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Synchronization Issues for Smart Grids

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Abstract—The loss of time synchronization across a Smart Grid due to local A/D and D/A conversion processes between the digital domain and the analogue control domain is considered. It is shown that a local calibration can be implemented to enable a determination of clock skew in individual analog sub-systems. Given this information two correction strategies are explained, one based entirely on network-side modification of the control signal data stream. A second approach is based on modification of the control signal on individual client sub-systems allows use of a multi-cast control signal and facilitates both local and global synchronization of the control signals.

Keywords- smart grid; synchronization; analog control; clock skew, standards IEEE 1588, IEC 61850

I. INTRODUCTION

Smart Grid is the integration of communications networks with the power grid in order to create an electricity communications superhighway extending from generation nodes right through transmission and distribution into end user premises. Such a Smart Grid has two distinct features; firstly it allows flexible and real-time decision making based on real-time pricing; furthermore, it is capable of monitoring its own health at all times, alerting operators immediately when problems arise and automatically taking corrective actions that enable the grid to fail gracefully and prevent a local failure from cascading out of control.

One can think of Smart Grid as a system of systems, each with its own architecture [1]. Some of the key infrastructure requirements are reliable distribution of information and time synchronization among network elements in order to correlate different network events. Time management and clock synchronization requirement in Smart Grid varies from system to system.

PSRC (Power System Relaying Committee) [2] working group H7 is defining IEEE1588 standard profile for power system applications to be called IEEE C37.238 [4]. The purpose of that standard is to facilitate adoption of IEEE1588-2008 for power system applications requiring high precision time synchronization. The profile specifies a well-defined subset of IEEE1588-2008 mechanisms and settings aimed at enabling device interoperability, robust response to network failures, and deterministic control of delivered time quality.

This set of PTPv2 parameters and options allows

IEEE1588-2008 based time synchronization to be used in mission critical power system protection, control, automation and data communication applications.

The world of precise synchronization is standardized by the IEEE 1588 document [3] also known as the Precision Time Protocol (PTP) facilitates both time and timing synchronization. In recent years, it has become highly relevant to network providers who are migrating from circuit switched SDH/SONET networks to IP Based Next Generation Networks. Such providers need a replacement mechanism to transfer timing (and also time) within their networks. Many application domains such as industrial automation, measuring, telecommunication, substation automation or audio/video transmission require a precise synchronization across their equipments to ensure a correct and safe execution. The main IEEE 1588 standard defines the basic rules and protocol elements to achieve precise synchronization, while profiles refine the main standard by adapting it to a specific application domain. Three profiles are currently under definition. The first one is the power systems profile driven by the IEEE Power Systems Relaying Committee (PSRC), the second one is the audio/video bridging of IEEE 802.1, while a third one addresses the telecom applications.

Another important standard is IEC 61850. This has been substantially developed for substations but is seen as a key standard for all field equipment operating under both real-time and non-real time applications. The use of IEC 61850 for wide-area communication is already discussed in IEC 61850-90-1 (Draft technical report) in the context of communication between substations.

Much of this work relies on the use of Network Time Protocol (NTP) to provide the underlying time synchronization for real-time systems [5]. Now NTP provides a well tested method to enable reasonably accurate time synchronization across TCP/IP networking infrastructure. It can be further refined using hardware extensions and taking advantage of the ubiquitous GPS 1pps signal to refine local time synchronization to the microsecond level.

However, returning to our earlier comment that the Smart Grid is a “system of systems” we can see that the above standards take a uniquely “digital” view of the Smart Grid,

conveniently ignoring that the underlying electricity which is carried by the grid is actually an “analog system” and must ultimately be monitored and controlled in the analog domain. Once we realize that Smart Grid relies on imposing a digital management, monitoring and control layer onto the underlying analog grid it becomes clear that we need to extend our considerations on synchronization beyond the digital domain.

In this paper we will outline some other fields where we have studied time synchronization, outlining the fundamental problem of moving from digital to analog signals and how the D/A process can introduce its own synchronization issues.

II. THE ANALOG SYNCHRONIZATION PROBLEM

NTP based techniques use a range of mechanisms to cleverly keep two networked digital systems in close time synchronization. However, if we step back a little from this, we realize that each local system has its own local clock and in a sense these digital techniques are simply providing us with a measurement of the clock skew between these two systems. The underlying problem, however, is that each networked system must in turn take input from a further series of analog monitoring sub-systems and/or drive a further series of analog control sub-systems as part of its role in monitoring/controlling the local power grid.

