CONTROL HARDWARE IN THE LOOP FOR IEC61850 GOOSE PERFORMANCE TESTING

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Abstract — **In modern power systems, communication between multiple intelligent electronic devices share time critical information for fault detection and discrimination. This has opened up a number of issues related to protection, automation and control. IEC61850 is the prominent communication standard for protection in smart grids. This paper proposes a practical approach to evaluate the performance of IEC61850 GOOSE-messaging. Dynamic system testing is suggested to evaluate real life performance of a protection scheme. Communication is central in a permissive transfer tripping scheme and is taken as example for the performance test. A three-bus transmission system is simulated using a real-time digital simulator with the protection relays in the control loop. Different methods are discussed leading to the desired performance test. Practical simulations on different fault locations were performed to evaluate latencies in hardwired and IEC61850 Ethernet-based signals. The performance is evaluated with regards to speed and dependability.**

Index Terms— **Digital substation, IEC61850, CHIL, RTDS**

I. Introduction

Digital substations provide many benefits over their traditional counterpart. High-speed communication has paved the way for a full automation and monitoring of the entire substation. High-bandwidth made it possible to transmit large data over a single Ethernet-cable reducing the amount of wiring needed in the substation. This should lead to less complicated and more dynamic substation. Despite the benefits, utilities remain hesitant adapting to the idea of a full digital substation. The report [27] tries to evaluate the reasons for the slow transition, overall there are concerns about the complexity and dependability of a digital substation. Standardization is a good tool to help this transition. The IEC61850 standard was created for the communication in substations to improve interoperability and future-proof the system. IEC61850 provides comprehensive models for how power system devices should organize data, that is consistent between all vendors. The dependability of protection is considered the most important function by utilities. The standard must prove that the benefits of the digital substation reaches the same level of availability as a traditional system and in the future improves on this premise. Progress has already been made in this field by [25] and [26] for monitoring and interoperability in a full digital substation.

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However IEC61850 still faces some challenges from a communication performance perspective into the overall system design [19]. The assumption that digital substations perform at par or better in terms of performance is not generally accepted by end-users. Therefore, this paper tries to determine the performance of GOOSE-message, by proposing a methodology based on several known methods handled in [6], [11], [19], [21], [22] and [24]. This paper differentiates by combining performance tests to rate an overall protection scheme of its performance. This paper starts with describing IEC61850 and GOOSE-messaging. Next, the different performance requirements are handled and the lab implementation is described.

II. IEC61850

IEC61850 is an approved international standard for communications in substations developed for power systems protection and control. Performance testing of protection devices compliant to the standard is important to rate the dependability of the device under test. The standard covers some possibilities and approaches for testing the standard in general [6]. It is important to note that these conformance tests do not completely guarantee that all functional and performance requirements are met. However, such tests can significantly reduce problems during system integration. Performance tests are best performed on a system as it is deployed in the field. The first part of IEC61850 [2] already defines main types of substations with examples of typical functionality levels. To test a system, a general approach makes some assumptions about terminal performance. The transfer time of signals is to be observed in real-time and depends on the performance of the sending and receiving Intelligent Electronic Device (IED). This must be taken into greater consideration when testing the interoperability of multiple devices.

A. GOOSE-messaging

The sending of status signals is generally supported in the standard by a Generic Object Oriented Substation Event (GOOSE). A GOOSE-message supports the exchange of common data organized by a data-set [4]. The data set is a collection of binary and analogue data elements sent in each message. For transmission of data, a GOOSE-message utilizes multicast services that allow simultaneous delivery of the same substation event to multiple IED's. The communication stack of a GOOSE-message consists of four layers, excluding the session layer, transport layer and network layer of the OSI-model, as seen in Fig.1. The most important feature of this structure is the low time delay it causes in the networks. For example, the delay caused by unpacking packets is reduced in order to improve the data transfer speed and decrease the possibility of congestion. Due to the multicasting, it is unknown which IED's have received the message. The delivery is not guaranteed and there is no acknowledgement. The lack of a network and addressing layer prevents traditional routing, so that GOOSE messaging cannot be used on a wide area network, as it is generally used on local area networks [16],[17],[18].

