GOOSE Timing Measurements in an IEC 61850 Substation – Using a Distributed Hybrid Signal Analyzer

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Abstract

In the protection, automation and control environment, the timing of control and measurement signals is of critical significance. This mainly relates to instantiating, transmitting, reading and responding to such signals. This timing needs to be accurate and reliable, and requires careful coordination so as to eliminate any ambiguity in a system's design, operation, maintenance and fault finding.

With IEC 61850 based solutions, this coordination has become a very interesting task that also comes with some challenges. Signals span across both, the physical domain (voltage/current signals, relay contacts, etc.) as well as the virtual domain (GOOSEs and SVs). Both domains are of equal significance and have direct as well as indirect impact on each other.

Furthermore, factors such as varying and unpredictable network loads, sometimes even sectional unavailability, bad connections, etc., need to be considered. Especially when daring to venture into less chartered territories, such as geographically distributed signaling, "GOOSEing" across WANs or maybe even VPNs, the determinism and timing challenges encountered become increasingly complex.

The question thus arises, how can timing be properly measured and assessed in systems scaling from a few devices to a few hundred devices? Both, the physical and virtual domains' timing parameters, often distributed over a multitude of diverse logical as well as electrical networks' locations, must be captured and analyzed – a challenge in itself when working with distributed systems.

This paper ventures into the realm of hybrid measurements and sheds some light onto the what, the why and the how.

In conclusion, end-to-end timing measurements were taken and analyzed. The method used, although in its infancy and unrefined, proved to be effective and resulted in valuable insight as to how the network performs, how signals propagate, determinism, robustness, redundant route performance, etc.

1 The Fuss about Timing

The correct timing of events and signals in and around an electric substation is of critical importance when it comes to the safe and effective operation of an electric transmission grid. In modern IEC 61850 based substations, the amount of such events and signals can easily outgrow quantities that are still manageable and maintainable by normal human observation and comprehension.

As such it has become necessary to develop methods and platforms that simplify and (at least to some extent) automate the collection, analysis, presentation and coordination of events and signals within the time domain. This requirement is further complicated by the fact that, with IEC 61850, events and signals can co-exist as physical (electrical) as well as virtual (data) entities. All of these contain important information, sometimes structured, sometimes unstructured. These bits and pieces need to be consolidated and properly related to each other, especially with regards to their exact timing parameters.

2 Why Timing is Important

Although it is fairly obvious why it is important to know, comprehend and coordinate exact timing parameters in a substation, it is still worthwhile to spend some thought on it.

Protection, automation and control functions are of course the first that come to mind. These need to be properly set up and tested so as to function together as a harmonious system. Their sequencing, reaction times and operating boundaries are all heavily time-dependent.

This time-dependence is also something that is given great consideration when it comes to factory acceptance testing. Both, suppliers and clients need to ascertain that specifications and requirements are adhered to.

Fault finding is another important aspect where timing information, but also accurate time synchronization is significant. When things start to go wrong, the sequence of events and signals needs to be properly presented and analyzed in order to trace out faults.

But there are also more subtle necessities for precise and reliable timing information. Condition monitoring, for example, can benefit greatly from accurate timing data of equipment's performance in order to indicate emerging maintenance requirements or similar issues.

3 How to Capture Timing Data

As mentioned earlier, the capturing of events and signals within the time domain needs to be performed on both, electrical as well as virtual signals. Having virtual signals defined by the IEC 61850 standard, their capturing in essence means to capture data network packages.

Thus, in principle, a device is required that can

- Capture analogue and binary electrical signals
- Capture and analyze data packets
- Timestamp all signals and events from an extremely accurate time source, for example IEEE 1588 Precision Time Protocol (PTP).

For the purpose of this study, the DANEO 400 from OMICRON was identified to be a well suited device. The DANEO 400:

- Captures network data packets
- Captures analogue and binary electric signals
- Utilizes PTP for time synchronization
- Stores Data
- Provides tools to look at time-synchronized data and events
- Provides both local and networked user access
- Can provide the networked user access without interfering with the station's LAN, thereby it does not interfere with other critical substation communications

Figure 1: The OMICRON DANEO 400

4 The Test Rig

In order to properly get acquainted with the DANEO 400 and the measuring tasks at hand, a test rig was set up at a transmission station in the west of Namibia. This station was specifically chosen because it forms part of a power transmission system that consists of four substations that are ring-connected on optic fiber Ethernet forming a distributed station bus, but with the entire system seen as a single station network. A conceptual schematic of the stations' interconnection is shown in Figure 2. T1 was used to set up the test equipment.