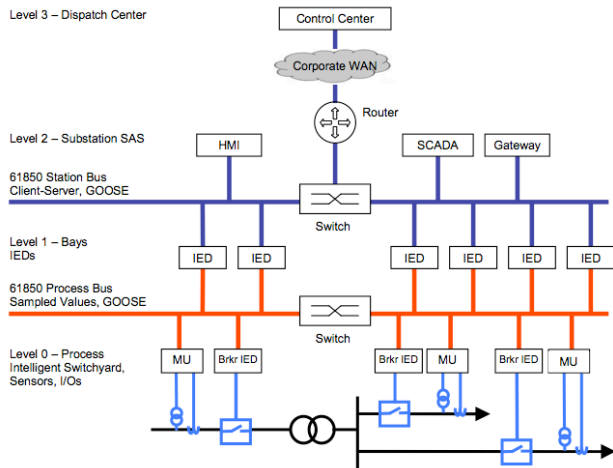


Fig 1: Architecture of IEC 61850 Substation Automation System with Station Bus and Process Bus [8]

Typically each of these individual sub-systems will have its own local clock hardware. Granted that it may take a signal from master clock derived from the original networked control system but while such master clock signals can provide microsecond levels of accuracy, peripheral clocks can be subject to buffering delays and jitter. More significantly, intelligent electronic devices (IEDs) within the substation infrastructure may connect to peripheral controllers or monitoring units over a local

control bus such as CAN or SPI [9]. Such secondary control networks do not support 1588 synchronization and may use asynchronous or semi-synchronous timing mechanisms.

In addition the 1588 standard only considers the synchronization of digital clocks, yet many embedded systems will have separate clocking subsystems for their analog circuitry. In particular the D/A functionality of many embedded sub-systems may rely on individual timing circuits or crystals. In **Fig 1(a)** we show a typical IEC 61850 architecture from ref [8].

In summary, the underlying problem is that even when there is precise synchronization of the top-level monitoring or control signals carried by the Smart Grid local timing offsets or accumulated delays may still exist due to mismatch between the analog and digital sub-systems in local monitoring or control nodes.

III. ANALOG SYNCHRONIZATION IN AN AUDIO SYSTEM

The analog synchronization problem can be best understood by considering a simplified substation architecture. In **Fig 2(a)** we illustrate a legacy Electric Substation architecture. Real-time digital control data is streamed over a network connection from a control center and this data is written into a memory buffer by the main *substation controller*. It will then be processed and used to manage/control local *substation processes*. Similarly local *status monitoring* is performed and relayed back to the *substation controller*. Note that in this configuration both monitoring and control processes are directly wired to the main *substation controller* and thus synchronization of the monitoring and control data is trivial at the substation level. Synchronization between local substations and the main electric grid control center can be easily achieved using IEC 61850/IEEE 1588 compatible network protocols.

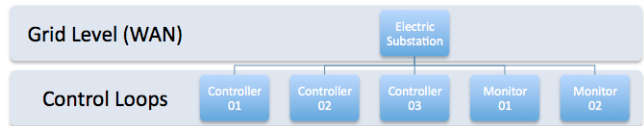


Fig 2(a): Legacy Electric Substation Architecture.

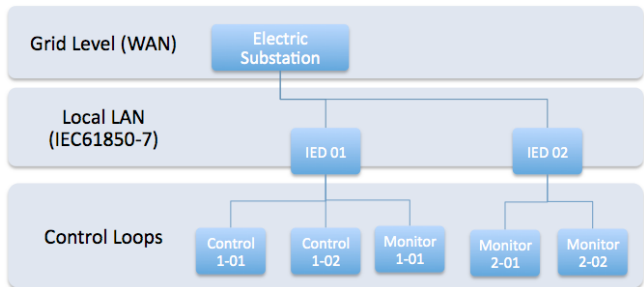


Fig 2(b): Next generation Electric Substation Architecture.

By contrast **Fig 2(b)** illustrates a next generation *distributed substation architecture* where two *intelligent electronic devices* (IED) are networked to the main *substation controller*. Now the embedded subsystems of such networked IEDs can be tightly synchronized using purely software techniques [3]. However the *analogue* control and monitoring subsystems of such client devices can introduce unspecified temporal drift. In normal operation, output analogue data is produced at a fixed rate, which is typically dependant on an internal (local) clock signal. As this signal is derived from some form of electronic oscillator it is subject to variations due to both manufacturing and environmental factors. Thus it is unlikely that two analogue subsystems can be exactly matched. Some local synchronization could be achieved using a local master clock for analogue subsystems but there are inherent difficulties in synchronizing between local, hard-wired environments.

