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Ingram, David Mark Edward, Campbell, Duncan, & Schaub, Pascal (2011) *Use of IEEE 1588-2008 for a sampled value process bus in transmission substations.* In: 2011 IEEE International Instrumentation and Measurement Technology Conference (I2MTC 2011), 10-12 May 2011, Binjiang, Hangzhou, China.

Use of IEEE 1588–2008 for a Sampled Value Process Bus in Transmission Substations

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***Abstract*—IEC Technical Committee 57 (TC57) published a series of standards and technical reports for "Communication networks and systems for power utility automation" as the IEC 61850 series. Sampled value (SV) process buses allow for the removal of potentially lethal voltages and damaging currents inside substation control rooms and marshalling kiosks, reduce the amount of cabling required in substations, and facilitate the adoption of non-conventional instrument transformers. IEC 61850-9-2 provides an inter-operable solution to support multi-vendor process bus solutions.**

A time synchronisation system is required for a SV process bus, however the details are not defined in IEC 61850-9-2. IEEE Std 1588-2008, Precision Time Protocol version 2 (PTPv2), provides the greatest accuracy of network based time transfer systems, with timing errors of less than 100 ns achievable. PTPv2 is proposed by the IEC Smart Grid Strategy Group to synchronise IEC 61850 based substation automation systems. IEC 61850-9-2, PTPv2 and Ethernet are three complementary protocols that together define the future of sampled value digital process connections in substations.

The suitability of PTPv2 for use with SV is evaluated, with preliminary results indicating that steady state performance is acceptable (jitter < 300 ns), and that extremely stable grandmaster oscillators are required to ensure SV timing requirements are met when recovering from loss of external synchronisation (such as GPS).

***Index Terms*—ethernet networks, IEC 61850, IEEE 1588, performance evaluation, power system simulation, power transmission, protective relaying, smart grids, time measurement**

I. Introduction

The objective of the IEC 61850 series of substation automation (SA) standards is to provide a communication standard that meets existing needs, while supporting future developments as technology improves. IEC 61850 communication profiles are based, where possible, on existing international standards. SA functions are decomposed into 'logical nodes' (LNs) that describe the functions and interfaces that are required, and are described in [1].

The smart transmission grid will use a digital platform for substation automation, with measurements having accurate time stamps [2]. IEC 61850-9-2 details how high speed sampled values (SV) shall be transmitted over an Ethernet network [3]. IEC 61850-8-1 defines how transduced analogue values and digital statuses can be transmitted over an Ethernet network using Generic Object Oriented Substation Events (GOOSE) and Manufacturing Messaging Specification (MMS, ISO 9506) [4]. The most stringent of the GOOSE timing requirements is 100 μs and for SV is 1 μs, and therefore SV sets the requirements for time synchronisation.

Fig. 1 shows a diameter of a 'breaker and a half' transmission substation that is typically used at voltage levels of 220 kV and above in Australia. The primary plant (transmission lines, circuit breakers, instrument transformers and power transformers) is connected to the secondary systems through 'process level' connections. A digital process bus provides the process connections in a digital form, rather than as instantaneous analogue values (typically 1 A and 110 V secondary signals) or relay switched battery voltage (125 V_{DC} for example). SV replaces CT and VT cabling through the use of merging units (MUs) that digitise instantaneous analogue signals, and are based around the 'TVTR' and 'TCTR' LNs for VTs and CTs respectively. Intelligent Electronic Devices (IEDs), such as smart circuit breakers and protection relays, that implement GOOSE use Ethernet in place of 4–20 mA loops and digital I/O cabling.

In an attempt to reduce the complexity and variability of implementing SV complying with [3], an implementation guideline was developed in 2004 that is commonly termed '9-2 Light Edition' or '9-2LE' [5]. This guideline specifies the data sets that are transmitted, sampling rates, time synchronisation requirements and physical interfaces, but does not specify the transient response of devices. The IEC 61869 series of standards are being developed by IEC TC38 to address this. MUs throughout a substation must accurately time stamp each sample to allow protection IEDs to use SV data from several MUs (through the use of time alignment of samples in buffer memory). 9-2LE specifies an optical 1 pulse per

