Article

Defining Benefits and Detecting Future Challenges of Digitalizing Distribution Network Substations

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Abstract:

With the introduction of the IEC 61850 standard, the path is set for a single communication topology covering all substation levels. The standard has the potential to change the way substations are designed, build, tested and maintained. This means that the key segment of the substation, its protection system, will go through a transition period with the end goal of having a digitalized substation where all information exchange is performed over an Ethernet communication bus. The goal of this paper is to analyse the performance impact of the IEC 61850-9-2LE on the protection system. To do this, a laboratory hardware-in-the-loop test setup is developed representing traditional, hybrid and digital substation topology. This setup served to simulate faults and create transient waveforms in an extended IEEE 123 node test system, which were then used to detect the reaction times of protection relay devices. To verify protection relay results significant number of tests are performed clearly showing benefits which can be gained by distribution system digitalization.

Keywords: IEC 61850; merging unit, digital substation; relay protection; SCL; Substation Configuration Language; IED; GOOSE

1. Introduction

Continuous development of communication technologies in terms of speed, reliability and flexibility made it possible to transform traditional substation wiring into a completely digital environment. Although basic communication technologies were used in substations since the 1980's, their implementation was focus on signal exchange between the bay and station level and between station level and dispatching centers. Communication protocols were mostly manufacturer dependent, and system interoperability between various devices, in particular between devices from different manufacturer, was extremely difficult.

Only by introducing the set of standards *IEC 61850 Communication Networks and Systems in Substation [1]*, communication barriers have been removed and interoperability on all station levels was enabled. By defining standardized communication blocks, data exchange on the bay level is eliminating the need for excessive bay cabling and wiring, completely shifting the design and interlocking logic to a new approach.

With an even bigger impact on substation design and equipment design, communication on the process bus introduced the potential for a completely digitalized substation. Primary switching equipment, such as circuit breakers and disconnectors, could be directly connected to the communication system thus controlled and monitored completely as an Intelligent Electronics Device

(IED). According to the IEC 61850-9-2 analogue representation of voltage and current in the primary circuit can be represented via sampled values, forming a continues data stream in the communication network, available for further processing for all IEDs connected to the same network [2].

Although foundation for a completely digital substation exists, the current state of technology is not there yet. With still numerous technical challenges, and various intermediate steps and attempts there is still a lot of research and development to do in order to realize the digital substation. The focus of this paper is to analyze the potential and limitations of sampled values in digitalized substation and hybrid substations by use of merging units or even protection relays. In order to do this the paper provides several contributions:

- An extended simulation mathematical model of the IEEE 123 Node Bus Test System has been developed in order to generate various fault current and voltage waveforms in order to test the digital representations in sampled values.
- A laboratory hardware-in-the-loop testbed has been developed with traditional current and voltage operated protection relays and protection functions operated by sampled values according to IEC 61850-9-2 LE.
- With a large number of performed test sequences, a statistical analysis of the digital and analogue performance has been conducted, and the results are shown in this paper.

2. IEC 61850 Standard basics

Today's Substation Automation Systems include three hierarchal levels; substation level, bay level and process level. Before the introduction of the IEC 61850 there was no comprehensive communication standard covering all substation levels, thus the information exchange between the levels was performed with incompatible standards which had to adapted by implementing various protocol gateways or simplified binary or analogue information exchange. Some of the basic standards used in substations are shown in Figure 1.