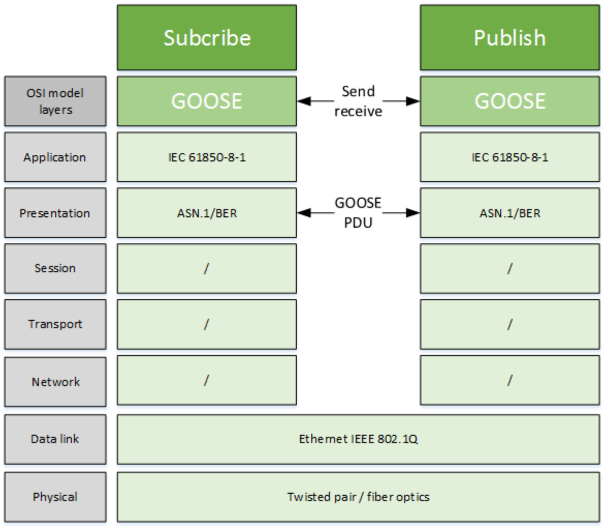

Figure 1: GOOSE communication stack

The reliability of GOOSE communication is not ensured by acknowledgements, instead a retransmission mechanism is used. GOOSE-messages are thus published constantly. Every frame sent by an IED is repeatedly sent as long as the state of that dataset did not change. In order not to flood the network, the time interval between each retransmission is increased. This is repeated until a maximum retransmission time is reached. In the standard this time is referred to as the maximum Time allowed To Live (TTL). The time intervals for the first frame, and the maximum time interval are configurable. Generally these are set to 2ms and 2 seconds, but can be more rapid for critical events. In short, when an element within a dataset (e.g. the trip signal) changes its state, a burst of frames is sent from the IED on to the network. After a while, if the state of the dataset hasn't changed, the GOOSE message is still present on the network but is repeated with a larger time interval. Each GOOSE-message is given a timestamp, thus every receiving IED can calculate the time between retransmission intervals and the given TTL. Besides the TTL, additional information regarding the sequence of frames (sqNum) and number of state changes are provided (stNum). This information is used to determine the quality of the connection in the receiving IED. The unit in which a certain layer handles data is called a Protocol Data Unit (PDU) and consists out of 13 parts described in [5], [6] and [16] and can be used to monitor the network. Besides the previous mentioned parameters, this paper also statistically assesses packet arrival times on the network and the time between state changes (t) within the PDU.

B. *Communication network considerations*

For protective relaying, a communication network with a variable transmission delay is a big concern. Data latency is the time delay between getting a network message from the host server and delivering it to the protection device. The latency is caused by either propagation delay, transmission delay, router delay, packet loss, recovery delay or the combination of. Extensive delay may affect the performance of a transfer trip or current differential application. The work in [7]-[10] already provides a lot of insight towards network performance, with regards to the communication architecture. For the performance test in this paper, techniques utilized by modern switches and routers for segregating and prioritizing network traffic are used. GOOSE is a real-time stack and thus relies on services provided by the data-link layer, which support MAC-addressing, 802.1Q VLAN and priority setting. To alleviate network burden, multicast messages use VLAN, this divides a physical connected network into several virtual networks. The VLAN is identified as a 12-bit number and is used to divide a GOOSE-message from other traffic on the network. A VLAN identifier should be appended to every virtual connection, thus separating different GOOSE-messages. One other technique is the use of priority tagging, which utilizes a Quality-of-Service (QoS). High priority frames are sent ahead of low priority frames, and this prioritization is weighted. The header is given a tag with a value between 0 and 7, with 7 being the highest and 1 the lowest, since 0 is used for regular network traffic and is handled whenever possible. The GOOSE-messages in this paper are given a priority of 4, high enough to perform under normal network conditions.

