TESTING OF IEC 61850 SAMPLED ANALOG VALUES BASED FUNCTIONS

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SUMMARY

One of the key components that distinguish IEC 61850 from previous standards for substation communications is the high-speed peer-to-peer communications. There is no doubt that the biggest impact on future development of substation protection and control systems are the result of the communication of sampled and calculated analog values.

The sampled analog values are unicast or multicast by specialized devices (Merging Units) and received and processed by different Intelligent Electronic Devices in the substation – protection and control devices, disturbance recorders and measuring devices.

The successful integration of these devices in IEC 61850 based substation automation systems requires that they be tested for functionality, interlocking, and performance for their application.

The paper introduces first the concept of distributed functions based on sampled analog values and describes in detail the components of the system. It compares the conventional IED that includes all required modules – input transformers, analog filters, analog-to-digital converters, digital filters, protection, control, measuring and recording elements – with the distributed functionality of an IEC 61850 sampled analog values based solution. Then it discusses the different components of a test system designed to enable the functional testing of sampled analog values based functions.

The first component of the test system is the configuration tool that takes advantage of the standard substation or IED configuration files defined in Part 6 of IEC 61850.

The second component of such a system is a Simulation Tool that generates the current and voltage waveforms. The specifics of each simulated test condition are determined by the complete, as well as the configured functionality of the tested device.

The third component is the Test Evaluation Tool that includes the monitoring functions used to evaluate the performance of the tested elements of a distributed sampled analog value based system. It receives, compares and evaluates the multicast by the merging unit sampled analog values with the original current and voltage waveforms applied to the merging unit. The IEC GOOSE virtual I/O may also be compared to the hard-wired relay outputs. The test system may also retrieve and compare the waveform records from the tested device to the original waveforms from the simulation tool.

The fourth component of the test system is the Reporting Tool that will generate the test reports based on a user defined format and the outputs from the simulation and evaluation tools.

KEYWORDS

IEC 61850, IED testing, system testing, sampled values testing

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DISTRIBUTED FUNCTIONS BASED ON SAMPLED ANALOG VALUES

Sampled analog values transmitted over the substation local area network are one of the key
differences between the typical communication protocols and IEC 61850. They allow the elimination
of copper wiring between the substation instrument transformers and the protection, control,
monitoring and recording devices. As a result the user can achieve significant savings in wiring, while
at the same time improve the functionality of the substation automation system and minimize the
commissioning and maintenance costs.

According to IEC 61850 all communications in the substation are based on logical interfaces. The
logical interface of interest in the case of distributed sampled analog values applications is IF4: CT
and VT instantaneous data exchange (especially samples) between process and bay level.
The communication of the sampled analog values is achieved over the process bus using one of two
possible methods: Unicast or Multicast.

With the continuous improvements in Ethernet technology and the reduced cost of switched local area
networks, the second option becomes the preferred choice for sampled measured values applications.
IEC 61850 defines a number of different groups of logical nodes that represent functional elements of
primary or secondary substation devices. It also describes functions as tasks, which are performed by
the substation automation system, and exchange data with other functions. The functions are
performed by IEDs (physical devices) and may be split in parts residing in different IEDs but
communicating which each other (distributed function) and with parts of other functions. In the
context of this standard, the decomposition of functions or their granularity is ruled by the
communication behavior only. Therefore, all functions considered in the standard, can be modeled by
logical nodes that exchange data. A function is considered distributed when performed by two or more
logical nodes located in different physical devices.
The above is another key characteristic of IEC 61850 that determines the functional requirements for
the testing of multifunctional devices or distributed applications using sampled analog values.

ANALOG SIGNAL PROCESSING FOR PROTECTION AND CONTROL

In order to better understand the testing requirements for sampled measured values applications we
need to analyze the functional elements that are involved in the complete process of interface with the
primary system and performance of specific tasks in a substation protection and automation system.
The fact that the functional elements that we typically find in the same conventional multifunctional
IED can appear in several different physical devices in an IEC 61850 based system determines the test
system specifications to be considered later in the paper.

Conventional multifunctional IED includes several required functional modules in order to perform
their tasks – input transformers, analog filters, analog-to-digital converters, digital filters, protection,
control, measuring and recording elements. Microprocessor based devices are today the typical
devices in substations around the world. They are connected with hard wires to voltage and current
transformers and the auxiliary contacts and trip coils of the breakers.

![Simplified IED block diagram](image-url)

The analog signals go through several transformations before they can be processed by the different
elements in the functional (protection, control, etc.) modules. If we consider a protection IED as an
example, it monitors the currents and voltages in order to determine any deviation from the normal
operating conditions. Once a fault or other abnormal condition has been detected and a decision to operate has been made, the protection module sends a command for the relay output module to close the required contacts and trip the breaker to clear the fault. Figure 1 shows a very simplified block diagram of a multifunctional protection IED connected to the substation primary equipment.