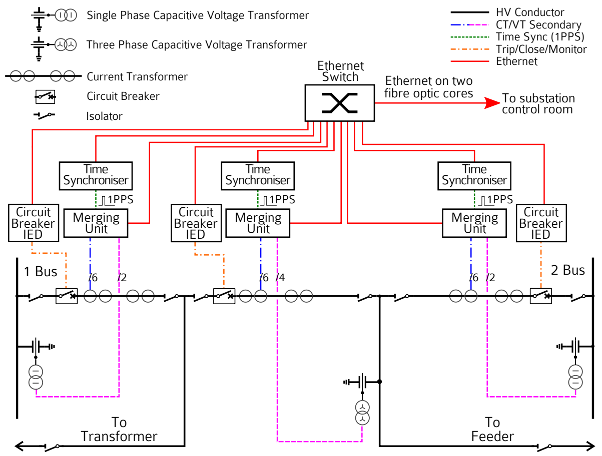


Figure 1. Schematic of a breaker-and-a-half (1½ CB) transmission substation bay.

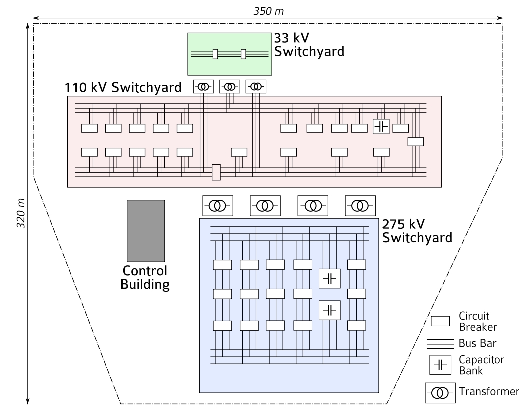


Figure 2. Arrangement of an urban transmission substation in Brisbane (Queensland, Australia) with three voltage levels. Feeder and transformer connections are not shown.

second (1PPS) timing signal with ±1 μs accuracy for this purpose.

IEEE Std 1588-2008, version 2 of the Precision Time Protocol (PTPv2) [6], significantly improves time synchronising performance, making this a viable option for synchronising SV merging units [7]. PTPv2 is recommend in the IEC Smart Grid Roadmap as a method of high accuracy time synchronisation [8]. The same network infrastructure can then be used for SV, GOOSE and for time synchronisation.

This is of great benefit when MUs are located throughout a substation, adjacent to the primary plant they are connected to. Synchronising with 1PPS signals over fibre optic cable is straightforward when merging units are located in substation control rooms (as done by many suppliers of non conventional instrument transformers), but distributed MUs would require a separate fibre optic network throughout the substation just for 1PPS, and this is avoided with PTPv2. Recently published work has described the first of many process bus substations in China using PTPv2 for time synchronisation of an IEC 61850-9-2 process bus [9].

A test and evaluation system based on IEC 61850-9-2, PTPv2 and a real time digital simulator (RTDS) is being constructed using 'live' equipment to assess SV protection schemes against the requirements of Australia's National Electricity Rules (NER). This system will provide information on how the competing demands for Ethernet between SV, GOOSE, MMS and PTPv2 can be met.

The work in this paper extends that of De Dominicis *et al.* [10] by focusing on the SV process bus application and by looking at the effect of outages in the timing system. The PTPv2 testbed described in [11] did not examine grandmaster holdover and recovery from loss of GPS synchronisation, but is investigated by this paper.

II. Use of PTPv2 for Sampled Value Time Synchronisation

It is expected that most master clocks in substations will be synchronised to International Atomic Time (TAI) via the GPS constellation, as GPS is an excellent tool for time transfer [12]. A time clock providing PTPv2 grandmaster functions may also be a source of IRIG-B and 1PPS signals for legacy devices within substation protection and control buildings.

Outdoor transmission-level substations (typically 110 kV and above) cover a large area of land and cable lengths are significant. IRIG-B can be distributed over copper or fibre optic cables, but rarely has the accuracy required for SV synchronisation. 1PPS distributed over fibre optic cable is recommended by the 9-2LE guideline, but this does not contain absolute time information which will be required by the data security techniques proposed in IEC TS 62351-6 to prevent 'replay' attacks.

