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Time Synchronization for Transmission Substations Using GPS and IEEE 1588

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Abstract—Time synchronization systems that utilize the global navigation satellite systems (GNSS) are widely used in the monitoring, control, and protection of transmission networks. They ensure that phasor measurement units (PMUs) can accurately monitor voltage phase angles, increase the accuracy of fault locators, enhance the capabilities of disturbance recorders, and allow differential feeder protection to use re-routable communication networks. However, concern about the reliability of GNSS receivers used in intelligent electronic devices (IEDs) have been reported; problems include mal-operations of differential protection, erroneous satellite timing/location messages, inappropriate installations, and blocking of satellite signals due to illegal use of GNSS jammers in vehicles.

Utilities now require a timing system less dependent on the use of low cost GNSS receivers integrated into IEDs, but one that uses Grandmaster clocks, slave and transparent clocks, and an Ethernet communication network. The IEEE 1588-2008 synchronization protocol uses the Ethernet to disseminate a global time reference around a substation. A future substation will probably include duplicate 1588 grandmasters, each incorporating stable oscillators with GNSS and terrestrial receivers, in conjunction with a 1588 compliant Ethernet data network with slave and transparent clocks, and redundancy boxes for interfacing with IEDs.

Although IEEE 1588 protocol is promising for future substation automation systems, its performance and impact has to be fully evaluated before it can be used in real substations. This paper describes how an IEEE 1588 time synchronization testbed is designed, constructed, and tested. Testing involves measuring the time offset when the Ethernet is heavily loaded with other traffic and the holdover capability of 1588 clocks. Additional delay introduced by IEEE 1588 traffic is also measured. As there is limited testing on GPS receivers within the power industry, this paper also uses the testbed to evaluate the steady state and transient behavior of GPS receivers. The results show a 1588 time synchronization system is accurate, secure, and ideally suited for protection and control applications, compared to a timing system merely based on GPS receivers. The information described in this paper should increase a utility’s confidence in applying IEEE 1588 timing in a real substation.

Index Terms—GNSS, GPS, IEDs, IEEE 1588, substations, time synchronization, transmission networks.

I. INTRODUCTION

INTELLIGENT electronic devices (IEDs) used in substations ensure a transmission network operates in a stable state. But when an abnormal event occurs, the IEDs must rapidly restore the network from the abnormal state back to a normal state. An IED measures power system quantities (voltage, current, frequency, power, etc.) and the operational states of switches and circuit breakers. This data is processed by the local IED and communicated to other IEDs in the substation, remote IEDs, network controllers, and/or system operators where further processing and analysis is carried out. The resulting knowledge is used by one or more IEDs to respond to the event that first triggered the change in the measured quantities. The event might be a short-circuit fault or an extreme overload that should be solved locally, or an event such as switching action, generator or feeder tripping, a voltage or frequency excursion, which requires remote responses. These measurements, acquired in each bay of each substation, only describe the actual real time operating state of the power system if they are synchronized to a common time reference.

IEDs can be synchronized using either a dedicated timing system based on standalone cabling and signal repeaters, or a network timing system shared with other automation applications and normally based on Ethernet cables and switches [1]. Dedicated timing systems often use one pulse per second (1-PPS) to provide an accurate timing reference at the start of each second, or the IRIG-B time code for time and date information. GPS (or GNSS) receivers convert the time information received from GNSS into a 1-PPS signal and the IRIG-B time code, which are then used to synchronize all the IEDs in a substation [2]. An example of a dedicated timing network that operates independent of the substation communication network is shown in Fig. 1. When the 1-PPS signal travels from the GPS receiver to the device, a propagation delay is introduced. During commissioning, this delay must be measured and compensated.

Substation applications, such as SCADA or disturbance recorders, requiring timing accuracy in the millisecond range, can use a network time protocol (NTP) system operating over an existing Ethernet communication network, as illustrated in Fig. 2. However, most substation applications require timing accuracies in microseconds and consequently NTP is not suitable. For example, phasor measurement units (PMUs), travelling wave fault locators (TWFL) and IEC61850-9-2 sample value merging units (SV-MU) require an accuracy of
±1 μs. Whilst current differential protection (CDP) generally requires 20 μs and IEC61850-8-1 GOOSE messaging requires accuracy better than 1 ms.