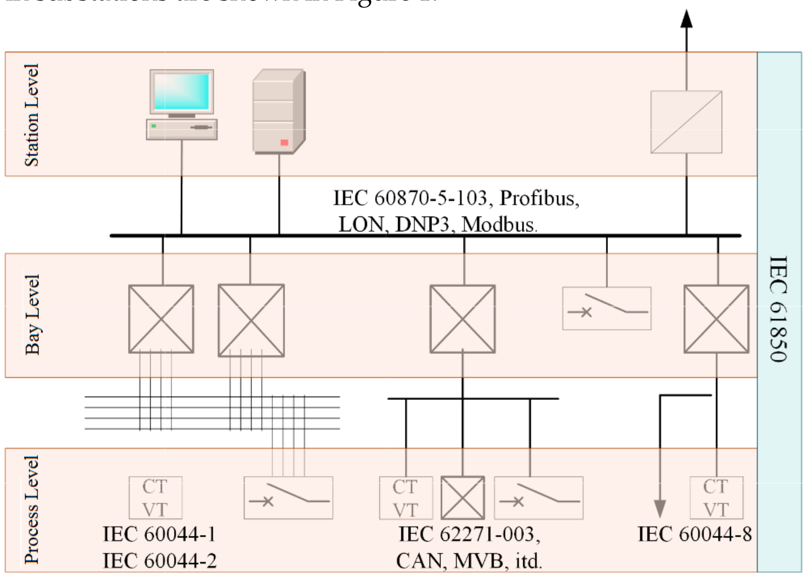

Figure 1. Basic communication standards in substations

The data exchange according to the standard IEC 61850 is performed on the Ethernet data link layer, which was enabled by the continuous development of network technology in terms of speed and reliability. The Ethernet network topology has a significant impact on the overall communication performance. The five basic topology types used in substation are a) Bus Topology b) Ring Topology c) Star Topology d) Multiple Star Topology and e) Ring-Star Topology. Depending on the network topology, it is possible to incorporate advanced communication functions like network redundancy and enhanced speed and reliability.

Object oriented modelling of substation, according to IEC 61850, is based on Logical Nodes which represent the smallest functional object that can receive and send data [3]. Logical Nodes are

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standardized function blocks organized and defined with alphanumeric characters (e.g. PTOC – Protection Time OverCurrent), wherein the first sign indicates the node subgroup. Two main Logical Node groups are:

- Logical Nodes representing equipment on the process level
- Logical Nodes representing substation automation and protection functions

Although the initial standard was created for communication networks within substation, due its flexible and expandable data structure, the application since has spread to various industries (e.g. Oil and Gas, Renewables, Hydro power plants) creating numerous application specific Logical Notes [4].

All Intelligent Electronic Devices are represented with a Physical Device which is performing numerical calculations, emulating Logical Devices which are the representation of function related Logical Devices. On a single Physical Device it is possible, and even common, to incorporate a series of grouped Logic Devices. A simplified illustration of the data models according to IEC 61850 is given in Figure 2 [5].

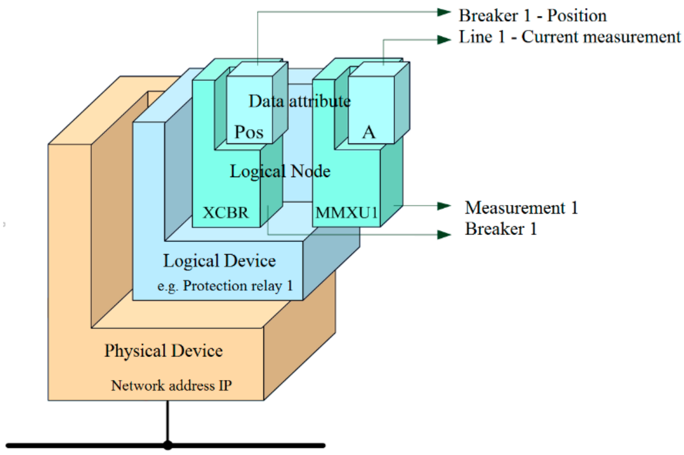

Figure 2. Simplified physical device communication data structure

In addition to the function defining data structure, the standard IEC 61850 defines groups of commutation mechanisms for information exchange as; 1-Sampled Values, 2-GOOSE messages, 3-Time synchronization, 4- Vertical communication. As Ethernet technology is the underlying data link layer, the communication is inherently nondeterministic, hence it introduces a certain level of communication uncertainty. However, to ensure proper and timely action of the control, protection and monitoring functions in substations a priority tag is added to every data packet on the communication bus [6]. This priority tags enable network elements to transfer data with the highest priority first, ensuring that signals like *Trip* to arrive at the designation within the maximum transfer time limit defined by the standard. The most widely used group within the IEC 61850 is Generic Object Oriented Substation Event (GOOSE) message. This is an extremely flexible tool as it is an event triggered data exchange event transferred from and to all station levels that can contain binary states or even analogue values [6].

