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<th>Optimisation of a Hybrid Energy Storage System for Autonomous Photovoltaic Applications</th>
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Optimisation of a Hybrid Energy Storage System for Autonomous Photovoltaic Applications

Margaret Glavin
B.E., National University of Ireland, Galway

Submitted in Fulfilment of the Requirement for the Degree of Doctor of Philosophy at the National University of Ireland, Galway

September 2012

Electrical and Electronic Engineering Department
College of Engineering and Informatics

Supervisor: Prof. W.G. Hurley
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Finally, I thank my family and friends for all their support and encouragement throughout the last few years.
DECLARATION

This Thesis is submitted to the National University of Ireland, Galway in partial fulfilment of the requirements for the doctorate of philosophy and has not been submitted as an exercise for a degree at any other university.

____________________________________
Margaret Glavin
ABSTRACT

As the world’s population grows and becomes more dependent on technology the demand for energy increases. Alongside the increasing energy demand there is a reduction in the availability of natural resources. The production of energy from fossil fuels has environmental implications, which has lead policymakers throughout the world put clean energy targets in place. Solar energy as a clean technology can be employed to meet these targets.

Due to the nature of solar energy, autonomous photovoltaic (PV) systems require an energy buffer to match the generation with the time distribution of demand. Generally the most common storage technology utilised is the Valve Regulated Lead Acid (VRLA) battery, because of its low cost, maturity, and wide availability. PV panels are not an ideal source for battery charging; the output is unreliable and heavily dependent on weather conditions. Therefore, an optimum charge/discharge cycle cannot be guaranteed.

The demand profile experienced by the PV system also influences the battery storage. Some load applications require high power for a short period of time, for example the operation of devices which involves starting motors. VRLA batteries in this situation are large in order to deal with the high power requirement.

To overcome these issues a combination of VRLA batteries and ultracapacitors in a Hybrid Energy Storage System (HESS), which increases the power density of the overall system, is developed. Operating the ultracapacitor bank under high power conditions reduces the strain of large current extraction from the battery bank. The addition of the ultracapacitor bank presents the need for a methodology to optimise the PV system in order to prevent excess battery storage.

A methodology to optimise the PV system ensures the demand can be met, while preventing an excessively large and expensive energy storage system. The optimisation process takes into account the solar radiation at the system location and the demand profile over the course of a year.
# NOMENCLATURE

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<tbody>
<tr>
<td>AGM</td>
<td>Absorbed Glass Mat</td>
</tr>
<tr>
<td>Ah</td>
<td>Battery rated capacitance</td>
</tr>
<tr>
<td>$Ah_{Cap}$</td>
<td>Nominal battery capacity</td>
</tr>
<tr>
<td>$Ah_{peuk}$</td>
<td>Peukert’s adjusted battery capacity</td>
</tr>
<tr>
<td>ARV</td>
<td>Array Reconnect Voltage</td>
</tr>
<tr>
<td>ASPO</td>
<td>Association for the Study of Peak Oil and Gas</td>
</tr>
<tr>
<td>$b_0, b_1, b_2, b_3, b_4$</td>
<td>Coefficients</td>
</tr>
<tr>
<td>Batt_{Float}</td>
<td>Float life of the battery</td>
</tr>
<tr>
<td>Batt_{Replace}</td>
<td>Number of battery replacements during system lifetime</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
</tr>
<tr>
<td>C</td>
<td>Conductance</td>
</tr>
<tr>
<td>$C_{B1}$</td>
<td>Battery Capacitance representing the charge in the double layer</td>
</tr>
<tr>
<td>$C_{BatDisRated}$</td>
<td>Battery rated capacity at the discharge rate (Ah)</td>
</tr>
<tr>
<td>$C_{Cap}$</td>
<td>Nominal ultracapacitor capacitance</td>
</tr>
<tr>
<td>$C_{CapReq}$</td>
<td>Required capacitance of the ultracapacitor bank</td>
</tr>
<tr>
<td>$C_{capital}$</td>
<td>Component capital cost</td>
</tr>
<tr>
<td>$C_{UcapR}$</td>
<td>Ultracapacitor rated capacitance</td>
</tr>
<tr>
<td>$C_{replacement}$</td>
<td>Component replacement cost</td>
</tr>
<tr>
<td>$C_{maintenance}$</td>
<td>Component maintenance cost</td>
</tr>
<tr>
<td>CCM</td>
<td>Continuous conduction mode</td>
</tr>
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</table>
D    Duty ratio

DayInadChar Number of consecutive days the battery is not recharged

DOA     Days of Autonomy

EBatt   Available battery energy

ECap    Energy requirement of the ultracapacitor (J)

EIA     Energy International Association

EMS     Energy Management System

EPR     Equivalent Parallel Resistance

ESR     Equivalent Series Resistance

EV      Electric Vehicle

FKL     Clearness factor

G       Solar radiation (W/m\(^2\))

G\(_{NOCT}\) Solar radiation at NOCT (W/m\(^2\))

G\(_{ref}\) Reference solar radiation (W/m\(^2\))

GSM     Global System for Mobile Communication

H       Battery Rated discharge time (Hours)

H\(_{BH}\) Beam radiation on a horizontal plane (W/m\(^2\))

H\(_{BT}\) Beam radiation on a tilted plane (W/m\(^2\))

H\(_{DH}\) Diffuse horizontal surface radiation (W/m\(^2\))

H\(_{DT}\) Diffuse tilt surface radiation (W/m\(^2\))

HESS    Hybrid Energy Storage System
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>$H_{\text{Gh}}$</td>
<td>Global horizontal surface radiation ($W/m^2$)</td>
</tr>
<tr>
<td>$H_{\text{GTeff}}$</td>
<td>Total effective global radiation on tilted PV panel</td>
</tr>
<tr>
<td>$H_{\text{RT}}$</td>
<td>Reflected radiation on a tilted plane ($W/m^2$)</td>
</tr>
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<td>HOGA</td>
<td>Hybrid Renewable Optimisation by Generic Algorithms</td>
</tr>
<tr>
<td>I</td>
<td>Actual discharge current (A)</td>
</tr>
<tr>
<td>IAM</td>
<td>Incident Angle Modifier</td>
</tr>
<tr>
<td>IAM$_B$</td>
<td>Incident Angle Modifier for beam radiation</td>
</tr>
<tr>
<td>IAM$_D$</td>
<td>Incident Angle Modifier for diffuse radiation</td>
</tr>
<tr>
<td>IAM$_R$</td>
<td>Incident Angle Modifier for ground reflected radiation</td>
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<tr>
<td>$i_{\text{Batt}}$</td>
<td>Battery current (A)</td>
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</tr>
<tr>
<td>IC</td>
<td>Intermittent Charging</td>
</tr>
<tr>
<td>ICC</td>
<td>Interrupt Charge Control</td>
</tr>
<tr>
<td>ICM</td>
<td>Incremental Conductance Method</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Diode current of the PV cell circuit model</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>INSEL</td>
<td>Integrated Simulation Environmental Language</td>
</tr>
<tr>
<td>$I_0$</td>
<td>PV output current (A)</td>
</tr>
<tr>
<td>$I_{\text{ph}}$</td>
<td>Photocurrent (A)</td>
</tr>
<tr>
<td>$i_{\text{pv}}$</td>
<td>Instantaneous PV current (A)</td>
</tr>
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</table>
IPv: PV Current (A)
Isat: Saturation current (A)
Reference conditions are given by the manufacturers as 25°C and solar radiation level of 1000W/m² (A)
k: Boltzmann’s constant (J/K°)
ke: Battery V_{emf} voltage vs SOC
kp: Peukert’s constant
kv: Capacitance representing the voltage dependence of the ultracapacitor
LOLE: Loss of Load Expectation
LOLP: Loss of Load Probability
LPSP: Loss of Power Supply Probability
LRV: Load Reconnect Voltage
LVD: Low Voltage Disconnect
MaxDailyDischar: Maximum energy discharged from the battery in one day
MPP: Maximum Power Point
MPPT: Maximum Power Point Tracking
n: Ideality factor of diode
NBattPar: Number of parallel batteries
NBattSer: Number of series batteries
NCapPar: Number of parallel ultracapacitors
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$N_{\text{CapSer}}$</td>
<td>Number of series ultracapacitors</td>
</tr>
<tr>
<td>NOCT</td>
<td>Nominal operating cell temperature (°C)</td>
</tr>
<tr>
<td>NPC</td>
<td>Nett Present Cost</td>
</tr>
<tr>
<td>$N_{\text{PVmax}}$</td>
<td>Max number of PV panels</td>
</tr>
<tr>
<td>$N_{\text{PVmin}}$</td>
<td>Min number of PV panels</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of PV cells connected in series</td>
</tr>
<tr>
<td>Other</td>
<td>Equipment not include as a decision variable in the optimisation</td>
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<tr>
<td>$P_{\text{Load}}$</td>
<td>Load power</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>Perturb and Observe</td>
</tr>
<tr>
<td>$P_{\text{PV}}$</td>
<td>PV panel output power</td>
</tr>
<tr>
<td>$p_{\text{PV}}$</td>
<td>Instantaneous PV power</td>
</tr>
<tr>
<td>$P_{\text{PVMax}}$</td>
<td>Maximum PV power from a fixed PV panel at Optimum tilt angle</td>
</tr>
<tr>
<td>$P_{\text{Storage}}$</td>
<td>Storage power</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulator</td>
</tr>
<tr>
<td>$q$</td>
<td>Electron charge (C)</td>
</tr>
<tr>
<td>$Q_{\text{tot}}$</td>
<td>Total ultracapacitor charge</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Battery ohmic resistance</td>
</tr>
<tr>
<td>$R_1$</td>
<td>Battery resistance representing the charge transfer energy loss</td>
</tr>
<tr>
<td>$r_{\text{in}}$</td>
<td>MPPT Buck converter input impedance</td>
</tr>
</tbody>
</table>
\( R_l \)  
MPPT Buck converter load resistance

\( R_p \)  
PV parallel resistance, representing the leakage current of the cell P-N junction

\( R_s \)  
PV series resistance, representing the cells internal resistance

\( R_{\beta} \)  
Geometric factor

\( \text{SAIDI} \)  
System Average Interruption Duration Index

\( \text{SAM} \)  
System Advisor Model

\( \text{SOC} \)  
State of Charge

\( \text{SOC}_{\text{init}} \)  
Initial battery SOC

\( \text{SOC}_{\text{Limit}} \)  
Battery SOC limit

\( \text{SOH} \)  
State of Health

\( t_1 \)  
1\textsuperscript{st} point on ultracapacitor charge phase (approx 1.2V)

\( t_2 \)  
2\textsuperscript{nd} point on ultracapacitor charge phase (approx 2.3V)

\( t_3 \)  
Start time of the initial ultracapacitor self discharge

\( t_4 \)  
End time of the ultracapacitor self discharge phase

\( T \)  
Optimisation horizon

\( T_a \)  
Ambient temperature (°C)

\( T_{a\text{NOCT}} \)  
Ambient temperature at NOCT (°C)

\( T_B \)  
Actual battery discharge time (Hours)

\( t_c \)  
Ultracapacitor charge time

\( T_{\text{cell}} \)  
PV cell temperature (°C)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput&lt;sub&gt;life&lt;/sub&gt;</td>
<td>Calculated energy throughput of the battery before failure</td>
</tr>
<tr>
<td>Throughput&lt;sub&gt;year&lt;/sub&gt;</td>
<td>Actual energy throughput for a year</td>
</tr>
<tr>
<td>T&lt;sub&gt;ref&lt;/sub&gt;</td>
<td>PV cell reference temperature (°C)</td>
</tr>
<tr>
<td>TSC</td>
<td>Three Stage Charging</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptable Power Supply</td>
</tr>
<tr>
<td>V&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Ultracapacitor voltage at t&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Ultracapacitor voltage at t&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;2f&lt;/sub&gt;</td>
<td>Ultracapacitor voltage at τ&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Ultracapacitor initial self discharge voltage at t&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Ultracapacitor final self discharge voltage at t&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>V&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Maximum ultracapacitor operating voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Minimum ultracapacitor operating voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;Batt&lt;/sub&gt;</td>
<td>Battery rated voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;cap&lt;/sub&gt;</td>
<td>Ultracapacitor voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;emf&lt;/sub&gt;</td>
<td>Battery EMF Voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;emfmin&lt;/sub&gt;</td>
<td>V&lt;sub&gt;emf&lt;/sub&gt; at zero SOC</td>
</tr>
<tr>
<td>V&lt;sub&gt;o&lt;/sub&gt;</td>
<td>PV output voltage (V)</td>
</tr>
<tr>
<td>V&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>PV open circuit voltage (V)</td>
</tr>
<tr>
<td>v&lt;sub&gt;pV&lt;/sub&gt;</td>
<td>Instantaneous PV voltage</td>
</tr>
<tr>
<td>V&lt;sub&gt;ocref&lt;/sub&gt;</td>
<td>PV open circuit voltage at standard operating conditions (V)</td>
</tr>
<tr>
<td>V&lt;sub&gt;Sys&lt;/sub&gt;</td>
<td>System operating voltage</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>VR</td>
<td>Voltage Regulation</td>
</tr>
<tr>
<td>VRLA</td>
<td>Valve Regulated Lead Acid</td>
</tr>
<tr>
<td>VT</td>
<td>Battery terminal voltage</td>
</tr>
<tr>
<td>$\alpha_{sc}$</td>
<td>Short circuit current temperature coefficient (%/°C)</td>
</tr>
<tr>
<td>$\alpha_{voc}$</td>
<td>PV module open circuit voltage temperature coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td>PV panel tilt angle (°)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Ground reflection coefficient</td>
</tr>
<tr>
<td>$\tau_{c2}$</td>
<td>Ultracapacitor 2nd branch time constant</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Angle of incidence (°)</td>
</tr>
<tr>
<td>$\Theta_{eff}$</td>
<td>Effective angle of incidence (°)</td>
</tr>
<tr>
<td>$\Theta_b$</td>
<td>Beam effective angle of incidence (°)</td>
</tr>
<tr>
<td>$\Theta_d$</td>
<td>Diffuse effective angle of incidence (°)</td>
</tr>
<tr>
<td>$\Theta_r$</td>
<td>Reflective effective angle of incidence (°)</td>
</tr>
<tr>
<td>$\Theta_Z$</td>
<td>Solar zenith angle (°)</td>
</tr>
<tr>
<td>$\Delta C$</td>
<td>Incremental Conductance</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>Change in ultracapacitor voltage when load turned on/off</td>
</tr>
<tr>
<td>$\Delta I$</td>
<td>Change in ultracapacitor current when load turned on/off</td>
</tr>
</tbody>
</table>
CHAPTER 1.
TECHNICAL REVIEW AND OBJECTIVES

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that."

*Thomas Edison (1847 – 1931)*

The world's population continues to grow, with increased reliance on technology, resulting in an increase in the demand for energy as shown in Figure 1.1[1].

Currently the main source of energy is from finite resources such as coal, oil and natural gas. The world's resources of fossil fuel are declining, with the ability to produce high quality, cheap and economically extractable oil on demand shortly running out. According to the Association for the Study of Peak Oil and Gas (ASPO) the peak in oil will occur in the early 21st century. The peak in global oil field discovery occurred in the 1960's and since the mid 1980's oil companies have been producing more oil than they have been discovering [2]. The utilisation of fossil fuels is also harmful to the environment. When fossil fuels are burned to produce energy they emit greenhouse gases, carbon dioxide and sulphur dioxide. The release of these gases into the atmosphere is contributing to climate change and the production of acid rain. The emission of certain greenhouse gases also has a harmful effect on the ozone layer, which is being depleted [3].

The increase in energy demand, the decline in fossil fuel resources, along with the environmental issues involved with burning fossil fuels has increased the need for alternative energy resources. Renewable resources that will not diminish from their utilisation include sun, wind, earth and water. There has been a growth in the level of research being conducted in the development of technologies to utilise these resources, to obtain the maximum output energy.
Renewable energies are harnessed in different ways in the various regions of the world. The ranges of renewable resources that are being utilised include biomass, geothermal energy, wind power, hydropower and solar energy. Each of these renewable technologies has their advantages and disadvantages. Hydropower and geothermal energy are location specific limiting their utilisation. The development of biomass has had implications on food production, as food crops are displaced to grow crops with a better yield for biomass. Wind turbines require regular maintenance due to moving parts and are not considered aesthetically appealing. Solar power has its disadvantages; however, photovoltaic (PV) panels require minimal maintenance, generate no noise and are being developed to be integrated into building designs. The cost of PV panels is also falling dramatically.

As outlined by Thomas Edison solar energy is a powerful resource, with the earth’s surface receiving a total annual amount of solar energy that is nearly 10,000 times the world’s total primary energy requirement [4]. Significant growth has been seen
by the PV industry in recent years. In 2010 the global installed capacity grew by 17GW from 23GW in 2009 to 40GW in 2010, in 2010 in the EU it was the number one renewable technology in terms of capacity growth. Figure 1.2 outlines the growth that occurred in the PV industry between 2000 and 2010, along with the predicted growth going forward to 2015. Two predicted growth outlooks are included, a moderate outlook and a higher policy driven outlook [5].

The PV panel is an intermittent sustainable energy source whose output is time and weather dependent. There are two forms of PV systems, grid connected and autonomous. In grid connected systems, excess energy can be provided to the electricity grid, at a set Feed in Tariff, with the grid providing the required energy at night and in times of low solar radiation. In this form the PV system does not require any energy storage. The same is not true for autonomous PV system, which requires energy storage to balance the generation and demand.

Standalone PV systems produce power independently of the electricity grid and are most common in remote areas that are outside the reach of the electricity grid, due to the large expense involved in extending the grid. Applications of standalone PV
systems in remote areas include lighthouse operation, remote communication stations, rural housing and water irrigation systems. For rural housing, the development of building integrated PV systems means the cost of the PV can be offset against the cost of the material being replaced, for example the roof tiles. An important consideration when designing standalone PV systems is the use of low energy and energy efficient appliance, to ensure the electricity demand of the building is as low as possible. This will lead to a reduction in the PV system cost. Figure 1.3 illustrates the topology of a typical standalone PV system incorporating a PV panel, regulator, energy storage system, and load.

![Figure 1-3 Standalone PV system topology](image)

A number of different technologies can be utilised for energy storage in PV systems, the Valve Regulated Lead Acid (VRLA) battery being the most common choice. The influence of combining an ultracapacitor with the battery bank in a hybrid system for pulse and peak current loads is assessed in this work. When designing the standalone PV system it is important that the system is optimised to ensure that the load can be maintained to the system specifications.

This chapter reviews the failures incurred by batteries in autonomous PV systems and the advantages of including an ultracapacitor in combination with the battery. A number of optimisation programs for PV systems currently exist; these programs are compared, to obtain their advantages and disadvantages. Finally an evaluation of the control systems for autonomous PV systems is performed. PV systems adopt a control system to monitor the state of the storage system, the load requirement
and the output power from the PV panels, to control the power flow throughout the system.

1.1. **Lead Acid Battery Failures**

Energy storage is an important part of an autonomous PV system. Generally lead acid batteries are the most common storage technology, due to their wide availability, low cost, and low maintenance. PV panels are not ideal for battery charging since they are time and weather dependent. An optimum charge/discharge strategy cannot be guaranteed resulting in poor battery life. Therefore, the batteries are regularly replaced making them the main contributor to the system lifetime cost [6].

K. Nakamura et al [7] inspected the failure modes of VRLA batteries. The reduced cycle life of the battery is regularly attributed to the deterioration of the battery positive plate. K. Nakamura found that problems also arise with the negative plate, separator, and other parts in electric vehicles (EV) and uninterruptible power supplies (UPS). In EV applications it was found that lignin, an additive in the negative electrode, decays at high temperatures reducing the battery capacity. In a hybrid electric vehicle (HEV) the batteries are charged with high currents, operated in a partial state of Charge (SOC) and receive irregular charging. A result of this operation is a build up of lead sulphate on the negative electrode, reducing the capacity of the electrode. Increasing the amount of carbon in the electrode reduces the amount of lead sulphate accrued. In UPS applications the battery capacity is reduced for high discharge rates, due to increased internal resistance. The internal resistance is increase with poor contact between the plates and the separator, due to separator shrinkage. Separator shrinkage is caused by consumption of the electrolyte.
T. Hund [8] investigated capacity loss in PV batteries. Long term electrolyte stratification was found to cause negative plate deterioration. At the bottom of the plate the active material was removed due to high concentration on acid in the electrolyte. This can be common in PV batteries as the recharge process can be cut short and adequate gassing to mix the electrolyte does not take place. Gas bubbles on the negative plate due to differences in plate activity also leads to reduced capacity. Excessive sulphation occurs in batteries due to extended periods in an undercharge state, low specific gravity of the electrolyte and high temperature operation. It was found that premature capacity loss also occurred as a result of positive active mass degradation.

A. Jossen [9] investigated the operating conditions of batteries in PV applications. The failure modes of the batteries where highlighted as stratification, sulphation, corrosion, erosion, short circuits, reverse charging and low/high temperature operation.

1. Stratification affects the operating characteristics of the battery, reduces the battery capacity, and causes other forms of aging to occur.

2. Sulphation is caused by extended periods of low battery SOC. Increased sulphation occurs at the lower part of the electrodes due to stratification and eventually this region of the electrodes become unusable.

3. Corrosion of the lead grid occurs due to high positive potential at the positive electrodes. The cross section of the grid is decreased, increasing the grid resistance. A layer of lead oxides and sulphates is formed between the grid and the active material, increasing the contact resistance. These result in an increased ohmic voltage drop.

4. Erosion is the result of loosening of the active material of the electrodes due to mechanical loads incurred during cycling operation. The loosened material can be separated from the electrode and collected as sludge at the
base of the battery. If the volume of the sludge is large it can result in a short circuit of the electrodes.

5. Short circuits can also occur from the growth of dendrites from the positive to the negative electrode through the separator. Prolonged time at a low SOC, low acid concentration, increases the dendrites growth rate.

6. Reverse charging of a single cell can occur when a cell within the string has a lower capacity and becomes overcharged.

7. Oxidation of additives to the lead sponge of the negative electrode results in large lead crystals forming on the negative electrode resulting in the loss of internal surface area and capacity.

8. Ice formation prevents battery operation and can also damage the battery casing while high temperature reduces battery lifetime. Increasing battery temperature accelerates corrosion, sulphation, gassing, and self discharge.

Incorrect sizing and poor battery management can lead to overcharging of the PV battery in periods of high solar radiation. G.P. Corey [10] examined battery utilisation and premature battery failure. It was found that overcharging can result in warping and possibly shorting of the battery grids. Excessive gassing can result in dry-out, active material shedding and there is a risk of thermal runaway. High discharge rates result in increased temperature. Expansion of the grids due to the increased temperature can lead to active material shedding. Battery capacity is also reduced when operated at low temperatures. Corey also highlighted the importance of choosing the correct battery for the required application either power or energy.
1.2. Hybrid Battery Ultracapacitor Energy Storage

As seen in Section 1.1 the system load profile and operating conditions influences the battery life. Standalone PV system can be employed to power telecommunication stations or for water irrigation in remote locations, requiring pulse and peak power respectively. Pulse and peak power applications can require large battery banks and reduce the operating life of the battery. The impact of a battery storage system compared to a battery ultracapacitor HESS has been examined in the literature for various applications.

G. Sikha and B.N. Popov [11] examined the effect of operating parameters on a Li-ion battery compared to a hybrid of the battery and an ultracapacitor under a pulse power load. It was found that the duty cycle had an impact on the increase in discharge capacity for the hybrid system. The discharge capacity of the hybrid system was higher compared to the battery at lower duty ratios, less than 0.4. The hybrid system has a lower effective resistance compared to the battery storage. This results in a decreased ohmic drop leading to better utilisation of the battery. The polarisation drop was also found to reduce in the hybrid system, since lower currents are passed through the battery in the hybrid configuration. These lead to increased run time of the battery bank in the system.

R.A. Dougal et al [12] analytically explored the power and life extension of a battery in an ultracapacitor passive hybrid system, with a pulse load of 5A, 1Hz, and a duty cycle of 10%. It was shown that the peak power of the system was increased, the internal losses were reduced and the battery discharge life was extended. The benefits of the hybrid system are increased as the duty cycle is decreased, the pulse frequency is increased and the ultracapacitor equivalent series resistance (ESR) is decreased. Adding ultracapacitors in parallel to increase capacitance reduces the ESR, while adding ultracapacitors in series to increase voltage increases the ESR.

L. Gao et al [13] investigated the power enhancement of an actively controlled Li-ion battery ultracapacitor hybrid system, with a DC-DC converter placed between
the battery and ultracapacitor/ load. Greater specific power and efficiency is achieved by the hybrid system. The current draw from the battery is reduced resulting in lower internal losses and lower temperature operation, benefiting battery life. Investigations were performed for a 30A pulse current load of 0.2Hz with a duty ratio of 10%. Compared to a passive hybrid configuration, the active system was found to have a threefold increase in power capability and an increase of seven times the battery only power capability. Other advantages of the active system include smaller battery current ripple and better output voltage regulation. The passive system had an increased cycle time compared to the active system due to converter losses and ultracapacitor losses as a result of high current discharge.

S. Y. Kan et al [14] studied the utilisation of an ultracapacitor to buffer the energy from the PV panel to the battery and from the battery to the load. When charged from a PV panel the battery can experience fluctuating charging currents and charge interruption. The ultracapacitor buffer is charged quickly from the PV panel, the ultracapacitor then charges the Li-ion battery at a slower rate. The reduced charge current results in a lower battery temperature, reducing capacity fading from high temperature cycling and increase battery lifetime.

D. Cericola et al [15] analysed an ultracapacitor Li-ion hybrid storage system. Two hybrid systems were considered, an internal and external hybrid system. The internal hybrid system utilises a battery electrode and a capacitor electrode in a single cell. According to Cericola the internal hybrid energy is limited by the capacitor electrode, with the power limited by the battery electrode. Therefore, an external hybrid configuration was found to be a better option.

Liu et al [16] models and designs an autonomous PV power plant for a telecommunication relay station with virtual test bed software. The power system includes an ultracapacitor at the load in parallel to the battery to increase the power density. The system was analysed for a 24 hour period for 3 scenarios, yearly average, winter and summer solstice. The importance of optimisation of the
system is observed. The system is optimised for the average profile, with power wasted during the summer solstice and a power shortage occurring during the winter solstice. The addition of the ultracapacitor is shown to reduce the battery current and current ripple. The decrease in battery current reduces the battery internal losses and the cycle life of the battery is increased. Therefore, the addition of the ultracapacitor increases the power capability and efficiency of the system.

A. Kuperman et al [17] performed a review of battery ultracapacitor hybrids for pulsed current loads. It was found that passive, semi active and fully active hybrids provides enhanced performance compared to battery only storage for pulsed loads. Generally batteries are designed to have either high power or high energy characteristics. This paper examined both passive and active hybrid configurations. The Battery Management System (BMS) disconnects the battery bank from the load when its terminal voltage reaches a predefined value. A pulse current discharge resulted in earlier load termination than a constant current discharge with the same average value, because of higher losses and higher terminal voltage drops. In the hybrid system the battery supplies constant current reducing internal \( I^2R \) losses, reducing the battery ripple voltage and terminal voltage dips. The choice of hybrid system can be a trade off between performance, active hybrid and cost and simplicity, passive hybrid.

Holland et al [18] performed experimental characterisation of the power and energy density for a Li-ion battery, ultracapacitor and a parallel Li-ion battery ultracapacitor hybrid under pulse current loads. Ragone plots were used to analyse the system performance. From the system analysis it was found that on a per mass basis the energy and power density of the hybrid system was lower than the battery system. For the battery system at high currents the available energy increases with decreasing duty, while at low currents the available energy was independent of the duty. The hybrid system achieved higher power at a lower cost. There was an increase in the capability of the system to supply large currents and a small increase in the available energy. The analysis was performed with a passive
system, using an active configuration allowing better utilisation of the ultracapacitor energy should further improve the results.

From the literature it can be seen that a hybrid system of ultracapacitors and batteries have improved performance over a battery only system for loads that have a high peak to average power requirement. The battery terminal voltage drop is reduced, increasing the runtime of the system and reducing the battery bank size. The hybrid system performance was analysed but a method to correctly size the combination of the battery and ultracapacitor to prevent excess system cost has not been described.

### 1.3. Optimisation of Autonomous Renewable Systems

The importance of optimisation is increased for standalone renewable energy generators, as the security of a connection to the national grid for backup power is removed. A number of different methods are employed for the optimisation of autonomous intermittent generators. These methods include intuitive, analytic methods and system simulation approaches [19]. This section provides an overview of the optimisation of PV systems as discussed in the literature.

A method of sizing a PV array is described in the IEEE guide for array and battery sizing in standalone PV systems [20]. The number of PV panels required is based on the solar radiation, array to load ratio, system losses and load. If the load is constant the solar radiation for the worst month is used in the calculations. For changing loads the worst case is selected as the month with the lowest array to load ratio. The number of batteries required is determined based on the Days of Autonomy (DOA), assuming no power is supplied by the PV array.

J. Lagorse et al [21] developed an optimisation method for a PV lighting system with hydrogen and battery storage. The proposed methodology uses a two step approach to determine the optimum solution. First a generic algorithm is used to
find a convergence trend; the value obtained from the generic algorithm is used as
the starting point for a simplex algorithm. The optimisation function was set as the
system cost. The parameters considered during the optimisation were PV and fuel
cell power, PV tilt angle, battery capacity and SOC, the starting and stopping fuel
cell and battery SOC. The battery current and voltage were not taken into account
during the process.

B.Y. Ekren and O. Ekren [22] performed simulation based optimisation for a PV
wind system with battery storage for a GSM mobile communication station and for
a domestic profile. The optimisation was performed with various load profiles and
auxiliary energy costs. The simulations and optimisation was performed in the
study with the ARENA and Opt-Quest software. Opt-Quest requires the suggested
maximum and minimum number of components to be entered for the optimisation
to be performed.

H. Yang et al [23] developed a sizing methodology for a standalone hybrid PV wind
system with battery storage utilising a genetic algorithm. The optimisation is
performed taking the Loss of Power Supply Probability (LPSP) and the annualized
cost of the system into account. The methodology outlines the number of PV
panels, batteries and wind turbines along with the tilt angle of the panels and the
height of the wind turbines. The genetic algorithm uses hourly data and
component models to search for the optimum solution. Initial values for each of the
components are required for the optimisation process.