Regarding performance, the transport medium (e.g. optical fibers) and the Ethernet switches or routers impose a small delay. Ethernet switches process every message received or transmitted by each port. It takes time for a switch to process messages, and this introduces a short, but unavoidable processing delay. A message may need to go through several switches in a network to reach its destination. Work in [8] and [9] already set some network guidelines to prevent excessive delays and congestions. The actual communication bus structure must be selected on the base of requirements and the desired performance class. Within a lab the distances are fairly short and contain just a few IED's, thus in this paper a star network topology is maintained for simplicity. The origin of the data latency is hard to distinguish. The performance test measures this latency through a packet round trip time. Suggested is sending a message through the network and subscribing to that same message. Since not all IED's support this, a message is send to a different IED, which will immediately respond by sending a message back to the previous IED. By monitoring of packet arrival times, the network will reveal the network performance. Loss of packets and recovery delay are depended of the implemented bus structures. For high network requirements, network redundancy methods like HSR and PRP are advised and can be found in the IEC62439 standard. Performance testing can run with different topologies in mind and under multiple levels of network activity, as performed in [9] and [19].

Within an automation network, to perceive the data at the required time and accurately produce the timestamp, it is important that the internal clocks of each IED run synchronously. A lot of measurement and control data in the power grid requires an accuracy of approximately 1ms. This accuracy is fairly easy to reach with a Simple Network Time Protocol (SNTP), where reference time is taken from a network-IP. For the GOOSE-messaging in this paper, synchronous accuracy gained by SNTP is sufficient. Time stamping assigned to data changes and sampled values requires a resolution of microseconds. For this purposes a standard like IEEE1588 should be implemented [23].

III. PERFORMANCE TESTING

Fault-clearing time is an important consideration regarding the performance of power systems and protection. Requirements for the speed of a relay should carefully be determined. Slow operation times may result in system instability, equipment damage, and adverse effects on grid users. The goal of performance testing is to verify the behaviour of the protection under certain conditions. It includes dynamic aspects such as fault resistance, the relative line to fault distance and various types of faults. Numerical protection devices contain a large number of functionalities. This makes it difficult to test all relay functions. Therefore, a performance test is limited to practical protection applications. Since IEC61850 focusses primarily on communication, this paper will evaluate a permissive transfer tripping scheme for distance relays. In this scheme communication is central. Pilot relaying schemes are used to achieve high-speed tripping for faults at different locations of a line. These schemes require that during a fault, information be transmitted between the protection devices. The time interval that both relays receive this information will influence the overall fault-clearing time. This time must be less than the time for which a fault can remain on the system. Entso-e states that on transmission systems levels of 110 kV and above, fault clearance times of 150ms are reasonable. The protection system performance is frequently assessed statistically. In this case each operation time is classified as 'correct' if the last trip signal of an IED is received. With this value, a percentage of correct clearances can then be determined.

A. Definitions

Specific standards [1], [3] and [20] handle how fast a protection relay and tele-control signals must perform to be reliable. In testing the performance of a control message it is important to define which time is to be examined. The instant a fault is detected until the physical output of a protection relay operates is called the decision time [1], while transfer time is defined [3] as the complete transmission of a message including the necessary handling at both ends. Meaning that the time counts from the moment the sender puts its data content on top of the transmission stack until the moment the receiver extracts the data from the transmission stack. Here IEC61850 classifies application types based on how fast the messages are required to be transmitted among networked IED's. Signals involving trip, reclose or tele-protection have high requirements, the total transmission times are considered time critical and are defined under class P2/3, and based on the type is defined at 3ms for a trip and 20ms for a pilot signal. All other messages are important for the interaction of the automation system but have less demanding requirements. Last, [11] defines the relay operation time as the time interval from when the power system fault starts to when the relay operates and trips the breaker. This paper considers each of these times but will rate performance towards the operation time of a certain tele-protection scheme. Meaning that the operation time is the time that two relays or IED's on the opposite end of a line send out a trip signal to the local circuit breaker. Within the standard IEC60834-1 [1] the total operation time ($\sum t$) is referenced as the sum of fault recognition (a), relay decision (b), relay-output (c) and circuit-breaker operation (d). An example of these times is given below:

$$\sum t = a + b + c + d = 30 + 30 + 5 + 80 = 145ms$$

Since breaker-speed in the simulation is assumed the same, this paper concludes its operation time at receiving a trip signal of both IED's. Entso-e states that on transmission systems level 110 kV and above fault clearance times of 150ms are reasonable for fault allocated over the entire line by the primary protection. The percentage of operation times below this limit can be seen as correct.