However, exchange of measured value data, in terms of Sampled Values of primary voltage and current, has not been extended to practice excluding pilot projects and proof of concept projects. The data exchange of Sampled Values is based on the principle of publisher and subscriber. Measurement transformers or merging units digitalize analogue values and store/publish them in the output buffer, making them available for any subscriber on the network. Each sampled value data package is marked with a time tag in order to form a continuous stream of measured values. Sampled Value Control (SVC) system is introduced to control the data stream from the Publisher output buffer to the subscriber input buffer [7,8]. Two types of Sample Value models are used:

- For protection functions: a stream of 80 samples per cycle is used (4000 samples/second).
- For power quality measurement functions: a stream of 256 samples per cycle is used (12800 samples/second) in data blocks of 8 samples, resulting in 32 data blocks per cycle.

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The time needed to generate and transmit information from and to IED on the network is defined with the following equation:

$$t_p = t_a + t_b + t_c \quad (1)$$

t_a - time needed to save the data to the outgoing buffer of the publisher
t_b - time delay caused by the network communication system
t_c - time needed to save the data to the incoming buffer of the subscriber

The standard IEC61850 defines the requirements and methods for statistical analysis of the total data transition time with the corresponding standard deviation. The standard defines the standard deviation with the Gauss distribution [9]:

$$f(x) = \frac{1}{\sqrt{2\Pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (2)$$

It has been confirmed that the data transmission time for 99,99% of the tested cases is shorter than 1ms, and on a sample of 250.000 data packages it has been confirmed that the actual distribution of standard deviation is significantly more reliable than required by the standard [10]. A large number of IEDs support diagnostic reports of GOOSE messages, which enable statistical analysis of the received and sent data for the user. It should be mentioned that no additional hardware or IED configurations are needed to extract the diagnostic report, making this a practical and useful tool and a base for communication system analysis in IEC 61850 [11].

3. Testing of numerical protection relays

Numerical protection relays in traditional substation topologies determine the state of protected object or zone based on the analogue measured values of current and voltage. In case of a fault state of the protected object or zone, protection relays activate tripping signals in order to isolate the fault as fast as possible and as close to the fault as possible. As already mentioned before, digitalized substations do not use analogue values of current and voltage obtained by measurement, rather sampled values which are the representation of the primary circuit of the substation.

Testing of traditional numerical relays is performed by simulating faults in the grid condition by generating fault values for voltage and current though the use of secondary injection test instruments. Depending on the programmed configuration of the relay, the test instrument can monitor binary outputs or the communication signals of the tested object. The test is performed by a protection relay specialist which must have profound knowledge of the power grid and protection relay operation. All test sequences are managed and monitored by the lay protection specialist, making him a key figure in terms of periodical testing of protection relays [12].

Unlike in traditional substation topologies, information exchange on IEC 61850 based digital substation is completely performed on the Ethernet bus, hence the test tool differs significantly and introduces new possibilities. Traditional secondary test instrument is obsolete in a digital substation configuration, as all signals are simulated virtually. The simulated test values of current, voltage and binary states can be generated by newly developed IEC 61850 based simulator test sets or PC workstations connected only to the station communication network. Faulty current and voltages are simulated with a sampled value stream and the trip action in terms of GOOSE messages of the tested relay are monitored on the communication bus. The test approach in digital and traditional substations is the same, only the test media is changed [13].

For the testing of local and distribution protection function blocks in numerical protection relays, besides the current and voltage simulation, the information of the relay configuration and the protection parameter settings are necessary. Although every protection relay manufacturer has developed its own support software for protection relay programming and setting, with the introduction of IEC 61850 relay manufacturers have the possibility to display the relay settings within the relays configured description file. Basic testing topology of traditional, digital and hybrid substations is shown on Figure 3 below.