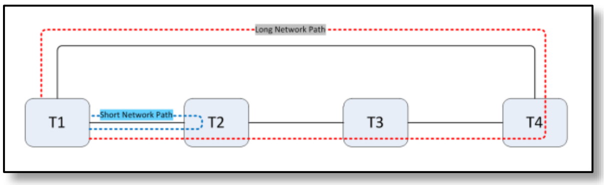

Figure 2: Station Network Paths

This setup allows for tests to be performed locally at T1 but also provides the opportunity to test network propagation times across different paths, as indicated by "Short Network Path" and "Long Network Path".

The equipment used to perform the tests is show in Figure 3. It consists of:

- IO unit: Used to switch a DC pulse which ultimately triggers the entire test event.
- A pair of ISIO 200 units: Connected back to back across the network, to carry the input from the IO unit into the first ISIO 200 over the network and cause a corresponding output pulse on the second ISIO 200.
- DANEO 400: Used to record the input pulse, the corresponding output pulse as well as the related GOOSE traffic on the network.
- Laptop: Used to trigger the IO unit pulse and to control and interface the DANEO 400 over the network.
- Managed Ethernet Switch: As part of the substation's network infrastructure, the switch carries all relevant traffic and provides the packet data to the DANEO 400.

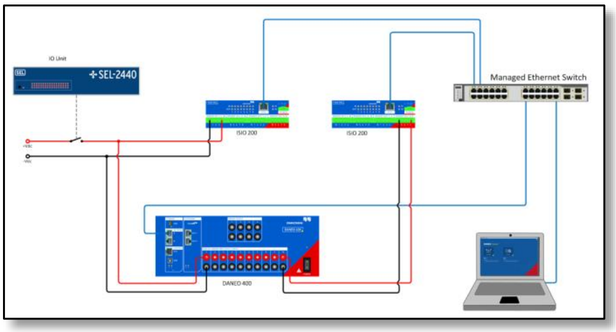

Figure 3: Equipment Used

In principle, this setup can be split into two layers, an electrical layer and a network layer:

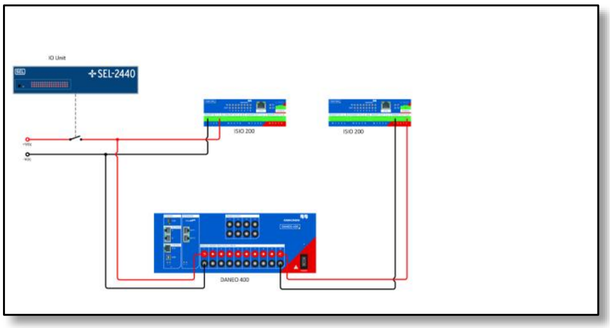

Figure 4: Electrical Layer

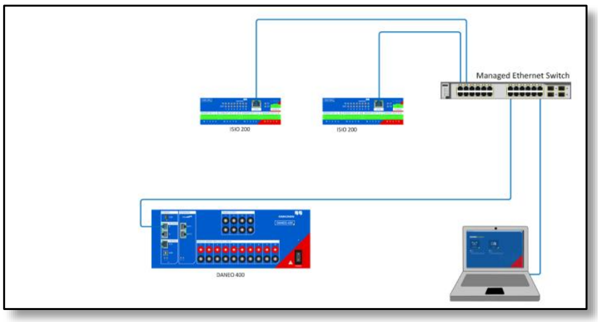

Figure 5: Network Layer

As can be seen from Figure 4 and Figure 5, the DANEO 400 monitors both domains, making it a fully hybrid test device.

5 Measurement Concepts

Even though the emphasis of the measurements is on the timing (signal propagation and delays) of GOOSE messages specifically, the test setup inherently captures timing of signal processing and device response. It was found that this was beneficial to the study especially when considering the practicality of applying the findings in actual Protection, Automation and Control (PAC) systems.