B. Distance and differential relaying

Distance relaying is widely used as transmission line protection. It offers several advantages with respect to fault discrimination and influence by system changes. The relay measures the ratio of voltage and current, calculating the impedance of the fault to the impedance of the line. The discrimination is obtained by limiting relay operation to certain ranges of impedances or zones of protection. If the measured impedance is lower than impedance setting, a fault is detected, and the distance protection will send a trip signal to the circuit breaker. These protection zones are set as stepped ranges of impedances or a percentage of distances. A fault located in the first zone instantaneously operates the relay. To avoid undesirable tripping this zone is set shorter than the full line length. Typically, the first zone of protection (zone 1) covers 80% to 90% of the line. This is done because a relay is susceptible to erroneous measurements for faults near the end of the line and due to overreaching and under-reaching effects, like infeed from multiple sources. Therefore, the second zone of protection typically overreaches the line and covers a minimum of 120%. Here the relay is set with a small time delay, typically a 200ms operation delay. In this paper the second zone is set to 150%, which is fair for parallel lines, but must be set with caution with regards to selectivity as secondary zones can overlap. For redundancy, a third or fourth zone will provide local back-up. The third zone is set in the reverse direction to provide reverse back-up and to determine if a fault is external. The fourth zone acts as back-up zone to all perceivable faults and is set to cover beyond 150% of the line. These zones are set with a higher time delay than the second zone to avoid unwanted tripping whilst overlapping with zones of other relays. As mentioned before, different overreaching and under-reaching effects can have a major influence on these settings, more in-depth settings are handled in [13], [14] and [15]. The disadvantage of stepped relaying scheme is that simultaneous high-speed tripping of breakers at each end of the line are only achieved if the fault is located within the first protective zone of both local relays. The only solution to this problem is pilot relaying. A Permissive Under-reach Transfer Trip (PUTT) and Permissive Overreach Transfer Trip (POTT) are two widely used pilot-schemes in European transmission systems. Fig. 2 shows the operation of these schemes. In the figure left, a permissive under-reach scheme sends a request to trip the adjacent relay if the first protection zone of the local relay picks up the fault. If the remote relay receives this signal and perceives the fault in its forward overreaching zone (zone 2), the relay will order an immediate trip. For a permissive overreach scheme, right of the figure, the request is not sent in the first zone but in the second protective zone. Both relays will trip immediately if both relays have received the request and saw the fault in the forward direction (zone 2).

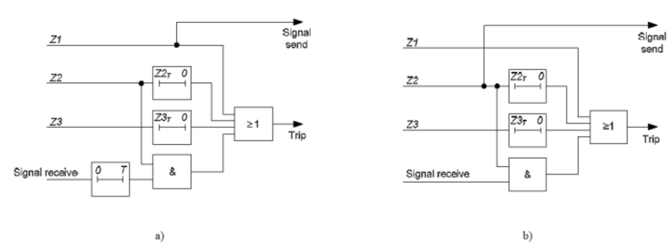

Figure 2: pilot scheme logic a) PUTT and b) POTT

Differential relaying is selective by design and will only trip in case the measured currents at the end of each line differ above a certain limit. Due to measuring errors from CT's, the operation limit is increased proportional with the operational current. For the performance test, the differential protection serves as a reference for the distance protection as to see if local tripping provides a quicker solution.

C. Test considerations

The IEC60255-121 standard [11] specifies the minimum requirements for functional and performance evaluation of distance protection relays. The distance characteristics depend greatly on the considered power system. Additionally, relays from different manufacturers may have different philosophies towards these settings. This makes it hard to define a single conform test. The standard can however guarantee basic accuracy guidelines. The standard notes that the impedance characteristics are to be published for a phase to earth, two-phase and three-phase fault. A test is proposed to publish the relay operation time as function of the fault position, fault type and source impedance ratio. The operate time of the relay is taken as the median value of the statistical distribution.

The IEC61850 standard describes a simple GOOSE performance test [6], a loopback test. The test in the standard only considers the IED process time, but not the time required by the application to return the GOOSE message. The standard makes an assumption by considering the in- or output latency on each end to be less than 80% of the total transmission time, leaving 20% for network latencies. This implies that if a GOOSE is configured for a response of 3ms, the transmission time is considered 600µs. To ensure that the transmission times are met under any operating conditions, the dynamic performance must be considered. Monitoring of the network will reveal the actual network performance.