**II. 1588 Time Synchronization**

**A. Introduction to 1588 Time Synchronization**

An increasing number of IEDs are using the Ethernet data network for communication purposes [3] and most experts expect Ethernet to become the communication backbone for future transmission substations. Considering the cost, complexity and reliability, it would be ideal if high accuracy synchronization can utilize the Ethernet. Unfortunately, an Ethernet based NTP timing system only achieves 1–4 ms accuracy, which is inadequate for most applications, including IEC 61850-9-2 SVs, CDP, TWFL, and PMUs. An alternative to NTP is the IEEE 1588 timing standard, which operates over a data network and achieves significantly improved timing accuracy. The IEEE 1588-2008 standard (IEEE 1588v2) [4], also known as the Precise Time Protocol Version 2 (PTPv2), is an IP/Ethernet based time synchronization protocol that realizes sub micro-second timing accuracy.

A master-slave IEEE 1588 synchronization network consisting of different types of IEEE 1588v2 devices is shown in Fig. 3, where each 1588v2 device is referred to as a clock. Four types of clock are available in IEEE 1588v2 standard [4]:

1) An ordinary clock is an end device and can be a grandmaster clock for the whole substation, or a master clock if it supplies the time source for other clocks on a single communication path, or a slave clock if it is synchronised by a grandmaster or master clock.
2) A boundary clock is basically a network bridge or switch and is the combination of slave clocks and master clocks. It will act as a slave clock for the connected upstream master/grandmaster clock and becomes the master clock for its downstream slave clocks. In terms of non-1588 messages and IEEE 1588 management messages, the boundary clock will forward them as a normal Ethernet bridge or switch. On the contrary, IEEE 1588v2 messages related to synchronization and clock selection will terminate in the boundary clock.
3) An end-to-end transparent clock is a network bridge or switch capable of measuring the time required for a 1588 message to pass through the end-to-end transparent...
clock. In comparison, this clock passes all non-1588 packets as a normal bridge/switch. For all 1588 “timing” packets, the end-to-end transparent clock measures the residence time and accumulates the value in a special field (correctionField) of the IEEE 1588 message. The final destination of the message (i.e., a slave clock) can then compensate the residence delay time, as shown in Fig. 4.

Fig. 4. End-to-end transparent clock measuring 1588 message residence time [4].

4) A peer-to-peer transparent clock is a network bridge or switch with the ability to measure the residence time of an IEEE 1588 message and the delay of the link on which the receiving port locates. Similarly, the peer-to-peer transparent clock will forward all non-1588 messages as a normal bridge/switch. For specific 1588 packets, the peer-to-peer transparent clock will measure the residence time and link delay and then update the value of the “correctionField” so that the receiver of the messages (i.e., a slave clock) can compensate for both the switching delay and the path delay. The residence time and link delay measurement model of a peer-to-peer transparent clock is shown in Fig. 5.

B. Working Principle of 1588v2

The 1588v2 synchronization process requires the selection of the grandmaster or master used to synchronize the slaves and subsequently the establishment of master-slave hierarchy. The best master clock algorithm defined in [4] can determine which clock in the network is the best clock so that it can be selected as the grandmaster clock. The best master clock algorithm can then determine the state of each port (i.e., master, slave or passive) on a clock. Once the clock selection and state determination are accomplished, the master-slave hierarchy can be established and ports in the master state will start to send out 1588 messages. After that, the intermediate IEEE 1588v2 transparent clocks (network bridges/switches supporting 1588v2 features) will measure the delay of 1588 messages between the port in the master state and the port in the slave state. This will be used by the port in the slave state to adjust the clock’s local time. Note: ports in the passive state will neither transmit nor receive 1588 messages. Once the master-slave hierarchy is established, the slave clock(s) will estimate the time offset between itself and the Master Clock using data packets containing time information. With reference to Fig. 6; the relationship between timestamps $t_1$ and $t_4$ is:

$$t_1 + \text{time}_{-}\text{offset} + \text{propagation}_{-}\text{delay} = t_4 \quad (1)$$

$$\text{time}_{-}\text{offset} = t_4 - t_1 - \text{propagation}_{-}\text{delay} \quad (2)$$

