
<tr>
<td>Magnet Volume ( V )</td>
<td>0.785 x 10⁻⁶ m³</td>
</tr>
<tr>
<td>Magnet Mass ( m )</td>
<td>0.0059 Kg</td>
</tr>
<tr>
<td>Atmospheric Pressure ( \text{Pa} )</td>
<td>101325 N/m²</td>
</tr>
<tr>
<td>Y-Adiabatic Gas Constant ( \gamma )</td>
<td>1.4</td>
</tr>
<tr>
<td>Spring Constant ( k )</td>
<td>123.79 N/m</td>
</tr>
<tr>
<td>( \omega_n )</td>
<td>17.3 Hz</td>
</tr>
</tbody>
</table>

As mechanical resonance cannot be achieved in the given generator structure, it is expected that the maximum load power can simply be obtained from the voltage division between load resistance and coil resistance.
3.2.2.2 Opposing Magnet Generator

For the opposing magnet structure two magnets are considered, one fixed and one free to move. Once more mechanical energy is maximised either by two thin magnets with a large magnet displacement or two thicker magnets with a small displacement. In this case the moving magnet is displaced from one end of the generator to the other where it meets the fixed magnet during the acceleration the structure experiences during walking, thus the peak displacement is calculated from:

\[ x_p = l_{\text{gen}} - (2 \times l_m) \]

based on the model presented in Figure 3.4.

Similar analysis to that described for the SMG mechanical model may be applied to the opposing magnet structure with (3.2) to (3.7) describing magnet displacement. On this occasion however, the opposing magnet structure has a magnetic spring constant due to the opposing magnetic forces between the magnets. Although the OMG does not vibrate at resonance either, it is different as the coil and one of the magnets is fixed while the second magnet is moving. The frequency of the moving magnet is varied as in one direction the magnet displacement is based on the force applied by the user (where \( F=ma \), and \( m \) is based on the weight of the user) during the stance phase of the gait cycle while in the opposite direction the magnet displacement is based on the opposing force between the two magnets (where \( F=-kx \), and \( k \) is based on the magnet spring constant between the two magnets) when the heel is lifted during the beginning of the swing phase.

Figure 3.5: Model of Electromagnetic Generators

Figure 3.5 presents the force between the magnets as the moving magnet is displaced from a distance of 15 mm from the fixed magnet until it sits on top of the
fixed magnet. Results were predicted using both FEA analysis and also predicted using analytical models described previously [195]. Based on this graph the spring constant \( k \) is estimated to be 138.9 N/m from the slope of the graph for the 5mm closest to the fixed magnet. Using this value the natural frequency of the generator can be estimated based on \( \omega_n = \sqrt{k/m} \) for when the heel lifts off the moving magnet and is forced in the opposite direction. The mechanical parameters for the opposing magnet structure during the heel off phase of the gait are presented in Table 3.2 where the magnet parameters are the same as described in Table 3.1 for the sliding magnet structure. The natural frequency calculated is based on the magnet mass only and does not consider the sole it might be attached to, which will reduce the speed as the magnet is forced back through the coil due to the maximum magnetic opposing force presented in Figure 3.5.

<table>
<thead>
<tr>
<th>Generator Parameter</th>
<th>Calculated Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Displacement or ( l (x_p) )</td>
<td>0.015 m</td>
</tr>
<tr>
<td>Spring Constant ( k )</td>
<td>138.9 N/m</td>
</tr>
<tr>
<td>( \omega_n )</td>
<td>23 Hz</td>
</tr>
</tbody>
</table>

For the same reasons as discussed for the sliding magnet generator, it is clear that a resonant frequency of 23 Hz is not practical for a person walking, and therefore it is expected that maximum power will be achieved by matching the load and coil resistance.

**3.2.3 Electromagnetic Models**

Electromagnetic models for both structures are necessary due to the non-standard nature of the generators; i.e. non-resonant structures. Therefore electromagnetic modeling and optimisation is important as the induced voltage is based on magnet movement, which in turn is based on foot movement during the gait cycle and the mechanical structure as described in sections 3.2.1 & 3.2.2 respectively.

**3.2.3.1 Magnet Choice**

Due to the testability provided by the author, the dimensions of the selected shoe sole were standardised to a man’s size 10 sports shoe with \( 28 \times 7 \times 2 \text{ cm}^3 \) [196]
available space for integration. However, the most unobtrusive and realistic approach is to restrict the generator location to the heel of the shoe sole which provides only $10 \times 7 \times 3 \ cm^3$ of available space for the generator. The designed generators need to be integrated unobtrusively into this area without adding significant extra weight or strain on the user that it affects the normal gait cycle, and so the generators are designed to be integrated into a maximum shoe sole thickness of 10 to 20 mm. The magnet dimensions were chosen to fit within this restricted available space and depending on the magnet structure used, the remaining space was designated to accommodate the coil and former of the generator. The generator designs will provide methods of optimising for all sizes of shoes.

### 3.2.3.1.1 SMG Magnet Choice

Based on the shape, size and strength of typical magnets available, it was identified that the SMG structure is best divided into several parallel lengths, where the coils surround permanent magnets that are free to slide up and down inside the coils when the user walks. The number of parallel lengths that can be integrated depends on the strength (grade) of the magnets used, as attraction/repulsion forces between the magnets and to the outside environment can influence the desired movement of the individual magnets in the shoe in which they are embedded, hence hindering the operation of the generators during walking or running. When the size and strength of the magnets coupled with the available space in the shoe sole is considered, it was identified that 2 sliding magnets and their associated generator structures is the maximum that can be efficiently integrated without affecting each other. The application of magnetic material in this work is for the design of an electromagnetic generator small enough to be embedded in the sole of a shoe without influencing the user’s gait. The NdFeB material has been identified in Chapter 2 as the optimum magnetic material to achieve the largest flux linkage with the generator’s coil and hence inducing a larger voltage.

The available magnet shapes include rectangles, horseshoes, cylindrical discs (buttons), cylindrical rings, cylindrical rods, flexible sheet and pot magnets. Disc magnets for example are available in different grades with varying diameters from 3 to 33 mm and thicknesses of between 1 and 10 mm [197]. As the human foot moves through a natural walking step the magnet experiences various forces which results in
motion through the generator. One of the forces that would counteract the magnets motion is the friction between the magnet and the coil former of the generator it is sliding through. The frictional force is estimated from $F_{fr} = \mu F_N$ where $\mu$ is the coefficient of friction (static friction ($\mu_s$) or kinetic friction ($\mu_k$)) between the two materials and $F_N$ (mg) is the normal force. The normal force is estimated from the mass of the magnet in this case while $\mu$ is based on the coefficient of friction between metal plastic (0.4) as described in section 3.2.1. In order to reduce this friction the surface of both the magnet and former need to be as smooth as possible. The former material for the SMG design is chosen to be PTFE plastic. The less area that the magnet and coil former have in contact with each other the less friction reducing magnet motion would be generated. As the generator will be at an angle to ground during the swing phase of the gait cycle as described in section 3.2.1 the normal force will be reduced to $F_N = mg\cos\theta$.

Disc or button NdFeB magnets were identified as the most suitable magnet structures for use in the SMG structure as $F_{fr}$ and magnet mass are reduced. A range of such disc NdFeB magnets are readily available from “AssemTech” [198] and these magnets were the basis of all generator designs investigated in this work. The properties of the AssemTech range of disc 30H grade NdFeB magnets are available on the AssemTech website and each of these fit within the test space available. The sizes available vary from $\phi 3\text{mm}\times1\text{mm}$, $\phi 3\text{mm}\times2\text{mm}$, $\phi 4\text{mm}\times3\text{mm}$, $\phi 6\text{mm}\times2\text{mm}$ to $\phi 10\text{mm}\times5\text{mm}$. The largest magnet size of $\phi 10\text{mm}\times5\text{mm}$ from this range was initially selected as the base magnet for all generator designs as it fits within the available space, provides maximum strength per unit area and provides less friction $F_{fr}$ for the sliding magnet design. However, initial performance investigations identified that due to its larger diameter, a 5 mm thickness does not allow a stable motion through the SMG structure. To counteract this instability a second $\phi 10\times5 \text{mm}^3$ NdFeB magnet was used where the north or south of the first magnet would be attracted to the opposite pole of the second magnet, forming a single magnet structure. This new double magnet has a combined thickness of 10 mm and demonstrated a more stable motion through the generator structure.
3.2.3.1.2 **OMG Magnet Choice**

Similar conditions that influence the SMG must also be considered for the OMG whereby the external environment and other local generator structures cannot hinder the full scale displacement of the generator. As both the SMG and OMG are to be compared under similar test conditions to identify the optimum design the same $\phi 10 \times 5$ mm$^3$ NdFeB magnet was also chosen for the opposing magnet design. The OMG structure will also use two of these $\phi 10 \times 5$ mm$^3$ NdFeB magnets, one fixed and the other free to move through the generator coil. The strength (grade) of the magnets is also vital as the opposing strength between the magnets cannot be so large that the user cannot close the gap between them during a normal gait cycle. Thus it was established that the optimum design is to distribute a number of these smaller opposing magnet structures around the heel rather than one big magnet. Secondly, the attraction between these opposing structures may interfere with the free moving magnet so the number of structures that can be distributed around the heel is limited.

3.2.3.2 **SMG Electromagnetic Model**

In order to predict the induced voltage and power that the SMG is capable of achieving, the magnetic flux distribution of the magnet must firstly be considered based on (2.1). Using this flux distribution, the coil that could utilise the changing magnetic flux caused by the magnet passing through the generator structure in the shoe sole may be designed. For that purpose, an FEA simulation was used to calculate the field distribution around a given magnet, from which an optimum coil area is deduced. Maxwell 2D Simulator [42] from Ansoft (Now ANSYS) was used to carry out these magnetic simulations, as it is capable of producing results of any magnet’s flux distribution. The transient option in the software is also available which generates results based on the actual movement of the magnet but this process is much slower. The most attractive option was to simulate the static flux distribution using Ansoft and applying this to calculate induced voltage using separate analytical models.
In this initial study there are two disc magnets each with a diameter of 10 mm and a thickness of 5 mm, positioned side by side due to the attraction of their opposite poles. The magnet is drawn in the simulation by a half elevation view along the R-axis and is then rotated around the cylindrical Z-axis by the software as demonstrated in Figure 3.6. Magnetic flux distribution is calculated using the flux line (representing the radius) function in the simulator where the flux results are calculated based on the position and length of the flux lines drawn from the center Z-axis as demonstrated in Figure 3.6. In this case for example $F_{P1}$, $F_{P2}$, $F_{P3}$ and $F_{P4}$ are flux lines with a length of 6 mm, 6.5 mm, 7 mm and 7.5 mm (1 mm, 1.5 mm, 2 mm and 2.5 mm from the outer radius of the disc magnet) and positioned at different locations along the length of the magnet. The simulation then calculates the magnetic flux at those points by integrating around these flux lines. By simulating a range of flux lines with a certain radius along the R-axis (6 mm for example) distributed along the length of the magnet on the Z-axis, the flux distribution of the magnet at that distance (1 mm) from the magnet’s outer radius can be established.
Chapter 3: Shoe Integrated Electromagnetic Generator Design

Figure 3.7: Flux Distribution at varying Distances from center of Magnet

Flux lines ranging in radius from 6 mm to 10 mm are drawn along the magnet’s Z-axis and the corresponding magnet flux data at those points is calculated by the simulator. The resultant flux represents the flux along a straight line at varying distances from the magnets outer radius, which in this case varies from 1 mm to 5 mm. Figure 3.7 illustrates the magnetic flux distribution at these varying distances (1 mm to 5 mm) from the magnet’s outer radius with the strength reducing the further away from the magnet the line is taken, as expected. The flux calculated by the simulation due to the flux lines $F_{P1}$, $F_{P2}$, $F_{P3}$ and $F_{P4}$ presented in Figure 3.6, are also identified in Figure 3.7 at the various distances from the magnet surface. This data is used to design the coil area and also to predict the induced voltage that can be achieved at each distance from the magnet.

Once the flux distribution of the magnet at any distance from the magnet is known the induced voltage at that distance can be predicted. Maximum flux is seen at the outer radius of the magnet, $R_{mag}$, and there is a decay in flux with increasing distance from the magnet. This is shown in more detail in the plot of flux versus radius at the axial centre of the magnet in Figure 3.8 where the first 5 mm from the magnet surface is the most critical based on the maximum radius of 20 mm of the final generator. In order to maximise magnetic flux linkage, the coil should be wound as close as possible to the magnet. However, the magnet must be free to slide through the coil for electromagnetic induction and the thickness of the coil former needs to be accommodated. An inner coil radius of 6 mm was chosen in the initial design to allow
for a coil former thickness of 0.75 mm, with ~ 0.25 mm for free movement on either side of the magnet.

![Figure 3.8: Plot of flux versus radius at the axial centre of the magnet](image)

Operation of the SMG is based on electromagnetic induction, where the movement of one or more of magnets through the coil produces a change in magnetic flux linkage. Referring to Figure 3.9 the resultant open-circuit voltage, $V_{oc}(t)$, induced on a coil with $N$ turns may be expressed in terms of instantaneous values of flux linking with individual $i$ turns, $\phi_i(x_i,t)$, located along the length of the coil at $x_i$ as:

$$
V_{oc}(t) = \sum_{i=1}^{N} \frac{d\phi_i(x_i,t)}{dt}
$$

(3.8)

$$
\phi_i = \int_A B_i dA_i
$$

(3.9)

where $\phi_i$ and $B_i$ are magnetic flux and magnetic flux density that link with turn $i$, respectively and $A_i$ is the area enclosed. For a particular coil and magnet combination such as shown in Figure 3.9, $\phi_i(x_i,t)$ may be given in terms of the flux established along the length of the magnet, $\phi_m(x_{mi})$, as:

$$
\phi_i(x_i,t) = \phi_m(l_{sf} + \frac{l_c}{2} + x_{mi} - sl)
$$

(3.10)

Where $x_{mi}$ is the axial distance from the centre of the magnet, $s$ is magnet speed, $l_c$ is the coil length and $l_{sf}$ is the starting distance between the centre of the
magnet and the end of the coil. Substituting for $\phi_i(x_i,t)$ in terms of $\phi_m(x_{mi})$ into (3.11), the instantaneous open-circuit coil voltage may also be given as:

$$v_{oc}(t) = -(s + t) \frac{ds}{dt} \sum_{i=1}^{N} \frac{d\phi_m(x_{mi})}{dx_{mi}}$$

(3.11)

where $x_{mi}$ varies from $(l_\phi - st)$ for $i = 1$ to $(l_\phi + l_c - st)$ for $i = N$ at time $t$. In this way, it is seen that calculation of the open-circuit voltage is based largely on the magnetic flux gradient established by the magnet within the coil at any instant. In the case of the OMG there is another non-varying flux distribution due to the second magnet and the electromagnetic model will identify how this affects the induced voltage.

Assuming that the input force producing relative motion between the magnet and coil is much larger than the electromagnetic damping force, a simple equivalent circuit model of the generator can be applied that consists of a voltage source, $V_{oc}(t)$, with a series resistance and inductance representing coil impedance. Due to the low frequency of the generated voltage, the contribution of coil inductance is neglected in this case and the equation for open-circuit voltage is applied to predict the maximum available power produced by the generator:

$$P_o = \frac{V_{oc}^2 R_L}{(R_c + R_L)^2}, \quad \text{where} \quad V_{oc}^2 = \frac{1}{T} \int_0^T v_{oc}(t)^2 dt$$

(3.12)
where $R_c$ and $R_L$ are the coil and load resistances respectively. Clearly, as identified for other loosely coupled electromechanical systems; maximum available power is achieved by setting the load resistance equal to the coil resistance.

### 3.2.3.3 OMG Electromagnetic Model

While the structure of both generators may differ, there are a number of similarities. The OMG is integrated into the same space that is available for the SMG. As the same $\phi$10mm×5mm NdFeB disc magnet chosen for the sliding magnet design is also suitable for integration into the space available in the shoe heel it is also used for the OMG to provide a good comparison in terms of performance. The coil should be wound as close as possible to the magnet outer radius as described for the SMG. Coil inductance and resistance are the same for both generator structures but optimum coil length requires further consideration in this case.

![Flux Distribution of two Opposing Disc Magnets in Ansoft](image)

**Figure 3.10:** Flux Distribution of two Opposing Disc Magnets in Ansoft

Furthermore, there is a substantial difference in how voltage is induced on generator coils as there are two magnet fluxes in this case. However the electromagnetic models ((3.8) to (3.12)) described for the SMG are also applied to the OMG were the only difference is due to the changing flux ($d\phi$) produced by the two magnets. As with the SMG magnet flux distribution is predicted using Maxwell Ansoft FEA analysis. Figure 3.10 demonstrates the predicted magnet flux of one magnet on its own at varying distances from the magnet surface using FEA.
Figure 3.11: Magnetic Flux Linkage of Opposing Magnet Structure

Magnetic flux linkage within the coil in this case is the sum of the contributions from each of the opposing magnets, as shown in Figure 3.11. Clearly, so long as the separation between the magnets is maintained within the extent of the magnet fields, there is changing flux linkage at every point along the coil when the free magnet moves. As with the SMG, there are different levels of flux linkage produced depending on the relative locations of magnets to the coil. The first aspect of design was to determine the separation of the magnets at which maximum rms voltage is produced; optimum total coil length is then chosen equal to this distance. This is investigated in section 3.3.2. There are situations when there is increasing and decreasing flux linking simultaneously with different parts of the coil as illustrated in Figure 3.11. While the SMG has a single flux linking with the coil as the magnet passes through the generator structure the OMG coil has a changing flux due to two magnet contributions. The division of the optimum coil length is investigated so that the resulting positive and negative voltages can be added constructively, similar to that described for the SMG. The flux distribution of a single NdFeB disc magnet was applied to determine the optimum coil design for the 2 opposing 10 mm diameter magnets. For the purposes of calculations, the flux $\phi_o(x)$ is taken with $x = 0$ at the centre of the magnets as shown in Figure 3.11. Flux linkage with a winding turn at a distance $x'$ from the fixed magnet is then given as:

$$\phi_n = \phi(x', t) = \phi_o(x') - \phi_o(d - x' - v_m t)$$  \hspace{1cm} (3.13)

for an initial magnet separation; $d$ and constant magnet velocity; $v_m$. The total coil voltage is found by summing $d\phi (x', t)/dt$ for finite distances along the length of the coil.
3.2.4 Electrical Models

The general formula used to calculate the DC resistance of a coil as seen in Figure 3.12 based on the wire length, wire area and resistivity of the coil material which in this case is copper (1.7 x 10\(^{-8}\) $\Omega$m). The area of the copper wire used can be related to the overall cross sectional area available for the coil $A_{coil}$, by assuming a copper fill factor $k_{cu}$ (which is assumed to be 0.6 here [192]), thus:

$$A_{wire} = \frac{k_{cu}A_{coil}}{N}$$  \hspace{1cm} (3.14)

Thus, for a given inner $ri_C$ and outer coil radius $ro_C$ (defined below in Figure 3.12) the coil resistance can also be calculated from [192]:

$$R_c = \frac{\rho_{cu}N^2\pi(ro_C + ri_C)}{k_{cu}(ro_C - ri_C)i_C}$$  \hspace{1cm} (3.15)

![Figure 3.12: Parameters Involved in Coil Resistance Calculation](image)

The coil inductance is also calculated as a function of the number of coil turns and the coil geometry. The inductance can be calculated from [192]:

$$L_c = \frac{\mu_0N^2A_{coil}}{l}$$  \hspace{1cm} (3.16)

where $\mu_0$ is the permeability of free space. It is suggested in [192] that inductance can be neglected because the resistive impedance of the coil is significantly larger than the
inductive impedance at frequencies less than 1 kHz. This is also the case here with a calculated coil inductance of 273 µH for a 15 mm coil, based on the induced voltage frequency due to the speed of the magnet passing through the generator coils. Generally the inductance of the coil can be ignored in this generator design as the magnet frequency will never come close to 1 kHz as the measured and simulated results presented in Chapter 4 and 6 provide a maximum magnet speed of < 50 Hz, so the contribution of 273 µH to coil impedance is << 1 Ω.

3.2.5 Implementation of Generator Models

Microsoft Excel [199] was used to develop analytical models to predict the AC induced voltage and power on the coils of the generator based on (3.8) to (3.16). Matlab [200] was also exploited to generate analytical predictions of the AC voltage waveforms provided by various magnet and coil combinations, due to the additional Simulink [201] functionality available. Based on the flux distribution data of a given magnet from Ansoft Maxwell 2D a program was written in MATLAB, which predicts the output open circuit AC voltage for any given generator. The flux distribution for any magnet predicted using Ansoft can be curve fit in Matlab using an 8th degree polynomial or larger. This procedure was carried out for a range of magnet diameters (2.5 - 14 mm) and magnet thicknesses (2.5 - 25mm) and for each of these magnets the flux distribution at varying distances from the magnet was numerically fit.

Initially the changing flux linkage is calculated as the magnet moves at a given constant velocity through a given coil. This allows for the optimisation of the generator design based on these settings. An important variable on which the output also depends on is the time delay between pulses (which depends on the frequency of shoe movement, i.e. walking/running). The Matlab model calculates the generator coil output voltage based on all the various generator variables; magnet size/shape/strength, distance of coil from magnet, length of coils, magnet speed, different combinations of coils, number of turns, number of coils in the generator. The data generated by the M-file can then used by Simulink using circuit blocks to perform further simulations that predict the AC power of the generator based on the predicted generator coil voltage pulses. This feature of Matlab also allows the user to build the necessary circuit blocks to perform AC and DC operations if required. Subsequent analysis applies these voltage waveforms to predict the output AC and
DC power that can be achieved by any set of coil and magnet combinations using the Simulink feature of MATLAB.

Modeling of the OMG is similar to that of the SMG in terms of how the magnetic flux distribution of the magnet (predicted by Maxwell Ansoft) is implemented in MATLAB. Coil resistance, velocity, voltage and power are also predicted using the same methods outlined for the sliding magnet structure. The main difference is the how changing flux linking with the coil is predicted using MATLAB using (3.13). Flux linkage depends on the starting distance of the moving magnet as well as the coil position from the fixed magnet and length of the coil, which are variables entered by the user. The flux of the fixed magnet is always there and only one half of this flux distribution can be considered as seen in Figure 3.11. The points of the fixed magnet flux distribution that link with the coil depend on the position and length of the coil. The points of the moving magnet flux distribution that link with the coil and combine with the fixed magnet flux distribution depends on its starting position and length of the coil. Once the required variables are entered the model predicts the flux linkage with the turns of the coil and corresponding induced voltage based on the moving magnets’ speed and number of turns in the coil is achieved.

3.3 Generator Design and Optimisation

The analysis in section 3.2.1 and 3.2.2 characterised the mechanical influences on the generator designs proposed in this work. It has been identified that the excitation forces applied by the foot during walking cause a mass or magnet to travel through a structure located in the heel of the shoe with a velocity of 1 – 3 m/s. The objective of this work is to harness this movement and convert it to electric power using the principle of electromagnetic induction. The design of the coil based on the magnet flux distribution is described in detail in this section; while the analytical models for optimising generator power performance is also presented.

3.3.1 SMG Coil Optimisation

To predict the optimum coil length for a specific magnet both the magnetic flux and flux gradient are required. Results of magnetic flux in Figure 3.13 were predicted using finite element analysis Maxwell Ansoft FEA simulation at a radius of 6.5 mm parallel to the axis of a φ10 mm × 10 mm NdFeB disk magnet, with magnetic
flux gradient subsequently calculated numerically. Interestingly, \( \frac{d\phi}{dz} \) has odd symmetry about the centre of the magnet. It is maximal at the edges of the magnet and it extends to \(-2.5\) mm beyond it to values of approximately 10% of the maximum. Assuming 10% of maximum flux gradient to define a cut-off value, it is found that the optimum coil length for the \( \phi 10 \text{ mm} \times 10 \text{ mm} \) magnet of Figure 3.13 is 15 mm. The zero flux gradient occurs at 0 mm while the maximum and 10% of the maximum flux values occur at \( \pm5 \) mm and \( \pm15 \) mm respectively. For maximum flux linkage the coil should be set equal to the distance between the zero flux gradient to 10% of the maximum flux gradient, thus achieving the 15 mm coil length which was subsequently verified experimentally.

![Figure 3.13: Magnetic flux and magnetic flux gradient along the length of a magnet](image)

It may be expected that larger voltages would be achieved with longer coils or with coils that incorporate a large number of turns. However, as the magnet travels through the coil, different levels of flux link with different turns along its length. Coils that are longer than the extent of the magnetic flux have positive voltage induced in one section of the coil with negative voltage in a neighboring section. This results in the cancellation of voltage induced over part of the generation period. Obviously this is undesirable as it reduces the rms value of the voltage generated. For maximum power and voltage, this period should be minimised, as any additional coil length only contributes to increasing the coil resistance.
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**Figure 3.14**: Illustration of Induced Voltage vs. Magnet Movement

Figure 3.14 investigates the issue of optimum coil length. While the magnet is entering the coil there is increasing flux linkage producing positive voltage \( (\frac{d\phi}{dz} \text{ is positive}) \) for all turns linked up to the point when the maximum flux enters the coil. When the magnet continues to move until it is completely enclosed in the coil there is then increasing flux with some of the coil turns and decreasing flux with others. In the case where there are equal numbers of turns having positive and negative flux gradient linking with them, i.e. \( \sum \frac{d\phi}{dz} = 0 \), the total flux linkage with the coil is constant and the overall voltage induced is zero. No further voltage is induced until the magnet approaches the other end of the coil, when the number of turns with increasing flux linkage reduces; a net negative voltage is induced until the magnet has completely exited from the coil.

To optimize the design of the coil length a mathematical formula was generated which represents the open circuit output generator voltage for each of the three magnet positions in the generator. Figure 3.14 describes the three stages of magnet movement versus induced voltage. The magnet travels with velocity \( v_m \), the magnetic flux has a length of \( l_\phi \), the coil has a length of \( l_c \), the open circuit output voltage is represented by \( v_{oc}(t) \) and the number of turns in the coil is \( N \).

Magnet Entering Generator:

\[
0 \leq t < \frac{l_\phi}{v_m} : v_{oc}(t) = \sum_{n=1}^{N} \frac{d\phi_n}{dt} > 0
\]  

(3.17)
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Magnet Enclosed in Generator:

\[
\frac{l_c}{v_m} \leq t < \frac{l_c + l_e}{v_m} : v_{oc}(t) = \sum_{n=1}^{N} \frac{d\phi_n}{dt} = 0 \quad (3.18)
\]

Magnet Leaving Generator:

\[
\frac{l_e}{v_m} + \frac{l_c}{v_m} \leq t < \frac{l_c + 2l_e}{v_m} : v_{oc}(t) = \sum_{n=1}^{N} \frac{d\phi_n}{dt} < 0 \quad (3.19)
\]

In order to maximise rms voltage, the length of the coil should be limited so that the flux is not completely enclosed by the winding (\(\sum \frac{d\phi}{dz} \neq 0\)) over any significant part of the generation period. This is achieved by limiting the length of the coil to the extent of magnetic flux gradient; i.e. \(\sim 15\) mm for the \(\Phi 10\)mm x 5mm specification magnets. For maximum \(v_{oc}(rms)\), coil length must be limited so that \([\frac{(l_c - l_e)}{l_e}] = 0\), i.e. \(l_c = l_e\). The space available in the shoe is \(>> l_e\) and so the remaining available length in the shoe may be used by defining replicate coils and connecting them so when the magnet leaves one coil and enters another, respective negative and positive voltages are added constructively. Using (3.8 – 3.16), it is found that for a given magnet size, irrespective of its velocity, an optimum coil length can be identified for which the product of average power and peak voltage is maximum. This is found to be equal to the extent of the magnetic flux gradient, \(|\frac{d\phi}{dx}|\) from the centre of the magnet along its axial length.

The effect of coil length is illustrated in Figure 3.15 in terms of voltage and instantaneous power waveforms predicted for different coils linking with the magnet of Figure 3.13 for a constant normalised magnet speed of 1 m/s (based on the excitation forces presented in section 3.2.1). In this way, the performance of different generator structures can therefore be compared independently of magnet speed, although it is shown later that 1 m/s is quite accurate for the test structures considered. In all cases, the coil consists of 12 turns of 0.25 mm diameter copper wire per mm of coil length. It should be noted that the given structure was applied to confirm the voltage waveforms and power levels predicted, and it is optimised only in terms of coil length. Coil resistance ranged from 1.72 \(\Omega\), 2.58 \(\Omega\) to 3.44 \(\Omega\) for coil lengths of 10 mm, 15 mm and 20 mm respectively. The open circuit voltages presented in Figure 3.15 (a) are predicted in each case using (3.11) and (3.12) based on the magnetic flux distribution predicted using Maxwell Ansoft FEA simulation.
It is found that up to a coil length of 20 mm, the amplitude of the induced voltage increases with coil length as the magnetic flux linkage increases. For longer coils, the voltage amplitude remains constant, but the separation between positive and negative voltage pulses increases thereby indicating an increasing portion of time for when the net voltage induced is zero. Instantaneous power levels given in Figure 3.15 (b) are calculated using (3.12) with $R_L = R_c$. It is shown that the largest instantaneous power is predicted for the shortest coil, which is explained by the lowest coil resistance in this case. Similarly, coil resistance limits the power produced by the longest coil, which has the lowest power levels. The criterion for optimum coil length
is to achieve a usable pk-pk peak voltage with a corresponding power that is close to maximum. When averaged over the time taken for one step during walking (0.5 s for a rate of 2 steps per second), it is found that the 10 mm coil produces the highest average power of 1.46 mW, while in terms of combined peak-peak voltage and average power, the optimum coil length is found to be 15 mm. This matches the predicted coil length estimation based on the 10% of maximum flux linkage \( \frac{d\phi}{dx} \) presented in Figure 3.13.

3.3.1.1.1 SMG Electromagnetic Actuation and Damping Forces

![Figure 3.16: Electromagnetic Damping Force on a 15 mm Coil & Magnet Velocity of 1 m/s](image)

In order to verify the assumption of low electromagnetic damping force, results of the force exerted on a 15 mm coil length by a \( \Phi 10 \) mm x 10 mm NdFeB disk magnet as it moves through the coil are presented in Figure 3.16. Based on (3.6) the electromagnetic damping force can also be predicted for any magnet passing through a coil. Figure 3.16 presents the predicted electromagnetic damping force based on a magnet with a velocity of 1 m/s passing through a 15 mm coil (predicted using the method described in section 3.3.1) with 3 layers of 0.25 mm diameter wire corresponding to a 180 turn/2.58 \( \Omega \) coil. The induced voltage in this case is presented in Figure 3.15 (a) with a peak voltage of 0.65 V. Based on these results a peak electromagnetic damping force of 12.4 mN is predicted. Clearly, this is much lower than the actuating force acting on the magnet described in section 3.2.1 and it can be assumed that as the electromagnetic damping force is much lower than the applied user forces, magnet movement can be maintained. Furthermore, given the condition
that the mass of the magnet, \( m \), is much less than the mass of the foot and shoe, \( M \), it is clear that the electromagnetic damping force is much lower than the applied user forces and therefore the impact of electromagnetic generation would be expected to be minimal on the user's gait.

### 3.3.2 OMG Coil Length Investigation

The aim is to maximise OMG power. However scope for a magnet to travel is limited by the height of space available where a displacement of greater than 15 mm becomes intrusive. Further consideration is to ensure that the force between the magnets maintains repetitive motion. For the \( \phi 10 \text{ mm} \times 5 \text{ mm} \) disc magnets the maximum distance is limited to \( d = 15 \text{ mm} \) to ensure that the magnetic force produces repeated motion as the free magnet returns to a distance of 15 mm from the fixed magnet once the pressure from the heel is lifted during the swing phase. Consider the case where the coil length extends over the maximum distance between the magnets: Flux linking at each point is produced by 2 magnets, only changing flux causes induced voltage, for maximum \( V_{\text{oc}} \), \( l_c = l_m \) as with the SMG and ideally a total distance of \( 3 \times l_m \) is required.

![Figure 3.17: Opposing magnet Induced Voltage for 5mm, 10mm and 15mm Coil Lengths](image)

\( l_c \) Predicted (b) Measured
For a single 5 mm thick magnet the optimum coil length is predicted to be 12 mm based on the same method described for the SMG in section 3.3.1. When the coil is centered between the magnets, maximum pk-pk and rms voltage is predicted and measured with coil lengths of 10 mm and 15 mm so the 12 mm coil length is also a good prediction of optimum coil length for the OMG. This may be explained by the maximum change in flux which also occurs over this distance. Figure 3.17 (a) shows the results predicted for three different values of d (5, 10 and 15 mm), with corresponding measurement results illustrated in Figure 3.17 (b) confirming the accuracy of the models in predicting voltage wave shapes. Corresponding coil resistances of 0.86 \( \Omega \) (60 Turns), 1.72 \( \Omega \) (120 Turns), and 2.58 \( \Omega \) (180 Turns) are predicted for the 5mm, 10mm and 15mm coils respectively.

The different waveforms are explained by the different changing flux waveforms produced while the magnet travels through the different length of coils. There are much sharper and higher measured peak voltages for each coil length and this variation between predicted and measured can be explained by the actual increasing magnet speed achieved during measurement, while the predicted models are based on a constant slower speed. It can also be noted that a gap exists between the positive and negative pulses of each measured waveform, explained by the time delay from when the foot forces the magnet through the coil during heel strike to when the foot lifts off the shoe sole at heel off where the free magnet is forced back through the coil due to the opposing forces of the magnets. This is described by the accelerometer measurements presented in Figure 3.2. This is also taken into account in the predicted models.

3.4 Prototype Generator Measurements

3.4.1 SMG Prototype Performance

The accuracy of the predicted generator models presented in this chapter were verified by building and testing an initial generator structure based on a double NdFeB disc magnet with a 10 mm magnet diameter \( (d_m) \), 10 mm magnet thickness \( (l_m) \), corresponding to a 15 mm coil length \( (l_c) \), magnet velocity \( (v_m) \) of 1000 mm/s (based on the excitation force analysis presented in 3.2.1) and a 13 mm generator diameter \( (d_g) \). In order to verify the predicted optimum coil length described in section
3.3.1, three coil sections each of 15 mm length were wound side by side around a coil former. A 45 mm section was tested at first to investigate the operation of a simple generator structure. Each coil consisted of 180 turns (3 layers of 60 turns) of φ0.25 mm copper enameled wire. This section describes the measurements carried out and compares the results to the predicted models. Due to the length of the generator chosen, three coils were wound along the length of the generator structure.

Initially, the output from each of the separate coils was predicted and tested individually. The resulting open circuit voltages predicted for each of three separate 15 mm length coils wound axially and sequentially are given in Figure 3.18 (a). The open circuit measurement results performed on this demonstrator generator are presented in Figure 3.18 (b). The timescale shows the magnet travelling once in each

Figure 3.18: Prototype 3 Coil Generator Structure (a) Predicted Induced Voltage (b) Measured Induced Voltage
direction through the coils. Measurements were taken while shaking the coils with the double \( \phi 10 \text{ mm} \times 5\text{ mm} \) thick NdFeB disc magnets inside. The rate of shaking was controlled to produce a frequency of \(~5\text{ Hz}\) between pulses which was ambitious as it does not correspond well with a walking speed of 2 steps per second but did allow a good comparison between predicted and measured voltage. The speed of the magnet used in the predicted models are similar to those measured so the 1 m/s estimated from the measured excitation forces presented in section 3.2.1 is a good average.

The shape of measured waveforms in Figure 3.18 (b) is similar to those predicted in Figure 3.18 (a), the voltage amplitudes are of the same order; peak voltage levels are \(~0.6\text{ V}\) and the rms voltages generated varied between 192 mV and 250 mV at a frequency of 5.556 Hz. Clearly, for the optimum predicted coil length, there are no significant periods of zero induced voltage. The periods of positive and negative voltage correspond to the times when the magnet enters and leaves the coil section, respectively. The variation in pk-pk of measured voltage from each coil is due to the changing velocity of the magnet as it passes through the generator structure and hence through each of the three separate coils.

If the length of space available to accommodate the generator is much longer than the optimum coil length, several coils of optimum length can be applied, in a bid to address the low voltage levels generated. When positive voltage is induced in one coil section, the voltage in the neighboring coil section is negative. Therefore, if the coils are connected in series, there is cancellation of voltage over the generation period as illustrated in Figure 3.19 (a). However, by connecting successive coils in series-alternating (where the negative terminal of the first coil is connected to the negative terminal of the second coil and the positive terminal of the second coil is connected to the positive terminal of the third coil), the voltages add constructively to give higher peak and rms values. Peak voltages of up to 1.6 V are shown for open circuit conditions. Corresponding rms voltages were measured as 450mV and 503mV at frequencies of 5.26Hz to 5.556Hz, respectively. This was verified using the demonstrator generator with the coils connected directly in series and then in series-alternating as illustrated in Figure 3.19 (b).
Chapter 3: Shoe Integrated Electromagnetic Generator Design

How, the output power is limited by the series resistance of multiple connected coils in this case. Assuming the coils have separate and ideal rectifier circuits, a parallel coil connection provides the highest output power, as current only flows in a given coil when it has a voltage induced on it. Initial power output calculations using equation (3.12) predict that up to 4.5 mW may be achieved in this way with the existing demonstrator element, based on the fact that maximum power is provided by $R_{\text{load}} = R_{\text{coil}}$. By connecting several such elements in series and/or parallel, this level may be increased, as there is space for more such sections in a typical shoe sole. For example, if 3 such elements were connected in parallel the same voltage level would be produced, but $R_{\text{coil}}$ would be reduced by a factor of 3. The power levels predicted are quite low when compared to the power requirements of electronic devices presented in Chapter 2; however these are based on one element of $\sim 45 \times 10 \times 10 \text{ mm}^3$ in size. Optimisation of a generator to fit within the larger space available within a shoe heel is described in Chapter 4.
3.4.2 OMG Prototype Performance

Figure 3.20: OMG Induced Voltage on Separate 3 Coils, (a) Predicted (b) Measured

Figure 3.21: OMG Induced Voltage for Series and Series Alternating Connected Coils, (a) Predicted (b) Measured
In order to compare results obtained for the OMG with that of the sliding magnetic generator, the initial analysis of the structure was based on the same φ10 mm NdFeB disc magnets. Predictions and measurements were based on the same 5 Hz excitation frequency to that of the SMG. To illustrate the possibility for increasing peak and rms voltage levels by varying the connections of the coils, the results for three separate 5 mm coils distributed equally along the optimum length of 15 mm are presented in Figure 3.20. As expected, there are periods when positive and negative voltages are induced simultaneously on different coils. By varying the connections of subsequent coils it was demonstrated how larger voltages are achieved as before for connection in series and series-alternating as seen in Figure 3.21. Maximum peak and rms voltage levels of 704mV Pk-Pk and 43.8mV respectively are attained in this case with the series connected coils.