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The standard IEC 61850 introduces a description code for the configuration of substations (SCL-Subsystem Configuration description Language), which is manufacturer independent and enables interoperability between various IEDs. The standard introduces four types of the description files:

- ICD - IED Capability Description
- CID - Configured IED description
- SSD - System Specification Description
- SCD - System configuration description

The substation configuration description language is XML (eXtensible Markup Language) code, which is not compliable, but serves only as a description structure [14].

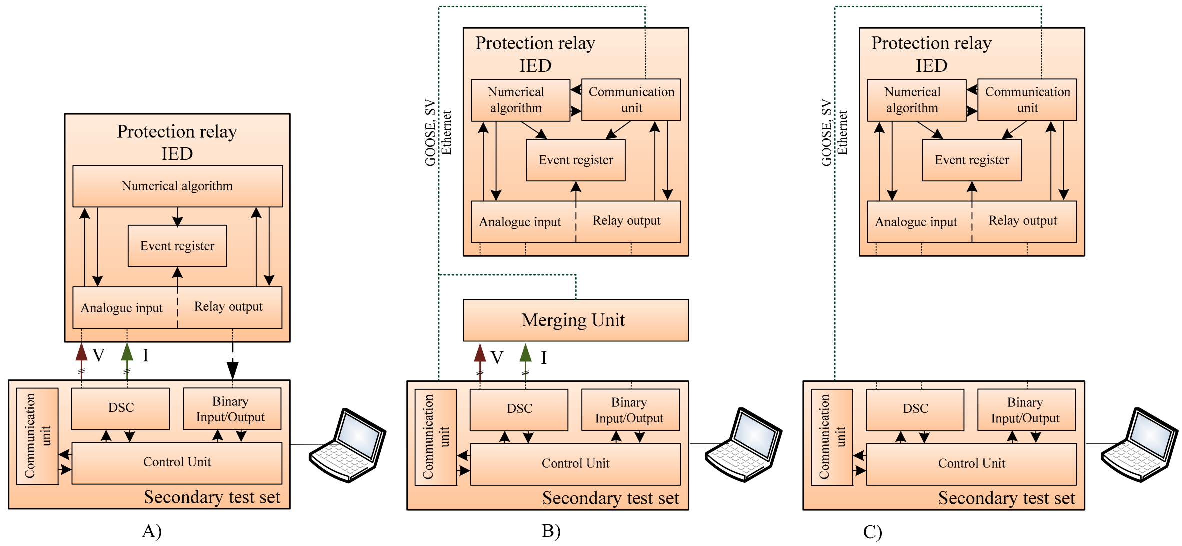

Figure 3. A) Relay testing in traditional substations B) Relay testing in hybrid substation C) Relay testing in digital substations

4. Testing environment for Intelligent Electronic Devices

In order to determine the potential and limitations of numerical protection relays in digital substations compared to traditional substations, hardware in the loop model has been developed which incorporates a MATLAB based grid fault simulation in combination with a secondary voltage and current injection test set and sampled values test set. In order to improve the fault state simulation and bring the relay reaction closer to actual grid operation, an extended IEEE 123 Node Test Feeder has been implemented in order to realistically simulate current and voltage waveforms.

4.1. IEEE Distribution Test Feeder

Common test systems have been widely used by researchers to provide standardized testbeds for new algorithms, protection and control schemes in order to enable independent verifications and test replications. The initial IEEE Test environment was introduced in 1991, and initially there were four test feeders and they were used primarily to check the accuracies of new power flow analyses. There have not been any comparisons of the results of short circuit studies. The original four test feeders are [15]:

- 13 Node Test Feeder – provided a good test of the convergence of a program for a very unbalanced system
- 34 Node Test Feeder – a very long feeder requiring the application of voltage regulators to satisfy ANSI voltage standards
- 37 Node Test Feeder – a three wire delta underground system
- 123 Node Test Feeder – a large system consisting of overhead and underground single phase, two-phase and three-phase laterals along with step voltage regulators and shunt capacitors

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Additional test feeders have been developed and various expansions and improvement of the initial test feeders have been added for special applications like testing the impact of a distributed generation [16].