The analog input module provides the interface between the protection IED processor board(s) and the voltage and current signals coming into the IED. This input module may consist of one or more boards. The number of current and voltage inputs depends on the primary protection function of the device. The input transformers are used both to step-down the currents and voltages to levels appropriate to the IED’s electronic circuitry and to provide effective isolation between the device and the power system. The connection arrangements of both the current and voltage transformer secondaries provide differential input signals to the input board to reduce noise.

Analog input boards are shown as a simplified block diagram in Figure 2. It provides the circuitry for the analogue-to-digital conversion for the analogue signals. Hence it takes the differential analogue signals from the current and voltage input transformers and converts them into digital samples and transmits the samples to the protection (or other processing modules) via the internal data bus. On the input board the analogue signals are passed through an anti-alias filter before being multiplexed into an analogue-to-digital converter chip. The A/D converter provides a sampled data stream output.

The signal multiplexing arrangement depends on the number of analog signals and provides for multiple analogue channels to be sampled. The sampling rate for protection applications is usually maintained at a fixed number of samples per cycle of the power waveform by a logic control circuit that is driven by the frequency tracking function of the device. A calibration memory (usually an E2PROM) holds calibration coefficients that are used by the processor board to correct for any amplitude or phase error introduced by the transformers and analogue circuitry.

The analog input function in IEC 61850 is modeled by multiple instances of two logical nodes from the Instrument Transformers group T-TCTR and TVTR. Both use one instance per phase. These three or four instances of TCTR(n) and TVTR(n) may be allocated to different physical devices mounted within the instrument transformer per phase.

The currents and voltages from TCTR and TVTR accordingly are delivered as sampled values to the protection, measuring or recording functional elements over the IED digital data bus.

In the case of a multifunctional IED all the logical nodes are located within the same physical device and the interaction between them is performed over the internal digital data bus of the device. This is not the case in a distributed function using the sampled measured values communications defined in IEC 61850. Even that the application will be modeled using the same logical nodes, they are not anymore located within the same physical device – i.e. we have a case of distributed function according to the IEC 61850 definitions.

The processing of the secondary currents and voltages represented by the TCTR and TVTR is performed in a new type of device – the Merging Unit. It is defined as an interface unit that accepts multiple analogues CT/VT and binary inputs and produces multiple time-synchronized serial unidirectional multi-drop digital point-to-point outputs.

The sampled values are transmitted as engineering values, i.e. as “true” (corrected) primary current values. This means that some configuration data stored in the memory of the IED will be used to calculate these primary values from the outputs of the A/D converter. The sampled values are sent to the substation LAN using one of the communication modes described earlier in the paper. In this case the network becomes the data bus that provides the interface between the instrument transformer logical nodes and the different logical nodes that are used to model the functional elements of the IED.

The information exchange for sampled values is also based on a publisher/subscriber mechanism. The publisher writes the values in a local buffer at the sending side, while the subscriber reads the values from a local buffer at the receiving side. A time stamp is added to the values, so that the subscriber can check the timeliness of the values and use them to align the samples for further processing. The communication system shall be responsible to update the local buffers of the subscribers. A sampled value control (SVC) in the publisher is used to control the communication procedure.

In the case when any other function requires exchange of sampled data between two or more logical nodes located in different physical devices, we can call it a "distributed analog function". The currents and voltages from TCTR and TVTR accordingly are delivered as sampled values over the substation LAN using one of the communication modes described earlier in the paper. In this case the network
becomes the data bus that provides the interface between the instrument transformer logical nodes and the different logical nodes that are used to model the functional elements of the IED.

The status of the breakers in the substation is modeled using the XCBR logical node. It will provide information on the three phases or single-phase status of the switching device, as well as the normally open or closed auxiliary contacts.

![Simplified block diagram of a merging unit](image)

The sampled values from TCTR and TVTR are directly used as analog signals by the protection or waveform recording function.

The difference between conventional multifunctional IED set of functions and the same distributed function implemented in a merging unit (TCTR and TVTR) and a sampled measured values based IED (Pxxx, RDRE, etc) is that in the single IED case all sampled measured values exchanged between the Txxx logical nodes and protection and recording logical nodes are sampled at the same moment in time using a sample-hold type method, while in the distributed applications (especially if there are multiple merging units involved) the sampling may occur at different times.

Figure 2 shows a simplified block diagram of a merging unit including amplifiers, filters, analog to digital converter and DSP signal processing. The merging unit is synchronized using 1 PPS signal from a GPS receiver. As can be seen from the figure, there is a time delay \(D = D1 + D2\) introduced within the device. If this time delay is not compensated, it will be seen as a phase shift (Figure 4) that will affect all functions using the sampled analog values.