The overlap of periods of positive voltage for neighboring coils shown in Figure 3.20 suggests that the division of the coils is not optimum. This also explains why the series coil connection is better than the series alternating coil connection. By examining the voltage waveform at different positions along the length of the coil, it was identified that it is better to divide the coil into 6 sections over the 15 mm length. This can be verified by examining the voltage waveforms induced at different positions along the length of the coil where improvements are predicted in induced pk-pk and rms voltage [184].

3.4.3 Generator Comparison - 3 Coil Prototype Structures

Due to the results achieved from the SMG it can be identified that the sliding magnet structure provides a more promising performance in terms of usable power. The voltage levels achieved from the sliding magnet structure are generally higher than those of the opposing magnet, but so too is its footprint area. Therefore, the performances of the maximum number of each unit that can be accommodated within the space of a shoe sole were compared. For the sliding magnet structure, some sections of coil have no voltage induced during magnet motion, but these would have current flowing in them when loaded. All turns of the OMG have voltage linked during motion. This would suggest that a higher efficiency is achieved with this structure. To illustrate these differences the results of voltage measurements taken across maximum power load resistors are presented in Figure 3.22.
Maximum power levels achievable with the two unit structures were calculated based on equal load and coil resistances. Average power values of up to 10 mW were predicted for the sliding magnet structure, with up to 0.5 mW for the opposing magnet. Measurements were performed on both structures using a 3.3 Ω resistive load for the SMG and a 2.5 Ω resistive load for the OMG, which is approximately equal to coil resistance in both cases. The SMG produced 8.5 mW while the opposing magnet structure produced 0.23 mW. The measured maximum power load voltage waveforms for the two structures are illustrated in Figure 3.22.

The SMG produces a larger voltage when compared to the OMG. However, when these generators are integrated into the sole of a size ten sports shoe, the number of these generator structures that can be accommodated becomes important in terms of maximizing power. The SMG produced 8.5 mW of power under load for a 45 mm coil section at 5 Hz. There is 100 mm available along the heel length of a size ten sports shoe which corresponds to 2 x 45 mm coil sections. A maximum of two of these parallel lengths could be fitted in one sole corresponding to 2 x 2 x 8.5 mW of power for each step. The SMG would theoretically produce 68 mW of power every second for two steps per second walking speed per shoe pair. Within the same
available area less power was calculated with the maximum amount of opposing magnet structures accommodated in the shoe sole set at 5 fitted along the same length as the SMG, with a 10mm space between them. Two of these lengths within in each shoe would correspond to just $5 \times 2 \times 0.23 \text{ mW}$ of power for each step taken. The OMG would then produce $2.3 \text{ mW}$ of power every second for the same walking speed.

3.5 Conclusions

This chapter has satisfied a range of objectives set out at the beginning of this thesis as two unobtrusive electromagnetic generators have been designed and optimised based on foot excitation forces, mechanical models and electromagnetic models. A large number of the electromagnetic energy harvesting designs described in Chapter 2 are obtrusive in nature and therefore would cause the normal gait of the user to be affected. Therefore, an unobtrusive electromagnetic generator that converts human energy during walking is desirable, and to date has not been achieved. A linear type electromagnetic generator structure designed in this work is shown to be capable of passively converting the wasted human energy dissipated during the swing phase of the gait cycle while walking. Similarly a different opposing magnet linear type electromagnetic generator structure is demonstrated to be capable of passively converting the stance phase of the gait cycle. Although a linear electromagnetic design is not new the novelty lies with the operating principles of two different designs as well as how they are integrated unobtrusively into a shoe sole which has not been achieved to date.

Accelerometer measurements are presented and used to predict the excitation force applied to the generators designed in this work. While Von Buren [62] investigated suitable locations around the body for vibrating generator designs with accelerometer results, this work’s accelerometer data predicts the force applied to a linear generator located at the foot. During a normal gait cycle -2g and up to 4g of acceleration is achieved by the heel of the foot in the horizontal direction during the swing phase of the gait cycle. With the SMG embedded in the heel of the shoe this normal foot acceleration causes a double movement of the magnet through the length of the generator. The magnet is predicted to have a velocity of between 1 and 3.5 m/s in this structure due to the forces applied. Pressure analysis of the heel strike
identified that up to 1771 N of force is applied by a standard user corresponding to a vertical acceleration of -3g achieved in the heel sole area during the heel strike of the gait cycle. This negative acceleration is due to the foot being in contact with the ground with the pressure applied by the user. As long as the force between the opposing magnets is <<1771N the generator structure should not hinder the gait cycle of the user. The complete analysis of the long term effects of both generator structures on the user should be investigated further but is outside the scope of this work.

NdFeB permanent magnet material is the optimum material to use as the magnet for both generator structures as it provides maximum residual flux density corresponding to maximum flux linkage. The optimum magnet shape for the SMG design is a cylindrical shape. For comparison the same shaped magnet can be used for the OMG. Using FEA analysis the magnetic flux distribution of any cylindrical shaped NdFeB permanent magnet can be predicted. A method of predicting the induced voltage on the generator coil based on this static magnetic flux distribution is achieved which accounts for the generator variables including coil length, coil diameter, coil thickness, magnet speed and length of generator. The mathematical program MATLAB is implemented to develop models that predict the AC performance of both electromagnetic generators. The optimum coil length in mm for the SMG is predicted based on the location of the 10% of maximum flux gradient value from the magnet. This optimum coil length (15 mm for a φ10mm ×10mm disc magnet) prediction is based on the criterion of maximising power with a usable voltage with the smallest generator coil resistance possible. The optimum coil length for the OMG using the same magnet is more difficult to achieve due to the space available in the heel. However, if the coil is broken up into a number of sections maximum pk-pk voltage and power can be achieved.

Under the same electromagnetic generator design and test conditions i.e. an excitation frequency of 5 Hz, coil diameter of 0.25 mm, coil length of 15 mm, NdFeB disc magnets and 0.75 mm coil thickness the SMG produces ~12 times more power than the OMG. While the power performance of the OMG may be improved based on further investigations [230] it will never be increased enough to compete with the power levels achieved by the SMG. Therefore the SMG should be considered the superior design and investigated further in Chapter 4 to maximise the amount of power available for electronic devices such as those presented in Table 2.12 and Table
2.13 of Chapter 2. The resultant generated power should be at least >10mW to satisfy the power requirements set out in the objectives of this work.
Chapter 4: Generator Parameter Analysis and Optimisation

4. Chapter 4 - Generator Parameter Analysis and Optimisation

4.1 Introduction

Chapter 3 identified the SMG as the optimum electromagnetic design to convert foot motion during walking. The output voltage and AC power levels presented in Chapter 3 were produced using a prototype generator structure based on a 10 mm diameter, 10mm thick NdFeB disc magnet that was constructed to verify generator operation and for comparison to the predicted models. However, the power levels achieved are low, < 10mW even at a high walking frequency of 5 Hz. The objective of this chapter is therefore to optimise this generator design using novel methods to provide output power levels that are > 10mW which is one of the main objectives of this work.

The relative effects of all parameters of a SMG when designed to fit within the heel of a man’s size 10 shoe sole heel with a volume of 100 × 75 × 20 mm³ are investigated in this chapter. Normalised results of peak-peak voltage and average power per unit generator length are presented for the simplest case of one magnet and one coil in section 4.2. Results are then applied to define optimum magnet and coil combinations for a given generator length (100 mm in this case) in section 4.3. The optimisation procedure is similar in some respects to Von Buren’s [86] work described in Chapter 2 as it included analysing a range of generator parameters such as; the ratio of magnet radius to outer radius, ratio of magnet height to pole pitch, number of poles and total height to outer radius. By varying these parameters the authors’ optimum generator design in terms of maximum power was identified. Similarly, Wang et al [202] have investigated an optimisation procedure for tubular permanent magnet machines. However, Wang’s investigation was not specifically for human harvesting generators and included different design parameters such as different pole pitches and thermal constraints. Although both the SMG and Von Buren’s designs are similar in terms of linear motion, Von Buren’s design is a resonant structure that includes soft magnetic spacers between each of the magnets and requires a translator to provide the linear motion of the magnets, which are not included in this SMG design. Thus the analysis in this chapter is different and
relevant. Detailed analysis is developed to produce design guidelines to maximise the output power for similar electromagnetic generator designs of any scale. Section 4.4 presents measured results from three such structures and identifies the optimum design. The analytical results are then compared to the measured results in section 4.5 where a number of generator parameters that influence the actual induced voltage of the generator, are identified.

### 4.2 Parameter Analysis

The generator parameters include magnet dimensions: $d_m, l_m$ and coil dimensions: $d_{ic}, d_{oc}, l_c$ as illustrated Figure 4.1. The effect of wire diameter ($w_d$) is also investigated, where a diameter of 0.25 mm is assumed otherwise. As the magnet dimensions change, the corresponding coil length varies to ensure that the generator is optimised for maximum output power as described in Chapter 3. Similarly, as the generator diameter is varied so too will the magnet diameter, coil depth and associated number of turns. In all cases, the optimum coil length is set equal to the extent of magnetic flux gradient (to 10% of its maximum value) as calculated at a radius 1 mm larger than the magnet radius. On each occasion the flux distribution of a particular magnet is predicted using Maxwell Ansoft and this is then input to the Matlab model as described previously. The flux linkage on the coil and the open-circuit voltage are then predicted by the Matlab model. The magnet is assumed to move at a constant normalised speed of 1 m/s. Finally, the load resistance is set equal to the coil resistance. Average power from each coil is then predicted using Matlab Simulink.
Chapter 4: Generator Parameter Analysis and Optimisation

Results are presented for one structure, but it should be noted that this volume can be replicated twice across the width of a shoe. Table 4.1 presents sample data from the range of generator single coil structures that are investigated in this work. In each case the generator diameter is fixed at 15 mm, the coil former is fixed at 1 mm, wire diameter is fixed at 0.25 mm and the copper fill factor is fixed to 0.6 where the wires are wound on top of each other.

Table 4.1: Sample Generator Coil Variables

<table>
<thead>
<tr>
<th>Magnet Diameter (mm)</th>
<th>Magnet Length (mm)</th>
<th>Coil Length (mm)</th>
<th>Coil Thickness (mm)</th>
<th>Number of Turns</th>
<th>Coil Resistance (Ω)</th>
<th>Pk-Pk Voltage</th>
<th>Power (mW)</th>
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<tr>
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<td>6</td>
<td>5.25</td>
<td>504</td>
<td>9.6</td>
<td>0.21</td>
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<td>136</td>
<td>1.87</td>
<td>1.19</td>
<td>0.911</td>
</tr>
</tbody>
</table>

4.2.1 Effect of magnet diameter

Within a fixed generator volume, the cross sectional area is divided largely between magnet area, $\phi_d m^2/4$, and coil area, $\phi(d_{oc}^2 - d_{ic}^2)/4$, as shown in Figure 4.1. The effect of increasing coil depth at the expense of decreasing magnet diameter is investigated in this case, to determine if the greater number of coil turns overcomes the reduced magnet flux sufficiently to provide higher output power. As the generator diameter is fixed the coil depth and corresponding number of coil turns is varied as the diameter of the magnet is varied. Thus for a small magnet diameter there is a large coil depth and the weaker flux of the magnet is linking with the coil turns furthest away. Results of average output power per unit coil length vs. magnet diameter are given for different generator diameters in Figure 4.2 (a), while corresponding results of peak-peak voltage per coil length are compared in Figure 4.2 (b). In all cases, the length and diameter of the magnet are equal so that the magnet retains its axial orientation as it slides through the coil.

Normalisation of the results with respect to the coil length in this case allows applications to define optimised designs in section 4.3. In each case the generator length associated with each magnet is calculated from (4.3). Results are produced for single coil generators, and the length available accommodates the coil, entry and exit distances (gaps) of the magnet from the coil and the length of the magnet itself. From Figure 4.2 (a), it is clear that for a given generator size, there is an optimum magnet
diameter that provides maximum output power per coil length. Table 4.2 presents the power per coil length results for a 15mm generator diameter. Analysis of the results presented in Table 4.2 and Figure 4.2 (a) shows that this optimum point is found when the cross sectional area of the magnet equals that of the coil in each case:

\[
\pi r_m^2 = \pi (r_c^2 - r_m^2) \quad \text{or} \quad r_m = r_c / \sqrt{2}
\]  

(4.1)

Table 4.2: Power per Coil Length – 15mm Generator Diameter

<table>
<thead>
<tr>
<th>Magnet Radius (mm)</th>
<th>Magnet Length (mm)</th>
<th>Magnet Area (mm²)</th>
<th>Area of Coil (mm²)</th>
<th>Power Per Coil Length (µW/mm)</th>
<th>( r_c / \sqrt{2} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>2.5</td>
<td>4.909</td>
<td>160.810</td>
<td>0.650</td>
<td>5.303</td>
</tr>
<tr>
<td>2.5</td>
<td>5</td>
<td>19.635</td>
<td>138.230</td>
<td>12.389</td>
<td>5.303</td>
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<tr>
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<td>82.333</td>
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</tr>
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<td>113.097</td>
<td>22.777</td>
<td>53.603</td>
<td>5.303</td>
</tr>
</tbody>
</table>

Figure 4.2: (a) Output Power and (b) Peak-Peak Voltage vs. Magnet Diameter
Chapter 4: Generator Parameter Analysis and Optimisation

Therefore, it may be deduced that the increase in voltage provided by increasing numbers of turns is offset by increased coil resistance when the magnet diameter is made smaller than \( r_o / \sqrt{2} \) mm. It should be noted that values of power in this case are averaged over the time between successive steps of walking, so that instantaneous power levels are much higher.

Table 4.3: Vpk-pk Per Coil Length – 15mm Generator Diameter

<table>
<thead>
<tr>
<th>Magnet Radius (mm)</th>
<th>Magnet Length (mm)</th>
<th>Magnet Area (mm(^2))</th>
<th>Area of Coil (mm(^2))</th>
<th>Vpk-pk Per Coil Length (V/mm)</th>
<th>( r_m/2 ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>2.5</td>
<td>4.909</td>
<td>160.810</td>
<td>0.036</td>
<td>3.75</td>
</tr>
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<td>138.230</td>
<td>0.115</td>
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</tbody>
</table>

Table 4.3 presents the peak to peak voltage per coil length results for a 15mm generator diameter. In terms of peak-peak voltage, it is interesting to note that the largest values are achieved for \( r_m \approx r_o / 2 \) mm in Table 4.3 and Figure 4.2 (b). When compared with designs optimised for maximum power, this indicates that the reduction in voltage produced with a larger \( r_m \) is more than compensated for by the corresponding reduction in coil resistance. Higher voltage may be achieved by using a smaller wire diameter so that more turns can be fitted within the same space. For illustration, results of average power and peak-peak voltages are presented in Figure 4.3 for a \( \phi 10 \) mm \( \times 10 \) mm magnet sliding through a coil with diameter and length both equal to 15 mm.

Figure 4.3: Power and peak-peak voltage per unit length vs. wire diameter
Clearly, voltage levels increase dramatically with decreasing wire diameter as the number of turns that can be accommodated increases. At the same time, the variation in average power is much lower. This is explained by the fact that coil resistance is approximately proportional to the square of the coil turns, thereby offsetting the increase in voltage squared with turns. The slight decrease in power with decreasing wire diameter is explained by the reduction in percentage conductor area due to wire insulation.

4.2.1.1 Effect of Coil Former

Obviously, a small portion of the generator area is taken up by a coil former, but this doesn’t impact significantly on the result if it remains fixed to as small as possible value. However if the coil former thickness is increased the strength of flux of the magnet that links with the coil turns is significantly reduced. Obviously, the thicker the coil former the less induced peak to peak voltage that is generated. Figure 4.4 demonstrates how the generated power is affected by the increase in coil former thickness for a single coil structure. The analysis carried in this work focuses on a 1 mm coil former as it is demonstrated to be large enough and strong enough to withstand the weight of the user when the generator is embedded in the heel of the shoe sole.

![Figure 4.4: Effect of Coil Former Thickness](image)

4.2.2 Effect of magnet length

By increasing the length of the moving magnet, the extent of $|\frac{d\phi}{dx}|$ and therefore coil length and number of turns increases. Since the shape of the magnetic
flux distribution also changes, the relationship between output power and magnet length is not clear. In order to illustrate this effect, results of power and voltage per unit length are presented as a function of magnet length in Figure 4.5 for the optimum magnet diameter within generator diameters of 15 mm and 20 mm. As shown, power per unit length increases with magnet length, however due to the need to accommodate the magnet entrance and exit distances within the space, the rate of increase levels off for longer magnets. This poses the question of whether it’s better to use one long magnet instead of several shorter magnets in a given generator space, and this issue is investigated in detail in section 4.3.

Figure 4.5: (a) Power and (b) Peak-Peak Voltage per Unit Length vs. Magnet Length
For peak-peak voltage levels, it is interesting to see that the graph levels off when the magnet length equals half the generator diameter in both cases (\( l_m = l_{gen}/2 \)). This can be compared to the magnet diameter investigation in section 4.2.1 where it was found that the maximum peak to peak voltage observed was found when the radius of the magnet was equal to half the generator radius:

4.3 **Optimisation for a given space**

The analysis presented in this chapter to date has been based on single coil generators, whose size depends on the size of magnet chosen. In this section, the results from section 4.2 are applied to predict the maximum power that can be generated within a specific generator volume of \( 15 \times 15 \times 100 \text{ mm}^3 \), which can be accommodated within the heel of a shoe sole. With such a restriction on space, obviously there are only certain magnet and coil combinations that can be accommodated. The performance of single magnets passing through multiple coils, as well as multiple magnets passing through the same coils are investigated. For each magnet, the coil length is chosen to provide maximum power.

The ultimate goal is to achieve the maximum AC power for each possible generator design and hence discover the optimum generator solution. In the final design the generator will be required to produce maximum DC power in order to make it usable in most portable applications, however results of this AC analysis should also correspond to maximum DC power. In this way the output of the generator is investigated in terms of instantaneous AC power which theoretically can be visualised as the converted DC power through a full bridge rectifier utilising ideal diodes. This corresponds to generator AC output being converted to DC power with 100% efficient conversion circuitry, hence identifying the maximum DC power the generator designs are capable of.

4.3.1 **Single magnet**

Figure 4.2 illustrates that the optimum magnet diameter for a given generator cross sectional area is given by \( d_m = d_0/\sqrt{2} \text{ mm} \); i.e. a magnet diameter of 10.6 mm is optimum for the given area of \( 15 \times 15 \text{ mm}^2 \). The closest available standard magnet has a diameter of 10 mm. Clearly, the length of the space under consideration is much
longer than the magnet diameter, so that the question of optimum magnet length arises. The choice of magnet length however is not so obvious, which may be explained by the non-linear relationship of power per unit length with magnet length illustrated in Figure 4.5 (a). Results in Figure 4.5 (a) indicate that the power per coil length increases with increasing magnet length, thereby suggesting the use of the longest magnet that can be accommodated is desirable. However, the rate of increase in power reduces for longer magnets and finally begins to reduce after ~25 mm; therefore it can be expected that the power output achievable with several smaller units is greater than that from a single large unit. It should also be noted that in addition to the length of the coil, \( l_c \), and magnet, \( l_m \), entry & exit distances between the magnet and coil (2\( l_\phi \)) must also be accommodated in the given generator space as shown in Figure 4.6. For maximum power, it’s found that a minimum value of \( l_\phi = l_c/2 \) mm is required (as described in Section 3.3.1), thereby reducing the length of available space for fitting generator coils by \( l_c \). Physically the distance between the magnet and the coil for maximum power should be:

\[
l_\phi = \frac{l_c}{2} - \frac{l_m}{2}
\]  
(4.2)

For this reason, it’s found that it’s more effective to use several shorter coils (corresponding to a shorter magnet) wound one after another, as shown in Figure 4.6, rather than one longer magnet.

For an \( n \)-coil generator the maximum coil length, \( l_c \) that can be fitted within a total generator length of \( l_{gen} \) is then given by:

\[
l_{gen} = l_m + 2l_\phi + nl_c = l_m + (n + 1)l_c
\]  
(4.3)
with \( l_0 = l_c/2 \). The optimum value of \( l_c \) can be defined for a given magnet dimension, (4.1) can be applied to define a range of generator designs with increasing numbers of coils. The optimum generator solution will depend on space available, as only certain magnet sizes will have an optimum coil combination that fits exactly within the given space. As the magnet length increases the number of coils that will fit into a 100 mm length decreases, due to the length of the coil increasing with magnet thickness for a fixed magnet diameter. The relationship between the optimum coil length and magnet dimensions is shown for three disk magnet diameters (7.5 mm, 10 mm and 12 mm) in Figure 4.7, where it is clear that the relationship is linear. Results were produced using Finite Element Analysis simulation of the flux distribution at a radial distance of 1 mm from the magnets in all cases. For the generator volume of \( 15 \times 15 \times 100 \text{ mm}^3 \) being investigated, the relationship between \( l_c \) and \( l_m \) for a 10 mm magnet diameter is found by linear regression as:

\[
l_c = 0.52 \times l_m + 9.5
\]  
(4.4)

or for a fixed 10 mm magnet thickness:

\[
l_c = 0.61 \times d_m + 8.68
\]  
(4.5)

where \( l_c, d_m \) and \( l_m \) are in mm. By comparing the linear relationship found for the different magnet thicknesses a relationship between \( l_c \) and \( l_m \) for any magnet thickness can be identified. Similarly a further relationship between \( l_c \) and \( d_m \) for any magnet diameter can be found. The prediction of coil length achieved by (4.5), for varying magnet diameters, identifies the case when the magnet length is fixed at 10 mm. However, similar linear regressions were achieved for a much wider range of magnet lengths. By plotting the x-multiple (0.61 in (4.5) for example) and the constant (8.68 in (4.5) for example) achieved by each of these formulae against the magnet lengths, further linear regressions are achieved. The resultant formula can then be used to predict the coil length for any magnet dimensions based on the maximum to +/- 10% flux gradient method described in Chapter 3.

\[
l_c = (0.004 \times d_m + 0.5) \times l_m + (0.6 \times d_m + 3.4)
\]  
(4.6)

Substituting for \( l_c \) into (4.6), the range of coil designs given in Table 1 is defined for \( l_{gen} = 100 \text{ mm} \). In order to coincide with standard magnet sizes, \( l_m \) is rounded to 2.5 mm, and \( l_c \) to the nearest mm.

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Another aspect of the generator design is to identify which method of coil connection will maximise the total generator power. Each magnet has a corresponding coil length and hence number of coils that will fit into the 100 mm generator length. The coils could be connected in series alternating and then loaded as described in Chapter 3, which will provide a higher peak to peak voltage at the expense of larger source impedance. Alternatively the coils could be individually loaded and then connected in parallel. In this way the power is induced on a coil by coil basis and can be combined to provide the total power. Although $V_{pk-pk}$ is less than for the series-alternating connection in this case, the much smaller source impedance provides maximum power.
FEA results of magnetic flux distribution were applied to predict voltage and power levels produced by the different generator designs as described in Chapter 3. In all cases, coils were assumed to be connected in parallel to a matched load through ideal full-wave rectifier circuits, so that maximum power is provided. Results of average power and peak-peak voltage are compared for three magnet diameters with increasing numbers of coil sections in Figure 4.8 (a) for a 15 mm diameter generator.

Figure 4.8: (a) Average power (b) peak-peak voltage vs. number of coil sections in $15 \times 15 \times 100$ mm$^3$
The results of power generated by magnets with diameters of 7.5 mm and 12 mm are also included to illustrate the effect of choosing the optimum magnet diameter for a given generator diameter. For a 100 mm generator length, if the magnet diameter is fixed to 7.5 mm or 10 mm with the smallest magnet thickness then a maximum of seven coils is possible. Whereas for the 12 mm diameter magnet a maximum of only six coils is possible. A maximum average power of almost 8 mW is predicted for 3 coils connected in parallel, which is over twice that predicted for one larger coil that fits within the same space. Analysis of these results shows that maximum power designs are found for magnets whose product of power per coil length and total coil length that can be accommodated within the given space is maximum; i.e. the results of Figure 4.5 can be applied directly along with (4.4), (4.5) and (4.6) to predict maximum power designs. As expected, maximum power is achieved with a magnet diameter of 10 mm in this case.

A comparison between parallel and series alternating connected coils is presented in Appendix A where it is clear that parallel coils achieve the maximum power. It can be seen that while the 10 mm diameter magnet achieves a maximum of 8 mW with three coils connected in parallel, a maximum of 4.2 mW is achieved when these three coils are connected in series-alternating.

Plots of peak-peak voltage in Figure 4.8 (b) show a decrease in voltage with increasing number of coils, which is expected as the length of individual coils reduces. Higher peak-peak voltage achieved for smaller diameter magnets is explained by the combination of higher flux gradient and larger number of coil turns. As noted in section 4.2, voltage levels can be tuned for different applications by changing the coil wire size used. The $V_{pk-pk}$ reduces linearly with increasing number of parallel coils confirming that more coils do not necessarily generate maximum power. For comparison the total generator $V_{pk-pk}$ is presented for both parallel individually loaded coils and series-alternating connected coils in Appendix A. The results for the 7.5 mm, 10 mm and 12 mm diameter magnets are also presented, along with the maximum achievable $V_{pk-pk}$ for corresponding coil numbers. On this occasion the maximum $V_{pk-pk}$ results are generated by the series alternating connected coils, as explained by the addition of successive voltage peaks. For series alternating connected coils the maximum power was achieved using 3 coils connected in series alternating, subsequently reducing with increasing numbers of generator coils.
4.3.2 Multiple magnets

Up to this point, all results are based on a single magnet travelling through the coil. The effect of adding several magnets within the generator length is investigated here, where the case of opposing magnet poles is considered. In order to prevent cancellation of voltages within a given coil, it is found that the minimum magnet separation should be:

$$m_s = l_c + (l_c - l_m)$$

as illustrated in Figure 4.9 for the case of a 5-coil, 2-magnet generator. Practically, this separation may be provided by a non-magnetic spacer, however with increasing numbers of magnets, the scope for magnet travel is limited.

Voltage and power levels produced by the generator are predicted by applying the models described in Chapter 3 (using Ansoft and Matlab) for each magnet and coil combination, and adding the total contributions. Clearly, with increasing number of magnets, the instantaneous values of flux linkage are increased within the coils. The number of pulses and hence rms voltage on individual coils is also increased in the center of the generator. For example, in the case of a 5–coil, 2–magnet generator, there are 2 voltage pulses instead of 1 produced on the central coil, with 1½ pulses each on the 2\textsuperscript{nd} and 4\textsuperscript{th} coils (for each excursion of the magnets in one direction). Open-circuit voltage waveforms for the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} coils are shown in Figure 4.10 for illustration, where it is assumed that the magnet speed is the same as that applied for single magnets.
Additional voltage pulses clearly contribute to increasing rms voltage and power levels. For direct comparison with the case of a single magnet in section 4.3.1, the total average power levels predicted within a 100 mm length are compared in Figure 4.11 for different numbers of magnets. As before, the generator coils are assumed to be connected to one load through individual full wave rectifier circuits. As might be expected, higher power is predicted for two magnets over one in all cases, where increasing numbers of voltage pulses produce larger rms voltages. In comparison to Figure 4.8 it is clear that any generator incorporating the separated magnet technique will have an improved power output, provided that the separated magnet achieves the same velocity as the single magnet. Similarly, three magnets provide higher power than one magnet in all designs, but not necessarily higher than two magnets. This is explained by the reduced scope for magnet travel as the number of magnets increases. For the same reason, it is found during measurements in section 4.4 that the average magnet speed reduces and therefore overall, the best results are achieved with one magnet. The comparative analysis for the 17 mm and 20 mm diameter generators are described in Appendix A.
4.3.3 Half Coils

The performance of the generators could be improved by introducing a half coil section at either end of the generator. These sections (gaps) were provided during the design phase of this work in order to maximise flux linkage into the first and last coils of the generators. As such, these gap sections are wasteful but filling them with additional coil sections improves the generator output power. The level of improvement will depend on the number of coil sections available within the generator length. For example if the generator contains a single coil then the addition of the half coils could effectively double the total generator power. For a two coil generator the total power will increase by a third, and so on. Figure 4.12 illustrates the improvement of generator power for a generator volume of $100 \times 15 \times 15$ mm$^3$ following the addition of the extra two half coils. Figure 4.12 (a) identifies the thickness of the 10 mm diameter magnet at which the maximum power is observed. Previously, it was shown that this had been achieved with the 20 mm thick magnet. However, it is identified that the power increase due to the half coils does not affect the shape of the plot and the maximum power is located at the same magnet thickness. Subsequently, it is clear that the relative increase in power decreases with increasing number of generator coils within a 100 mm length. The improvement factor observed with the addition of the half coils is detailed in Figure 4.12 (b) where the rate of estimated improvement is plotted against the number of generator coils.
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Figure 4.12: 100 mm Generator Influence of Extra Half Coils (a) Power (b) Factor of Improvement

4.4 Measurements

Table 4.5: Details of Test Coil Structures

<table>
<thead>
<tr>
<th># coils</th>
<th>( l_m ) (mm)</th>
<th>( l_c ) (mm)</th>
<th># coil turns</th>
<th>( k_{cu} )</th>
<th>( R_c ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>20</td>
<td>20</td>
<td>480</td>
<td>0.6</td>
<td>7.181</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>17</td>
<td>408</td>
<td>0.6</td>
<td>6.1</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>15</td>
<td>360</td>
<td>0.6</td>
<td>5.4</td>
</tr>
</tbody>
</table>

In order to verify the design guidelines proposed, a series of measurements was performed on three test generator structures as described in Table 4.5, based on a 10 mm diameter magnet and 15 mm diameter generator. All coils were wound on top of each other using 0.25 mm diameter wire on a custom PTFE former with a thickness of 1 mm and an inner diameter of 10.5 mm. The magnets are stopped by a piece of PTFE that is glued to cover the circular opening of the cylindrical former at each end.

Figure 4.13: Test Generators Placed Within the Sole of a Sports Shoe
A photograph of the 3 and 4-coil generators within a sports shoe is given in Figure 4.13. As shown, the generators were located under the insole of a shoe at the heel; the internal plastic was hollowed out to accommodate the generators and a layer of foam was applied before replacing the insole so as to minimise discomfort to the wearer. Two generator structures were tested at a time for an approximate walking speed of 2 steps/second. A portable oscilloscope [203] was used to capture the voltage waveforms at the generator coil terminals for different loads.

Figure 4.14: Measured 3 Coil Generator Open Circuit Induced Voltages

Figure 4.14 presents the induced open circuit voltage on all three individual coils of the three coil generator during a single step. For comparison a four coil generator pulse and a five coil generator pulse are detailed in Appendix B. For each design, the generator was tested with coils connected in parallel to individual loads, and connected in series alternating to a single load (to represent an ideal AC/DC power conversion circuit). For illustration, load voltages measured on the central coils of the 3 and 5 coil generators are shown in Figure 4.15 for the case of one sliding magnet and matched load.
Figure 4.15 shows two sets of pulses within a 2 second time interval in both cases, confirming a walking speed of 2 steps/second. The amplitude of the second half of each pulse is larger than the first, illustrating how the magnet speed increases as it travels through the coil. The double pulse is due to the successive positive and negative accelerations experienced by the magnet during a single step as described in Chapter 3. As might be expected, the voltage amplitudes and pulse duration are smallest for the shortest coil (smallest magnet), while the opposite is true for the longest coil. Given that measurements were performed for the same walking conditions as assumed in calculations, the match with predicted voltages presented in Figure 4.8 (b) identifies that the assumption of an average magnet speed of 1 m/s is not validated as the measured pk-pk voltages are much higher than predicted.

In terms of power, voltages on individual coils were measured for a range of load resistors and corresponding average power levels were calculated using (3.12).
Total power for each generator was found by summing the power levels for each of its coils. Results presented in Appendix C describe the AC power generated on each of the coils as well as the total generator AC power due to varying load resistances on each of the generators. Results are compared in Figure 4.16.

**Figure 4.16:** Measured Output Power vs. Load for 3, 4 and 5-Coil Generators with One Magnet

Figure 4.16 illustrates that the highest power is measured for the 3 coil generator, which corresponds to predictions. In this case, the power level is higher than predicted, and this is most likely explained by instantaneous magnet speeds of greater than 1 m/s. The maximum power was achieved where $R_{\text{Load}} = R_{\text{Source}}$ on each occasion as predicted. Voltage waveforms were applied to predict corresponding levels of instantaneous power; up to 200 mW was measured for each coil of the 3 coil generator, while levels of 130 mW and 60 mW were more typical of coils in the 4 and 5 coil generators, respectively. It should be noted that for parts of the waveforms, instantaneous power levels are doubled in each generator due to simultaneous contributions from two successive coils.
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Figure 4.17: Voltage waveforms for 3-coil generator with one magnet (a) parallel coils (10 $\Omega$ load each), (b) Coils Connected in Series Alternating (30 $\Omega$ load)

Measured voltages for both parallel and series alternating loaded coil connections are compared for the 3-coil generator in Figure 4.17. Clearly, voltages on successive coils overlap somewhat for the parallel coils in Figure 4.17 (a), and increasing magnet speed can be seen in terms of increasing voltage pulse amplitudes as the magnet progresses in each direction. As expected, voltage amplitudes are larger when the coils are connected in series alternating in Figure 4.17 (b), while the total number of pulses is smaller than for parallel coils. Corresponding average power levels were calculated for the different coil connections as before, where it is found that the maximum power achieved with the parallel coils is approximately twice that measured for the series alternating connection. As explained in Chapter 3, this is caused by current flowing through coils when there is no voltage induced on them for part of the magnet travel time.
The improvements in rms voltage due to multiple magnets is also presented whereby measured step pulses of both the 4 and 5 coil generators with separated magnets are compared. The measured performance of coils with 2 sliding magnets is illustrated in Figure 4.18, where voltages on the central coils of the 4 and 5 coil generators are presented for matched load conditions. The additional pulses produced are evident, as are higher voltage amplitudes for the larger magnet (4-coil) case. Average power levels were deduced from measurements of voltages under different load conditions as before, and results are compared in Figure 4.19. All measured open circuit voltage results for both the 4 and 5 coil generators with additional magnets are presented in Appendix B.
Figure 4.19: Output Power vs. Load Resistance for 1 and 2 Magnets in (a) 4-Coil and (b) 5-Coil Generators

In the case of the 4-coil generator, it is seen that average power levels measured with 2 magnets are lower than those achieved with 1 magnet when the coils are connected in parallel. This contradicts predictions which were based on an assumption of constant magnet speed (of 1 m/s). However, due to the combined effects of reduced scope for magnet travel and increased moving mass, the speed of 2 magnets is lower than that of a single magnet. This may be seen by comparing voltage waveforms for the 5 coil generator in Figure 4.15 and Figure 4.18, which have the same time period between pulses, but the distance travelled in the case of 2 magnets is
lower. The effect is less significant in the case of the 5-coil generator, where the magnet size and separation are both smaller, so that power levels for 1 and 2 magnets coincide.

It is interesting to see that power levels for the series alternating connections are improved by the addition of a magnet in both cases. The improvement is attributed to the increased level of coincidence between voltage pulses on successive coils than produced with a single magnet, as may be seen in Figure 4.10. Notwithstanding this, overall it may be concluded that the highest power level is achieved with one magnet travelling through parallel coils, each of which is connected to a matched load. In this case, the optimum generator design according to Figure 4.16 is the same as that predicted; i.e. a 3-coil generator with a $\phi 10 \times 10$ mm magnet.

4.5 Modelled Vs. Measured

4.5.1 Generator Structure

![Modelled Structure Vs. Physical Generator](image)

Figure 4.20: (a) Modelled Structure Vs. (b) Physical Generator

The accuracy of prediction models for AC power measurements is established in this chapter where it is confirmed that maximum power from the generator is achieved when the load resistance matches the source impedance. To verify the performance of the DC analytical models developed in Chapter 5 it is critical that variables involved exactly match the built generator structure. Variables such as peak voltage, source impedance and coil voltage pulse width which are generated by the
AC models are subsequently used by the DC models to predict the DC performance of the generator.

Table 4.6: Comparison between Modelled and Built Structures

<table>
<thead>
<tr>
<th>Generator Variables</th>
<th>Modelled Structure</th>
<th>Built Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Length</td>
<td>100 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Generator Outer Diameter</td>
<td>15 mm</td>
<td>15.7 mm</td>
</tr>
<tr>
<td>Magnet Diameter</td>
<td>10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Magnet Thickness</td>
<td>20 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>Magnet Material</td>
<td>NdFeB</td>
<td>NdFeB</td>
</tr>
<tr>
<td>Former Thickness</td>
<td>0.75 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Free Movement Gap</td>
<td>0.25 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>0.25 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Coil Enamel Thickness</td>
<td>0 mm</td>
<td>17 µm</td>
</tr>
<tr>
<td>Number of Coil Turns</td>
<td>480</td>
<td>480</td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>7.2 Ω</td>
<td>7.95 Ω</td>
</tr>
<tr>
<td>Magnet Speed</td>
<td>1 m/s</td>
<td>Variable m/s</td>
</tr>
</tbody>
</table>

The ideal structure of the generator is presented in Figure 4.20 (a) while the actual built generator structure is presented in Figure 4.20 (b). The generator variables for both modeled and constructed generator structures are compared in Table 4.6. A number of generator variables exactly match such as the generator length, generator inner diameter, magnet material, magnet length and magnet diameter. However, the coil structure is slightly varied between the predicted models and actual built structure due to the influence of the coil enamel. The generator outer diameter is also affected by the air gap and coil former thickness of the machined structure. It was presented in this chapter that the Grade 1 copper enameled wire used in this work includes an enamel thickness of 17 µm. Although minimal, the effect of this enamel is to increase the length of wire wrapped around the generator structure, which will in turn increase the coil impedance, if the full 480 coil turns are wrapped around the built structure. Applying the coil resistance models, DC resistance is predicted to increase from 7.2 Ω to 7.5 Ω in this case, while the actual measured resistance was 7.95 Ω due to the copper fill factor. The presence of the enamel layer also affects the distance between coil and magnet and hence the flux linking the coil turns. These variables were subsequently updated in the models to provide a more accurate representation of the built structure.
4.5.2 Open Circuit Measurements

A closer investigation of the open circuit performance of the 3 coil generator is illustrated in Figure 4.21 will aid in determining the exact magnet speed as it passes through each coil. The analytical models presented in Chapter 3 estimate a 1.5 V peak voltage, which is based on a 1000 mm/s magnet speed. Results were measured while walking at a constant speed. It can be seen in Figure 4.21 that the double magnet movement achieved while walking generates two separate voltages on each coil.