IV. Lab implementation

A. Hardware in the loop (HIL)

For HIL applications, a physical device is connected to a virtual power system run on a Real-Time Digital Simulator (RTDS). RTDS performs a simulated representation of the operations and features of an actual power system. The main advantages of HIL testing is its dynamic and cost benefit compared to a physical setup. The simulator can be used for multiple applications and provides more options towards setting conditions for repeating results. The installation offers the possibility to connect actual hardware, in this case protection relays, to an EMT model run in real-time. HIL testing is important since relay actions may influence the power system, increase distortions, and thus effect performance of other relays on the grid. For a real-time simulation to be valid the real-time simulator must accurately produce the internal variables and outputs of the simulation within the same length of time that's its physical counterpart would. The time-step is thus depended on the frequency of the highest transients to be picked up by the relay. The relays chosen in the setup have an internal sampling frequency fixed at 16 kHz. If the relay decides that the absolute value of phase and time constant are correct, the sampling frequency is reduced by 8kHz. Practically, it is best to use a simulation time-step of 50µs to accurately produce transient up to 2 kHz [12], [13].

For each time-step, the simulator executes the same series of tasks: read inputs and generate outputs, solve model equations, exchange results with other simulation nodes. Necessary voltages and currents for the relays are selected and presented by the simulator through an analogue output card (GTAO). This card provides an external analogue voltage signal between +/- 10V. The signals are than amplified to gain a better representation and greater accuracy equal to the secondary of a real CT or PT. Voltage and currents are analysed by the relay and depending on the current grid situation, status signals (e.g. trip signals) are returned to the simulator. For the performance test, hard-wired trip and tele-protection signals where fed-back to the relay using a digital input card (GTDI). The same signals were also presented in a GOOSE-message to the network communication card of the simulator (GTNET). For receiving and sending GOOSE-messages this card is able to simulate four individual IED's. Upon receiving the trip signal of a relay, the appointed circuit breaker in the simulation opens and disconnects the fault from the system, thus closing the loop. Fig. 3 shows the layout of the lab set-up.

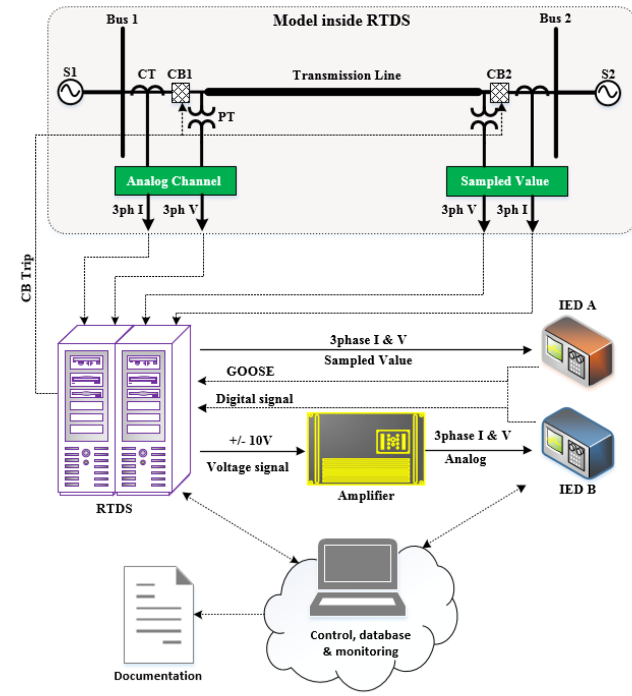

Fig. 3 HIL-setup for IED performance testing

During multiple fault occurrences, measured quantities are identified and recorded in a database. The setup will record the impedance, currents and voltages at each end of the line normally seen by the relays, and store them in a file. Wired and GOOSE signals are monitored at arrival, where the times are recorded to complement the analysis.