B.S. Borowy and Z.M. Salameh [24] developed a methodology to optimally size the
combination of a battery bank and a PV array in a standalone PV wind hybrid
system. The system is optimised to minimise the system cost for a set load profile
and LPSP utilising hourly data. In the methodology the wind turbine size is set,
with an iterative approach employed to determine the number of batteries and PV
panels required based on the LPSP constraint. The optimisation was performed for
each hour of a typical day in each month.
G.C Seeling-Hochmuth [25] jointly optimised the size and control strategy for hybrid systems, comprising wind, PV, a diesel generator and battery bank. The optimisation was performed using genetic algorithms. The optimisation is performed in two steps, the main algorithm deals with the system sizing while the second sub system deals with the control optimisation. For the selected system size the control limits are adjusted to minimise the objective function subject to operating constraints, for example minimise the system cost. The result of the process is an optimised system configuration and control strategy for the given application and location.

The optimisation methodologies discussed in the literature average the generation and load profiles on an hourly base to determine the component size. The process of using averaged data is satisfactory when the energy requirement is being considered. However the magnitude of the peaks in power is dampened when averaged on an hourly base. Therefore, when considering the effects of peak power on the storage system, shorter time horizons are required to capture the effects of power spikes on the battery voltage.

### 1.4. Industry Utilised Simulation Software

The increased utilisation of renewable energy systems has lead to the development of optimisations programs to find the optimal system configuration for the required load. In addition to the academic optimisation methodologies discussed in the previous section a number of optimisation and simulation programs are commercially available. Some of the programs are developed for multiple renewable energy generators while others are designed specifically for PV systems.

RETscreen clean energy project analysis software is developed and maintained by National Resources Canada with the contribution of numerous experts from governments, industry and academia. The software is free of charge and can be
utilised worldwide. It is based around excel macros and gives a comparison between a base case, typically a conventional generation technology, and a proposed case, the clean energy technology. RETScreen uses meteorological and product data as inputs to determine whether the cost and saving over the project life makes for a good investment. RETScreen contains models for wind energy, small hydro, biomass/waste heat recovery, solar air heating, solar water heating, passive solar heating, PV and ground source heat pump. The chosen model is provided with the setting and site conditions. The Energy model is used to collect information on the chosen technology. A cost, emission, and financial analysis, along with a sensitivity and risk analysis is performed on the base and proposed systems.

The choice of storage in the PV model is limited to batteries. A suggestion is made to the value of the PV array and battery size, and the generator size for a hybrid system. The suggestion is basic with the generator size based on the max AC demand, the battery size is based on the DOA selected by the user as in [20] and the PV array size is selected to ensure the output is greater than 1.2 times the load for all months of the year. Where a generator is utilised the PV array is capped at 75% of the load and is generally 25% of that of a system without a generator. The analysis can be performed up to 50 years with monthly or yearly time steps. The inputs of solar radiation and load are taken as an average daily value for each month of the year [26].

PVSYST software developed at the University of Geneva is utilised to size, simulate and analysis PV systems (grid connected, standalone, pumping and DC grid systems). Similar to [22] PVSYST is a simulation based program, which performs a detailed hourly simulation of the system.

. It contains a 3D CAD modelling environment for analysing the shading effects on the system. A preliminary design option aims to quickly define the general features of the planned PV system and gives an approximate cost evaluation. The system is
evaluated using monthly values and general system characteristics. The preliminary design stage gives the DOA, Loss of Load Probability (LOLP), and system voltages. These values are taken into consideration when designing the final system. In the project design phase a detailed hourly simulation is conducted for different variants to obtain the best solution.

PVSYS T contains an extensive library of PV panels, inverters, solar pumps, batteries and regulators. It uses meteorological data which can be imported from many different sources or by the user. Hourly metrological synthetic files can be generated from monthly values. Different options are available for setting up the load profiles. The loads can be kept constant throughout the year, changed on a monthly/seasonal base, normalised on a monthly basis, or a separate profile for weekdays and weekends both constant throughout the year.

The results are outputted in a full report containing tables and graphs of the outputs, which include the solar radiation on the panel along with shading effects. Various graphs are presented on the system component’s behaviour. The electrical array behaviour under different conditions, partial shading and mismatch, are examined. Real PV system data can be imported into the program for comparison [27].

Integrated Simulation Environmental Language (INSEL) developed at the University of Oldenburg, Germany is a general purpose graphical programming language. It is a modular simulation program used to plan and analysis renewable energy systems. The system structure is developed by connecting individual component blocks together. INSEL contains metrological data, monthly mean solar radiation, temperature, wind speed and air humidity, for 2000 locations worldwide. Stochastic algorithms can be employed to generate hourly data from monthly data. The user can generate source code and import it into the INSEL environment. INSEL provides results on the energy balance and economics of the system being reviewed, but does not perform an optimisation of the system [28].
Hybrid Renewable Optimisation by Genetic Algorithms (HOGA) is a simulation and optimisation program developed at the University of Zaragoza, Spain. The main objective of the optimisation like in [23] and [24] is to minimise the systems Net Present Cost (NPC). Multi-objective optimisation can also be performed where the emissions or unmet load can also be optimised. The program contains component models for PV panels, wind turbines, hydraulic turbines, fuel cells, H₂ tank and electrolyser, batteries, regulators, inverters, rectifiers and non-renewable generator. As well as component optimisation the system control strategies can be optimised, the optimisation of the control strategy was also considered in [25]. The genetic algorithm approach, also utilised in [21], [23] and [25], helps to speed up the process when a large number of possible combinations are available. HOGA can also evaluate all possible combinations during the optimisation using the enumerative method. The simulations are performed on an hourly basis with the values maintained throughout the hour period. The hourly solar radiation can be imported or generated by the software from monthly published data. The minimum and maximum number of the batteries, PV panels and wind turbines connected in parallel needs to be input into the software. Therefore, the user is required to have knowledge of the load requirement and the power generation to select the component values [29].

The System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) is a performance and financial model utilised by people to aid in the decision making process. Grid connected power projects are examined in the software for cost and energy performance. The simulations are performed in hourly steps, with the results presented in tabular or graphical form. This is not optimisation software; it adopts an iterative approach to gain knowledge of the system and refines the parameters [30].

Hybrid2 developed by the University of Massachusetts and NREL is another simulation program for the analysis of hybrid power systems. The system designer can study the operating options of the system based on economics and system
performance. Hybrid2 utilises both time series and statistical approaches to determine the operation of the system. The program adopts a modular structure to help with preparing and performing the simulation and for examining the results. The time step utilised by the program can be set between 5 minutes and 2 hours, 1 hour is typically chosen for long term simulations. Within each time step calculations on the energy generation, load and energy flow are calculated. As in [30] Hybrid2 does not optimise the system; an iterative approach is adopted for component sizing [31].

Homer also developed by NREL is a micro power system simulation and optimisation program for off grid and grid connected systems. The cost and environmental impact of a range of technologies can be evaluated using Homer. The Homer library contains models for PV panels, wind turbines, hydrogen storage, generators, micro turbines, fuel cells and batteries. Homer can synthesize hourly data from average monthly solar radiation or the hourly profiles can be imported. Hourly load profiles are imported into the system design. These inputs are used to perform hourly energy balance calculations for the different system configurations. Simulation results are presented as a list of feasible solutions constructed in order of NPC. Homer allows for sensitivity analysis to be carried out, to examine which factors, for example available resources, have the greatest impact on the system. An iterative approach is adopted to find the optimal system design. During the iteration, the optimisation is performed only for the component sizes entered in the component size table [32].

1.5. Photovoltaic Energy Management

Autonomous PV systems utilise an Energy Management System (EMS) to control the flow of power throughout the system. The EMS is generally responsible for controlling the converters in the system, implementing MPPT, along with the charging/discharging protocol of the storage system.
R. Kaiser [33] investigated the control of battery storage in a PV system. The battery bank was split into multiple battery strings with each of the strings interconnected with switches. The switches are employed to select the strings to be charged/discharge. The operation of the switches is controlled by the BMS based on the SOC and State of Health (SOH) of each string. This arrangement allows greater control over the rate of charge/discharge current applied to the battery strings. The BMS feeds into the overall system management, which decides the number of strings to be connected to the dc bus. A charge and discharge priority list is setup for the individual strings, according to a set of criteria, to aid the selection of strings for charging/discharging. With this arrangement intensive full charges and capacity tests can be performed on individual cells without affecting the normal operation of the system.

M. Uzunoglu et al [34] describes the control procedure implemented for a PV system with a fuel cell ultracapacitor HESS. The PV panel is given priority for supplying power to the load. Excess power is supplied to charge the ultracapacitor until it reaches full SOC at which point the excess power is used to generate hydrogen. Once the limits of the hydrogen storage tank have been attained the excess energy is dumped. A deficit in PV power is supplied by the fuel cell to a predefined limit with the remainder supplied by the ultracapacitor. The ultracapacitor also compensates for the slow response time of the fuel cell.

H. Zhou et al [35] proposed an energy management scheme to actively distribute the power between a high energy battery and a high power ultracapacitor in a PV micro grid. The storage system adopts a modular approach with each of the batteries and ultracapacitors utilising a separate converter. The power management of the system was split into three cases. In the first case the steady state power is provided by the battery with the transient power supplied by the ultracapacitor. The second case deals with the energy management of individual batteries in a string. The discharge current is proportioned between the batteries according to their SOC to prevent one battery having a lower SOC compared to the
others. The weakest battery in the link determines the overall performance of the battery bank. The third case controls the SOC of the ultracapacitor, the ultracapacitor voltage is monitored and the ultracapacitor current is adjusted to maintain the battery within predefined limits. The modular approach utilising a number of converters will increase the initial system cost.

Wang et al [36] proposed an energy management strategy to control a buck boost dc-dc converter for a battery ultracapacitor HESS in a PV system. The PV panel is always operated with MPPT. The buck boost converter is operated in constant voltage mode or current limit mode for the battery, when the current is greater than the maximum battery current. The ultracapacitor operated in constant voltage mode is utilised to minimise small charging/discharging cycles and to filter the output of the PV panel. The buck boost converter employs dual loop control. The outer loop is voltage controlled and stabilises the dc bus voltage. The inner loop is current limit controlled to ensure the battery current is within its operating limits.

A. Moreno et al [37] investigated controlling the load in a standalone PV system to improve reliability, by assigning a priority rating to the various loads, with a fuzzy controller. To determine the required actions, the controller takes into account the available energy, the predicted PV power and load and the priority assigned to the various loads. Assigning priority to the various loads, allowing them to be individually turned off at times of inadequate power has implications on the calculation of the LOLP. A weighted LOLP of the individual loads was introduced to take into account that the load can be partially met at particular times. It was found that the fuzzy controller performed better than a conventional controller, this was more evident when the system was undersized.

J. M. Lujano-Rojas et al [38] developed a load management strategy for a wind turbine system with battery storage and a diesel generator. Predictions of the power from the wind turbines are used to control the load to minimise the energy supplied by the diesel generator and battery bank. Improvements are seen with the
utilisation of the load strategy, controllable loads are moved to times of high wind peaks increasing the battery SOC and reducing the need for the diesel generator. The controllable loads are scheduled for timeslots with high wind power based on hourly forecasts for the next 24 hours. Compared to a system with no load management, the proposed system maintained the battery at a higher SOC and reduced the operating time of the diesel generator.

The battery discharge current has an impact on its SOC and operating time. From the literature a number of EMS’s have been implemented to control the flow of power throughout the system. Improvements are seen in the battery SOC and lifetime by implementing load management were possible. For a HESS an EMS is required to control the power between the different storage elements. An EMS to limit the battery current in a HESS to best utilise an ultracapacitor should be investigated in greater detail to determine the impact of different current limits.

1.6. Research Hypothesis

PV panels are continually improving and becoming more efficient but remain an intermittent power generator. A storage system is required in an autonomous PV system to consistently meet the load requirement. In general, lead acid batteries are the chosen storage technology. As can be seen from the literature PV batteries have a number of failure modes which reduce the battery lifetime, increasing the system cost. The runtime of the battery is also affected by the voltage drop which occurs during high current discharge.

A number of PV power applications require relatively low average power but a relatively high peak power. From the technical review it becomes apparent that combining an ultracapacitor and a battery to form a HESS reduces the strain of high discharge currents from the battery. This results in extended battery runtime and lifetime. The battery SOC limit will have an impact on the effectiveness of the
ultracapacitor in the system; this should be further investigated when comparing a HESS to a system with battery only storage. The system cost difference between a HESS and a battery storage system has not been discussed in the literature. The cost of the storage system will always have an impact on the chosen configuration.

This work focuses on a battery ultracapacitor HESS for PV applications that require high peak to average power or pulse power. A methodology to optimally proportion the combination of batteries and ultracapacitors in the HESS is required to prevent excess system cost and to prevent loss of load. The current optimisation processes are designed for the storage system and do not take into account the impact the tilt angle of the PV panel can have on the system. As seen in the literature current PV optimisation programs average the data on an hourly basis. When the load profile is averaged the peak power requirement of the load is dampened, which may result in an undersized system for peak power requirements.

Other factors can impact the design of the PV system. Limitations may be put on the number of components that can be implemented in the system due to the availability of space, to house the PV panels and the storage system. These limitations warrant further investigation to determine their impact on the system cost and performance. The option to optimise the system to allow non-critical loads to be dropped during extended periods of low solar radiation should be considered when optimising the system to minimise the system lifetime cost.

An EMS is required to control the flow of power in the HESS. The EMS should implement MPPT, monitor each of the components in the system and execute control over the charge/discharge strategy of the storage system. Unlike a battery only storage system the charge/discharge power to/from the HESS must be split between the battery and the ultracapacitor. The priority or ratio of the power split between both components for charging and discharging should be examined to
develop a control strategy that best utilises the available energy and maintains the battery at a high SOC to prevent premature failure to meet the load requirement.

1.7. Proposed Methodology

The motivations for this research may be summarised as follows:

- To develop a new methodology to optimise an autonomous PV system with an ultracapacitor battery HESS, given the solar radiation on a horizontal surface and the load profile. The optimisation program should have a time step capable of capturing fluctuations in the load and solar radiation profiles. Therefore the peak power requirement of the load is taken into consideration when designing the system. The optimisation program should also provide the best orientation for the PV panel to generate the maximum annual power.

- The area available for the PV system being designed maybe limited. The optimisation program is to enable constraints on the components to be implemented. Sensitivity analysis on the component volume and the criticality of the load investigates how these factors affect the system lifetime cost.

- To explore the benefits of including an ultracapacitor in the battery storage element of an autonomous PV system for various load profiles. The optimisation program is utilised to determine the cost saving of the battery ultracapacitor HESS.

- The energy management controller for the complete system is investigated. The Battery SOC limit and the discharge current limit placed on the battery has an effect on the battery life and system lifetime cost. The energy
management controller should ensure that the ultracapacitor is recharged between peaks.

1.8. Thesis Organisation

The optimisation and development of an autonomous PV system with a battery ultracapacitor HESS is the focus of this thesis. The thesis is organised into the following chapters: Chapter 2 describes the components of the PV system and provides models for each of the components. The lead acid battery is compared to the ultracapacitor, to investigate the strengths and weakness of each technology. The different hybrid configurations for the system are explored, to obtain the best arrangement for the system.

Chapter 3 describes the development of a methodology to optimise the standalone PV system. The sampling rate is set to enable the peak power requirements of the load to be taken into account. The program is developed in Matlab to optimise the system for minimum system lifetime cost. The required inputs are the load profile over the optimisation horizon and the solar radiation on a horizontal plane at the site location. The program is developed to allow the component size and the LPSP be considered when designing the system.

Chapter 4 utilises the optimisation methodology developed in Chapter 3 to design a PV system for a peak, pulse and domestic power load. The optimisation horizon was set to a year and the assumptions utilised for the optimisation are presented. The system is optimised using different constraints for component volume and LPSP. The component values obtained from the optimisation program are simulated in a Simulink model for verification, with the results for the battery and ultracapacitor displayed.
Chapter 5 describes the development of an experimental setup to analyse the HESS. The setup is used to assess the impact combining ultracapacitors and batteries in the HESS have over utilising either of the components separately.

Finally, in Chapter 6, the conclusions of this work are outlined and possible scope for future work is presented.
CHAPTER 2.
PHOTOVOLTAIC SYSTEM

Autonomous PV systems are comprised of various elements, PV panels, Maximum Power Point Tracker, converters and energy storage. A range of energy storage components exist to buffer the PV energy, these include flywheels, hydrogen, batteries and ultracapacitors. Each technology has its advantages and disadvantages. A hybrid system combines two or more of these technologies to improve the overall systems operating performance. Figure 2.1 shows an example of an autonomous PV system containing a VRLA battery and ultracapacitor HESS. A number of different hybrid configurations can be employed as discussed in section 2.8.

![Figure 2.1  Autonomous PV system with HESS](image)

This chapter describes the components of the PV system of Figure 2.1 and illustrates the individual models compiled to simulate the system. Both mathematical and electrical component models are utilised in the system design. Also discussed in this chapter are maximum power point trackers and the different hybrid configurations available.
2.1. Photovoltaic Panel

PV panels convert solar radiation into dc electricity using the photoelectric effect. A number of different semiconductor materials are used for the construction of PV panels with different levels of efficiency. A PV model simulates the output power of a particular panel for a given solar radiation and temperature input using data provided from the PV panel manufacturer.

The output characteristics of the PV panel are represented by the equivalent circuit model in Figure 2.2. In the model a current source generates the photocurrent $I_{ph}$ which depends on the incident solar radiation and temperature. The diode represents the p-n junction of the cell. The series resistor $R_s$ and the parallel resistor $R_p$ represent the losses in the PV cell. $R_s$ denote the internal resistance of the cell. The parallel shunt resistor $R_p$ characterises the leakage current of the p-n junction. $R_p$ is generally high and therefore can be neglected to simplify the model. The net output current of the PV cell is the difference between the photocurrent $I_{ph}$ and the diode current $I_D$.

![PV cell equivalent circuit model](image)

I-V and P-V characteristic curves of a PV panel can be generated from (2.1) to (2.5). The PV cell temperature is calculated from the ambient temperature using (2.1) [39].
\[ T_{\text{cell}} = T_a + (\text{NOCT} - T_{a\text{NOCT}}) \frac{G}{G_{\text{NOCT}}} \]  

Where:
- \( T_a \): Ambient temperature (°C)
- \( \text{NOCT} \): Nominal operating cell temperature (°C)
- \( T_{a\text{NOCT}} \): Ambient temperature at NOCT (°C)
- \( G \): Solar radiation (W/m²)
- \( G_{\text{NOCT}} \): Solar radiation at NOCT (W/m²)

The photocurrent, \( I_{\text{ph}} \), is given in (2.2)

\[ I_{\text{ph}} = I_{\text{scref}} \frac{G}{G_{\text{ref}}} \left(1 + \alpha_{\text{isc}} (T_{\text{cell}} - T_{\text{ref}})\right) \]  

Where:
- \( I_{\text{scref}} \): Short circuit current at reference temperature and solar radiation. Reference conditions are given by the manufacturers as 25°C and solar radiation level of 1000W/m² (A)
- \( G_{\text{ref}} \): Reference solar radiation (W/m²)
- \( \alpha_{\text{isc}} \): Short circuit current temperature coefficient (%/°C)
- \( T_{\text{ref}} \): PV cell reference temperature (°C)

The PV open circuit voltage, \( V_{\text{oc}} \), is given in (2.3)

\[ V_{\text{oc}} = V_{\text{ocref}} + \alpha_{\text{voc}} (T_{\text{cell}} - T_{\text{ref}}) \]  

Where:
- \( V_{\text{ocref}} \): PV open circuit voltage at standard operating conditions (V)
- \( \alpha_{\text{voc}} \): PV module open circuit voltage temperature coefficient

The saturation current, \( I_{\text{sat}} \), is outlined in (2.4)
The output current, $I_o$, of the PV panel used to generate the I-V characteristic curve is calculated in (2.5)

$$I_o = I_{ph} - I_{sat} \left( \exp \left( \frac{q}{n k T_{cell} N_s} V_o \right) - 1 \right)$$

(2.5)

Where $V_o$ PV output voltage (V)
Table 2-1  BP Solar BP350U 50W panel parameters [40]

<table>
<thead>
<tr>
<th>PV Panel Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gref</td>
<td>1000W/m²</td>
</tr>
<tr>
<td>Iscref</td>
<td>3.17A</td>
</tr>
<tr>
<td>Tref</td>
<td>25°C</td>
</tr>
<tr>
<td>Vocref</td>
<td>21.8V</td>
</tr>
<tr>
<td>αisc</td>
<td>0.065%/°C</td>
</tr>
<tr>
<td>αvoc</td>
<td>-80mV</td>
</tr>
<tr>
<td>NOCT</td>
<td>47°C</td>
</tr>
<tr>
<td>Tanoct</td>
<td>20°C</td>
</tr>
<tr>
<td>Gnoct</td>
<td>800 W/m²</td>
</tr>
<tr>
<td>Ns</td>
<td>36</td>
</tr>
<tr>
<td>n</td>
<td>1.265</td>
</tr>
</tbody>
</table>

Figure 2.3 to Figure 2.6 demonstrate the impact PV cell temperature and solar radiation have on the PV panel output power. Figure 2.3 and Figure 2.4 give the I-V and P-V characteristic curves for the BP350U panel with a constant solar radiation of 1000W/m² under varying cell temperature. The impact solar radiation has on the PV panel is highlighted in Figure 2.5 and Figure 2.6, the I-V and P-V characteristic curves under varying solar radiation with a constant cell temperature of 25°C is shown.
Figure 2.3  BP350U I-V characteristic curve for varying levels of temperature

Figure 2.4  BP350U P-V characteristic curve for varying levels of temperature
CHAPTER 2. PHOTOVOLTAIC SYSTEM

Figure 2.5  BP350U I-V characteristic curve for varying levels of solar radiation

Figure 2.6  BP350U P-V characteristic curve for varying levels of solar radiation
2.2. Maximum Power Point Tracker

The PV panel operating voltage has a significant impact on the panel's output power, as highlighted in Figure 2.4 and Figure 2.6. The Maximum Power Point (MPP) of the PV panel occurs at the point where the load is matched to the PV panel resistance. A dc-dc converter with MPPT, operating as an optimal electrical load for the PV panel, is implemented in the system to achieve maximum power transfer. The voltage and current levels of the panel are varied by controlling the duty ratio of the Pulse Width Modulator (PWM) of the converter, so the PV panel is able to deliver its maximum available power. The operation of the MPP tracker is described in Figure 2.7. The buck converter consists of a solid state switch, diode, inductor, input capacitor and output capacitor.

The input impedance of the buck converter $r_{in}$ is changing when the duty ratio, $D$, of the PWM is changing. When the converter is operated in Continuous Conduction Mode.
Mode (CCM), the relation between the input impedance, load and D is represented in (2.6)

\[
    r_{in} = \frac{R_L}{D^2}
\]

(2.6)

Where \( R_L \) Converter load resistance

When \( D \) of the PWM tends to zero, \( r_{in} \) of the converter will become infinity. If \( D \) tends to one, \( r_{in} \) of the converter will become \( R_L \). Therefore, the output impedance of the PV panel is able to change from infinity to \( R_L \) when \( D \) of the PWM changes from zero to one [41].

Various MPPT controllers have been developed to control the duty ratio of the converter. The Perturbed and Observe (P&O) and the Incremental Conductance Method (ICM) are the most common MPPT algorithms. The P&O algorithm is the simplest, it perturbs the operating voltage of the PV panel by a small increment and the resulting change in output power is monitored. The main drawback of the P&O algorithm is inaccurate tracking of the MPP under rapidly changing atmospheric conditions. The ICM of MPPT is implemented in this work, as it solves the problem of the P&O algorithm under rapidly changing atmospheric conditions. The ICM compares the instantaneous panel conductance with the incremental panel conductance to compute the direction of a perturbation. The operation of the ICM is illustrated in Figure 2.8. The instantaneous output power of the PV panel is given in (2.7) [42].

\[
    p_{pv} = i_{pv} * v_{pv}
\]

(2.7)

Where \( i_{pv} \) Instantaneous PV current

\( v_{pv} \) Instantaneous PV voltage

Differentiating (2.7) with respect to \( v_{pv} \) gives (2.8)
\[
\frac{dpv}{dv_{pv}} = i_{pv} + v_{pv} \frac{di_{pv}}{dv_{pv}} 
\]  

(2.8)

Hence

\[
\frac{1}{v_{pv}} \frac{dpv}{dv_{pv}} = \frac{i_{pv}}{v_{pv}} + \frac{di_{pv}}{dv_{pv}} 
\]  

(2.9)

Letting \( C = \frac{i_{pv}}{v_{pv}} \) and \( \Delta C = \frac{di_{pv}}{dv_{pv}} \) be the conductance and incremental conductance of the PV panel respectively gives

\[
\frac{1}{v_{pv}} \frac{dpv}{dv_{pv}} = C + \Delta C
\]

(2.10)

\[ 
\]

![Figure 2.8 Operation of ICM of MPPT](image)

At MPP \( \frac{dpv}{dv_{pv}} = 0 \), therefore \( C = -\Delta C \). When \( C > -\Delta C \), \( \frac{dp}{dv_{pv}} > 0 \), the duty ratio of the PWM should be reduced. If \( C < -\Delta C \), \( \frac{dpv}{dv_{pv}} < 0 \), the duty ratio of the PWM should be
increased. The methodology used by the ICM of MPPT is described in greater detail by the flow chart of Figure 2.9.

![ICM of MPPT flowchart](image)

**Figure 2.9** ICM of MPPT flowchart

The ICM of MPPT is implemented in Matlab Simulink to operate the PV model described in Section 2.1 at its MPP. The size of the perturbation is important as a large perturbation will result in faster tracking but the algorithm will be less accurate, the opposite applies to smaller perturbations. Figure 2.10 illustrates the MPPT operation of BP350U PV panel for a change in temperature from 75°C to...
50°C and then to 25°C at a constant solar radiation of 1000 W/m². The MPPT also tracks the MPP under varying levels of solar radiation.

![Diagram](image.png)

**Figure 2.10**  MPPT for BP350 PV panel under varying temperature

### 2.3. Lead Acid Battery

The lead acid battery is a mature technology which is chosen for many applications because it is reliable, low cost and low maintenance. The battery produces electrical energy through chemical reactions. There are different types of lead acid batteries - flooded lead acid and VRLA batteries. VRLA batteries (Gel and Absorbed Glass Mat (AGM)) are lower maintenance. The hydrogen and oxygen are recombined back into water inside the battery, negating the need to refill the electrolyte. Valves allow excess pressure to be released from the battery preventing damage.
Battery charging is a very important factor for prolonging battery life. PV panels are not an ideal source for charging as their output is unreliable and heavily dependent on weather conditions. An optimum charge/discharge strategy cannot be guaranteed, which may result in prolonged periods of low battery SOC. The SOC is a measure of the available capacity remaining in the battery, calculated as a function of the rated capacity. Typically charge controllers are utilised in PV systems to protect the battery from over discharge and over charging. Set points are employed by the charge controller as illustrated in Figure 2.11 [43].

Figure 2.11  Battery charge controller set points

The Voltage Regulation (VR) set point limits the maximum voltage the battery can reach before being disconnected from the PV array during charging, to prevent overcharging. The battery voltage must then drop to the Array Reconnect Voltage (ARV) set point before being reconnected to the PV array for charging. Similar limits are employed during battery discharge. The Low Voltage Disconnect (LVD)
set point gives the minimum voltage the battery can be discharged to before it is disconnected from the load to prevent over discharge. The Load Reconnect Voltage (LRV) set point indicates the voltage at which the load can be reconnected to the battery.

Various battery charging methods can be utilised in PV systems, including Intermittent Charging (IC), Three Stage charging (TSC) and Interrupted Charge Control (ICC). IC is the most commonly used method in commercial chargers. The battery is charged with MPPT between the predefined voltage thresholds VR and ARV. When the battery reaches the VR set point, the charging is stopped; the battery voltage is monitored until it drops to ARV at which point charging recommences [44]. TSC delivers power to the battery in three steps. The first step (bulk charging) charges the battery with maximum current until the battery reaches its final charging voltage, known as the absorption voltage. This step replaces 70-80% of the battery's capacity. The second step is absorption charging. The charging current is steadily decreased while the battery voltage is maintained at the absorption voltage. This step replenishes the remaining 20-30% of the capacity. The final stage is float charging, where a small current is supplied to the battery to maintain the battery voltage [45]. ICC is a variation of IC. ICC avoids the potential undercharging problem faced by IC. ICC charges the battery in four modes. Mode 1 - the battery is charged with constant current with a charge rate of 0.1C to an upper threshold. Mode 2 - The battery is then left in open circuit until the lower threshold limit is reached. In Mode 3 the battery is pulse charged with a charge rate of 0.05C until the upper voltage limit is reached again. In Mode 4 the battery is at full capacity and is disconnected. Modes 1-3 are repeated when the battery voltage falls to 97% SOC [46]. The voltage and current profiles implemented for each of these charging methods is given in Figure 2.12.
Figure 2.12 Battery charging voltage and current profiles for (a) IC (b) TSC and (C) ICC
The batteries used for PV energy applications are cycled regularly. They are required to supply power to the load during night time or under low solar radiation conditions, and are charged during daylight hours. A battery model is utilised to assist with the design and optimisation of the PV storage system. The model represents the storage capability of the battery under various operating condition.

2.4. VRLA Battery Model

Battery models fall into different categories which include mathematical, electrochemical, thermal and electrical models. An electrical equivalent circuit model is utilised to represent the battery in this situation. Various electrical models exist ranging from the simple to more accurate complex models. The simplest model consists of an ideal voltage source with a series resistance to model the internal resistance of the battery. Both the voltage and internal resistance are functions of the battery SOC. Monitoring of the SOC is important in PV systems as it gives an indication of the remaining battery run time. When periods of low battery SOC is known certain loads may be prioritised.

The model selected to represent the battery for system analysis is a resistance capacitance (RC) model shown in Figure 2.13 [47].

![RC electrical equivalent battery model](image)

Figure 2.13  RC electrical equivalent battery model
R₀ is the ohmic resistance which causes the initial voltage drop due to the cell connectors, electrodes and the ionic path through the electrolyte. R₀ affects the performance or rate capability of a cell. It causes a voltage drop during operation and also consumes part of the useful energy as waste heat. A charge separation exists between the solid electrodes and the electrolyte. A positive/negative ionic layer absorbed onto the electrode surface is balanced by an equal quantity of negative/positive charge in an adjacent layer in the electrolyte. This may be considered as the structure of a plate capacitor and is known as a double layer.