Figure 4.21: 3 Coil Generator Measured Open Circuit Pulse – 1 Second Period

Figure 4.22: 3 Coil Generator Measured Magnet Speed Investigation (a) Outward Direction (b) Backward Direction
On closer inspection of Figure 4.21 it is clear that not only are two separate voltages generated on each coil per second but there is also a varying peak to peak voltage as the magnet passes through each coil in either direction. By expanding the data in Figure 4.21 it is clear that this varying peak voltage is due to the increasing magnet speed as the magnet travels through the generator coils in either direction as seen in Figure 4.22. In fact the magnet speed is increasing at such a rate that there is also a variation between the positive and negative peaks generated on each coil. Because the magnet begins 10 mm outside the first coil, it has to travel a distance of 20 mm to be positioned in the center of the first coil and induce a negative pulse. The time required by the magnet to travel this full coil length (20 mm in this case) is identified in Figure 4.22 as 32 ms. Each 20 mm movement of the magnet induces further positive and negative voltage pulses on the generator coils and the time taken for these corresponding 20 mm magnet movements through the generator coils is also described in Figure 4.22.

Based on these measured times, the magnet velocity for every 20 mm magnet movement can be established. Figure 4.22 demonstrates how the magnet speed passing through the first half of the 1st coil on the outward direction is ~ 600 mm/s, and by the time it exits the second half of the 3rd coil it has reached a speed of ~1700 mm/s. On the backward direction the magnet speed increases at a more rapid rate as it varies from ~600 mm/s through the first half of the 3rd coil to 2500 mm/s through the second half of the 1st coil. These results indicate the predicted 1.5 V peak voltage at the conservative 1000 mm/s magnet speed is lower than what is actually generated. Based on the accelerometor measurements presented in Chapter 3 a peak magnet velocity of >3000mm/s was predicted and this speed matches more closely what has been achieved from the measured induced voltage results. By varying the magnet speed as it passes through each coil (on both the outward and backward journeys) in the models described in Chapter 3 a more accurate estimation of induced coil voltage can be achieved. Figure 4.23 illustrates the predicted 3 coil voltages on both the outward and backward journeys which compare well with the measured results presented in Figure 4.21.
4.5.3 Varying Walking Speed

The rate of the double magnet movements occurring during each step will increase at the same rate as the walking speed (or step/s), thereby decreasing the time between generated pulses. Consequently it is predicted that the average DC power of the generator would be greatly enhanced by the increased rate of the double magnet movement through enhanced walking speed. To quantify how the rate of pulse voltage is affected by the rate of walking speed, three walking speeds were investigated. The slowest speed was 4.5 km/hr walking speed as used to produce all measurement results presented up to this point. The walking speed was then increased to 7.5 km/hr (fast walking speed) and 10 km/hr (slow jogging speed) respectively. The objective of this experiment was to identify if the number of coil voltage pulses are increased as the walking speed is increased, before applying any conversion circuits. Figure 4.24 demonstrates the open circuit voltages from the 3 coil generator for each of the three different walking speeds. It is clear that the numbers of pulses (or double magnet movements) that occur in the same time frame (in this case 5 seconds) are increased as the walking rate is increased, as predicted.

At 4.5 km/hr there is one double magnet movement (or two generated pulses per coil) every second giving a total of ten pulses per coil in the five second period as seen in Figure 4.24 (a). This rate increases to ~ 3 coil pulses per second when the walking speed increases to 7.5 km/hr as illustrated in Figure 4.24 (b). Finally at a
walking speed of 10 km/hr there are ~4 generated pulses per coil per second as shown in Figure 4.24 (c).

![Figure 4.24: Generator Open Circuit Voltage – Varying Walking Speed (a) 4.5 km/hr (b) 7.5 km/hr (c) 10 km/hr](image)

It was established that at a walking speed of 4.5 km/hr the magnet speed ranges from ~500 mm/s to 2500 mm/s as the magnet passes through the generator on both the outgoing and return journeys. Based on the measurements presented in Figure 4.24 it can be identified that the magnet speed remains fairly constant over the three walking speeds as the largest peak voltage in all cases is ~4V. Therefore
although the magnet does pass through the generator an increasing number of times, it doesn’t travel through the generator at a faster speed than achieved at 4.5 km/hr. This may be explained by how the double magnet movement is achieved during the gait cycle which is described in Chapter 3. Briefly, the initial magnet movement occurs when the foot lifts off the ground and is swung back causing the magnet to be propelled backwards based on the forces acting upon it. The second movement occurs while the foot is slowing down as it aligns itself to return to the ground causing the magnet to slip forward once the frictional forces are overcome. As the speed of walking is increased the forces that cause both these magnet movements does not necessarily increase significantly to cause these magnet movements to increase in velocity (even though accelerometer data in Figure 3.5 demonstrates that the measured force on the ankle is increased when running). Therefore the peak voltages achieved for each walking velocity remain approximately constant as seen in Figure 4.24.

### 4.5.4 Effect on Gait

Finally a preliminary investigation on the influence of the generator embedded in the shoe sole on the human gait is carried out. In this case a further accelerometer (MS9010.D) from Colibrys [204] is integrated onto the back of the heel of the shoe with the sensing Z-direction of the accelerometer directed towards the toe of the foot as demonstrated in Figure 4.25 (a). Initially results are achieved for walking a number of steps with no generator embedded in the heel of the shoe sole and this measured acceleration data is presented in Figure 4.25 (a). The next step is to embed the 3 coil generator with unloaded coils into the heel and as before, and results are generated from the accelerometer fixed to the heel as shown in Figure 4.25 (b). A further advantage of this measurement is that magnet movement during a human gait can be identified by comparing heel movement during the gait described by the accelerometer and generated coil voltage.

The influence of the embedded generator is minimal as the acceleration data of Figure 4.25 (a) and (b) compare well. By carrying out the same measurements with loaded coils the influence of any electromagnetic forces can also be identified. Once more the effects are seen to be minimal as shown in Figure 4.25 (c), and acceleration data matches well with the previous results while the generated voltage and hence magnet movement also appears to be unaffected as predicted. Finally, these results
confirm the excitation forces described in Chapter 3, where it is seen that the start of magnet movement (indicated by voltage pulses) occurs close to peak values of acceleration. The acceleration data indicates that the foot does not add extra accelerations to maintain the gait cycle with the generator embedded in the shoe sole. However, to fully establish the long term effects of the generator embedded in the shoe sole a study would be required on a range of users over a range of time periods. This is outside the scope of this work.

Figure 4.25: Acceleration Vs. Generator Influence (a) No Generator (b) Unloaded Generator (c) Loaded Generator
4.6 Conclusions

This chapter presents a novel method for designing an optimum sliding magnet electromagnetic generator as set out in the objectives on this work. Results are normalised so that they can be applied to design similar generators for a range of application environments and generator sizes. The main findings show that in order to achieve maximum output power, there is an optimum coil length for a given magnet size and an optimum magnet diameter for a given total generator diameter. Based on the 10% of maximum flux gradient method of obtaining the coil length of each magnet, an analytical model can be established based on magnet diameter and magnet length to predict the coil length of any cylindrical magnet. For a given magnet diameter, maximum power is found when the cross sectional area of the magnet equals that of the coil, while maximum peak-peak voltage is achieved for \( r_m \approx r_o/2 \) mm. Based on the optimum magnet diameter, power per unit length increases with magnet length but the rate of power increase levels off for longer magnets. Peak-peak voltage levels in this case, levels off when the magnet length equals half the generator diameter. In terms of wire diameter voltage levels increase dramatically with decreasing wire diameter, while at the same time the variation in average power is much lower.

Due to the space available for the electromagnetic generator structure the design can include multiple coils and multiple magnets. Multiple magnets can be separated by a fixed distance within a generator length and this is predicted to provide improved generator performance for generators with more than 3 coils. However, no improvement in generator power is achieved due to the limited magnet velocities achieved during a normal gait cycle. Maximum power was found on Von Buren’s [86] design with a number of magnets and coils which is not the case with the SMG. However, the optimum ratio of magnet radius to outer generator radius (~0.75) found to provide maximum power is similar to what was identified in optimisation of the SMG design. This result of is also similar (0.8) to what Wang [202] has estimated for a different type of tubular linear generator.

The highest power predicted is achieved by using one magnet with dimensions of \( \phi 10 \) mm x 20 mm and several coils connected in parallel to a load that matches the coil resistance. In this case the generator will have three coils of 20 mm length with the remaining space required for entry and exit of the first and last coils allowing for
maximum flux linkage. The highest power level demonstrated in a $\Phi 15 \times 100$ mm$^3$ space (corresponding to a volume of $\sim 18$ cm$^3$) is an average of 14 mW and an instantaneous value of 200 mW for normal walking speeds. These levels compare favourably with the power produced by piezoelectric generators in the shoe heel [9] while also satisfying the >10mW requirement set out in the objectives of this work. Most significantly the proposed structure is much more amenable to integration in the shoe than other electromagnetic generators discussed in Chapter 2.
5. Chapter 5 - AC/DC Circuit Modelling

5.1 Introduction

In this chapter, the effects of rectification stages required to convert the SMG AC waveforms into a usable DC form are investigated. Due to the AC nature of the generator output it is clear that if the generator is to supply power to typical portable electronic device conversion of the AC waveform to a constant DC level is required. The hand held electronic devices that the generator could ideally supply would include Smartphones (3.7V at ~3 W) or digital cameras (3.5 V at 1.25 W) as described by Table 2.12 in Chapter 2. However in reality, as will be presented in this chapter and as demonstrated in Chapter 4, the maximum DC power produced by the generator would only be capable of charging a battery or powering devices in the mW range. These devices might include an RF radio (10.5 mW) or a range of sensors (1 – 10 mW) or specifically shoe mounted sensor systems as described by Table 2.13 in Chapter 2.

Many energy harvesting systems are designed for actuation at one specified vibrating frequency at which the generator structure is designed to resonate. However, as the walking period and style of different walkers varies from person-to-person and from time-to-time (for example during walking vs. running), resonant operation is not so effective for wearable generator systems. Some attempts at generator optimisation over a range of frequencies have been described for vibrating generators [14], [113], but these are for continuous sinusoidal sources. In this case, the voltage waveform tends to be of a discontinuous pulsed nature, having bursts of AC pulses followed by often significant periods of no voltage. Based on the requirements of this work the aim of this chapter is to provide analytical models that enable identification of the conditions for maximum output power for different AC/DC conversion circuits with typical wearable generator voltage waveforms applied. Circuits investigated are half and full-wave rectifiers including capacitive filters, and voltage doubler and quadrupler circuits.

Previously Ottman et al [113] developed analytical AC/DC models for a piezoelectric source and identified the output/input voltage relation. However this model, as well as all the other AC/DC circuit designs described in Chapter 2 are based on a constant sinusoidal voltage source. While all the circuits investigated in this work
are well known for steady-state sinusoidal voltage sources, analysis for a wearable
generator source is complicated firstly by the fact that source impedance is non-zero,
and secondly because its voltage is discontinuous. Analysis is also complicated by the
fact that AC generator voltage levels are quite low (average peak voltage of 2.5V)
when compared with the forward voltage drops of diodes (0.7V). Finite source
impedance causes the output voltage to vary with load resistance resulting in an
optimum resistance value at which maximum output power is achieved. However, due
to the discontinuous nature of the generator voltage waveform, this optimum
resistance is not trivial to identify. Analytical modelling is also applied to determine if
the generator should be redesigned so that the maximum output DC power can be
achieved when combined with AC/DC conversion methods.

Circuit simulation using Pspice [205] is also applied to provide a more
accurate prediction of generator DC performance using manufacturers’ diode models.

Although much of the AC/DC conversion research described in the energy harvesting
literature (as presented in Chapter 2) is focused on multiplier circuits and synchronous
rectification methods, this is not the case here because much better peak voltages are
achieved from the output of this generator. An optimum diode is identified and the
predicted results that are presented in this chapter are based on this. However for
comparison synchronous rectification is also investigated as part of this work.

With the generator length fixed at 100 mm it was identified in Chapter 4 that the
3 coil generator provides the best output when compared to the other generator
structures considered. The 3 coil generator demonstrates the maximum performance
of 14 mW of AC power; therefore the following analysis focuses solely on this
generator. Similar analysis can be performed for all other generator designs including
the 4 coil and 5 coil generators. The 3 coil generator pulse is analysed initially by
converting the individual coil outputs (single coil initially to describe the analytical
method and also parallel coils individually converted to a single load) as well as
converting the series alternating connected generator coils. Section 5.3.4 introduces
the concept of pulsed DC power which provides an alternative to constant power.

Circuit analysis is complicated by the discontinuous nature of the source voltage
and by a non-zero source impedance, and therefore a new analytical modeling
approach based on numerical techniques is required to determine optimum load
conditions for a given generator source. Section 5.2 describes the generator source
voltages as well as the AC/DC circuit models while section 5.3 and 5.4 describe the
derivation of analytical models for both constant and pulsed power to predict the DC performance of the generator source converted through a number of AC/DC circuits. The remainder of this chapter (section 5.5) compares the performance of different AC/DC converter circuits that produce a constant and pulsed DC output voltage for such waveforms, and solutions for maximum output power are identified. Note that due to similarities in generated voltage waveforms, the same approach may be applied to other piezoelectric and electromagnetic generator structures designed for power harvesting from human motion. Section 5.5 also investigates a number of factors that influence the DC performance of the generator including wire diameter, walking speed and utilising synchronous rectification.

5.2 AC/DC Circuit Simulation

5.2.1 Generator Circuit Model

Figure 5.1: Circuit Model of Wearable Generator Connected to a Conversion Circuit (a)

Parallel connected coils (b) Series Connected Coils
As described in Chapter 4, the sliding magnet wearable generator structures consist of several small individual generating elements, each of which produces an independent voltage waveform and therefore there are several methods of combining the individual elements with AC/DC conversion stages for feeding power to a load. For the given electromagnetic generator structures, two configurations are considered; i.e. an AC/DC stage connecting between each coil and a common load resistor, $R_{l_{\text{par}}}$, enabling parallel operation of the coils as shown in Figure 5.1 (a), and a single AC/DC stage connected between the series connected coils and a load, $R_{l_{\text{ser}}}$ shown in Figure 5.1 (b). Note that each generator coil is represented as an ideal voltage source, $V_{\text{genx}}(t)$, connected in series with a resistance, $R_{cx}$, and an inductance, $L_{cx}$, and with the voltage source equal to the generator open-circuit voltage.

### 5.2.2 Definition of Generator Voltage Waveforms

In the equivalent circuit models of Figure 5.1, values of coil resistance, $R_{cx}$, and inductance, $L_{cx}$, depend on the coil structure (number of turns, wire diameter, inner/outer radius, magnetic core regions), while the open-circuit voltage, $V_{\text{genx}}$, depends also on applied actuating forces. For the sliding magnet structure described in Chapters 3 and 4, formulas for resistance and inductance of a solenoid coil can be applied and the open circuit voltage predicted from the combination of magnet flux density distribution, coil structure and magnet speed. The voltage generated by each coil is discontinuous, comprising a single short voltage pulse when the magnet is travelling through it, followed by a longer interval when there is no magnet movement and therefore no voltage. This is typical of wearable generators, where the forces causing electromagnetic or piezoelectric actuation occur over short intervals of the walking period. For illustration, results of predicted open-circuit voltage waveforms are shown in Figure 5.2 for one movement of the magnet per step in the optimum 3-coil generator from Chapter 4. Results for parallel and series connections of the generator coils are included. In practice, there are two magnet movements per walking step but as these are distributed non-uniformly over the walking period, analysis is first based on single coil voltage pulses per step for simplicity. The open circuit pk-pk voltage is predicted to be $\sim$5 V with a pulse duration of $\sim$40 ms ($P_w$) and a repetition rate of 1 s ($T$).
In order to ensure that the predicted results correspond more closely to the measured AC results presented in Chapter 4, it was found necessary to adjust the AC/DC models applied in this chapter to signify the actual generated peak voltage. Due to the significant variation in speed observed as the magnet passes through each coil an average speed is estimated from the data presented in Figure 4.22. A constant magnet speed of 1.35 m/s is assumed in this case, as measured to be average for a walking speed of 2 steps per second (as described in Chapter 4). If an average magnet speed of 1350 mm/s is input to the AC generator models presented in Chapter 3, a

---

**Figure 5.2:** 3 Coil Generator (a) Individual Coil Pulses (b) Series Alternating Pulse
peak open circuit voltage of ~2.5 V is predicted. Similarly the coil voltage pulse width $P_W$ is reduced from ~70 ms (assumed at a magnet speed of 1000 mm/s) to ~40 ms. The source impedance of the coil is also adjusted to reflect the measured DC resistance of 7.95 Ω. These adjustments along with adjustments to account for the variation between modelled and built generator structures also discussed in Chapter 4 improve the accuracy of the modelled results.

![Figure 5.3: Pspice Repeated 3 Coil Generator Pulse](image)

(a) Individual Coil Pulses (b) Series Alternating Pulse

The generator source pulses and AC/DC conversion circuits are implemented in ORCAD Pspice [205] in order to verify analytic models developed for predicting different AC/DC circuit performance. A number of AC/DC conversion circuits are considered including typical rectifier circuits and multiplier circuits, which are
connected as illustrated in Figure 5.1. Using the “repeat forever” function in Pspice the open circuit generator pulses presented in Figure 5.2 can be repeated indefinitely as shown in Figure 5.3 which shows (a) the 3 coil individual coil voltages and (b) series alternating connected coil voltage, produced during every 1 second period for open circuit conditions. Another advantage of ORCAD Pspice [205] is that manufacturers’ models of the diodes can easily be incorporated into the simulations yielding more accurate predictions.

### 5.2.3 Commercial Diode Choice

The voltage amplitude produced by the generator structure is relatively low (~2 – 4 V\textsubscript{pk}), achieving approximately 2 to 5 times that of the forward voltage drop (0.7V) across a standard silicon diode. As the performance of rectifier circuits is largely dependent on the forward voltage drop, output power will vary depending on the type of diode used and on the current flowing in the circuit. Typically a voltage drop of 0.7 V holds for standard silicon diodes, however new low forward voltage drop diodes are available where voltage drops of 0.15 V to 0.46 V (depending on the current flowing) or less are achieved due to the Schottky effect [206]. With equivalent circuit models of the diodes being available from the manufacturers [207] they can then be easily implemented into the design to generate an accurate prediction of how each circuit’s output/efficiency may be improved by individual diodes.

While higher AC power is achieved for parallel coils, the series connection is considered because it provides a higher voltage level thereby reducing the relative effect of the diode forward ON voltage. A range of low-voltage drop MEGA Schottky diodes from Philips [208] is found to provide ON voltages as low as 0.09 V. The choice of diode for this application is thus dependent on a number of critical diode parameters. The diode forward voltage (V\textsubscript{F}) and forward current (I\textsubscript{F} which is related to the diode R\textsubscript{DSON}) are the most important factors but perhaps the most effective change that is seen is due to the diode reverse leakage current (I\textsubscript{Leak}) especially when the discontinuous nature of the generator source voltage is considered. In particular, the models listed in Table 1 are identified as having the lowest values of both ON voltage and reverse leakage current; and for a given current the PMEG1020 has the lowest ON voltage. However, it has a much higher reverse leakage current than the PMEG2010 and this causes significant power loss during the diode OFF times, which
for these wearable generator voltages typically constitutes more than 50% of the voltage waveform period. The PMEG1020 conducts a slight negative current during the negative pulse of the source voltage, and the relative magnitude of this negative current is increased as the load is increased. Therefore, the rate of discharge of the output rectified voltage is larger (when compared to the PMEG2010) during periods in between the source voltage pulses. The PMEG2010 diode model was assumed in all remaining circuit models and simulations described in this chapter. The various diodes investigated are summarised in Table 5.1, where some of the main characteristics of each component are highlighted.

Table 5.1: Parameters of the Various Diode Models Investigated

<table>
<thead>
<tr>
<th>Diode Type</th>
<th>Reverse Current (mA) Max:</th>
<th>Reverse Voltage (V)</th>
<th>Forward Current (mA)</th>
<th>Forward Voltage mV (I_F = 0.1mA -1000mA)</th>
<th>Power Dissipation mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMEG2010EH</td>
<td>0.04 – 0.2</td>
<td>20</td>
<td>0.1- 1000</td>
<td>Typ: 90 – 420</td>
<td>375 - 830</td>
</tr>
<tr>
<td>[209]</td>
<td></td>
<td></td>
<td>0.1 -1000</td>
<td>Max: 130 – 500</td>
<td></td>
</tr>
<tr>
<td>PMEG1020EH</td>
<td>2 - 3</td>
<td>10</td>
<td>2000</td>
<td>Typ: 100 – 350</td>
<td>375 - 830</td>
</tr>
<tr>
<td>[210]</td>
<td></td>
<td></td>
<td></td>
<td>Max: 130 – 460</td>
<td></td>
</tr>
</tbody>
</table>

The value of the diode forward voltage drop (V_D) used for all analytical conversion models described in this chapter was 0.25V and was based on the V_F data presented in the PMEG2010EH datasheet [209] summarised in Figure 5.4.

Figure 5.4: PMEG2010EH Forward Voltage (V_F) Data vs. Forward Current (I_F)

5.3 Analytical Modelling of Rectifier Circuits

This section describes the analytical models for a HWR filter where the additional effects of source resistance and non-ideal diode parameters are included as illustrated in Figure 5.5 to provide a more accurate model of the generator. Analysis
of the circuit presented in Figure 5.5 is complicated firstly by the source impedance being non-zero, and secondly because the source voltage is discontinuous. The source impedance causes the output voltage to be significantly lower than the source peak voltage, while the discontinuous nature of the source requires that care is taken in defining circuit operation during different time intervals. In order to enable efficient mathematical modeling in this case, the voltage pulse during the actuating force is assumed to be sinusoidal with a peak value, \( V_{pk} \), and a period, \( P_W \). Therefore, the voltage for the first generator coil in the 3-coil generator is given by:

\[
    v_{\text{gen}1}(t) = \begin{cases} 
        V_{pk} \sin(\omega_{pw} t), & 0 \leq t \leq P_W \\
        0, & P_W \leq t \leq T 
    \end{cases}
\]

where \( P_W \) corresponds to the time taken by the magnet to pass through the coil and \( T \) is the longer walking period for one foot for a walking speed of 2 steps per second. Similarly, voltages on coils 2 and 3 are phase-shifted versions of \( v_{\text{gen}1}(t) \), each having a delay of \( P_W/2 \) between them:

\[
    v_{\text{gen}2}(t) = v_{\text{gen}1}(t - P_W/2), \quad v_{\text{gen}3}(t) = v_{\text{gen}1}(t - P_W)
\]

and the voltage across the series connected coils is given by:

\[
    v_{\text{gen-ser}}(t) = v_{\text{gen}1}(t) - v_{\text{gen}2}(t) + v_{\text{gen}3}(t)
\]

where the polarity of coil connections is alternated to exploit the simultaneous positive and negative voltage pulses induced in neighbouring coils.

Substituting 2.5 V for \( V_{pk} \) into (5.1) for \( v_{\text{gen}1}(t) \), along with 40 ms and 1 s for \( P_W \) and \( T \), respectively, and combining with values of \( R_s = 7.95 \Omega \) and \( L_s = 1.5\mu\text{H} \) for resistance and inductance of a 480 turn coil with 0.25 mm diameter wire, the circuit model of Figure 5.1 is complete for each generator coil of the optimised 3-coil generator. This model is used to determine the performance of different AC/DC conversion stages connected to parallel and series combinations of the coils, and to identify the optimum circuit configuration in terms of providing maximum output power to a constant DC load. Note that similar voltage definitions may be applied to model the SMG structure with any number of magnets and coils as determined by the space available.

### 5.3.1 Single Generator, Constant Power

The simplest case of a half-wave rectifier shown in Figure 5.5 is considered in detail to illustrate the modelling approach in this section, but results are provided later
for other AC/DC circuit configurations. As in the case of an ideal voltage source, if the output capacitance value is chosen so that it provides an effective DC output voltage (with a low ripple voltage level), capacitor charging occurs each time the source voltage is higher than the output voltage, and discharging occurs once the source voltage is lower than the output voltage. However, because the output voltage is significantly lower than the peak generator voltage, the capacitor charging interval is approximately symmetrical around the peak voltage as shown in the predicted waveforms illustrated in Figure 5.5, due to voltage divider action between the source impedance and load resistance. The upper output voltage (red) represents the ideal output voltage (assuming ideal diodes and zero source impedance) and the center voltage waveform (green) represents the actual output voltage. The voltage is charging across an approximately symmetrical time period, 2\(\phi\), centered around the maximum of the source voltage pulse.

![Diagram](image)

**Figure 5.5**: Single Coil Generator Connected to a Half-wave Rectifier with a Filter Capacitor  
(a) circuit Schematic, (b) Voltage Waveforms

The maximum output voltage; \(V_{o,\text{max}}\), can be calculated in terms of the source voltage from:
This occurs at $\omega t = \left(\frac{\pi}{2} + \phi\right)$, when:

$$v_m(t) = V_{p_k} \times \sin\left(\frac{\pi}{2} + \phi\right)$$

(5.5)

for an input voltage amplitude of $V_{p_k}$. Thus the overall maximum output voltage is given by:

$$V_{O_{-\text{Max}}} = V_{p_k} \times \cos\phi - V_D$$

(5.6)

Solution to $V_o$ therefore requires that the parameter $\phi$ is defined in terms of other known quantities. This is achieved by setting the total charge provided by the source during capacitor charging to be equal to the charge dissipated in the resistor during capacitor discharging. The loop from the source through the load when the diode is ON and the capacitor is charging is initially considered. Note that source inductance is ignored in this case due to the low frequency of the source:

$$v_m(t) - R_s \times i_s(t) - V_D - v_o(t) = 0, \quad (\pi / 2 - \phi) < \omega_{p_w} t < (\pi / 2 + \phi)$$

(5.7)

The currents flowing in the circuit during the conducting time of the diode are related according to:

$$i_s(t) = i_c(t) + i_o(t) = C \frac{dv_c(t)}{dt} + \frac{v_o(t)}{R_{\text{Load}}} = C \frac{dv_o(t)}{dt} + \frac{v_o(t)}{R_{\text{Load}}},$$

$$\quad (\pi / 2 - \phi) < \omega_{p_w} t < (\pi / 2 + \phi)$$

(5.8)

where $i_s, i_c$ and $i_o$ are source current, capacitor current and output current respectively. Combining (5.7) and (5.8):

$$\frac{v_m(t) - V_D - v_o(t)}{R_s} = R_s \times \left(C \times \frac{dv_c(t)}{dt} + \frac{v_o(t)}{R_{\text{Load}}}\right) = R_s \times \left(C \times \frac{dv_o(t)}{dt} + \frac{v_o(t)}{R_{\text{Load}}}\right)$$

$$\frac{v_m(t) - V_D - v_o(t)}{R_s} = C \times \frac{dv_c(t)}{dt} + \frac{v_o(t)}{R_{\text{Load}}}$$

(5.9)

Substituting $i_c = C \times \frac{dv_c}{dt}$ the capacitor current during charging can then be calculated as:
where \( v_{in}(t) > v_o(t) + V_D \). The change in capacitor charge during the charging interval is then given as:

\[
\Delta Q_+ = \int_{t_i}^{t_f} i_C(t) dt = \int_{t_i}^{t_f} \left[ \frac{V_{pk} \times \sin(\omega_{pw} t)}{R_s} - \frac{V_{O_{\text{Max}}}}{R_{\text{Load}}} \right] dt
\]

(5.11)

During discharge when the diode turns OFF, the capacitor current is equal to negative of the output load current:

\[
i_C(t) = -i_\text{o}(t), \quad (\pi / 2 + \phi) < \omega_{pw} t < \left[ T + \frac{\pi}{2} - \phi \right]
\]

(5.12)

Assuming that the output percentage ripple voltage is low, the output voltage can be assumed constant and equal to \( V_{O_{\text{Max}}} \) and the corresponding charge dissipation is then calculated as:

\[
\Delta Q_- = C \times V = C \times \left( \int_{0}^{t_i} i_C(t) dt \right) = \int_{t_i}^{t_f} \left[ \frac{V_{O_{\text{Max}}}}{R_{\text{Load}}} \times dt \right)
\]

(5.13)

over the time when the diode turns OFF at \( t = \left( \frac{\pi}{2} + \phi \right) / \omega_{pw} \) until it turns ON again at \( t = T + \left( \frac{\pi}{2} - \phi \right) / \omega_{pw} \) (remember \( T \) is the repetition period of the single generator pulse).

Solving, the total reduction in charge is found by:

\[
\Delta Q_- = \left[ \frac{V_{O_{\text{Max}}}}{R_{\text{Load}}} \times \left( T - \frac{2\phi}{\omega_{pw}} \right) \right]
\]

(5.14)

A relationship between \( V_{O_{\text{Max}}} \) and \( \phi \) is identified by setting the charge provided by the generator source when the diode is ON equal to the charge dissipated in the resistor when the diode is OFF. Equating this with the charge provided to the
Chapter 5: AC/DC Circuit Modelling

capacitor and substituting for the current \( i_c(t) \) with (5.10) defines a relationship between \( V_{O_{\text{Max}}} \) and \( \phi \) in terms of other known quantities:

\[
Q = \int \left[ \frac{V_{O_{\text{Max}}} \times \sin(\omega_p t)}{R_s} - \frac{V_D - V_{O_{\text{Max}}}}{R_{\text{load}}} \right] \times dt = \left[ \frac{V_{O_{\text{Max}}}}{R_{\text{load}}} \right] \times \left( T - \frac{2\phi}{\omega_p} \right) \tag{5.15}
\]

After integration the final charge on the capacitor is estimated from:

\[
Q = \left[ \frac{V_{O_{\text{Max}}}}{R_{\text{load}}} \right] \times [T] + \left[ \frac{V_{O_{\text{Max}}} + V_D}{R_s} \right] \times \left[ \frac{2\phi}{\omega_p} \right] = \left[ \frac{2 \times V_p}{\omega_p \times R_s} \right] \times \sin \phi \tag{5.16}
\]

Inputting the expression already estimated for output voltage from (5.6):

\[
Q = \left[ \frac{V_p \times \cos \phi - V_D}{R_{\text{load}}} \right] \times [T] + \left[ \frac{V_p \times \cos \phi}{R_s} \right] \times \left[ \frac{2\phi}{\omega_p} \right] = \left[ \frac{2 \times V_p}{\omega_p \times R_s} \right] \times \sin \phi \tag{5.17}
\]

The solution to (5.17) for \( \phi \) requires the application of numerical techniques. Many of these are implemented in mathematical software tools. In this work the solver tool numerical techniques [211] from Microsoft Excel [212] was applied to solve the equation, which is an optimisation model based on algebraic modeling languages like GAMS or AMPL [213]. The value of \( \phi \) can be calculated due to any variable changes (generator peak voltage, source impedance, load resistance, etc.) in (5.17). Using this value of \( \phi \) on each occasion the new value of maximum output voltage can be calculated from (5.6).

The waveform analysis above assumes that the capacitance value is large enough to provide a small voltage ripple. Given that \( T_D \) defines the discharge time as:

\[
T_D = \left( T - \frac{2\phi}{\omega_p} \right) \tag{5.18}
\]

the minimum voltage before the next generator pulse is calculated in terms of \( T_D \):

\[
V_{\text{Min}} = V_{\text{Max}} e^{-\left\{ \frac{T_D}{R_{\text{load}} \times C} \right\}} \tag{5.19}
\]

The frequency implied here is the walking frequency (period of \( T \)) while \( T_D \) describes the discharge time between the generated pulses. Using (5.19) the
capacitance needed for a given percentage ripple level for the HWR filter with load resistor, $R_{\text{Load}}$, can then be calculated from:

$$ C = \frac{[T_p]}{R_{\text{Load}} \times \ln \left( \frac{V_{O_{\text{Max}}}}{V_{O_{\text{Min}}}} \right)} \quad (5.20) $$

and the average output DC voltage is given by:

$$ V_{\text{Average}} = \frac{V_{O_{\text{Max}}} + V_{O_{\text{Min}}}}{2} \quad (5.21) $$

Average output power is calculated as:

$$ P_{\text{Average}} = \frac{V_{\text{Average}}^2}{R_{\text{Load}}} \quad (5.22) $$

### 5.3.2 Multiple Generator, Constant Power

![Figure 5.6: Charging and Discharging of HWR Filter with Parallel Coils Generator Source](image)

Taking this model a step further, the case of a generator with multiple coils is considered, with each having a separate HWR and their outputs connected to a common load. Voltages on coils 2 and 3 are phase-shifted versions of $V_{\text{gen1}}(t)$. The resultant charging and discharging of the output capacitor due to the increased number of pulses is presented in Figure 5.6. As with the single coil the initial pulse has a period, $P_w$ charging the RC of the HWR filter, but on this occasion the next generator coil pulse is achieved from $\pi/\omega_{p_w}$ to $2\pi/\omega_{p_w}$ from the second coil. This is followed by a third pulse between $2\pi/\omega_{p_w}$ and $3\pi/\omega_{p_w}$ from the third coil, but again in a one second
The change in capacitor charge $\Delta Q_+$, during the charging interval is then given as:

$$
\Delta Q_+ = \begin{cases}
\int \frac{\pi - \phi}{\omega \phi} V_{O\text{-Max}1} \times dt + \\
\int \frac{\pi + \phi}{\omega \phi} V_{O\text{-Max}2} \times dt + \\
\int \frac{2\pi + \phi}{\omega \phi} V_{O\text{-Max}3} \times dt
\end{cases}
$$

Again, the total charge provided during charging equals the total charge dissipated in the load during discharge as calculated by (5.15):

$$
Q = \begin{cases}
\int \frac{\pi - \phi}{\omega \phi} i_c(t) \times dt + \\
\int \frac{\pi + \phi}{\omega \phi} i_c(t) \times dt + \\
\int \frac{2\pi + \phi}{\omega \phi} i_c(t) \times dt = \frac{V_{O\text{-Max},\text{Avg}}}{R_{\text{Load}}} \times \left( T - \frac{6\phi}{\omega \phi} \right)
\end{cases}
$$

Assuming that each generator contributes the same charge when its half-wave rectifier is on, the total charge transferred is given by:

$$
Q = 3 \times \begin{cases}
\int \frac{\pi - \phi}{\omega \phi} V_{O\text{-Max},\text{Avg}} \times \sin(\omega \phi t) - V_D - \frac{V_{O\text{-Max},\text{Avg}}}{R_{\text{Load}}} \times dt
\end{cases} = \frac{V_{O\text{-Max},\text{Avg}}}{R_{\text{Load}}} \times \left( T - \frac{6\phi}{\omega \phi} \right)
$$
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where \( V_{\text{pk,avg}} \) is the average voltage peak of the multiple voltage pulses, and \( V_{O,\text{avg}} \) is the average output voltage, which is calculated from:

\[
V_{O,\text{max,avg}} = V_{\text{pk,avg}} \times \cos \phi - V_D
\]

(5.27)

The 3 coil generator predicted parallel coil voltage pulses have the same peak voltage and hence the diode voltage drop is also the same. This however may not always be the case. Following integration and inputting the expression for average output voltage from (5.27) the final formula simplifies to:

\[
\frac{V_{\text{pk,avg}} \times \cos \phi - V_D}{R_{\text{load}}} \times [T] + 3 \times \left[ \frac{V_{\text{pk,avg}} \times \cos \phi}{R_S} \right] \times \left[ \frac{2\phi}{\omega_{p_w}} \right] = 3 \times \left[ \frac{2 \times V_{\text{pk,avg}}}{\omega_{p_w} \times R_S} \right] \times \sin \phi
\]

(5.28)

On this occasion discharge time is calculated from:

\[
T_D = \left( T - \frac{6\phi}{\omega_{p_w}} \right)
\]

(5.29)

There are a number of similarities between (5.17) and (5.28) for generator pulses, leading to an overall formula for the HWR filter which is based on the number of pulses (N coils in the generator) in a waveform for any generator source as long as the source peak voltages are the same. The average peak voltage, overall charge times and discharge times are necessary to implement the formula. Thus for any generator with N coil pulses (with the same peak voltages) into a HWR filter the formula is simplified to:

\[
\left[ \frac{V_{\text{pk,avg}} \times \cos \phi - V_D}{R_{\text{load}}} \right] \times [T] + N_{\text{RP}} \times \left[ \frac{V_{\text{pk,avg}} \times \cos \phi}{R_S} \right] \times \left[ \frac{2\phi}{\omega_{p_w}} \right] = N_{\text{RP}} \times \left[ \frac{2 \times V_{\text{pk,avg}}}{\omega_{p_w} \times R_S} \right] \times \sin \phi
\]

(5.30)

where \( N_{\text{RP}} \) is the number of rectified pulses (or charge pulses) for a given generator source pulse that actually occur during the walking period T. \( N_{\text{RP}} \) is calculated based on the number of coils (N) in the generator and the conversion circuit used. If for example N is equal to 3 and if a HWR is used, \( N_{\text{RP}} \) would be equal to 3 while \( N_{\text{RP}} \) would increase to 6 if a FWR is used with the same number of generator coils. By comparing (5.18) and (5.29) for the generator source voltages the discharge time can be simplified for any generator pulse into a half-wave filter by:
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\[ T_D = T - \left[ \frac{2 \times N_{RP} \times \phi}{\omega_{pw}} \right] \]  \hspace{2cm} (5.31)

\textit{Figure 5.7:} Charging and Discharging of HWR Filter with Series Alternating Coils Generator Source

The final example of the 3 coil generator pulse charging and discharging the RC filter at the output of the HWR is the series alternating connected coil pulse. In this case there are two separate pulses seen by the RC load at the output of the HWR, and again there is still a large discharge time due to the nature of the generator source voltage pulse. Figure 5.7 illustrates how the output DC voltage would perform after passing through the HWR filter. Once more the upper output voltage (in red) signifies the ideal output voltage with ideal diodes and zero source impedance while the lower output voltage (in green) represents the actual output voltage. The period of the generator series alternating connected coil pulses are again considered to be the width of the pulse charging the RC of the HWR filter, but on this occasion there is a discharge time of \((2\pi - 2\phi)\) before the next pulse is achieved as the negative pulse of the source is dropped by the rectification method. This is followed by a second pulse between \(2\pi/\omega_{pw}\) and \(3\pi/\omega_{pw}\), but in a standard walking period there would still be a duration of \(T\) for this generator, before the next pulse is seen at the output of the filter.