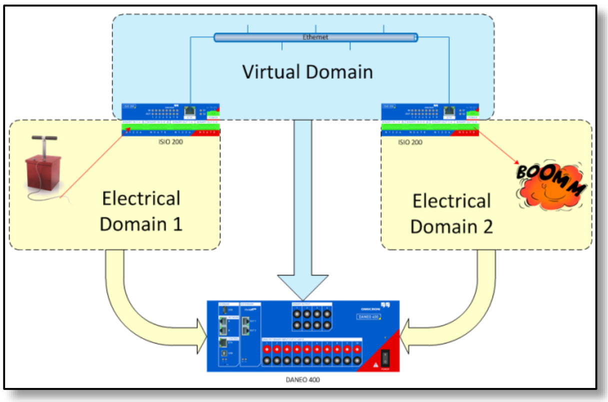

Figure 6: Different Domains - Electrical and Virtual

The challenge is to measure stimulus vs. response times in different domains (Figure 6), i.e., the electrical- and virtual (network) domains. As already mentioned, the DANEO 400 is a device purpose-built for analyzing systems of this nature.

Shortly, the timing information obtained is (from Figure 7):

- Time of GOOSE message published to GOOSE message received, t_{G-A} to t_{G-B} equals Δt_G (network propagation delay),
- The "electrical domain" timing, Δt_{E-G}, is the sum of:
- Electrical impulse to published GOOSE message, t_{E-A} to t_{G-A} (device processing time),
- GOOSE message received to electrical output/response, t_{G-B} to t_{E-B} (device response time),
- Inherently, the entire system response is a combination of the "electrical propagation" (electromechanical relay coil pickup/contact output delays, etc.) and network propagation, t_{E-A} to t_{E-B} equals Δt_E (system response).

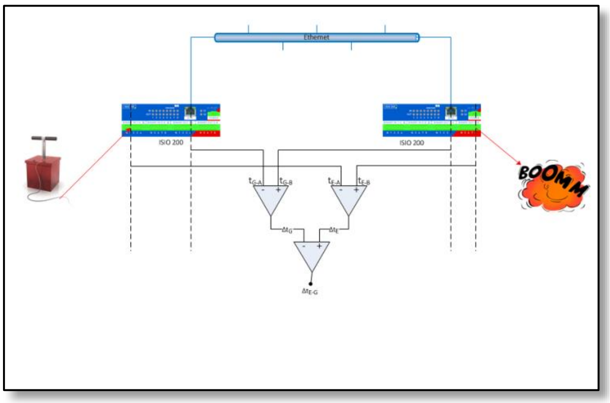

Figure 7: Conceptualised Timing

6 Test Scenarios

Invariably PAC systems can be viewed as "local" or "distributed" type systems, i.e., systems that either share a single geographic location or network or are distributed over several geographic locations or networks. Fortunately geographic separation does not necessarily imply network segregation. The first test scenario described here is a "local" system while the second scenario is a hybrid combination of the two system types, both a single/local network and geographically distributed.

The "local" test scenario is represented in Figure 8. This test was performed at a single substation and all measured impulses and responses were captured from within the actual commissioned substation PAC system in service. However, in an effort to achieve minimal interference with PAC system it was decided to connect two OMICRON ISIO 200 devices to the substation system and related infrastructure (both network- and physical plant) to provide the test impulses and responses (Figure 3).

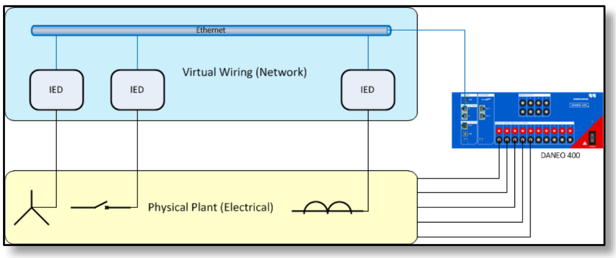

Figure 8: "Local" Test Scenario

For the "distributed" test scenario (Figure 9) it was necessary for testing equipment to be simultaneously set up at the first substation (used in "local" test scenario) and a second substation roughly 20 km from the first. This required configuring remote access to the testing equipment at the first substation. Again and as for the "local" test scenario, minimal system intrusion was achieved by making use of the two ISIO 200 devices with the exception that one device was used per substation to interface with the physical- and virtual plant.