The electrical characteristics of the double layer are described in the model. The capacitor C_B1 represents the charge shifting within the double layer and accumulating at the phase boundary between the active material and the electrolyte. The resistor R_B1 represents the energy losses of the charge transfer within the double layer. The voltages and SOC of the battery model can be calculated using equations (2.11) to (2.16)

\[
V_{B1} = V_{B_{1t-1}} + \frac{dV_{B1}}{dt} (t - t_{t-1})
\]  

(2.11)

\[
I_2 = \frac{v_{emf} - V_{B1}}{R_B}
\]  

(2.12)

\[
\frac{dV_{B1}}{dt} = \frac{1}{C_B} (I_2 - i_{batt})
\]  

(2.13)

\[
V_T = V_{B1} - (i_{batt} R_0)
\]  

(2.14)

\[
SOC = SOC_{init} - \frac{1}{Ah} \int i_{batt} d\tau
\]  

(2.15)

\[
V_{emf} = V_{emf_{min}} + k_e SOC
\]  

(2.16)

Where

- \( V_T \) Battery Terminal Voltage
- \( Ah \) Battery rated capacity
- \( i_{batt} \) Battery current
- \( k_e \) Battery EMF voltage VS SOC
SOC\textsubscript{init} Initial battery SOC

V\textsubscript{emf} Battery emf voltage

V\textsubscript{emf,min} V\textsubscript{emf} at zero SOC

Table 2-2 outlines the model parameters for the Yuasa NP18-12 VRLA battery required by equations (2.11)-(2.16) when determining the terminal voltage and SOC of the battery in the model. The parameters $R_0$, $R_1$, and $C_{B1}$ were determined by curve fitting. The performance of the model was assessed in Figure 2.14; the measured and simulated terminal voltage of the battery under a 0.2C pulse charge is illustrated. The simplified model of the battery utilised in the system lead to deviations in the two profiles. The difference between both profiles can be reduced by employing a more complex and accurate model. For the required application this was not deemed necessary.

Table 2-2 Yuasa NP 18-12 VRLA battery model parameters [48]

<table>
<thead>
<tr>
<th>Battery Model Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>0.157Ω</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.063Ω</td>
</tr>
<tr>
<td>$C_{B1}$</td>
<td>5.283F</td>
</tr>
<tr>
<td>$K_e$</td>
<td>1.5</td>
</tr>
<tr>
<td>$V\textsubscript{emf,min}$</td>
<td>11.5V</td>
</tr>
<tr>
<td>Ah</td>
<td>17.25Ah</td>
</tr>
</tbody>
</table>
An improvement to the RC model is an RC model with parasitic or self discharge resistance. Self discharge is usually down to gassing, which results from battery overcharging [49]. PV batteries can frequently be left undercharged and an energy management system is implemented to prevent battery over charging, therefore the parasitic branch is omitted from the model.

2.5. Ultracapacitor

Ultracapacitors also known as supercapacitors or electrical double layer capacitors are electrochemical storage devices developed in 1957. Ultracapacitors utilises a physical reaction to produce power unlike batteries which depend on chemical reactions, therefore ultracapacitors allow faster charge and discharge rates compared to batteries of similar volume. Ultracapacitors have a greater power
density than batteries by a factor of 10, allowing the ultracapacitors to provide more power over a shorter period of time. Conversely, batteries have a higher energy density compared to the ultracapacitors also by a factor of 10. For this reason ultracapacitors are not substituted for batteries but often employed as a complementary technology in HESS to increase power density.

The ultracapacitor employs the same principals as normal capacitors but its capacitance is in the thousands of farads range. The ultracapacitor is constructed of two electrodes immersed in an electrolyte with an ion permeable separator placed between the electrodes to prevent electrical contact, but to still allow ions from the electrolyte to pass through. Figure 2.15 shows the basic cell structure of the ultracapacitor [50].

![Ultracapacitor basic cell structure](image)

In the ultracapacitor the charge is stored in the ionic layer that forms at the interface between each of the electrodes and the electrolyte, hence the accumulated charge forms an electric double layer. The large capacitance of the ultracapacitor is as a result of the high surface area of the electrodes. The most common electrode material used is highly porous activated carbon with a surface area of 2000m$^2$/gram due to its low cost, high surface area and availability. The
development of the carbon electrode material influences its porous structures. It is the accessibility of the pores to the electrolyte that is important, if the pores are too small for access by the electrolyte ions they will not contribute to the electric double layer. Alternative electrode materials such as metal-oxides and conducting polymers are also being investigated.

The thickness of the dielectric also influences the capacity of the capacitor. For the ultracapacitor the dielectric thickness is based on the size of the ionized electrolyte molecules and, therefore, is of the order of 10Å (approximately 1.0nm). The voltage of the ultracapacitor is determined by the type of electrolyte utilised, organic or aqueous. The organic electrolyte is the most common due to its high cell voltage range (2-2.7V) while the aqueous electrolyte has a breakdown voltage of approximately 1V. The separators are chosen depending on the type of electrolyte utilised. Polymer or paper separators are used with organic electrolytes while ceramic or glass fibre separators are employed with aqueous electrolytes.

The ultracapacitor has a low electrical series resistance making it capable of delivering high currents. Ultracapacitors also have a low operating voltage of 2V – 2.7V. To increase the operating voltage of the ultracapacitor bank to the required application voltage a number of ultracapacitor cells are connected in series. Connecting the cells in series reduces overall capacitance while parallel connection of the cells can be employed to increase capacitance. Since the series connected cells may not behave identically the voltage applied to the bank may not divide equally among the individual cells resulting in overvoltage of an individual cell, which could cause the cell to fail [51]. Cell balancing is employed to maintain individual ultracapacitors within their rated voltage. Cell balancing circuits can be either active or passive.

The simplest method of cell balancing is a passive circuit utilising resistors in parallel with the ultracapacitors, illustrated in Figure 2.16. Resistors are generally ten times the average leakage current of the cell. Passive cell balancing is simple
and low cost, but it has a slow response due to the linearity of the leakage current with voltage and high parasitic losses due to ten times additional leakage current. Therefore, passive cell balancing is suited to low duty cycle applications which can tolerate higher leakage e.g. backup power supplies.

![Passive resistor cell balancing circuit](image)

Figure 2.16 Passive resistor cell balancing circuit

Active cell balancing circuits shown in Figure 2.17 are utilised in application with high duty cycles and where low parasitic losses are necessary. The circuits use active switching devices; a voltage detection circuit controls the switches turning the switches on when the voltage across the cell approaches the bypass threshold voltage. Active balancing is fast, provides accurate equalisation of the voltage distribution and has minimal parasitic losses but is more expensive than passive cell balancing.

Examples of active cell balancing circuits include switched resistors in parallel to each other. The resistor bypasses the main circuit when the switch is on. Each cell voltage is measured in this method. DC-DC converters connected across two neighbouring cells can actively equalise the cell voltages. There are power losses due to the converters. This method has higher efficiency than other methods, but the hardware control is costly. An alternative method utilise zener diodes in parallel to the cells. The cell voltage is held constant as soon as the zener voltage is reached and the diode is used to bypass the main circuit. There are high power losses in the diode and the zener voltage has a strong temperature dependency. Another example of an active balancing circuit uses a comparator across two cells,
comparing their voltages and moving charge to equalise the two cells. Maxwell technology adopts a linear voltage balancing system which always attempts to balance two adjoining ultracapacitors based on the variation in voltage between the cells [52].

(a)  
(b)
Figure 2.17  Active cell balancing circuits (a) Switched resistors  
(b) DC-DC converters (c) Zener diodes (d) Comparators

2.6.  Ultracapacitor Model

The electrical behaviour of an ultracapacitor is characterised using an electrical equivalent circuit model. Several different models have been developed in [53]. The simplest of the ultracapacitor models is the classical equivalent circuit model of Figure 2.18, which consists of a capacitance in parallel with an ESR, which models the power losses that result from internal heating and an equivalent parallel resistance (EPR) which models the current leakage. This model can give an approximation of the ultracapacitor operation
Zubieta and Bonert [54] proposed a more detailed three branch model of the ultracapacitor described in Figure 2.19. The model consists of three RC branches, each having a different time constant. The first branch labelled the “immediate branch” contains the ESR and represents the behaviour of the ultracapacitor in the seconds range. The second branch or “delayed branch” contains $R_2$ and represents the behaviour of the ultracapacitor in the minute range. The final branch or “long term branch” represents the long-term behaviour of the ultracapacitor after approximately ten minutes. The capacitor $K_V$ reflects the voltage dependency of the ultracapacitor and the EPR models the leakage current.

![Ultracapacitor classical equivalent circuit model](image1)

Figure 2.18 Ultracapacitor classical equivalent circuit model

![Three branch ultracapacitor model](image2)

Figure 2.19 Three branch ultracapacitor model
The three branch model was reduced to a two branch model in this work as the ultracapacitor is utilised to provide short peak loads, the long term branch was removed from the model of Figure 2.19. The component parameters are determined from the constant current charge and self discharge characteristics of the ultracapacitor. Equation (2.17) to (2.22) are utilised to determine the model component values, based on the topology discussed in [55]. Table 2-3 outlines the ultracapacitor parameters utilised in the model of the Nesscap 2.7V 600F carbon electrode ultracapacitor. Figure 2.20 represents the simulated and measured voltage for the ultracapacitor under 18A constant current charge. The ultracapacitor is left to self discharge after full SOC is achieved. Increasing the number of branches in the model will increase the model accuracy, reducing the percentage error.

\[
ESR = \frac{\Delta V}{\Delta I} \quad (2.17)
\]

\[
C_0 = \left( \frac{t_1}{V_1} - \frac{t_1 t_2 - t_1 V_2}{V_2^2 - V_1 V_2} \right) I_c \quad (2.18)
\]

\[
K_V = 2 \left( \frac{V_1 t_2 - V_2 t_1}{V_1 V_2^2 - V_1 V_2} \right) I_c \quad (2.19)
\]

\[
C_2 = \frac{I_c t_C}{V_2 f} \left( C_0 + \frac{K_V V_2 f}{2} \right) V_2 f \quad (2.20)
\]

\[
R_2 = \frac{\tau C_2}{C_2} \quad (2.21)
\]

\[
EPR = \frac{t_4 - t_3}{\ln \left( \frac{V_4}{V_3} \right) C_{\text{capR}}} \quad (2.22)
\]

Where

- \( \Delta V \)  Change in ultracapacitor voltage when load turned on/off
- \( \Delta I \)  Change in ultracapacitor current when load turned on/off
- \( t_1 \)  1st point on ultracapacitor charge phase (approx 1.2V)
V₁ Ultracapacitor voltage at t₁

V₂ 2nd point on ultracapacitor charge phase (approx 2.3V)

Iₐ Ultracapacitor charge current

Qₜₒₜ Total ultracapacitor charge

tₙ Ultracapacitor charge time

V₂f Ultracapacitor voltage at τc₂

τc₂ Ultracapacitor 2nd branch time constant

V₃ Ultracapacitor initial self discharge voltage at t₃

t₃ Start time of the initial ultracapacitor self discharge

V₄ Ultracapacitor final self discharge voltage at t₄

Cᵤₐₖₐ₇ Ultra capacitor rated capacitance

t₄ End time of the ultracapacitor self discharge phase
Table 2-3  Nesscap 2.7V 600F ultracapacitor model parameters

<table>
<thead>
<tr>
<th>Ultracapacitor Model Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESR</td>
<td>0.324mΩ</td>
</tr>
<tr>
<td>C₀</td>
<td>0.13014F</td>
</tr>
<tr>
<td>Kᵥ</td>
<td>1nF</td>
</tr>
<tr>
<td>R₂</td>
<td>5.4949Ω</td>
</tr>
<tr>
<td>C₂</td>
<td>0.04506F</td>
</tr>
<tr>
<td>EPR</td>
<td>2500Ω</td>
</tr>
</tbody>
</table>

Figure 2.20  Simulated and measured results of Nesscap 2.7V 600F ultracapacitor
2.7. **Battery Ultracapacitor Comparison**

The lead acid battery and ultracapacitor were described in Section 2.3 and Section 2.5 respectively. These are complementary technologies which benefit from being combined in hybrid systems. The two main characteristic taken into consideration when comparing both technologies is the energy and power density of each device. The ultracapacitor has a greater power density than the battery, allowing the ultracapacitor to provide more power over a shorter period of time. Conversely, the battery has a higher energy density compared to the ultracapacitor to supply the lower power for a longer period of time. The ragone chart in Figure 2.21 shows the energy and power comparison of different storage technology. Table 2-4 compares the ultracapacitor and battery characteristics.

![Ragone chart for storage technology](image_url)

Figure 2.21  Ragone chart for storage technology
Table 2-4  Battery ultracapacitor comparison [48][56][57]

<table>
<thead>
<tr>
<th></th>
<th>Ultracapacitor</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>2.7V/cell</td>
<td>2V/cell</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>-40°C - +65°C</td>
<td>-20°C - +50°C</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>0.85 – 0.98</td>
<td>0.7 – 0.85</td>
</tr>
<tr>
<td><strong>Life cycle</strong></td>
<td>&gt;500,000</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Power density</strong></td>
<td>&lt;10,000 W/Kg</td>
<td>&lt;1000 W/Kg</td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>1 – 10 Wh/Kg</td>
<td>10 – 100 Wh/Kg</td>
</tr>
<tr>
<td><strong>Charge time</strong></td>
<td>0.3 – 30 sec</td>
<td>1 – 5 hrs</td>
</tr>
<tr>
<td><strong>Discharge time</strong></td>
<td>0.3 – 30 sec</td>
<td>0.3 – 3 hrs</td>
</tr>
</tbody>
</table>

2.8. Hybrid Configuration

Different configurations can be employed to combine batteries and ultracapacitors in the HESS. The simplest configuration is a passive HESS, the battery and ultracapacitor are directly connected in parallel to the load as shown in Figure 2.22. The power supplied by/to the battery and ultracapacitor is determined by the components internal resistance limiting the power enhancement of the HESS. This configuration utilises a common voltage bus which is not controlled. The voltage is set by the battery leading to under utilisation of the ultracapacitor [58].
Active HESS enables better utilisation of the ultracapacitor by including dc/dc converters. The converters actively control the power to/from the battery and ultracapacitor, allowing more efficient utilisation of the ultracapacitor leading to increased power capability. The HESS with dc/dc converter can adopt different forms. The first layout of the active HESS places a dc-dc converter between the battery and ultracapacitor as illustrated in Figure 2.23. In this configuration the dc-dc converter controls the power from the battery to the ultracapacitor and load, which improves the power density of the storage system. Other advantages to the active hybrid system include smaller battery ripple current and wider operating voltage range [13].
An alternative with two dc/dc converters is illustrated in Figure 2.24. The first converter allows the ultracapacitor and battery to be operated at different voltage levels, giving greater flexibility in the design of the battery and ultracapacitor banks. The current output of the battery is controlled with the remaining load power requirement met by the ultracapacitor. The ultracapacitor voltage becomes the bus voltage, which varies with SOC. The second dc-dc converter is required to maintain the load voltage. There is a large voltage swing on the converter input due to the large voltage range of the ultracapacitor. High input current for low ultracapacitor SOC leads to high IR losses [59].

A third form of active HESS configuration is shown in Figure 2.25. Both the battery and the ultracapacitor are connected to the load through a two input bidirectional converter. The battery dc-dc converter is current controlled with the ultracapacitor dc-dc converter voltage controlled. The current supplied by each component is based on the load requirement and the component SOC. This configuration gives the highest efficiency, reliability, and flexibility [59].

Figure 2.24  HESS with bidirectional converter between the battery and ultracapacitor
This chapter outlined a standalone PV system with a VRLA battery ultracapacitor HESS. Each of the technologies utilised in the PV system was described in detail. The available models for the PV panel, battery and ultracapacitor were reviewed. MPPT was investigated to ensure the maximum power transfer between the PV panel and the load. A comparison of the battery and ultracapacitor is provided. The different configurations utilised to combine the battery and the ultracapacitor in the HESS were presented. The most efficient and flexible configuration connects the battery and the ultracapacitor to the load with a two input bidirectional converter.

Figure 2.25  HESS with two input bidirectional converter between the battery ultracapacitor and load
Autonomous PV panels are intermittent sustainable energy sources which require energy storage to balance generation and demand, as PV generation is time and weather dependent. Traditionally batteries are the most common storage technology for PV systems. PV batteries can encounter extended periods of low SOC resulting in sulphation and stratification, which reduces battery lifetime. Optimisation is important in standalone systems to ensure that adequate power is available to supply the demand as required. A combination of depleted battery SOC and a high burst current requirement can result in premature loss of load due to stringent battery LVD limits implemented by the BMS.

A review of current optimisation techniques was undertaken in Chapter 1. These techniques average the generation and load profiles on an hourly basis to determine the component size. The process of using averaged data is satisfactory when the energy requirement is being considered. However, the magnitude of the peaks in the load power is damped when averaged on an hourly base. Therefore, when considering the effects of peak power on the battery storage system, shorter time steps are required to capture the effect of spikes in demand on the battery voltage.

This chapter outlines the development of an optimisation methodology for a standalone PV system with a battery ultracapacitor HESS taking the peak power requirements of the load into account. The program is developed in Matlab to optimise the system for minimum system lifetime cost. The required inputs are the load profile over the optimisation horizon and the solar radiation on a horizontal plane at the site location.
3.1. System Optimisation Flow Chart

A lot of research has been carried out in the area of power system optimisation through industry and academia as discussed in Chapter 1. This chapter describes the development of a methodology to optimise an autonomous PV system with a battery ultracapacitor HESS given the site location, solar radiation on a horizontal plane and the load profile. A flowchart describing the process is illustrated in Figure 3.1.

Optimisation programs have been developed utilising a time step of one hour. In this case the fluctuations in the solar radiation and load profiles are not taken into account. The power output from the PV panels can be over/under estimated. In the HESS the ultracapacitor is utilised to supply the peak power requirements of the load, which last for a short period of time, requiring a time step smaller than an hour. The optimisation program has been developed with a time step in the second’s range, allowing the peaks in the load profile to be considered in the optimisation. The program sampling rate is adapted in the program to capture the changes in the solar radiation and load profile based on the time stamps of the profiles.

Autonomous PV systems are utilised in different areas for various applications. In some situations the load being supplied is critical and the main concern is that the load will be maintained at all times. A system may also be developed in an area where the availability of space for the PV array and the battery is limited. If the load is non critical and does not need to be maintained for 100% of the time, the system can be designed at a lower cost. In addition to optimising the system the program has been developed to allow the user to take these factors into account for the system design. In this case a weighting is applied to the different constraints (LPSP, component volume and cost) by the user given the requirements of the system.

In addition to optimising the components in the system, the program generates the optimum tilt angle the PV panel should be placed at to generate the maximum
energy over the optimisation horizon. This is the first step in the optimisation process. The number of PV panels is varied between a minimum and maximum level calculated based on load requirement. The next step is to determine the configuration of the storage system. The size of the storage system depends on the size of the PV array and the battery threshold voltage implemented by the system controller. Different combinations of the battery and ultracapacitor size are generated for each of the PV arrays. The chosen system design is the one that has the lowest system lifetime cost, taking the user entered requirements into account.

The formulas utilised for the calculations performed in each of the blocks of the flow chart are described in detail in the following sections with the Matlab code developed given in Appendix B.

The LVD limit implemented by the control system can be varied to observe its impact on the system design. Implementing a high LVD limit increases the storage capacity required to meet the demand at certain times of the year. A more optimum solution can be to reduce the LVD limit, with the limit being approached for a small portion of the optimisation horizon resulting in a more economical system. The LVD limit is varied down to the equivalent of 20% SOC to investigate its impact on the system.
Figure 3.1 Optimisation methodology flowchart
3.2. Optimum Tilt Angle

The level of solar radiation falling on the surface of the PV panel plays an important role in the output power generation. PV panels can utilise a mechanical tracking system to track the sun over the course of the day to capture the maximum solar radiation. Alternatively, the panel can be maintained at a fixed tilt angle throughout the year; the optimum tilt angle and orientation is important in this case to capture the maximum possible solar radiation. The optimisation methodology was developed for a PV system with fixed tilt angle. Therefore, the first step in the process is to calculate the optimal tilt angle for the PV array to produce the maximum power output over the optimisation horizon.

The global solar radiation falling on the surface of the tilted PV panel is composed of three variables the beam, reflected and diffuse radiation. The global radiation incident on the tilted panel is calculated using horizontal values of solar radiation. Each of the three variables is calculated separately with a range of models existing to estimate the diffuse solar radiation on the tilted panel. These models can be categorised as isotropic or anisotropic. Isotropic models assume the intensity of diffuse sky radiation is uniform over the sky dome while the anisotropic model takes into account the brightening around the solar disk plus the isotropically distributed diffuse component from the rest of the sky dome. The isotropic models include Liu-Jordan [60], Tian [61] and Koronakis [62] models while Hay–Davies [63], Temps–Coulson [64], Klucher [65] and Perez [66] are examples of anisotropic models.

The tilt angle of the PV panel is varied from 0°, horizontal panel, to 90°, vertical panel and the global radiation is calculated at each step point. The tilt angle which captures the largest solar radiation over the optimisation horizon is chosen as the optimal tilt angle. The Beam, reflective and diffuse radiations are calculated separately before being added to give the global radiation on the tilted panel. Figure 3.2 illustrates the solar radiation falling on the PV panel. The beam radiation
on the tilted panel is calculated from (3.1) – (3.2). The solar angles utilised in calculating the radiation on a tilted plane are described in Appendix A [67].

\[
H_{BT} = H_{BH} R_{\beta} \quad \text{(3.1)}
\]

\[
R_{\beta} = \frac{\cos(\theta)}{\cos(\theta_{z})} \quad \text{(3.2)}
\]

Where

- \(H_{BH}\) Beam radiation on a horizontal plane (W/m²)
- \(R_{\beta}\) Geometric factor, the ratio of the beam radiation on an inclined surface to the radiation on a horizontal surface
- \(\theta\) Angle of incidence (°)
- \(\theta_{z}\) Solar zenith angle (°)
The reflected radiation on a tilted plane is obtained from (3.3)

\[ H_{RT} = \rho H_{GH} \left( \frac{1 - \cos(\beta)}{2} \right) \]  (3.3)

Where

- \( \rho \)  Ground reflectance coefficient
- \( H_{GH} \)  Global horizontal surface radiation, beam and diffuse (W/m²)
- \( \beta \)  PV panel tilt angle (°)

The ground reflectance coefficient varies depending on the surface surrounding the PV panel. In this work the coefficient is taken as 0.2. Table 3-1 outlines the ground reflectance coefficient for different surfaces.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Ground Reflectance Coefficient</th>
<th>Surface</th>
<th>Ground Reflectance Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass (July/Aug)</td>
<td>0.25</td>
<td>Forests</td>
<td>0.05–0.18</td>
</tr>
<tr>
<td>Lawn</td>
<td>0.18–0.23</td>
<td>Water Surface (Ys&gt;45C)</td>
<td>0.05</td>
</tr>
<tr>
<td>Untilled Field</td>
<td>0.26</td>
<td>Water Surface (Ys&gt;30C)</td>
<td>0.08</td>
</tr>
<tr>
<td>Barren Soil</td>
<td>0.17</td>
<td>Water Surface (Ys&gt;20C)</td>
<td>0.12</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.18</td>
<td>Water Surface (Ys&gt;10C)</td>
<td>0.22</td>
</tr>
<tr>
<td>Clean Concrete</td>
<td>0.2</td>
<td>Fresh Layer of Snow</td>
<td>0.80–0.90</td>
</tr>
<tr>
<td>Clean Cement</td>
<td>0.55</td>
<td>Old Layer of Snow</td>
<td>0.45–0.70</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A number of models can be employed to calculate the diffuse radiation on a tilted plane. The Temps and Coulson anisotropic model modifies the Liu-Jordan isotropic model to take the diffuse radiation coming from around the sun’s disc and the sky radiation close to the horizon into account. This model is only valid for clear skies and was modified by Klucher to account for radiation changes due to overcast skies, by adding a clearness factor \( F_{KL} \). The value of \( F_{KL} \) approaches zero as the sky...
becomes more overcast. On completely overcast days when the global and diffuse radiation is equal, \( F_{KL} \) is zero and the model reduces to the Liu-Jordan isotropic model. Equations (3.4) and (3.5) are used to calculate the diffuse radiation on the tilted surface, \( H_{DT} \), according to the Klucher model [65].

\[
F_{KL} = 1 - \left( \frac{H_{DH}}{H_{GH}} \right)^2
\]  

(3.4)

\[
H_{DT} = H_{DH} \left( \frac{1 + \cos(B)}{2} \right) \left( 1 + F_{KL} \sin^3 \left( \frac{B}{2} \right) \right) \left( 1 + F_{KL} \cos^2(\theta) \sin^3(\theta_z) \right)
\]  

(3.5)

Where

- \( H_{DH} \)  Diffuse horizontal surface radiation (W/m²)

The angle of incidence, the angle between the beam of light and the normal of the PV panel, affects the amount of solar radiation that can be absorbed by the panel. Increasing the angle of incidence also increases the radiation reflected off the PV panel reducing the output power. Considerable effects of inclination have been found to occur at angles greater than 65⁰ [69]. The Incident Angle Modifier (IAM) is the ratio of global radiation absorbed by the panel to the radiation that would be absorbed if the panel was at normal incidence. The IAM calculated in (3.6) according to King et al [70] is used to adjust the global radiation on the tilted PV panel to take the effects of the incidence angle into account.

\[
IAM = b_0 + b_1 \theta_{eff} + b_2 \theta_{eff}^2 + b_3 \theta_{eff}^3 + b_4 \theta_{eff}^4
\]  

(3.6)

Where

- \( \theta_{eff} \)  Effective angle of incidence (⁰)

\( b_0, b_1, b_2, b_3, b_4 \)  Coefficients derived empirically and dependent on the PV panel material. Taken as 1, -1.098x10⁻⁴, -6.276x10⁻⁶, 6.583x10⁻⁷, -1.4272x10⁻⁸ for \( b_0, b_1, b_2, b_3, b_4 \) respectively

Separate IAMs are required for the beam, diffuse and ground reflected radiation, each having a different effective angle of incidence, \( \theta_b, \theta_d, \) and \( \theta_r \) for the diffuse, reflective and beam radiation respectively, as outline in equations (3.7) – (3.9)
\[
\theta_d = 59.7 - 0.1388 \beta + 0.00149 \beta^2 \\
\theta_r = 90 - 0.5788 \beta + 0.002693 \beta^2 \\
\theta_b = \theta
\]

The total effective global radiation on the tilted PV panel, \(H_{GT\text{eff}}\), is calculated according to (3.10)

\[
H_{GT\text{eff}} = H_{BT\text{IAM}_B} + H_{DT\text{IAM}_D} + H_{RT\text{IAM}_R}
\]

Where
- IAM\(_B\) Angle of incidence modifier for beam radiation
- IAM\(_D\) Angle of incidence modifier for diffuse radiation
- IAM\(_R\) Angle of incidence modifier for ground reflected radiation

### 3.3. PV Array Size

In autonomous PV systems the PV panels are the only source of generation. Therefore, the PV panel needs to be large enough to generate a minimum of the annual load requirement taking the system losses into account. As the power produced from the PV array varies throughout the year a trade off between increasing the number of PV panels and increasing the storage system, which supplies the load during periods of low or no solar radiation, exists. To find the optimum quantity of PV panels to supply the load throughout the year with an ultracapacitor battery HESS the number of PV panels is varied between a minimum and maximum quantity of PV panels. The minimum quantity of PV panels, the number of PV panels required to meet the annual load requirement, is calculated according to (3.11) for an optimisation horizon of one year.

\[
N_{PV\text{min}} = \frac{\int_{t_1}^{t_1^{8760}} P_{\text{Load}}}{\int_{t_1}^{t_1^{8760}} P_{P_{\text{PVmax}}}}
\]

CHAPTER 3. PHOTOVOLTAIC SYSTEM OPTIMISATION

Where \( P_{\text{Load}} \) Load power taking account of system losses

\[ P_{\text{PVmax}} \] Maximum power output from one PV panel fixed at the optimum tilt angle calculated from the Equations (2.1) – (2.5)

The maximum quantity of PV panels is set to the minimum number of PV panels required to supply the maximum daily load for the worst day of the year, the day when the PV panel receives the lowest solar radiation. The maximum quantity of PV panels is determined by (3.12)

\[
N_{\text{PVmax}} = \frac{\max[\int_1^{24} P_{\text{Load}}(\text{day})]}{\min[\int_1^{24} P_{\text{PVmax}}(\text{day})]}
\]

(3.12)

Where \( \text{day} \) varies from 1 to 365, to step through each day of the year

The minimum and maximum values of PV panels are two opposite extremes which are not optimal and would require a large storage system for the minimum quantity of PV panels and a small storage system if the maximum quantity of PV panels is utilised. While varying the quantity of PV panels the PV power and the load requirement are compared to obtain the charge/discharge profile of the storage system for each step point over the optimisation horizon.

### 3.4. Ultracapacitor Bank Size

In the HESS the ultracapacitor bank is utilised to supply the peak power requirements of the load discharged from the storage system with the lower average power supplied by the battery bank. The required capacitance of the ultracapacitor bank is calculated from the energy equation of (3.13)

\[
C_{\text{CapReq}} = \frac{2E_{\text{cap}}}{V_a^2 - V_b^2}
\]

(3.13)

Where \( E_{\text{cap}} \) Energy requirement of the ultracapacitor (J)
\( V_a \) Maximum ultracapacitor operating voltage

\( V_b \) Minimum ultracapacitor operating voltage

The ultracapacitor operating range can vary between its rated voltage and zero volts. In this work the ultracapacitor bank is allowed to discharge to half its maximum voltage i.e. \( V_b = 0.5V_a \), which utilises approximately 75% of the ultracapacitor energy. This gives the best utilisation of the ultracapacitor energy without increasing the voltage drop [71].

In the optimisation methodology the ultracapacitor bank is given priority with respect to charging. To endeavour to maintain the ultracapacitor bank at an adequate SOC to supply the load peak power requirements, both the PV Array and the battery bank can be utilised for ultracapacitor charging. The peak power requirement of the load can be unpredictable and adequate recharge between peaks cannot be guaranteed, for this reason \( E_{cap} \) is varied during the optimisation process.

The peak power requirements of the load are assessed when choosing the minimum and maximum \( E_{cap} \) values. The minimum value is selected to ensure the largest peak in the load occurring during the optimisation horizon can be met. As the load peaks can occur in quick succession the maximum value of \( E_{cap} \) is calculated to enable the ultracapacitor to supply the largest daily peak power requirement since ultracapacitors are not intended for energy storage.