An analytical model was developed (using similar analysis to that carried out for the single and parallel coils) for the series alternating half wave rectified pulse parameters, combined with (5.30) and (5.31). Here, there are two source peak voltages (2.2V and 4.8V in this example) in the generator pulse, and so each individual source
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peak is input to (5.6), (5.30) and (5.31) with $V_{\text{Out}}$ calculated individually as for the single coil pulse. The average of these two $V_{\text{Out}}$ values for each peak source voltage then provides the combined $V_{\text{Out}}$ result. $N_{RP}$ is equal to 1 on this occasion. Alternatively a more accurate method is achieved using an adjusted version of (5.23) and (5.24) where the two separate source peak voltages are considered. This corresponds to discharge of the capacitor $\Delta Q_-$, being estimated from:

$$\Delta Q_- = \int_{t_2}^{T_2} \left( \frac{V_{O_{\text{Max}1}}}{R_{\text{Load}}} \times dt \right) + \int_{t_1}^{T_1} \left( \frac{V_{O_{\text{Max}2}}}{R_{\text{Load}}} \times dt \right)$$

(5.32)

where $V_{O_{\text{Max}1}}$ and $V_{O_{\text{Max}2}}$ are identified by (5.6) based on the two peak voltages generated from the series alternating coil connections. The total charge on the capacitor, $\Delta Q_+$, is then estimated from:

$$\Delta Q_+ = \int i_{C1}(t) \times dt + \int i_{C2}(t) \times dt$$

(5.33)

where each capacitor charging current, $i_{C1}(t)$ and $i_{C2}(t)$, are based on two separate Vpk's using (5.11). After integration the solution simplifies to:

$$\left[ \frac{V_{pk1} \times \cos \phi - V_D}{R_{\text{Load}}} \times \frac{2\pi}{\omega_{\text{pw}}} \right] + \left[ \frac{V_{pk2} \times \cos \phi - V_D}{R_{\text{Load}}} \times \left( T - \frac{2\pi}{\omega_{\text{pw}}} \right) \right]$$

$$+ \left[ \frac{V_{pk1} \times \cos \phi + V_{pk2} \times \cos \phi}{R_S} \times \frac{2\phi}{\omega_{\text{pw}}} \right] = \left[ \frac{2 \times V_{pk1} + 2 \times V_{pk2}}{\omega_{\text{pw}} \times R_S} \times \sin \phi \right]$$

(5.34)

with the discharge time estimated from:

$$T_D = T - \left[ \frac{(2 \times \pi) + (2 \times N_{RP} \times \phi)}{\omega_{\text{pw}}} \right]$$

(5.35)

As demonstrated in Chapter 4 a double pulse is actually generated during each period of a walking step due to the double movement of the magnet. This additional
pulse obviously doubles the number of coil pulses delivered to the RC output of the HWR. By doubling the time interval $\Delta Q^+ = \Delta Q^-$ and altering the variables involved in the models to represent these extra pulses a more accurate prediction of the 3 coil generated DC power performance from the HWR can be achieved. The analysis presented in Appendix D demonstrates how the model can be altered to investigate a similar model for the FWR filter. The final analytical model for the FWR filter with non sinusoidal generator sources is described by:

$$V_{O\_Max} = V_{Pl} \times \cos \phi - 2 \times V_D$$ (5.36)

and

$$\left[ \frac{V_{Pl, AVG} \times \cos \phi - 2 \times V_D}{R_{Load}} \right] \times \left[ T + \left[ \frac{2 \times N_{PST} \times \phi}{\omega_{Pw}} \right] \right] + N_{RP} \times \left[ \frac{V_{Pl, AVG} \times \cos \phi}{R_S} \times \left[ \frac{2 \phi}{\omega_{Pw}} \right] \right] = N_{RP} \times \left[ \frac{2 \times V_{Pl, AVG}}{\omega_{Pw} \times R_S} \right] \times \sin \phi$$ (5.37)

where $N_{PST}$ is the number of pulses that are presented to the RC of the FWR filter at the same time. Thus the discharge time that can be calculated from:

$$T_D = \left( T - \left[ \frac{2 \times N_{RP} \times \phi + 2 \times N_{PST} \times \phi}{\omega_{Pw}} \right] \right)$$ (5.38)

### 5.3.3 Constant Power Capacitor Choice

In order to produce a DC voltage with a voltage ripple level ($\Delta V$) of approximately 10% for example (which is at least required since the output voltage level is low), a very large capacitor is required due to the very low frequency of the input voltage, at 1 Hz. This can be estimated by:

$$C = \frac{V_{O\_Max}}{R_{Load} \times f \times \Delta V}$$ (5.39)

The percentage ripple of the output voltage is estimated from:

$$\% \text{Ripple} = \left( \frac{V_{O\_Max} - V_{O\_Min}}{V_{O\_Max}} \right) \times 100 = \left( \frac{\Delta V}{V_{O\_Max}} \right) \times 100$$ (5.40)

Based on this calculation an output capacitor of $\sim 0.1 \text{ F}$ would be selected for all load resistances (even though using (5.39) the capacitor requirement ranges from 6 mF to 157 mF with increasing load resistance) as it is shown to be suitable for the
range of load resistances at which maximum power is achieved with the generator coils. If this capacitance value is reduced the output ripple voltage would increase (due to the AC level of voltage being generated and the long periods between generator coil pulses), significantly altering the capability or usability of the generator. However, the output capacitor should be reduced as much as possible to decrease the steady state charge times. Charge time is the time required by the output to charge up to the steady state DC voltage based on the output capacitance and load resistance (RC). If the load was an IC for example with a particular supply voltage requirement the charge time would be the time required by the generator before it would be capable of turning on the IC (startup time).

![Figure 5.8: % Ripple and Charge Times of Generator Structures with Individually Converted Parallel Coils (a) HWR Filter (b) HWR Filter](image)

Figure 5.8 illustrates the effect of output capacitance in terms of the output ripple and charge times at maximum power for the predicted 3 coil generator (parallel coils) pulses. Results are presented for the HWR and FWR circuits. In each of the generator AC/DC conversions presented the charge times are increased with increasing output capacitance while at the same time the percentage ripple is decreased. The percentage ripple is less than 20 % for an output capacitance > 0.01 F.
and it jumps up to 100 % for smaller values. Therefore if the output capacitor is < 0.01 F the DC output would be unusable as a constant voltage supply. Furthermore, because the DC voltage levels are so low here (typically 1 – 3 V as presented in following section 5.5) it would be more desirable to decrease the ripple to between 5 and 10 %. This can be achieved easily by an output capacitor of 0.1 or 0.22 F with the latter providing a larger capacitor charge time. Therefore the initial analytical model prediction of a 0.1 F output capacitor to achieve a usable steady state DC output from each of the generator designs is acceptable.

Conventional capacitors cannot achieve such a large capacitance in an area suitable for integration into a shoe sole. To achieve such large capacitance in a small scale package supercapacitor technology was investigated. Typical supercapacitor manufacturers provide capacitance values at 100 mF, 220 mF, etc. [214]. However, one of the main criteria on the output supercapacitor is that the large capacitance is available with a small ESR (equivalent series resistance). A large ESR in the output capacitor of the AC/DC conversion circuits will increase output voltage ripple and reduce generator DC performance. Figure 5.9 demonstrates the performance of each conversion circuits (HWR and FWR) when the ESR of the filter capacitor is increased from 0 to 100 Ω. The 3 coil parallel coil generator is investigated in each case, with the load set to the value that achieves maximum power for each circuit. As the ESR is increased the output voltage ripple is increased, leading to a decrease in both average voltage and power for each circuit. The 0.1 F EDLC supercapacitor [215] for example, has an ESR value of ~75 Ω which would significantly hinder the

![Figure 5.9: % Ripple Vs. ESR for Rectifier Conversion Circuits](image-url)
performance of the generator and the output would not be a usable steady DC voltage. However if the ESR value is in the mΩ range the maximum generator output DC power is maintained.

Thus the output capacitor required for this generator design must have a high capacitance (>0.1 F), in a small scale package and with a low ESR. A number of commercial options are available that achieve all three requirements, including “BestCap” ultra-low ESR high power pulse supercapacitors from “AVX” which provide high power pulse characteristics due to the combination of very high capacitance and ultra-low ESR together with extremely low leakage current [216]. Capacitance values ranging from 10 mF to 560 mF are possible with ESR values in the region of 25 to 500 mΩ depending on the case size and voltage rating of the capacitor. However it is the family of supercapacitors available from Cap-XX [214] which provide the best output capacitor solution for any of the conversion circuits considered. This is due to their very small size (thickness < 3mm), high capacitance (90 mF to 2400 mF) and very low ESR (26 mΩ to 200 mΩ). The closest value in the Cap-XX range to the required 0.1F is the GW209F which has a capacitance of 0.14 F and an ESR of only 70 mΩ. This supercapacitor was integrated into all constant power conversion circuits described throughout the remainder of this thesis unless otherwise specified.

5.3.4 Multiple Generator, Pulsed Power

Under steady state constant power conditions the generator charges up to a constant DC value based on a large RC product \(R_{\text{Load}}C_{\text{Out}}\) at the output, and this DC output remains (with some ripple) between each step, as long as the user continues walking. This analysis is based on a large discharge time \(T_D\) and also depends on the conversion circuit used. This section will examine the pulsed power output from the generator which can be useful in providing power for a wider range of loads when compared to the constant power case. In the pulsed power case, the DC output is only required to be held up for the duration of the pulse itself and returns to zero in-between steps, once any specified load discharges the capacitor. In essence the generator can be viewed as an AC source with a much higher frequency \(1/P_W = \sim 25Hz\) when compared to the steady state condition, where the output capacitance is designed for the walking frequency \(1/T\).
Figure 5.10: Generator HWR DC Output Comparison (a) Constant Power (b) Pulsed Power

Figure 5.10 illustrates the predicted generator DC output in terms of steady state and pulsed power for a HWR filter (with ideal diodes and zero source impedance for illustration) with the same load resistance of 180 $\Omega$. Clearly the 0.14 F output capacitor used in the constant power models holds up the output during the stance phase of the human gait until the next generated pulses are achieved as seen in Figure 5.10 (a). While Figure 5.10 (b) illustrates how a much smaller 1000 $\mu$F capacitor can be utilised in the same circuit to hold up the voltage in between the pulses created by a given step, but allows the output to discharge to zero long before the next set of voltage pulses are generated by the next step. The DC generator energy is supplied to a given load each time a step is taken, and the generator supplies enough energy to charge the RC output during a single output pulse rather than requiring a constant supply of pulses as seen with constant power.
By similar analysis to that developed for the constant power models but on this occasion viewing the generator as a constant sinusoidal source the final model for the pulsed power HWR reduces to:

\[ \left[ \frac{V_{pk} \times \cos \phi - V_D}{R_L} \right] \times \left[ \frac{2\pi - 2\phi}{\omega_{Pw}} \right] + \left[ \frac{V_{pk} \times \cos \phi}{R_s} \right] \times \left[ \frac{2\phi}{\omega_{Pw}} \right] + \left[ \frac{V_{pk} \times \cos \phi - V_D}{R_L} \right] \times \left[ \frac{2\phi}{\omega_{Pw}} \right] \]

\[ = \left[ \frac{2V_{pk}}{\omega_{Pw} \times R_s} \right] \times \sin \phi \]  \hspace{1cm} (5.41)

while the final model for the pulsed power FWR reduces to:

\[ \left[ \frac{V_{pk} \times \cos \phi - 2 \times V_D}{R_L} \right] \times \left[ \frac{\pi - 2\phi}{\omega_{Pw}} \right] + \left[ \frac{V_{pk} \times \cos \phi}{R_s} \right] \times \left[ \frac{2\phi}{\omega_{Pw}} \right] + \left[ \frac{V_{pk} \times \cos \phi - 2 \times V_D}{R_L} \right] \times \left[ \frac{2\phi}{\omega_{Pw}} \right] \]

\[ = \left[ \frac{2V_{pk}}{\omega_{Pw} \times R_s} \right] \times \sin \phi \]  \hspace{1cm} (5.42)

The peak voltage is calculated using the same model as the constant power case using (5.6). The value T included in the constant power models representing the walking period is now eliminated from the discharge time \( T_D \) calculations. The discharge time \( T_D \) is now calculated from \( \frac{(2\pi - 2\phi)}{\omega_{Pw}} \) or \( \frac{(\pi - 2\phi)}{\omega_{Pw}} \) in this case depending on the conversion circuit used, where the frequency \( \omega_{Pw} \) is based on the frequency of voltage pulses produced by the magnet as it travels through the generator. The HWR discharge time is calculated from:

\[ T_D = \frac{1}{\omega_{Pw}} \times (2\pi - 2\phi) \]  \hspace{1cm} (5.43)

and the FWR discharge time is calculated from:

\[ T_D = \frac{1}{\omega_{Pw}} \times (\pi - 2\phi) \]  \hspace{1cm} (5.44)

When analysing the pulsed power condition using (5.20) the capacitance required is much less due to the reduced discharge time \( T_D \) calculated from (5.43) or (5.44). In this application, <1000 \( \mu \)F capacitance is now required to provide the necessary hold up time for a DC voltage with less than 20% ripple, for the duration of the magnet movement for the 3 coil generator source pulses. The predicted generated voltage on each of the three 20 mm length coils of the 3 coil generator is shown in Figure 5.11 (a). During steady state analysis it was identified that the maximum power
can be achieved by individually converting each coil (using any conversion circuit) and combining each conversion at a single load. During pulsed power conditions the smaller capacitor (< 1000 µF) can be used to hold up the peaks of the generator as the magnet is moving, resulting in output pulses similar to those presented in Figure 5.11 (b).

![Figure 5.11: Predicted Pulsed Voltage of the 3 Coil Generator - (a) Input (b) Pulsed Output](image)

The pulsed power generated in each case may also be investigated in terms of energy. The energy is estimated from the generator output pulse due to the load resistance and the much smaller output capacitance of <1000 µF over the full pulse duration, $T_{\text{Pulse}}$; for example ~0.4 s as presented in Figure 5.11 (b) for a 180 Ω load, or until the output is fully discharged to zero. The DC prediction models are also exploited here to predict the generator output pulsed voltages. The models predict peak voltage and peak power, but the difference here is that they are now also used to
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predict the energy performance of the generator. For example the predicted 3-coil generator pulses shown in Figure 5.11 (a) are initially rectified based on the particular circuit model of the AC/DC conversion circuit being used. Using the analytical models the rectified pulses from each coil can be predicted, as presented in Figure 5.11 (b) for the HWR pulses. The discharge rate of the output voltage from each coil pulse is estimated based on the exponential $V_{\text{Max}} e^{-t/(RC)}$ until the next rectified coil pulse is seen by the output RC. The final rectified coil pulse is discharged to zero until the next magnet movement as illustrated in Figure 5.10 (b). Instead of calculating the power, the integration of power over the pulse is required to calculate the total energy. The DC energy produced by each generator pulse is calculated from:

$$E_{\text{Pulse}} = \left[ \frac{1}{R_{\text{Load}} \times T_{\text{Pulse}}} \right] \times \int_{0}^{T_{\text{Pulse}}} \left[ V_o \right] \cdot dt \times T_{\text{Pulse}}$$

(5.45)

where $T_{\text{Pulse}}$ is the duration of the rectified generator pulse with the lower output capacitance and $V_o$ is the output voltage achieved through simulations in Pspice or created analytically in Microsoft Excel using the models described.

5.4 Analytical Modelling of Multiplier Circuits

A simple solution to powering integrated circuits and other circuits that require DC levels from low voltage sources is the use of voltage multiplier circuits. Using these circuits also requires few parts as they are basically a capacitor-diode network capable of converting an AC input voltage $V_{\text{IN}}$ into a DC output voltage of $V_{\text{OUT}} = nV_{\text{IN}}$ where $n \geq 2$ [217]. The measured output voltage of a voltage multiplier may in fact be several times greater than the input voltage. Voltage multipliers may be classified as voltage doublers, triplers, quadruplers or even octuplers. This classification depends on the ratio of the output voltage to input voltage required. In order to increase the peak input voltage to twice its value a multiplier called a voltage doubler is required.

The operating principle of all multiplier circuits is essentially the same whereby capacitors are charged when connected in series, and discharged when connected in parallel on alternate half-cycles of the supply voltage. Rectifier circuits with additional capacitors are used to cause equal voltage increments across each of the capacitors and hence the output to a voltage multiplier circuit is simply the sum of these series capacitor voltages. If any passive load is connected across a capacitor
such that it will draw only a finite amount of charge from the capacitor for all $t \geq 0$, then this lost charge will eventually be replenished by the source during the subsequent cycles of $V_{IN}$ similar to the rectifier circuits.

The full wave rectifying voltage doubler (Greinacher) [218] is a very simple but effective method of converting an AC voltage to a DC voltage as shown in Figure 5.12. It consists of two capacitors and two diodes and has better voltage regulation when compared to a half-wave (cascade) voltage doubler. During the negative half cycle of the input voltage, capacitor $C_2$ is charged through rectifier $D_2$ to a voltage of $V_{IN}$. While on the positive half cycle the capacitor $C_1$ is also charged to a value of $V_{IN}$ through the rectifier $D_1$. The series of these capacitors, $C_1$ and $C_2$ will cause the desired voltage of $2 \times V_{IN}$ to be created across the output. The available output current is only half the current that would be available from a full-wave rectifier on its own as the output voltage is doubled.

![Figure 5.12: Full-Wave Rectifying Voltage Doubler Circuit](image)

By connecting two cascade doublers together [218], a circuit can be generated that provides approximately 4 times the AC peak input voltage as a DC output voltage. It is essentially a 2-stage cascade doubler circuit and produces $2 \times 2 \times V_{IN}$ across the output (as for an n stage cascade doubler the output voltage produced is $2n \times V_{IN}$ [218]. The circuit shown in Figure 5.13 is a quadrupler and when the diode $D_3$ is forward biased the capacitor $C_3$ is charged to the peak AC input voltage and it will retain this value. Once the diode $D_1$ becomes forward biased the capacitor $C_1$ is charged to a value equivalent to the sum of the AC input voltage and the voltage of the capacitor $C_3$, or alternatively twice the peak input AC voltage. The same process will repeat in the lower half of the circuit, for example $C_4$ and $D_2$. The output DC
voltage which is 4 times the peak AC input voltage is obtained at the combination of capacitor $C_1$ and capacitor $C_2$, which is essentially the output capacitor. Thus, the output capacitors $C_1$ and $C_2$ must withstand at least $2 \times V_{IN}$ individually while the other capacitors in the circuit $C_3$ and $C_4$ are only required to hold $V_{IN}$.

Generally the size of the capacitors used in multiplier circuits (as with rectifier circuits) is inversely proportional to the input frequency. The voltage rating of the capacitors is determined solely by the type of multiplier circuit used. For example in a half wave doubler illustrated in Figure 5.12, the negative pulse capacitor must be capable of withstanding a maximum voltage of $V_{IN}$, while the output capacitor must be capable of withstanding $2 \times V_{IN}$. A general rule of thumb would suggest that capacitor selection would require them to have a voltage rating of approximately twice that of the input peak applied voltage [217]. Similar design rules can be utilised when designing the quadrupler circuit. The value of capacitance required by the multiplier circuits is similar to that identified in section 5.3.3 for the rectifier circuits and a value of 0.14 F is implemented in all constant power models while a capacitance of < 1000 µF is implemented in pulsed power models.

![Figure 5.13: Voltage Quadrupler Circuit](image)

**5.4.1 Single Generator, Constant Power**

The output voltage of the doubler circuit presented in Figure 5.12 can be visualised in Figure 5.14 with each capacitor charging occurring each time the source voltage is higher than the output voltage, and discharging through the load occurring once the source voltage is lower than the output voltage. Due to voltage divider action
between the source impedance and load resistance, the output voltage is lower than
the peak source voltage depicted in Figure 5.14. The voltage is charging across an
approximately symmetrical time period centered around the maximum of the source
voltage pulse, whereas on this occasion the voltage on capacitor $C_2$ (which is the
rectified voltage on the negative half cycle) is added to the voltage on $C_1$. The overall
output voltage $V_o$ is the summation of both capacitor voltages as shown in Figure
5.14.

![Diagram of Doubler Capacitor Voltages](image)

*Figure 5.14: Doubler Capacitor Voltages (a) Output Voltage (Combined Capacitor Voltage),
(b) $V_{C2}$ and (c) $V_{C1}$*

The analysis of this circuit will initially focus on a generator single coil
voltage pulse with an open-circuit amplitude of $\approx 2.5$ V, a pulse width of $\approx 40$ ms ($P_W$),
a repetition period of 1 second ($T$), the generator impedance parameters described in
section 5.2 as well as the PMEG2010EH diode. Applying basic analysis such as
Kirchhoff’s voltage and current laws [219], the capacitor current can be calculated.
The loop around the whole circuit as seen in Figure 5.12 ignores source inductance due to low frequency of the source. Let the function $\phi$ represent the angle of charge on either side of the center of the rectified source pulse. Consider the first the loop in the circuit including $C_2$ when diode $D_2$ is ON, i.e. $V_{in}$ is negative.

$$v_{C_2}(t) = v_{in}(t) - R_s \times i_s(t) - V_{D_2},$$

$$(\pi + \pi / 2 - \phi) < \omega_{pu} t < (\pi + \pi / 2 + \phi) \quad (5.46)$$

where $V_{C_2}$ is the voltage across capacitor $C_2$. The second loop around the circuit when $D_1$ is ON ($V_{in}$ is positive) is described as:

$$v_{in}(t) - R_s \times i_s(t) - V_{D_1} - v_o(t) + v_{C_2}(t) = 0,$$

$$(2\pi + \pi / 2 - \phi) < \omega_{pu} t < (2\pi + \pi / 2 + \phi) \quad (5.47)$$

With $V_{D_1} = V_{D_2} = V_D$ and combining (5.46) and (5.47):

$$2 \times v_{in}(t) - 2 \times (R_s \times i_s(t)) - 2 \times V_D - v_o(t) = 0,$$

$$(2\pi + \pi / 2 - \phi) < \omega_{pu} t < (2\pi + \pi / 2 + \phi) \quad (5.48)$$

The current flowing in the circuit is:

$$i_s(t) = i_{C_2}(t) + i_o(t), \quad (\pi + \pi / 2 - \phi) < \omega_{pu} t < (\pi + \pi / 2 + \phi)$$

$$i_s(t) = i_{C_1}(t) + i_o(t), \quad (\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi) \quad (5.49)$$

where $i_s$, $i_o$, $i_{C_1}$ and $i_{C_2}$ are the source current, output current and currents flowing in the first and second capacitors respectively. The currents flowing in the circuit are then related according to:

$$i_s(t) = i_{C_1}(t) + i_o(t) = C_1 \frac{dv_{C_1}(t)}{dt} + \frac{v_o(t)}{R_{Load}},$$

$$(\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi) \quad (5.50)$$

Combining (5.48) and (5.50):

$$2 \times v_{in}(t) - 2 \times V_D - v_o(t) = 2 \times \left( R_s \times \left( C_1 \times \frac{dv_{C_1}(t)}{dt} + \frac{v_o(t)}{R_{Load}} \right) \right) + R_s \times \left( \frac{v_o(t)}{R_{Load}} \right)$$
The total capacitor current can then be calculated from:

\[
i_{c1}(t) = \frac{2 \times v_{in}(t) - 2 \times V_D - v_o(t)}{2 \times R_s} - \frac{v_o(t)}{R_{Load}}
\]  
(5.52)

The total change in capacitor charge during the charging interval is then given as:

\[
\Delta Q_v = \int i_{c1}(t)dt + \int i_{c2}(t)dt = 2 \times \int 2 \times \int \frac{2 \times V_{pk} \times Sin(\omega_{pk}t) - 2 \times V_D - V_{\text{o-max}}}{2 \times R_s} \frac{V_{\text{o-max}}}{R_{Load}} dt
\]
(5.53)

The maximum output voltage can be calculated by:

\[
2 \times v_{in}(t) = v_{\text{o-max}}(t) + 2 \times V_D
\]
(5.54)

This occurs at \(\omega_{pk}t = \left(\frac{\pi}{2} + \phi\right)\), so that:

\[
2 \times V_{pk} \sin\left(\frac{\pi}{2} + \phi\right) = V_{\text{o-max}} + 2 \times V_D
\]
(5.55)

Thus the overall maximum output voltage is calculated by:

\[
V_{\text{o-max}} = 2 \times V_{pk} \times Cos\phi - 2 \times V_D
\]
(5.56)

The output voltage waveform can be visualised concurrently with the individual capacitor voltages, as shown in Figure 5.14, and this will once again aid in calculating the capacitor current during charging and discharging. Separate charging and discharging intervals occur for capacitor \(C_2\), which are added to the overall charging and discharging voltages established on \(C_1\). The charging and discharging voltages on each of the capacitors \(C_2\) and \(C_1\) are similar to that of a HWR, but the overall charging and discharging across capacitors \(C_1\) and \(C_2\) connected in series is similar to that of the FWR as it represents the combination of both capacitors. The overall result of change in capacitor charge during a given magnet movement is
calculated by realising that the total charging current must equal the discharge current and using similar basic equations identified in (5.15). The discharge current can be calculated from:

\[
\Delta Q_+ = \int_{t_1}^{t_2} \frac{V_{O_{Max}}}{R_{Load}} \times dt + \int_{t_1}^{t_2} \frac{V_{O_{Max}}}{R_{Load}} \times dt
\]

(5.57)

Overall the charge on the capacitor is:

\[
Q = \int_{t_1}^{t_2} i_{C2}(t) \times dt + \int_{t_1}^{t_2} i_{C1}(t) \times dt = 2 \times \left[ \frac{V_{O_{Max}}}{R_{Load}} \times \left( T - \frac{2\phi}{\omega_{pu}} \right) \right]
\]

(5.58)

Expanding with what is already known to be the capacitor current in both individual capacitor cycles and including (5.53) and (5.58):

\[
Q = 2 \times \left[ \left( \frac{\pi + \phi}{2\omega_{pu}} \right) \times \frac{2V_{pk} \times \sin(\omega_{pu}t) - 2V_D - V_{O_{Max}}}{2R_S} \right] \times \left[ \frac{V_{O_{Max}}}{R_{Load}} \right] \times \left( \frac{T - \frac{2\phi}{\omega_{pu}} \right) \right]
\]

(5.59)

After integration the final charge on the capacitor is estimated from:

\[
\left[ \frac{V_{O_{Max}}}{R_{Load}} \right] \times [2T] + 2 \times \left[ \left( \frac{2V_{pk} \times \cos(\omega_{pu})}{2R_S} \right) \times \left[ \frac{2\phi}{\omega_{pu}} \right] \right] = 2 \times \left[ \left( \frac{2V_{pk}}{\omega_{pu} \times R_S} \right) \times \sin(\phi) \right]
\]

(5.60)

Inputting the expression already estimated for output voltage from (5.56), a numerical equation for \( \phi \) is found:

\[
\left[ \frac{2V_{pk} \times \cos(\phi) - 2V_D}{R_{Load}} \right] \times [2T] + 2 \times \left[ \left( \frac{V_{pk} \times \cos(\phi)}{R_S} \right) \times \left[ \frac{2\phi}{\omega_{pu}} \right] \right] = 2 \times \left[ \left( \frac{2V_{pk}}{\omega_{pu} \times R_S} \right) \times \sin(\phi) \right]
\]

(5.61)
When compared to the half wave and FWR filter capacitor charge/discharge equations calculated in (5.17) and (5.37) respectively, it is clear that the diode voltage drop remains at $2V_D$ similar to the FWR filter, and the discharge time is $\left[T - 2\phi / \omega_{pu}\right]$ similar to the HWR filter as described by (5.18). In this case, however, the output voltage term is now doubled over the value for rectifier circuits to $2V_{pk} \times \cos\phi$. The minimum voltage is calculated as before from (5.19) and the capacitance needed for the doubler is calculated using (5.20).

### 5.4.2 Multiple Generator, Constant Power

By similar analysis to that carried out for the generator source pulses passing through the rectifier filter circuits and combining it with the doubler formula already established for a single coil generator, a general formula can be defined for the doubler circuit for different combinations of generator source pulses. By combining (5.30), (5.37) and (5.61) a generalised formula for the doubler with non-sinusoidal source pulses can be defined as:

$$\frac{2V_{pk, AVG} \times \cos\phi - 2V_D}{R_{load}} \times [2T] + \left[N_{RP} \times \left[\frac{V_{pk, AVG} \times \cos\phi}{R_s} \times \frac{2\phi}{\omega_{pu}}\right]\right]$$

$$= \left[N_{RP} \times \frac{2V_{pk, AVG}}{\omega_{pu} \times R_s} \times \sin\phi\right]$$

(5.62)

where $N_{RP}$ is once again the number of rectified pulses delivered to the load. With the 3 coil generator parallel full wave rectified output there are two instances where more than one pulse charges the RC load simultaneously, and this is also the case with the full wave doubler. The discharge time in this case is estimated from:

$$T_D = \left[2 \times T - \frac{2 \times N_{RP} \times \phi}{\omega_{pu}}\right]$$

(5.63)

This analytical model for the doubler when combined with (5.6), (5.56) and (5.21) can be used to predict the doubler DC performance of each of the generator source pulses under varying load conditions. A further formula can be generated by adjusting (5.53) and (5.57) whereby two separate source peak voltages are considered for the series alternating connected coils. This results in total discharge of the output capacitors $\Delta Q$, being estimated from:
Chapter 5: AC/DC Circuit Modelling

\[
\Delta Q = \int \frac{V_{O_{Max1}}}{R_{Load}} t_1 dt + \int \frac{V_{O_{Max2}}}{R_{Load}} t_2 dt + \int \frac{V_{O_{Max1}}}{R_{Load}} t_3 dt + \int \frac{V_{O_{Max2}}}{R_{Load}} t_4 dt
\]

(5.64)

where \( V_{O_{Max1}} \) and \( V_{O_{Max2}} \) are estimated from (5.56) based on the two peak voltages generated from the series alternating coil connections. The total charge on the output capacitors \( \Delta Q_+ \) is estimated from:

\[
\Delta Q_+ = \int i_{C1}(t) \times dt + \int i_{C2}(t) \times dt + \int i_{C2}(t) \times dt + \int i_{C3}(t) \times dt
\]

(5.65)

where each capacitor charge \( i_{C1}(t) \) and \( i_{C2}(t) \) are based on two separate Vpk’s using (5.56). After integration the solution simplifies to:

\[
\left[ \frac{2 \times V_{pk1} \times \cos \phi - 2 \times V_D}{R_{Load}} \right] \times [T] + \left[ \frac{2 \times V_{pk2} \times \cos \phi - 2 \times V_D}{R_{Load}} \right] \times [T]
\]

\[
+ N_{RP} \left[ \frac{V_{pk1} \times \cos \phi + V_{pk2} \times \cos \phi}{R_S} \right] \times \left[ \frac{2 \phi}{\omega_{pu}} \right] = N_{RP} \left[ \frac{2 \times V_{pk1} + 2 \times V_{pk2}}{\omega_{pu} \times R_S} \right] \times \sin \phi
\]

(5.66)

with the discharge time estimated from:

\[
T_D = T - \left[ \frac{2 \times N_c \times \phi}{\omega_{pu}} \right]
\]

(5.67)

where \( N_c \) is the number of voltage capacitor charges, which for a doubler is 2.

A more accurate representation of measured conditions is achieved by including the effect of the second movement of the magnet during each step taken. By altering the variables involved in each of the final analytical models of each circuit to represent these extra pulses a more accurate prediction of the 3 coil generator (embedded in a sole) DC power performance from each of the conversion circuits can be achieved. The analysis presented in Appendix E demonstrates how the model can be altered to achieve a similar model for the quadrupler. The analytical model for the
quadrupler with a non sinusoidal generator source pulse is achieved in (E.20), (E.21), (E.24) and (E.25).

5.4.3 Multiple Generator, Pulsed Power

As with the rectifier circuits the doubler circuit was also investigated in terms of the pulsed power performance. Again by viewing the generator source into the doubler circuit as a constant sinusoidal source the final model with reduced discharge times reduces to:

\[
\frac{1}{R_L} \left[ 2 \times V_{pk} \times \cos \phi - 2 \times V_D \right] \times \left[ 2 \pi - 2 \phi \right] + \frac{V_{pk} \times \cos \phi}{R_s} \times \frac{2 \phi}{\omega_c} \\
+ \frac{2 \times V_{pk} \times \cos \phi - 2 \times V_D}{R_L} \times \frac{2 \phi}{\omega_c} = \frac{2 \times V_{pk}}{\omega c \times R_s} \times \sin \phi
\]

(5.68)

The discharge time \(T_{D}\) in this instance is again calculated from (5.43) and the required pulse power capacitance is again calculated from (5.20). The peak voltage is calculated using the same model (5.56) as the constant power case. The quadrupler circuit is not investigated in this case as the generated peak pulsed voltage would be much higher than required and some regulation would be required to convert it to a usable voltage.

5.5 Modelling Verification and Circuit Analysis

5.5.1 Verification of AC/DC Circuit Models

Under rectification with no output capacitor, the maximum average output power is found with the load resistance matching the source resistance. In order to investigate whether this is also true for the HWR and FWR with a filter capacitor as well as the doubler and quadrupler multiplier circuits, a series of different load resistance values (0 – 3000 \(\Omega\)) were considered with an output capacitance of 0.14 F (due to commercial availability) and the maximum average DC power was calculated as detailed in Figure 5.15 and Figure 5.16. This was achieved using the circuit simulation models in Pspice and these results are compared to the analytical models that are described for all circuits in sections 5.3 and 5.4. Exploiting the solver tool from Microsoft Excel the value of \(\phi\) can be calculated due to any variable changes in
each of the derived models, and using this value of $\phi$ on each occasion the new value of maximum output voltage can be calculated, followed by average voltage and output power calculations according to (5.21) and (5.22) respectively.

Figure 5.15: Parallel Coil Generator Circuit Models Analytical Vs. Pspice – (a) Voltage Vs. Load (b) Power Vs. Load
In this case, the optimised 3-coil generator voltage pulses were assumed \( V_{pk} = 2.5\, \text{V}, R_{\text{coil}} = 7.95\, \Omega \) with a pulse repetition rate of 0.5s. The load resistance, \( R_L \) was varied in order to determine load conditions for maximum output power. Figure 5.15 demonstrates the predicted DC voltage and power performance of the parallel connection of the 3 coil generator based on the analytical and simulation models. Based on this data it is clear that a good representation of all circuits is achieved using the analytical models with parallel connected generator coil source pulses for every load resistance selected. On each occasion maximum power from each conversion circuit is identified. Maximum output DC powers levels of 4.88 mW (0.71V), 7.38 mW (0.7V), 10.2 mW (1.42V) and 10.7 mW (2.3V) are predicted for the HWR, FWR, Doubler and Quadrupler conversion circuits’ respectively. For each circuit higher DC output voltage is achieved with larger load resistances. The multiplier circuits provide the optimum power where the quadrupler achieves maximum power (closely followed by the doubler) when compared to the rectifier circuits but with a much larger load resistance. On each occasion the maximum output power is not found (by both the analytical and Pspice models) with a load resistance of 7.95 \( \Omega \), but with a loads of 100 \( \Omega \), 70 \( \Omega \), 200 \( \Omega \) and 500 \( \Omega \) with the HWR, FWR, Doubler and Quadrupler conversion circuits’ respectively. This is a similar trend to what was described by Saha’s VM circuit [125] where it was also described how the load resistance that achieves maximum power for each generator is significantly changed due to the VM circuit.

For maximum power transfer of generator coils under AC conditions it was identified in Chapter 3 that this is achieved when load resistance is equal to source resistance. This is acceptable due to the low frequency of the source [220] even though there is some reactance associated with the coil inductance (which is small as described in Chapter 3). If the diode in the conversion circuits are ideal, in order to achieve maximum power transfer of generator coils with an output capacitor and resistor load, the load impedance would have to be the complex conjugate of the source impedance [220], [221] but only if the source frequency is continuous, which isn’t the case here. Maximum power for the HWR is achieved when the output voltage is 0.71V for example.
Similarly Figure 5.16 demonstrates the predicted DC voltage and power performance of the series alternating connection of the 3 coil generator based on the analytical and simulation models. Again a good representation of all circuits is
achieved using the analytical models with series alternating connected generator coil source pulses for every load resistance selected. Maximum output DC powers levels of 2.63 mW (1.4 V), 4.14 mW (1.27V) and 5.64 mW (2.35V) are predicted for the HWR, FWR and Doubler conversion circuits respectively. The Quadrupler circuit is disregarded on this occasion due to the very large resistance (>3 k Ω) required to achieve maximum power. As with the parallel connected coil the maximum output power is not found with a load resistance each to the source impedance, but with a loads of 750 Ω, 400 Ω and 1000 Ω with the HWR, FWR and Doubler conversion circuits respectively.

When compared to the generator parallel connected coils the series alternating connection provides much larger DC voltage from each circuit. However this does not correspond to larger power due to the higher source impedance of the series connection. The larger load resistance on this occasion is due to the larger source impedance of the series connected coils. The outcome of this analysis is the emergence of an obvious optimum coil connection to maximise power from the generator where the parallel connection provides the best results for constant power.