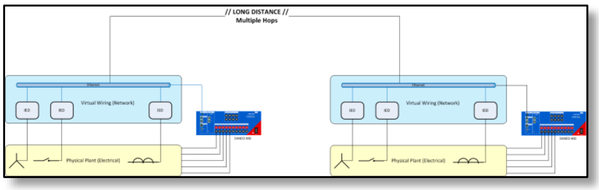

Figure 9: "Distributed" Test Scenario

7 Actual Measurements and Results

Results obtained for the "local" test scenario were as follows:

- Impulse to GOOSE, t_{E-A} to t_{G-A} (ISIO 200 processing time including input debouncing), $|t_{E-A} - t_{G-A}| = 1.125\,ms$ (Figure 10)
- GOOSE to electrical response, t_{G-A} to t_{E-B}, $|t_{G-A} - t_{E-B}| = 4.275\,ms$ (Figure 11)

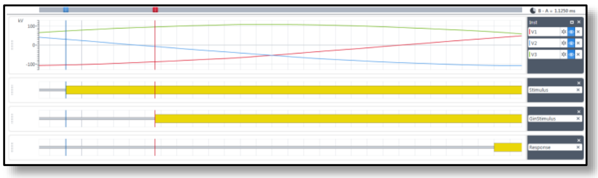

Figure 10: Impulse to GOOSE

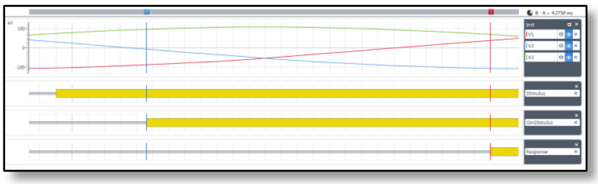

Figure 11: GOOSE to Response

The GOOSE to electrical response delay is mainly influenced by the output relay operating time of the ISIO 200 output contact. We did not further consider the effect of the propagation delay within the local network, as both, the DANEO and ISIO were connected to the same network switch and the local network delay was assumed to be negligible.

The subsequent "distributed" test scenario proved this assumption to be valid. It will be shown that the ISIO 200 output relay operating time makes up the bulk of the measured $4.275\,ms$ and that the GOOSE propagation delay within the local network is negligible when compared to these values. Also, a remarkable level of repeatability was observed during testing.

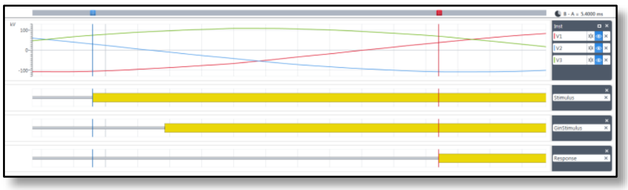

Figure 12: Total Response of Entire System Tested

Figure 12 shows the response and timing performance of the entire system under test, $|t_{E-A} - t_{E-B}| = 5.4\,ms$. Given that the majority of timing delays is from ISIO 200 input debouncing and output relay operating and that the network propagation delays are the least, it is impressive to note that times in this region were regularly achieved. This yielded a satisfactory system performance.

As for the "distributed" test scenario, this offered the unique opportunity to evaluate GOOSE message timing and network propagation in terms of when a GOOSE message is published in one network and when that same GOOSE message "appears" in a second (distant) network. For this measurement we used the propagation delay measurement function of the DANEO, where hundreds of such measurements are combined into a histogram. It is important to note that also for this test it was crucial to have a stable, accurate and reliable time synchronization source at both locations. The OMICRON OTMC 100 PTP Grandmaster Clock was used to achieve this.

This scenario offered the opportunity to also evaluate the performance of redundant network routes/paths between the two locations. Therefore, this propagation delay measurement yielded two sets of system performance results. In the first instance the most direct network route was evaluated. Figure 13 shows the results. An average delay of $148.8\,\mu s$ was measured for 504 packets captured. An outlier was observed at $200\,\mu s$ which was acceptable and well within system design tolerances.