The number of ultracapacitors connected in series and parallel can be obtained by (3.14) and (3.15) respectively using the capacitance calculated in (3.13) based on the minimum and maximum value of \( E_{cap} \).

\[
N_{CapSer} \geq \frac{V_a}{V_{Cap}} \tag{3.14}
\]

\[
N_{CapPar} \geq \frac{C_{CapReq} \times N_{CapSer}}{C_{Cap}} \tag{3.15}
\]
Where \( V_{\text{cap}} \) Ultracapacitor voltage

\( C_{\text{cap}} \) Nominal ultracapacitor capacitance

### 3.5. Peukert’s Law

Peukert’s law expresses the capacity of the battery in terms of the discharge rate. Increasing the rate of discharge of the battery decreases the battery available capacity. The battery capacity is modified in the optimisation process according to (3.16-3.17) to take the impact of Peukert’s law into account [72].

\[
T_B = H \times \left( \frac{C_{\text{BatDisRated}}}{I H} \right)^{K_p}
\]

(3.16)

\[
A_{\text{Peak}} = IT_B
\]

(3.17)

Where \( H \) Battery rated discharge time (Hours)

\( C_{\text{BatDisRated}} \) Rated capacity at the discharge rate (Ah)

\( I \) Actual discharge current (A)

\( T_B \) Actual time to discharge the battery (Hours)

\( K_p \) Peukert’s constant, specified by the manufacturer, typically in the range 1.1 to 1.3 for lead acid batteries

\( A_{\text{Peak}} \) Adjusted battery capacity.

A Peukert’s constant of close to one indicates the efficiency of the battery is good with minimal loss of energy due to increased discharge rate. Increasing Peukert’s constants indicates less efficient batteries.
3.6. **VRLA Battery Bank Size**

The PV array is the only charging source for the battery bank. In the HESS the main function of the battery bank is energy storage as the ultracapacitor provides the power requirements. The battery bank is optimised taking the PV array and the ultracapacitor bank capability into account. The HESS charge discharge profile is adjusted using the ultracapacitor profile to obtain the charge discharge profile of the battery bank. The number of series connected batteries is calculated according to (3.18)

\[
N_{\text{BattSer}} = \frac{V_{\text{Sys}}}{V_{\text{Batt}}}
\]

Where
- \(V_{\text{Sys}}\) System operating voltage
- \(V_{\text{Batt}}\) Battery rated voltage

Determining the number of batteries connected in parallel to increase the battery bank capacity is more complicated. The available energy from the batteries and the reduction in capacity due to the discharge current are taken into account. The accessible battery energy in the HESS is dependent on the SOC limit implemented in the system and is determined by (3.19)

\[
E_{\text{Batt}} = V_{\text{Batt}}Ah_{\text{cap}}(1 - \text{SOC}_{\text{limit}})
\]

Where
- \(E_{\text{Batt}}\) Available battery energy
- \(Ah_{\text{cap}}\) Nominal battery capacity
- \(\text{SOC}_{\text{limit}}\) Battery SOC limit

Traditionally in PV systems the size of the battery bank is determined based on the daily load requirement and the number of Days of Autonomy (DOA). The DOA outlines the number of days the PV system can deliver full power to the load from the battery bank without charge from the PV array, utilised to ensure the load can
be maintained during rainy and cloudy periods [73]. This work adopts a different approach to calculating the DOA, days of inadequate charge. In this methodology, the daily charge and discharge battery energy is compared to calculate the number of consecutive days the battery bank is inadequately charged. Therefore, in this situation the contribution of the PV array and the ultracapacitor bank to the load is taken into account which will reduce the initial battery bank size. The initial number of parallel batteries in the battery bank is calculated from (3.20)

$$N_{\text{BattPar}} = \left(\frac{\text{MaxDailyDischarge}}{E_{\text{Batt}}}\right) \times \text{DayInadChar} \quad (3.20)$$

Where

- $\text{MaxDailyDischarge}$: Maximum energy discharged from the battery bank in one day during the optimisation horizon
- $\text{DayInadChar}$: Number of consecutive days the battery is not recharged

The $\text{MaxDailyDischarge}$ is chosen, worst case, to ensure the battery bank will be large enough to supply the maximum battery load energy for the required number of days. If the battery bank is fully recharged every day, $\text{DayInadChar}$ equals 1, as battery storage is required to supply the night time load. Both the $\text{MaxDailyDischarge}$ and the $\text{DayInadChar}$ are dependent on the ultracapacitor and PV array capacity and vary accordingly.

The initial battery bank capacity calculated in (3.20) uses the worst case values over the optimisation horizon. The worst case conditions may only occur for a short period of time, therefore, the battery bank may be oversized. To optimise the battery bank for the given PV array and ultracapacitor bank the operation of the battery bank is observed with respect to the LVD limit implemented by the control system over the optimisation horizon with the battery capacity adjusted according to Peukert’s law. The capacity is reduced until the minimum battery bank capacity which obeys the LVD limit is obtained.


### 3.7. Constraints on Component Size

The optimisation function is to minimise the system lifetime cost. A range of constraints can be implemented in the optimisation methodology. The components in the system can be large requiring a large area to be made available, which is not always possible. The program has been developed to incorporate constraints on the size of components utilised to produce a viable solution for the area available to accommodate the system. The area constraint can be placed on the PV array and the HESS. For the HESS the ultracapacitor bank is not limited, but its area is taken into account and the battery bank is reduced as required. To implement the constraints on the area of the PV array and the HESS the maximum allowable number of the components is reduced depending on the available space.

### 3.8. Loss of Power Supply Probability

The LPSP is the probability that loss of power supply occurs, meaning the PV and energy storage system is not capable of supplying the load when required. Therefore, it is the fraction of the load that cannot be supplied in the operating time period, ranging from 0 to 1[19]. The LPSP is calculated by (3.21)

\[
\text{LPSP} = \frac{1}{T} \int_1^T \left( (P_{PV} + P_{Storage}) < P_{Load} \right)
\]

Where

- \( P_{PV} \) PV power
- \( P_{Storage} \) HESS power
- \( P_{Load} \) Load power
- \( T \) Optimisation horizon

When the LPSP is equal to 1 the demand is never satisfied and a system redesign is required. A LPSP equal to 0 means the demand is satisfied at all times, which
depending of the criticality of the load may result in overdesign of the system with increased cost.

In Ireland, Eirgrid, the transmission system operator utilises a statistical indicator Loss of Load Expectation (LOLE). LOLE is a measure of how long on average the available capacity is likely to be less than the demand, but it does not quantify the extent to which the demand is not met. An accepted generation adequacy standard of eight hours LOLE currently exists. Therefore, the system is designed to have a maximum loss of load of eight hours, a LOLE greater than eight hours implies the system fails to meet the standard and more plant is required [74].

ESB Networks, the Irish distribution system operator, utilises the international reliability indicator System Average Interruption Duration Index (SAIDI), the average duration of interruption for each customer served during the year, calculated according to (3.22) [75].

\[
\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}}
\]  

(3.22)

The commission for energy regulation sets the SAIDI target for ESB networks, the target was set at 152.3 minutes in 2010 and reduced to 141.1 minutes in 2011 [76]. Given that grid connected systems can incur loss of load due to outages throughout the year a similar approach can be taken when designing the autonomous system, by utilising the LPSP constraint, to obtain a more economically optimised solution provided the load is non critical.

### 3.9. System Life Time cost

The optimisation function is to minimise the system lifetime cost. The lifetime of each of the components in the system needs to be determined in calculating the cost. According to the manufacturers datasheet the PV panels have a lifetime of 20 years, which is taken as the system lifetime [40]. Ultracapacitors are not replaced
during this time as they have a cycle life of greater than 500,000 cycles [77]. To determine the number of battery replacements required throughout the system lifetime a battery life model was incorporated into the optimisation process. The battery model is an energy throughput model based on the model utilised in the Homer optimisation program [32].

Figure 3.3 illustrates the number of cycles to failure for the Yuasa NP 18-12 battery as a function of the SOC [48]. Given the number of cycles to failure for a particular SOC the lifetime throughput energy of the battery can be calculated.

![Figure 3.3 Number of cycles to failure as function of SOC](image)

The battery throughput is the amount of energy that is cycled through the battery annually. The battery lifetime curve, supplied by the manufacturer, outlines the number of charge discharge cycles the battery can undergo at a particular SOC. The number of charge discharge cycle’s decreases as the SOC limit is decreased. To determine the lifetime throughput from the curve the average annual SOC of the battery is calculated by the optimisation program and the number of charge discharge cycles is determined. This differs from the HOMER model, which
simplifies matters by assuming the lifetime throughput is independent of the SOC. The HOMER model calculates the lifetime energy throughput as the average of the points on the lifetime curve above the minimum SOC. The lifetime throughput is the product of the number of cycles, the nominal voltage, the SOC and the maximum capacity of the battery.

The number of battery replacements required during the system lifetime is determined by comparing the annual battery throughput and the lifetime throughput capability of the battery (3.23).

\[
\text{Batt}_{\text{Replace}} = \min \left( \frac{\text{Throughput}_{\text{Life}}}{\text{Throughput}_{\text{Year}}}, \text{Batt}_{\text{Float}} \right) \tag{3.23}
\]

Where
- \( \text{Throughput}_{\text{Life}} \): Calculated energy throughput of the battery before failure
- \( \text{Throughput}_{\text{Year}} \): Actual energy throughput for a year
- \( \text{Batt}_{\text{Float}} \): Float life of the battery

The optimisation function is to minimise the system lifetime cost which is calculated from the capital, replacement and maintenance cost of each of the system components (3.24).

\[
\text{System Lifetime Cost} = C_{\text{capital}}(\text{PV + Battery + Ultracapacitor + Other}) + C_{\text{replacement}}(\text{Battery}) + C_{\text{maintenance}}(\text{PV + Battery + Ultracapacitor + Other}) \tag{3.24}
\]

Where
- \( C_{\text{capital}} \): Component capital cost
- \( C_{\text{replacement}} \): Component replacement cost
- \( C_{\text{maintenance}} \): Component maintenance cost
- \( \text{Other} \): Equipment not included in the decision variables e.g. controller, inverter, rectifier and cabling etc.
For simplicity only the components that are varied and have a major impact on the system cost during the optimisation process are considered in the calculation. Therefore, Other is set equal to zero in (3.24) as it is taken to be equal for all combinations. It is assumed the maintenance cost between the various system configurations will be minimal as a result $C_{\text{maintenance}}$ is neglected in (3.24).

The optimisation program produces an array of various PV panel, battery and ultracapacitor combinations. The various combinations are assessed to establish if they meet all the constraints on component size and the LPSP set out in the optimisation process. The system lifetime cost of the viable solutions are analysed to determine the least cost configuration, which is chosen as the optimal system configuration.

### 3.10. Summary

This chapter described the development of a PV optimisation program developed in Matlab. The program is designed to optimise an autonomous PV system with an ultracapacitor battery HESS. The optimisation function of the program is to minimise the system lifetime cost. The program analyses the possible tilt angle of the PV panel and calculates the tilt angle which receives the maximum solar radiation over the year. Limitations in available space for the PV array or the storage system can arise. These limits were taken into account developing the program. In addition, optimisation can be performed for different LPSP values which can result in a lower lifetime system cost as the load can be dropped for a particular length of time over the optimisation horizon. Only the components of the system lifetime cost that vary depending on the configuration were included in calculating the cost to simplify the calculation.
Chapter 3 described the development of a methodology to optimise an autonomous PV system with a battery ultracapacitor HESS. The optimisation of the system is performed on an annual basis to minimise the system lifetime cost under a number of constraints. The constraints employed in the optimisation include the battery LVD limit, restrictions on component dimensions and an LPSP limit. The input data required for the optimisation include the annual solar radiation and the load profile. Matlab code was written, Appendix B, according to the methodology described in Chapter 3.

Simulink part of Matlab by Mathworks provides an interactive graphical environment to design, simulate and test a variety of time varying systems. A Simulink model of the system was developed, utilising the models described in Chapter 2, to analysis the results of the optimisation program.

This chapter describes the Simulink system model. It provides a number of load profiles employed to assess the optimisation program, the solar radiation and temperature profiles required by the program. Simulations are performed to analysis the impact of including the ultracapacitor in the storage system, along with the influence the different HESS configurations have on the system. The assumptions made during the analysis are explained in Section 4.3. Several graphs summarising the results of the simulations performed are presented in this chapter with additional graphs included in Appendix D.
4.1. Load Profiles

A number of load profiles were developed to analyse the optimisation methodology under varying conditions. The load profiles utilised were developed to represent a peak, pulse and domestic load profile. The peak load profile was developed to represent the starting of a DC motor. The current required to initially start the motor is significantly greater than the current necessary to keep the motor running in steady state. Typically, the starting current of the motor could be six times the steady state current [78]. The peak load profile has a peak power of 200W and the continuous power around 32W. The motor is operated for 45 minutes every hour as illustrated in Figure 4.1, with the load profile repeated daily over the optimisation horizon.

![Figure 4-1 Daily peak load profile](image_url)
A pulse load profile is the second profile developed to assess the methodology. The pulse load operates for 200 seconds out of every 250 seconds with a high pulse power of 50W and a lower base power of 10W. The duty cycle of the pulses is 0.5 with a period of 20 seconds. The load profile is shown in Figure 4.2 and operates continuously. Typical pulse load applications would be transmitters for telecommunications and radar [16].

![Figure 4-2 Pulse load profile](image)

The domestic load profile was utilised to examine the optimisation methodology under a varying load profile. The annual domestic load profile described in Figure 4.3 was based on data obtained from a 65m² apartment in Northern Europe, occupied by a single male, to represent low domestic electric energy consumption. The average power consumption was recorded every five minutes during the day.
throughout 2005 [79]. The profile is seen to have a range of spikes of varying size occurring each day. Spikes in the load power are common in domestic settings as most appliances require extra power during start-up, Table 4-1 outlines the difference between the start-up and continuous operating power of some common domestic appliances to highlight the difference in magnitude between the peak and operating power of particular devices.

Figure 4-3 Domestic load profile
### Table 4-1 Appliance starting and continuous power [80]

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Starting Power (W)</th>
<th>Continuous Power (W)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing Machine</td>
<td>3,400</td>
<td>1150</td>
<td>3</td>
</tr>
<tr>
<td>Well pump 1/3hp</td>
<td>3,000</td>
<td>1,000</td>
<td>3</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>6,750</td>
<td>1,350</td>
<td>5</td>
</tr>
<tr>
<td>Fridge/Freezer</td>
<td>2,900</td>
<td>700</td>
<td>4.1</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>3,000</td>
<td>1,500</td>
<td>2</td>
</tr>
<tr>
<td>1/2hp Garage Door</td>
<td>3,225</td>
<td>875</td>
<td>3.7</td>
</tr>
</tbody>
</table>

#### 4.2. Solar Radiation and Ambient Temperature

The optimisation program developed requires the solar radiation on a horizontal plane and the ambient temperature as inputs to generate the maximum output power from the PV panels over the optimisation horizon. As the solar radiation varies over the course of the year a yearly solar radiation profile was obtained from a located in Northern Europe, geographically located at 53-17-N latitude and 9-04-W longitude. A computer based weather station was installed at the site to create a database of solar radiation, wind speed and ambient temperature for system simulations, using a solar radiation sensor and wind anemometer. The measurements of the temperature and solar radiation are recorded on minute by minute basis [81]. Figure 4.4 and Figure 4.5 give a graphical representation of the solar radiation and ambient temperature respectively as recorded at the site during 2008 - 2009.
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Figure 4-4 Annual solar radiation profile

Figure 4-5 Annual ambient temperature profile
4.3. Modelling Assumptions

A number of assumptions were made to enable the design and optimisation of the PV system. A few problems were encountered at the weather station which resulted in incorrect or no data being recorded for periods of time. In these situations the solar radiation data was replaced with data from the preceding available day. The temperature profile for the missing data was obtained from a weather monitoring station at Shannon airport 52-7-N latitude 8-9-W longitude, the closest recording site.

The domestic load profile utilised the low energy data from “Three European Domestic Electrical Consumption profiles July 2006”. Similar to the weather station some missing data was experienced. This profile replaced the missing data points with data points assumed to have the same characteristics, e.g. missing Monday data are replaced by other existing Monday data [79]. The data provided was averaged over five minute periods. This data was manipulated to have smaller time steps to highlight the short duration peak power requirements of domestic appliances, as the ultracapacitors are generally intended to supply the peaks in power for a short duration of time.

The system voltage is taken as 12V. The component values utilised in the design were the BP350 50W PV panel, the Yuasa NP18-12 18Ah 12V VRLA battery and a Nesscap 2.7V 600F ultracapacitor. Since the optimisation function is to minimise the system lifetime cost, the cost utilised for the components can have a big impact on the resulting system. The component costs employed to calculate the system cost were taken as €200 for the PV panel, €70 for the battery and €45 for the ultracapacitor.

The PV panel orientation is facing due south to obtain the maximum solar radiation throughout the year. The optimised system can result in excess power being produced by the PV panel during times of high solar radiation, producing dump
energy. Once the PV panels are installed there is no cost incurred in producing power, therefore, no penalty cost has been associated with dump energy.

For the optimisation and the simulations both the ultracapacitor and battery banks were assumed to have an initial SOC of 100%. A controller is included in the system to prevent over charge of the batteries and ultracapacitors and to limit their discharge to the LVD limits being implemented. During charging the ultracapacitors are given priority to best ensure they have adequate charge to meet the next peak in power. The ultracapacitors can be charged from either the PV panels or the battery bank during low solar radiation.

### 4.4. Simulink System Model

Simulink models constructed according to the component models described in Chapter 2 with the addition of a controller are combined to develop the system model. Two system models are developed to compare the battery only and the ultracapacitor battery HESS. The controller for the battery only and the HESS are described in Table 4-2 and Table 4-3 respectively. Figure 4.6 and Figure 4.7 illustrate the top level battery only and the HESS respectively with the detailed component models shown in Appendix C.
Table 4-2  Battery storage system control

<table>
<thead>
<tr>
<th>Condition</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>((P_{mppt} = P_{Load}))</td>
<td>(I_{Bat} = 0)</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{pv} + I_{Bat})</td>
</tr>
<tr>
<td>((P_{mppt} &gt; P_{Load}) &amp; (BatSOC \geq 100%))</td>
<td>(I_{Bat} = 0)</td>
</tr>
<tr>
<td></td>
<td>(Dump\ Energy = P_{mppt} - P_{Load})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{pv} + I_{Bat} - \text{Dump\ Energy})</td>
</tr>
<tr>
<td>((P_{mppt} &gt; P_{Load}) &amp; (BatSOC &lt; 100%))</td>
<td>(I_{Bat} = (P_{Load} - P_{mppt})/V_{sys})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{Bat} + I_{pv})</td>
</tr>
<tr>
<td>((P_{mppt} &lt; P_{Load}) &amp; (BatSOC &gt;  BatSOClim))</td>
<td>(I_{Bat} = (P_{Load} - P_{mppt})/V_{sys})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{Bat} + I_{pv})</td>
</tr>
<tr>
<td>(\text{Else})</td>
<td>(I_{Bat} = P_{mppt}/V_{sys})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = 0)</td>
</tr>
</tbody>
</table>

Table 4-3  Hybrid storage system control

<table>
<thead>
<tr>
<th>Condition</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>((P_{mppt} = P_{Load}) &amp; (UcapSOC &lt; 100%) &amp; (BatSOC &gt; BatSOClim))</td>
<td>(I_{Bat} = B_{lim})</td>
</tr>
<tr>
<td></td>
<td>(I_{Ucap} = -B_{lim})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{pv} + I_{Bat} + I_{Ucap})</td>
</tr>
<tr>
<td>((P_{mppt} = P_{Load}) &amp; (UcapSOC &gt; 100%) &amp; (P_{mppt} = P_{Load}) &amp; (BatSOC \leq BatSOClim))</td>
<td>(I_{Bat} = 0)</td>
</tr>
<tr>
<td></td>
<td>(I_{Ucap} = 0)</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{pv} + I_{Bat} + I_{Ucap})</td>
</tr>
<tr>
<td>((P_{mppt} &gt; P_{Load}) &amp; (UcapSOC &lt; 100%))</td>
<td>(I_{Bat} = 0)</td>
</tr>
<tr>
<td></td>
<td>(I_{Ucap} = (P_{Load} - P_{mppt})/V_{sys})</td>
</tr>
<tr>
<td></td>
<td>(I_{Load} = I_{pv} + I_{Bat} + I_{Ucap})</td>
</tr>
<tr>
<td>((P_{mppt} &gt; P_{Load}) &amp; (BatSOC &lt; 100%) &amp; (UcapSOC \geq 100%))</td>
<td>(I_{Bat} = (P_{Load} - P_{mppt})/V_{sys})</td>
</tr>
<tr>
<td></td>
<td>(I_{Ucap} = 0)</td>
</tr>
</tbody>
</table>
### CHAPTER 4. MATLAB SYSTEM ANALYSIS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equation</th>
</tr>
</thead>
</table>
| $(P_{mppt} > P_{Load}) \& (BatSOC \geq 100\%) \& (UcapSOC \geq 100\%)$ | $I_{Bat} = 0$  
$I_{Ucap} = 0$  
Dump Energy: $P_{mppt} - P_{Load}$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$-Dump Energy |
| $(P_{mppt} < P_{Load}) \& (BatSOC > BatSOClim) \& (UcapSOC > UcapSOClim) \& (I_{storage} \leq Batlim) \& (UcapSOC < 100\%)$ | $I_{Bat} = B_{lim}$  
$I_{Ucap} = ((P_{Load} - P_{mppt})/V_{sys} - B_{lim}$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| $(P_{mppt} < P_{Load}) \& (BatSOC > BatSOClim) \& (UcapSOC > UcapSOClim) \& (I_{storage} \leq Batlim) \& (UcapSOC \geq 100\%)$ | $I_{Bat} = (P_{Load} - P_{mppt})/V_{sys}$  
$I_{Ucap} = 0$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| $(P_{mppt} < P_{Load}) \& (BatSOC > BatSOClim) \& (UcapSOC < BatSOClim) \& (I_{storage} > Batlim)$ | $I_{Bat} = Batlim$  
$I_{Ucap} = ((P_{Load} - P_{mppt})/V_{sys}) - B_{lim}$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| $(P_{mppt} < P_{Load}) \& (BatSOC > BatSOClim) \& (UcapSOC \leq UcapSOClim) \& (I_{storage} \leq Batlim)$ | $I_{Bat} = Batlim$  
$I_{Ucap} = ((P_{Load} - P_{mppt})/V_{sys}) - B_{lim}$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| $(P_{mppt} < P_{Load}) \& (BatSOC > BatSOClim) \& (UcapSOC \leq UcapSOClim) \& (I_{storage} > Batlim)$ | $I_{Bat} = ((P_{Load} - P_{mppt})/V_{sys})$  
$I_{Ucap} = 0$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| $(P_{mppt} < P_{Load}) \& (BatSOC \leq BatSOClim) \& (UcapSOC > UcapSOClim)$ | $I_{Bat} = 0$  
$I_{Ucap} = ((P_{Load} - P_{mppt})/V_{sys})$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |
| Else                                           | $I_{Bat} = 0$  
$I_{Ucap} = -P_{mppt}/V_{sys}$  
$I_{Load} = I_{PV} + I_{Bat} + I_{Ucap}$ |

**Note:**  
$IPV = P_{mppt}/V_{sys}$
Figure 4-6 Simulink top level system model with battery only storage
Figure 4-7 Simulink top level system model with HESS
4.5. Battery storage VS Battery Ultracapacitor HESS

The battery only storage and the HESS system models were utilised to compare both systems, analysing the impact of including the ultracapacitor. The ultracapacitor employs a physical reaction to produce power whereas the battery depends on chemical reactions, therefore, the ultracapacitor had a faster reaction time than the battery. The comparison of the two systems was performed over a 24 hour period utilising the peak load profile of Figure 4.1 with an un-optimised system, an identical battery bank is utilised in both systems. The battery voltage for the battery only system and the HESS are given in Figure 4.8 and Figure 4.9 respectively.

Figure 4-8 Battery voltage for the battery only system
The battery capacity varies with the discharge rate; high currents reduce the battery capacity leading to voltage drops. In Figure 4.8 a voltage drop can be seen on the battery due to the increased current each time the motor is started. The voltage drop is eliminated on the battery in the HESS as shown in Figure 4.9; the ultracapacitor provides the high power required to start the motor reducing the current drawn from the battery.

Implementing a LVD of 11.8V representing a 20% SOC limit in the PV system with battery storage shown in Figure 4.8 triggers the limit every time the motor is started, this could result in the motor burning out from repeat attempts to start. In Figure 4.9, with the high power requirement of the motor supplied by the ultracapacitor, the battery does not experience the voltage drop. Employing the same LVD limit on the battery in the HESS extends the operating time of the system.
by approximately 16 hours. Increased battery capacity is required in the battery only system of Figure 4.8 to enable the motor to be started throughout the day without breaching the LVD limit. This could result in a large battery pack, increasing the lifetime system cost as generally batteries need to be replaced every three to five years [82].

4.6. Passive VS Active HESS Configuration

The active and passive HESS configurations discussed in Chapter 2 were investigated utilising the simulation model to find the best arrangement. The passive HESS configuration connects the parallel battery and ultracapacitor directly to the load with no control over the operation of the HESS. The active configuration implements control over the battery and ultracapacitor allowing both components to be operated at different voltages. A SOC limit can be employed for the ultracapacitor similar to that of the battery allowing better utilisation of the components. Setting the ultracapacitor SOC limit to 50% utilises approximately 75% of its available energy.

The controller was removed from the HESS model to evaluate the impact of using the passive HESS configuration. Figure 4.10 illustrates the battery and ultracapacitor voltage for the pulse load profile of Figure 4.2. In this case the voltage of the ultracapacitor follows the battery voltage. Since the ultracapacitor SOC is directly related to its voltage, the ultracapacitor always remains at a high SOC causing under utilisation of the ultracapacitor available energy. In Figure 4.10 the circuit voltage does not fall below 11.6V, therefore, the ultracapacitor SOC remains above 86% at all times. With the passive HESS the initial power is supplied from both the battery and ultracapacitor split according to the internal resistance of both components. The ultracapacitor has a much lower internal resistance than the battery; therefore, the ultracapacitor provides the majority of the initial transient power. In Figure 4.10 this is highlighted by the initial voltage drop which
is the result of the ultracapacitor discharging from 13.5V to match the battery voltage.

Employing an active HESS the output from both the battery and the ultracapacitor can be controlled, which enhances the energy consumption from the ultracapacitor as shown in Figure 4.11, the active HESS ultracapacitor SOC for the pulse load profile. A SOC limit of 20% is employed for the ultracapacitor. With the pulse power load the passive system utilised only approximately 26% of the available energy from the ultracapacitor, this is increased to over 90% for the active HESS.
To investigate the optimisation methodology of Chapter 3, a yearly optimisation was performed with the peak load profile described in Figure 4.1 repeated on a daily basis for the solar radiation and temperature profiles of Figure 4.4 and Figure 4.5 respectively. The simulations were performed taking the assumptions of Section 4.3 into account. The LVD limit was varied to represent SOC limits from 20% to 90% SOC to examine its impact on the system lifetime cost. Both the battery only and the battery ultracapacitor HESS were analysed to observe the benefit of the ultracapacitors in the optimised system.

Figure 4-11  Ultracapacitor voltage for active HESS

4.7.  Peak Power Load Analysis

To investigate the optimisation methodology of Chapter 3, a yearly optimisation was performed with the peak load profile described in Figure 4.1 repeated on a daily basis for the solar radiation and temperature profiles of Figure 4.4 and Figure 4.5 respectively. The simulations were performed taking the assumptions of Section 4.3 into account. The LVD limit was varied to represent SOC limits from 20% to 90% SOC to examine its impact on the system lifetime cost. Both the battery only and the battery ultracapacitor HESS were analysed to observe the benefit of the ultracapacitors in the optimised system.
4.7.1. Peak Load Without Constraints

The results of the optimisation are outlined in Table 4-4 providing the number of PV panels, batteries, ultracapacitors along with the system lifetime cost and the days of consecutive inadequate recharge experienced by the battery over the year for varying SOC limits. The optimum fixed angle for the site to produce the maximum annual power from the PV panels was found to be 36° facing south. No restrictions on component volumes were implemented in the cases described in Table 4-4. Lowering the battery SOC limit reduces the system costs as more energy is made available from the battery bank.

Table 4-4  Optimised HESS VS battery storage system for various SOC limits

<table>
<thead>
<tr>
<th>SOC Limit</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>No Par Ucap</th>
<th>Cost</th>
<th>Days InadChar</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>27</td>
<td>14</td>
<td>1</td>
<td>€10,525</td>
<td>7</td>
<td>29</td>
<td>16</td>
<td>€11,400</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>29</td>
<td>14</td>
<td>1</td>
<td>€10,925</td>
<td>7</td>
<td>33</td>
<td>15</td>
<td>€11,850</td>
<td>7</td>
</tr>
<tr>
<td>40</td>
<td>31</td>
<td>15</td>
<td>1</td>
<td>€11,675</td>
<td>7</td>
<td>31</td>
<td>19</td>
<td>€12,850</td>
<td>7</td>
</tr>
<tr>
<td>50</td>
<td>33</td>
<td>16</td>
<td>1</td>
<td>€12,425</td>
<td>7</td>
<td>33</td>
<td>21</td>
<td>€13,950</td>
<td>7</td>
</tr>
<tr>
<td>60</td>
<td>33</td>
<td>20</td>
<td>1</td>
<td>€13,825</td>
<td>7</td>
<td>33</td>
<td>25</td>
<td>€15,350</td>
<td>7</td>
</tr>
<tr>
<td>70</td>
<td>34</td>
<td>26</td>
<td>1</td>
<td>€16,125</td>
<td>7</td>
<td>34</td>
<td>32</td>
<td>€18,000</td>
<td>7</td>
</tr>
<tr>
<td>80</td>
<td>56</td>
<td>23</td>
<td>1</td>
<td>€19,475</td>
<td>4</td>
<td>52</td>
<td>34</td>
<td>€22,300</td>
<td>4</td>
</tr>
<tr>
<td>90</td>
<td>83</td>
<td>29</td>
<td>1</td>
<td>€26,975</td>
<td>4</td>
<td>75</td>
<td>50</td>
<td>€32,500</td>
<td>2</td>
</tr>
</tbody>
</table>

The optimised results of Table 4-4 were simulated utilising the Simulink system models. The optimised system returns the battery to 100% SOC for the majority of the year. There are two periods of extended low solar radiation, one occurring at the start of the optimisation horizon and one near the end. During these extended periods the battery is inadequately recharged each day, resulting in an additional drop in the battery SOC each day. Figure 4.12 gives the daily minimum and maximum SOC of the battery bank, for the HESS over the optimisation horizon for a SOC limit of 20%.
Returning the battery bank to 100% SOC each day helps to prevent sulphation and stratification. Sulphation is caused by maintaining the battery in an undercharged state for an extended period of time. Lead sulphate crystals are usually converted into lead during the charging process. If the battery is not adequately recharged some of the lead sulphate crystals remain on the plates. Eventually the soft lead sulphate crystals become hard and act as an insulating layer preventing the battery from receiving charge. The capacity of the battery is reduced and eventually cell shorting can occur. Stratification caused by the insufficient charging of the battery occurs in flooded lead acid batteries. It arises when the heavier sulphuric acid in the electrolyte sinks to the bottom of the battery case leaving almost pure water on top. The almost pure water at the top of the battery case is not a good conductor of electricity, for this reason only the lower part of the battery plates is available for
conducting electricity reducing the battery capacity. Oxidation occurs on the upper part of the plates causing corrosion. The corrosion results in permanent damage, reduces the performance of the battery and shortens the battery life. Equalization and gassing can help to prevent stratification by agitating the electrolyte [83].