1PPS systems do not automatically compensate for propagation delay. Fig. 2 shows an urban transmission substation arrangement. The longest cable distance from the control building to an instrument transformer at this site is approximately 420 m, and cable runs of 300–400 m are not uncommon in transmission substations. This would result in propagation delays in excess of 2 μs. Some substation arrangements include multiple buildings with protection and control equipment, but there is usually a central communication building where the master time reference is located. PTPv2 provides a means of distributing time across a substation that compensates for propagation delay.

Applications for PTPv2 in power systems extend beyond SV and also includes synchronisation of measurements for synchrophasors, which are a critical component of Wide Area Monitoring Systems (WAMS).

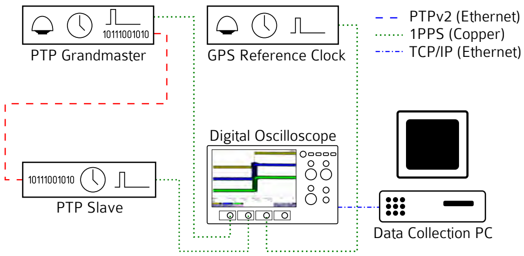


Figure 3. Experimental arrangement to assess performance of PTPv2 with directly connected grandmaster and slave.

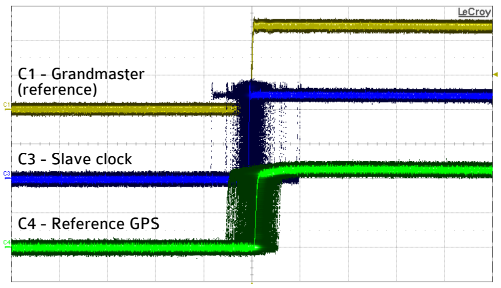


Figure 4. Oscilloscope capture for pulse delay measurement. C1 is the reference (grandmaster), C3 is PTP slave clock and C4 is a reference GPS. The time scale is 1 µs per division.

A. Generation of 1PPS Signal by a PTPv2 Time Slave

PTPv2 slave clocks that can generate a 1PPS signal are available from many suppliers. Merging units can use this 1PPS signal as if it was generated from a GPS or IRIG-B receiver, but will not experience the propagation delays inherent in these systems. 9-2LE requires merging units to compensate for propagation delay if this exceeds 2 µs and this is supported by several manufacturers, but this is not an issue for locally generated 1PPS signals.

Native support of PTPv2 is desirable as most of the extra data available with PTPv2 is lost with 1PPS, including accuracy information, absolute time and date (which could be incorporated into SV or synchrophasor messages) and details of the clock source. An IED that has internal support for PTPv2 can make use of PTP messages sent more often than once per second, and this may reduce the effect of clock error during recovery from outages (discussed in later sections). An IED relying on a slave clock's 1PPS output cannot update its internal clock faster than once per second, regardless of the PTP message rate.

B. Testing

Substation protection, metering and control functions must meet strict the requirements of the NER, and this extends to any communications and timing systems that they rely upon. Tests have been performed with commercially available PTPv2 clocks to determine whether PTPv2 is a viable source of 1PPS timing signals. These tests examined steady-state and dynamic performance of ordinary clocks when recovering from contingencies. Fig. 3 illustrates the equipment used to measure the jitter and wander of 1PPS outputs from a slave clock directly connected to a grandmaster, which is the best case scenario. The GPS reference clock provided a pulse synchronised to TAI at all times and allowed the wander of the grandmaster to be measured when its GPS antenna was disconnected. This technique is similar to that described in [13].

Automatic pulse delay measurements were made with a digital oscilloscope sampling at either 500 ps (one or two channels) or 1 ns (three or four channels) between samples. The standard record length was 200 000 samples per channel, giving a pulse delay measuring range of ±100 µs when three or four channels were in use. The oscilloscope was computer controlled, with a standard configuration sent to the oscilloscope at the start of each test. Fig. 4 is a sample of the 1PPS waveforms captured by the oscilloscope, with infinite persistence to show the jitter on screen. Pulse delay measurements in each direction were transferred to the PC after each 1PPS pulse for further statistical analysis.

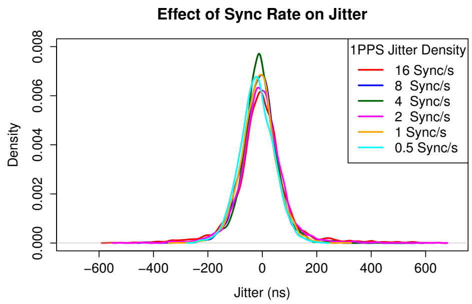
III. Results

Jitter and wander were the two performance indicators considered, with jitter being of most interest with the system intact, while wander was of more importance during contingency events.