![Analog signal phase shift](image)

It is possible to define several groups of distributed applications based on the design of the IEDs and the location of the different logical nodes that are used to perform a specific function. These include: protection, control, measuring, monitoring, and recording applications that are quite different functionally but will have similarities in the requirements for functional testing. At the same time there will be differences in the testing of individual components of a distributed function and the distributed function as a whole.

**SAMPLED MEASURED VALUES TEST SYSTEM COMPONENTS**

A test system designed for IEDs or distributed applications based on IEC 61850 9-2 have multiple components that are needed for the testing of the individual components as well as a complete application. A simplified block diagram of such a system is shown in Figure 4.
The first component of the test system is the test Configuration Tool. It takes advantage of one of the key components of the IEC 61850 standard – the Substation Configuration Language. The Configuration Tool is used to create the files required for configuration of different components of the test system. It imports or exports different configuration files defined by Part 6 of IEC 61850.

The test system Configuration Tool reads the information regarding all IEDs, communication configuration and substation description sections. This information is in a file with .SCD extension (for Substation Configuration Description) and is used to configure the set of tests to be performed.

The overall functionality of any IEC 61850 compliant device is available in a file that describes its capabilities. This file has an extension .ICD for IED Capability Description.

The IED configuration tool sends to the IED information on its instantiation within a substation automation system (SAS) project. The communication section of the file contains the current address of the IED. The substation section related to this IED may be present and then shall have name values assigned according to the project specific names. This file has an extension .CID (for Configured IED Description).

The second component of such a system is a Simulation Tool that generates the current and voltage waveforms. The specifics of each simulated test condition are determined by the complete, as well as the configured functionality of the tested device or application.

The simulation tool requirements will also be different depending on the type of function being tested. For example, if the tested function is based on RMS values or phasor measurements, the simulation tool may include a sequence of steps with the analog values in each of the steps defined as Phasors with their magnitude and phase angle. Based on these configuration parameters the simulation tool will generate the sine waveforms to be applied as analog signals or in a digital format to the tested components or systems.

If the tested functions are designed to detect transient conditions or operate based on sub-cycle set of samples from the waveform, an electromagnetic transients simulation will be more appropriate.

Figure 5 shows the simulation tool interface that allows the user to configure the specifics of the network model, type of fault, fault location, etc. that are then used to calculate the waveforms to be applied to a device or system under test.

The third part of the test system is the Virtual Merging Unit simulator. While under conventional testing the waveforms generated by the simulation tool will be applied to the tested device as current and voltage analog signals, a Virtual Merging Unit will send sampled measured values as defined in IEC 61850 over the Ethernet network used for the testing.

The Virtual Merging Unit simulator should support multiple sampling rates and allow the user to select a protection, power quality, or recording mode. As agreed in IEC 61850 9-2 LE, in the first case the simulator should send 80 samples/cycle in 80 messages/cycle. Each message contains one sample.
of the three phase currents and voltages (WYE class). In the second mode, 256 samples/cycle are being sent in groups of 8 samples in a single message, thus requiring 32 messages/cycle.

![Network simulator interface](image)

**Figure 5.** Network simulator interface

The fourth component of the test system is the Test Evaluation Tool that includes the monitoring functions used to evaluate the performance of the tested elements within a distributed sampled analog value based system. Such evaluation tool requires multiple evaluation sub-modules that are targeted towards the specifics of the function being tested. They might be based on monitoring the sampled measured values from a tested merging unit, GOOSE messages from a tested IED, as well as reports or waveform records from the tested device.

The fifth component of the test system is the Reporting Tool that will generate the test reports based on a user defined format and the outputs from the simulation and evaluation tools.

**FUNCTIONAL TESTING OF IEC 61850-9-2 BASED MERGING UNITS**

Since Merging Units are an essential component of any IEC 61850 process bus based application, they have to be tested to ensure that they provide the required sampled measured values.

The currents and voltages applied to the Merging Unit will be based on current and voltage waveforms produced from the network simulator in order to simulate different system conditions, such as high current faults or low current minimum load conditions.

At the same time the Test Evaluation tool will need to receive the sampled analog values from the tested merging unit and compare the individual sampled values from the Merging Unit with the samples coming from the network simulator. The testing of Merging Units will require first of all a very accurate time synchronization of both the test device and the tested MU.
It is necessary to analyze the phase (time) and magnitude differences of the individual samples and compare these to the calibration specifications of the MU. Proper documentation and reporting is required in the same manner as meter testing is performed today.