For the test purposes of this paper, a modified version of the IEEE 123 Node Test Feeder was developed. In order to enable the use of simulated fault currents and voltages for protection relay testing purposes, the IEEE 123 Node Test Feeder was switched from the initial 60Hz system to a 50Hz system. Additional modifications include the elimination of stabilization transformer from the initial topology and adding additional generation units, which represent a more modern distribution grid with an increased number of distributed energy resources. A simplified illustration of the IEEE test model is shown in Figure 4.

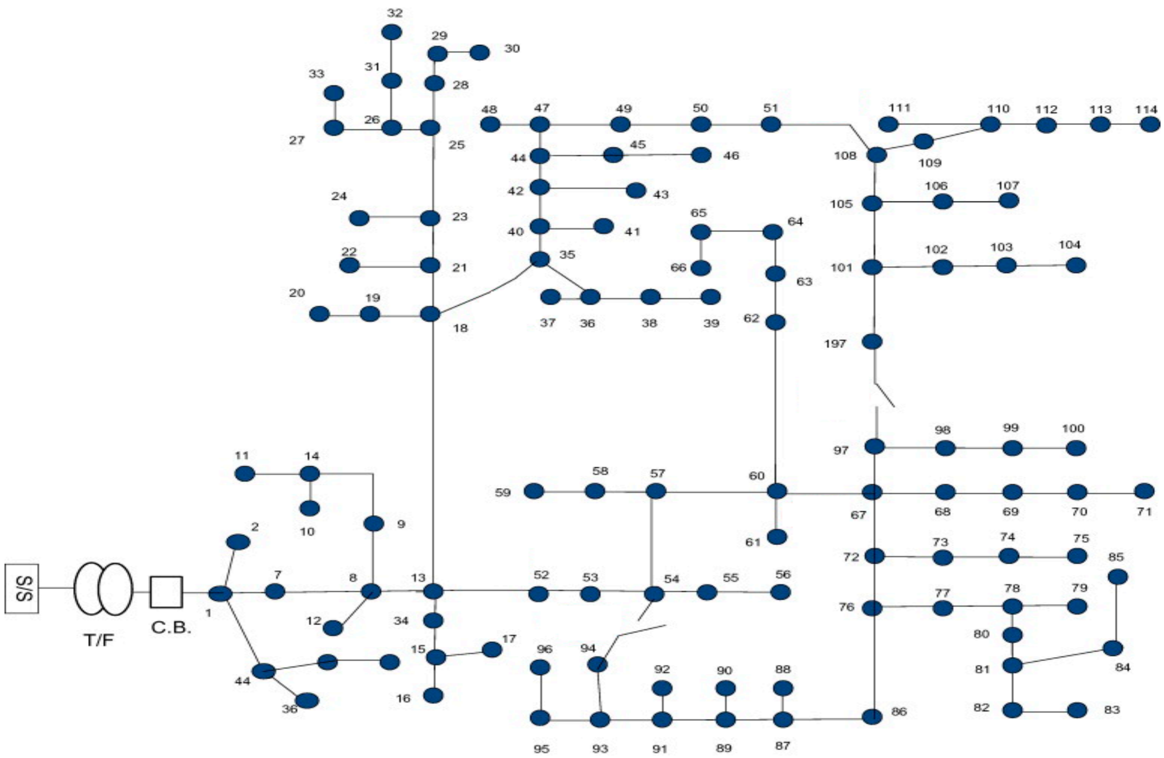

Figure 4. The simplified illustration of the IEEE 123 Node Test Feeder topology

Unlike the initial IEEE 123 node model, which was developed for power flow analysis, the extended short circuit analysis model is capable of analyzing all possible types of short circuits at all nodes. All model parameters, including source and fault impedances have been defined by the revised IEEE model [17].