Figure 13: Direct Network Route Propagation Delays

Next, the "longer" redundant route was evaluated and found to perform satisfactorily given the greatly increased amount of network hops involved. The results are shown in Figure 14. An average delay of $476.48\,\mu s$ was measured for 556 packets captured. An outlier was observed at $658\,\mu s$ which was acceptable and well within system design tolerances.

Figure 14: Redundant Network Route Propagation Delays

Overall, both systems on average achieved timing performances below 500 μs and maintained a negligible contribution to timing delays for the total system response. Figure 15 shows the overall system performance measurement from impulse to response.

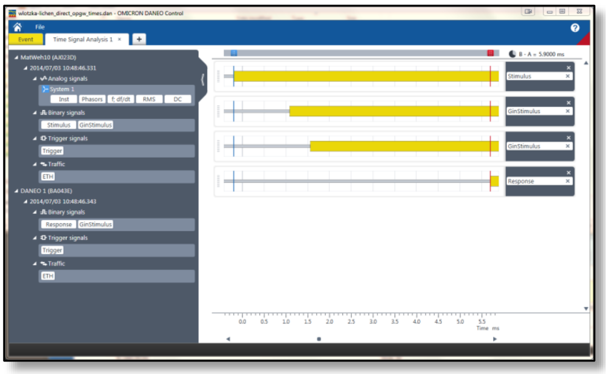

Figure 15: Overall "Distributed" System Response Measurement

When comparing the result of the "distributed" test scenario to that of the "local" test scenario it is noted that the network propagation delay is, for all intents and purposes, negligible. Compare 5.4 ms to 5.9 ms and the difference is roughly 500 μs, as supported by the findings of the network propagation delay study. This falls well within the system design tolerance which was specified as sub 1 ms delay between substations. This is further supported by Figure 16 which shows the actual GOOSE message propagation delay (as from Figure 15) as measured for the redundant network route and found to be 474 μs.

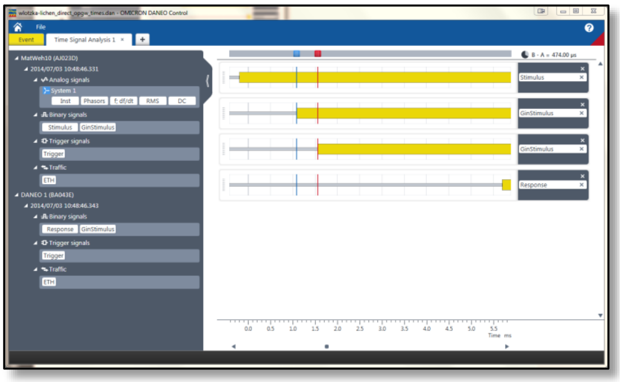

Figure 16: GOOSE Message Network Propagation Delay

8 Future Tests

As already described, the tests were performed within a single logical network. It is the intention of the authors to explore the routing possibilities of GOOSE messages and evaluate system performance under these conditions. Possibilities that stem from doing this are:

- Wide Are Monitoring Protection and Control (WAMPAC) systems with integrated inter-substation GOOSE messaging.
- Selective routing of GOOSE messages.
- Extending intelligent PAC system functionality into so-called SMART grids.
- Evaluate network architectures/systems with regards to IEC 61850-based systems performance.
- Expanding conventional SCADA systems control and monitoring functionalities.

9 Conclusion

The performance study proved that it is possible to determine design parameters and performance specifications for IEC 61850 systems. Current technologies enable the composition of IEC 61850 systems that seamlessly integrate and reliably operate in substation environments. Such systems exhibit near to deterministic operation and performance.

In the network/virtual domain it was found that the amount of network hops is the main contributing factor to network propagation delays. These delays, however, remain negligible when compared to "electrical propagation" delays in the electrical domain, as long as the network system is designed to maintain propagation delays in the region of below 1 ms. Once these delays are known from measured results it becomes possible to fairly accurately predict expected performances for subsequently designed systems based on this information.

Main and redundant routes (and consequently, entire redundant systems) can be evaluated individually. This provides invaluable information that ultimately describes the overall performance of the entire system. In the end it comes down to the requirements and design specifications that make up the final engineered solution. Realistic, practical and logical goals must first be set to yield a practically acceptable IEC 61850 solution.

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