![Diagram of Testing of Merging Units](Image)

Figure 6. Testing of Merging Units

Keeping in mind that the standard allows different sampling rates, as step one the Merging Unit test module shall support the sampling rates defined in IEC 61850 9 – 2 LE. This means that depending on what is the mode of the Merging Unit being tested, the evaluation tool will receive different messages:
- For protection applications – 80 samples/cycle in 80 messages/cycle
- For power quality and recording applications – 256 samples/cycle in 32 messages/cycle (8 samples per message)

Things are more complicated with a generic implementation of the IEC 61850 9-2 process bus, when the sampling rate can have any value. This will require appropriate configuration tools and support by the Merging Units simulator.

**FUNCTIONAL TESTING OF IEC 61850-9-2 BASED IEDS [1]**

The testing of different functions in IEDs that are based on sampled measured values can be achieved in a couple of different ways depending on the requirements of the specific test. One approach is acceptable when testing the IED only, while another can be used if the testing includes the complete MU/IED system. The difference is that in the first case there is no hard wiring between the test device and the tested IED – i.e. the test system can be communications based only.

The key component of this module is the Merging Unit simulator described earlier in the paper. It will have to take the waveforms generated from the Network Simulator and then format them in the required 80 samples/cycle and multicast the individual sampled values to the LAN 80 times per cycle (e.g. 80 messages/cycle).

For power quality and recording applications the Merging Unit simulator will have to take the waveforms generated from the Network Simulator and then format them in the required 256 samples/cycle and multicast the individual sampled values to the LAN 32 times per cycle (8 samples per message).

The functions that can be tested in an IEC 61850 9-2 based IED are:
- Protection
- Measurements
- Recording
- Fault location

The testing of these different types of functions available in the IED will be similar to what was described earlier for the hybrid device. This applies to both the configuration and analysis modules of the test system.
The test system needs to subscribe to and monitor the GOOSE messages received from the tested IED that represent the operation of the tested functional elements in order to determine if the devices operated as required. If the tested device has relay outputs as well, they will have to be wired into the test device and their operation (time tag) will be compared with the received GOOSE messages to determine if the performance of communications based solutions is analogous to the hard-wired case. The test system may also retrieve the waveform records from the tested device and again compare them with the original waveforms from the simulation tool.

**Figure 7. Testing of IED with process bus and hard wired interface**

Figure 7 shows the system configuration for hybrid testing of IEDs that have relay outputs and at the same time support GOOSE messages.

**FUNCTIONAL TESTING OF IEC 61850-8-1 AND IEC 61850-9-2 BASED BAY AND SUBSTATION LEVEL DISTRIBUTED APPLICATIONS**

The testing of distributed bay and substation level functions that are based on communications only – IEC 61850 8 – 1 or 9 – 2 – will be similar functionally to the testing an individual IEDs. The main difference is that in this case there will be multiple test devices with virtual simulators or analog outputs. The simulation of the substation and system environment required for the functional testing of bay and system level functions will require the simulation of multiple merging units (IEC 61850 9-2 interface) and other IEDs (IEC 61850 8-1 interface).

Considering the fact that 100 MB/s is the common Ethernet today, the number of Merging Unit simulators may require multiple computers to simulate all the required sampled analog values and GOOSE messages.

The simulation tool will also be different, because first of all it will require a multi-node system simulator. Once the results from the simulation are available, it requires the development of methods to split the results from the Network System Simulator and distribute them between the individual physical devices that perform the simulations, as well as to make them available as sampled measured values from the virtual merging units that participate in the test.

The evaluation of the performance of the distributed functions in this case will be based on the subscription of the test system components to the GOOSE messages from the different IEDs participating in the tested distributed applications. If these devices also have relay outputs hardwired to the test devices, their operation will have to be monitored as well in order to evaluate the performance of the tested system and if necessary compare the communications based to hardwired solutions. [2]. A simplified block diagram of this test system is shown in the Figure 9.
CONCLUSIONS

IEC 61850 9-2 sampled measured values based systems require a different approach and set of tools for proper testing of the individual components of the systems, as well as the evaluation of the performance of the distributed functions.

The paper presents the concept of distributed functions based on sampled analog values and describes in the components of the system. It compares the conventional multifunctional IED with the distributed functionality of an IEC 61850 sampled analog values based solution. The allocation of these modules in Merging Units and protection, control, measuring and recording devices is described. The next section of the paper describes the different components of a test system designed to enable the functional testing of sampled analog values based functions, including:

- Configuration tool based on the Substation Configuration Language defined in Part 6 of IEC 61850.
- Simulation tool that generates the current and voltage waveforms
- Virtual Merging Units and IED simulators
- Test Evaluation tool
- Reporting tool

If the tested device has relay outputs as well, their operation will be compared with the received GOOSE messages to determine if the performance of communications based solutions is analogous to the hard-wired case.

The test system may also retrieve the waveform records from the tested device and again compare them with the original waveforms from the simulation tool.

The paper describes the test system architecture for the testing of individual devices using sampled analog values, as well as protection or recording schemes that involve multiple devices.

BIBLIOGRAPHY