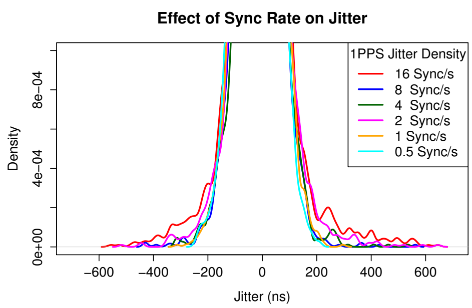
A. Steady State Performance

PTPv2 provides flexibility in how the synchronisation system will operate and a key parameter is synchronisation message rate. The results presented here show that less frequent synchronising messages resulted in less jitter. Fig. 5 shows the 1PPS jitter density observed over one hour intervals with sync message rates ranging from once every two seconds through to sixteen times per second. In each case the grandmaster and slave were directly connected to each other with a cross-over Ethernet cable to remove any influence from other network traffic. Peer-peer delay requests and grandmaster announcements were set to 2 s intervals and one-step operation was used.

Scheiterer *et al.* [14] suggested that less frequent updates allow a slave clock to better estimate its rate correction factor (RCF) used for its local oscillator compensation and this would improve performance when clock aging was not an issue. The best performance was found to be with synchronising message sent every one or two seconds, which is contrary to results given in [11]. [11] used slave clocks with high performance TXCO local oscillators, whereas the slave clocks in this study used low cost crystal oscillators (XO) without



(a) Entire jitter range.



(b) Jitter extremity detail.

Figure 5. Jitter observed between 1PPS outputs of a grandmaster and slave, using peer-peer path delay and one-step operation.

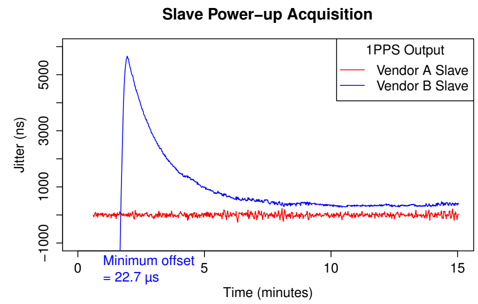


Figure 6. Power up performance for slave clock from two vendors.

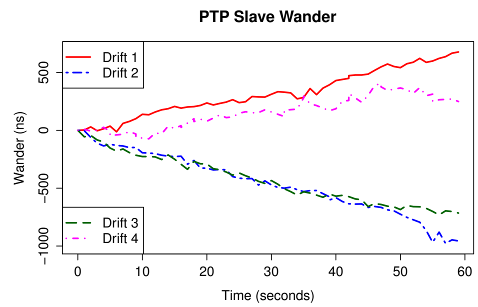


Figure 7. Wander between PTPv2 grandmaster and slave when the network connection was broken.

compensation. An XO local oscillator may naturally deviate further from its nominal frequency, and so improved RCF estimation through less frequent updates may outweigh the noise reduction a faster update rate would provide.

Jitter was less than ±300 ns, and for much of the time was less than ±200 ns. This meets the requirements of 9-2LE, and future work will determine whether this achievable with a larger timing network and in the presence of SV network traffic (up to 5.4 Mbit/s per MU).

B. Power On Performance

Slave clocks vary significantly in their ability to synchronise to a grandmaster when first powered on. Slaves from two different manufacturers were connected to the same grandmaster (which incorporated a transparent clock) and were powered up at the same time. Fig. 6 shows the 1PPS output from each slave, relative to the grandmaster. The slave clock from Vendor A required 35 s to synchronise and its 1PPS output was within the 9-2LE specification (±1 µs) immediately. Vendor B's slave clock required 10 min to stabilise, although it was within the ±1 µs specification at 5 min and exhibited less jitter overall (albeit with an offset). This has ramifications for substation operation after maintenance, especially since Vendor B's slave clock enabled its 1PPS output when the offset exceeded 20 µs. MU samples would be skewed if these slaves were providing the sampling reference, and may result in deterioration of protection performance (especially for differential protection).