Hence, it is necessary to measure the propagation delay before calculating the time offset. When using 1588v2 in power industry, the IEEE 1588 Power Profile [6] specifies the use of Peer Delay Request-Response to measure the propagation delay. More specifically, this measures the propagation delay between the Master port and associated Slave port(s) using the messages “Sync, Pdelay_Req and Pdelay_Resp” as shown in Fig. 6. If a 1-step clock is used, there is no Follow_Up and Pdelay_Resp_Follow_Up message. If a 2-step clock is used, a Follow_Up and a Pdelay_Resp_Follow_Up are required. A 1-step clock measures the actual time $t_1$ when the Sync message is sent out and encapsulates the precise timestamp in the Sync message. Whilst the 2-step clock only packs a coarse timestamp in the Sync message and the actual time is carried in the associated Follow_Up message later.

The synchronization process using the Peer Delay Request-Response mechanism is described below:

1) Master clock generates the Sync message and transmits it; the time $t_1$ when the Sync message is sent out is carried in Sync message or in the Follow_Up message.
2) When a Sync message arrives at a peer-to-peer transparent clock, timestamp $t_2$ is recorded by the clock as the ingress timestamp. When the Sync message is forwarded, timestamp $t_3$ is generated as the egress timestamp. The time difference between $t_3$ and $t_2$ is the residence time that is accumulated in the correctionField of Sync (or Follow_Up). The peer-to-peer transparent clock also accumulates the link delay in the correctionField of Sync. If there are multiple peer-to-peer transparent clocks, the residence time and link delay measurement and accumulation process is repeated in each clock.

3) Slave clock receives the Sync message (and Follow_Up message), records the receiving time $t_4$, and extracts the timestamp $t_1$ and correctionField data.

Once the slave clock receives the sending and receiving timestamps with propagation delay of Sync, it can calculate the time offset between the master clock and the slave clock. Finally, once the time offset is calculated, the local time of the slave clock is adjusted to follow the master clock time.
correctionField of Sync / Follow_Up = fractional ns = CF₀

correctionField of Sync / Follow_Up = CF₀ + linkDelay 1 = CF₁

correctionField of Sync / Follow_Up = CF₁ + residenceTime = CF₂

correctionField of Sync / Follow_Up = CF₂ + linkDelay 2

Initially, slave time = master time + time offset
Clock output: 1-PPS or IRIG-B

Fig. 6. Peer delay request-response mechanism.

C. Previous Application and Research of IEEE 1588

In China, IEEE 1588 has been employed in real substations since December 2009 and details of network design and engineering are provided in [7]. However, no results on the performance of IEEE 1588 timing have been given.

IEEE 1588 devices including clocks and Ethernet switches from various manufacturers with power profile were tested in the IEEE 1588 power profile plugfest hosted by the IEEE Power & Energy Society (PES) Power System Relaying Committee (PSRC) in early 2010. Results indicated the achievable timing accuracy was in the range between a few hundred nano-seconds and a few micro-seconds when there was no other traffic in the network. It was also discovered the best master clock algorithm would select a non-qualified clock as the grandmaster clock during the transient state. The report also suggested a multi-vendor testbed would be useful in identifying implementation issues.

Authors in [8] integrated IEEE 1588 timing in a real substation automation system in Italy in 2011. In this system, the Ethernet switches did not support 1588 and the delay request-response mechanism had to be used instead of the Peer Delay Request-Response mechanism that is specified by the 1588 power profile. Experimental results showed the time of the slave clock drifted even when the background traffic only occupied 1% of the bandwidth. It was advised that IEEE 1588v2 Ethernet switches would be necessary to achieve sub micro-second timing accuracy.

A hardware testbed integrating IEEE 1588 and IEC 61850 was set up during the UCAIug Network Interoperability Demonstrations at CIGRE 2012 [9]. It was reported that good interoperability between different vendors was achieved (detailed results were not published); however, utilities may not obtain sufficient confidence on IEEE 1588 timing because the testing period was too tight.