In this paper, the testbed modelling has been performed in the MathWorks Simulink environment. In order to use the simulation results for generation of transient power system disturbances in a COMTRADE format, the discrete execution time of the simulation was adjusted to the sample rate of process bus sampled values of 4000 Hz.

4.2. Testing environment sampled values communication

Digitalized substation according to IEC 61850 include data exchange between bay and process level, not only for status signals and commands, but also for measured currents and voltages. Only a few fully digitalized substations are completed as pilot projects. Primary equipment with inbuilt communication capabilities are not market ready, meaning that currently the use of external digitalization equipment is necessary. In those substations merging units are IEDs which can monitor binary input and control binary outputs in order to digitalize binary signals on the process level. They can be installed in marshalling kiosks in order to avoid excessive cable routing from the process level to the bay level, as they can send receive binary data over the IEC 61850 communication port [18].

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Another type of merging unit digitalizes current and voltages from the measurement transformers. They are connected to the secondary sides of the current and voltage transformers and publish the voltage and current values as sampled values Ethernet packets. Digitalized analogue data is transferred by fiber optic cables to receiving protection relays (IEDs) via IEC 61850 process bus, a packet of data includes sampled values, GOOSE messages and Precision Time Protocol (PTP)[19]. IEDs are connected into process bus by Ethernet switches.

For testing purposes of this paper, a hardware in the loop model has been developed which represents three development stages of the substation topology as shown in Figure 3:

- traditional topology with current and voltage being physically measured by the protection relay,
- hybrid topology with current and voltage being digitalized in the merging unit and transferred to the protection relay via communication bus,
- digitalized topology with current and voltage being directly transferred to the protection relay via communication bus.

The hardware configuration was implemented with protection relays, which have the ability of receiving and sending sampled values and the test set, shown in Figure 5.

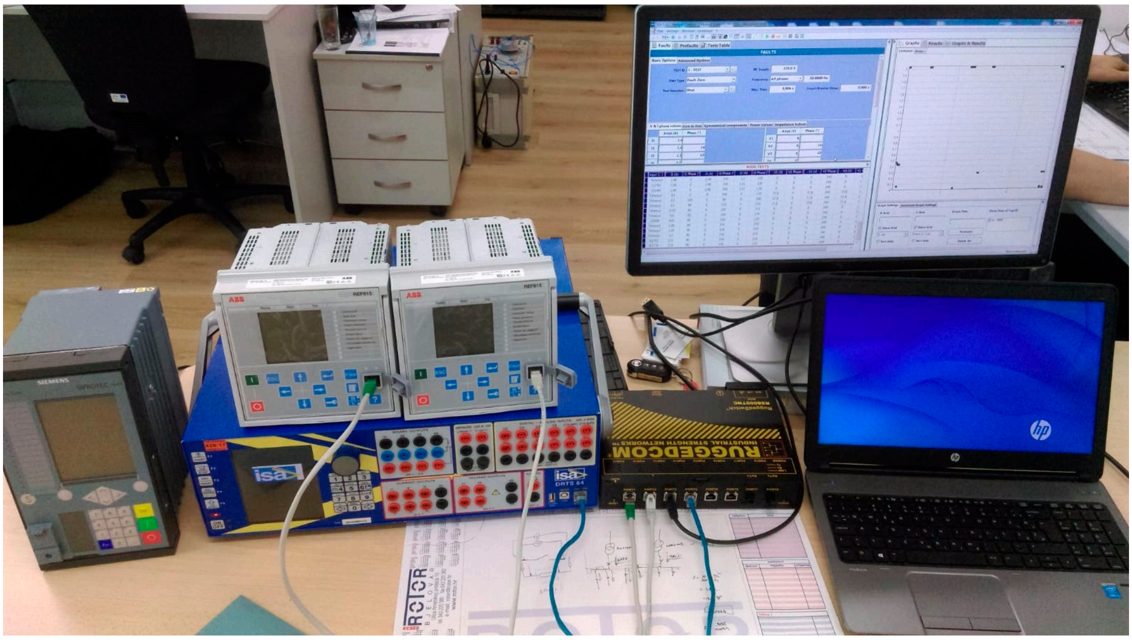

Figure 5. Illustration of the IEC 61850 testbed

In order to test the performance of the traditional topology one of the protection relays was configured as a traditional protection relay operating with voltages measured directly from the test set simulated the COMTRADE transient waveform according to Matlab simulation of the IEEE 123 Node Feeder model. The reaction of the relay was measured a physical relay trip.