C. Loss of Network between Grandmaster and Slave

The effect on time synchronisation when a slave clock lost its connection to the grandmaster was investigated. This may occur due to network cabling faults or a failure of the grandmaster. The Best Master Clock algorithm is intended to deal with loss or degradation of a grandmaster, but does not deal with a network failure at a slave [6].

The slave and grandmaster were synchronised with one PTP message per second and then the network cable between the two was disconnected. The slave was configured to keep generating its 1PPS output using its internal oscillator by using a long holdover time. Fig. 7 shows wander can vary in sign and magnitude. The slope varied between 10 ns/s and 20 ns/s, giving approximately 35 s of operation before the ±1 µs limit of 9-2LE was reached (based on an initial worst case jitter of 300 ns). This is useful information when setting appropriate holdover times.

Two instances of the a slave clock recovering from a loss of PTP connection are shown in Fig. 8. In the first instance the wander between the slave and grandmaster was 6 µs and in the second instance was increased to

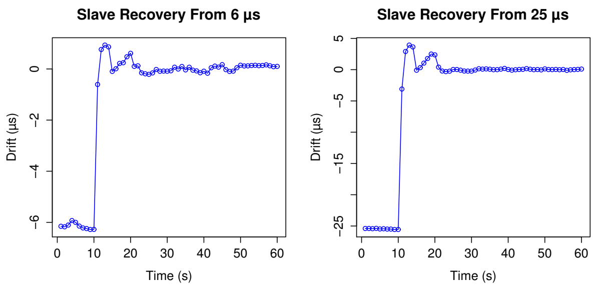


Figure 8. Slave clock reacquiring synchronisation with the grandmaster after reinstatement of PTP connection, from a wander of 6 µs (left panel) and 25 µs (right panel), showing the recovery characteristic is identical.

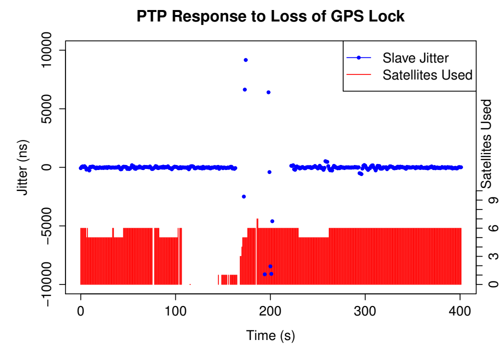


Figure 9. Slave clock jitter when grandmaster reacquires GPS lock after an outage.

25 µs. The transient response of the recoveries are the same shape, suggesting that the servo in the slave clock has a linear response. Oscillations in the observed jitter take approximately 10 s to decay.

The internal oscillators in the grandmaster and slave clocks used for this experiment are low-cost crystal oscillators. Use of temperature controlled oscillators (TXCO) or oven controlled oscillators (OCXO) would improve performance, but at increased expense. 10 ns/s was the worst case wander for slaves with TXCO local oscillators [11], however [14] concluded that a costly master has a much larger benefit compared to spreading the same expense across the slave clocks (which would be numerous in a transmission substation).

D. Loss of Grandmaster GPS Synchronisation

A clear view of the sky is required for optimum GPS reception as the satellites move in low earth orbit. There are times where building shading that reduces the viewable area of the sky may result in a GPS receiver losing synchronisation to TAI. The internal oscillator will wander from TAI, with the wander rate dependent on its stability [14]. Loss of lock between the grandmaster and the GPS system was identified as a problem during this investigation when the 1PPS output of the slave clock exhibited large jumps for no apparent reason. Data logging from the GPS receiver showed that the jumps occurred when the GPS receiver reacquired lock, as illustrated in Fig. 9.

This effect was recreated by disconnecting the GPS antenna on the grandmaster and observing the wander between its 1PPS output and that of a reference GPS. The wander was allowed to reach 1 µs, 2 µs and 4 µs before the antenna was reconnected.