In Australia, a full IEEE 1588 hardware testbed with Peer Delay Request-Response mechanism was built in 2012 [10]. Test results indicated that timing accuracy better than 500 ns could be obtained when three transparent clocks were used between grandmaster and slaves. However, all tests were conducted with no background traffic and the testing period was only 1800 s, which was relatively short.

Therefore, this paper expands the research work by integrating assessment of long-term stability of GPS receivers and IEEE 1588 slaves and investigation of impact of IEEE 1588 traffic on network latency.

III. PERFORMANCE ANALYSIS FOR GPS & 1588 TIMING

A. Timing Stability of GPS

The timing system for a transmission substation needs to maintain a high level of accuracy over a long period. However, direct use of GPS is now considered unreliable because of problems related to climatic conditions and signal
interference. Hence, it is necessary to investigate the long-term time differences when using different GPS receivers. This is critically important since automation systems use phasor measurement information from widely separated substations and this relies on time references derived from different GPS receivers.

The laboratory system used for measuring the time offset between different GPS receivers is shown in Fig. 7. One of the GPS receivers is selected as the reference and its 1-PPS is used as the reference input to the measurement server. The other GPS receivers, A and B, also feed their own 1-PPS to the measurement server. The server then measures the time difference between the rising edge of the 1-PPS from reference GPS receiver and receiver A and B under test. Note that the mask angle for GPS signal reception is only configurable on GPS receiver A and the device manual suggests increased mask angle reduces the field of view and lowers the timing error caused by multi-path satellite signals situated low in the sky.

The time offset between GPS receiver A and reference GPS receiver is shown in Fig. 8, and Fig. 10 shows the time offset between receiver B and the reference. The time offset for receiver A is always significantly less than ±1 μs and the time offset spikes are reduced when the mask angle is increased. More specifically, the minimum offset value is −379 ns and the maximum value is 456 ns when the mask angle is less than 8°. When the mask angle is increased to above 15°, the timing offset varies between −346 ns to 318 ns. This verifies an increased mask angle can improve the timing accuracy by reducing the occurrence of spikes in the timing signal.

A reason for the time offset spikes is the location of a high wall to the south of the GPS antennas. Results indicate satellites are lost at the southern edge and the signal quality might not be sufficient for ideal synchronization; see Fig. 9.

According to Fig. 10, the accuracy of the 1-PPS from receiver B is worse than receiver A; occasionally the time offset of GPS receiver B exceeds the threshold value ±1 μs, which might lead to mal-operation if an application requires an accurate time reference from multiple GPS receivers. The minimum and maximum time offset of receiver B measured during the tests are −677 ns to 1372 ns.

**B. Timing Stability of IEEE 1588 Synchronization System**

Unlike direct use of GPS, 1588 timing relies on a wired data network to accomplish time synchronization within a substation. This means it is more controllable as the data network can be carefully designed, engineered and monitored so that it could always operate correctly.

The lab setup to measure the time offset between the reference GPS receiver (1588 grandmaster) and the 1588 slaves is indicated in Fig. 11. The reference GPS receiver can transmit 1588 timing packets as well as output 1-PPS to the measurement server. The 1588 slaves are synchronized and then feed 1-PPS to the measurement Server for time offset measurement. The Grandmaster and Slave clocks use the 1588 Power Profile and all Ethernet switches utilize the Peer Delay Request-Response Mechanism as required by the 1588 Power Profile. The background traffic in the data network occupies 85% of the bandwidth and is multicast traffic with priority 4. The bandwidth of the network is 100 Mb/s. Note: 1588...
Power Profile requires the worst-case time offset to be less than ±1 μs with a network load up to 80% of total bandwidth and the priority of 1588 traffic is 4.

The measured time offsets for both 1588 Slave clocks are shown in Fig. 12. The offsets are always less than ±150 ns and the fluctuation is significantly less than achieved with individual GPS receivers. Note: during the measurement period, a single 1588 packet is randomly lost due to deficiencies in the Ethernet switch. However, the 1588 slaves always maintain synchronization.