B. Network Analysis

During every case, a network analysis software 'Wireshark' scouts the communication network for GOOSE-messages. This software utilizes different tools that are easy to automate. The software captures the GOOSE messages and stores the time of capture, frame arrival time, source-address and GOOSE-PDU in the same database as the data from the simulator. This data is later used for analysis and study. The monitoring reveals the transmission time (a) and the internal process time of a IED (b). During each test, the relay is reset remotely with a GOOSE from the simulator. Since this alters the data from the IED, it immediately publishes a new GOOSE. The simulator receives this message and immediately publishes a new message on the network. Since the simulator receives the signal within a given time step (c) and publishes it the next, it is considered that:

$$\sum t = 2a + b + 2c$$

The transmission time (a) can be calculated, because the time step (c) is set at 50µs, while monitoring reveals the total event time ($\sum$t) and the functional time to reset the trip, known as the response time to be the sum of (a) and (b). After this, the process time is calculated. The average of the transfer time and the response time is taken.

C. Simulation

The power system is simulated in the RTDS software, 'RSCAD'. This software utilises its own library of components and is similar to PSCAD. Fig. 4 shows a representation of the simulated network. This is a three-bus transmission system at 150 kV. The three-bus system gives the possibility to test the performance under several overreaching and under-reaching effects (e.g. parallel lines, zero-sequence coupling, infeed/outfeed). For the performance test, the relays will first be deployed on a single transmission line and next on the full system. Voltages and currents from the top line between A and B will be fed to the relays. During the test, the fault location on the line is varied between 1 and 99% of the line distance.

The test is automated internally in RTDS and externally using 'Matlab', as Matlab sets the conditions and RSCAD will produce the data. This data is than retrieved by Matlab to generate a report.

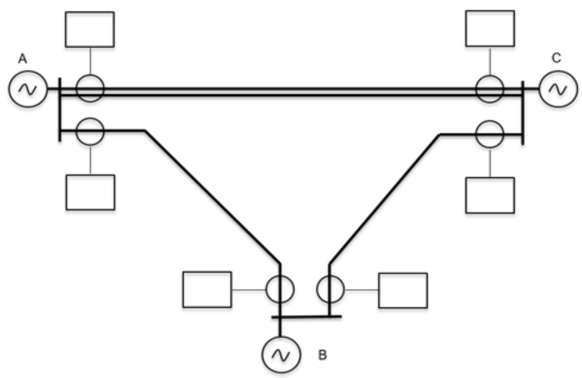

Fig. 4 layout of the 150 kV simulated three-bus system

At each fault location the operation time of the wired and GOOSE signals are documented for a single, two and three phase fault against a single and full system. With this data the average operation time of the overall system and at each fault location is calculated. A percentage is taken from how many of these points stay below the threshold of 150ms. These points are classified as 'correct'. During every case a network analysis is performed by utilizing a round trip test. From this test average response time and transfer time can be tracked.

V. Results

Table 1 and 2 gives a summary of the operational values of the PUTT and POTT. Fig. 5 reveals the operation time of a PUTT under the performed tests. The operation times are presented as dots and the average is plotted for the respective signal. It can general be noted that in the figure the GOOSE performed better for the PUTT, as the average operation time is less than the wired signal. Fig. 6 reveals the operation time of a POTT under the performed tests. Here the wired signal performed better for the POTT, as the average operation time is less than the GOOSE-signal. However, GOOSE-signals are more likely to operate under the 150ms. Over all cases the GOOSE appeared to be faster than the wired digital signals, as 65% of GOOSE was faster. Deviations between GOOSE and wired signals are at average 8,12ms, with the maximum deviation at 16,3ms and the minimum is at 0,16ms. In the table, it can be seen that the differential protection performs overall better and more consistent as the tripping is decided locally. However, the exchange of line current information in a differential protection is also vulnerable for latency's as not to operate unintentionally. Another interesting point is the great deviation between operation times at the beginning of the line caused by infeed, effecting the time of pickup and the operation of the pilot-scheme.