The optimisation process was performed over the course of a year taking component lifetime into consideration when calculating the system cost. Therefore, due to the short lifetime of the battery it was found to be more economical to increase the number of PV panels required to supply the load during periods of low solar radiation, generating dump energy during the periods of high solar radiation. There was no cost constraint placed on the dump energy as the cost associated with the generation of PV power is taken as zero. The optimum combination of the battery bank and PV array is such that the batteries are recharge to full SOC for the majority of the year.

The ultracapacitor SOC over a three day period in December is displayed in Figure 4.13. The active HESS of Figure 2.25 was implemented in the design. The minimum operating voltage of the ultracapacitor was set to 6V in the optimisation process. The ultracapacitor is recharged by both the PV panels and the batteries, therefore, the ultracapacitor is maintained at a high SOC. Designing the dc-dc converter to have a lower input voltage will allow the number of series connected ultracapacitors to be reduced, utilising more of the ultracapacitors energy.
The battery storage system needs to be optimised taking the voltage drop at motor start up into account, resulting in an increased battery bank and, therefore, increased system lifecycle cost as seen in Table 4-4. The HESS cost remains lower for all SOC limits in comparison to the battery system, however, greater benefit can be seen when the SOC limit is at a high level, as only a small voltage drop would be acceptable before the LVD limit would be triggered by the battery storage system. The SOC limit of 20% was found to give the lowest HESS system cost as the majority of the available energy in the HESS can be utilised for the periods of low solar radiation which can occur for several days.

Figure 4-13  Ultracapacitor SOC for 3 days in December for HESS with a SOC limit of 20%
4.7.2. Peak Load With Volume Constraints

The HESS with a 20% SOC limit imposed on the battery bank was examined for volume restrictions on the individual component in the system. The number of PV panels for this case was restricted to 15, a reduction of 12 panels. The reduction in the number of PV panels lead to the number of consecutive days the battery experiences inadequate recharge increasing to 8, with the number of batteries required to satisfy the SOC limit increasing to 40. The reduction in the number of PV panels increases the need for energy storage. The battery bank in the HESS is increased to enable the load to be supplied for the extended periods of low solar radiation. As the number of PV panels is reduced the amount of dump energy produced during the year also diminishes. The increase in the number of batteries required and their replacement cost throughout the lifetime of the system increases the overall cost to €17,225. The battery daily minimum and maximum SOC over the course of the year can be seen in Figure 4.14. Compared to Figure 4.12 the battery bank is not as frequently recharged to 100% SOC during the winter period.

A second sensitivity analysis limiting the number of batteries to seven in the HESS with a battery SOC limit of 20% was also performed. Limiting the battery bank in the HESS necessitates a larger PV array to be installed, to generate the daily power requirement of the load as the battery bank is not large enough to provide the load for an extended period of time. In this situation, the number of PV panels is nearly doubled to 51, increasing the system cost to €12,875. The large number of PV panels also increases the amount of dump energy produced by the PV array during high solar radiation. The annual daily minimum maximum battery SOC can be seen in Figure 4.15. The large number of PV panels returns the battery bank to 100% SOC for the majority of the year but the reduction in the number of batteries means the batteries are discharged to a lower SOC. Comparing the lifetime system cost of both sensitivity analysis highlights further the impact the battery bank has on the lifetime cost due to number of battery replacements required during this period.
Figure 4-14 Battery daily maximum/minimum SOC with the PV array limited to 15 panels and SOC limit of 20%

Figure 4-15 Battery daily maximum/minimum SOC with the battery bank limited to 7 batteries and a SOC limit of 20%
4.7.3. Peak Load With a LPSP Constraint

The system size and lifecycle cost can be reduced if the loads supplied were non critical and an LPSP of greater than zero is considered. Throughout the majority of the year the batteries in the system are maintained at a high SOC in the HESS. If the system was allowed to drop the load for a short period of time during prolonged periods of low solar radiation which only occurs twice during the year the battery bank could be reduced. Setting the LPSP to $0.9132 \times 10^{-3}$ in the optimisation process for the HESS with a SOC limit of 20% reduces the system cost to €9,825. This is achieved by reducing the size of the battery bank. A loss of load of approximately nine hours was observed during the period of low solar radiation at the end of the year. The daily maximum and minimum Battery SOC for the HESS system is shown in Figure 4.16. Allowing a larger LPSP limit to be observed will further reduce the system lifetime cost at the expense of a less reliable system.

Figure 4-16 Battery daily maximum/minimum SOC for system optimised with a SOC limit of 20% and a LPSP of $0.9132 \times 10^{-3}$
4.7.1. Peak Load With Varied Component Cost

Since the optimisation function is to minimise the system lifetime cost, the price of each of the components in the system will have an impact on the results. To evaluate the impact of component cost, a sensitivity analysis is carried out by varying the component prices. The peak load profile of Figure 4.1 was utilised for this analysis. The cost of the PV panel, battery and ultracapacitor were originally €200, €70 and €45 respectively. Table 4-5 outlines the optimised system for the varied component costs when the battery LVD limit was set to 12.85V.

Table 4-5  Optimised system with varied component costs for a peak load

<table>
<thead>
<tr>
<th>Cost Varied</th>
<th>PV Cost</th>
<th>Ucap Cost</th>
<th>Batt Cost</th>
<th>No PV Panels</th>
<th>No of Ucap</th>
<th>No Par Battery</th>
<th>System Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>200</td>
<td>45</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,325</td>
<td>2</td>
</tr>
<tr>
<td>PV</td>
<td>150</td>
<td>45</td>
<td>70</td>
<td>85</td>
<td>1</td>
<td>29</td>
<td>23,125</td>
<td>2</td>
</tr>
<tr>
<td>PV</td>
<td>100</td>
<td>45</td>
<td>70</td>
<td>88</td>
<td>1</td>
<td>28</td>
<td>18,825</td>
<td>1</td>
</tr>
<tr>
<td>PV</td>
<td>50</td>
<td>45</td>
<td>70</td>
<td>107</td>
<td>1</td>
<td>23</td>
<td>13,625</td>
<td>0</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>70</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,450</td>
<td>2</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>60</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,400</td>
<td>2</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>50</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,350</td>
<td>2</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>40</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,300</td>
<td>2</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>30</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,250</td>
<td>2</td>
</tr>
<tr>
<td>Ucap</td>
<td>200</td>
<td>20</td>
<td>70</td>
<td>76</td>
<td>1</td>
<td>34</td>
<td>27,200</td>
<td>2</td>
</tr>
<tr>
<td>Batt</td>
<td>200</td>
<td>45</td>
<td>60</td>
<td>54</td>
<td>1</td>
<td>47</td>
<td>25,125</td>
<td>4</td>
</tr>
<tr>
<td>Batt</td>
<td>200</td>
<td>45</td>
<td>50</td>
<td>54</td>
<td>1</td>
<td>47</td>
<td>22,775</td>
<td>4</td>
</tr>
<tr>
<td>Batt</td>
<td>200</td>
<td>45</td>
<td>40</td>
<td>53</td>
<td>1</td>
<td>48</td>
<td>20,425</td>
<td>4</td>
</tr>
<tr>
<td>Batt</td>
<td>200</td>
<td>45</td>
<td>30</td>
<td>50</td>
<td>1</td>
<td>52</td>
<td>18,025</td>
<td>4</td>
</tr>
<tr>
<td>Batt</td>
<td>200</td>
<td>45</td>
<td>20</td>
<td>32</td>
<td>1</td>
<td>78</td>
<td>14,425</td>
<td>7</td>
</tr>
</tbody>
</table>

From Table 4-5 it can be seen that varying the cost of the ultracapacitor has no impact on the quantity of components required to meet the load, as the ultracapacitors are operated only to supply the peak power requirements and are not utilised for energy storage. Varying the cost of the PV panels and the batteries has an impact on the optimised system. Small variations in the battery and PV
panel cost have minimal impact on the volume of component. Reducing the cost of the PV panels means it is more economical to increase the quantity of PV panels reducing the battery bank. With the number of PV panels approaching the point where they can supply the power requirements for the worst day of the year. Decreasing the cost of the batteries in the system increases the energy storage, reducing the power generated by the PV array. In this case, the energy generated by the PV array is better utilised as less dump energy will be generated.

4.7.2. Peak Load With Varied Optimisation Horizon

All previous optimisation has been carried out on an annual basis. To observe the impact the chosen optimisation horizon has on the system cost, the optimisation was performed for the day, week and month with the lowest solar radiation. The load profile utilised is the peak load profile of Figure 4.1 with the LVD limit set to represent a SOC of 20%. The optimisation was performed for the 21st of December, Week 51, and the month of December. The results of the optimisation are given in Table 4-6.

<table>
<thead>
<tr>
<th>Optimisation Horizon</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>No Par Ucap</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>104</td>
<td>4</td>
<td>0</td>
<td>22,200</td>
<td>0</td>
</tr>
<tr>
<td>Week</td>
<td>33</td>
<td>10</td>
<td>1</td>
<td>10,325</td>
<td>5</td>
</tr>
<tr>
<td>Month</td>
<td>26</td>
<td>16</td>
<td>1</td>
<td>11,025</td>
<td>7</td>
</tr>
</tbody>
</table>

The results of the optimisation were assessed to determine the optimised systems performance on an annually basis. Figure 4.17 to Figure 4.19 illustrate the daily maximum and minimum battery SOC limits for the Day, Week and Month optimisation results respectively for a yearly simulation.
Figure 4-17  Battery daily SOC for an optimisation horizon of 1 day

Figure 4-18  Battery daily SOC for an optimisation horizon of 1 week
In Figure 4.17 the battery SOC remains above the SOC limit throughout the year, but analysing the battery voltage shows the LVD limit was triggered during the year, except for the summer months. Performing the optimisation for one day resulted in an optimised system that did not include an ultracapacitor bank; therefore, a voltage drop is experienced by the battery each time the motor is started. During the night time hours and in the early morning these voltage drops break the LVD limit. Including an ultracapacitor in the system will prevent this from occurring and the load would be supported at all times.

Optimising the system for the worst week of the year resulted in two periods one at the start and one at the end of the year where the load was not met as shown in Figure 4.18 where the battery SOC reaches 20%. A period of extended low solar radiation greater than one week will result in this situation as it is outside the period observed during the optimisation. Utilising an optimisation horizon of one

Figure 4-19 Battery daily SOC for an optimisation horizon of 1 month
month, Figure 4.19, resulted in an optimised system that met the load requirements at all times, since the complete period of low solar radiation was taken into account when designing the system.

### 4.7.3. Alternative Peak Load

The benefit of the HESS can be seen in Table 4-4 for a motor load that is repeatedly started throughout the day. This will not be the case for all motor applications. For water irrigation the motor may only be required to start once per day. The load profile of Figure 4.1 was adapted for two situations - a motor started daily at 4am for 45 minutes and a motor started daily at 5pm for 45 minutes. The results of the optimisation are outlined in Table 4-6 and Table 4-7 for the profile of the motor started at 4am and 5pm respectively. The results of Table 4-6 and Table 4-7 are similar and follow the trend of those in Table 4-4. The addition of the ultracapacitor reduces the system lifetime cost, with the greatest benefit seen when the battery SOC limit is high. The daily maximum minimum battery SOC for the motor started at 5pm is illustrated in Figure 4.20.

Table 4-7  HESS VS battery storage system for motor operated daily at 4am for 45 minutes

<table>
<thead>
<tr>
<th>SOC Limit</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>Hess System</th>
<th>Cost</th>
<th>Days InadChar</th>
<th>Battery Storage System</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>€1,125</td>
<td>7</td>
<td>1</td>
<td>€1,250</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>€1,125</td>
<td>7</td>
<td>2</td>
<td>€1,450</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>€1,125</td>
<td>7</td>
<td>1</td>
<td>€1,600</td>
<td>7</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>€1,325</td>
<td>4</td>
<td>2</td>
<td>€1,800</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>€1,325</td>
<td>4</td>
<td>2</td>
<td>€2,150</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>€1,525</td>
<td>2</td>
<td>3</td>
<td>€2,700</td>
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<td>80</td>
<td>3</td>
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<td>1</td>
<td>€1,875</td>
<td>2</td>
<td>3</td>
<td>€3,750</td>
<td>2</td>
</tr>
<tr>
<td>90</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>€2,775</td>
<td>1</td>
<td>3</td>
<td>€6,900</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 4-8  HESS VS battery storage system for motor operated daily at 5pm for 45 minutes

<table>
<thead>
<tr>
<th>SOC Limit</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>Hess System</th>
<th>Cost</th>
<th>Days InadChar</th>
<th>Battery Storage System</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>1</td>
<td>€1,125</td>
<td>7</td>
<td>3</td>
<td>€1,250</td>
<td>7</td>
</tr>
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<td>30</td>
<td>1</td>
<td>2</td>
<td>1</td>
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<td>7</td>
<td>2</td>
<td>€1,450</td>
<td>4</td>
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<tr>
<td>40</td>
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<td>2</td>
<td>1</td>
<td>€1,125</td>
<td>7</td>
<td>1</td>
<td>€1,600</td>
<td>7</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>€1,325</td>
<td>4</td>
<td>2</td>
<td>€1,800</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>2</td>
<td>1</td>
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<td>4</td>
<td>2</td>
<td>€2,150</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>€1,675</td>
<td>4</td>
<td>3</td>
<td>€2,700</td>
<td>2</td>
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<td>80</td>
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<td>3</td>
<td>1</td>
<td>€1,675</td>
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<td>3</td>
<td>€3,750</td>
<td>2</td>
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<tr>
<td>90</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>€2,725</td>
<td>4</td>
<td>3</td>
<td>€6,900</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 4-20  Battery daily SOC for motor started daily at 5pm
4.8. Pulse Power Load Analysis

The optimisation program was utilised to design a PV system for the pulse load profile of Figure 4.2 with a duty cycle of 0.1. The results of the optimisation with the SOC limit varied from 20% to 90% are given in Table 4-9. Similar to the peak load profiles the HESS results in a lower lifetime system cost compared to the battery only system, while reducing the SOC limit also reduces the system cost.

Table 4-9 Optimised HESS VS battery storage system for pulse load profile

<table>
<thead>
<tr>
<th>SOC Limit</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>No Par Ucap</th>
<th>Cost</th>
<th>Days InadChar</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>€4,255</td>
<td>7</td>
<td>13</td>
<td>6</td>
<td>€4,700</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>€4,255</td>
<td>7</td>
<td>14</td>
<td>6</td>
<td>€4,900</td>
<td>7</td>
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<td>6</td>
<td>1</td>
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<td>6</td>
<td>1</td>
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<td>90</td>
<td>26</td>
<td>14</td>
<td>1</td>
<td>€10,255</td>
<td>2</td>
<td>26</td>
<td>23</td>
<td>€13,250</td>
<td>4</td>
</tr>
</tbody>
</table>

The daily maximum and minimum battery SOC for the system with a SOC limit of 20% is illustrated in Figure 4.21. The battery current limit implemented by the EMS impacts the ability of the system to maintain the load. The ultracapacitor needs to be recharged between pulses by the combination of PV panels and the battery bank. If the battery current limit is set to low the ultracapacitor is not recharged and the battery bank will be required to supply the pulses. The increased current discharged from the battery will result in higher $I^2R$ losses and voltage drops.
The duty cycle of the pulses also has an impact on the system design. As the duty cycle is increased the ultracapacitor has less time between pulses to recharge. The battery discharge current limit is increased in this situation reducing the benefit of the HESS. Eventually the battery discharge current approaches the high pulse current and the battery only storage system is sufficient to supply the load. Table 4-10 outlines the difference the duty cycle has on the system design for a SOC limit of 20%.

Figure 4-21  Battery daily maximum/minimum SOC for HESS with a SOC limit of 20% for the pulse load
Table 4-10  HESS for pulse load with varied duty cycle for SOC limit of 20%

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>No PV Panels</th>
<th>No Par Battery</th>
<th>No Par Ucap</th>
<th>Cost</th>
<th>Days InadChar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>€4,255</td>
<td>7</td>
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<tr>
<td>0.2</td>
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<td>7</td>
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<td>14</td>
<td>10</td>
<td>1</td>
<td>€6,525</td>
<td>7</td>
</tr>
</tbody>
</table>

4.9. Domestic Power Load Analysis

The domestic load profile of Figure 4.3 has a number of spikes in demand occurring throughout the year. A PV system with a battery ultracapacitor HESS was design for the profile. The optimised system consists of 122 PV panel, 88 parallel batteries and 5 series connected ultracapacitors. Figure 4.22 illustrates the daily maximum and minimum battery SOC for the HESS with a SOC limit of 20%.
The optimised system contains a large quantity of parallel connected batteries. In this case the batteries and the ultracapacitors work together to supply the large peak power requirement of the load. The battery current limit implemented by the EMS has an effect on the operation of the system. Setting the battery current limit low will result in the ultracapacitor supplying a large portion of the peak power. This can discharge the ultracapacitor before the end of the peak requirement. A small increase in the battery current limit can prevent this from occurring without the need to increase the ultracapacitor bank.
4.10. Summary

In this chapter the optimisation methodology described in Chapter 3 was analysed for a peak, pulse and domestic load profile. The assumptions made during the process were outlined in Section 4.3. The systems were optimised utilising a Matlab program, with the results assessed with Simulink models of the battery only and the battery ultracapacitor HESS. The main optimisation function is to minimise the system lifetime cost.

The addition of the ultracapacitor in the system reduces the voltage drops experienced by the battery with an increased discharge current, extending the system runtime when a LVD limit is implemented. The active combination of the battery and ultracapacitor leads to better utilisation of the ultracapacitor. The HESS has a lower lifetime system cost compared to a battery only storage system when there is a high peak to average power ratio. The cost benefit is greater with a higher LVD limit as a small voltage drop will trigger the limit.

In addition to the system cost a sensitivity analysis was also performed on the component volumes which may be limited due to the availability of space. Limiting the number of PV panels can result in a greater increase in the system lifetime cost as an increased number of batteries are required to meet the load. Allowing an LPSP of greater than zero will reduce the system lifetime cost as the load can be dropped for a particular length of time during extended periods of low solar radiation. The cost of the PV panels and the batteries has an impact on the system configuration. The optimisation horizon chosen also impacts the design of the system. Optimising the system using the worst day of the year can lead to an oversized system as this day will not be typical of most days of the year. An annual optimisation is preferred as the seasonal variation in solar radiation will be considered.
CHAPTER 5.

EXPERIMENTAL ANALYSIS

In Chapter 4 a Matlab Simulink system model was utilised to analyse the battery ultracapacitor HESS. The methodology developed in Chapter 3 was employed to obtain the component sizes in the system model for a given load and solar radiation profile. Comparing the HESS to a battery only storage system showed advantages of employing the HESS. The battery did not experience large voltage drops resulting in an extension of the battery run time.

The advantages of the HESS over the battery only storage system are investigated in this chapter by employing an experimental test bench. A solar simulator with a starter motor or electronic load was utilised in the test setup. The recorded solar radiation and load profiles of Chapter 4 were modified for the analysis. This chapter describes the test setup and investigations performed.

5.1. Test Bench

A test bench was setup in the laboratory to simulate the PV system. It consists of a tracker, PV panel emulator, DC-DC converter, battery, ultracapacitor, load and sensors. The test setup is controlled with Labview software. The block diagram of the test bench with battery storage is shown in Figure 5.1.
5.1.1. Photovoltaic Panel Emulator

The PV panel emulator is to replicate the characteristics of a high power PV panel using a low power PV cell. This approach has several advantages. The emulator allows the user to obtain reliable results that are reproducible at any time regardless of the weather conditions. The solar radiation for the PV cell is much easier to generate and control compared with a large PV panel.

The PV panel emulator consists of a solar generator, PV cell and a power amplifier as shown in Figure 5.2. The solar generator, a dimmable 12V/50W halogen lamp, replicates the solar radiation. The radiation of the halogen lamp is controlled by an Agilent E3633A DC power supply. Based on the characteristic of the PV cell, a power amplifier is connected to the cell to amplify the power generated. The output of the amplifier will have the amplified I-V characteristic of the PV cell. Figure 5.3 shows the I-V and P-V characteristics of the PV panel emulator which models a 12V/50W PV panel.
5.1.2. Maximum Power Point Tracker

MPPT was implemented in the test setup with the buck converter, illustrated in Figure 2.7. The converter consists of a solid-state switch, diode, inductor and input...
and output capacitor. The MPPT is implemented using the ICM described in Section 2.2. The control of the MPPT is implemented by an ADuC7020 microprocessor. The algorithm of the MPPT includes three operating modes for battery charging, similar to the TSC discussed in Section 2.3, MPP (mode 1), absorption (mode 2) and float (mode 3). In mode 1, the battery is charge at the MPP instead of constant current because the PV panel is not an ideal power sources. Therefore, it cannot supply a constant current in all weather conditions. Figure 5.4 shows the flowchart of the charge controller.

![Flowchart of the charge controller](image)
In addition to the MPPT a rotating stage is employed to simulate PV panel tracking. The tracker is to replicate the changing angle between the sun and the solar cell normal that would usually be observed under fixed and solar tracking conditions. In the test setup the halogen light is stationary and the PV cell is rotated according to the different tracking methods. The PV cell is fixed for dual axis tracking but is rotated to mimic single axis tracking and a fixed panel.

5.1.3. Bidirectional Converter

A bidirectional converter is required for the PV system with a battery ultracapacitor HESS to provide an active platform to control the flow of power between the ultracapacitor, battery, PV panel and load. Figure 5.5 shows the circuit diagram for the bidirectional converter utilised in the system. The bidirectional converter is a buck boost topology consisting of two solid-state switches, two power diodes, inductor and input and output capacitor.

![Bidirectional Converter Diagram](image)

Figure 5-5 Circuit diagram of the bidirectional converter

The control of the bidirectional converter is implemented by the ADuC7020 microcontroller. The algorithm to control the converter is separated into the two
operating modes. In buck mode, the higher voltage side (battery) will deliver energy to the lower side (ultracapacitor). In the program, the current extraction is set to 1.5A for charging the ultracapacitor. If a load connected in parallel with the battery draws more than 1.5A and the controller is in buck mode, the battery will deliver the energy to the load and stop charging the ultracapacitor. If the load draws less than 1.5A the remaining current will pass through the converter to charge the ultracapacitor. After the ultracapacitor voltage reaches 9.5V the converter switches to boost mode. The energy stored in the ultracapacitor is allowed to release to the load connected to the battery when the load exceeds 1.5V until the ultracapacitor voltage drops to its minimum threshold voltage. The flowchart of the converter is shown in Figure 5.6

![Flowchart of the bidirectional converter operating modes](image)

Figure 5-6 Flowchart of the bidirectional converter operating modes
5.1.4. Overall Test Setup for a Starter Motor

The elements described in Section 5.1.1 - Section 5.1.4 are combined to form the complete PV system with a battery ultracapacitor HESS to drive a starter motor. The large inrush power of the motor is drawn from the ultracapacitor bank instead of the battery. The block diagram of the system is illustrated in Figure 5.7 with the laboratory setup shown in Figure 5.8. The system has been designed to enable low power loads to be connected in parallel to the battery with the high power load connected in parallel to the ultracapacitor.

![Figure 5-7 Block diagram of the PV simulator](image-url)
Figure 5-8 Laboratory setup of the PV-battery-ultracapacitor HESS with controller unit
5.2. Peak Power Load Impact on Voltage

When supplying high power the battery experiences a voltage drop. The magnitude of the voltage drop will depend on the battery capacity and the power requirement. The magnitude of the voltage drop was assessed for a 12V 12Ah lead acid battery for the peak power loads of Figure 5.9 in Figure 5.10.

![Graph showing peak power loads](image-url)

Figure 5-9 Peak power loads representing 1.38C, 1C, 0.8C, 0.6C and 0.4C battery discharge rates given a 12V/12Ah Lead acid battery
Figure 5-10  Battery voltage for the peak power loads of Figure 5.9

As seen in Figure 5.10 increasing the battery discharge rate results in an increased voltage drop. In a battery HESS the peak power requirements of the load are supplied from the ultracapacitor with the lower power requirement supplied by the battery. Figure 5.11 demonstrates the voltage drop experienced by the ultracapacitor for the peak load profiles of Figure 5.9 with the battery voltage for the lower 33W load shown in Figure 5.12. In Figure 5.12 the large voltage drops seen in Figure 5.10 have been removed.

The transient voltages for the battery and the ultracapacitor for the application of a 200W load are provided in Figure 5.13 and Figure 5.14 respectively. It can be observed that the ultracapacitor experiences a lower voltage drop, approximately 300mV, compared to the battery, approximately 1V, when supplying the 200W load.
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5-11  Ultracapacitor voltage for peak power loads of Figure 5.9

Figure 5-12  Battery voltage for the 33W power requirement
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5-13  Battery voltage and current waveforms when a 200W load is applied

Figure 5-14  Ultracapacitor voltage and current waveforms when a 200W load is applied
5.3. **Actual Vs Averaged Load Profile**

Generally optimisation programs have been developed for solar radiation and load profiles that have been averaged on an hourly basis. Utilising averaged data reduces the impact of peak power fluctuations on the storage system. The actual load profile and the hourly averaged profile of Figure 5.15 were utilised to assess their effect on battery storage. The battery voltage for the actual and averaged profiles is shown in Figure 5.16.

![Figure 5-15 Actual Vs average load profile](image-url)
Figure 5-16 Battery voltage for average and actual load profile of Figure 5.15

In Figure 5.16 a large voltage drop is observed when a high power load is applied to the battery. Where a LVD limit is implemented in the control system, the limit will be triggered earlier for the actual profile compared to the averaged profile. To prevent the LVD limit being broken the capacity of the battery will need to be increased. In the actual profile the battery is also allowed to recover during the periods where no load is applied.

The concern is when data is averaged on an hourly basis the battery storage will not be able to supply high peak power requirements experienced by the system. Averaging the solar radiation on an hourly basis can also have an effect on the system as the fluctuation in solar radiation is not taken into account. During these periods of time the storage system may be required to support the load for a short duration due to passing cloud cover.
5.4. **Starter Motor**

Figure 5.17 shows the conventional setup of the starter motor demonstration model which includes a starter motor with solenoid, switch and VRLA battery. When the switch is turned on the current flows and energises the solenoid coil. The energised coil becomes an electromagnet which pulls the plunger into the coil; the plunger closes a set of contacts which allows high current to reach the starter motor. The start-up current and voltage waveforms of the battery, when the switch is turned on, are provided in Figure 5.18. The results show the start-up current goes over 150A for a few milliseconds before reducing to the normal current of approximately 30A.
In order to provide the large current requirement when the motor is started the capacity of the battery will need to be sufficient. The positive and negative terminals of the battery will also need to be larger and thicker which will increase the price, size and weight of the battery.

The test setup was modified to energise the motor with an ultracapacitor module Figure 5.19. The ultracapacitor module is a Maxwell BMOD0110-P016. It is a 16V/110F module comprised of six 2.7V/650F individual cells connected in series with bus bar connections and active voltage management circuitry as shown in Figure 5.20. The current and voltage waveforms of the ultracapacitor module at motor start-up are shown in Figure 5.21. It can be observed that a lower voltage drop is experience by the ultracapacitor compared to that of the battery.
Figure 5-19  Setup of starter motor with ultracapacitor module

Figure 5-20  Ultracapacitor module, internal structure and active voltage management circuitry
5.5. Passive Vs Active HESS

A passive and active HESS was compared to investigate the utilisation of the ultracapacitor in both situations. For the passive system an ultracapacitor bank, consisting of five series connected Maxwell Boostcap 650F 2.7V ultracapacitors, are connected in parallel to a 12V 12Ah lead acid battery to supply the load of Figure 5.22. When both devices are connected in parallel the stored energy is distributed between the devices until their voltages are balanced. The battery and ultracapacitor voltage for the system is given in Figure 5.23.

Figure 5-21 Start-up current and voltage of the ultracapacitor
CHAPTER 5. EXPERIMENTAL ANALYSIS

Figure 5-22 Load profile for passive HESS

Figure 5-23 Ultracapacitor and battery voltage for the passive HESS
In the passive HESS the power supplied to the load is split between the battery and the ultracapacitor based on the internal resistance of both devices. Therefore, the battery contributes to the peak power resulting in voltage drops for peak power instances. In the passive system the ultracapacitor voltage follows that of the battery. In this case the ultracapacitor will never discharge to a low voltage leading to under utilisation of the ultracapacitor. If the battery voltage is limited to 11.8V only approximately 24% of the ultracapacitor available energy will be utilised compared to approximately 75% if the voltage was allowed to discharge to 6V.

To enable better utilisation of the ultracapacitor an active HESS was utilised. The battery and ultracapacitor bank were connected with the bidirectional converter described in Section 5.1.3 with the peak load of Figure 5.24 connected at the battery side of the converter. The peak load power was limited to 58W due to the current rating of the converter. The battery and ultracapacitor voltage are given in Figure 5.25 and Figure 5.26 respectively.

![Figure 5-24 Peak load profile for active HESS](image-url)
Figure 5-25  Battery voltage in active HESS for load of Figure 5.24

Figure 5-26  Ultracapacitor voltage in active HESS for load of Figure 5.24
In the active HESS the ultracapacitor supplied the peak power requirement of the load. Therefore the voltage drop experience by the battery in the passive HESS is removed. The battery is allowed to recover when there is no load and charges the ultracapacitor when the capacitor voltage drops below a preset threshold. The battery and the ultracapacitor can be maintained at different voltage levels in this configuration leading to better utilisation of the ultracapacitor as the minimum discharge level can be set lower than the battery. With the voltage drops on the battery removed the size of the battery bank can be reduced, as the peak power requirement does not need to be taken into consideration when determining the capacity of the battery bank.

5.6. **Active HESS with Pulse Load**

The active HESS was examined for the pulse power load of Figure 5.27. The pulse load has a duty ratio of 0.5 and duration of two minutes. The battery and ultracapacitor voltage for the pulse load is given in Figure 5.28. In this configuration the load is connected to the ultracapacitor side of the bidirectional converter. The ultracapacitor supplies the load pulses and the battery is maintained at a high SOC. When the ultracapacitor reaches a predefined limit the battery will recharge the ultracapacitor with a low current. The level of current available to recharge the battery and the duty cycle of the pulses in this type of application will have a substantial effect on the ability of the ultracapacitor to maintain a high SOC, allowing it to meet the load requirements. The load profile of Figure 5.27 was modified to have a duty ratio of 0.1; the battery and ultracapacitor voltage for this case is shown in Figure 5.29.
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Figure 5-27  Pulse power load with duty ratio of 0.5

Figure 5-28  Battery and ultracapacitor voltage for pulse load duty ratio of 0.5
Figure 5-29  Battery and ultracapacitor voltage for pulse load duty ratio of 0.1

In Figure 5.29 the ultracapacitor maintains the load and is recharged by the battery when it reaches a lower threshold voltage until the voltage increases to the upper threshold voltage. During this period the bidirectional converter is in buck mode. The battery maintains a high SOC at all times with its voltage recovering during rest periods. The control algorithm for the HESS could be adapted to allow the battery to recharge the ultracapacitor once its SOC has dropped below its full SOC instead of waiting until it reaches its minimum threshold level, which could result in loss of load for a more severe load or if the duty ratio was increased.