To place this in context, even if the two networked IEDs illustrated in **Fig 2(b)** were resynchronized at the start of every control cycle – say every 3 minutes – a drift of 0.01% or 1 in 10,000 between two control channels will produce an inter-channel delay of 18mS which is more than sufficient to produce a significant phase difference and induce unwanted sub-harmonics onto the powerline.

IV. CLOCK SKEW IN ANALOG SUBSYSTEMS

A. Client-Side Calibration

Now it is well known that the local clock skew of the control and monitoring subsystems on each networked client IED can be accurately determined [6], [7].

In the field of digital multimedia it is known to determine a local clock skew rate and modify the received multimedia stream in a manner, which does not affect the quality of the rendered analog signal [7]. For a practical embodiment the client device or sub-system must be able to:

- (i) perform real-time interrupt-driven analysis of its output signal in order to measure real-time clock skew;
- (ii) at the same time it must decode the digital control signal and may also need to de-interleave the received control stream; and finally,
- (iii) in order to increase, or decrease the size of a received audio data packet to compensate for the determined clock skew the client device should perform an analysis of each received audio packet to determine where, and how, to insert (or remove) audio samples.

All of these methods must be further implemented in real-time placing a high computational load on the client device typically requiring a powerful, high-end processing unit with significant power requirements. Furthermore, in a complex system architecture such as Smart-Grid there

should be a uniform approach to such client-side recalibration of digital signals.

Also worth noting is that problems will occur in higher-level control algorithms if some sub-systems are accurately calibrated and others are not. Thus, even if local calibration were adopted as a solution, it would still be necessary to inform the external Smart-Grid of the local calibration status.

B. Network-Side Calibration

The alternative approach is to pass the calibration problem back to a server, or a network-side service. This approach is actually quite sensible in the context of Smart-Grid applications as it simplifies the requirements at the client-side (i.e. at the local substation level) and enables a uniform services model to be developed at the network level.

In such implementations the local client should initially register with the network service, providing technical details of the various analogue sub-systems integrated into the local grid infrastructure. Then from time-to-time the network service would send out calibration requests to these subsystems during slack periods. Each client device can perform a local clock skew measurement. Typically a control sequence would be provided which should be implemented by the local analogue sub-systems, which returns time-stamped messages at the start and after the completion of each digital control sequence. It is thus possible to determine the likely time deviations of individual systems from their ideal. Or in cases involving a sensing sub-system a fixed length dataset is recorded and returned to the central service with start and end-timestamps derived from a local time-synchronized clock.

The recording and statistical analysis of these data can be better performed and managed by a centralized network service. Further, it is more practical for network-level control algorithms to access such centralized data. It also offers a method of monitoring and determining local sub-systems that may require maintenance or replacement. If data is recorded over a period of time then degradation in performance or sub-systems accuracy will be easy to track.

These data are analysed as part of the network service and are statistically analysed to determine a long term clock skew rate which will be applied to each individual monitoring or controlling client sub-system. Also, these clock skew measurements should typically be initiated from the network-side and, typically, a more intensive calibration regime would be applied when a device is initially connected to the Smart Grid until a reliable clock skew rate is determined for it. Certain methods and techniques employed by NTP may be advantageously adapted for this purpose.

IV. CORRECTION STRATEGIES

Now that we have developed a strategy for determining the clock skew of individual analog monitoring or control subsystems we can consider a number of correctional approaches. As per our earlier discussion it makes sense to implement most of the corrections on the network-side rather than on the local system. This makes sense because correction of multiple local clock skews will be most important where Smart Grid algorithms are implemented across a section of the power grid, spanning multiple local substations. Similarly it is when local data is gathered to a central location that the correction of individual clock skews are most important so that individual monitoring data sets can be compared across a common timebase.

Because of the real-time nature of most Smart-Grid control applications it is important that correction strategies for measured signals and for applied digital control signals are simplified where possible. Thus in this preliminary consideration we will only look at correction strategies where individual bits of data can be dropped without significantly affecting the measured or applied signals.

A. A First Approach: Stripping of Signal Data

When the server is requested to initiate multiple new control signals spread across multiple control sub-systems it will need to prepare the data for digital streaming. The raw digital control data can typically be pre-encoded, or optionally passed through a codec which may be implemented as a hardware subsystem. The encoded signal data is next packetized and this process may also incorporate an interleaving step wherein the data from a single control sequence is spread over multiple data packets. This minimizes the effects of packet loss on the signal at the client. The precise implementation of each of these steps of encoding, packetization and interleaving will depend on the format of the digital data stream. Data formats may be optimized to facilitate packet de-interleaving, stream re-assembly and stream decoding.