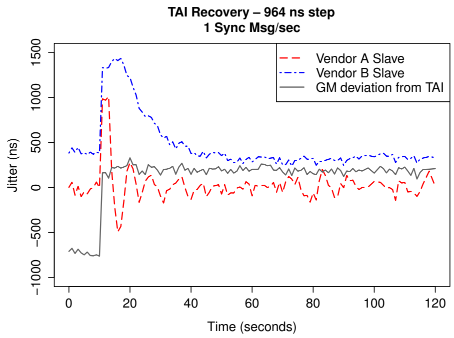
Fig. 10 shows the behaviour of the slave when the grandmaster recovers synchronisation with TAI after a wander of 1 µs with two PTP message rates, as well as recovery from 2 µs and 4 µs wanders with one PTP message per second. The step and oscillation in synchronism are not acceptable for a SV based protection system and this must be addressed, and the difference in response between vendors is a major concern.

One solution to this problem is to use a highly stable internal oscillator in the grandmaster, such as an OCXO or rubidium cell, to reduce the wander from TAI when synchronisation with the GPS system is lost. These typically have four (OCXO) or six (Rb) orders of magnitude better stability than uncompensated crystal oscillators [15]. There are typically one or two master clocks in a substation and so the additional expense of an extremely stable oscillator in the PTPv2 grandmaster is manageable, and further supports the conclusion in [14] regarding investment in the master clock rather than the slaves.

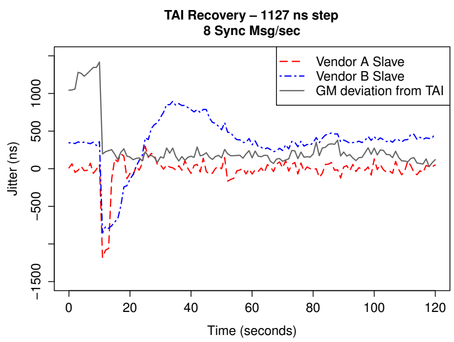
IV. Conclusions

PTPv2 has been demonstrated to be a viable method of providing time synchronisation for a sampled value process bus using IEC 61850-9-2, in particular 9-2LE. Propagation delays are compensated for by PTPv2, providing benefits over IRIG-B and 1PPS systems in transmission substations with long cable. This may allow the synchronising pulse specification of 9-2LE to be relaxed to ±2 µs, which in turn would reduce the cost and complexity of implementing PTPv2. The best case timing jitter with directly connected low-cost PTPv2 clocks presented here is ±300 ns, and future work will assess whether this is achieved in the presence of SV network traffic and with larger timing networks incorporating several transparent clocks.

Uncompensated oscillators do exhibit significant wander when their discipline source is removed. The slave clock has less overshoot when correcting for a wander between the grandmaster and slave (approximately 15% overshoot) than when the grandmaster experiences a time correction and propagates this through PTP (approximately 100% overshoot). The wander from TAI experienced by a grandmaster when GPS synchronisation is lost is a significant concern, and while such wander



(a)



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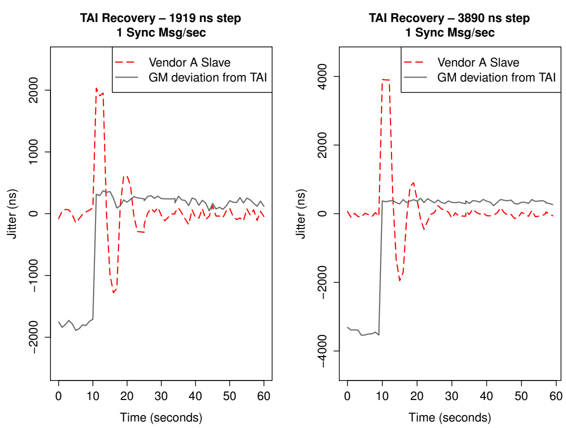

(c)

Figure 10. Slave clock jitter after (a) 1 µs TAI recovery, with one PTP message per second, (b) 1 µs TAI recovery, with eight PTP messages per second, (c) 2 µs and 4 µs TAI recovery with 1 PTP message per second.

cannot be eliminated, minimisation through the use of grandmasters with extremely stable internal oscillators is recommended.

The design of slave clocks plays an important part in the performance of a PTP system. The design of the servo-loop in the clock recovery function is a compromise between smoothing out variation in packet arrival times (low frequency) and noise (high frequency), and also affects start-up time [16].

A digital process bus is an important building block for the transmission smart grid as it enables interoperable use of digitised primary voltages and currents, transduced signals and digital I/O. IEEE Std 1588-2008 will facilitate the adoption of this technology, and more work is required to understand, and then standardise, its behaviour before it can be widely and routinely implemented in transmission substations.

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