The results presented in this paper demonstrate IEEE 1588 delivers long term timing accuracy within ±150 ns when 1588 Power Profile is enabled on 1588 Grandmaster and Slave clocks and all Ethernet switches support 1588 Peer Delay Request-Response mechanism, regardless of the network load (85% bandwidth in this test) and the loss of 1588 packets. The variation in the timing accuracy is −79 ns to 107 ns for slave C and −109 ns to 72 ns for slave D.

In comparison, conventional GPS timing system delivers inferior long term timing accuracy as factors such as signal interference, antenna positions, and system installation techniques degrade the performance of the system. The situation often becomes worse when a large number of distributed GPS antennas and receivers are used and each IED obtains the time signal from its own GPS Receiver. In addition, the clock adjustment algorithm used in different GPS receivers is not the same, and in some cases the time offset between GPS receivers can fail to satisfy the ±1 μs requirement. However, when 1588 timing is used, only one GPS receiver operates as the 1588 grandmaster for the whole substation at any point in time, and all 1588 Slaves follow this grandmaster and deliver ±1 μs accuracy more easily.

C. Resynchronization of GPS Timing

In a real substation, a local clock may lose global/national/regional synchronization due to a power supply failure or the loss of an external synchronization signal. For example, U.K. National Grid reported a number of differential protection mal-operations resulting from corruption of the 1-PPS output of GPS receivers upon GPS restoration. To understand the issue, the test facility shown in Fig. 7 is used to monitor the behavior of two GPS Receivers after the loss of GPS synchronization and then its subsequent restoration. To emulate the loss of the GPS signal, the GPS Antennas connected to receivers A and B are temporarily disconnected. The measurement results are illustrated in Fig. 13 and 14. When receiver A loses the GPS signal, the time offset between itself and the reference GPS receiver drifts at 2 ns/s. The mask angle of receiver A is 20° and the worst-case initial time offset is 150 ns. Therefore, receiver A can maintain micro-second accuracy for 425 s. When receiver A regains GPS signal, an 8 μs timing spike in the time offset occurs and its duration is several seconds. This could cause a problem for an IED if precise timing is required [2].

Fig. 11. Measurement of time offset between 1588 grandmaster and 1588 slaves.

Fig. 12. Time offset between 1588 slaves and grandmaster.

Fig. 13. Receiver A time offset: loss and recovery of GPS.

Fig. 14. Receiver B time offset: loss and recovery of GPS.
D. Resynchronization of 1588 Timing

The test facility shown in Fig. 11 is used to investigate how 1588 slave clocks behave when 1588 timing packets are lost and then recovered. The loss is emulated by disconnecting the 1588 slaves from their adjacent Ethernet switches. The impacts on slave C and D are shown in Fig. 15 and 16 respectively. When slave C is disconnected from the data network, it drifts at 0.8 ns/s, resulting in a 1 μs accuracy holdover time of about 1116 s. Once the connection is restored and it starts to receive the 1588 packets, it immediately synchronizes to the grandmaster. In comparison, when slave D is disconnected, it drifts at −3.6 ns/s and the holdover time is about 248 s. Again, it rapidly synchronizes to the grandmaster when the communication is restored.

Fig. 15. Time offset slave C: Loss-recovery 1588 packets.

Fig. 16. Time offset slave D: Loss-recovery 1588 packets.

Based on these observations, re-synchronization of 1588 timing ensures 1588 slave clocks follow the grandmaster in a fast and secure manner. In comparison, restoration of the GPS signal in a conventional GPS receiver might introduce a time offset spike that corrupts the output of the receiver and could cause mal-operation of an IED.

E. Impact of 1588 Traffic

The IEEE1588 protocol uses data packets within an Ethernet network to disseminate the time reference from the grandmaster. Sharing an Ethernet network between 1588 traffic and traffic related to other IED applications can result in an inevitable interaction. This might affect a critical IED especially if the traffic is not carefully managed and the network is not appropriately engineered.