5.7. Comparison of Charging Regimes

PV panels are not an ideal source for battery charging as their output is unreliable and heavily dependent on weather conditions. Different charging methods have
been developed to protect and charge the battery more effectively. The IC, TSC and ICC charging methods discussed in Section 2.3 were compared in the laboratory using the test bench. The charging algorithm operating parameters employed for the analysis are given in Table 5-1.

**Table 5-1  Operating Parameters for IC, TSC, ICC**

<table>
<thead>
<tr>
<th>Charging Algorithm</th>
<th>Upper Voltage Threshold</th>
<th>Lower Voltage Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>14.2V</td>
<td>12.84V</td>
</tr>
<tr>
<td>TSC</td>
<td>14.2V</td>
<td>13.2V</td>
</tr>
<tr>
<td>ICC</td>
<td>14.7V</td>
<td>13V</td>
</tr>
</tbody>
</table>

The ideal solar radiation pattern of Figure 5.30 was utilised in the analysis. The battery SOC for IC, TSC and ICC are given in Figure 5.31 for no load battery charging.

![Solar Radiation Profile](image)

**Figure 5-30  Solar radiation profile**
For IC charging, the upper and lower thresholds need to be chosen carefully. If the threshold voltages are close together charging will begin too early and will operate close to float charge. If the thresholds are far apart the battery will discharge to an unacceptable level. With no load the battery was charged to 95% SOC shortly after 10.30am on the simulated day with the lower threshold voltage not being reached due to the slow self discharge of the battery.

The TSC method returned the battery to 100% SOC with some overcharging observed. The maximum charge rate provided by the PV simulator system was C/5, where C is the rated capacity of the battery in ampere-hours.

For the ICC the battery charging current was maintained at 0.1C until the upper voltage threshold was met. The battery was then left in open circuit until it reached 98% SOC. For the simulated day the battery does not self discharge to this level.
therefore, the battery remained in Mode 2. ICC takes longer to recharge the battery compared to the IC and TSC method as the charging current is limited to 0.1C compared to charging with the maximum PV current. The battery charging algorithms were also investigated under the varying load profile of Figure 5.32. The resulting battery SOC levels are provided in Figure 5.33.

Figure 5-32  Varying load profile
The IC method returns the battery to 100% SOC, but some overcharging is experienced. When the voltage drops below the lower threshold MPPT is implemented. This delivers all the available current to the battery that is not required by the load causing the overcharging to occur. The TSC method returns the battery to 100% SOC. The ICC maintains the battery at the lowest SOC due to the current limit imposed in mode 1.

For the three algorithms investigated the TSC method is the most suitable algorithm for a regularly cycled PV system. The ICC method is the least effective at returning the battery to full SOC due to the current limits imposed. Under regularly cycled conditions the full benefit of the algorithm is not experienced as the battery does not enter mode 3. Mode 3 reduces the degree of overcharging experienced by the other charging regimes and provides better equalisation of the cell voltages in a
string of batteries. The results suggest that this charge regime would be better utilised in a standby application.

The TSC method implemented in the test bench was utilised to recharge the HESS with no load. In a passive HESS the charging current will be split between the battery and the ultracapacitor according to the internal resistances of the devices. In the active HESS the battery charges the ultracapacitor with a preset low current level, when the ultracapacitor is below its threshold limit. The battery is then charged by the MPPT. The battery and ultracapacitor voltage for the solar radiation profile of Figure 5.34 is displayed in Figure 5.35.

![Solar radiation profile for HESS charging](image.png)
Figure 5.35  Battery and ultracapacitor voltage for HESS charging

The light falling on the solar cell in the emulator needed to reach a set level, a lamp voltage of approximately 3V equivalent to solar radiation of 479W/m², before battery charging commenced. At this point the ultracapacitor was connected to the system. The discharged ultracapacitor is given priority and it is quickly recharged to its minimal accepted level by the battery. After the ultracapacitor is recharged the output power from the solar emulator is utilised to charge the battery. Battery charging is performed with the maximum generated PV power and therefore follows the solar radiation profile. The battery voltage reached its upper threshold level at shortly after half past three. At this point the battery charging switched from bulk charging to absorption charging as can be seen by the battery voltage drop in Figure 5.35. As seen in Figure 5.34 the solar radiation is low at this point and charging is terminated.
5.8. **Summary**

An experimental test bench constructed to investigate a battery only and a battery ultracapacitor HESS was described in this chapter. The test bench consisted of a PV panel emulator, MPPT and bidirectional converter. Investigations were performed to analyses the effect of different load profiles on the system. In the HESS the large voltage drop experience during the peaks in power was removed. This will allow the operating time of the battery to be extended in a control system with a LVD limit. Most optimisation programs average the load profile on an hourly basis removing the peak power requirements. The impact on the battery voltage was examined for an averaged and an actual load profile. The battery experienced voltage drops for the actual profile but not for the average profile. Therefore, the optimisation could result in a system that would not be able to meet the peak demands of the load. Active and passive HESS’s were investigated, with the active system allowing better utilisation of the ultracapacitor bank. For pulse load applications the duty cycle of the pulses has an impact on the operation of the ultracapacitor. When D is small the ultracapacitor is allowed more time to recharge between the pulses. Three battery charging methods were examined, TSC, IC, and ICC. TSC was found to be most suitable for a PV system were the battery is regularly cycled with ICC better suited to standby applications. In the HESS the ultracapacitor is given priority and charged for the PV panel and battery. During days with low solar radiation the battery may not reach full SOC.
CHAPTER 6.
CONCLUSIONS

This thesis investigated a sustainable energy system consisting of a PV array with a battery ultracapacitor HESS to supply a non grid connected load. The impact of including an ultracapacitor in the PV system was analysed. The batteries and ultracapacitors complement each other in terms of their power and energy densities.

Electrical loads that contain motors can have spikes of between three and seven times their rated wattage, while loads requiring large capacitors to be charged at start-up can result in surge power up to three times their rated wattage.

A DC system was analysed in this thesis but the same principals apply to AC systems. In an AC system the inverter must be sized to take into account the starting power requirement of the load, with the battery bank being sized to handle the voltage drop due to the high current surge. Otherwise the drop in voltage could cause the inverter to shut down even when correctly sized.

In the PV system the battery bank supplies power to the load through chemical reactions with the capacity of the battery depending on the discharge rate. Peak power loads requiring high power reduce the battery capacity, resulting in a voltage drop. When the battery is at a low SOC the voltage drop can trigger the LVD limit leading to the load being shut down prematurely. The ultracapacitor in the active HESS provides the peak power, alleviating the battery voltage drop, thus maintaining the load for a longer period of time. The ultracapacitor also has a faster response time compared to the battery.

A methodology to optimise an autonomous PV system with a battery ultracapacitor HESS was developed in Chapter 3. The optimisation program was written in Matlab.
to minimise the system lifetime cost with constraints on the SOC limit, component volume restrictions and LPSP constraints. The inputs required include the load profile and the solar radiation on a horizontal plane at the site location. The program generates the optimum fixed tilt angle, the number of PV panels, ultracapacitors and batteries. A short duration time step was utilised in the program to capture the fluctuations in the load and the solar radiation. Since the PV panel output power can be significantly reduced from full power in seconds due to passing clouds [84].

The optimisation methodology was utilised in Chapter 4 to optimise a peak power load over the course of one year. The optimised system was analysed utilising a Simulink system model. From the analysis performed it was found that an ultracapacitor battery HESS should be employed to minimise the system lifetime cost of the autonomous PV system operating a load with a high peak to average power requirement. An active HESS configuration makes best use of the available ultracapacitor energy. To further reduce the cost the SOC limit for the battery should be low to utilise as much battery energy as possible. If feasible, no limits should be placed on the number of components in the system as this can significantly increase the cost. Finally, utilising a LPSP of greater than zero reduces the number of batteries needed to cover the longest period of low solar radiation, as the load is allowed to be drop in this situation for a particular period of time.

For the load profiles assessed, the cost saving incurred by employing the ultracapacitor battery HESS over battery only storage varied depending on the SOC limit. For the peak load profile with the motor started every hour, the cost saving between the two storage systems changed from approximately 20% for a SOC limit of 90% to approximately 8% for a SOC limit of 20%. For the HESS increasing the SOC limit from 20% to 90% incurred an increase in the system cost of approximately 256%. In the alternative case where the motor was started once a day the cost saving varied from approximately 153% for a SOC of 90% to
approximately 11% for a SOC of 20%, with the cost increasing by approximately 242% if the SOC limit is increased from 20% to 90% in the HESS.

The impact the optimisation horizon has on the system was analysed by altering the optimisation horizon time. The system was optimised for the day, week and month with the lowest solar radiation and the results were compared. Optimising the system for the worst day of the year resulted in a large PV array and small battery bank with a high cost. The system did not include an ultracapacitor bank and it was found that the LVD limit was regularly broken. Optimising the system for the worst week resulted in two short periods where the load was not met, as the length of the low solar radiation period was longer than the optimisation horizon. When the system was optimised for the worst month of the year the load was maintained at all times.

The cost of components is varying all the time. Therefore, a sensitivity analysis was performed to assess the impact the component cost has on the system size and cost. As the ultracapacitor bank is sized to provide the peak power requirement and not for energy storage varying its cost had no impact. Varying the cost of the PV panel and the battery has an impact on the optimised system as there becomes a trade off between generation and storage.

The optimisation methodology was performed on a pulse power load. It was found that in this type of load the duty cycle of the pulse has an impact on the system design. Placing a current limit on the battery also affects the sustainability of the load. If the limit is too low the battery cannot recharge the ultracapacitor between pulses eventually leading to a depleted ultracapacitor that cannot meet the peak load requirement.

In Chapter 5 the impact of using actual and averaged data for the optimisation was inspected. Optimising the system with averaged data removes the impact of load fluctuations which can include increases in the power requirement. This may lead to a system that cannot accommodate high peak power, resulting in loss of load.
Three battery charging algorithms, Intermittent Charging, Three Stage Charging and Interrupt Charge Control, were examined. It was found that TSC was the most suitable method for regularly cycled PV systems, as it quickly returned the battery to a high SOC using the maximum available current. ICC would be better employed in for standby applications as in mode 3 a pulse current is applied, which reduces the degree of overcharging experienced. ICC also provides better equalisation of the cell voltages in a battery string.

### 6.1. Possible Future Work

The focus of this thesis is

- The development of an optimisation methodology for an autonomous PV system with an ultracapacitor battery HESS given the solar radiation on a horizontal surface and the load profile. The optimisation program was developed to allow a small time in the seconds range be utilised to capture the fluctuations in both the load and solar radiation profiles.

- The main optimisation function is to minimise the system lifetime cost. Apart from the cost there are a number of different factors that affect the chosen system design. For example with critical loads reliability is more important than cost. Taking these factors into account the program was developed to cater for various applications, critical/ non critical loads and systems with limited space. The user determines which factors are the most critical for the design.

- The benefit of including an ultracapacitor in the system is investigated by comparing to a battery only storage system, through simulations and experimental analysis.
- The effect of energy management and the different hybrid configurations is assessed with the Simulink system model.

This work could be further advanced by including additional components for selection in the optimisation program. Generally the lead acid battery, included in this work, is the most common choice for energy storage. Advances in other battery technology NiMH and Li-ion batteries as well as hydrogen storage and fuel cells are making the utilisation of these technologies more attractive.

Research carried out on the hybridisation of renewable generators has shown benefits to combining different types of generators. Wind and PV generation are seen to be complementary technologies. Generally the periods of low solar radiation during the winter period corresponds to an increase in wind and vice versa during the summer months. Provision should be made in the optimisation program to enable the sizing of a hybrid generator.

A set load and solar radiation profile are utilised as the input to the optimisation program. Stochastic modelling could be introduced into the optimisation program to vary the load and solar radiation to determine the optimal system taking variations in both profiles into account.

In remote locations the alternative option to an autonomous system is to extend the national grid. There will be a breakeven point at which, depending on the chosen system, it will be more economical to extend the national grid. It may be beneficial for this to be included in the optimisation program to provide the user with the economics of both available options. This could be further developed by including the option of a grid connection in the optimisation process.

In the battery ultracapacitor HESS the ultracapacitor supplies the peak power while the battery provides the average load power. The option to utilise the ultracapacitor for battery charging should be investigated. The battery charging regime is implemented by the energy management system. The charging current to
the battery will vary with the power being produced by the PV array. This could lead to sudden short interruptions during charging. Utilising the ultracapacitor can smooth the battery charging current, preventing dips and spikes in power during the charging process.

A simple energy throughput model was implemented to help determine the battery life. A more accurate battery lifetime model could be investigated to increase the accuracy of the calculated battery life.

The complexity of the optimisation program will be increased with the addition of new features, component choices, option of a hybrid generator and grid connection. The benefits of utilising alternative programming languages compared to Matlab should be investigated.
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Solar geometry including the solar angles utilised in Chapter 3 for calculating the global radiation falling on the tilted plane are described in this appendix. Figure A1 gives a graphical representation of the solar angles.

Figure A.1 Solar Angles [85]

A.1 Declination Angle

The solar declination angle, δ, is an angle between a plane perpendicular to the incoming radiation and the rotational axis of the earth. The earth’s tilt angle is approximately 23.45°. The solar declination varies throughout the year from 23.45° on June 21st (summer solstice, earth’s axis is tilted towards the sun) to -
23.45° on 21st December (winter solstice, earth’s axis is tilted away from the sun), reaching 0° on the Equinoxes occurring on 21st of March and September in the northern hemisphere. Changes in the declination angle as the earth revolves around the sun cause cyclic changes in the solar radiation, which contributes to the seasons. The declination angle can be calculate for any day, D, using equation A1.

\[
\delta = 23.45\sin\left(360 \frac{(D-284)}{365}\right) \tag{A1}
\]

### A.2 Equation of Time

The Equation of Time (EOT) is the difference between the true solar time and the clock time. The difference between solar and clock time arises because the time needed for the earth to complete one revolution about its own axis with respect to the sun is not uniform throughout the year with the average day length being 24 hours. The EOT in minutes is given in A2

\[
\text{EOT} = (9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)) \tag{A2}
\]

Where B in radians is given by A3

\[
B = \frac{2\pi(D-81)}{365} \tag{A3}
\]

### A.3 Solar Time

The solar time, \(T_s\), is given as

\[
T_s = T_c + \frac{\text{LSTM-Longitude}}{15} + \frac{\text{EOT}}{60} \tag{A4}
\]

Where

- \(T_c\) Clock time
- LSTM Longitude of the local standard time meridian
A.4 Hour Angle

The hour angle, $\omega$, is calculated from the solar time. The hour angle is the angle the earth has rotated since solar noon, when the sun is directly overhead in the sky for a particular location on the earth’s surface. The earth rotates $15^\circ$ every hour with respect to the sun, varying the angle the solar radiation strikes the PV panel and causing the sun to rise and set. In a 24 hour period the hour angle changes by $360^\circ (-180^\circ - +180^\circ)$ reaching $0^\circ$ at solar noon; it is negative before solar noon and positive after solar noon.

$$\omega = 15(T_s - 12) \quad (A5)$$

A.5 Solar Zenith Angle

The solar zenith angle, $\theta_z$, is the angle between the sun’s rays and the vertical. The solar zenith is the complement of the solar altitude angle and varies with latitude, time of day and year. The solar zenith angle is calculated by

$$\theta_z = \cos^{-1}(\sin(\delta) \sin(\phi) + \cos(\delta) \cos(\phi) \cos(\omega)) \quad (A6)$$

Where

$\phi$ Latitude, the angle between a line from the centre of the earth to the site of interest and the equatorial plane

A.6 Solar Altitude Angle

The solar altitude angle, $\alpha$, is the apparent angular height of the sun in the sky as the observer faces it. The solar altitude angle is defined as the angle between the sun’s rays and the horizontal plane. It is the complement of the zenith angle and determined by

$$\alpha = \sin^{-1}(\sin(\delta) \sin(\phi) + \cos(\delta) \cos(\phi) \cos(\omega)) \quad (A6)$$


A.7 Solar Azimuth Angle

The solar azimuth angle, $\lambda_s$, is the angle between the line from the sun’s rays in the horizontal plane and the due south in the northern hemisphere or due north in the southern hemisphere, with westward taken as positive. The solar azimuth is obtained by

$$\lambda_s = \cos^{-1}\left(\sin(\alpha) \sin(\phi) - \frac{\sin(\delta)}{\cos(\alpha) \cos(\phi)}\right) \quad (A7)$$

A.8 Surface Azimuth Angle

The surface azimuth, $\lambda$, is the angle between the direction of the surface of the PV panel and due south.

A.9 PV panel Tilt Angle

The tilt angle of the PV panel, $\beta$, is the angle between the PV panel and a horizontal plane.

A.10 Angle of Incidence

The angle of incidence, $\theta$, is the angle between the sun’s rays and the normal of the surface of the PV panel. For a horizontal panel, the incidence angle and the zenith angle are equal. The angle of incident is calculated by

$$\theta = \cos^\wedge(-1) \left[(\sin(\varphi) \sin(\delta) \cos(\beta) - \sin(\delta) \sin(\beta) \cos(\varphi) \cos(\lambda) + \cos(\delta) \cos(\lambda) \cos(\omega) + \cos(\delta) \sin(\varphi) \sin(\beta) \cos(\omega) + \cos(\delta) \sin(\lambda) \sin(\omega) \sin(\beta))\right] \quad (A8)$$

When the PV panel is facing due south its surface azimuth is $0^\circ$ and (A8) is simplified to

$$\theta = \cos^{-1}(\sin(\delta) \sin(\varphi - \beta) + \cos(\delta) \cos(\omega) \cos(\varphi - \beta)) \quad (A9)$$
APPENDIX B.
MATLAB OPTIMISATION CODE

%Optimisation program
%Calculate the optimal tilt angle using the Klucher model to calculate
%the solar radiation on a tilted panel from the available radiation
%on a horizontal plane; tilt angle varied from 0-90 degrees over the year.

Lat=53.286581;    %Enter latitude angle
Long=-9.0672;     %Enter longitude angle
rho=0.2;          %Reflective radiation co-efficient
DeltaGMT=0;       %Difference in local time from GMT
LSTM=15*DeltaGMT; %Local standard time meridian
SurAzim=0;
GTotalOpt=0;
TiltOpt=0;

S=xlsread('SolarIrradYear.xlsx','Data'); %Import file with solar data

for Tilt=0:1:90;
    DayNo=S(:,5); %Vary the DayNo over the year
    Declin = 23.45*sind((360.*(DayNo+284))/365);
    WsHor=acosd(-tand(Declin).*tand(Lat));
    WsTilt=acosd(-tand(Declin).*tand(Lat-Tilt));
    Ws=min(WsHor,WsTilt);
    GH=S(:,2); %Measured global radiation on a horizontal plane
    DH=S(:,3); %Measured diffuse radiation on a horizontal plane
    BH=GH-DH; %Calculate beam radiation
    Tc=S(:,4);
    B=(360.*(DayNo-81))/365;
    EOT=(9.87.*sind(2*B)-(7.53.*cosd(B))-1.5.*sind(B));
    TCF=4.*(LSTM-Long)+EOT;
    T=Tc+TCF/60;
    W=15.*(T-12);
    suna=(W=(W>=(-Ws)));
    sunb=(W=(W<=Ws));
    sun=suna&sunb;
    Zen=acosd(sind(Declin).*sind(Lat)+cosd(Declin).*cosd(Lat).*cosd(W));
    Alt=asin(sind(Declin).*sind(Lat)+cosd(Declin).*cosd(Lat).*cosd(W));
    Azim=acosd((sind(Alt).*sind(Lat)-ind(Declin))/([cosd(Alt).*cosd(Lat)]));
    AOITilt=acosd((sind(Declin).*sind(Lat).*cosd(Tilt))...-
sind(Declin).*cosd(Lat).*sind(Tilt).*cosd(SurAzim))...
    +cosd(Declin).*cosd(Lat1).*cosd(Tilt).*cosd(W))...+
cosd(Declin).*sind(Lat1).*sind(Tilt).*cosd(SurAzim).*cosd(W)...+
cosd(Declin).*sind(SurAzim).*sind(W).*sind(Tilt));
    CosZen=cosd(Zen);
    CosAOITilt=cosd(AOITilt);

    for g=1:length(CosZen)
        if (CosZen(g,1)<0.007) && (CosZen(g,1)>-0.007)
            CosZen(g,1)=0;
        end
        if (CosAOITilt(g,1)<0.007) && (CosAOITilt(g,1)>-0.007)
            CosAOITilt(g,1)=0;
        end
    end
end
APPENDIX B. MATLAB OPTIMISATION CODE

% Geometric factor
RbTilt = Cos(A0ITilt) / Cos(Zen);
RbTilt(isinf(RbTilt)) = 0;
RbTilt = max(0, RbTilt);
RTilt = 0.5 * rho * (1 - cosd(Tilt)) * GH; % Reflected radiation on tilted panel

% Angle of Incidence Modifiers (Total radiation = Gb*Ib + Gd*Id + Gr*Ir)
Thetad = 59.7 - 0.1388 * Tilt + 0.001497 * (Tilt^2); % Effective diffuse angle
Thetar = 90 - 0.5788 * Tilt + 0.002693 * Tilt^2; % Effective reflective angle
Thetab = AOITilt; % Effective beam angle

Id = 1 - ((1.098 * 10^-4) * Thetad) - ((6.267 * 10^-6) * Thetad^2) + ((6.583 * 10^-7) * Thetad^3); % Diffuse Modifier
Ir = 1 - ((1.098 * 10^-4) * Thetar) - ((6.267 * 10^-6) * Thetar^2) + ((6.583 * 10^-7) * Thetar^3); % Reflected Modifier
Ib = Ib_pre - (Ib_pre < 0) * Ib_pre;

AM = real(1 ./ ((cosd(Zen)) + (0.50572 * ((96.07995 - Zen).^(^-1.6364))));
DN = real(1353 .* (0.7 .* AM.^0.678));
Ho = 1367 * (1 + (0.033 * cosd((360 * DayNo) / 365)));

% Klucher model to calculate diffuse radiation on a tilted panel
F_KL = 1 - ((DH.s_ERROR.).^2); % Klucher modulating function, F_KL
DT = DH.s_ERROR().^2 .* (1 + F_KL.* (sind(Tilt/2)).^3) .* (1 + F_KL.* ((cosd(A0ITilt)).^2) .* (sind(Zen)).^3));
DT(isnan(DT)) = 0;
BT = BH.s_ERROR.*sun;
GT = (BT.s_ERROR() + (DT.s_ERROR() + (RTilt.s_ERROR() + (Ib.s_ERROR() + (AM.s_ERROR().^2));
GTotal = trapz(Tc, GT); % Global radiation on a tilted panel
if GTotal > GTotalOpt
GTotalOpt = GTotal;
GTOpt = GT;
TiltOpt = Tilt;
end

% Calculate total radiation falling on panel over the year
GTotalOpt(:, 1) = S(:, 7);
GTotalOpt(:, 2) = GTOpt;

% ************************************ Calculate the power output from a BP 350 PV panel ************************************
q = 1.6e-19; % Electron charge
n = 1.265; % Ideality factor of the diode
k = 1.38e-23; % Boltzmann's constant
Ns = 36; % Number of cells connected in series
Isc_ref = 3.17; % Photocell short circuit current @ Tref and Gref
Gref = 1000; % Reference solar irradiance
Alpha_s = 0.00065; % Short circuit current temperature coefficient
Tref = 298; % Reference cell temperature
Voc_ref = 21.8; % Open circuit voltage of PV module at standard operating conditions
Alpha_Voc = 0.08; % PV module open circuit voltage temperature coefficient
NOCT = 47; % Nominal operating cell temperature
G=GTiltOpt(:,2); %Solar Irradiance
Temp=xlsread('TempYearMin.xlsx','Temp'); %Ambient Temperature
TcellC=Temp(:,2)+(((NOCT‐20)./800).*G); %Convert ambient to cell temperature
Tcell=TcellC+273; %Solar cell temperature in kelvin
DeltaT=Tcell‐Tref;
ArrayLen=length(G(:,1));
P(ArrayLen,25)=0; %Initialise array

for Vo=1:25
    Voc=Vocref+(AlphaVoc.*(DeltaT)); %Open circuit voltage of PV module
    Ip=Ipcref.(G./Gref).*(1+(Alphaisc.*(DeltaT))); %Photocurrent
    Isat=Ip./exp((q.*Voc)./(n.*k.*Tcell.*Ns))‐1; %Sat current
    Io=Ip‐Isat.*(exp((q.*Vo)./(n.*k.*Tcell.*Ns))‐1); %O/P PV cur
    P(:,Vo)=Io.*Vo;
    if P(:,Vo)<0;
        P(:,Vo)=0;
    else
        P(:,Vo)=P(:,Vo);
    end
end
PmpptPanel=max(P(:,2)); %Calculate the max power
PmpptEff(:,1)=GTiltOpt(:,1);
PmpptEff(:,2)=PmpptPanel.*0.95; %mppt power efficiency of 95%

%************************************************** Daily Energy Values **************************************************
a=1;
b=1440;
DayPmppt=10000;
EpanelDay(1,365)=0;

for i=1:365;
PmpptPanelDay=PmpptEff(a:b,1:2);
EpanelDay(1,i)=trapz(PmpptPanelDay(:,1),PmpptPanelDay(:,2));
if EpanelDay(1,i)<DayPmppt;
    DayPmppt=EpanelDay(1,i);
end
a=a+b;
b=b+1440;
end

%************************************************** Weekly Energy Values **************************************************
r=1;
s=10080;
WeekPmppt=100000;
EpanelWeek(1,52)=0;

for i=1:52;
PmpptPanelWeek=PmpptEff(r:s,1:2);
EpanelWeek(1,i)=trapz(PmpptPanelWeek(:,1),PmpptPanelWeek(:,2));
if EpanelWeek(1,i)<WeekPmppt;
    WeekPmppt=EpanelWeek(1,i);
end
r=r+s;
s=s+10080;
end

%************************************************** Monthly Energy Values **************************************************
%APPENDIX B. MATLAB OPTIMISATION CODE

u=1;
v=[44640 84960 129600 172800 217440 260640 305280 349920 393120 437760 480960 525600 0];
MonthPmppt=100000;
v1=v(1);
EpanelMonth(1,12)=0;
for i=1:12;
    PmpptPanelMonth=PmpptEff(u:v1,1:2);
    EpanelMonth(1,i)=trapz(PmpptPanelMonth(:,1),PmpptPanelMonth(:,2));
    if EpanelMonth(1,i)<MonthPmppt
        MonthPmppt=EpanelMonth(1,i);
        Emonthmin=i;
    end
    u=v1+1;
    v1=v(i+1);
end

%***************************************************
% Yearly Energy Values
%***************************************************

PmpptPanel=trapz(PmpptEff(:,1),PmpptEff(:,2)) ;%o/p from PV panel

%***************************************************
% Read in load data and calculate the total energy requirement
%***************************************************

Demand=xlsread( ‘PeakLoadYear.xlsx’,’Sheet1’);

%*****************************************************
% Daily Demand Energy Values
%*****************************************************

c=1;
d=144;
DayDemand=0;
EDemandDay(1,365)=0;
for i=1:365;
    DemandDay=Demand(c:d,1:2);
    EDemandDay(1,i)=trapz(DemandDay(:,1),DemandDay(:,2));
    if EDemandDay(1,i)>DayDemand
        DayDemand=EDemandDay(1,i);
        Edemanddaymax=i;
    end
    c=d+1;
    d=d+144;
end

%*****************************************************
% Weekly Demand Energy Values
%*****************************************************

e=1;
f=1008;
WeekDemand=0;
EDemandWeek(1,52)=0;
for i=1:52;
    DemandWeek=Demand(e:f,1:2);
    EDemandWeek(1,i)=trapz(DemandWeek(:,1),DemandWeek(:,2));
    if EDemandWeek(1,i)>WeekDemand
        WeekDemand=EDemandWeek(1,i);
        Edemandweekmax=i;
    end
    e=f+1;
    f=f+1008;
end

%*****************************************************
% Monthly Demand Energy Values
%*****************************************************

h=1;
APPENDIX B. MATLAB OPTIMISATION CODE

```matlab
j=[4464 8496 12960 17280 21744 26064 30528 34992 39312 43776 48096 52560];
MonthDemand=0;
j1=j(1);
EDemandMonth(1,12)=0;
for i=1:12;
    DemandMonth=Demand(h:j1,1:2);
    EDemandMonth(1,i)=trapz(DemandMonth(:,1),DemandMonth(:,2));
    if EDemandMonth(1,i)>MonthDemand;
        MonthDemand=EDemandMonth(1,i);
        Emdemonthmax=i;
    end
    h=j1+1;
    j1=j(i+1);
end
%**************************************** Yearly Demand Energy Values ****************************************
TotalDemand=trapz(Demand(:,1),Demand(:,2));
%**************************************** Calculate the number of PV panels and the total Pmpt *******************************************************
NumberPVPanelDay1=DayDemand/DayPmppt
NoPVPanelDay1=ceil(NumberPVPanelDay1);
NumberPVPanelWeek=WeekDemand/WeekPmppt;
NoPVPanelWeek=ceil(NumberPVPanelWeek);
NumberPVPanelMonth=MonthDemand/MonthPmppt;
NoPVPanelMonth=ceil(NumberPVPanelMonth);
NumberPVPanelYear=TotalDemand/PmpptPanel
NoPVPanelYear=ceil(NumberPVPanelYear);
%************************************************ Panel Area *******************************************************
AreaPan=0.4399;
MaxPanArea=1000
NoPVPanelDayArea=AreaPan*NoPVPanelDay1;
if NoPVPanelDayArea>MaxPanArea
    NoPVPanelDay=floor(MaxPanArea/AreaPan);
else
    NoPVPanelDay=NoPVPanelDay1;
end
%************************************************ Time Series*******************************************************
PVmpptEff=timeseries(PVmpptEff(:,2),PVmpptEff(:,1),'name','PVmpptEff');
Load=timeseries(Demand(:,2),Demand(:,1),'name','Load');
PVmpptEffTimeInfo.units='hours';
Load.TimeInfo.units='hours';
[PVmpptEff Load]=synchronize(PVmpptEff,Load,'union');
Load2=get(Load);
ArrayLen2=length(Load2.Time);
LoadTest(:,1)=Load2.Time;
clear Load;
%************************************************ Initialise arrays ****************************************************
iter=(floor((NoPVPanelDay-NoPVPanelYear+1)/2))*9;
NoPVPanelArray(1,iter)=0;
StorDischarEnergyArray(1,iter)=0;
AvgStorageDischargeArray(1,365)=0;
EUcapD(1,365)=0;
```