Fig 4

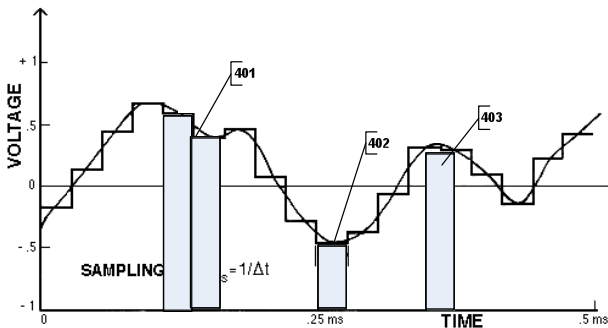


Fig 4: Examples of Redundant Signal Samples (RSS).

In our approach an additional step is now added to this

chain of server-side processes. By employing the predetermined clock skew rates for each networked client device. This step performs additional stream processing to adjust the signal data for each individual client subsystem. The precise form of stream processing is, to some extent, dependent on the underlying control signal format. However we can identify two generalized techniques, which cover most applications where frequency spectrum characteristics must be preserved:

(i) an appropriate number of redundant signal samples are either removed or added to each analog channel; alternatively, as shown in figure 4;

(ii) where the underlying digital format requires close phase synchronization in addition to overall time synchronization, then redundant analog samples which should be added to (or removed from) the signal data are marked separately from the signal data and are conveyed to individual client sub-systems by means of a parallel data channel, or in the form of a packet header

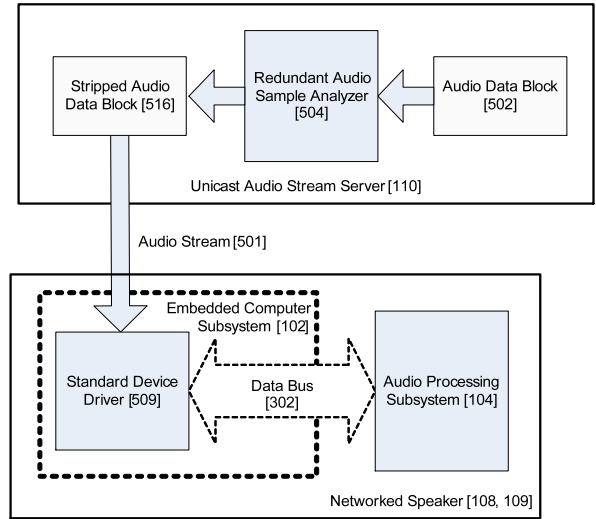


Fig 5: Server-Side Stripping of Media Stream

Hereafter we refer to method (i) as “stripping” and method (ii) as “marking”. Now the preferred method of stream processing in a simple embodiment of the present invention is method (i) as it allows all of the stream processing to be achieved on the server side and, in turn, does not require any client side modifications. This embodiment is illustrated in **Fig 5**.

For clarity the steps of encoding, packetization and interleaving are omitted. Thus, according to method (i) an signal data block is analyzed by a redundant signal sample analyzer which determines, based on the clock skew of the receiving subsystem, how many, redundant analog samples need to be removed to achieve clock skew compensation for the receiving subsystem. This process generates a stripped analog data block that may be optionally encoded prior to being packetized and broadcast over the network. As the

required clock skew compensation has been entirely performed on the server no modifications are required on the client devices.

B. A Second Approach: Marking of Signal Data

However there are potential disadvantages to this method, particularly where an algorithm needs to be applied across multiple local sub-systems. For example, the present implementation can be simply extended to multiple sub-stations each with more than one local analogue control (or monitoring) sub-system, as illustrated in **Fig 7**. Thus multiple control sub-systems located in different sub-stations can simultaneously apply the same synchronized control algorithm data, each control group being locally synchronized within the sub-station environment, and globally synchronized with multiple sub-stations at diverse geographic locations. Each local control group obtains the signal data from the same multi-cast control data stream so that network bandwidth requirements are optimized. Evidently the “stripping” method of signal synchronization will not be suitable for such more widely-deployed control algorithms.

Thus method (ii), although being more complex to implement and requiring a combined client-server processing can have advantages over method (i). This marking method is illustrated in **Fig 6**. The server must obtain clock skew rates for each networked analog sub-system and provide a “marked” list of redundant analog samples customized for each in the main control data. Typically there will be overlap between these “marked” lists and this data may be optionally organized in a set of difference tables to reduce network bandwidth requirements.