In order to test the performance of the hybrid topology one of the protection relays was configured as an IEC61850-9-2LE merging unit, while the second relay was configured as a protection relay operated by sampled values. The test instrument generates transient voltage waveforms and applies them to the physically operated relay which is working as a sampled value generator. The reaction of the relay was measured as a GOOSE message response [20].

In order to test the performance of the digital substation topologies, one of the protection relays was configured to be operated by sampled values while the test set directly simulated the Matlab transients to the tested object. The reaction of the relay was measured as a GOOSE message response.

4.3. Test results

In order to analyze and the performance of traditional, hybrid and sampled values operated protection relays, a hardware in the loop setup was set up. The extended mathematical model of the

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IEEE 123 node test feeder is used for generating faulty waveforms of voltage and currents. A software was used to convert the Matlab short circuit fault calculation to COMTRADE file. The test set is capable to replay imported transient waveforms as physical currents and voltages or optionally as sampled values according to IEC 61850-9-2LE.

In order to have a statistical overview of the different performances of the substation topologies, three different reference fault locations, have been chosen from the IEEE 123 Node Test Feeder model (nodes 13, 108, 114). These faults represent typical fault currents which a protection relay in the node 13 would measure in radial grid topology. Each fault has been performed 100 times for each fault location. Only single-phase earth fault simulation results are shown. The protection function activated in the relay was a short circuit function block with a 50ms trip delay.

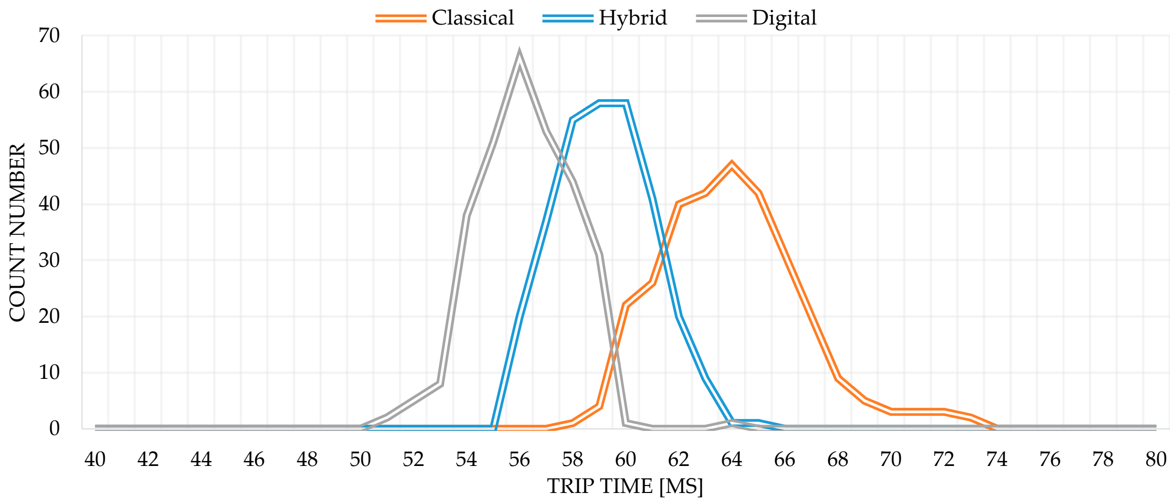

Figure 5. Test results of the fault simulation on different substation topologies

The results of the fault simulation on different substation topologies are shown in Figure 5. All topologies have been tested with a total of 300 test samples, in groups of three different fault waveforms. It is important to point out that all topologies have resulted in a trip signal for all conducted simulations.