Similar to the constant power case, pulsed power is also examined by comparing the analytical models to the Pspice models. Once again a range of load resistances are investigated ranging from 10 to 1000 Ω and in the case of the analytical models the value of $\phi$ is calculated for each load and input to the models described in section 5.3.4 and section 5.4.3. Figure 5.17 compares the analytical and Pspice predicted peak voltage from the pulsed power generator using HWR, FWR and doubler conversion circuits. In Figure 5.17 (a) the parallel coil generator results are presented while in Figure 5.17 (b) the series alternating coil results are displayed. In comparison to the constant power case it is clear that much higher DC voltage is available from the generator for the duration of the generated pulse. For loads of $>100\Omega$ a peak voltage of ~2V or more is available from the parallel coil generator while in the series alternating case there is an even higher peak voltage of $>3V$ available for loads $>100\Omega$. In both coil connection methods the doubler provides maximum peak voltage for loads $>100\Omega$. 
However, these attractive peak voltage levels are only available while the magnet is moving as described in section 5.3.4, whereby the duration (~0.4 s) the DC voltage level is at these peaks may be enough time to operate some electronic devices. The duration that the DC voltage pulse maintains these attractive voltage levels depends on the peak power and energy available in the generated pulse. Based on the peak voltages described in Figure 5.17 the available pulsed peak power is also predicted using both analytical and Pspice models. Figure 5.18 presents the predicted power data based on both analytical and Pspice models over a range of load resistances. Clearly the pulsed power available during the pulse is much higher (>25 times) than the constant power design for both parallel and series alternating coil connections. For the parallel generator case, maximum output peak pulsed power levels of 171 mW, 255 mW and 69 mW are predicted for the HWR, FWR and Doubler conversion circuits respectively. Meanwhile the series alternating generator is predicted to generate peak power levels of 205 mW, 185 mW and 162 mW is for the HWR, FWR and Doubler conversion circuits respectively. Therefore the series alternating generator provides higher peak voltage and higher peak power over the range of loads. However the parallel generator overall provides maximum peak power with the FWR circuit. The rectifier circuits provides much higher peak power at the lower load resistances (<100 Ω), However with loads <100 Ω the doubler provides the optimum power for both generator coil connections.
If the pulsed power generator is to be capable of providing power for any demonstrator load; not only should the peak generated voltage be at the required level but the energy available in the generated pulse must be greater than that required by the demonstrator load. Figure 5.19 compares the pulsed energy provided by both the parallel and series alternating generators converted using the HWR, FWR and doubler conversion circuits. Again there is good correlation between the analytical and Pspice
Chapter 5: AC/DC Circuit Modelling

models. Once more the rectifier circuits provide maximum energy at the smaller loads while the doubler produces maximum energy at loads >100 \( \Omega \). The parallel generator is predicted to produce maximum energy levels of 7.1 mJ, 10.2 mJ and 2.41 mJ for the HWR, FWR and Doubler circuits respectively, while the series alternating generator produces maximum energy levels of 3.39 mJ, 5.92 mJ and 5.05 mJ for the HWR, FWR and doubler circuits respectively. Therefore any demonstrator load should have maximum energy requirements <10 mJ for the pulsed power generator to be capable of delivering enough power.

### 5.5.2 Effect of Wire Diameter

In Chapter 4 it was established by the methods described, that for a generator dimension of 100 mm length and 15 mm diameter the generators presented in Table 5.2 are the structures which could produce maximum AC power, with the 3 coil generator performing the best. In this section these generators are compared in terms of predicted DC power due to a number of wire diameters. The four main generators described in Table 5.2 were each modelled (using Pspice and analytical models presented in this chapter) through the HWR, FWR and doubler circuits with a 0.14 F output capacitance as before, and the results are presented in Figure 5.20 and Figure 5.21. The analytical models were used on all generator structures to provide further verification of the predicted results across the larger range of source resistances and generated peak voltages. The parallel coil technique is only considered here as it has been shown to provide the maximum power in all cases. For all conversion circuits it is clear that the 3 coil generator does in fact provide maximum DC voltage and power as demonstrated with the AC power investigation.

### Table 5.2: Summary of Optimum AC Generator Designs

<table>
<thead>
<tr>
<th>Coil Length (mm)</th>
<th>Number of Coils</th>
<th>Magnet Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>25</td>
</tr>
</tbody>
</table>

In Chapter 4 it was identified under AC analysis that if the wire diameter was decreased, the peak-peak voltage and source resistance increases, while the average
power would remain constant as the diameter was reduced. Similar analysis, with each of the generator structures connected to each of the conversion circuits (using the models described in this chapter), was carried out under DC conditions to investigate if this pattern remains. From the AWG range of copper wires [77] a wire diameter of 0.125 mm was chosen as it is also exactly half the wire diameter of 0.25 mm used throughout the generator design procedure. The output voltage is increased, due to the combination of increased number of turns and the percentage voltage dropped across diodes is also reduced due to the increased peak voltages. The tradeoff here is lower current, and a higher load resistance requirement to achieve maximum DC power, which results in longer charge times. Figure 5.20 demonstrates the DC voltage performance of each generator structure through each of the conversion circuits with the generator wire diameter varied from 0.25 mm to 0.125 mm. Figure 5.21 demonstrates the DC power performance of each generator structure through each of the conversion circuits for the same values of generator wire diameter.

It is clear from these results that the optimum generator design for maximum DC power concurs with what was predicted in the AC power simulations/predictions and the 3 coil generator yields maximum results for all wire diameters. For a 0.25 mm wire diameter maximum voltage and power is achieved with the doubler for all generator structures, but due to the circuit operation the output DC current is low. However, improved current is found with the full-wave rectifier at the expense of voltage and power. In Figure 5.20 it can be seen that the DC voltage produced by each of the circuits is increased as the wire diameter is decreased, as expected. The decrease in wire diameter increases DC voltage to a much higher level but consequently reduces the current due to a much higher source impedance and hence a much higher optimum load. While the power is increased significantly when the wire diameter is decreased from 0.25 mm to 0.2 mm, it is not significantly altered following a decrease from 0.2 mm to 0.125 mm as seen in Figure 5.21, indicating a similar trend to that observed under AC power conditions.
Figure 5.20: DC Voltage Comparison through Conversion Circuits - Parallel Coils - Various Generator Structures – (a) 0.25 mm (b) 0.2 mm (c) 0.125 mm Wire diameter
Figure 5.21: DC Power Comparison through Conversion Circuits - Parallel Coils - Various Generator Structures – (a) 0.25 mm (b) 0.2 mm (c) 0.125 mm Wire diameter
Furthermore as the wire diameter is decreased the performance of the FWR is significantly improved and matches and outperforms the doubler circuit at a wire diameter of 0.125 mm. This is due to the FWR producing increased DC voltage with decreasing wire diameter while maintaining a significant current level which cannot be achieved with the doubler circuit due to its operation. A more ideal generator may be developed by setting the wire diameter between the original 0.25 mm and 0.125 mm. The wire diameter of 0.2 mm provides the most attractive option as it achieves usable voltage levels while maintaining the power levels of the 0.125 mm wire diameter. Also, the 0.2 mm wire diameter corresponds to lower source impedance than achieved with a 0.125 mm wire diameter which establishes short charge times.

5.5.3 Conversion Efficiency

![Diagram showing generator average power comparisons]

Figure 5.22: Generator AC Maximum Power vs. DC Converted Maximum Power – varying Wire diameters

When the maximum power DC results for the 3 coil generator are compared to the maximum AC power results for the same generator coil settings presented in Chapter 4 the power performance is reduced significantly when a 0.25 mm wire diameter is considered. Figure 5.22 illustrates the comparison between the maximum AC power and the maximum DC power generated from the HWR, FWR, doubler and quadrupler for the same generator coil settings and walking frequencies. Significant power is lost when a 0.25 mm wire diameter is implemented. In each case the average AC maximum power is significantly larger than the maximum DC power produced by
any of the circuits. Although there is an improvement when going from the rectifier circuits to the multiplier circuits the maximum efficiency is nonetheless estimated to be < 50%. However this efficiency can be improved by decreasing the wire diameter from 0.25 mm to 0.2 mm and 0.125 mm as in Figure 5.22.

Maximum power transfer to the load does not achieve maximum efficiency [220], [221]. When maximum power transfer is achieved efficiency is only at 50% but this can be increased towards 100% if the load approaches infinity if the diodes were ideal. When the load impedance is higher than the source impedance the power passed through the circuit is reduced due to the high impedance but voltage transfer is improved. As the circuits being used here are rectifier circuits with associated diode voltage drops it can be identified why the higher load resistances (with higher voltage transfer) achieve maximum power when the smaller wire diameter is introduced.

![Image of bar chart]

**Figure 5.23:** Predicted Maximum Power AC/DC Conversion Efficiency – Varying Wire diameter

A more realistic approach to evaluate the conversion efficiency of each circuit would be to predict both the input and output power at a certain load for each circuit. To achieve this, output power is predicted using the analytical models described in this chapter and compared to the Pspice models for validation. AC power is estimated by combining the AC power generated on each individual coil on the anode side of the diodes. Figure 5.23 presents the predicted conversion efficiency for each AC/DC circuit for the various maximum power load resistances and the three different generator wire diameter sources. With a 0.25 mm wire diameter source the maximum
efficiency is ~68% for both the HWR and doubler circuits while the FWR achieves by far the worst conversion efficiency at ~49%. However with a wire diameter of 0.2 mm and 0.125 mm the conversion efficiency for each circuit increases to ~75% and ~85% respectively with the performance of the FWR improving the most dramatically as the wire diameter decreases. A decrease in wire diameter is not the only means to improve power loss, as it can also be achieved by improving the diode voltage drops ($V_D$). The investigation into synchronous rectification in section 5.5.5 highlights how this efficiency can be improved.

### 5.5.4 Effect of Walking Speed

The analysis in section 4.5 of Chapter 4 identified that the magnet speed reaches a peak of ~2500 mm/s as the walking speed is increased from 4.5 km/hr to 10 km/hr. When the magnet speed is increased for any reason then the coil pulse width ($P_w$) is decreased and the coil voltage peak ($V_{peak}$) is increased. With the step period ($T$) fixed at one step per second, Figure 5.24 (a) demonstrates that when the magnet speed is increased the output DC voltage of the 3 coil generator increases linearly (maximum power results presented). Similarly as the magnet speed increases, the DC power from both the FWR and doubler circuits will also increase but at more rapid rate. The initial conservative 1 m/s magnet speed is also displayed indicating the improvement achievable with only a minor magnet speed adjustment for both voltage and power results presented in Figure 5.24. The actual average maximum magnet speed of 1.35 m/s has been identified in section 4.5 of Chapter 4.

![Figure 5.24: 3 Coil Generator DC Performance – Varying Magnet Speed](image-url)
If the walking speed (step rate) is increased as described in section 4.5 of Chapter 4, the time between magnet movements (or generator coil pulses) will decrease thus increasing the overall performance of the generator. As the walking speed or step rate is increased then the double magnet movement or the voltage generated on each coil of the generator will occur at a more rapid rate which also improves the generator power performance as indicated in Figure 5.25 (a), where maximum power results are presented. DC voltage in this case remains approximately constant but the load resistance required for maximum power is decreased as step rate is increased. The results for the FWR and doubler circuits from a 3 coil generator source at maximum DC power are presented in Figure 5.25. The 1 step/s rate used throughout the generator modelling in this thesis is identified for comparison. The x-axis in Figure 5.25 [Step Period (s)] identifies the period for one step or one double magnet movement. A step rate faster than the 1 step/s will provide improved power results, while anything slower < 1 step/s will reduce the performance of the generator.

![Figure 5.25: 3 Coil Generator DC Performance – Varying Coil Pulse Rate](image)

**5.5.5 Effect of Synchronous Rectification**

Synchronous rectification is used to improve switching-power-supply efficiency, particularly in low voltage power applications. A regulator circuit such as the buck converter can replace the low-side diode rectifier with an electronic switch typically a MOSFET [222] with a low $R_{d\text{on}}$, whereby the voltage drop can be significantly reduced due to the low resistance conduction path formed when the switch is turned on hence improving the converter efficiency. Much of AC/DC work
described in the literature review (Chapter 2) present conversion efficiencies of > 80% and even > 90% using synchronous rectification.

Diodes are the main component in the AC/DC conversion circuitry described to date in this work therefore an investigation was carried out on the suitability of synchronous rectification as a replacement for these diodes. As the voltage involved in these circuits is low, the efficiency of the generator AC/DC conversion could be increased by reducing the voltage drop. The trade-off between using a diode or a MOSFET in an AC/DC conversion is whether the power required to drive the MOSFET gate cancels the efficiency gained from the reduced forward voltage drop. The maximum DC power achieved for the SMG was through the use of a FWR and voltage doubler (based on the analysis carried out in this chapter), hence synchronous rectification is described in this section for both these circuits. The models presented in this chapter for both circuits are valid as the diode voltage drop can be replaced by the lower $\text{IR}_{\text{DS(on)}}$ voltage drop in the models, while the additional load of the MOSFET gate drivers can also be input based on their supply voltage and current requirement. The synchronous rectification analysis is presented in Appendix F details the two methods explored for driving the gates of the MOSFETs. The two methods investigated based on simulation models are low power LM2903 comparators [223] and CMOS LMC555 [224] timers. While the comparators are shown to provide optimum results the Pspice model of the LMC555 timer does not reflect the CMOS power requirements and it is expected that improved results can be achieved with accurate models.

Therefore based on the analysis carried out in Appendix F it is identified that the application of synchronous rectification to the AC/DC conversion circuits can significantly improve output voltage, power and conversion efficiency. Although the improvement is estimated to be minimal with a FWR using certain comparator models, it can be enhanced with lower power consumption comparators. While the doubler can already achieve an improvement of > 5% in conversion efficiency with the LM2903 comparator model used throughout this analysis, this can also be improved with lower power consumption comparators. The main drawback of this design is the amount of extra components required to achieve such efficiency and given the space constraints of the environment the generator will be integrated into, it may be regarded as unsuitable.
5.5.6 Optimum Load

The levels of maximum constant power achievable with the various generator structures connected to the different AC/DC conversion circuits is established. This maximum power was found by varying the load resistance from \(<10 \ \Omega\) (typical coil resistance) to \(40 \ \text{k}\ \Omega\) (depending on the conversion circuit). In reality the demonstrator electronics has a certain load power demand and the generator/conversion combination can be optimised to meet this load demand. The following simulated/modelled analysis identifies which generator and converter design would suit a given constant demonstrator electronics load. To simplify this analysis only the 3 coil parallel connected generator is considered here as it has been clearly identified to provide the maximum DC power.

![Figure 5.26: Constant Voltage/Current at Varying Loads - 3 Coil Generator](image)

Figure 5.26 illustrates the predicted constant DC voltage and associated DC current achieved using the 3 coil generator with either the FWR or doubler circuits. The wire diameter is also investigated as it was proven in section 5.5.2 that improved results can be achieved with a wire diameter of less than 0.25 mm. The diameters considered are 0.25 mm, 0.2 mm and 0.125 mm respectively. Depending on the demonstrator load required, a different generator structure, AC/DC circuit and wire diameter combination may produce the required voltage and current. A number of loads that represent common demonstrator electronic devices as described in Chapter 2 are also identified in Figure 5.26 by their voltage and current demands. Clearly
many of the loads considered could be powered by the 3 coil generator constant power design even with a 0.25 mm wire diameter. With reduced wire diameter the range of demonstrator loads that can be powered by the generator is increased. A significant problem with constant power is that there is a certain amount of time required to achieve steady-state conditions (startup time), which means that the load cannot operate until the output capacitor has charged up to the voltage levels indicated in Figure 5.26. This delay depends on the RC time constant of the generator load and is typically > 60 seconds. To demonstrate the generator capabilities the alternative and perhaps more suitable option to constant power demand would be to exploit the pulsed energy method of the generator.

**Figure 5.27: Peak Pulsed Voltage at Varying Loads - 3 Coil Generator**

Similar to constant DC power demands, the demonstrator electronics have a certain load power demand and the generator/conversion combination is designed to meet this load demand. Figure 5.27 demonstrates which 3 coil generator and converter design would suit a given load in terms of the achievable current and peak voltage. The different decreased wire diameters previously reported were also considered. The pulsed voltage and current levels achieved are much higher than those levels attained with a constant voltage seen in Figure 5.26. A significantly larger range of demonstrator loads from Table 2.13 in Chapter 2 can be powered by the 3 coil generator when a pulsed power configuration is exploited. However, this power is only available while the magnet is moving during each step. From Table 2.13 in
Chapter 2 and Figure 5.27, it is obvious that the generator developed would be capable of intermittently powering a sensor, pedometer or even a micro-controller.

5.6 Conclusions

This chapter presents novel accurate analytical models to predict the DC performance of the designed generators based on the intermittent AC output being passed through the available AC/DC conversion circuits. The most significant difficulty encountered in this analysis was due to the large periods of zero voltage being produced by the generator coils as well as zero ohm source impedance. Using the optimum designed generator’s predicted AC voltage peak ($V_{\text{peak}}$), source resistance ($R_{\text{source}}$), load resistance ($R_{\text{load}}$), capacitance ($C$), AC voltage pulse width ($P_{\text{w}}$), walking rate (number of steps in period $T$), number of generator coils ($N$) and number of rectified pulses ($N_{\text{RP}}$), the DC output voltage and power can be predicted for any generator design. Based on the discontinuous nature of the generator source voltage pulses, using these variables analytical models for the HWR, FWR, doubler and quadrupler conversion circuits are also developed. These analytical models provide an accurate comparison with Pspice simulation models.

Therefore, any similar generator structure of any power levels with similar time lags between generated pulses can easily be analysed in terms of their DC performance based on the models presented in this work. These models have been verified for parallel coil pulses as well as series alternating connected coils where two different peak voltages are input into the conversion circuit. The parallel connected 3 coil generator produces the maximum DC power when compared to the series alternating connected coils while the series alternating connected coils provide maximum DC voltage. The doubler and quadrupler circuits provide maximum voltage and power for the 3 coil generator with a 0.25 mm wire diameter. A doubler circuit is more suitable as it requires less capacitance corresponding to reduced charge times and circuit components. However as the wire diameter is decreased the FWR provides power levels equal to those established by the multiplier circuits. A pulsed power method can also be used to generate useful DC power where power is available only when the magnet is moving during each step. Similar models can be developed for this power method and while the doubler produces maximum peak voltage, the rectifier circuits achieve maximum pulsed power and energy with the FWR producing
the optimum performance. If a demonstrator is to be supplied with the pulsed power method from the generator the demonstrator energy demand must be <10mJ.

Wire diameter and walking speed heavily influence the performance at the DC output of the generator design. The wire diameter can significantly improve constant power and voltage as well as the conversion efficiency results on each circuit. Wire diameter should be investigated in conjunction with AC/DC conversion circuits so that the optimum generator design can be established. Therefore, during generator design the AC development and AC/DC development of the generator should be considered at the same time. With the models developed in this chapter coupled with the models described in Chapter 3 and the optimisation established in Chapter 4, this can now be achieved. The AC/DC models can also be used to predict the synchronous rectification performance by applying $R_{ds,on}$ values to model the current path through MOSFET’s.

Based on the models and analysis described in this chapter accurate predictions of the DC generator performance can be achieved which will aid the design of any similar generator particularly those with intermittent source supplies which satisfies one of the main objectives of this work. Maximum constant power of 10mW is predicted which satisfies the power objectives set out in the introduction. However, using pulsed DC power it is predicted that >100 mW is available from the generator which is much more than power objectives set out in the introduction. When the power requirements of a number of commercial loads are investigated and compared to the predicted performance of the generator under both constant power and pulsed power conditions a range of applications that can be powered by the generator are identified. Both methods of generator DC power are predicted to be capable of powering a number of demonstrator loads. This DC power will be measured in Chapter 6.
6. Chapter 6 - DC Power Measurements

6.1 Introduction

To fulfil the remaining objectives of this work this chapter investigates the measured DC performance of the optimum generator and identifies the conversion circuit that maximises the DC power in the shoe sole environment. The 3 coil generator is specifically considered in this chapter as it has been identified as the generator which produces maximum constant DC power. The goal of this analysis is to initially demonstrate the measured constant DC power performance of the 3 coil generator in section 6.2. A number of AC/DC conversion circuits are considered including the half-wave rectifier (HWR), full-wave rectifier (FWR) and doubler circuits, to identify which circuit delivers maximum power within a measurement environment. Although the doubler has been established as the optimum conversion circuit in Chapter 5 this is based on the assumption of perfect repeatable source pulses from the generator within the shoe sole environment. The influence of the generator environment, diodes and capacitors as well as steady state charge times for each circuit can be established during measurement so that the optimum generator connection and conversion circuit design can be identified.

In section 6.2 the measured DC performance of the generator and AC/DC conversion circuits are presented and compared to the predicted models described in the Chapter 5. These measured results confirm the predicted values from Chapter 5 for the 0.25 mm wire diameter and confirms that these predictions are accurate for when the generator system in embedded in the shoe sole environment. In this way maximum power is identified based on varying the load resistances for each circuit while maintaining a constant walking speed. Also the charge times required to reach steady state are established which identifies the start-up time required before a constant power application may be powered. The results for increasing walking speed are also presented and compared to the prediction models in section 6.2, to confirm the adaptability of the models described in Chapter 5. Furthermore this chapter also addresses the significant effect of the output capacitance on the performance of the conversion circuits demonstrated.
Chapter 6: DC Power Measurements

The scope of applications that can exploit the power created by the generator is limited due to the location of the system. In the future this power may be transmitted wirelessly but for the moment the power produced by the generator is only utilised for on-shoe applications which are discussed in this chapter. The objective of this chapter is to illustrate the maximum DC power and energy capabilities of such generators, and to demonstrate their functionality by successfully operating an electronic device. The analysis in Chapter 5 identified that a larger range of demonstrator loads may be powered using the pulsed power method. Therefore, this chapter will also investigate the generator system where pulsed DC power can be used to power an electronic device only while a step has been taken. In Chapters 3 and 4 this magnet movement was identified to occur twice during each step and the desired effect of pulsed power is for the load to draw power from the generator only during these instances.

Realistically a combination of the sensor and microcontroller would provide a good biomedical demonstrator, but in the end a pedometer application (without the need for a separate sensor) was chosen to demonstrate the generator pulsed power. Based on the pulsed voltage and power available from this generator it is established that a pedometer system based on the Nordic semiconductor nRF24E1 IC [225] can provide a suitable demonstrator load due to the nRF24E1’s voltage and power requirements as identified in Figure 5.27. In this study the proposed demonstrator system is an integrated Radio Frequency (RF) pedometer similar to that of the Nike and iPod sports Kit identified in Chapter 2. The transmitter circuit is embedded in the shoe and powered by the generator, while the receiver might be a watch or an mp3 player which would require a battery. The pedometer system exploits a microcontroller and transceiver IC [225] to transmit data to the receiver indicating when a step has been taken. In this way the generator is performing like a sensor in the shoe where a generated pulse due to foot motion is seen by the receiver side as a data packet indicating a step taken. All factors involved in the microcontroller/transceiver are described in section 6.3, including an investigation into transceiver low power transmission. Also, the development of test boards for both the transmitter powered by the generator and the receiver is described in section 6.3. Section 6.4 describes how the demonstrator is operated under a “range demo” test program to identify the capabilities of both the transmitter and more importantly the generator.
Chapter 6: DC Power Measurements

6.2 Constant Power Performance

The following results demonstrate the constant DC output power performance of the three coil generator embedded in the heel of a standard trainer shoe (size 10) while walking at a constant speed of 4.5 km/hr on a treadmill. The measurements allow the generator the full charge time needed to establish steady-state conditions and this is illustrated in 6.2.2 followed by a comparison with predicted steady-state performance in 6.2.3. Measurements from the HWR and FWR as well as the doubler circuits are presented initially for parallel coil connections. The objective of carrying out these measurements was twofold; to demonstrate the DC performance of the generator embedded in a shoe sole while walking at a speed of 4.5 km/hr, and to confirm predicted models described in Chapter 5. In the case of the rectifier circuits, the series alternating coil connections were also investigated and results for each are presented. Results for the doubler circuit are presented for the parallel coil connection only, as the voltage level achieved by series alternating connected coils did not require a doubler to provide a usable DC voltage.

6.2.1 Experimental Setup

![Figure 6.1: Lab Experimental Setup – Treadmill, Oscilloscope, Shoe with Generator](image)

Figure 6.1: Lab Experimental Setup – Treadmill, Oscilloscope, Shoe with Generator
To generate measurement data in a lab environment a means of walking at constant speeds with access to the generator output is required. To that end a commercial treadmill (“Roger Black” treadmill [226]) was exploited to provide a platform for a constant walking speed in the laboratory environment. The treadmill is capable of speeds varying from 0.8 km/hr to 14 km/hr which compliments the scope of this work. A Tektronix DPO 4054 Digital Phosphor Oscilloscope [203] was included in the experimental design to measure the generators’ performance throughout the experiments. One of the main advantages of this oscilloscope is its ability to provide large time scales of 10, 20 and even 40 seconds per division which is critical in order to capture the steady state output voltages when a large output capacitor is involved. It is capable of providing data for a number of minutes rather than seconds, which is demonstrated to be more than sufficient for each experiment undertaken in this work. Figure 6.1 provides an illustration of the treadmill, oscilloscope and shoe which has the generator embedded in the heel as well as the
conversion circuit fixed to the front for ease of access. In general the treadmill was set to a constant walking speed of 4.5 km/hr throughout the measurements except during the analysis of increased walking speed provided in section 6.2.4.

A number of other components, besides the generator structure itself, are required for measuring the DC performance of the generator. The shoe used is the same one used to measure the AC performance as detailed in Chapter 4 and the generator is integrated into the shoe sole as presented in Figure 4.13. This shoe provides the facility to embed the 3 coil generator structure into the heel section of the sole, and the output of each generator coil can be wired out to the front of the shoe for connection with any AC/DC conversion circuit, illustrated in Figure 6.2. One of the most important components required for DC measurements is the PMEG2010 diode, which has physical dimensions of only 3.6 mm×1.7 mm×1.2 mm as seen in Figure 6.2. A dual version is also available, but for this work the single diode structure was used. Basic circuit board, IC surface mount sockets and 30 AWG wires were also used to provide interconnections between the AC/DC circuit components. In the case of the doubler circuit because 6 capacitors are required a number of Cap-XX capacitors were used. Both the 140 mF GW209F and the 75 mF GZ215 were used for the positive capacitor and negative capacitors respectively of the doubler circuit for each coil. The main issue with the doubler structure is the number of capacitors required. Although the capacitor can be flattened out as much as possible due to their structure it would make it difficult to integrate the doubler design into the shoe with the same ease as with the rectifier circuits.

6.2.2 Charging

6.2.2.1 Parallel Connected Coils

This section presents the measured performance of the parallel connected 3 coil generator when converted through a HWR, FWR and doubler with an output filter capacitor. The presented results illustrate the start-up time of walking/generating to reach a steady state power level. In Chapter 5 maximum steady state power was predicted (using analytical and simulation models) with load resistances of 100Ω, 75Ω and 150Ω for the HWR, FWR and doubler circuits respectively. The output capacitor used in these initial walking experiments was the GW209F from Cap-XX [214] which has a capacitance of 140 mF and an ESR of only 70 mΩ. The circuits
were built as described in Chapter 5 where each individual coil is converted through a separate conversion circuit and the output of all three converted coil pulses are combined at the output to supply the load, \( R_{\text{Load}} \). Figure 6.2 demonstrates how the generator, conversion circuits and output capacitor were integrated into the shoe during experiments. Obviously these circuits could be integrated in a more miniature size but for test purposes it was sufficient to produce the required results.

A series of different load resistances were attached to the output of each circuit and the walking was maintained at 4.5 km/hr until a steady DC output voltage was established in each case. Obviously the time to establish steady state DC voltage is increased with increasing load resistance according to the RC charging profile. Figure 6.3 compares the charging profile to the steady state voltage established by each of the circuits for the load resistances that are predicted by the models presented in Chapter 5 to establish maximum power with each circuit. In this way the performance of the HWR with its associated maximum power load of 100\( \Omega \) is compared to the performance of the FWR and doubler with the same load. Similarly the performance of all three conversion circuits are compared with the FWR and doubler maximum power loads of 75\( \Omega \) and 150\( \Omega \) respectively. The associated power levels achieved with each of these and other loads is presented and compared in section 6.2.3. As predicted the FWR provides a larger DC voltage when compared to the HWR with the same load. The doubler produces the maximum constant DC voltage for the same load when compared to the rectifier circuits, except with loads < 100\( \Omega \). However, the time it takes the doubler to achieve steady state voltage is much larger than that of the rectifier circuits especially the FWR. For example, with an 150 \( \Omega \) load the FWR takes \(~50\) s to reach steady state voltage but the doubler is charging for a further \(~50\)s before it achieves steady state voltage.

To establish how a smaller capacitance (capable of reducing charge times) would perform, measurements were also carried out using a 75mF/150m\( \Omega \) Cap-XX capacitor. Figure 6.4 then compares the charging profile of the rectifier circuits with this smaller capacitance, but with the same load resistances. When compared to Figure 6.3 it is clear that the ripple voltage is larger with half the value of output capacitance especially at the smaller resistances.
Figure 6.3: 3 Coil Generator Parallel Coils 0.14 F Charging Profile – (a) 100 Ω, (b) 75 Ω (c) 150 Ω
However this ripple value is < 20% even at the lower resistance loads. Once again the FWR provides a larger DC voltage with the same load. The steady state
charge times are considerably reduced for both conversion circuits with the smaller capacitance. For instance the FWR’s steady state charge time with a 200 Ω and 0.14F output capacitor is ∼50s but this is reduced to ∼30s when the capacitance is reduced to 0.075F. The average DC voltage levels achieved for the same load are similar for both capacitor values. Clearly these results identify that a smaller scale size and lower capacitance could be used for the 3 coil generator if a highly regulated output voltage is not required.

When the performance of the HWR is compared to the FWR performance there is no significant variation apparent between the ripple voltages as might be expected. As the FWR also delivers the negative rectified pulse to the load it could be assumed that the full wave ripple would be less than that of the HWR. However, as described in Chapter 5, the nature of the generated pulses provides large periods of zero voltage to both circuits and this “discharging period” is approximately the same for both circuits. The improved ripple provided by the FWR is minimal when the whole generator voltage period is taken into account. But the improved power performance of the FWR can be explained by the increased number of rectified pulses delivered to the output capacitor when magnet movement does occur.

![Figure 6.5: HWR Predicted and Measured Voltage Ripple 0.14 F Vs. 0.075 F](image)

Figure 6.5 demonstrates a 10 second profile of the measured output voltages from the HWR with both the 0.14F and 0.075 F capacitors based on the maximum power load of 120 Ω. The predicted DC voltage using both capacitor values (using the models described in Chapter 5) for the same load is also plotted for comparison. Clearly the GW209F 140 mF/70 mΩ from Cap-XX is more than sufficient to provide
a low ripple output DC voltage. In fact the ripple measured is very small, most of which is contributed by the ripple on the oscilloscope probe itself. It is more apparent from these measured results that the ripple is slightly larger when using the 75 mF capacitor; however the average voltage levels are similar. It is also clear that the models derived in Chapter 5 provide an accurate prediction of generator performance embedded in the shoe sole during walking.

Figure 6.6 provides the same analysis and comparison for the FWR but on this occasion the maximum power load of 75 Ω used. Once again the voltage ripple is increased (still < 20 %) with the smaller capacitance value (0.075 F) but the average voltage levels are comparable. Figure 6.6 also compares the doubler voltage ripple achieved with its maximum power load of 150 Ω. Clearly the voltage ripple is very small due to the large amount of capacitance developed by the three doubler circuits connected in parallel. It is also evident that the analytical models developed in Chapter 5 for both circuits provide an accurate prediction of generator performance embedded in the shoe sole during walking.

Figure 6.6: FWR and Doubler Predicted and Measured Voltage Ripple 0.14 F Vs. 0.075 F

Figure 6.7 illustrates a 10 s profile of the 3 AC coil voltage pulses measured during each step that are input to the HWR with a 75 mF capacitor, while at the same time the output voltage due a 120 Ω load can be seen. It is clear that charging of the output voltage occurs when the 3 coil pulses are generated during each step (every second) can be seen in Figure 6.7. This charging occurs twice every second due to the double movement of the magnet. The reduction in voltage with the discharge of the output capacitor in-between steps (or generated pulses) can also be seen. Similarly
Figure 6.8 demonstrates the 3 generator AC coil voltage pulses measured during each step input to the doubler as well as the output voltage due to the 150 Ω load. A similar charging and discharging profile of the output voltage of the doubler due to generated coil voltages can be visualised in Figure 6.8.

**Figure 6.7:** 3 Coil Generator Parallel Coils – HWR Input and Output Voltages – 120 Ω Load

**Figure 6.8:** 3 Coil Generator Parallel Coils – Doubler Input and Output Voltages – 150 Ω Load

### 6.2.2.2 Series Alternating Connected Coils

This section presents the performance of the series alternating connected 3 coil generator when converted through a HWR and FWR with an output filter capacitor. The output capacitor used in these initial walking experiments was the 75 mF GZ215
from Cap-XX as before. The circuits are built as described in Chapter 5 where the generator coils are connected using the series alternating method described in Chapter 3 and then converted through a single conversion circuit supplying a single load, \( R_{\text{Load}} \). The experimental set up was similar to that described for the parallel connected coils in Figure 6.1 and Figure 6.2. The objective of these measurements is to demonstrate the DC performance of the generator (with higher voltage and larger source impedance) embedded in a shoe sole while walking at a speed of 4.5 km/hr, and to validate the predicted models described in Chapter 5.

**Figure 6.9:** 3 Coil Generator Series Alternating Coils 0.075 F Charging Profile – (a) 500 \( \Omega \), (b) 1000 \( \Omega \)

As before a series of different load resistances were attached to the output of the each circuit and the walking was maintained at 4.5 km/hr until a steady DC output
voltage was established in each case. Figure 6.9 compares the charging profile to the steady state voltage established by each of the circuits for the predicted maximum power load resistances of the HWR (500Ω) and FWR (1000Ω) circuits. As predicted the FWR provides a larger DC voltage when compared to the HWR with the same load. Similarly the HWR charge time is longer than with the FWR where the HWR takes >80s to reach steady state while the FWR takes only >60s with the same load. However, charging time is much higher than in the parallel coil case due to the higher source impedance and the higher DC voltage levels achieved. For instance with a 500 Ω the FWR with a parallel connection charges up to a steady state voltage of 1.42 V in <60s while in the series alternating case charge time is increased to ~100s to reach a steady state of 1.4 V with the same load resistance. For the range of loads presented a timescale of > 60s is required in each case to achieve the steady state DC voltage level. The associated power levels achieved with each of these and other loads is presented and compared in section 6.2.3.

### 6.2.3 Predicted Vs. Measured Constant Power

By combining all the measured results the optimum generator coil connection and conversion circuit can be identified. Using the analytical models derived in Chapter 5 the parallel coil connection with the doubler circuit was established as the combination that maximised the output from the generator. Figure 6.10 presents the voltage performance of the 3 coil generator based on the range of load resistances tested at the output of each circuit during walking experiments at 4.5 km/hr. Both the parallel and series alternating methods of coil connection are presented. The results from the HWR, FWR and doubler circuits are presented from the parallel connected coil DC measurements. While results from the HWR and FWR circuits are presented from the series alternating connected coil DC measurements. In each case the results from the models derived in Chapter 5 are also presented and compared. Figure 6.11 demonstrates the corresponding power results for the voltage measurements presented in Figure 6.10. The variation between predicted and measured results at higher loads can be explained by the fact that the magnet speed in the prediction model was restricted to the average measured speed which corresponds to a lower peak voltage than some of the peaks actually produced. Nonetheless, the analytical models perform well especially at the lower loads around where maximum power occurs.
Maximum DC power from the HWR is achieved with a load resistance of 100 Ω corresponding to 4.81 mW, while maximum power from the FWR is achieved with a load resistance of 75 Ω corresponding to 7.3 mW. Clearly the FWR delivers much higher power when compared to the HWR although the corresponding DC voltage levels are similarly <1V. However maximum power from the doubler is 9.81 mW achieved with a load resistance of 150 Ω which is by far the optimum at a more usable DC voltage level of ~1.2V. In each case the analytical models provide a good
prediction of circuit performance and the maximum power load is identified correctly in each case.

When the series alternating coil connection is considered the maximum DC power from the HWR is achieved with a much larger load resistance of 1000 \( \Omega \) corresponding to 2.46 mW, while the maximum power of 3.86 mW from the FWR is achieved with a load resistance of 500 \( \Omega \). While comparing the series alternating

**Figure 6.11:** 3 Coil Generator Power Performance (4.5 km/hr Walking Speed) – Prediction Models Vs. Measured (a) Parallel Coils (b) Series Coils
maximum power measured for the HWR (2.46 mW) it can be seen that the FWR produced ~1.5 times more power. However when the measured performance of the parallel (HWR - 4.81 mW, FWR – 7.3 mW and Doubler – 9.81 mW) or series alternating (HWR – 2.46 mW, FWR – 3.86 mW) connected coils are compared, the parallel connection achieves significantly greater power as predicted in Chapter 5. It can also be noted that the analytical models provide a good estimation of generator performance when converted using the series alternating coil connection. Table 6.1 summarises the 3 coil generator’s measured performance with a 0.14 F output capacitor.

Table 6.1: Measured Generator Performance

<table>
<thead>
<tr>
<th>Coil Connection</th>
<th>Conversion Circuit</th>
<th>Maximum Power</th>
<th>Maximum Power Load</th>
<th>Maximum Power Voltage</th>
<th>Charge Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>HWR</td>
<td>4.81 mW</td>
<td>120 Ω</td>
<td>0.76 V</td>
<td>35 s</td>
</tr>
<tr>
<td>Parallel</td>
<td>FWR</td>
<td>7.3 mW</td>
<td>75 Ω</td>
<td>0.74 V</td>
<td>55 s</td>
</tr>
<tr>
<td>Parallel</td>
<td>Doubler</td>
<td>9.81 mW</td>
<td>150 Ω</td>
<td>1.18 V</td>
<td>80 s</td>
</tr>
<tr>
<td>Series</td>
<td>Alternating</td>
<td>HWR</td>
<td>2.46 mW</td>
<td>1000 Ω</td>
<td>110 s</td>
</tr>
<tr>
<td>Series</td>
<td>Alternating</td>
<td>FWR</td>
<td>3.86 mW</td>
<td>500 Ω</td>
<td>90 s</td>
</tr>
</tbody>
</table>

6.2.4 Effect of Walking Speed on Constant Power

![Figure 6.12: HWR (0.075F Capacitor) – Varying Speed Performance – Predicted Vs. Measured (a) Power (b) Voltage](image)

Measured analysis was also carried out with FWR and HWR circuits attached to the 3 coil generator as before, but this time at varying walking speeds. Improving the analytical models to incorporate the varying magnet speed at the increased
walking rate achieves a good estimation of the generator performance. The magnet speed, associated voltage peak ($V_{pk}$), pulse width ($P_W$), step period ($T$) were all adjusted to reflect the increased walking rate, and a good correspondence between measured and predicted results is achieved for both circuits as seen Figure 6.12 and Figure 6.13. According to the open circuit results presented in Figure 4.24 of Chapter 4, the magnet speed was estimated to be approximately the same for 4.5 km/hr, 7.5 km/hr and 10 km/hr walking speeds in the models, but the time between pulses was reduced and the corresponding improvement is reflected in the measurements achieved. Measured power levels of 4.8 mW to 6.42 mW and 7.55 mW are achieved from the HWR at walking speeds of 4.5 km/hr, 7.5 km/hr and 10 km/hr respectively, achieving a linear improvement in power with increased walking speed. Similarly power levels of 7.3 mW to 11.6 mW and 15 mW are measured from the FWR, which also represents a linear power improvement at the same increased walking speeds.