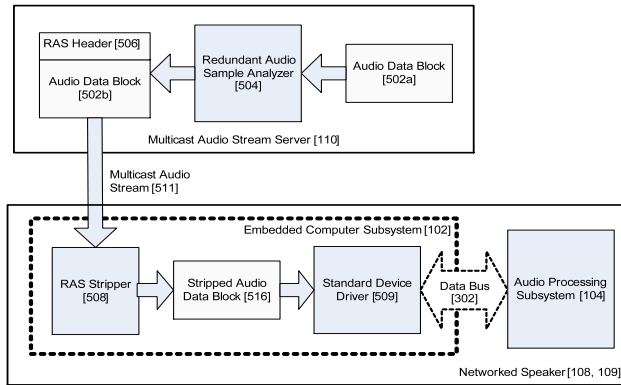


Fig 6: Server-Side marking combined with Client-Side Stripping of the Control Signal Stream

The operation of this embodiment is illustrated for a single client in **Fig 6**. A control signal data block is analyzed as before by a redundant signal sample analyzer which determines, based on the clock skew of the receiving device which, and how many, redundant signal samples need to be removed from the digital signal block, for each

receiving client sub-system, in order to achieve clock skew compensation for the receiving sub-system. In this embodiment these samples cannot be simply stripped from the signal stream as each client device will have a unique clock skew and require a different set of samples to be stripped. Accordingly the stripping operation must be performed separately on each client and the required “marking” data for each client is recorded within an RSS Header or otherwise communicated to the clients. The original audio data block remains in an unaltered form. This signal data is next packetized into a multicast stream which can be received by a plurality of networked client sub-systems.

When a signal data block (or payload) is received at the client the relevant list of “marked” audio samples is extracted or reconstructed, as appropriate, from the RSS Header by an RSS stripper, which may be implemented in either hardware or software or some combination thereof. The RSS stripper then determines from said list if audio samples should be inserted or removed at the “marked” locations. According to our preferred embodiment samples are either removed or simply duplicated, as appropriate. This has the advantage that only the location of a redundant audio sample needs to be recorded in the RSS header. The resulting stripped data block is next passed to the standard device driver for the analog subsystem and written over the data bus into the analogue output of the control subsystem. In this case the stripping operation occurs on the client, rather than on the server.

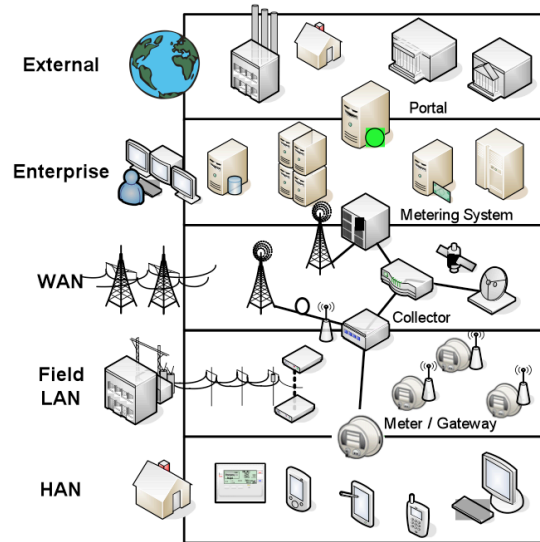


Fig 7: Enterprise systems view of Smart-Grid

V. CONCLUSIONS

We have outlined some issues in achieving accurately synchronized real-time control over the Smart-Grid. These are caused by differences in the behaviors of local D/A and A/D monitoring and control sub-systems.

Given the availability of calibration data we then examined two different approaches to modifying algorithm control sequences. The first is implemented entirely on the network-side and requires no modification to local subsystems. Our second approach relies on some client-side intelligence where individual analog subsystems can identify corrections to their data stream and modify a multi-cast control sequence accordingly. This approach has to benefit of allowing local corrections within a substation environment and a more global synchronization correction across multiple substations.

Compensation techniques can be applied at the local substation level, but we have noted that these are best developed and driven from a network control center, rather than being implemented within the local system components. It was also observed that centralized gathering and management of calibration data would enable long-term monitoring of Smart-Grid systems and provide indications of a need to service or replace components. The importance of this approach can be understood by considering the Enterprise level view of the smart-grid infrastructure shown in **Fig 7** above. While it would be possible to manage all timing aspects of the control cycle locally, our argument is that a local controller can only be aware of local issues. Some straightforward logic quickly makes it apparent why it may be sensible to have a higher-level management of these subtle local timing aberrations.

Consider a particular IED that is standard equipment across a power grid. Each device will behave slightly differently and while it could be compensated for at the local substation level it is not possible to consider the possible side effects of several dozen or even hundreds of these IEDs at a grid level, unless their control and calibration patterns are managed centrally. However this remains a topic for future investigation and further discussion.

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