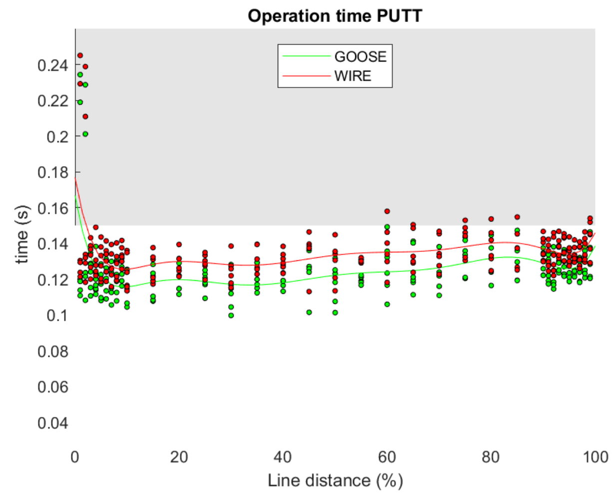

Fig. 5 Operation time of a PUTT

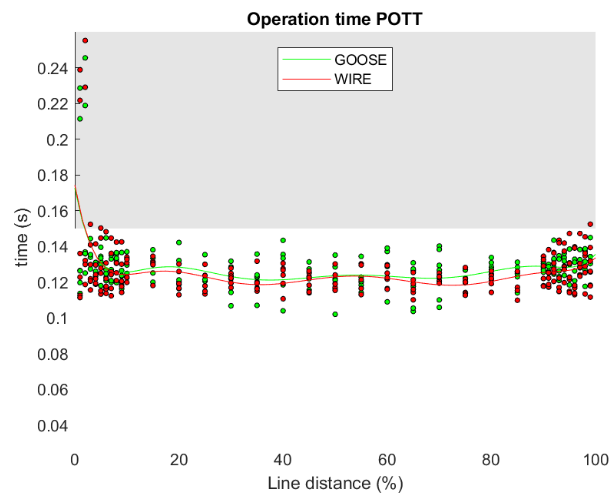

Fig. 6 Operation time of a POTT

PUTT	Average time(ms) W : wire G : GOOSE	
Distance operation	W: 134,7	G: 125,0
Δt local pickup & adjacent response	W: 29,7	G: 20,1
Differential operation	W: 99,7	G: 97,8
Correct: (<150ms)	W: 94,76%	G: 98,01%

Table 1. Average operation time PUTT

POTT	Average time(ms) W : wire G : GOOSE
Distance operation	W: 126,7 G: 128,6
Δt local pickup & adjacent response	W: 21,8 G: 23,3
Differential operation	W: 99,8 G: 97,8
Correct: (<150ms)	W: 96,67% G: 98,1%

Table 2. Average operation time POTT

Fig.7 shows the normal distribution of the response time of a IED. The performance is revealed to average around 10,7ms. This contains for a large part the processing time of the IED, as the transmission time is comparatively small and averages around 441µs. However, this time is less consistent and can vary depending on the network architecture and traffic on the network.

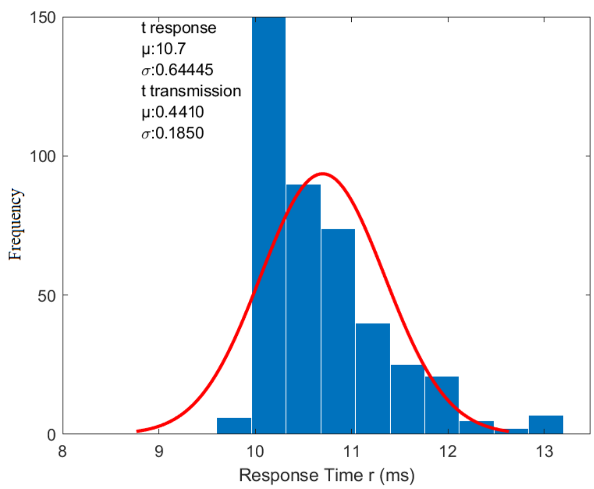

Fig. 7 Normal distribution IED response time

Conclusions

It can be concluded that GOOSE-messaging is not always faster than traditional wiring. If operation times become critical (e.g. in HVDC) than performance testing of the communication standard IEC61850 is essential. It is shown that dynamic testing of performance has an impact on the speed and dependability of signals. Therefore, performance testing must consider the protection application and all influential factors. The short cable length between IED's and the simple Ethernet topology in this paper are to be considered in the performance results. Other mediums (e.g. optical fibre cable) and more GOOSE-messaging on the network can show different results. Future testing must contribute to revealing the greatest impact factor on the performance.

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