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UcapDischarDayArray(1536,365)=0;
EUcapH(1,24)=0;
NoUcapSerArray(1,iter)=0;
NoPVPanelArray(1,iter)=0;
StoDischarEnergyArray(1,iter)=0;
EBatCharDay(1,365)=0;
EBatDischarDay(1,365)=0;
EBatDischarDayArray(365,iter)=0;
EBatCharDayArray(365,iter)=0;
MaxDailyEdefArray(1,iter)=0;
DayOfautonArray(1,iter)=0;
NoParBatArray(1,iter)=0;
SOC1(ArrayLen2,1)=0;
OCV1(ArrayLen2,1)=0;
V11(ArrayLen2,1)=0;
VT1(ArrayLen2,1)=0;
I21(ArrayLen2,1)=0;
AhCapPeukArray(ArrayLen2,1)=0;
dvdt1(ArrayLen2,1)=0;
BatStorageCur(ArrayLen2,1)=0;
VUcap(ArrayLen2,1)=0;
SOCUcap(ArrayLen2,1)=0;
BatAHCapArray(1,iter)=0;
BatSOCDayMax(365,1)=0;
BatSOCDayMin(365,1)=0;
SOCDayMax(365,iter)=0;
SOCDayMin(365,iter)=0;
SOCMinArray(1,iter)=0;
NoParBatArray(1,iter)=0;
NoSerBatArray(1,iter)=0;
LPSPArray(1,iter)=0;
BatVolLimArray(1,iter)=0;
NoUcapParArray(1,iter)=0;
BatLife(1,(length(NoParBatArray)))=0;
z=1;
zz=1;
%**************************************************************************************************************************
for NoPVPanel=NoPVandYear:1:NoPVPanelDay;

Pmppt(:,1)=PmpptEff(:,1);
Pmppt(:,2)=PmpptEff(:,2).*NoPVPanel;		%Generate the PV profile
PmpptTotal=trapz(Pmppt(:,1),Pmppt(:,2));		%Calculate total power output from the PV array
PVmppt=timeseries(Pmppt(:,2),Pmppt(:,1),'name','PVmppt');
Load=timeseries(Demand(:,2),Demand(:,1),'name','Load');
PVmppt.TimeInfo.units='hours';
Load.TimeInfo.units='hours';
PVmppt.DataInfo.Interpolation=tsdata.interpolation('zoh');
Load.DataInfo.Interpolation=tsdata.interpolation('zoh');
[PVmppt Load]=synchronize(PVmppt,Load,'union');
Storage1=(PVmppt‐Load);		%Input/Output of storage
Storage2=get(Storage1);
Storage(:,1)=Storage2.Time;
Storage(:,2)=(Storage2.Data);

for i=1:(length(Storage));
    if Storage(i,2)>0
        Storage(i,2)=Storage(i,2)*0.97;
    else
        Storage(i,2)=Storage(i,2)*1.03;
    end
%***********************************************
Storage requirement ****************************************************

StorChar(:,1)=Storage(:,1);  
StorChar(:,2)=Storage(:,2)*(Storage(:,2)<0).*Storage(:,2);  
StorDischar(:,1)=Storage(:,1); 
StorDischar(:,2)=Storage(:,2)-(Storage(:,2)>0).*Storage(:,2); 
StorCharEnergy=trapz(StorChar(:,1),StorChar(:,2));  
StorDischarEnergy1=trapz(StorDischar(:,1),StorDischar(:,2));  
StorDischarEnergy=abs(StorDischarEnergy1);  

%*************************************************  
Ultracapacitor Sizing  
***************************************************

r=1;  
x=1;  
y=64;  
s=1536;  
EUcapDay=0;  
EUcapHr=0;  
EUcapP=0;  

for i=1:365;  
StorageDischargeDay=abs(StorChar(r:s,1:2));  
Avg1=find(StorageDischargeDay(:,2));  
AvgStorageDischargeDay=mode(StorageDischargeDay(Avg1,2));  
AvgStorageDischargeArray(1,i)=AvgStorageDischargeDay;  
r=s+1;  
s=s+1536;  
end  
AvgStorageDischargeDay=min(AvgStorageDischargeArray);  

%*****************************************************************************  
Daily**************************************************************

r=1;  
s=1536;  

for i=1:365;  
StorageDischargeDay=abs(StorChar(r:s,1:2));  
UcapDischargeDay(:,1)=StorageDischargeDay(:,1);  
UcapDischargeDay(:,2)=StorageDischargeDay(:,2)-AvgStorageDischargeDay;  
UcapDischargeP=UcapDischargeDay;  

for l=1:length(UcapDischargeDay);  
if UcapDischargeDay(l,2)<=0;  
UcapDischargeDay(l,2)=0;  
UcapDischargeP(l,2)=0;  
else  
UcapDischargeDay(l,2)=UcapDischargeDay(l,2)+AvgStorageDischargeDay;  
UcapDischargeP(l,2)=UcapDischargeP(l,2)+AvgStorageDischargeDay;  
end  
end  
EUcapD(1,i)=trapz(UcapDischargeDay(:,1),UcapDischargeDay(:,2));  
if EUcapD(1,i)>EUcapDay;  
EUcapDay=EUcapD(1,i);  
end  

UcapDischargeDayArray(:,i)=UcapDischargeDay(:,2);
%*******************************************************Hourly ****************************
for hr=1:24;
    StorageDischargeHr=abs(StorDischar(x:y,1:2));
    UcapDischargeHr(:,1)=StorageDischargeHr(:,1);
    UcapDischargeHr(:,2)=StorageDischargeHr(:,2)-AvgStorageDischargeDay;
    for l=1:length(UcapDischargeHr);
        if UcapDischargeHr(l,2)<=0;
            UcapDischargeHr(l,2)=0;
        else
            UcapDischargeHr(l,2)=UcapDischargeHr(l,2)+AvgStorageDischargeDay;
        end
    end
    EUcapH(1,hr)=trapz(UcapDischargeHr(:,1),UcapDischargeHr(:,2));
    if EUcapH(1,hr)>EUcapHr;
        EUcapHr=EUcapH(1,hr);
    end
    x=y+1;
    y=y+64;
end
%********************************************************Peak ****************************
z1=UcapDischargeP(:,2);
    if (max(z1)==0)
        EUcapPeak=0;
    else
        z2=find(z1==0); z3=diff(z2);
        if (max(z3)==1);
            z4=z2(1);
        else
            z4=find(z3>1);
        end
        clear PeakStart;
        clear PeakEnd;
        for z5=1:length(z4);
            PeakEnd(z5)=sum(z3(1:(z4(z5))))+1;
        end
        PeakStart=[1 PeakEnd(1:length(PeakEnd)-1)];
    for z5=1:length(PeakEnd);
        EUcapPeak(z5)=trapz(UcapDischargeP(PeakStart(z5):PeakEnd(z5),1),UcapDischargeP(PeakStart(z5):PeakEnd(z5),2));
        if EUcapPeak(z5)>EUcapP;
            EUcapP=EUcapPeak(z5);
        end
        end
    end
    r=s+1;
    s=s+1536;
end
%*******************************************************Calculate number par/ser Ultracapacitors *******************************************************
Vmin=6; %Min ultracapacitor operating voltage
Ccell=600; %Rated cell capacity
EUcapDayJoule=EUcapDay/2.7778e‐4; %convert the energy requirement to joules for use in the ucap energy formula

CD=(2*EUcapDayJoule)/((2*Vmin)^2‐Vmin^2); %calculate the capacitance required to provide the energy
NoUcapSer=ceil((2*Vmin)/2.7); %calculate the no of series Ucaps required to provide the voltage required
NoUcapDPar=ceil(CD*NoUcapSer/Ccell); %Calculate the no of parallel Ultracpacitors required

EUcapHRJoule=EUcapHR/2.7778e‐4; %Number of capacitors required for hour
CHr=(2*EUcapHRJoule)/(2*Vmin^2‐Vmin*2); %Number of capacitors required for peak
NoUcapHRPar=ceil(CHr*NoUcapSer/Ccell); %Calculate the capacitance required to provide the energy

EUcapPJoule=EUcapP/2.7778e‐4;
CP=(2*EUcapPJoule)/(2*Vmin^2‐Vmin*2);
NoUcapPPar=ceil(CP*NoUcapSer/Ccell);

%**************************************************************************************************************************

r=1;
s=1536;
for i=1:365;
    UcapStorageDischarge(r:s,1)=UcapDischarDayArray(:,i);
s=s+1536;
end

UcapStorage(:,1)=Storage(:,1);
UcapStorage(:,2)=(UcapStorageDischarge.*‐1)+StorChar(:,2);
for NoUcapPar=0:1:NoUcapDPar;
    Vmax=2.7*NoUcapSer;
    VUcap_init=2.7*NoUcapSer;
    TUcap_init=0;
    CUcap=Ccell*NoUcapPar/NoUcapSer;
    LUcap=length(UcapStorage);
    for i=1:LUcap;
        VUcap(i,1)=sqrt(VUcap_init^2‐(2*(‐1)*((UcapStorage(i,2)*(UcapStorage(i,1)‐TUcap_init))/2.7778e‐4)/CUcap));
        SOCUcap(i,1)=VUcap(i)*100/Vmax;
        if SOCUcap(i,1) > 100;
            SOCUcap(i,1)=100;
            VUcap(i,1)=Vmax;
            UcapStorage(i,2)=0;
        else if SOCUcap(i,1) < 50;
            SOCUcap(i,1)=SOCUcap(i‐1,1);
            VUcap(i,1)=SOCUcap(i‐1,1)*Vmax/100;
            UcapStorage(i,2)=0;
            else
                UcapStorage(i,2)=UcapStorage(i,2);
        end
    end
    VUcap_init=VUcap(i,1);
    TUcap_init=UcapStorage(i,1);
end

%**************************************************************************************************************************

BatStorage(:,1)=Storage(:,1);
BatStorage(:,2)=Storage(:,2)‐UcapStorage(:,2); %Battery profile
for i=1:length(BatStorage(:,2))
    if BatStorage(i,2)<(‐33.99);

%**************************************************************************************************************************

APPENDIX B. MATLAB OPTIMISATION CODE
BatStorage(2) = -33.99;
else
    BatStorage(2) = BatStorage(2);
end

if NoUcapPar == 0;
    BatStorage(:,2) = Storage(:,2);
end;

BatChar(:,1) = BatStorage(:,1);
BatChar(:,2) = BatStorage(:,2) - (BatStorage(:,2)<0).*BatStorage(:,2);
BatDischar(:,1) = BatStorage(:,1);
BatDischar(:,2) = BatStorage(:,2) - (BatStorage(:,2)>0).*BatStorage(:,2);
BatCharEnergy = trapz(BatChar(:,1), BatChar(:,2));
BatDischarEnergy1 = trapz(BatDischar(:,1), BatDischar(:,2));
BatDischarEnergy = abs(BatDischarEnergy1);
BatDischarEnergyArray(1,z) = BatDischarEnergy;

%**************************************************************************************************************************
%********************************************************Daily Charge Energy**********************************************
SysVolt = 12;
BatVolt = 12;
AhCap = 17.25;
DODLim = 0.1;
BatEnergy = BatVolt * AhCap * DODLim;
NoSerBat = ceil(SysVolt / BatVolt);
m = 1;
n = 1536;
Echarday = 100000;

for i = 1:365;
    BatCharDay = BatChar(m:m+n-2);
    EBatCharDay(1,i) = trapz(BatCharDay(:,1),BatCharDay(:,2));
    if EBatCharDay(1,i) > Echarday;
        Echarday = EBatCharDay(1,i);
        Echardaymin = i;
    end
    m = m + 1;
n = n + 1536;
end

%**************************************************************************************************************************
%********************************************************Daily Discharge Energy*********************************************

for i = 1:365;
    BatDischarDay = BatDischar(o:p-1,2);
    EBatDischarDay(1,i) = abs(trapz(BatDischarDay(:,1),BatDischarDay(:,2)));%
    if EBatDischarDay(1,i) > Edischarday;
        Edischarday = EBatDischarDay(1,i);
        Edischardaymax = i;
    end
    o = o + 1;
p = p + 1536;
end

Einad = EBatDischarDay - EBatCharDay;
MaxDailyEdef = max(EBatDischarDay);
MaxDailyEdefArray(1,z) = max(EBatDischarDay);

%energy needed from battery worst case max daily bat discharge
for i=1:365;
    if Einad(i)<0;
        Einad(i)=1;
    else
        Einad(i)=0;
    end
end

Ind=find([1 Einad(:)’ 1]);
CountConsec=diff(Ind)-1;

DaysOfAuton=max(CountConsec);
DayOfAutonArray(1,2)=DaysOfAuton;

NoParBat1=ceil(DaysOfAuton*(MaxDailyEdef/BatEnergy));
if DaysOfAuton==0;
    NoParBat1=ceil(MaxDailyEdef/BatEnergy);
end

NoParBat1Array(1,z)=NoParBat1;

% Battery array size before component constraint

%********************************************************************************
% Check Battery Volume
%********************************************************************************

BatVol=0.0023;
UcapVol=0.001;
UcapArrayVol=NoUcapPar*NoUcapSer*UcapVol;
MaxBatVol=1000-UcapArrayVol;
BatArrayVol=BatVol*NoParBat1*NoSerBat;

if BatArrayVol>MaxBatVol
    NoParBat=floor(MaxBatVol/BatVol*NoSerBat);
else
    NoParBat=NoParBat1;
end

mg=0;
LPSPLim=0;
SOCMin=100;
LPSP=0;
NoParBat=NoParBat+1;
VTmin=13;
VTlim=12.85;

%while LPSP<=LPSPLim;
%while (SOCMin>((1-DODLim)*100));

while VTmin<VTlim;
    NoParBat=NoParBat-1;
    mg=mg+1;
    T_int=0;
    T=BatStorage(:,1);
    V1_int=13;
    VT_int=13;
    dvdt_int=0;
    SOC_int=100;
    m=length(BatStorage(:,2));
    HPeuk=20;
    Kpeuk=1.1;
    %Lead acid 1.1-1.3 value for Peukerts constant

    BatEnergyT=BatEnergy*NoParBat;
    BatAHCap=ceil(BatEnergyT/(BatVolt*DODLim));
    PStorage1=BatStorage(:,2)/(NoParBat);
PStorage=PStorage1.*(-1);

%**************************************************************************************************************************
for i=1:1:m;
    BatStorageCur(i,1)=PStorage(i)/VT_int;
% Peukerts law
    AhCapPeuk=AhCap;
    if BatStorageCur(i,1)>0;
        TimePeuk=HPeuk*(AhCap/(BatStorageCur(i,1)*HPeuk))^(Kpeuk);
        AhCapPeuk=TimePeuk*BatStorageCur(i,1);
    else
        AhCapPeuk=AhCap;
    end
    AhCapPeukArray(i,1)=AhCapPeuk;
    SOC1(i,1)=SOC_int+((BatStorageCur(i,1)*((T_int‐T(i,1)))*100)/AhCapPeuk);
    if SOC1(i,1)>100;
        SOC1(i,1)=100;
    end
    if SOC1(i,1)>=100 && BatStorageCur(i,1)<0;
        BatStorageCur(i,1)=0;
    end
    SOC_int=SOC1(i,1);
    OCV1(i,1)=((SOC1(i,1)/100)*1.5)+11.5;
    V11(i,1)=V1_int+(dvdt_int*(T(i,1)‐T_int));
    V1_int=V11(i,1);
    VT1(i,1)=V11(i,1)‐(BatStorageCur(i,1)*0.157);
    VT_int=VT1(i,1);
    I21(i,1)=(OCV1(i,1)‐V11(i,1))/0.063;
    dvdt1(i,1)=(1/5.283)*(I21(i,1)‐BatStorageCur(i,1));
    dvdt_int=dvdt1(i,1);
    T_int=T(i,1);
end

SOCMin=min(SOC1);
VTmin=min(VT1);

%************************************************************************************************************************** Calculate the LPSP
LPSPLim=0;
LPSP1=[(1‐DODLim)*100‐SOC1];
for L=1:length(LPSP1)
    if LPSP1(L,1)<0;
        LPSP1(L,1)=0;
    else
        LPSP1(L,1)=1;
    end
end
LPSP2=trapz(BatDischar(:,1),LPSP1(:,1));
LPSP=LPSP2/8760;

mags=0;
% if SOCMin<((1‐DODLim)*100);
% LPSP>LPSPLim
if VTmin<VTlim
    NoParBat=NoParBat+1;
    mags=1;
%*******************************************************
Battery Model
*******************************************************

\[
T_{\text{int}}=0; \\
V_{1\text{,int}}=13; \\
V_{T\text{,int}}=13; \\
I_{2\text{,int}}=0; \\
dvdt_{\text{int}}=0; \\
SOC_{\text{int}}=100; \\
\]

\[
\text{BatEnergyT} = \text{BatEnergy} \times \text{NoParBat}; \\
\text{BatAHCap} = \text{ceil} \left( \frac{\text{BatEnergyT}}{\text{BatVolt} \times \text{DODLim}} \right); \\
PStorage_1 = \text{BatStorage}(:, 2) / \text{NoParBat}; \\
PStorage = PStorage_1 \times (\text{-1}); \\
\]

\[
T_{\text{int}}=0; \\
V_{1\text{,int}}=13; \\
V_{T\text{,int}}=13; \\
I_{2\text{,int}}=0; \\
dvdt_{\text{int}}=0; \\
SOC_{\text{int}}=100; \\
\]

\[
\text{BatEnergyT} = \text{BatEnergy} \times \text{NoParBat}; \\
\text{BatAHCap} = \text{ceil} \left( \frac{\text{BatEnergyT}}{\text{BatVolt} \times \text{DODLim}} \right); \\
PStorage_1 = \text{BatStorage}(:, 2) / \text{NoParBat}; \\
PStorage = PStorage_1 \times (\text{-1}); \\
\]

\[
%*******************************************************
\]

\[
\text{for} \ i=1:1:m; \\
\text{BatStorageCur}(i,1)=PStorage(i,1)/V_{1\text{,int}}; \\
\text{AhCapPeuk} = \text{AhCap}; \\
\]

\[
\text{if} \ \text{BatStorageCur}(i,1)>0; \\
\text{TimePeuk} = HPeuk \times (\text{AhCap} / (\text{BatStorageCur}(i,1) \times HPeuk))^Kpeuk; \\
\text{AhCapPeuk} = \text{TimePeuk} \times \text{BatStorageCur}(i,1); \\
\text{else} \\
\text{AhCapPeuk} = \text{AhCap}; \\
\text{end} \\
\text{AhCapPeukArray}(i,1)=\text{AhCapPeuk}; \\
\]

\[
\text{SOC}(i,1)=\text{SOC}\_\text{int}+((\text{BatStorageCur}(i,1) \times (T_{\text{int}}-T(i,1))) \times 100) / \text{AhCapPeuk}; \\
\text{if} \ \text{SOC}(i,1) \geq 100; \\
\text{SOC}(i,1)=100; \\
\text{end} \\
\text{if} \ \text{SOC}(i,1)>100 \text{&&} \text{BatStorageCur}(i,1)<0; \\
\text{BatStorageCur}(i,1)=0; \\
\text{end} \\
\]

\[
\text{SOC}\_\text{int}=\text{SOC}(i,1); \\
OCV(i,1)=(\text{SOC}(i,1)/100)^1.5+11.5; \\
V_{11}(i,1)=\text{V}_{1\text{,int}}+(dvdt_{\text{int}} \times (T(i,1)-T_{\text{int}})); \\
V_{1\text{,int}}=\text{V}_{11}(i,1); \\
V_{T1}(i,1)=\text{V}_{11}(i,1)-\{\text{BatStorageCur}(i,1) \times 0.157\}; \\
V_{T\text{,int}}=V_{T1}(i,1); \\
I_{21}(i,1)=(OCV(i,1)-V_{11}(i,1)) / 0.063; \\
dvdt_{11}(i,1)=\{1 / 5.283\} \times (I_{21}(i,1) \times \text{BatStorageCur}(i,1)); \\
dvdt_{\text{int}}=dvdt_{11}(i,1); \\
T_{\text{int}}=T(i,1); \\
\]

\[
\text{SOCMin}=\text{min} \text{SOC}(i,1); \\
\text{VTmin}=\text{min} \text{VT}(i,1); \\
\]

\[
%*******************************************************
\]

\[
\text{LPSP}(i,1)=\{(1-DODLim) \times 100\} \times \text{SOC}(i,1); \\
\text{for} \ L=1:\text{length} \text{LPSP}(i,1) \\
\text{if} \ \text{LPSP} (L,1) \leq 0; \\
\text{LPSP} (L,1)=0; \\
\text{else} \\
\text{LPSP} (L,1)=1; \\
\text{end} \\
\]

end

%*******************************************************

end

%*******************************************************
Calculate the LPSP
*******************************************************
LSPS2=trapz(BatDischar(:,1),LPSP1(:,1));
LPSP=LSPS2/8760;

mgt=0;
%while (SOCMin <((1-DODLim)*100));
%LPSP>LPSPLim;
while VTmin<VTlim;
    mgt=mgt+1;
    NoParBat=NoParBat+1;

    T_int=0;
    V1_int=13;
    VT_int=13;
    I2_int=0;
    dvdt_int=0;
    SOC_int=100;

    BatEnergyT=BatEnergy*NoParBat;
    BatAHCap=ceil(BatEnergyT/(BatVolt*DODLim));
    PStorage1=BatStorage(:,2)/(NoParBat);
    PStorage=PStorage1.*(−1);
    for i=1:m;
        BatStorageCur(i,1)=PStorage(i,1)/VT_int;
        AhCapPeuk=AhCap;
        if BatStorageCur(i,1)>0;
            TimePeuk=HPeuk*(AhCap/(BatStorageCur(i,1)*HPeuk))^Kpeuk;
            AhCapPeuk=TimePeuk*BatStorageCur(i,1);
        else
            AhCapPeuk=AhCap;
        end
        AhCapPeukArray(i,1)= AhCapPeuk;
        SOC1(i,1)=SOC_int+((BatStorageCur(i,1)*((T_int−T(i,1))*100)/AhCapPeuk);
        if SOC1(i,1)>100;
            SOC1(i,1)=100;
        end
        if SOC1(i,1)>=100 && BatStorageCur(i,1)<0;
            BatStorageCur(i,1)=0;
        end
        OCV1(i,1)=((SOC1(i,1)/100)*1.5)+11.5;
        V11(i,1)=V1_int+(dvdt_int*(T(i,1)−T_int));
        V1_int=V11(i,1);
        VT1(i,1)=V11(i,1)−(BatStorageCur(i,1)*0.157);
        VT_int=VT1(i,1);
        I21(i,1)=(OCV1(i,1)−V11(i,1))/0.063;
        dvdt1(i,1)=(1/5.283)*(I21(i,1)−BatStorageCur(i,1));
        dvdt_int=dvdt1(i,1);
        T_int=T(i,1);
    end

SOCMin=min(SOC1);
VTmin=min(VT1);
LPSP1 = ((1-DODLim)*100)-SOC1;
for L=1:length(LPSP1)
  if LPSP1(L,1)<0,
    LPSP1(L,1)=0;
  else
    LPSP1(L,1)=1;
  end
end

LPSP2 = trapz(BatDischar(:,1),LPSP1(:,1));
LPSP = LPSP2/8760;

%------------------------------------------------------------------------------

BatArrayVol = BatVol*NoParBat*NoSerBat;
if BatArrayVol>MaxBatVol;
  BatVolLim = 0;                  %0 => Broken
else
  BatVolLim = 1;                  %1 => OK
end

o = 1;
p = 1536;
for i=1:365;
  BatSOCDay = SOC1(o:p,1);
  Temp1 = diff(diff(BatSOCDay)>0);
  Temp2 = find(Temp1);
  if isempty(Temp2)==1;
    BatSOCDayMax(i,1) = max(BatSOCDay);
    BatSOCDayMin(i,1) = min(BatSOCDay);
  else
    Temp3 = Temp1(Temp2);
    Temp4 = find(Temp1)+1;
    Temp5 = BatSOCDay(Temp4);
    Temp6 = max(Temp5.*(Temp3*(−1)));
    Temp7 = find(Temp5==Temp6);
    Temp8 = min(Temp5(1:min(Temp7)));
    BatSOCDayMax(i,1) = Temp6;
    BatSOCDayMin(i,1) = Temp8;
  end
  o = o+1;
p = p+1536;
end

SOCDayMax(:,z)=BatSOCDayMax;
SOCDayMin(:,z)=BatSOCDayMin;
SOCMinArray(1,z)=SOCMin;
VTminA(:,z)=VTmin;
NoParBatArray(1,2)=NoParBat;
NoSerBatArray(1,2)=NoSerBat;
BatVolLimArray(1,2)=BatVolLim;
LPSPArray(1,2)=LPSP;
NoUcapParArray(1,2)=NoUcapPar;
NoUcapSerArray(1,2)=NoUcapSer;
NoPVPanelArray(1,2)=NoPVPanel;
StorDischarEnergyArray(1,2)=StorDischarEnergy;
BatAHCapArray(:,z)=BatAHCap;

z=z+1;
end

VT(:,zz)=min(VTminA);
zz=zz+1;
end
DODDay(1:364,1:(z‐1))=SOCDayMax(1:364,1:(z‐1))‐SOCDayMin(2:365,1:(z‐1));
AverageDOD=mean(DODDay);
MinDOD=min(DODDay);
MaxDOD=max(DODDay);

%************************************************
Battery lifetime AH Throughput *************************************************

FloatLife=5; %Years
Cyclelife10=1620; %value for 100, 50, and 30 DOD given in datasheet remainder calculated using
Cyclelife20=1410;
Cyclelife30=1200;
Cyclelife40=825;
Cyclelife50=450;
Cyclelife60=390;
Cyclelife70=330;
Cyclelife80=270;
Cyclelife90=210;
Cyclelife100=150;

AHthroughput10=(AhCap*0.1)*CycleLife10;
AHthroughput20=(AhCap*0.2)*CycleLife20;
AHthroughput30=(AhCap*0.3)*CycleLife30;
AHthroughput40=(AhCap*0.4)*CycleLife40;
AHthroughput50=(AhCap*0.5)*CycleLife50;
AHthroughput60=(AhCap*0.6)*CycleLife60;
AHthroughput70=(AhCap*0.7)*CycleLife70;
AHthroughput80=(AhCap*0.8)*CycleLife80;
AHthroughput90=(AhCap*0.9)*CycleLife90;
AHthroughput100=(AhCap)*CycleLife100;

for i=1:length(AverageDOD)
    if ((AverageDOD(1,i)>0) && (AverageDOD(1,i)<=10))
        BatLife(1,i)=(AHthroughput10*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>10) && (AverageDOD(1,i)<=20))
        BatLife(1,i)=(AHthroughput20*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>20) && (AverageDOD(1,i)<=30))
        BatLife(1,i)=(AHthroughput30*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>30) && (AverageDOD(1,i)<=40))
        BatLife(1,i)=(AHthroughput40*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>40) && (AverageDOD(1,i)<=50))
        BatLife(1,i)=(AHthroughput50*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>50) && (AverageDOD(1,i)<=60))
        BatLife(1,i)=(AHthroughput60*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>60) && (AverageDOD(1,i)<=70))
        BatLife(1,i)=(AHthroughput70*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>70) && (AverageDOD(1,i)<=80))
        BatLife(1,i)=(AHthroughput80*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>80) && (AverageDOD(1,i)<=90))
        BatLife(1,i)=(AHthroughput90*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
    if ((AverageDOD(1,i)>90) && (AverageDOD(1,i)<=100))
        BatLife(1,i)=(AHthroughput100*BatVolt*NoParBatArray(1,i)/BatDischarEnergyArray(1,i));
    end
end
for i=1:length(BatLife)
    if BatLife(1,i)>FloatLife;
        BatLife(1,i)=FloatLife;
    end
end

%************************************************** System	Cost	**************************************************
SystemLife=20;
PVCapCost=200;
BatCapCost=70;
UcapCapCost=45;

PVSystemCapCost(1,:)=NoPVPanelArray(1,:).*PVCapCost;
BatSystemCapCost(1,:)=NoParBatArray(1,:).*NoSerBat.*BatCapCost;
UcapSystemCapCost(1,:)=NoUcapParArray(1,:).*NoUcapSerArray(1,:).*UcapCapCost;
NoBatReplace=floor(SystemLife./BatLife(1,:));

BatSystemMainCost(1,:)=NoParBatArray(1,:).*NoSerBat.*BatCapCost.*NoBatReplace(1,:);

SystemLifetimeCost(1,:)=PVSystemCapCost(1,:)+BatSystemCapCost(1,:)+BatSystemMainCost(1,:)+UcapSystemCapCost(1,:);

[MinSystemLifetimeCost,M]=min(SystemLifetimeCost);
MinNoPBat=NoParBatArray(M);
MinNoPUcap=NoUcapParArray(M);
MinNoPVPanel=NoPVPanelArray(M);
MinBatReplace=NoBatReplace(M);
MinBatSOC=SOCMinArray(M);
StorageLimObser=BatVolLimArray(M);
MinDOA=DayOfautonArray(M);
APPENDIX C.

MATLAB SIMULINK MODELS

PV Panel Model

Figure C-1 PV Panel Simulink model
**MPPT Model**

![MPPT Simulink model](image)

*Figure C-2 MPPT Simulink model*

**Battery Model**

![Battery Simulink model](image)

*Figure C-3 Battery Simulink model*
Ultracapacitor Model

![Ultracapacitor Simulink model](image)

Figure C-4 Ultracapacitor Simulink model

Battery Controller Model

![Battery controller Simulink model](image)

Figure C.5 Battery controller Simulink model
HESS Controller Model

Figure C.6 HESS controller Simulink model
Figure D.1 Battery SOC for peak load profile with a SOC limit of 20%
Figure D.2 Ultracapacitor SOC for peak load profile with a SOC limit of 20%

Figure D.3 Ultracapacitor SOC for peak load profile with a SOC limit of 20% and a LPSP of 0.9132x10^-3
Figure D.4 Battery SOC for an optimisation horizon of 1 day

Figure D.5 Battery SOC for an optimisation horizon of 1 week
Figure D.6 Battery SOC for an optimisation horizon of 1 month

Figure D.7 Ultracapacitor SOC for the pulse load profile with a SOC limit of 20%
Figure D.8 Battery SOC for the pulse load profile with a SOC limit of 90%

Figure D.9 Ultracapacitor SOC for the pulse load profile with a SOC limit of 90%
Figure D.10  Battery SOC for the pulse load profile with a duty cycle of 0.1 and a SOC limit of 20%

Figure D.11  Ultracapacitor SOC for the pulse load profile with a duty cycle of 0.1 and a SOC limit of 20%
APPENDIX E.