Two extremely important components of the network traffic are the IEC 61850 9-2 sample values (SV) and the IEC 61850 GOOSE messages. These maintain the correct operation of the primary plant used in a substation and ensure the power system operates in a stable state. As defined in the IEC 61850 standards and IEEE 1588 Power Profile, 1588, SV and GOOSE traffic all have the same priority value of 4. This means a particular packet from any of these sources would be randomly placed in the output queue as shown in Fig. 17, which means the residence time within a switch is un-deterministic. If a 1588 Ethernet switch is used, un-deterministic residence time values will not affect the 1588 timing accuracy since the delays are measured and compensated and this is previously proved by the tests described in Section B. However, a data packet such as a SV message is very sensitive to the network latency [11]. Hence, it is necessary to investigate how the 1588 traffic affects the data traffic from other applications that share the same Ethernet network.

Fig. 17. Interaction of traffic with same priority.

The test setup illustrated in Fig. 18 is used to investigate the impact of 1588 traffic on the latency of SV packets through an Ethernet switch. The grandmaster injects 1588 messages into the switch with a rate up to 128 packets/s and the latency of SV packets can be measured under various 1588 traffic load conditions. More specifically, a MU produces the SV stream which will be copied by an Ethernet tap before entering the 1588 switch. The copied SV packet is captured...
and timestamped by an Ethernet capture card at \( T_1 \). After the original SV packet is sent out from the switch, it is captured and timestamped by the capture card at \( T_2 \). Hence, the latency of a SV packet is \( (T_2 – T_1) \). The measurement error introduced by the Ethernet tap and the capture card is \( \pm 60 \) ns, which is negligible for the network latency measurement.

The measurement results are shown in Fig. 19; the average latency for a SV packet is about 18 \( \mu \)s. This is because the size of the SV packet from the MU is 141 bytes or 1128 bits and the transmission delay within the switch is 1128/(100 \times 10^6) = 11.28 \( \mu \)s @ 100 Mb/s. According to IEC 61850-90-4 [12], there is a minimum switching delay of 8 \( \mu \)s within an Ethernet switch and thus the total latency for a SV packet is about 19.28 \( \mu \)s, which is similar to the measurement results.

It is also observed latency can increase to about 24 \( \mu \)s when there is no 1588 traffic. The reason is that an Ethernet switch has to periodically send a bridge protocol data unit (BPDU) according to the Ethernet standard [13]. A BPDU contains 64 bytes or 453 bits, which causes additional latency of 544/(100 \times 10^6) = 5.44 \( \mu \)s @ 100 Mb/s if it is transmitted before a SV packet.

When 1588 traffic is present in the network, the maximum latency for a SV packet increases from 24 \( \mu \)s to 29 \( \mu \)s. Considering a 1588 Sync message contains 72 bytes or 576 bits, the transmission latency is thus 576/(100 \times 10^6) = 5.76 \( \mu \)s. 29 \( \mu \)s indicates a BPDU and a 1588 message are transmitted before a SV packet. Consequently, if 1588 traffic shares the data network with critical automation applications, it will introduce additional delay of about 5.76 \( \mu \)s at a data rate of 100 Mb/s or 0.576 \( \mu \)s at 1000 Mb/s. This has to be considered when planning and designing the data network.

**IV. CONCLUSION**

Centralized time synchronization based on the IEEE1588 protocol has numerous advantages, including: the ability to use high quality antennas and receivers; simplified installation requirements; automatic compensation of the propagation delay from the time reference; removal of the need for manual measurement of signal delay; operation over general substation Ethernet network; removal of the need to construct a dedicated time distribution network; reduced requirements on number of output modules on GPS receivers; future scalability; immunity to GPS synchronization degradation and loss; and ease of maintenance and replacement. However, if high timing accuracy (< 1 \( \mu \)s) is required from IEEE 1588, two extra requirements are required, which significantly increase the capital cost: all Ethernet switches must be 1588 compliant and additional 1588 slave clocks are required to translate 1588 and provide 1-PPS and IRIG-B signals for non-1588 IEDs.

In comparison with timing approaches directly using 1-PPS and/or IRIG-B from GPS receivers, 1588 timing over a fully compliant 1588 network has the following advantages: better long term accuracy; no time offset spike when synchronization is restored; correct operation under heavy network load conditions and during the loss of 1588 packets; negligible bandwidth consumption and negligible impact on sample values or GOOSE messages. In conclusion, time synchronization system based on IEEE 1588 is an ideal method for accurate timing of IEDs in a transmission substation.

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