![Figure 6.13: FWR (0.075F Capacitor) – Varying Speed Performance – Predicted Vs. Measured (a) Power (b) Voltage](image)

6.3 Pulsed Power Demonstrator

A self-powered pedometer system has been chosen as the system that will demonstrate the power from the generator designed in this work. The power requirements of both the microprocessor and transmitter are the main requirements in selecting each device. One such device is the very low voltage MSP430 microprocessor from Texas Instruments® which works from 1.8V [167]. An issue
with this microprocessor is that a separate RF transmitter which is capable of running off the same power supply must be found. One such device: CHIPCON1000 [227] again from Texas Instruments® does fall into the required power range however a more efficient approach would be to consider a global component which would incorporate both devices as well as an Analogue to Digital Converter. Two such devices identified as superior in terms of functionality, power requirements and dimensions are the RFPIC12F675 from Microchip® [228] which includes an integrated EEPROM and the nRF24E1 from Nordic Semiconductor [225] which requires a separate EEPROM. Comparing both components the nRF24E1 is most suitable due to its lower power consumption. Furthermore the nRF24E1 also includes a transceiver which can be utilised to perform both transmission and reception functions. It should be noted that the generator is not optimized for the power requirements in this case, but nonetheless, successful operation of a sensor which can be used in a pedometer application is demonstrated. Future work would include the optimisation of the generator for this load application.

6.3.1 Pedometer Implementation

Each of the demonstrator nRF24E1 components described in this chapter have a minimum voltage operation of 1.9 V with a maximum load requirement of 10.5 mA for the transceiver component. Based on the generator’s pulsed DC power predicted performance presented in Chapter 5 it can be predicted that the generator will be capable of supplying the required amount of voltage and power to operate the nRF24E1 demonstrator. In this way the generator with both the FWR and doubler circuits is predicted to be capable of delivering pulsed power with a peak voltage > 1.9 V.

With the generator connected to the supply pins of the nRF24E1, once the supply voltage and energy required for operation are provided during a step of walking, the nRF24E1 microprocessor and transmitter turn on and a one byte packet is transmitted as requested by the “range demo” program. This is indicated by a flashing LED on the receiver side, confirming that the generator is activated and that enough energy is produced to turn on the nRF24E1 and carry out the “range demo” transmission program. More details of the “range demo” program are provided in section 6.4.1. Once the generator power reduces after the step is taken and the data
packet indicating a step has been transmitted, the nRF34E1 system switches off once the power level falls below the level required for the microcontroller to operate. Therefore the reception of a data packet on the receiver side program indicates that a step has been taken by the user and can be used to implement pedometer functionality on the receiver side.

6.3.2 Overview of nRF24E1 RF Transceiver

The nRF24E1 [225] is a 2.4 GHz RF transceiver with an embedded 8051 compatible microcontroller and 9 input, 10 bit ADC. The circuit is supplied by a single voltage in the range of 1.9 V to 3.6 V. The main parameters of interest are the supply current required for the microcontroller (during power up, regular memory and A/D operations) and RF transmission which are identified to be 3 mA and 10.5 mA respectively. The transceiver part of the circuit has an identical functionality to the nRF2401, which is a radio transceiver for the worldwide 2.4 - 2.5 GHz ISM band integrated in the nRF24E1. This transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a modulator and two receiver units. Output power and frequency channels and other RF parameters are easily programmable by the transceivers register. As a power saving feature the transceiver can be turned off or on under software control using the PWR_UP and CE bits of the RADIO register. The nRF2401 subsystem has two active (TX/RX) modes; ShockBurst and Direct Mode (which is not supported by nRF24E1).

**Figure 6.14:** Illustration of Transmission Operation using Shockburst Technology [225]
Chapter 6: DC Power Measurements

The ShockBurst technology uses on-chip FIFO to clock in data at a low data rate and transmit at a very high rate thus enabling a large power reduction. When operating the nRF2401 subsystem in ShockBurst, high data rates (Mbps) are achievable with the 2.4GHz band without the need for power hungry, costly, high speed microcontrollers for data processing. Further advantages of ShockBurst are: highly reduced current consumption (which brings the power consumption down to the level achieved by the generator), lower system cost and reduced risk of ‘on-air’ collisions due to the short transmission time. If the digital part of the application is run at low speed while maximising the data rate on the RF link, the average current consumption is reduced considerably. Figure 6.14 illustrates a transmission operation using ShockBurst technology (10kbps in this example), where the data is clocking with the CPU and then sent. The second part of Figure 6.14 compares the current consumption during transmission with and without the use of the ShockBurst technology.

In order to demonstrate a successful generator operation, a sample program provided by the manufacturers was downloaded to the EEPROM of both the transmitter and receiver. The function of this test program is to identify that everything is operating correctly and more importantly to determine the range of the transmitter/receiver communication. This program called “range demo” causes the transmitter to continuously send one byte packets; while the receiver sets P0.1 (a single digital output) low once a packet is received and subsequently turns on an indicator LED. At the same time a 20 ms timer is started and if a new packet is not received before the 20 ms time-out the pin P0.1 is set high, turning off the indicator diode. If a new packet is received before the time-out a new 20 ms time-out period is started and the process begins again and the indicator LED remains on. Results of the generator output voltage during successful operation of the “range demo” program are presented in section 6.4.1.

6.3.3 Programming the nRF24E1

The nRF24E1 microcontroller instruction set is compatible with the 8051 industry standard, but several differences were identified whereby a reduced number of clock cycles are needed for each instruction (4 to 20 compared to 12 to 48 for the 8051 standard), and also the interrupt controller is required to support not only the
typical 8051 standard interrupts but 5 additional interrupt sources; ADC, SPI, RF receiver 2 and wakeup timer. A crystal oscillator is utilised to derive the microcontroller clock. The microcontroller includes a 256 byte RAM and a small ROM of 512 bytes which contains a bootstrap loader (which is executed automatically after power reset or by software). The user program is loaded into a 4k byte RAM from an external serial EEPROM by the bootstrap loader. The small internal ROM (512 bytes) of the nRF24E1 contains a bootstrap loader that downloads the program contained in the external EEPROM to the 256 byte data internal RAM utilising the Serial Peripheral Interface (SPI) on Port 1 (P1). The SPI interface uses the pins P1.2/DIN0 (EEPROM SDO), P1.0/DIO0 (EEPROM SCK), P1.1/DIO1 (EEPROM SDI) and P0.0/DIO2 (EEPROM CSN).

The nRF24E1 is programmed by firstly writing the program in C-language and then exploiting a “Keil compiler” (provided by Nordic [225]) to translate the program into a series of hexadecimal bytes (hex file). This hex file is then sent by an EEPROM Programmer into external memory (EEPROM) by firstly including a 3 byte header in the hex file which is required by the compiled hex file to make it suitable for the bootstrap loader. The file contains the data rate speed plus crystal frequency used, the offset to start off the program and the number of 256 byte blocks in the program. All required information to develop a program for the nRF24E1 can be found in the IC datasheet [225]. This information includes the analogue to digital converter (ADC), serial peripheral interface (SPI), the transceiver radio subsystem, interruption, display and peripheral RF, etc.

6.3.4 nRF24E1 Pedometer Circuit Design and PCB Layout

Figure 6.15 illustrates the nRF24E1 IC with all the pins necessary during transmission highlighted. The P1.2 (DIN0), P1.0/T2 (DIO0), P1.1 (DIO1) and P0.0 (DIO2) are associated with the EEPROM memory. VDD, VSS, AREF, IREF and DVDD are associated with the power supply. AIN0-7 are the analogue inputs (which can take the coil voltage to indicate a step taken or also for a sensor to be exploited by a further developed system) and ANT1, ANT2, XC1, XC2 and VDD_PA are associated with the antenna output. P0.1 – P 0.7 are not used during transmission and are instead connected to ground. Figure 6.15 illustrates the full circuit layout for the transmission operation.
Figure 6.15: nRF24E1 Circuit layout for Transmitter

Figure 6.16: nRF24E1 Circuit layout for Receiver

Figure 6.16 illustrates the nRF24E1 IC, with all the reception essential pins highlighted. The same pins used for the transmitter are also used for the EEPROM, power supply and antenna, but on this occasion the analogue inputs are sent to ground. The pins P0.1 – P0.6 can now be exploited as digital outputs. Figure 6.16 also illustrates the full circuit layout for the receiver operation. The ANT1 and ANT2 output pins provide a balanced RF output to the antenna. The load impedance seen between the ANT1/ANT2 outputs should be in the range of 200 – 700 Ω. A load of 100 Ω + j175 Ω is recommended for maximum output power (0dBm). The crystal oscillator is recommended to have a low value of crystal load capacitance in order to achieve lower power consumption coupled with fast start-up time. Generally the
recommended value of capacitance for the crystal is 12pF. The microcontroller, ADC and RF front end run from a crystal oscillator generated clock. Crystal frequencies from 4 to 20 MHz may be utilised by the device but a 16 MHz crystal is recommended to give the best overall performance as well as enabling the use of the Shockburst method during transmission.

A well designed PCB is vital to achieve a good RF performance. Nordic provides a number of recommendations for good PCB layout including using a minimum of two layers including a ground plane for optimum performance. For this demonstrator the standard 0603 size layout was chosen and the Gerber file associated with it is illustrated in Figure 6.17 (a). Figure 6.17 (b) displays the overall circuit with the complete placement of all components of the nRF24E1 including the chip itself, the EEPROM, the oscillator, capacitors and resistors.

![Manufactured PCB Board](image1)
![Built nRF24E1 Circuit Board](image2)

**Figure 6.17:** (a) Manufactured PCB Board (b) Built nRF24E1 Circuit Board

The EEPROM is programmed directly on the PCB boards therefore eight wire extensions are taken from the eight pins of the 25AA320 EEPROM chip and then wired into an eight pin chip socket so that programming can occur. The pins SCK, SDO, SDI and CSN of the EEPROM which connect to the nRF24E1 P1.2/DIN0, P1.0/DIO0, P1.1/DI01 and P0.0/DIO2 pins each require a 10 kΩ resistor in series so the EEPROM chip can be easily programmed without interference from the nRF24E1 IC on board, as presented in Figure 6.18. The PCB can then be oriented as a transmitter or a receiver by firstly downloading the appropriate programs onto the EEPROMs of each board and then grounding the unused analogue input pins or digital output pins depending on the circuit operation required.
Figure 6.18: nRF24E1 PCB Board with 10 K Resistors and Pin Extensions for Programming

6.4 Pedometer Performance

Based on the predicted pulsed DC power performance of the generator presented in Chapter 5 it was identified that peak voltage levels of >2 V is available from the generator while the magnet is moving for load resistances > 100Ω. Similarly the corresponding peak power available from the generator during magnet movement is predicted to be between 25mW and 50mW. The most practical applications have variable load resistance values depending on the operations being completed, like sensing, data conversion, transmission, etc. Based on the predicted models the generator is expected to provide peak power levels that will satisfy many of these operations.

The objective of the demonstrator is to establish the power capabilities of the developed generator to provide enough peak voltage and pulse energy for microcontroller and transceiver operations, where step data is detected and transmitted.
in a pedometer application. For this to be successful, during each step taken by the user the generator must provide enough peak current and voltage for the microcontroller to turn on, detect a step, convert this step detection into data and finally transmit this data to the receiver. In other words the energy provided during a step must be equal or preferably larger than the total energy required by the demonstrator system, while also providing a sufficiently high voltage level over the timescale of all circuit operations. Figure 6.19 illustrates the comparison between generator, transceiver and microcontroller energy levels. It also describes how the generator pulse energy is capable of fulfilling both the transceiver and microcontroller energy requirements as once the step has been detected and transmitted they are not required to function again until the next step occurs.

**Table 6.2:** Total Energy Requirements of Microcontroller and Transceiver [225]

<table>
<thead>
<tr>
<th>Process Block</th>
<th>Voltage (V)</th>
<th>Current (mA)</th>
<th>Power (mW)</th>
<th>Pulse Width</th>
<th>Energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>1.9</td>
<td>4.7</td>
<td>8.93</td>
<td>1 s</td>
<td>8.93</td>
</tr>
<tr>
<td>Transceiver</td>
<td>1.9</td>
<td>10.5</td>
<td>19.95</td>
<td>200 µs</td>
<td>0.004</td>
</tr>
<tr>
<td>ADC</td>
<td>1.9</td>
<td>0.9</td>
<td>1.71</td>
<td>1 s</td>
<td>1.71</td>
</tr>
<tr>
<td>Total nRF24E1</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
<td>10.64</td>
</tr>
</tbody>
</table>

For a VDD of +3V the microcontroller requires a maximum of 3 mA of current during operation (corresponding to a 1k Ω), the ADC requires 0.9 mA (corresponding to 2 kΩ), which is assumed to be required at the same time as the microcontroller. The transceiver however, requires a much larger 10.5 mA of current (From the datasheet of the nRF24E1 [225]). The input voltage range is from 1.9 V to 3.6 V so obviously a minimum input voltage of 1.9V will suffice to operate the demonstrator. Energy is calculated from $E = P \times t$. Table 6.2 illustrates the total amount of energy required by the transmitter to detect a step and transmit the data to the receiver as specified in the nRF24E1 datasheet (current is adjusted to maintain microcontroller power at 3V).

A maximum of 10.64 mJ is required during every step in order for the demonstrator system to register and transmit the step data to the receiver. The transceiver utilising ShockBurst technology only requires the period of maximum power for 200 µs, while the microcontroller is only required until the step data has been sent (at which stage the power is drawn from the generator which is no longer
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capable of sustaining the microcontroller power, once magnet movement is finished). Therefore the microcontroller pulse width is reduced from 1s to 400 ms (generator output pulse width with a 300µF filter capacitance) and the required energy reduces from 10.61 mJ to 4.26 mJ.

The maximum power required by the demonstrator can be considered as the peak voltage and current required by the transceiver which is 1.9 V and 10.5 mA (19.95 mW) respectively. This is represented by a ~181 Ω load. Thus if a 181 Ω load is connected to the output of each generator with AC/DC conversion then the energy produced must be between 4.26 mJ and 10.61 mJ. However this is more severe than what occurs practically, as with this scenario the load of 181 Ω is drawing from the source (generator) during the entire pulse width. The nRF24E1 transmitter only begins to draw power after a certain amount of time, i.e. the time it takes the generator to reach the amount of peak threshold voltage required by the microcontroller to turn on, plus the time taken for the microcontroller to then detect the step and forward the data to the transceiver subsystem utilising the SPI interface. However, implementing the over-estimated requirement for a 181 Ω load gives a good indication of the capabilities of the generator with AC/DC conversion and identifies if the 4.26 mJ or the maximum 10.61 mJ energy requirements can be achieved. Figure 5.27 demonstrates that even if the transmitter load is on for the total generator output pulse the generator could provide the necessary peak voltage and energy with < 0.2 mm wire diameter.

Using Pspice, a more realistic approach to represent how the nRF24E1 demonstrator is applied to the generator output can be completed. The simulation identified that the turn of the microprocessor and ADC load would only occur after the output voltage level has reached ~1.9V peak. These would be applied for 400 ms, i.e. the duration of the generator output pulse. Then after a short time period the 10.5 mA load can be switched in for the 200 µs ShockBurst period.
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Figure 6.20: Practical nRF24E1 Demonstrator Performance Circuit

Figure 6.20 presents a model of the Pspice 3 coil generator circuit used to predict if the 0.25 mm diameter wire generators could power the nRF24E1 demonstrator during normal operation. Both the doubler and FWR conversion circuits were simulated in this way. Initially the substitute microprocessor and ADC loads are applied after the output DC voltage has reached its peak voltage. The transceiver load is then applied for the 200\(\mu\)s ShockBurst period. A promising result is found here, where the 3 coil generator with a 0.25 mm wire diameter, (converted through a doubler) is predicted to achieve the 1.9 V required by the nRF24E1 demonstrator as seen in Figure 6.21. This pulse also corresponds to 5.55 mJ which is sufficient to match the required 4.26 mJ of the demonstrator. The FWR is also predicted to supply enough voltage with this implementation of the nRF24E1 demonstrator load as shown in Figure 6.21. The 200 \(\mu\)s ShockBurst period is a very small fraction of the total period of the generator pulse and there is no large voltage discharge when this is applied, even with a 300 \(\mu\)F capacitor.
In order to identify if the generator would be capable of powering the transmitter a simple program is downloaded to the EEPROM of both the transmitter and receiver. This program called “range demo” causes the transmitter to continuously send one byte packets. The receiver is powered by a power supply with 2V and can be adjusted to light an LED by setting the digital output P0.0 low every time a packet of data is received confirming that enough power has been provided to the transmitter to transmit the said data packets.

The 3 coil generator embedded in the heel is analysed in terms of this sample program whereby two main objectives are investigated. Firstly if the LED on the receiver side lights up it would verify that enough power is produced by the generator, confirming that the pedometer demonstrator would be possible. Secondly this sample program would also identify the range between the transmitter and receiver that can be achieved, whereby the LED on the receiver side would still be able to light indicating a successful receipt of the data packet. For instance if the pedometer system is designed to transmit step data from the shoe to say an iPod or watch, then a maximum transmitter distance of around 1.5 meters would be required between it and the generator in the shoe sole.
Figure 6.22: Induced Voltage from 3 Coil Parallel Generator -Transmitter Load

(a) FWR (b) Doubler

Figure 6.22 illustrates the voltage pulses achieved at the output of the 3 coil generator with individual coil conversion with FWR and doubler circuits, while the demonstrator is running the range demo program. On each occasion enough energy is produced by the generators for the microcontroller and transceiver to turn on, detect a step and transmit the data to the receiver as indicated by the flashing LED on the receiver side as each step is taken. The Dig Out P0.1 signal in Figure 6.22 indicates when the receiver has received a packet of data from the transmitter powered (by the generator) and set the digital output (Dig Out P0.1) high. Clearly for both circuits this occurs twice during each step due to the double magnet movement so long as the voltage is greater than 1.9 V. The 3 coil generator peak voltages ($V_{Pk} \sim 3$ V) are higher than the peak voltages ($V_{Pk} \sim 1.9$ V) required by the demonstrator. The measured generator output voltages with the demonstrator load identify that the output voltage is not discharged fully to zero indicating the demonstrator had switched off
once the packet of data had been sent and the required operating voltage of 1.9 V had been lost.

The following analysis is carried out on the best series alternating connection associated with the 3 coil generator. The larger pk-pk voltages that are achieved with this coil connection may be counteracted by the higher source impedance which could prevent the transmitter load from operating effectively. Figure 6.23 displays the voltage pulses of the generator which is converted using the FWR. The effect of increasing the number of 100 µF output capacitors (one per coil), is also investigated. The two scenarios are; one 100 µF capacitor at the output of each rectified coil voltage (multiple capacitors) or one single capacitor at the load. It is clear from Figure 6.23 that a much wider pulse can be achieved with increased output capacitance (300 µF) and this is further clarified by a longer LED lighting time (or digital output on time) on the receiver side as described in section 6.3.2.

![Figure 6.23: Induced Voltage from 3 Coil Series Alternating Generator -Transmitter Load](image)

(a) FWR Multiple Capacitors (b) FWR Single Capacitor
Figure 6.24 displays the voltage pulses of the generator with the best series alternating coil connection now converted using the Doubler. It is clear from this analysis that the energy produced in a step is enough to power the microcontroller/transceiver and transmit the data to the receiver. Based on the measurements it has also been identified that any of the generator and conversion combinations considered are capable of producing enough energy to power the demonstrator. Overall, the 3 coil parallel connected generator provides maximum pulsed power (as seen in higher voltage levels for the same load) when compared to any other generator design and any further development of this pedometer system can be based on this generator as the power source. However the series alternating coil connection with the transmitter load is capable of keeping the required voltage level for longer than the parallel connection due to the voltage levels achieved. Hence the data packets are being sent for longer when compared to the parallel coil case, indicated by the digital output being set high at the receiver side for longer. This demonstrates how the generator could support additional functionality like for example sensing in the shoe, and the models presented in this thesis provide a good basis for optimizing such systems.

6.5 Conclusions

To satisfy the objective of a DC power generator set out in the beginning of this thesis the aim of this chapter is to demonstrate the DC performance of the wearable generator. The measured results validate the relative performance of the
various AC/DC conversion circuits in terms of DC voltage, DC power and steady state charge times for constant power loads. When both methods of generator coil connection are compared, clearly a parallel connection is superior, while maximum DC voltage and power levels are achieved by the doubler circuit, as predicted in Chapter 5. Constant DC voltage levels of > 1V and ~10mW of power are achieved with this coil connection and circuit combination which is much larger than generated using the rectifier circuits. If the walking speed is increased an improved generator performance or linear increase in power can be achieved which again matches predictions in Chapter 5. The measurements performed in this chapter serve to further validate the generator and AC/DC models described in Chapters 3, 4 and 5. The models represent an accurate comparison to the measured results especially when the varying magnet speed is considered for all of the conversion circuits investigated during measurements.

A pedometer transceiver system using an nRF24E1 microprocessor/transceiver IC is a suitable demonstrator load to verify the pulsed power capabilities of the 3 coil generator. Using the “range demo” program available from the nRF24E1 manufacturers, successful operation of the demonstrator verified that the 1.9V/10.5 mA load requirement is satisfied by the generator during each step taken. The measurements presented validate that the generated pulsed energy is more than sufficient for data transmission. In the pulsed power case a 100 µF capacitor at the output of every coil conversion provides enhanced results when compared to a single capacitor at the output of the combined coil conversions. Both the generator parallel and series coil connections are capable of delivering the required power with either the FWR or doubler circuits. Although the parallel connection provides more power, this application of data transmission identifies that the series alternating connection is optimum due to the higher voltage levels achieved. There is obviously scope to power other functions in the shoe, like sensors which could communicate with the microprocessor and deliver readings such as pressure, acceleration, temperature, etc. which would be useful in biomedical or sporting applications. However the objective of demonstrating generator performance in a useful application has been achieved for a pedometer system, and it has been confirmed that the power available from the developed generator is sufficient to run such an application. In this novel system the generator provides a self-powered pedometer system without the requirement of any battery which satisfies the final objective of this work.
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7. Chapter 7 - Conclusions

The overall objective of this work as stated in Chapter 1 was the design and optimisation of an unobtrusive wearable generator to harness and convert the energy developed while walking into usable DC electrical power. In achieving that objective, the work described in this thesis produced the following outputs:

Identification of a suitable wearable generator location and principle of operation: There are a number of locations on the human body where mechanical power is developed during walking including the upper body, legs and feet where human vibrations, center of mass motion, joint rotation, foot pressure and foot swing motions are all available. Maximum mechanical power is predicted during joint rotation at the foot during both the swing and stance phases of the gait cycle, and therefore this work focussed on generator design for integration at the foot. The most developed generator designs in terms of human energy harvesting are based on electromagnetic and piezoelectric technologies. When all human energy harvesting generator designs are compared the electromagnetic designs achieve much higher power levels than the piezoelectric ones. However, it is clear that these electromagnetic designs are mostly >100 cm$^3$ in volume and so cause a significant hindrance to the user to achieve these power levels. The piezoelectric designs although more integrable (especially into the shoe sole) provide much less power. Thus it was decided to target the design and optimisation of an electromagnetic generator to harness the energy developed at the foot during walking, using an unobtrusive design that can be integrated successfully into the shoe sole.

A linear electromagnetic generator structure has been validated in previous designs to be successful in body worn applications, but to date it has not been integrated into the shoe sole with attractive results. The human gait cycle can be broken up into the swing phase and the stance phase, and correspondingly two separate generators were designed in this work to enable a comparison of energy conversion using both these movements. Firstly, a linear type electromagnetic generator structure called the sliding magnet generator (SMG) is demonstrated as capable of passively converting the wasted human energy dissipated during the swing phase of the gait cycle while walking. Similarly a different opposing magnet linear
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type electromagnetic generator (OMG) structure is capable of passively converting the stance phase of the gait cycle. Both generator designs are housed in a volume <50 cm$^3$ and can be unobtrusively integrated into a limited volume of 10x7x3 cm$^3$. Although a linear electromagnetic design is not new, the novelty lies with comparing and analysing the performance of two different designs for unobtrusive integration into a shoe sole which has not been achieved to date.

**Development of analytic models for generator design and optimisation:** In order to enable generator modelling, accelerometer measurements were used to predict the excitation force applied to a linear type generator embedded in the shoe sole. During a normal gait cycle -2g and up to 4g of acceleration is achieved at the heel of the foot in the horizontal direction during the swing phase of the gait cycle, which results in a double movement of the magnet through the length of the SMG embedded in the heel of the shoe. The magnet has a velocity of between 1 and 3.5 m/s in this structure due to the forces applied. During the stance phase up to 1771 N of force is applied by a standard user corresponding to a vertical acceleration of -3g at the heel sole area during the heel strike of the gait cycle. As long as the force between the opposing magnets is <<1771N the generator structure should not hinder the gait cycle of the user. The complete analysis of the long term effects of both generator structures on the user should be investigated further. That is, analysis of a number of subjects, over a range of time lengths, wearing shoes with the integrated generators, should be carried out to fully establish the effect the integrated generators have on the human gait cycle.

NdFeB permanent magnet material is the optimum material to use as the magnet for both generator structures, as it provides maximum residual flux density corresponding to maximum flux linkage with the generator coils. The optimum magnet shape for the SMG design is a cylindrical shape. Using FEA analysis the magnetic flux distribution of any cylindrical shaped NdFeB permanent magnet can be predicted. Based on this flux distribution, analytical models were developed in MATLAB to predict the induced coil voltage for both generator structures, and for a number of the generator variables including coil length, coil diameter, coil thickness, magnet speed and overall generator length. Correspondingly it was possible to predict generated power based on the generator load resistance. In the future the influence of higher grades of NdFeB magnets should be investigated as it is predicted
that a linear improvement in generated power will be provided as the magnet grade is increased. The main stipulation would be that the influence of the outside environment or other generator structures in the shoe sole would not hinder the movement of the magnet as the magnet grade and hence strength is increased.

Using the analytic models developed, the optimum coil length for the SMG was predicted, based on the criteria of maximising power with a usable voltage with the smallest generator coil resistance possible. This is shown to depend on the magnet diameter and magnet length, where the optimum coil length is predicted based on the location of the 10% of maximum flux gradient value from the centre of the magnet. The optimum coil length for the OMG is more difficult to achieve due to the space available in the heel, but if the coil is broken up into a number of sections maximum pk-pk voltage and power can be achieved.

Parameter analysis and optimisation of the sliding magnet generator (SMG): Under the same electromagnetic generator design and test conditions the SMG produces ~12 times more power than the OMG, and so it was optimised further to generate target power levels of >10mW as specified in the objectives. Results of detailed parameter analysis found that in order to achieve maximum output power, there is an optimum magnet diameter for a given total generator diameter. For a given magnet diameter, maximum power is found when the cross sectional area of the magnet equals that of the coil, while maximum peak-peak voltage is achieved for $r_m \approx r_o/2$. Based on the optimum magnet diameter, power per unit length increases with magnet length but the rate of power increase levels off for longer magnets. Peak-peak voltage levels in this case, levels off when the magnet length equals half the generator diameter. In terms of wire diameter voltage levels increase dramatically with decreasing wire diameter, while at the same time the variation in average power is much lower. For maximum power the optimum ratio of magnet radius to outer generator radius is ~0.75. All results presented are normalised so that they can be applied to design similar generators for a range of application environments and generator sizes.

Future work may consider the integration of soft magnetic materials to maximise flux linkage in the generator design. Although a previous investigation [229] identified that interleaving soft magnetic material into the coil provided minimal improvement. By applying a method similar to Von Buren [86] in an actuator design
in the future the performance of the generator may be improved further, although care must be taken so the mechanical complexity or generator weight is not significantly increased by the inclusion of these materials.

**SMG optimisation for a fixed space:** The highest SMG power within a specified volume of ~18 cm$^3$ is achieved using one magnet with dimensions of φ10 mm × 20 mm and three coils connected in parallel to a load that matches the coil resistance. Multiple magnets can be separated by a fixed distance within a generator length; however no improvement in generator power is produced due to the limited velocities achieved. Analytical models are verified by measured results where a 3 coil generator is demonstrated to produce the highest power levels in a ~18 cm$^3$ volume, when compared to 4 and 5 coil generator designs with single and multiple magnets. An average power of 14 mW (200 mW instantaneous) for normal walking speeds is generated by the 3 coil generator design. These levels compare favourably with the power produced by piezoelectric generators in the shoe heel [9], while also satisfying the >10mW requirement set out in the thesis objectives. The proposed structure is also more amenable to integration in the shoe than other electromagnetic generators in the literature, satisfying the <50 cm$^3$ volume specification. It is found that magnet speed is increased as the magnet is propelled through the generator which causes an increased pk-pk voltage induced on each of the neighbouring coils as the magnet passes through each generator coil. As might be expected, enhanced output power is achieved with faster walking speeds or running; where the increased voltage pulses per second contribute to improving the instantaneous and average power levels, while it is found that magnet speed remains approximately constant for all walking speeds.

**Development of analytic models for AC/DC conversion circuits with discontinuous voltage sources:** Electromagnetic generator designs tend to generate much less voltage than piezoelectric designs and this poses a problem when converting to DC voltage. In order to achieve a usable DC voltage the number of coil turns in an electromagnetic generator need to be increased corresponding to a much higher source impedance. A number of AC/DC conversion designs incorporating synchronous rectification have been successful in reducing the conversion losses thus the generated source voltage and corresponding source impedance can be reduced.
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However the problem lies in the startup of these designs as well as providing power to turn on the MOSFET gates of these circuits. The majority of AC/DC conversion circuits for human power generators are based on a continuous sinusoidal electromagnetic source. However they do not consider the periods where no excitation of the generator is achieved. Thus it is easier to predict the performance of these AC/DC circuits. It is more difficult to predict the performance of AC/DC conversion circuits that have a source voltage with periods of zero induced voltage as with the generator designed in this work.

Accurate analytical models to predict the DC performance of the designed generators based on the intermittent AC generator output being passed through different AC/DC conversion circuits has been achieved. The most significant difficulty encountered in this analysis was due to the large periods of zero voltage produced by the generator coils. Using the designed generator’s predicted AC voltage peak ($V_{\text{peak}}$), source resistance ($R_{\text{source}}$), load resistance ($R_{\text{load}}$), capacitance ($C$), AC voltage pulse width ($P_{\text{w}}$), walking rate (number of steps in period $T$), number of generator coils ($N$) and number of rectified pulses ($N_{\text{RP}}$), the DC output voltage and power can be predicted for any generator design. Based on the discontinuous nature of the generator source voltage pulses, using these variables analytical models for the HWR, FWR, doubler and quadrupler conversion circuits have been developed, which provide an accurate comparison with Pspice simulation models. Therefore, any similar generator structure, of any power level and with similar time lags between generated pulses can easily be analysed in terms of their DC performance based on the models presented in this work. These models are accurate for parallel coil pulses as well as series alternating connected coils.

For the specified generator volume of ~18 cm$^3$, the parallel connected 3 coil generator is found to produce the maximum DC power when compared to the series alternating connected coils, while the series alternating connected coils provide maximum DC voltage. The doubler and quadrupler circuits provide maximum voltage and power (10.2 mW and 10.7 mW respectively) for the 3 coil generator with a 0.25mm. A doubler is more suitable as it requires less capacitance corresponding to reduced capacitor charge times and circuit components. However as the wire diameter is decreased the FWR provides power levels equal to those established by the multiplier circuits.
Chapter 7: Conclusions

A pulsed power method is shown to generate useful DC power during the time interval when the magnet is moving during each step. Similar models have been developed for this power method and while the doubler produces maximum peak voltage the rectifier circuits achieve maximum pulsed power and energy with the FWR producing the optimum performance. If a demonstrator is to be supplied with the pulsed power method from the prototype generator the demonstrator energy demand must be <10mJ.

Wire diameter and walking speed heavily influence the performance of the DC output of the generator design. The wire diameter can significantly improve constant power and voltage as well as the conversion efficiency results on each circuit. Wire diameter should be investigated in conjunction with AC/DC conversion circuits so that the optimum generator design can be established. With the models developed in Chapter 5 coupled with the models described in Chapter 3 and the optimisation established in Chapter 4, this can now be achieved. Therefore, during generator design the AC development and AC/DC development of the generator should be done at the same time. Models developed to predict the AC performance can be combined with the DC models so that the DC performance of any generator can be predicted based on any generator variable change such as magnet speed, coil thickness, wire diameter etc. This is one of the main objectives of this thesis. By applying synchronous rectification to the rectifier and multiplier circuits the conversion efficiency is expected to be improved by ~10%. In the future this technology should be investigated by applying it to demonstrator structures so that the generator DC power may be increased. With the advances in semiconductor technology today the conversion efficiency may be increased further to > 10%. The AC/DC models can also be used to predict the synchronous rectification performance by applying $R_{ds,on}$ values to model the current path through MOSFET’s. Based on the DC models developed in this thesis, accurate predictions of the DC generator performance can be achieved which will aid the design of any similar generator particularly those with intermittent source supplies.

Shoe integrated generator system providing 10 mW constant power and 100 mW pulsed power, at DC voltage levels > 1 V: Measured results validate the relative performance of the various AC/DC conversion circuits in terms of DC voltage, DC power and steady state charge times. When both methods of generator coil connection
Chapter 7: Conclusions

are compared a parallel connection is superior, while maximum DC voltage and power levels are achieved by the doubler circuit, as predicted by the DC models. Constant DC voltage levels of > 1V and ~10mW of power are achieved with this coil connection and circuit combination which is much more than anything generated using the rectifier circuits. If the walking speed is increased an improved generator performance or linear increase in power can be achieved which again matches what had been predicted in Chapter 5. The measurements performed serve to further validate the generator and AC/DC models described in Chapters 3, 4 and 5. The models represent an accurate comparison to the measured results especially when the varying magnet speed was considered for all of the conversion circuits investigated during measurements.

![Generator Volume Comparison](image)

**Figure 7.1:** Generator Volume Comparison

![Generator Power vs. Volume Comparison](image)

**Figure 7.2:** Generator Power vs. Volume Comparison
Chapter 7: Conclusions

When the volume of the generator designed in this work is compared to other generator designs in the literature it is clearly a more efficient design as it can realistically be integrated into the shoe sole unobtrusively as shown in Figure 7.1. The ~18 cm\(^3\) volume is several times (~12) smaller than the 210 cm\(^3\) heel volume available. This volume is also much less than other designs in the literature and while the power levels may not match the maximum power developed by other electromagnetic designs it does achieve maximum power when compared to all designs with the same volume as shown in Figure 7.2. However the designs that do provide higher power than that produced by the generator designed in this work not only have much larger volumes but are obtrusive to the user and require the user to carry extra loads. Furthermore, it should be noted that there is space to accommodate at least two generator units of size \(\phi 15 \times 100\) mm\(^3\) within the heel of a shoe, so that the total average DC power per person could conceivably be as high as 40 mW for moderate walking speeds. Alternatively this type of power could be charged on a supercapacitor without a load attached and then used as a power source for some demonstrator electronics once a usable DC level is achieved [230].

Identification of the range of applications for the proposed shoe integrated generator: The limited advances in battery technology pose a significant problem for the portable electronic devices industry today and the need for alternative power sources is clear. However, it is also obvious that portable electronic devices such as mobile phones or digital cameras cannot be powered by human harvesting methods alone, especially those that are designed to be unobtrusive to the user. Instead, a more realistic approach would be to design a microprocessor, transceiver and sensor system that combined require power levels of < 100 mW, which is a power level more achievable by unobtrusive generator designs. When the power requirements of a number of commercial loads are investigated and compared to the predicted performance of the generator under both constant power and pulsed power conditions a range of applications that can be powered by the generator are identified. A pedometer transceiver system using a nRF24E1 microprocessor/transceiver IC is a suitable demonstrator load to verify the pulsed power capabilities of the 3 coil generator. Using the “range demo” program available from the nRF24E1 manufacturers the demonstrator verified that the 1.9V/10.5 mA load requirement is satisfied by the generator during each step taken.
Chapter 7: Conclusions

The generated pulsed energy is more than sufficient to power the demonstrator for data transmission. In the pulsed power case a 100 µF capacitor at the output of every coil conversion provides much improved results when compared to a single capacitor at the output of the combined coil conversions. Both the generator parallel and series coil connections are capable of delivering the required power with either the FWR or doubler circuits. Although the parallel connection provides more power this application of data transmission identifies that the series alternating connection is best due to the higher voltage levels achieved. Further improvement of this pedometer system design could be achieved in the future by adding extra functionality, whereby the receiver could be programmed to identify the number of steps taken, calories burned and distance covered, etc and also display this data on an LCD. There is obviously scope to power other functions in the shoe, like sensors which communicate with the microprocessor and deliver readings such as pressure, acceleration, temperature, etc. which would be useful in biomedical or sporting applications. However the objective has been achieved through the use of the pedometer demonstrator and confirmed that the power available from the developed generator is sufficient to run an application with >10mW which satisfies what was specified in the objectives of this work.