PUBLICATIONS

Journal Publications


Conference Publications


Optimisation of a photovoltaic battery ultracapacitor hybrid energy storage system

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Abstract

Autonomous photovoltaic panels are intermittent sustainable energy sources which require energy storage to balance generation and demand, as photovoltaic generation is time and weather dependent. Traditionally batteries are the most common storage technology for photovoltaic systems. Photovoltaic batteries can encounter extended periods of low State of Charge (SOC), resulting in sulphation and stratification, reducing battery lifetime.

Stand-alone photovoltaic systems are often used in remote areas away from the national grid for water irrigation systems, requiring dc motor starting resulting in high inrush current, cathodic protection systems for oil and gas pipelines, emergency phones, warning signs, and telecommunication repeater stations, resulting in pulse discharging of the battery. A combination of depleted battery SOC and high burst current can result in premature loss of load due to stringent battery Low Voltage Disconnect (LVD) limits implemented by the battery management system.

A combination of Valve Regulated Lead Acid (VRLA) batteries and ultracapacitors in a Hybrid Energy Storage System (HESS), which increases the power density of the overall system, is examined. Operating the ultracapacitor bank under high power conditions reduces the strain of large current extraction from the battery bank. The addition of the ultracapacitor bank presents the need for a methodology to optimise the photovoltaic system to prevent excess battery storage.

This paper outlines the methodology utilised to optimise the combination of photovoltaic panels, batteries, and ultracapacitors for a given solar radiation and load profile employing Matlab software.

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Keywords: Optimisation; Photovoltaic; Battery; Ultracapacitor

1. Introduction

Diminishing supplies of fossil fuel, peak oil and the environmental impact of fossil fuels on the environment has encouraged a growth in sustainable energies such as wind and solar power. Significant growth was seen by the photovoltaic industry in 2010, when the global installed capacity grew by 17 GW from 23 GW in 2009 to 40 GW in 2010 (European photovoltaic industry association, 2015).

Autonomous photovoltaic systems are generally used in remote locations, due to the expense encountered in extending the national grid. A variety of isolated applications, for example domestic applications, water irrigation, and telecommunication repeater stations, have different power requirements. A water irrigation system utilising a dc motor is an example of a photovoltaic load which requires peak power several times the normal operating power of the load.

The current required to initially start the dc motor is significantly greater than the current necessary to keep the
motor running in steady state. Typically the starting current of the motor could be six times the steady state current.

In photovoltaic systems that employ battery only storage, fast power variations, as described for a dc motor load, considerably reduces the battery lifetime because of high discharge current (Van Voorden et al., 2007). In this case the battery capacity must be large enough to account for the increased current discharge at start-up, even though the current surge only needs to be met for a few seconds at a particular time.

Fig. 1 illustrates a photovoltaic system which includes a HESS encompassing both batteries and ultracapacitors. Ultracapacitors have a greater power density than batteries, allowing the ultracapacitors to provide more energy over a shorter period of time. Conversely, the batteries have a higher energy density compared to the ultracapacitors to supply the base load power requirement (Burke, 2000; Conway, 1999). The addition of an ultracapacitor bank to the storage system extends the life of the battery bank, as it does not experience high current discharge, which in turn reduces the system lifetime cost (Gao et al., 2005; Dougall et al., 2002; Liu et al., 2005).

Battery Management Systems (BMS) which control the charge/discharge of power to/from the batteries in photovoltaic systems monitor the battery terminal voltage. When high currents are discharged from the battery bank, a significant voltage drop can be seen across the battery terminals which can lead the BMS to disconnect the battery prematurely. In the hybrid system the ultracapacitor supplies the peak currents with the battery supplying the lower average current. This utilises the battery more efficiently and reduces the risk of premature loss of load (Kuperman and Aharon, 2011).

The addition of the ultracapacitor to the photovoltaic storage element necessitates a methodology to optimise both technologies in the HESS to avoid over/under design of the system, which could lead to increased system lifetime cost or unsatisfactory Loss of Power Supply Probability (LSP). LSP is the probability that the photovoltaic panels and energy storage system is not capable of supply the load when required. Therefore it is the fraction of the load that cannot be supplied in the operating time period, ranging from 0 to 1, with 0 being the load met at all times and 1 the load never being met.

A number of different methods are employed for the optimisation of intermittent generators, such as wind turbines and photovoltaic panels, in autonomous systems. These methods include intuitive, analytical methods, and system simulation approaches (Hontoria et al., 2005). The genetic algorithm (Vosan and Keller, 1999) and the simulation based (Koutoulia et al., 2006; Ekren and Ekren, 2009) optimisation techniques average the generation and load profiles on an hourly base to determine the component size. The process of using averaged data is satisfactory when the energy requirement is being considered. However the magnitude of the peaks in power is damped. Therefore when considering the effects of peak power on the battery storage system, shorter time horizons are required to capture the effect of the power spikes on the battery voltage.

This paper describes a methodology developed to optimise the various elements in the photovoltaic system taking into account peak power requirements given the solar

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**APPENDIX E. PUBLICATIONS**

**Nomenclature**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
</tr>
<tr>
<td>ESR</td>
<td>Electricity Supply Board</td>
</tr>
<tr>
<td>HESS</td>
<td>Hybrid Energy Storage System</td>
</tr>
<tr>
<td>LOLE</td>
<td>Loss of Load Expectation</td>
</tr>
<tr>
<td>LPSP</td>
<td>Loss of Power Supply Probability</td>
</tr>
<tr>
<td>LVD</td>
<td>Low Voltage Disconnect</td>
</tr>
<tr>
<td>SAIDI</td>
<td>System Average Interruption Duration Index</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>VR</td>
<td>Voltage Regulation</td>
</tr>
<tr>
<td>VRLA</td>
<td>Valve Regulated Lead Acid</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** Photovoltaic system with ultracapacitor battery HESS.
radiation on a horizontal surface and the load requirement. The optimisation process utilises a small time horizon to capture the peak power requirement and aims to minimise the system lifetime cost, while adhering to a set of constraints. The optimisation program was developed in Matlab and the results were analysed utilising a simulink model of the complete system.

2. Hybrid Energy Storage System

Generally VRLA batteries are employed as energy buffers in photovoltaic systems. Photovoltaic panels are not ideal for battery charging since they are time and weather dependent. An optimum charge/discharge strategy cannot be guaranteed resulting in poor battery life. Charge controllers are utilised to prevent over - charge/discharge of the battery by implementing voltage limit restrictions. The Voltage Regulation (VR) set point limits the maximum voltage threshold while the LVD set point determines the load cut off point.

Premature loss of load can occur due to a peak power battery voltage depression triggering the LVD limit. To prevent battery voltage drop, ultracapacitors are combined with the battery bank to form a HESS. In the HESS the power required during transient spikes is provided by the ultracapacitor, reducing the battery power requirement preventing large voltage drops. There are two battery ultracapacitor HESS configurations. The passive configuration comprises a direct connection of the battery and ultracapacitor to the load, with no dc–dc conversion as shown in Fig. 2. The ultracapacitor and battery internal resistances determine the power supplied by each component. The HESS voltage is not controlled and follows the terminal voltage of the battery, leading to utilisation of the ultracapacitor.

The second type of HESS is actively controlled. Dc–dc converters are located between the battery, ultracapacitor and the load. The converter then actively controls the power from the battery and ultracapacitor, allowing more efficient utilisation of the ultracapacitor leading to increased power capability. The ultracapacitor and battery can be operated at different voltage levels, giving greater flexibility in the design of the battery and ultracapacitor banks. The utilisation of the dc–dc converters enables a constant output voltage from the HESS (Guo et al., 2005).

In the active HESS a bidirectional dc–dc converter can be placed between the batteries and the ultracapacitors. As Fig. 3. The current output of the battery is controlled with the remaining load power requirement met by the ultracapacitor. The ultracapacitor voltage becomes the bus voltage, which varies with SOC. The second dc–dc converter is required to maintain the load voltage. There is a large voltage swing on the converter input with high input current for low ultracapacitor SOC. The increased current leads to high FR losses. Alternatively two bidirectional dc–dc converters are utilised in Fig. 4. This configuration gives the highest efficiency, reliability, and flexibility. The battery dc–dc converter is current controlled with the ultracapacitor dc–dc converter voltage controlled. The current supplied by each component is based on their SOC (Lucie et al., 2006).

3. Optimisation methodology

Optimisation of an autonomous photovoltaic system with storage is crucial as the photovoltaic panels are the only source of generation. The optimisation of the system is performed on an annual basis to minimise the system lifetime cost under a number of constraints. The constraints employed in the optimisation include the battery SOC limit, restrictions on component dimensions, and an LPSP limit. The input data required for the optimisation include the annual solar radiation and the load profile. The optimisation methodology is illustrated in Fig. 5.

To obtain the maximum energy output from the photovoltaic panels on an annual basis, the optimum fixed tilt angle for the system location is calculated based on the horizontal solar radiation of the site. A number of different models exist to estimate the diffuse solar radiation on a tilted surface. These models can be categorised as Isotropic or Anisotropic. Isotropic models assume the intensity of diffuse sky radiation is uniform over the sky dome while the Anisotropic models takes into account the brightening around the solar disk, plus the isotropically distributed diffuse component from the rest of the sky dome. In the optimisation process the diffuse radiation on the tilted panel is calculated based on the Klucher model, under overcast skies the model is reduced to an isotropic model while under clear skies it approximates a clear sky model (Evseev and Kodish, 2005; Noorani et al., 2006; Armstrong and Hurley, 2010).

The optimisation program varies the tilt angle from the horizontal to vertical position to determine the optimum tilt angle. The optimum tilt angle is selected as the angle at which the photovoltaic panel receives the highest global solar radiation over the optimisation horizon.

The photovoltaic energy available from the panels varies throughout the year. A trade off between increasing the number of photovoltaic panels and increasing the storage system to supply the load during periods of low solar radiation exists. To find the optimal solution the quantity of
photovoltaic panels is varied from best to worst case taking the system efficiency into account. The minimum number of photovoltaic panels required to supply the load is calculated based on the annual load energy requirement, with the maximum number of photovoltaic panels based on supplying the load for the worst day of the year. These are two extreme cases, which are not optimal and would require a large/small storage system for the minimum/maximum photovoltaic array.

The storage system is utilised as an energy buffer to supply power to the load at night time and during periods of low solar radiation. The extent of the storage elements required to supply the load throughout the year fluctuates depending on the quantity of photovoltaic panels installed in the system. The quantity of photovoltaic panels is varied from the best to the worst case and the storage system is optimised based on the power available to charge the storage elements and the load power required from the storage system. In the HESS the ultracapacitors are employed to supply the peak power requirements of the load with the average power supplied by the battery bank. The capacitance of the ultracapacitor bank is calculated based on the energy from equation (1)

\[ C_{Cap Req} = \frac{2E_{cap}}{V_a^2 - V_b^2} \]  

where \( E_{cap} \) is the energy requirement of the ultracapacitor, \( V_a \) and \( V_b \) are the maximum and minimum operating voltage of the ultracapacitor bank respectively. In the analysis the ultracapacitor bank is allowed to discharge to half of its maximum voltage to utilise approximately 75% of the ultracapacitor energy, i.e. \( V_b = 0.5V_a \).

In the HESS the ultracapacitors are given priority charging and can be charged from both the photovoltaic panels and the battery bank to ensure they contain adequate charge to supply the high power requirements of the load which can occur at any point. As the period between the peaks in load power is unpredictable, adequate recharge of a small ultracapacitor bank cannot be guaranteed, for this reason \( E_{cap} \) is varied during the optimisation process. The minimum value of \( E_{cap} \) is calculated as the energy required to meet the largest load peak occurring during the year. To provide for peaks in load power occurring in quick succession the maximum value of \( E_{cap} \) is selected to enable the ultracapacitor to supply the day with the largest peak energy requirement. The number of ultracapacitors connected in series and parallel can be obtained by (2) and (3) respectively using the value of \( C_{Cap Req} \) calculated in (1).

\[ N_{Cap Req} \geq \frac{V_a}{V_{Cap}} \]  

(2)

\[ N_{Cap Req} \geq \frac{C_{Cap Req} \times N_{Cap Req}}{V_{Cap}} \]  

(3)

where \( V_{cap} \) is the ultracapacitor voltage and \( C_{Cap} \) is the nominal capacitance of the ultracapacitor.

The charge discharge profile of the HESS is adjusted to take the ultracapacitor profile into account, to highlight the energy requirements of the battery bank. The discharge rate of the battery has an effect on its available capacity as outlined by Peukert's law, increasing the rate of discharge of the battery decreases its available capacity. The battery capacity is modified in the optimisation process according to (4) and (5) to take the impact of Peukert's law into account.

\[ T = H \times \left( \frac{C}{N} \right)^{1/k} \]  

(4)
Fig. 5. Optimization flowchart.
APPENDIX E. PUBLICATIONS

\[ \Delta h_{\text{red}} = IT \]  

(5)

where \( H \) is the rated discharge time in hours, \( C \) is the rated capacity at the discharge rate in ampere-hours, \( I \) is the actual discharge current in amps, \( T \) is the actual time to discharge the battery in hours, \( k \) is Peukert’s constant which is specified by the manufacturer, typically in the range 1.1–1.3 for lead acid batteries, and \( \Delta h_{\text{red}} \) is the adjusted battery capacity (Cugnet et al., 2010).

Traditionally in photovoltaic systems the size of the battery bank is determined based on the daily load requirement and the number of Days of Autonomy (Lead acid battery guide for standalone photovoltaic systems, 1999). The Days of Autonomy outlines the number of days that the photovoltaic system can deliver full power to the load from the battery bank without charge from the photovoltaic panels, utilised to ensure the load can be maintained during rainy and cloudy periods.

The photovoltaic panel is the only charging source for the battery. In the proposed optimisation process the battery bank is calculated for each of the photovoltaic panel and ultracapacitor combinations. The number of series connected batteries is calculated in equation (6)

\[ N_{\text{batt}} = \frac{V_{\text{bat}}}{V_{\text{bat}}} \]  

(6)

where \( V_{\text{bat}} \) and \( V_{\text{bat}} \) are the system and battery voltage respectively. The accessible battery energy in the HESS is limited depending on the SOC limit implemented in the system as given in equation (7)

\[ E_{\text{bat}} = \frac{V_{\text{bat}}}{V_{\text{bat}}} * \Delta h_{\text{bat}} * (1 - \text{SOC}) \]  

(7)

where \( \Delta h_{\text{bat}} \) is the nominal battery capacity. The charge/discharge profile of the battery bank is analysed to determine the number of consecutive days when adequate photovoltaic power is not available to fully recharge the battery bank. This value is utilised to calculate the initial number of parallel batteries required as given in equation (8)

\[ N_{\text{batt}} = \frac{\text{MaxDailyDischarge}}{E_{\text{bat}}} * \text{DaysInadeqChar} \]  

(8)

where \( \text{MaxDailyDischarge} \) is the maximum energy discharged by the battery in one day. \( \text{DaysInadeqChar} \) is the number of consecutive days the battery does not maintain full SOC. \( \text{DaysInadeqChar} \) is calculated in the optimisation program by comparing the charge/discharge profiles from the battery bank over the optimisation horizon. This value is set to one where the battery is fully recharged every day. Both these variables are dependent on the photovoltaic array size.

A range of constraints can be implemented in the optimisation process. Constraints on the volume of the components in the system, and the LPSP are employed. The volume constraint allows restrictions on the available space for the storage elements and/or the photovoltaic panels to be taken into account when designing the system.

The LPSP is a power system reliability assessment. When the LPSP is equal to 1, the demand is never satisfied and a system redesign is required. A LPSP equal to 0, means the demand is satisfied at all times, which depending of the criticality of the load may result in redesign of the system with increased cost. The LPSP is calculated by equation (9)

\[ \text{LPSP} = \frac{1}{T} \int_{T}^{T} \left( \left( P_{\text{PV}} + P_{\text{Storage}} < P_{\text{load}} \right) \right) \]  

(9)

where \( P_{\text{PV}}, P_{\text{Storage}} \) and \( P_{\text{Load}} \) are the photovoltaic, storage, and load power respectively, \( T \) is the time horizon over whic the optimisation is performed, 8760 for time horizon of 1 year (Borowy and Salameh, 1996). In Ireland, Eirgrid the transmission system operators utilise a statistical indicator Loss of Load Expectation (LOLE) with an accepted generation adequacy of 8 h LOLE (http://www.eirgrid.com/media/Winter%20Outlook%202010%2011.pdf). ESB Networks, the Irish distribution system operators, utilise the international measure System Average Interruption Duration Index (SAIDI), the average duration of interruption for all customers during the year. The commission for energy regulation sets the SAIDI target for ESB networks, the target was set at 152.3 min in 2010 and reduced to 141.1 min in 2011 (http://www.cer.ie/en/electricity-distribution-network-decision-documents.aspx/article-0b279c96-8053-43e1-808b-b234233c3e34c).

The lifetime of each of the components in the system needs to be determined in calculating the system lifetime cost. Photovoltaic panels are taken to have a lifetime of 20 years, set as the system lifetime. Ultracapacitors are not replaced during this time as they have a cycle life of greater than 500,000 cycles. To determine the number of battery replacements required throughout the system lifetime a battery life model was incorporated into the optimisation process. The battery model is an energy throughput model based on the model utilised in the Homer optimisation program (http://www.homenergy.com/documents/Micro\-\text{power}System\-\text{Modeling}With\-\text{Homer}\-\text{pdf}). The battery throughput is the amount of energy that is cycled through the battery annually. The battery lifetime curve, supplied by the manufacturer, outlines the number of charge discharge cycles the battery can undergo at a particular SOC. The number of charge discharge cycle’s decreases as the SOC limit is decreased. To determine the lifetime throughput from the curve the average annual SOC of the battery was established and the number of charge discharge cycles was calculated. The lifetime throughput is the product of the number of cycles, the nominal voltage, the SOC, and the maximum capacity of the battery. The number of battery replacements required during the system lifetime is determined by comparing the annual battery throughput and the lifetime throughput capability of the battery in equation (10).

\[ \text{BatteryLife} = \frac{\text{System lifetime}}{\text{Min} \left( \frac{\text{Throughput}}{\text{Throughput}}, \frac{\text{Throughput}}{\text{Capacity}} \right)} \]  

(10)
where $\text{Throughput}_{\text{eff}}$ is the calculated energy throughput of the battery before failure, $\text{Throughput}_{\text{year}}$ is the actual energy throughput in the year, and $\text{Batt}_{\text{Joule}}$ is the Joule life of the battery.

The optimisation function is to minimise the system lifetime cost, which is calculated from the capital and replacement cost of each of the system components. For simplicity only the components that are varied during the optimisation process are considered in the calculation

$$\text{System Cost} = C_{\text{capital}}(\text{PV} + \text{Battery} + \text{Ultrapacapistor}) + C_{\text{replacement}}(\text{Battery})$$

(11)

Various combinations of photovoltaic panels, batteries, and ultracapacitors which meet constraints set out in the optimisation process are presented, with the least cost option chosen as the optimal solution.

4. Simulation results and analysis

The optimisation methodology outlined in Section 3 results in the determination of the number of photovoltaic panels, the optimum tilt angle, along with the number of VRLA batteries and ultracapacitors required in the HESS.

The system voltage was taken as 12 V, with the component values designed for 50 W photovoltaic panel, 18Ah VRLA battery, and 600F Ultracapacitor. The components cost utilised to calculate the system cost were £200, £70, and £45 for the photovoltaic panel, battery, and ultracapacitor respectively. One of the required inputs to the optimisation program is the solar radiation on the horizontal surface. As the solar radiation varies over the course of the year, a yearly solar radiation profile was utilised as shown in Fig. 6, the profile was obtained from an onsite weather station located in Northern Europe (Armstrong et al., 2008).

The components of the photovoltaic system of Fig. 1 were modelled in simulink to analysis the results of the optimisation program utilising the daily load profile shown in Fig. 7 (Glavin et al., 2008). Simulations were performed assuming an initial battery and ultracapacitor SOC of 100%. The ultracapacitor utilises a physical reaction to produce power where as the battery depends on chemical reactions. The battery capacity varies with the discharge rate; high currents reduce the battery capacity leading to voltage drops. The benefits of the ultracapacitor in this situation can be seen in Figs. 8 and 9 for an un-optimised system. In Fig. 8 a voltage drop can be seen for the battery each time the motor is started. The same battery voltage is shown in Fig. 9 for the HESS.

Implementing a LVD limit of 11.8 V representing 20% SOC in the photovoltaic system with battery storage would trigger the limit every time the motor was started in Fig. 8, this could result in the motor burning out from repeated attempts to start. In Fig. 9 the high power requirement of the motor is supplied by the ultracapacitor, the battery does not experience the voltage drop. Employing the same LVD limit on the battery in the HESS extends the operating time of the system by approximately 16 h. Increased battery capacity is required in the system of Fig. 8 to enable the motor to be started throughout the year without reaching the LVD limit. This could result in a large battery pack, increasing the lifetime system cost as generally batteries need to be replaced every 3-5 years.

Active and passive HESS configurations were investigated to find the best arrangement. The active system allows both the battery and the ultracapacitor to be operated at different voltages, allowing better utilisation of the individual components. The ultracapacitor can be discharged down to a predefined limit similar to the battery SOC limit. Setting the ultracapacitor SOC limit at 50% utilises 75% of the available energy of the ultracapacitor.

A yearly optimisation was performed for the load described in Fig. 7 repeated daily, with the solar radiation profile illustrated in Fig. 6. The results of the optimisation are outlined in Table 1, for the number of photovoltaic panels, batteries, ultracapacitors along with the system lifetime cost and the days of consecutive inadequate recharge experienced by the battery over the year for varying SOC limits. The optimum fixed tilt angle for the site to produce the maximum annual energy from the photovoltaic panels was found to be 36° facing south. No restrictions on component volumes were implemented in the cases described in Table 1.

Lowering the battery SOC limit reduces the system cost as more energy is made available from the battery bank. For each of the SOC limits, the optimised systems return the battery to 100% SOC for the majority of the year except for two periods of extended low solar radiation, illustrated in Fig. 10 by the daily maximum SOC of the battery bank, for the HESS system with a battery SOC limit of 20%. Returning the battery bank to 100% SOC each day helps prevent sulphation and stratification (Dunlop and Farhi, 2001; Wong et al., 2008). Fig. 11 shows the battery SOC during the period of low solar radiation occurring in December.

The optimisation process is performed over the course of a year taking component lifetime into consideration when calculating the system cost. Therefore due to the short lifetime of the battery it was found to be more economical to increase the number of photovoltaic panels required to supply the load during periods of low solar radiation, generating dump energy during the periods of high solar radiation. There was no penalty cost placed on the dump energy as the cost associated with the generation of photovoltaic power is taken as zero, apart from the initial system and battery replacement cost.

The ultracapacitor SOC over a 3 day period in December is displayed in Fig. 12; this is representative of the ultracapacitor operation throughout the year. The active HESS of Fig. 4 was implemented in the design and the minimum operating voltage of the ultracapacitor was set to 6 V in the optimisation process. The ultracapacitor in the system is given priority and recharged by both the photovoltaic panels and the battery bank. Therefore the
ultracapacitor is maintained at a high SOC. The number of series ultracapacitors could be decreased utilising more of the energy available in the ultracapacitors to reduce the system cost, as the dc-dc converter will generate the power at the required load voltage.

From Fig. 8 the battery storage system needs to be optimised taking the voltage drop at motor start up into account, resulting in an increased battery bank and therefore increased system lifecycle cost as seen in Table 1. The HESS system cost remains lower for all SOC limits in comparison to the Battery system, however greater benefit can be seen with the SOC limit set at a high level, as only a small voltage drop would be acceptable before the LVD limit would be triggered by the battery storage system.

The SOC limit of 20% was found to give the lowest HESS system cost as the majority of the available energy in the HESS can be utilised for the periods of low solar radiation which can occur for several days.

The HESS with a 20% SOC limit for the battery bank was examined for volume restrictions on the individual component in the system. The number of panels for this
The reduction in the number of photovoltaic panels lead to the number of consecutive days the battery experiences inadequate recharge increasing to 8, with the number of batteries required to satisfy the SOC limit increasing to 40. With the reduction in the number of photovoltaic panels there is a need to increase the energy storage of the HESS to enable the load to be supplied for the extended periods of low solar radiation. As the number of photovoltaic panels is reduced the amount of dump energy produced during the year also diminishes. The increase in the number of batteries required and their replaced cost increases the system cost by approximately 62% to €17,225. The Battery daily maximum/minimum SOC over the course of the year can be seen in Fig. 13. Compared to Fig. 10 the battery bank is not as frequently recharged to 100% SOC during the winter period.

A sensitivity analysis limiting the number of batteries to 7 in the HESS system with a battery SOC limit of 20% was also performed. Limiting the battery bank in the storage system necessitates a large photovoltaic array to be installed, to generate the daily power requirement of the load as the battery bank is not large enough to provide for the load for an extended period of time. In this situation the number of photovoltaic panels is nearly doubled to 51.

Increasing the system cost by approximately 22% to €12,875. The large number of photovoltaic panels also increases the amount of dump energy produced during high solar radiation. The daily battery maximum/minimum SOC can be seen in Fig. 14. The large number of photovoltaic

| Table 1 | HESS VS battery storage system for the annual load profile of Fig. 7. |
|----------|------------------|------------------|------------------|------------------|------------------|
| SOC limit | 20               | 30               | 40               | 50               | 60               | 70               | 80               | 90               |
| PV panels | 27               | 29               | 31               | 33               | 33               | 34               | 56               | 83               |
| Battery | 14               | 14               | 15               | 16               | 20               | 26               | 23               | 29               |
| Ucnp | 1               | 1               | 1               | 1               | 1               | 1               | 1               | 1               |
| Cost (€) | 0,525            | 0,925            | 1,675            | 2,425            | 3,825            | 6,125            | 9,475            | 26,975           |
| Days In/Out | 7               | 7               | 7               | 7               | 7               | 7               | 4               | 4               |

| Battery storage system | 29               | 33               | 31               | 33               | 33               | 34               | 52               | 75               |
| PV Pans | 16               | 15               | 19               | 21               | 25               | 32               | 34               | 50               |
| Battery | 1               | 1               | 1               | 1               | 1               | 1               | 1               | 1               |
| Cost (€) | 11,400           | 11,850           | 12,850           | 13,950           | 15,350           | 18,000           | 22,200           | 25,200           |
| Days In/Out | 7               | 7               | 7               | 7               | 7               | 7               | 4               | 2               |
Fig. 12. Ultracapacitor SOC for 3 days in December for HESS system with a SOC limit of 20.

Fig. 13. Battery daily maximum/minimum SOC for photovoltaic panel sensitivity analysis.

panels return the battery array to 100% SOC for the majority of the year but the reduction in the number of batteries means the batteries are discharged to a lower SOC. Comparing the lifetime system cost of both sensitivity analysis highlights further the impact the battery bank has on the lifetime cost due to number of battery replacements required during this period.

The system size and lifecycle cost can be reduced if the loads supplied were non-critical and an LPSP of greater than zero is considered. Throughout the majority of the year the batteries in the system are maintained at a high SOC in the HESS. If the system was allowed to drop the load for a short period of time during prolonged periods of low solar radiation which only occurs twice during the year the battery bank could be reduced. Setting the LPSP to allow 8 h loss of load in the optimisation process reduces the system cost by approximately 4% to €10,175. This is achieved by reducing the size of the battery bank, a loss of load of approximately 4 h was observed during the period of low solar radiation at the end of the year.

The benefit of the HESS can be seen in Table 1 for a motor load that is repeatedly started throughout the day. This will not be the case for all applications. The load profile of Fig. 7 was adapted for two situations, a motor started daily at 4 am for 45 min, and a motor started daily at 5 pm for 45 min. The results of the optimisation are outlined in Tables 2 and 3 for the profile of the motor started at 4 am and 5 pm respectively. The results of Tables 2 and 3 are similar, and follow the trend of those in Table 1. The addition of the ultracapacitor reduces the system lifetime cost, with the greatest benefit seen when the battery SOC limit is high.

5. Conclusions

A sustainable energy system consisting of a photovoltaic array with a battery ultracapacitor HESS to supply a non-grid connected load was introduced. The impact of including the ultracapacitor in the photovoltaic system was analysed. The batteries and ultracapacitors complement each other in terms of their power and energy densities.

Electrical loads that contain motors can have power spikes of between three and seven times their rated wattage at start-up, while loads requiring large capacitors to be charged at start-up can result in a power surge up to three times their rated wattage.

A DC system was analysed in this paper but the same principals apply to AC systems. In an AC system the inverter must be sized to take into account the starting power requirement of the load, with the battery bank being sized to handle the voltage drop due to the high current surge. Otherwise the drop in voltage could cause the inverter to shut down.

The battery bank supplies power to the load through chemical reactions, with the capacity of the battery...
Table 2

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Table 3

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depending on the discharge rate. Peak power loads requiring high power reduce the battery capacity, resulting in a voltage drop. When the battery is at a low SOC the voltage drop can trigger the LVD limit leading to the load being shut down prematurely. The ultracapacitor in the HESS provides the peak power, alleviating the battery voltage drop, maintaining the load for a longer period of time.

A methodology to optimise the HESS was described. The optimisation process was performed for a peak power load with the results analysed with a simulink system model. It was found that an ultracapacitor battery HESS should be employed to minimise the system lifetime cost of an autonomous photovoltaic system operating a load with a high peak to average power requirement. An active HESS configuration makes best use of the available ultracapacitor energy. To further reduce the cost the SOC limit for the battery should be low to utilise as much battery energy as possible. If feasible no limits should be placed on the number of components in the system, as this can significantly increase the cost. Finally utilising a LPSP of greater than zero reduces the number of batteries needed to cover the longest period of low solar radiation.

For the load profiles assessed, the cost saving incurred by employing the ultracapacitor battery HESS over battery only storage varied depending on the SOC limit. For the load profile with the motor started every hour, the cost saving between the two storage systems changed from approximately 20% for a SOC limit of 90% to approximately 8% for a SOC limit of 20%. For the HESS increasing the SOC limit from 20% to 90% incurred an increase in the system cost of approximately 256%. In the case where the motor was started once a day the cost saving varied from approximately 153% for a SOC of 90% to approximately 11% for a SOC of 20%, with the cost increasing by approximately 242% if the SOC limit is increased from 20% to 90%.

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References