By comparing the deviation of the measured trip time to the configured trip time, it is obvious that the traditional topology has a lowest average trip time with 64ms, compared to 59ms for the hybrid topology and 55ms for the digital topology. The delay components responsible for the variation in the signal transmission delay shown in the equation (1) can be adapted for our test model with additional delays.

$$t_p = t_a + t_b + t_c + t_d + t_e \quad (1)$$

t_a - time needed for voltage and current data acquisition and processing

t_b - time needed to save the data to the outgoing buffer of the publisher

t_c - time delay caused by the network communication system

t_d - time needed to activate/publish the output trip

For the traditional substation topology, the time delays t_b and t_c do not contribute to the overall delay as the communication bus is not included in the protection system. However, a significant delay is added by the activation of the output trip relay. In the hybrid and digital topology the trip signal is not generated with an output relay, but with a GOOSE message which is significantly faster. By comparing the hybrid and digital topology, the additional delay in the hybrid topology caused by the implementation of the merging unit causes a 4ms slower response of the hybrid topology.

4.4. Potential for further test scenarios

For an in depth performance analysis of numerical protection relays in the IEC 61850 environment, it is not enough to just to verify the pickup values and trip time. A complete analysis of the protection system, including the related communication infrastructure is needed. The IEC

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61850 standard introduces tools and procedures which enable the relay protection specialist new viewpoints on protection system, enabling a clear focus on key segments of the protection system instead of procedural tests.

The standard itself does not define testing procedures of complex protection schemes or Logical Nodes, but rather transparently defines the data structure of protection relays. By introducing the SCL, key information like the communication topology, configuration of IED and even setting of protection function are available to the relay protection specialist. All that data can be used for development of semi-automated test sequences. The main station PC can analyze the network topology, simulate and test protection functions [21].

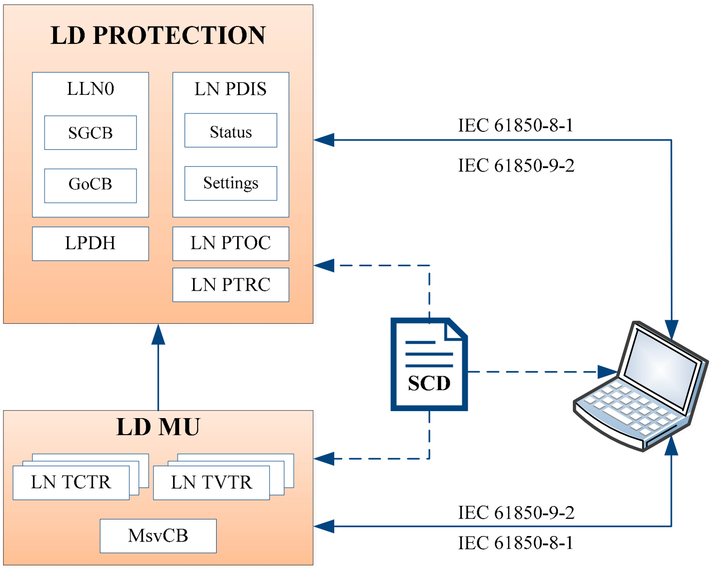

Figure 6. Automated adaptive protection function testing

5. Conclusions

The traditional substation topology is gradually going to be replaced with the digital substation topology in accordance to the IEC 61850 standard series. A digital communication bus which covers all substation levels will drastically change the way substations are designed, build, tested and maintained. A new approach in the way protection systems are tested and maintained, as new knowledge, tools and software for analysis of communication systems may will be needed. Due to ever increasing complexity of protection and communication systems, the need for adapted test software arises, which will make use of the potential of Substation Configuration Language and the transparent manufacturer independent data structure it consists.

In this paper, the performance of the traditional, hybrid and digital substation topology has been tested and compared. The trip signal generation time was the lowest for the protection relay in the traditional topology, due to the additional time delay of the trip coil. The overall signal transmission performance increases in the digital substation technology, as there are now signal delay besides the Ethernet communication network.

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