The scope for exploitation of these generators is immense and could find applications in areas such as sports monitoring and biomedical devices. Larger generator structures could also be considered for environments with larger potential forces and space based on the design guidelines for the SMG specified in this thesis. In conclusion this work has developed and critically evaluated a generator system which addresses not only the desire for passively and unobtrusively harnessing otherwise wasted energy but also addresses the significant need for enhanced systems to provide battery-less power for wearable electronics.
Appendix A: Parallel Vs Series Alternating Analysis

Appendix A - Parallel Vs Series Alternating Analysis

Figure A.1: Total ø15 mm Generator Power vs. Number of Coil Sections in a 100 × 15 × 15 mm$^3$ volume (a) Parallel Coils (b) Series Alternating Coils

Figure A.2: Total ø15 mm Generator Vpk-pk vs. Number of Coil Sections in a 100 × 15 × 15 mm$^3$ volume (a) Parallel Coils (b) Series Alternating Coils

Figure A.3: Total ø17 mm Diameter Generator Power, (a) Parallel Coils (b) Series Alternating Coils
Appendix A: Parallel Vs Series Alternating Analysis

Figure A.4: Total φ17 mm Diameter Generator Vpk-pk, (a) Parallel Coils (b) Series Alternating Coils

Figure A.5: Total φ20 mm Diameter Generator Power, (a) Parallel Coils (b) Series Alternating Coils

Figure A.6: Total φ20 mm Diameter Generator Vpk-pk, (a) Parallel Coils (b) Series Alternating Coils
Appendix B - 4 & 5 Coil Generator Pulse Measurements

Figure B.1: Measured 4 Coil Generator Open Circuit Induced Voltage – Single Magnet

Figure B.2: Measured 4 Coil Generator Open Circuit Induced Voltage – Separated Magnets
Figure B.3: Measured 5 Coil Generator Open Circuit Induced Voltage – Single Magnet

Figure B.4: Measured 5 Coil Generator Open Circuit Induced Voltage – Separated Magnets
Appendix C - AC Power Measurements

Figure C.1: 3 Coil Generator - Coil and Generator Power Vs. Varying load Resistance

(a) Single Magnet  (b) Separated Magnets

Figure C.2: 4 Coil Generator - Coil and Generator Power Vs. Varying load Resistance (a) Single Magnet (b) Separated Magnets

Figure C.3: 5 Coil Generator - Coil and Generator Power Vs. Varying load Resistance (a) Single Magnet (b) Separated Magnets
Appendix D: Full Wave Rectifier – Analytical Model

The full-wave filter circuit illustrated in Figure D.1 is considered where the effects of source impedance and non-ideal diode parameters are investigated with similar analysis to that carried out for the HWR filter with similar components. Due to voltage divider action between the source impedance and load resistance, the output voltage is again lower than the source voltage in this case as shown in Figure D.2. Capacitor charging occurs each time the source voltage is higher than the output voltage and discharging through the load occurs once the source voltage is lower than the output voltage. The voltage is charging across an approximately symmetrical time period centered around the maximum of the source voltage pulse. Let $\phi$ represent the phase angle during which charging occurs on either side of the center of the rectified source pulse.

If the generator single coil source pulse is initially investigated, instead of the ideal full wave rectified DC voltage pulses, the output voltage will charge and discharge due to the output RC filter, and the same approach to the HWR may be applied to analyse the response of the full-wave rectifier circuit to non-sinusoidal voltage sources. There are much larger discharge times due to the nature of the generator source voltage pulse, but on this occasion there are two positive rectified pulses seen by the output RC. Similar to the HWR, to enable efficient mathematical modelling, the voltage waveform induced on each generator coil is assumed to be a periodic discontinuous function, consisting of a sinusoidal pulse having a peak value, $V_{\text{peak}}$, and a frequency, $\omega_{\text{pw}} = 2\pi/P_w$, over one sinusoidal pulse, $P_w$, followed by zero volts over the remainder of the period $T$ (walking period). The other full wave
rectified pulses are also used to estimate number of charge pulses that are presented to the RC of the FWR for the two connected generator pulses. The following analysis will focus on a generator single coil pulse source of ~3 V Pk-Pk at 1 Hz and the generator impedance parameters described previously as well as the PMEG2010EH diode.

**Figure D.2:** Full-Wave Filter Output Voltage

Let the function $\phi$ represent the angle of charge on either side of the center of the rectified source pulse. On this occasion the two diode drops have to be considered. The maximum output voltage, $v_{o_{\text{max}}}$, can be calculated in terms of the source voltage from:

$$v_{in}(t) = v_{o_{\text{max}}}(t) + (2 \times V_D)$$

(D.1)

This occurs at $\omega_{pu} t = \left(\frac{\pi}{2} + \phi\right)$, when:

$$v_{in}(t) = V_{pk} \times \sin\left(\frac{\pi}{2} + \phi\right)$$

(D.2)

for an input voltage amplitude of $V_{pk}$. Thus the overall maximum output voltage is given by:

$$V_{o_{\text{Max}}} = V_{pk} \times \cos\phi - 2 \times V_D$$

(D.3)

By considering the current loop around the circuit as before, the current flowing in the circuit is calculated using similar analysis to that used for the HWR.
Appendix D: Full Wave Rectifier – Analytical Model

filter in (5.7) to (5.9) and considers the loop from the source through the load when the two diodes are ON and the capacitor is charging.

\[ v_{in}(t) - R_s \times i_s(t) - 2 \times V_D - v_o(t) = 0, \quad (\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi) \]  \hspace{1cm} (D.4)

Considering \( i_s(t) = i_c(t) + i_D(t) \) at \((\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi)\) and also at \((\pi + \pi / 2 - \phi) < \omega_{pu} t < (\pi + \pi / 2 + \phi)\) for a FWR so that the capacitor current can then be calculated from:

\[ i_c(t) = \frac{v_{in}(t) - 2 \times V_D - v_o(t)}{R_s} - \frac{v_o(t)}{R_{Load}} \]  \hspace{1cm} (D.5)

where \( v(t) > v_o(t) + 2 \times V_D \). The change in capacitor charge during the charging interval is then given as:

\[
\Delta Q_c = \int_{t_1}^{t_2} i_C(t) \times dt + \int_{t_1}^{t_2} i_c(t) \times dt = 2 \times \int_{t_1}^{t_2} \left[ \frac{V_F \times \sin(\omega_{pu} t) - 2 \times V_D - V_{O_{Max}}}{R_s} - \frac{V_{O_{Max}}}{R_{Load}} \right] \times dt
\]

\hspace{1cm} (D.6)

During discharge when the diode turns OFF, the capacitor current is equal to negative of the output load current:

\[ i_c(t) = -i_o(t), \quad (\pi / 2 + \phi) < \omega_{pu} t < \left[T + (\pi / 2 - \phi)\right] \]  \hspace{1cm} (D.7)

Assuming that the output percentage ripple voltage is low, the output voltage can be assumed constant and equal to \( V_{O_{Max}} \) and the corresponding charge dissipation is then calculated as:

\[
\Delta Q_c = \int_{t_1}^{t_2} \frac{V_{O_{Max1}}}{R_{Load}} \times dt + \int_{t_1}^{t_2} \frac{V_{O_{Max2}}}{R_{Load}} \times dt
\]

\hspace{1cm} (D.8)
Appendix D: Full Wave Rectifier – Analytical Model

over the time when the diode turns OFF at \
\[ t = \left( \frac{\pi}{2} + \phi \right) / \omega_{p_w} \]
and \
\[ t = \left( \frac{\pi}{2} + \phi \right) / \omega_{p_w} \]
until it turns ON again at \
\[ t = \left( \frac{\pi}{2} - \phi \right) / \omega_{p_w} \]
and \
\[ t = \left( T + \frac{\pi}{2} - \phi \right) / \omega_{p_w} . \]
Solving, the total reduction in charge is found as:

\[ Q = \int \frac{V_{O_{\text{Max,Avg}}}}{R_{\text{Load}}} \times DT \quad \text{and} \quad \int \frac{V_{O_{\text{Max,Avg}}}}{R_{\text{Load}}} \times DT \]

Equating this with the charge provided to the capacitor with the current of (D.5)
defines a relationship between 
\[ V_{O_{\text{Max}}} \] and \[ \phi \] in terms of other known quantities:

\[ Q = 2 \times \int \frac{V_{O_{\text{Max}}} \times \sin(\omega_{p_w} t) - V_D - V_{O_{\text{Max,Avg}}} - V_{O_{\text{Max,Avg}}}}{R_s} \left( \frac{2\phi}{\omega_{p_w}} \right) dt \]

After integration the final charge on the capacitor is estimated from:

\[ \left( \frac{V_{O_{\text{Max}}}}{R_{\text{Load}}} \right) \times [T] + 2 \times \left( \frac{V_{O_{\text{Max}}} + 2 \times V_D}{R_s} \right) \times \frac{2\phi}{\omega_{p_w}} \times \sin(\phi) \]

Inputting the expression already estimated for output voltage from (5.93):

\[ \left( \frac{V_{P_k,AVG} \times \cos(\phi) - 2 \times V_D}{R_{\text{Load}}} \right) \times [T] + 2 \times \left( \frac{V_{P_k,AVG} \times \cos(\phi)}{R_s} \right) \times \frac{2\phi}{\omega_{p_w}} \times \sin(\phi) \]

When compared to the HWR filter capacitor charge/discharge equation calculated in (5.19) it is clear that the main difference is due to the diode voltage drop changing from \[ V_D \] to \[ 2 \times V_D \], and the discharge time term being reduced from \[ [T - 2\phi / \omega_{p_w}] \] to \[ [T - 4\phi / \omega_{p_w}] \]. Evaluating (D.12), the discharge time is now calculated from:
Appendix D: Full Wave Rectifier – Analytical Model

\[ T_D = \left( T - \frac{4\phi}{\omega_{pw}} \right) \]  \hspace{1cm} (D.13)

By similar analysis to that carried out for the generator source pulses passing through a HWR filter and combining it with the FWR filter formula already established for a single coil source voltage a general formula can be defined for the FWR. Combining (5.30), (5.31), (D.12), and (D.12) the new formula for the FWR for non sinusoidal generator source pulses can be defined as:

\[
\left[ \frac{V_{pk, AVG} \times \cos \phi - 2 \times V_D}{R_{load}} \right] \times \left[ T + \frac{2 \times N_{PST} \times \phi}{\omega_{pw}} \right] + N_{RP} \times \left[ \frac{2 \times V_{pk, AVG}}{\omega_{pw} \times R_S} \times \sin \phi \right] = \frac{P_{W}}{\omega_{pw} \times \phi} \hspace{1cm} (D.14)
\]

where \( N_{PST} \) is the number of pulses that are presented to the RC of the FWR filter at exactly the same time. Thus the discharge time can be calculated from:

\[
T_D = \left( T - \left[ \frac{2 \times N_{RP} \times \phi + 2 \times N_{PST} \times \phi}{\omega_{pw}} \right] \right) \hspace{1cm} (D.15)
\]

The HWR has no instance of more than one rectified pulse appearing at the RC load at the same time. However with the 3 coil parallel coil connected generator, full wave rectified output, there are two instances where more than one pulse is charging the RC load as seen in Figure D.2. With the single coil and series alternating connected coil - full wave rectified pulses, \( N_{PST} \) is simply equal to zero. Therefore \( N_{PST} \) is increased as the number of coils in a given generator is increased.

The main difference between (5.30) for the HWR and (D.14) is due to the doubled diode voltage drop, and the number of rectified pulses \( N_{RP} \) which is increased for each of the three types of generator source voltage pulses. \( N_{RP} \) is equal to two, six and four for the single, parallel and series alternating coil voltage pulses respectively, when passed through a FWR. This analytical model for the FWR filter as well as (5.19), (5.21), (D.3) and (D.15) can be used to predict the FWR filter DC performance of each of the generator source pulses under varying load conditions.

In terms of the series alternating connected coils a further formula can be generated from (D.6) and (D.8) where the two separate source peak voltages are
considered. On this occasion there are four instances of rectified voltages. This corresponds to discharge of the capacitor $\Delta Q$, being estimated from:

$$\Delta Q = \int \frac{V_{O,Max1}}{R_{load}} \times dt + \int \frac{V_{O,Max2}}{R_{load}} \times dt + \int \frac{V_{O,Max3}}{R_{load}} \times dt + \int \frac{V_{O,Max4}}{R_{load}} \times dt$$

(D.16)

where $V_{O,Max1}$ and $V_{O,Max2}$ are estimated from (D.3) based on the two peak voltages generated from the series alternating coil connections. The charge on the capacitor $\Delta Q$, is estimated from:

$$\Delta Q = \int \frac{2\pi}{2\theta} \times dt + \int \frac{\pi}{2\theta} \times dt + \int \frac{2\pi}{2\theta} \times dt + \int \frac{3\pi}{2\theta} \times dt$$

(D.17)

After integration the solution simplifies to:

$$\left[ \frac{V_{pk1} \times \cos \phi - 2 \times V_D}{R_{load}} \right] \times \left[ T - \frac{2\pi}{\omega} \right] \left[ \frac{V_{pk1} \times \cos \phi - 2 \times V_D}{R_{load}} \right] \times \left[ \frac{2\pi}{\omega} \right]
+ N_{DP} \times \left[ \frac{V_{pk1} \times \cos \phi + V_{pk2} \times \cos \phi}{R_s} \right] \times \left[ \frac{2\phi}{\omega} \right] = N_{DP} \times \left[ \frac{2 \times V_{pk1} + 2 \times V_{pk2}}{\omega \times R_s} \right] \times \sin \phi$$

(D.18)

with the discharge time estimated from:

$$T_D = \left[ T - \frac{[(2 \times \pi) + (2 \times N_{DP} \times \phi)]}{\omega_{fw}} \right]$$

(D.19)

where $N_{DP}$ are the number of different peaks involved in the voltage achieved by the series alternating connected coils. $N_{DP}$ is equal to 2 on this occasion for the 3 coil generator.

The minimum voltage is calculated from (5.19). The capacitance required for the FWR filter can be calculated using (5.20) adjusting for the new discharge time. An investigation was carried out to identify where maximum DC power occurs with a
Appendix D: Full Wave Rectifier – Analytical Model

FWR consisting of a 0.14 F output capacitor. A series of different loads were attached to the output and the maximum average power was found as detailed in Figure D.3 and Figure D.4. This was also carried out with a FWR simulation model in Pspice and compared to the analytical model using (5.19), (5.21), (D.3), (D.14) and (D.15) Using the solver tool from Microsoft Excel the value of $\phi$ can be calculated due to any variable changes in (D.14), and using this value of $\phi$ on each occasion the new value of maximum output voltage can be calculated from (D.3). Both models compare well for all generator source voltage parameters.

**Figure D.3:** Single Magnet Movement FWR Filter – Voltage and Power Vs Load (a) Single Coil (b) Parallel Coils

**Figure D.4:** Single Magnet Movement FWR Filter – Voltage and Power Vs Load – Series Alternating Coils

The analytical models perform well against the simulated models and provide a good representation of the FWR filter for all types of generator source pulses. Maximum power on this occasion is achieved with loads of $\sim 200 \, \Omega$ (corresponding to
0.431 V and 0.927 mW) and ~75 Ω (corresponding to 0.455 V and 2.76 mW) for the single coil and parallel coils respectively, while a much larger ~400 Ω load resistance (corresponding to 0.841 V and 1.77 mW) is required for the series alternating coil pulse.

Any generator source pulse can now be analysed using (5.19), (5.21), (5.22), (D.3) (D.14), (D.15), (D.18) and (D.19) and a full wave rectified DC output can be predicted where the influence of the filter capacitor and load resistance can be quickly visualised using the created analytical models. The double magnet movement was also considered for the 3 coil generator coil connections passed through the FWR, and results are presented in Chapter 5.
Appendix E - Quadrupler – Analytical Model

The output voltage of the quadrupler circuit seen in Figure 5.13 can be visualised by the diagram in Figure E.1 with each capacitor charge occurring each time the diodes on the positive and negative input cycles are turned on with discharge through the load occurring once they are switched off. Due to voltage divider action between the source impedance and load resistance, the output voltage is lower than the source voltage in this case as shown in Figure E.1. The voltage is charging across an approximately symmetrical time period centered around the maximum of the source voltage pulse, where on this occasion the voltage on capacitors $C_1$, $C_2$, $C_3$ and $C_4$ are all added together. The overall output voltage $V_o$ can be visualised as the summation of the of these capacitor voltages as displayed in Figure E.1.

If the single coil source pulse is initially investigated, instead of the full wave rectified DC voltage pulses, the output voltage will charge and discharge due to the output RC filter. There are much larger discharge times, similar to the rectifier circuits, due to the nature of the generator source voltage pulse, but as with the FWR there are two rectified pulses (both positive and negative). To enable efficient mathematical modelling, the voltage waveform induced on each generator coil is assumed to be a periodic discontinuous function, consisting of a sinusoidal pulse having a peak value, $V_{\text{peak}}$, and a frequency, $\omega_{P_w} = 2\pi/P_w$, over one sinusoidal pulse, $P_w$, followed by zero volts over the remainder of the period $T$ (walking period). With this source pulse the quadrupler DC output voltage can be visualised by combining Figure E.1 for the charging portion of the output voltage and Figure 5.6 without the third pulse which illustrates the discharge time. Because it is a full wave rectifying quadrupler that is being considered, the other full wave rectified pulses are again considered to estimate number of charge pulses that are presented to the RC of the quadrupler for the two connected coil generator pulses.

Figure E.1 represents more accurately the time scale of how the capacitor is charged and discharged each time the diode is turned off or on by the generator single coil pulse. The following analysis will focus on a generator single coil source pulse of 5 V Pk-Pk at 1 Hz and the generator impedance parameters described previously as well as the PMEG2010EH diode. Performing basic analysis including Kirchhoff’s voltage and current laws [219] the capacitor currents can be calculated. Firstly
Appendix E: Quadrupler – Analytical Model

calculate the loop around the whole circuit as detailed in Figure 5.13 where source inductance is ignored in this case due to the low frequency of the source. Let the function $\phi$ represent the angle of charge on either side of the center of the rectified source pulse. Consider first, the loop in the circuit including $C_4$ when diode $D_4$ is ON, i.e. $V_{in}$ is negative.

The voltage $V_{c2}$ across capacitor $C_2$ when diode $D_2$ is ON, i.e. $V_{in}$ is positive is then estimated from:

$$v_{C_2}(t) = v_{in}(t) - R_s \times i_s(t) - V_{D_3} + v_{C_4}(t)$$

$$(\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi)$$ (E.2)

The next loop around the circuit when $D_3$ is ON ($V_{in}$ is positive) is described as:

$$v_{C_3}(t) = v_{in}(t) - R_s \times i_s(t) - V_{D_3}$$

$$(\pi / 2 - \phi) < \omega_{pu} < (\pi / 2 + \phi)$$ (E.3)

The voltage $V_{c1}$ across capacitor $C_1$ when diode $D_1$ is ON, i.e. $V_{in}$ is negative is then estimated from:

$$v_{C_1}(t) = v_{in}(t) - R_s \times i_s(t) - V_{D_1} + v_{C_3}(t)$$

$$(\pi + \pi / 2 - \phi) < \omega_{pu} t < (\pi + \pi / 2 + \phi)$$ (E.4)

If all loops are considered and combined then the overall circuit formula becomes:

$$v_{C_4}(t) + v_{C_2}(t) + v_{C_3}(t) + v_{C_2}(t) - v_o(t) = 0$$ (E.5)

giving

$$4 \times v_{in}(t) - 4 \times (R_s \times i_s(t)) - 4 \times V_D - v_o(t) = 0$$ (E.6)

The current flowing in the circuit is:

$$i_{c3}(t) = i_{c1}(t) + i_o(t), \ (\pi / 2 - \phi) < \omega_{pu} t < (\pi / 2 + \phi)$$

$$i_{c4}(t) = i_{c2}(t) + i_o(t), \ (\pi + \pi / 2 - \phi) < \omega_{pu} t < (\pi + \pi / 2 + \phi)$$ (E.7)

Thus:
Appendix E: Quadrupler – Analytical Model

\[ i_s(t) = i_{c1}(t) + i_{c2}(t) + i_o(t) = i_{c1}(t) + i_{c2}(t) + i_o(t) + i_o(t) = 2 \times \left(i_{c1}(t) + i_o(t)\right) \]

\[ (\pi / 2 - \phi) < \omega_p \cdot t < (\pi / 2 + \phi) \quad \text{(E.8)} \]

and

\[ i_s(t) = i_{c2}(t) + i_{c1}(t) + i_o(t) = i_{c1}(t) + i_{c2}(t) + i_o(t) + i_o(t) = 2 \times \left(i_{c2}(t) + i_o(t)\right) \]

\[ (\pi + \pi / 2 - \phi) < \omega_p < (\pi + \pi / 2 + \phi) \quad \text{(E.9)} \]

where \( i_{c1}(t) \) at \((\pi / 2 - \phi) < \omega_p < (\pi / 2 + \phi)\) is equal to \( i_{c2}(t) \) at \((\pi + \pi / 2 - \phi) < \omega_p < (\pi + \pi / 2 + \phi)\)

Combining (E.6), (E.8) and (E.9):

\[
4 \times v_v(t) - 4 \times V_p - v_o(t) = 4 \times R_s \times \left(2 \times C \times \frac{dv_{c1}(t)}{dt}\right) + 4 \times R_s \times 2 \times \frac{v_v(t)}{R_{\text{Load}}} = 8 \times R_s \times \left(C \times \frac{dv_{c1}(t)}{dt} + \frac{v_v(t)}{R_{\text{Load}}}\right)
\]

\[
\frac{4 \times v_v(t) - 4 \times V_D - v_o(t)}{8 \times R_s} = C \times \frac{dv_{c1}(t)}{dt} + \frac{v_v(t)}{R_{\text{Load}}}
\]

(E.10)

The capacitor current can then be calculated from:

\[
i_{c1}(t) = \frac{4 \times v_v(t) - 4 \times V_D - v_o(t)}{8 \times R_s} - \frac{v_v(t)}{R_{\text{Load}}}
\]

(E.11)

The total change in capacitor charge during the charging interval is then given as:

\[
\Delta Q_s = \int_{\frac{\pi - \phi}{2 \omega_p}}^{\frac{\pi + \phi}{2 \omega_p}} i_{c3}(t)dt + \int_{\frac{\pi - \phi}{2 \omega_p}}^{\frac{\pi + \phi}{2 \omega_p}} i_{c4}(t)dt + \int_{\frac{\pi - \phi}{2 \omega_p}}^{\frac{\pi + \phi}{2 \omega_p}} i_{c2}(t)dt + \int_{\frac{\pi - \phi}{2 \omega_p}}^{\frac{\pi + \phi}{2 \omega_p}} i_{c1}(t)dt
\]

\[
= 4 \times \int_{\frac{\pi - \phi}{2 \omega_p}}^{\frac{\pi + \phi}{2 \omega_p}} \left[4 \times V_p \times \text{Sin} \left(\omega_p \cdot t\right) - 4 \times V_D - V_{O\text{-Max}}\right] \times \frac{V_{O\text{-Max}}}{R_{\text{Load}}} \times dt
\]

(E.12)

The maximum output voltage can be calculated by:

\[
4 \times v_v(t) = v_o(t) + 4 \times V_D
\]

(E.13)
Thus the overall maximum output voltage is calculated by:

\[
V_{O_{\text{Max}}} = 4 \times V_{P_k} \times \cos \phi - 4 \times V_D
\]  
(E.14)

**Figure E.1:** Charging and Discharging of Quadrupler Capacitor Voltages  
(a) Output Voltage  
(b) \(V_{C_1}\) and \(V_{C_3}\)  
(c) \(V_{C_2}\) and \(V_{C_4}\)

A closer look at the output voltage waveform, shown in Figure E.1 will aid in calculating the output capacitor current during charging and discharging. The separate charging and discharging occurring at capacitors \(C_3\) and \(C_4\) are achieved concurrently, as visualised in Figure 5.13. These voltages that are firstly established on \(C_3\) and \(C_4\) will eventually contribute to the voltages across capacitors \(C_1\) and \(C_2\). Hence the overall voltages charging and discharging across capacitors \(C_1\) and \(C_2\) is similar to that described for the doubler circuit (charging and discharging on the capacitors on their own could be compared to that of a half-wave filter with the overall voltage established across capacitor \(C_1\) comparable to that described for a full-
Appendix E: Quadrupler – Analytical Model

wave filter), but with the addition of voltages already established in $C_3$ and $C_4$. The overall result of charge over the two cycles can be calculated from the charge current equal to the discharge current and using similar basic equations identified in (5.13) the discharge current can be calculated from:

$$\Delta Q = 2 \times \begin{bmatrix} \int \frac{x - \phi}{\omega_p} \frac{V_{O\text{-Max}}}{R_{Load}} dt + \int \frac{x + \phi}{\omega_p} \frac{V_{O\text{-Max}}}{R_{Load}} dt \end{bmatrix}$$

(E.15)

Overall the charge on the output capacitor is:

$$Q = 2 \times \begin{bmatrix} \int i_C(t) \times \phi \times \omega_p \times \frac{4 \times V_p \times \sin(\omega_p t) - 4 \times V_D - V_{O\text{-Max}}}{8 \times R_S} \frac{V_{O\text{-Max}}}{R_{Load}} \times dt \end{bmatrix} = 4 \times \begin{bmatrix} \frac{V_{O\text{-Max}}}{R_{Load}} \times \left( T - \frac{2 \phi}{\omega_p} \right) \end{bmatrix}$$

(E.16)

Expanding with what is already known to be the capacitor current by combing (E.12) and (E.16):

$$Q = 4 \times \begin{bmatrix} \int \frac{x - \phi}{\omega_p} \frac{4 \times V_p \times \sin(\omega_p t) - 4 \times V_D - V_{O\text{-Max}}}{8 \times R_S} \frac{V_{O\text{-Max}}}{R_{Load}} \times dt \end{bmatrix} = 4 \times \begin{bmatrix} \frac{V_{O\text{-Max}}}{R_{Load}} \times \left( T - \frac{2 \phi}{\omega_p} \right) \end{bmatrix}$$

(E.17)

After integration the final charge on the capacitor is estimated from:

$$\begin{bmatrix} \frac{V_{O\text{-Max}}}{R_{Load}} \end{bmatrix} \times [4 \times T] + 4 \times \begin{bmatrix} \frac{V_{O\text{-Max}} + 4 \times V_D}{8 \times R_S} \times \frac{2 \phi}{\omega_p} \end{bmatrix} = 4 \times \begin{bmatrix} \frac{8 \times V_p}{\omega_p \times R_S \times 8} \times \sin \phi \end{bmatrix}$$

(E.18)

Inputting the expression already estimated for output voltage from (E.14):

$$\begin{bmatrix} \frac{4 \times V_p \times \cos \phi - 4 \times V_D}{R_{Load}} \end{bmatrix} \times [4 \times T] + 4 \times \begin{bmatrix} \frac{V_p \times \cos \phi}{R_S} \times \frac{\phi}{\omega_p} \end{bmatrix} = 4 \times \begin{bmatrix} \frac{V_p}{\omega_p \times R_S} \times \sin \phi \end{bmatrix}$$

(E.19)

When compared to the doubler capacitor charge/discharge equations calculated in (5.30), it is clear that the diode voltage drop increases from $2 \times V_D$ to
Appendix E: Quadrupler – Analytical Model

4 × V_D, and the discharge term is again set to \([T - 2\phi / \omega_{pu}]\) similar to the doubler. The discharge time for a voltage quadrupler circuit can be estimated from (5.18). With this circuit however the term \(2 × V_{pk} × \cos \phi\) is now doubled to \(4 × V_{pk} × \cos \phi\). The first \([2\phi / \omega_{pu}]\) term in (5.61) is now decreased to \([\phi / \omega_{pu}]\), and the final \(2 × V_{pk}\) is reduced to \(V_{pk}\). The minimum voltage is calculated as before from (5.19) and the capacitance needed for the quadrupler is calculated using (5.20).

Through analysis similar to that carried out for the generator source pulses passing through the filter (and doubler) circuits and combining it with the quadrupler formula already established for a single coil source voltage a general formula can be defined for the quadrupler for the generator source pulses. Combining (5.30), (5.61), (E.12), (E.13), and (E.19), a new formula for the quadrupler non-sinusoidal generator source pulses can be defined as:

\[
\left[\frac{4 × V_{PL,AVG} × \cos \phi - 4 × V_D}{R_{load}}\right] × [N_c × T] + 2 × N_{RP} × \left[\frac{V_{PL,AVG} × \cos \phi}{R_p} × \left[\frac{\phi}{\omega_{pu}}\right]\right] = N_{RP} × \left[\frac{V_{PL,AVG}}{\omega_{pu} × R_p}\right] × \sin \phi
\] (E.20)

With the 3 coil generator parallel full wave rectified output there are two instances where more than one pulse charging the RC load at the same times as seen in Figure E.1, this is also the case with the quadrupler. The discharge time on this occasion is estimated from:

\[
T_D = \left(\frac{N_c × T}{\omega_{pu} × [N_c × N_{RP} × \phi]}\right)
\] (E.21)

Analysing the quadrupler with respect to the generator source pulses is similar to the FWR and doubler circuits, where \(N_{RP}\) is the same. However \(N_C\) (number of capacitor charges) is increased to 4 on this occasion and the \(4 × V_{pk} × \cos \phi\) does have to be considered and is the main difference between the quadrupler and doubler circuits. In terms of the series alternating connected coils a further formula can be generated from (E.12) and (E.15) whereby the two separate source peak voltages are considered. On this occasion there are four instances of rectified voltages. This corresponds to discharge of the capacitor \(ΔQ_c\), being estimated from:
Appendix E: Quadrupler – Analytical Model

\[
\Delta Q_v = 2 \times \left[ \int \frac{V_{O,\text{Max}2}}{R_{\text{Load}}} \times dt + \int \frac{V_{O,\text{Max}1}}{R_{\text{Load}}} \times dt + \int \frac{V_{O,\text{Max}1}}{R_{\text{Load}}} \times dt + \int \frac{V_{O,\text{Max}2}}{R_{\text{Load}}} \times dt \right]
\]

(E.22)

where \( V_{O,\text{Max}1} \) and \( V_{O,\text{Max}2} \) are estimated from (E.14) based on the two peak voltages generated from the series alternating coil connections. The charge on the capacitor \( \Delta Q_v \), is estimated from:

\[
\Delta Q_v = \int i_c(t) \times dt + \int i_c(t) \times dt + \int i_c(t) \times dt + \int i_c(t) \times dt
\]

(E.23)

After integration the solution simplifies to:

\[
\left[ \frac{4 \times V_{Pk1} \times \cos \phi - 4 \times V_D}{R_{\text{Load}}} \right] \times \left[ N_{DP} \times T \right] + \left[ \frac{4 \times V_{Pk1} \times \cos \phi - 4 \times V_D}{R_{\text{Load}}} \right] \times \left[ N_{DP} \times T \right] + N_C \times \left[ \frac{V_{Pk1} \times \cos \phi + V_{Pk2} \times \cos \phi}{R_S} \right] \times \left[ \frac{\phi}{\omega_{Pv}} \right] = N_C \times \left[ \frac{V_{Pk1} + V_{Pk2}}{\omega_{Pv} \times R_S} \right] \times \sin \phi
\]

(E.24)

with the discharge time estimated from:

\[
T_D = \left( N_{DP} \times T - \left[ \frac{2 \times N_C \times \phi}{\omega_{Pv}} \right] \right)
\]

(E.25)

A further investigation was carried out to identify where maximum DC power occurs with a quadrupler consisting of a 0.1 F output capacitor. A series of different loads were attached to the output and the maximum average power was found as depicted in Figure E.2 and Figure E.3. This was carried out with a quadrupler simulation model in Pspice and compared to the analytical model. The value of \( \phi \) can be calculated using the solver tool from Microsoft Excel for any variable changes in (E.20), and using this value of \( \phi \) on each occasion the new value of maximum output voltage can be calculated from (E.14). These analytical models for the quadrupler as well as (5.20), (5.21), (D.15), (E.14), (E.20), (E.21), (E.24), (E.25) can be used to
Appendix E: Quadrupler – Analytical Model

predict the quadrupler DC performance of each of the generator source pulses under varying load conditions.

![Figure E.2: Singe Magnet Movement Quadrupler – Voltage and Power Vs Load (a) Single Coil (b) Parallel Coils](image)

![Figure E.3: Singe Magnet Movement Quadrupler – Voltage and Power Vs Load – Series Alternating Coils](image)

The analytical models perform well against the simulated models and a good representation of the quadrupler is achieved for all types of generator source pulses. Maximum power was achieved with loads of ~3000 Ω (corresponding to 2.18 V and 1.59 mW) and ~1000 Ω (corresponding to 2.18 V and 4.75 mW) for the single coil and parallel coils respectively while a much larger ~6000 Ω (corresponding to 3.42 V and 2.34 mW) load resistance is required for the series alternating coil pulse. As with the other conversion circuits the double magnet movement was also considered for the 3 coil generator coil connections passed through the quadrupler and these results are presented in chapter 5.
Appendix F: Synchronous Rectification

Appendix F - Synchronous Rectification

The following analysis is initially generated through Pspice and is based on the 3 coil generator with a 0.25 mm wire diameter. Figure F.1 illustrates how the doubler can achieve synchronous rectification whereby the two diodes are now replaced with two MOSFETs. For simplicity the circuit presented describes the single source series alternating connected 3 coil generator. Initially for an accurate assessment of MOSFETs performance, the source voltage is a constant AC source with the actual 2.881 V series alternating Pk-pk voltage induced by the coil.

Figure F.2 compares the doubler output voltage and power with the various types of MOSFETs combinations and illustrates the maximum result achievable. The PMEG2010EH [209] diode which was established in Chapter 5 to provide maximum results was also included as a comparison. In the new design maximum efficiency is achieved by replacing the upper diode with a P-type MOSFET while the lower diode was replaced with an N-type MOSFET. The output voltage achieved with the 1500 Ω load (for demonstration) was increased from 4.31 V (with 2 PMEG2010EH [209] diodes) to 4.59V (with the upper P-Fet and Lower N-Fet) which corresponds to a 6.4 % improvement. All other MOSFET combinations yielded results that are lower than those already achieved with the two PMEG2010EH diodes. If the parallel coil peak voltage of 1.5 V is considered then under the same conditions, the output voltage would vary from 2.1025 V with the PMEG2010EH diodes to 2.395 V with the MOSFETs. This corresponds to a 12.2 % improvement, highlighting that output
voltage with MOSFETs increases with decreasing source voltage. The MOSFET improved results are achieved due to the low $R_{ds\text{ON}}$, which along with the current drawn by the load defines the voltage drop across the MOSFET.

Figure F.2 Voltage Doubler with Synchronous Rectification – MOSFET Combination vs Diodes

Figure F.3 demonstrates the input and output waveforms associated with a sinusoidal source voltage (representing the generator) passed through a voltage doubler circuit with MOSFETS, as well as the $V_{GS}$ voltages required to turn on and off the MOSFETS. The output voltage from a doubler with PMEG2010EH diodes is also presented to illustrate the improvement found with MOSFETS. Here the single supply comparator is powered by an external supply set to 4.5 V. The results demonstrate the 6.4 % difference between diodes and MOSFETS described earlier in this section.

Figure F.3 Voltage Synchronous Rectification vs. Diode Waveforms
Appendix F: Synchronous Rectification

The doubler synchronous rectification model was established for a sinusoidal source voltage, the following section describes how this model performs with the actual generator source voltages. Analysis is carried out in Pspice with all comparator and MOSFET models provided by the manufacturers [231].

**7.1.1.1 MOSFET Gate Driver – Comparator**

The most important aspect of incorporating synchronous rectification in the AC/DC conversion circuits described in this chapter is how to turn on and off the MOSFETs. The simplest option would be to incorporate a standard low power single supply comparator, whereby the inverting and non-inverting inputs would be connected so that a low signal would be achieved to turn on the P-Fet while a high signal would be achieved for the N-Fet. Figure F.9 illustrates such a circuit with the two comparators set up to drive the upper P-Fet (irf7410 [232]) and the lower N-Fet (irf7476 [233]). In this case the irf7410 P-Fet has a 7 mΩ and 9 mΩ $R_{dsON}$ with a $V_{GS}$ of 4.5 V and 2.5 V respectively, while the irf7476 N-Fet has an 8 mΩ $R_{dsON}$ with a $V_{GS}$ of 4.5 V. With the generator current low, the voltage drop can be greatly reduced with these $R_{dsON}$ values. The comparator chosen for this analysis was the LM2903 [223] from National Semiconductor due to its 400 μA operation current. Obviously there are new comparators on the market with even lower < 100 μA (or even nA) supply current requirements however LM2903 was the most appropriate for our study as it can be readily modelled in Pspice and it is suitable for operations with low power requirements.

The 3 coil parallel generator with a FWR incorporating synchronous rectification can be seen in Figure F.6, while the series alternating coil generator with the same conversion method can be seen in Figure F.5. Figure F.4 demonstrates the generator source voltages that were investigated, as well as the $V_{GS}$ signals that are provided to turn on each of the MOSFETs. In both generator connections, wherever there is a negative source pulse a positive $V_{GS}$ signal is required to turn on the N-Fet, and where there is a positive source pulse a negative $V_{GS}$ signal is required to turn on the P-Fet (as introduced previously).
Appendix F: Synchronous Rectification

Figure F.4: Synchronous Rectification (a) Series Alternating Coil Voltage and Associated $V_{GS}$. (b) Parallel Coil Voltage and Associated $V_{GS}$.

Figure F.5: Series Alternating Coil Generator – FWR with Synchronous Rectification – Comparator
In this analysis the load is varied to demonstrate how efficiency may be influenced by the load resistance. It can also be noted from Figure F.6 and Figure F.5
that the PMEG2010 diodes are also fixed in parallel across the MOSFETS to maintain the efficiency already achieved by the conversion circuits as the \( V_F \) of the MOSFETs own body diode will generally perform poorly when compare to the preferred Schottky diodes. The simulated results are presented under three conditions; the comparator supplied with an external 2 V supply, the comparator supplied with the generator DC output power fed-back and the conversion achieved with the PMEG2010 diodes for comparison. Although the external 2 V supply method is not a true reflection on conversion efficiency it does give a good indication on the maximum efficiency that can be achieved by each method using the same components.

Figure F.7 demonstrates the comparison between all three conversion methods. As illustrated in Figure F.7 when the comparator external supply set to 2 V, the generator output voltage improvement remains relatively constant over the load range for a parallel coil connected generator. However when compared to the PMEG2010EH diode, there is a vast improvement found in output voltage when MOSFETs are used and when an external supply is applied to the comparator. However a more realistic approach would be to feed the output power achieved by the PMEG2010 diodes back to supply the comparators which will in turn switch on the MOSFET gates and reduce the voltage drop from AC to DC. However when the power is fed back from the output there is minimal improvement if any as the 2V/400\( \mu \)A load that each of the comparators requires cancels out the improvements found when the MOSFETs are turned on as seen in Figure F.7. Although the output voltage is lower than the required 2 V the comparator will turn on at a lower voltage, supplying enough voltage to turn on the gate voltages of the MOSFETS. At lower loads the efficiency is slightly less which is due to the nature of the voltage drop across the MOSFET switch; MOSFET Voltage Drop = \( R_{on} \times I \). Thus as load decreases, current increases and so too does the voltage drop across the MOSFET switch.
Appendix F: Synchronous Rectification

Figure F.7: FWR with Synchronous Rectification (0.25 mm Wire diameter) – MOSFETs Combination vs. Diodes – (a) DC Power (b) DC Voltage (c) Efficiency

If the generator wire diameter is reduced corresponding to higher DC output voltage it would be expected that there would be further improvement found when the output power is fed back to supply the comparators. However this is not the case, as demonstrated in Figure F.8 where the MOSFET/Comparator with feedback power does not improve the results provided by the PMEG2010 diodes on their own. Although the gap between the results of the external supply method and the other two methods is reduced (when compared to the results in Figure F.7) this is expected due to the reduced wire diameter which improves conversion efficiency. A similar trend can be seen when the series alternating coil connected generator is considered by applying the external supply comparator/MOSFET, feedback power comparator/MOSFET and PMEG2010 conversion methods similar to the circuit model presented in Figure F.5.
In order to reduce the gap between the external supply method and the power feedback method a comparator with a lower power consumption is required. This can be achieved with either the LMC7225 from National Semiconductor [234] which has a power consumption per channel ~285 times less than the LM2903 [223] or the MAX9060 [235] which has a power consumption per channel of between ~285 and 500 times less than the LM2903 [223].
Similar analysis was carried out on the doubler circuit for both the parallel and series alternating coil connections as detailed in Figure F.9 and Figure F.10 respectively. Initially the parallel coil method is investigated and interestingly the higher output voltage that is being fed back to power the comparators reduced the gap between the PMEG2010 diode performance and the external supply method as seen in Figure F.11.
Appendix F: Synchronous Rectification

Figure F.10: Parallel Coil Generator - Doubler with Synchronous Rectification – Comparator Driver
Appendix F: Synchronous Rectification

When compared to the FWR parallel connected method with a 0.2 mm wire diameter even though both produce output voltage levels around the required 2 V the doubler with the 0.25 mm wire diameter achieves this with a source impedance 3 times less than that of the 0.2 mm coil. A similar trend can be seen when the series alternating coil connected generator is considered by applying the same three conversion methods to the doubler circuit.

Figure F.11: Doubler with Synchronous Rectification (0.25 mm Wire diameter) – MOSFET Combination vs. Diodes – (a) DC Voltage (b) Power (c) Efficiency

Therefore the application of synchronous rectification to the AC/DC conversion circuits can significantly improve output voltage, power and conversion efficiency. Although the improvement is estimated to be minimal with a FWR it is enhanced with lower power consumption comparators. While the doubler can already achieve an improvement of > 5% in conversion efficiency with the current LM2903 design used throughout this analysis, this can also be improved with lower power consumption comparators. The main drawback of this design is the amount of extra
components required to achieve such efficiency and given the space constraints of the environment the generator will be integrated into, it is regarded as unsuitable.

### 7.1.1.2 MOSFET Gate Driver – LMC555

An alternative to the op-amp MOSFET driver would be to exploit the monostable functionality of an LMC555 CMOS timer [224]. Figure F.12 illustrates how such a driver could be integrated with two separate implementations of the monostable function of the LMC555 in order to provide a negative pulse for the upper P-Fet MOSFET and a positive pulse for the lower N-Fet MOSFET.

![Figure F.12: Series Alternating Coil Generator – Doubler with Synchronous Rectification – LMC555 Timer Driver](image)

The advantage of using the CMOS LMC555 Timer is, apart from the fact that it can be powered from ~1.5V supply; it also has a supply current requirement of ~100uA. These values are very suitable for the 3 coil generator DC levels achieved. Synchronous rectification is only advantageous to the generator if the improvement...
found by the lower voltage dropped through MOSFETs in the conversion circuit, is still present when the output is fed back to power either the comparator driver or the CMOS LMC555 timer driver. With the required supply levels described for the LMC555 this could be the case. Secondly, with the use of the monostable function of the LMC555 there is more control on the amount of time the LMC555 driver is turned on (in comparison to the comparator driver), hence more control over the power fed back from the generator output. Therefore, by setting $R_A$ and $C$ correctly the LMC555 timer will only be turned on when the peak of the source voltage is passed through the conversion circuit.

For simplicity the circuit presented in Figure F.12 represents a synchronous rectified doubler sourced by the 3 coil generator connected in series alternating. In monostable mode the “Trigger” and “Threshold” pins are connected to the doubler circuit so that when the generator source pulses are passed through the circuit the LMC555 outputs are turned on or off. The LMC555 has internally generated voltage references which control the output in monostable mode, $1/3 \times V_{cc}$ and $2/3 \times V_{cc}$. The “Trigger” and “Threshold” pins then cause the output to be turned on or off when the voltage on these pins are lower or higher than the internal voltage references.

Figure F.13 illustrates the LMC555 signals including the $2/3$ reference voltage, Trigger, Threshold and output (MOSFET Vgs) voltages for both upper and lower MOSFETs when the series alternating 3 coil connected generator source is applied. When an external supply is applied to power the LMC555 timers an improvement is found in output DC voltage similar to that presented in Figure F.7 and Figure F.11 for a comparator. The design however is much more complex as depending on the load applied the resistors on the threshold and trigger pins need to be adjusted so that the internal reference voltages are achieved by the threshold and trigger voltages and hence the device can be turned on.
The option of the LMC555 timer as the driver for the MOSFETs was also investigated because by selecting $R_A$ and $C$ correctly the output could be controlled and would only be turned on at the very peak of the source voltage pulse, hence requiring less power than the comparator. Although this is achievable, the current required to generate the internal functions (voltage references, etc) of the LMC555 timer as well as driving the output for any length of time, still bring the generator’s output DC voltage below the levels achieved by the PMEG2010EH diodes in the simulated models. However it is expected that in reality the CMOS LMC555 timer will operate at much lower voltage and power consumption than the models and results similar or better to the comparator design can be achieved.
Appendix G: Journal Paper

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Modelling, design, and testing of an electromagnetic power generator optimized for integration into Shoes

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What is This?
Modelling, design, and testing of an electromagnetic power generator optimized for integration into shoes

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Abstract: Modelling and analysis of an electromagnetic generator designed for harvesting power produced during walking is presented. The generator is designed to be unobtrusive to the user by embedding it within the thickness of a normal shoe sole, and by applying a passive generation principle which requires minimal additional force over that normally exerted by the user during walking. In this way, a portion of the power used in walking is harvested for potential use in powering portable electronic devices. Analysis of different geometrical and material properties is applied to identify conditions for optimized designs; average power levels of up to 14 mW (200 mW of instantaneous power) are demonstrated within a volume of $15 \times 15 \times 100 \text{mm}^3$ at a walking speed of 2 steps per second. At least two of these volumes can be easily accommodated within a shoe heel to provide up to a 25 mW average power per user, and higher power levels can be achieved for faster walking or running speeds.

Keywords: energy harvesting, electromagnetic generator, wearable electronics

1 INTRODUCTION

With the increasing use of portable electronic devices for communication, entertainment, sports, and healthcare applications, issues relating to powering of low-power devices have become more significant. Ultimately, these translate to a limited battery lifetime and the associated inconvenience of needing to remove and wait for batteries to recharge. Energy-harvesting solutions have been developed to address these issues, where a range of different operating principles have been applied to convert kinetic energy into useful levels of electrical energy [1, 2]. The design of wearable power generators for generating electrical energy during walking is investigated in this work, where the energy may be supplied directly to portable devices or it may supplement the energy provided by a battery, thereby extending its life. As a first step, optimization of generator structures in terms of the maximum level of AC power output is investigated in this paper.

A range of generator structures has been investigated previously for integration into various personal accessories: e.g. [3–5]. However, previous analyses showed that the maximum potential for harvesting of energy around the body occurs in the feet during walking or running [6], and therefore this work focuses on the design of generators integrated into shoes. Other shoe-integrated generator structures proposed in the literature include those based on pneumatic [7], and piezoelectric and electromagnetic [8–10] principles of operation. While relatively high power levels have been reported for electromagnetic generators, their operation involves significant interference with the user’s normal gait. There are also issues with the reliability of the mechanical components used in these systems. In a bid to address these limitations, the possibility of

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redefining an electromagnetic generator structure specifically for integration into shoes has been proposed, so that power can be harvested passively from users without impacting on their gait [11]. Using the proposed structure, the user does not need to apply any significant additional force over that normally applied during walking. Furthermore, the generator does not involve complicated mechanical components and therefore reliability issues are addressed. Power levels are lower than those produced with more complicated electromechanical structures but they remain comparable with those produced by shoe-integrated piezoelectric generators. The principle of operation of such a structure is reviewed in section 2, along with the mechanical and electromagnetic models used to predict its performance.

Research in electromagnetic energy harvesting is very active with many authors developing new methods for producing miniaturized structures with improved electro-mechanical coupling e.g. [3, 12] and others investigating methods for increasing the operating frequency range of resonant-type structures e.g. [13, 14]. A comprehensive review paper on micro-scale magnetic generators that discusses the issue of scale reduction and the need for developments in magnetic materials and power conversion solutions, in addition to comparing the performance of an extensive range of generator structures has been presented in [15]. However, while some efforts have been made at optimizing the electromagnetic interactions, these are limited in detail. Owing to the passive nature of energy conversion in the proposed structure, generated power levels are relatively low and therefore the generator needs to be optimized in terms of the maximum possible power that can be harvested. For this purpose, analysis of a wide range of generator parameters is provided in section 3, where the effects of several geometrical and material properties are illustrated for normalized generator dimensions. A similar analysis can be applied to generator structures based on the same principle for use in other power-harvesting environments, where larger structures and therefore higher power levels may be generated. Optimization of the generator for integration within a shoe is investigated in section 4 and supporting measurement results are presented in section 5. It is shown that average AC power levels of up to 28 mW per shoe may be achieved during walking with corresponding instantaneous power levels of up to 400 mW. These levels are competitive with those achieved with shoe-integrated piezoelectric generators, and would be sufficient for some sensor applications [8-10]; higher levels can be achieved at faster walking speeds. When compared with typical levels of power generated during walking; e.g. 2-4.5 W/kg at the ankle [16], over 400 W in foot transition [17], it is clear that the energy level produced is a smaller percentage of the user input energy and therefore the corresponding impact on the user’s gait is expected to be minimal. In terms of applications, work is continuing to determine the most efficient AC/DC power conversion scheme for the generator in powering portable devices.

2 SHOE-INTEGRATED GENERATOR MODELLING AND DESIGN

Various shoe-integrated electromagnetic generator structures have been investigated previously by the current authors, and it was found that a higher power is predicted for a magnet sliding through a coil located horizontally in the shoe than with a series of opposing magnets being pushed through vertical coils [11]. While the latter approach is more active in that the user needs to apply a force against opposing magnets, it is found that the scope for magnet movement in the shoe is limited if the normal gait of the user is to be maintained. The basic structure of the alternative inertial sliding-magnet generator is shown in Fig. 1(a); it consists of a disk magnet that is free to slide up and down through a cylindrical coil, similar to those described in [5] and [18]; i.e. there are no springs or other fixtures used to connect between the magnet and the coil or former. In this case, when the coil is fixed horizontally in the shoe sole as shown in Fig 1(b), the pendulum motion of the foot during walking maintains bidirectional movement of the magnet through the coil. It should be noted that so long as the mass of the foot M continuous movement of the magnet is sustained by forces exerted normally by the foot during walking, and there is no significant or deliberate effort needed from the user as in the case of [18]. The application of springs to form a resonant structure as in [5] and [12] was not considered, because the structure is intended to harvest power for a range of walking speeds, which will vary from time to time and from person to person.

2.1 Mechanical analysis

Prediction of the exact force acting on the magnet versus time during walking is difficult because the force exerted by the user varies hugely with walking speed and style. Therefore, the results of measurement performed using an accelerometer attached to the outer heel of a shoe were used to predict the magnet motion. Similar measurements have previously been applied to compare the relative
performance of various inertial generators located at different locations around the body [19]. Results in Fig. 2(a) are typical g-forces exerted for a walking rate of 1.5 steps per second. Positive components of horizontal and vertical acceleration are defined relative to the shoe as indicated. Note that since an accelerometer measures the force acting on a reference mass that is free to move within a package that is in turn fixed to the body under test, the forces shown in Fig. 2(a) may be taken as the actuating forces applied to the magnet. In this case, measured forces include the combination of user-applied forces during walking and gravity; this is seen in results of the offset by 1g of the vertical force component during the stance phase.

Consider the forces applied at the start of a step before toe-off (TO) as indicated in Fig. 2(a) where it is assumed that the magnet is positioned towards the front of the heel. This is verified in photographs 1 and 2 in Fig. 2(b), where the magnet can be seen at the position indicated (by the red arrow) inside a transparent plastic tube attached to the outer side of the shoe. In Fig. 2(a), it is seen that after an initial forward force associated with lifting the heel from the ground, there is a net backward horizontal force (with respect to the shoe) of between 1g and 2g measured as the foot is lifted against gravity after TO. For a coil with an unconnected magnet inside, the corresponding horizontal forces acting on the magnet are shown in Fig. 2(c). These include the actuating force as measured by the accelerometer, $-F_{vm}$ (the minus sign is due to the reference directions defined in Fig. 2(a)) and friction, $F_{f1}$, which depends on the reaction force between the magnet and the coil former acting in the vertical direction (with respect to the shoe), and may be taken as minus the measured component of the vertical force, $F_{vm}$ in Fig. 2(a). Initially, the magnet remains in contact with the shoe but as the foot is lifted after heel-off, $-F_{vm}$ decreases thereby also causing reduced friction, $F_{f1}$. Taking $F_{vm}$ at an average of $0.5 m_{mg}$ during this phase for a magnet mass of $m_m$ and a coefficient of static friction, $\mu_s$, of 0.4 for metal-plastic, the frictional force, $F_{f1}$, is estimated by

$$F_f = \mu_s F_{vm} = 0.5 \mu_s m_m g$$  \hspace{1cm} (1)$$

using a value of 0.2 $m_{mg}$ for the magnet mass, $m$. When compared with a backward actuating force of greater than $1 m_{mg}$ it is clear that the magnet will be propelled backwards relative to the coil. This is seen in photographs 3 and 4 in Fig. 2(b). Magnet motion continues until it reaches the stop end of the coil former, with which it impacts. Estimated results of velocity are included in Fig. 2(b) where the net negative acceleration, $-F_{vm} + 0.4 F_{f1}$ was integrated over time from the instant when $-F_{vm} > 0.4 F_{f1}$. The velocity was reset to zero once the magnet travelled 100 mm, indicating that the magnet was stopped due to impact with the stop end of the coil former.

In a similar manner, forward motion of the magnet can be explained by forces exerted during the swing phase of the foot forward, when the horizontal force, $F_{f2}$, acting at the heel measured in Fig. 2(a) increases between 2g and 3g in the forward direction. In this case, the magnet is starting from the heel end of the shoe (see photographs 5 and 6 in Fig. 2(b)). The corresponding horizontal forces acting on the magnet are the same as previously described; i.e. $F_{f2}$ as measured by the accelerometer and friction, $F_{f2}$ as shown in Fig. 2(d), with a reaction force $-F_{vm}$ acting in the vertical direction. During this phase, it is seen that as $F_{f2}$ first increases from zero, so too does $-F_{vm}$ and estimation of the corresponding frictional force, $F_{f2}$ indicates that it is large enough to prevent magnet motion. Using $\mu_s = 0.4$ as before, with $-F_{vm}$ taken as $2 m_{mg}$ the maximum frictional force is estimated as $0.8 m_{mg}$ versus $F_{f2} = 1 m_{mg}$. However, it is found that
Fig. 2 (a) Measurement results from an accelerometer attached to the shoe heel during walking, (b) photographs of magnet position during different walking phases, (c) magnet forces around TO, and (d) magnet forces during foot swing forward.
just before heel strike (HS), when $F_{\text{magn}}$ is increasing towards a maximum, $-F_{\text{vis}}$, and therefore $F_{\text{vis}}$ both decrease as the heel lifts forward before striking. Taking $-F_{\text{vis}} = 0.5 m_{\text{mag}} g$ and $\mu_s = 0.4$, $F_{\text{vis}}$ is again estimated as $0.2 m_{\text{mag}} g$ acting against a $F_{\text{magn}}$ of over $2m_{\text{mag}} g$ and therefore the magnet slips forward through the coil towards the toe end of the shoe, where it is remains until after the TO phase of the next step. The estimated magnet velocity in Fig. 2a) is slightly higher during this phase due to higher actuating force, and this is confirmed by measurements in section 5.

In a generator structure with an attached load, once the magnet starts moving a current is induced in the coil, and an electromagnetic force, $F_{\text{elec}}$ will act against the motion of the magnet. However, it is shown in section 2.2 that the magnitude of this force is of the order of 0.19 mN or 0.0032 mN$^2$ which is much lower than the forces acting to produce magnet motion in either direction, and therefore it does not significantly impact on the magnet motion. Furthermore, it may be deduced that the associated electromagnetic reaction forces imposed by the moving magnet on the user (through the coil) is negligible when compared with the user-applied forces of several g acting on the mass of the foot and shoe. Future work will investigate the effects on user gait by comparing accelerometer measurements with and without the generator attached.

2.2 Electromagnetic model

Operation of the generator is based on electromagnetic induction, where the movement of one or more magnets through the coil produces a change in magnetic flux linkage. The resultant open-circuit voltage, $v_{oc}(t)$, induced on a coil with $N$ turns may be expressed in terms of instantaneous values of magnetic flux linking with individual turns, $\phi_i(x_i, t)$, located along the length of the coil at $x_i$ as:

$$v_{oc}(t) = \sum_{i=1}^{N} \frac{d\phi_i(x_i, t)}{dt}$$

(2)

For a particular coil and magnet combination such as shown in Fig. 3, $\phi_i(x_i, t)$ may be given in terms of the flux established along the length of the magnet, $\phi_m(x_{m})$, as:

$$\phi_i(x_i, t) = \phi_m \left( \frac{l_i}{2} + x_i - st \right)$$

(3)

where $x_{m}$ is the axial distance from the centre of the magnet, $s$ is the speed of the magnet, $l_i$ is the coil length, and $l_k$ is the starting distance between the centre of the magnet and the end of the coil. Substituting for $\phi_i(x_i, t)$ in terms of $\phi_m(x_{m})$ in equation (1), the instantaneous open-circuit coil voltage may also be given as:

$$v_{oc}(t) = -\left( s + \frac{l_k}{2} \right) \sum_{i=1}^{N} \frac{d\phi_m(x_{m})}{dx_{m}}$$

(4)

where $x_{m}$ varies from $(l_k - st)$ for $i=1$ to $(l_k + l_k - st)$ for $i=N$ at time $t$. In this way, it is seen that calculation of the open-circuit voltage is based largely on the magnetic flux gradient established by the magnet within the coil at any instant.

Assuming that the input force producing relative motion between the magnet and coil is much larger than the electromagnetic damping force, a simple equivalent circuit model of the generator can be applied that consists of a voltage source, $v_{oc}(t)$, with a series resistance and inductance representing the coil impedance. Owing to the low frequency of the generated voltage, the contribution of coil inductance is neglected in this case and equation (4) for open-circuit voltage is applied to predict the maximum available power produced by the generator

$$P_a = \frac{v_{oc}^2 R_c}{(R_c + R_k)^2}$$

where $v_{oc}^2 = \frac{1}{T} \int v_{oc}(t)^2 \, dt$ (5)

and $R_c$ and $R_k$ are the coil and load resistances, respectively. Clearly, as identified for other loosely coupled electromechanical systems the maximum available power is achieved by setting the load resistance equal to the coil resistance [3].

Using equations (4) and (5), it is found that for a given magnet size, irrespective of its velocity, an optimum coil length can be identified for which the product of the average power and peak voltage is maximum. This is found to be equal to the extent of the magnetic flux gradient $\left[d\phi / dx \right]$ from the centre of the magnet along its axial length. The results for the magnetic flux shown in Fig. 4 were predicted using finite element analysis (FEA) simulation [20] at a radius of 6.5 mm parallel to the axis of a $\Phi 10 \times 10$ mm NdFeB disk magnet, with the magnetic flux gradient then being calculated numerically. If the coil
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is longer than the extent of the flux gradient. It is found that there is an increasing time period for which positive and negative components of $\frac{d\psi}{dt}$ act so as to produce voltage cancellation within the coil. For maximum power and voltage, it is required that this period should be minimized, as any additional coil length only contributes to increasing the coil resistance. Taking 10% of the maximum flux gradient to define a cut-off value, it is found that the optimum coil length for the $10 \times 10$ mm magnet of Fig. 4 is 15 mm.

The effect of coil length in terms of voltage is illustrated in Fig. 5(a) and instantaneous power waveforms in Fig. 5(b) predicted for different coils linking with the magnet of Fig. 4 for a constant normalized magnet speed of 1 m/s. In this way, the performance of different generator structures is compared independently of magnet speed, although it will be shown later that 1 m/s is quite accurate for the test structures considered. In all cases, the coil consists of 12 turns of 0.25 mm diameter copper wire per millimetre of coil length. It should be noted that the given structure was applied to confirm the voltage waveforms and power levels predicted, and it is optimized only in terms of coil length.

It is found that up to a certain value, the amplitude of the induced voltage increases with coil length as the magnetic flux linkage increases. For longer coils, the voltage amplitude remains constant, but the separation between positive and negative voltage pulses increases thereby indicating an increasing portion of time for when the net voltage induced is zero. Instantaneous power levels given in Fig. 5(b) are calculated using equation (5) with $R_l = R_e$. It is shown that the largest power is predicted for the shortest coil, which is explained by the lowest coil resistance in this case. Similarly, coil resistance limits power produced by the longest coil, which has the lowest power levels. When averaged over the time taken for one step during walking (0.5 s for a rate of 2 steps per second), it is found that the 10 mm coil produces the highest average power of 1.46 mW, while in terms of combined peak-peak voltage and average power, the optimum coil length is found to be 15 mm.

In order to verify the assumption of a low electromagnetic damping force, results of the force exerted on a 15 mm coil length by a $10 \times 10$ mm NdFeB disk magnet as it moves through the coil are presented in Fig. 6. These results were calculated using FEA for a normalized ampere-turns product of 1 A

![Graph showing electromagnetic force vs. position](image)

**Fig. 6** Electromagnetic force produced on a 15 mm coil carrying 1 ampere-turns due to a magnet velocity of 1 m/s

![Graph showing open-circuit voltage and power waveforms](image)

**Fig. 5** (a) Open-circuit voltage and (b) instantaneous power waveforms predicted for a $10 \times 10$ mm magnet sliding through different coil lengths
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in the coil. Taking a peak voltage of 0.65 V predicted for a 15 mm coil in Fig. 4(a) with a coil resistance of 2.55 Ω for 180 turns of 0.25 mm diameter wire, a corresponding peak ampere-turns value of 49.5 Ampere-turns is found. This translates to a peak electromagnetic damping force of 0.19 mN or 0.0075 g for a 0.0039 kg magnet mass. Clearly, this is much lower than the actuating force acting on the magnet described in section 2.1. Furthermore, given the condition \( M < \alpha \), it is clear that the electromagnetic force is much lower than the applied user forces and therefore the impact of electromagnetic generation would be expected to be minimal on the user’s gait.

If the length of space available to accommodate the generator is much longer than the optimum coil length, several coils of optimum length can be applied. To address the low voltage levels generated, previous work has investigated connecting successive coils in series opposition [11]. However, the output power is limited by the series resistance of multiply connected coils in this case. It is found that, assuming the coils have separate and ideal rectifier circuits, a parallel coil connection provides the highest output power, as current only flows in a given coil when it has a voltage induced on it. Where relevant, this assumption will be made in the remainder of this paper.

3 PARAMETER ANALYSIS AND OPTIMIZATION

The relative effects of all parameters of a sliding magnet generator designed to fit within the thickness of a shoe heel (~20 mm) are investigated in this section. Normalized results of peak-peak voltage and average power per unit generator length are presented for the simplest case of one magnet and one coil. Results are then applied to define optimum magnet and coil combinations for a given generator length (100 mm in this case) in section 4. Variable parameters include magnet dimensions: \( d_{er} \) and \( l_{er} \) and coil dimensions: \( d_{co} \), \( d_{co} \) and \( l_c \) as shown in Fig. 3. The effect of wire diameter is also investigated, where a diameter of 0.25 mm is assumed otherwise. In all cases, the optimum coil length is set equal to the extent of magnetic flux gradient (to 10 percent of its maximum value) as calculated at a radius 1 mm larger than the magnet radius.

The open-circuit voltage is calculated using equation (4) and the magnet is assumed to move at a constant normalized speed of 1 m/s. Finally, the load resistance is set equal to the coil resistance.

3.1 Effect of magnet diameter

Within a fixed generator volume, the cross-sectional area is divided largely between magnet area, \( \pi d_{er}^2 / 4 \), and coil area, \( \pi (d_{co}^2 - d_{co}^2) / 4 \), as shown in Fig. 3. The effect of increasing coil depth at the expense of decreasing magnet diameter is investigated in this case. Results of average output power per unit coil length versus magnet diameter are given for different generator diameters in Fig. 7(a), while corresponding results of peak-peak voltage per coil length are compared in Fig. 7(b). In all cases, the length and diameter of the magnet are equal (to within 1 mm) so that the magnet retains its axial orientation as it slides through the coil. Normalization of the results with respect to the coil length in this case allows the results to be applied to define optimized designs in section 4.

From Fig. 7(a), it is clear that for a given generator size, there is an optimum magnet diameter that provides maximum output power per coil length. Analysis of the results shows that this optimum point is found when the cross-sectional area of the magnet equals that of the coil in each case

\[
\pi r_m^2 = \pi (r_t^2 - r_m^2) \quad \text{or} \quad r_m = r_t / \sqrt{2}
\]

(6)

Obviously, a small portion of the generator area is taken up by a coil former, but this does not impact

![Fig. 7: (a) Output power and (b) peak-peak voltage versus magnet diameter](image-url)

---

of power and voltage per unit length are presented as a function of magnet length in Fig. 9 for the optimum magnet diameter in generator diameters of 15 and 20 mm. As shown, power per unit length increases with magnet length, however, due to a decreasing flux gradient the rate of increase levels off for longer magnets. This poses the question of whether it is better to use one long magnet instead of several shorter magnets in a given generator space, which is investigated in detail in section 4. For peak-peak voltage levels, it is interesting to see that the graph levels off when the magnet length equals half the generator diameter in both cases.

3.3 Effect of magnet strength

Results presented up to this point are based on the lowest grade of NdFeB: 30H. The level of improvement that can be achieved by using higher material grades is illustrated in Fig. 10. The generator diameter is 15 mm with a $\Phi 10 \times 10$ mm magnet and 15 mm coil length in all cases. Clearly, the power per unit length may be increased by using different magnet grades; an increase of up to 75 per cent over grade 30H is achieved with grade G48, with a corresponding increase in voltage of approximately 30 per cent. However, the increase in force produced by higher grade magnets will limit the number of generator structures that can be integrated closely together within a given space.

4 OPTIMIZATION FOR A GIVEN SPACE

In this section, the results of section 3 are applied to predict the maximum power that can be generated within a volume of $15 \times 15 \times 100$ mm$^3$, which can be accommodated within the heel of a shoe sole. Generators with single and multiple magnets are considered in turn.

4.1 Single magnet

In Fig. 7, it is shown that the optimum magnet diameter for a given generator cross-sectional area is given by $d_m \approx r_{m1}/\sqrt{2}$; i.e. a magnet diameter of 10.6 mm is optimum for the given area of $15 \times 15$ mm$^2$. The closest available standard magnet has a diameter of 10 mm. Clearly, the length of the space under consideration is much longer than the magnet diameter, so that the question of optimum magnet length arises. Results in Fig. 9(a) indicate that the power per coil length increases with increasing magnet length, thereby suggesting the use of the longest magnet that can be accommodated. However, it should be noted that in addition to the
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Fig. 9 (a) Power and (b) peak-peak voltage per unit length versus magnet length

Fig. 10 (a) Power and (b) peak-peak voltage per unit length versus magnet grade

The length of the coil, \( l_c \), and magnet, \( l_m \), entry and exit distances between the magnet and coil (2\( l_0 \)) must also be accommodated in the given generator space as shown in Fig. 3. For maximum power, it is found that a minimum value of \( l_0 = l_c/2 \) is required, thereby reducing the length of available space for fitting generator coils by \( l_c \). For this reason, it is found that it is more effective to use several shorter coils (corresponding to a shorter magnet) wound one after another, as shown in Fig. 11, rather than one longer magnet.

For an \( n \)-coil generator the maximum coil length, \( l_m \), that can be fitted within a total generator length of \( l_{tot} \) is given by

\[
l_{tot} = l_m + 2l_0 + nl_c = l_m + (n + 1)l_c
\]

with \( l_0 = l_c/2 \). Remembering that an optimum value of \( L \) can be defined for a given magnet dimension, equation (6) can be applied to define a range of generator designs with an increasing number of coils. The relationship between the optimum coil length and magnet dimensions is shown for three disk magnet diameters in Fig. 12, where it is clear that the relationship is linear. Results were produced

Fig. 11 Multiple coil generator cross-section (across length)

Fig. 12 Optimum generator coil length versus magnet length
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Table 1 Dimensions of test generators fitted into the 15 x 15 x 100 mm$^3$ area

<table>
<thead>
<tr>
<th>N</th>
<th>l_m</th>
<th>l_c</th>
<th>l_gmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>40</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>27.5</td>
<td>24</td>
<td>99.5</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>17</td>
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<tr>
<td>5</td>
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</tr>
<tr>
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<td>7.5</td>
<td>13</td>
<td>98.5</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>12</td>
<td>101</td>
</tr>
</tbody>
</table>

using FEA simulation of the flux distribution at a radial distance of 1 mm from the magnets in all cases. For the generator volume of 15 x 15 x 100 mm$^3$ being investigated, the relationship between $l_c$ and $l_m$ for a 10 mm magnet diameter is found by linear regression as

$$l_c = 0.52l_m + 9.50$$  \hspace{1cm} (8)

where $l_c$ and $l_m$ are in millimetres. Substituting for $l_c$ in equation (7), the range of coil designs given in Table 1 is defined for $l_{gmax} = 100$ mm. In order to coincide with standard magnet sizes, $l_m$ is rounded to 2.5 mm, and $l_c$ to the nearest millimetre.

FEA results on the magnetic flux distribution were applied to predict voltage and power levels produced by the different generator designs as before. In all cases, coils were assumed to be connected in parallel to a matched load through ideal full-wave rectifier circuits, so that maximum power is provided. Results of average power and peak-peak voltage are compared for three magnet diameters in Fig. 13.

It is seen that a maximum average power of almost 8 mW is predicted for three coils connected in parallel, which is over twice that predicted for one large coil filling the same space. Analysis of these results shows that maximum power designs are found simply for magnets whose product of power per coil length and total coil length that can be accommodated within the given space is at a maximum; i.e. the results of Fig. 9 can be applied directly along with equations (7) and (8) to predict maximum power designs. As expected, maximum power is achieved with a magnet diameter of 10 mm in this case.

Plots of peak-peak voltage show a decrease in voltage with increasing number of coils, which is expected as the length of individual coils reduces. Higher peak-peak voltage for smaller diameter magnets is explained by the combination of higher flux gradient and larger number of coil turns. As noted in section 3, voltage levels can be tuned for different applications by changing the coil wire size used.

4.2 Multiple magnets

Up to this point, all results are based on a single magnet travelling through the coil. The effect of adding several magnets within the generator length is investigated here, where the case of opposing magnet poles is considered. In order to prevent cancellation of voltages within a given coil, it is found that the minimum magnet separation should be $2l_c$ as illustrated for the case of a five-coil, two-magnet generator in Fig. 14. Practically, this separation may be provided by a non-magnetic spacer.

Voltage and power levels produced by the generator are predicted by applying equations (4) and (5) for each magnet and coil combination, and adding total contributions. Clearly, the overall number of voltage pulses produced increases with increasing

---

Fig. 13 (a) Average power and (b) peak-peak voltage versus number of coil sections in 15 x 15 x 100 mm$^3$
5 MEASUREMENTS

In order to verify the design guidelines proposed, a series of measurements was performed on three test generator structures as described in Table 2. All coils were wound using 0.25 mm diameter wire on a custom polytetrafluoroethylene (PTFE) former with a thickness of 1 mm and an inner diameter of 10.5 mm. The magnets were stopped by a piece of PTFE that was glued to cover the circular opening of the cylindrical former at each end.

A photograph of the three and four-coil generators is given in Fig. 1(b). As shown, the generators were located under the insole of a shoe at the heel, the internal plastic was hollowed out to accommodate the generators and a layer of foam was applied before replacing the insole so as to minimize discomfort to the wearer. Two generator structures were tested at a time for an approximate walking speed of 2 steps/second. A portable oscilloscope was used to capture the voltage waveforms at the generator coil terminals for different loads. For each design, the generator was tested with coils connected in parallel to individual loads, and connected in series opposition to a single load. For illustration, load voltages measured on the central coils of the three and five-coil generators are shown in Fig. 17 for the case of one sliding magnet and matched load.

<table>
<thead>
<tr>
<th>Number of coils</th>
<th>( L_{o} ) (mm)</th>
<th>( L_{c} ) (mm)</th>
<th>Number of turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>20</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>15</td>
<td>340</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>15</td>
<td>360</td>
</tr>
</tbody>
</table>
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Two sets of pulses are shown within a 2s time interval in both cases, confirming a walking speed of 2 steps/second. It is seen that the amplitude of the second half of each pulse is larger than the first, illustrating how the magnet speed increases as it travels through the coil. As might be expected, the voltage amplitudes and pulse durations are smallest for the shortest coil (smallest magnet), while the opposite is generally true for the longest coil. Given that measurements were performed for the same walking conditions as assumed in the calculations, the match with predicted voltages presented in Fig. 13(b) confirms the assumption of an average magnet speed of 1 m/s. In terms of power, voltages on individual coils were measured for a range of load resistors and corresponding average power levels were calculated using equation (5). The total power for each generator was found by summing the power levels for each of its coils. Results are compared in Fig. 18.

It is seen that the highest power is measured for the three-coil generator, which corresponds to predictions. In this case, the power level is higher than predicted, and this is most likely explained by instantaneous magnet speeds of greater than 1 m/s. Maximum power is found around a load resistance of 10 Ω in all three cases, as this is the closest test value to the coil resistances (9.0, 8.0, and 7.0 Ω for the three-, four-, and five-coil generators, respectively). Voltage waveforms were applied to predict corresponding levels of instantaneous power; up to 200 mW was measured for each coil of the three-coil generator, whereas levels of 130 and 60 mW were more typical of coils in the four- and five-coil generators, respectively. It should be noted that for parts of the waveforms, instantaneous power levels are doubled in each generator due to simultaneous contributions from two successive coils.

Measured voltages for both cases of parallel and series opposition coil connections are compared for the three-coil generator in Fig. 19. Clearly, voltages on successive coils overlap somewhat for the parallel coils in Fig. 19(a), and increasing magnet speed can be seen in terms of increasing voltage pulse amplitudes as the magnet progresses in each direction. As expected, voltage amplitudes are larger when the coils are connected in series opposition in Fig. 19(b), while the total number of pulses is smaller than for parallel coils. Corresponding average power levels were calculated for the different coil connections as before, and it was found that the maximum power achieved with the parallel coils is approximately twice that measured for the series opposition connection. As explained in section 2, this is caused by current flowing through coils when there is no voltage induced on them for part of the magnet travel time.
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The measured performance of coils with two sliding magnets is illustrated in Fig. 20, where voltages on the central coils of the four- and five-coil generators are presented for matched load conditions. The additional pulses produced are evident, as are higher voltage amplitudes for the larger magnet (four-coil) case. Average power levels were deduced from measurements of voltages under different load conditions as before, and results are compared in Fig. 21.

In the case of the four-coil generator, it is seen that average power levels measured with two magnets are lower than that achieved with one magnet when the coils are connected in parallel. This contradicts predictions which were based on an assumption of a constant magnet speed (of 1 m/s). However, due to the combined effects of reduced scope for magnet travel and increased moving mass, the speed the magnets in the two-magnet case is lower than that of a single magnet. This may be seen by comparing voltage waveforms for the five-coil generator in Figs 17 and 20, which have the same time period between pulses, but the distance travelled in the case of the two-magnet case is lower. The effect is less significant in the case of the five-coil generator, where the magnet size and separation are both smaller, so that power levels for one and two-magnet cases coincide.

It is interesting to see that power levels for the series opposition connections are improved by the
addition of a magnet in both cases. The improvement is attributed to the increased level of coincidence between voltage pulses on successive coils than produced with a single magnet, as may be seen in Fig. 15. Notwithstanding this, overall it may be concluded that the highest power level is achieved with one magnet travelling through parallel coils, each of which is connected to a matched load. In this case, the optimum generator design according to Fig. 18 is the same as that predicted: i.e. a three-coil generator with a 10 mm magnet.

6 CONCLUSIONS AND FUTURE WORK

The design of an electromagnetic generator for integration within the heel of a person’s shoe is described, along with a method for optimizing its structure to provide maximum output power. The generator harvests power passively from the user without the need for significant additional force over that normally applied during walking. Therefore, while power levels are low, there is potential to produce sufficient energy for many portable applications by generating power over relatively long time scales compared to power consumption periods, as required by wireless sensors for example.

Analysis of generator performance in terms of different geometric and material parameters is presented to illustrate the relative effects of different generator designs. Results are normalized so that they can be applied to design similar generators for a range of application environments and generator sizes. The main findings show that in order to achieve maximum output power, there is an optimum coil length for a given magnet size and an optimum magnet diameter for a given total generator diameter. Effects of wire size, magnet length, and magnet grade are also determined.

Results of parameter analysis are applied to design an optimized generator structure to fit within a given space defined by the heel of the shoe. Multiple coils, multiple magnets, and various coil connections are considered. It is shown through models and measurements that the highest power is achieved by using one magnet and several coils connected in parallel to a load that matches the coil resistance. The highest power level demonstrated in a 15 x 15 x 100 mm³ space is an average of 14 mW and an instantaneous value of 200 mW for walking speeds. These levels compare favourably with the power produced by piezoelectric generators in the shoe heel, while the proposed structure is more amenable to integration in the shoe than other electromagnetic generators proposed.

Significantly higher output power will be achieved for faster walking speeds or running, where the combination of higher magnet speed and increased voltage pulses per second will contribute to increasing instantaneous and average power levels, respectively. Also, it should be noted that there is space to accommodate at least two generator units of size 15 x 15 x 100 mm³ within the heel of a shoe, so that the total average power per person could be as high as 56 mW for walking speeds. Work is ongoing to investigate AC/DC conversion schemes for the generator voltages, so that the power can be applied to supply portable electronic devices or to charge reusable batteries. The scope for application of the generators is also being investigated, including such areas as sports monitoring and biomedical applications. Larger generator structures are also being considered for environments with larger potential forces and space.
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