IEC 61850 OBJECT MODELS OF MULTIFUNCTIONAL PROTECTION RELAYS

Alexander Apostolov
AREVA T&D Automation
Los Angeles, USA
alexander.apostolov@areva-td.com

Abstract – **The paper analyzes the functional hierarchy of modern multifunctional protection relays from the point of view of IEC 61850 and provides examples of the models of such devices. Requirements for grouping of functional elements in sub-functions are discussed. The use of high-speed peer-to-peer communications between different IEDs and the mapping of incoming and outgoing GOOSE messages to the protection device programmable scheme logic is described. Configuration tools and methods for functional testing of IEDs are discussed at the end of the paper.**

Keywords: IEC 61850, substation automation, interoperability, protection, data model, multifunctional protection relays, peer-to-peer communication, configuration tools, testing, IED, GOOSE

1 INTRODUCTION

To support interoperable communication in substations, the standard IEC 61850 [1-5] defines the object models of different functions typically available in microprocessor-based protection IEDs. Logical Devices and Logical Nodes with their related data and attributes are used to model such devices and may cover a wide range - from simple to very complex. The modeling of such devices can be compliant with the definitions of the standard and at the same time it can be done using different approaches. In some cases it can be based on a single Logical Device model, while in other using multiple Logical Devices might be appropriate.

The paper analyzes the functional hierarchy of modern multifunctional protection relays such as transmission line and transformer protection relays. It provides examples of the models of such devices. Requirements for grouping of functional elements in sub-functions are discussed. Examples of modeling of functions based on multiple Logical Nodes are also presented in the paper.

The use of high-speed peer-to-peer communications between different IEDs connected to the substation bus is also discussed. Mapping of incoming and outgoing GOOSE messages to the protection device programmable scheme logic is described.

Requirements for configuration tools that are needed for IEC 61850 compliant applications are presented later in the paper. Methods for functional testing of multifunctional protection devices are discussed at the end of the paper.

2 FUNCTIONAL HIERARCHY

The modeling of any function in the substation is possible only when there is good understanding of the problem domain. At the same time we should keep in mind that the models apply only to the communications visible aspects of the IED.

The functions in relatively simple IED, such as a low-end distribution feeder or transmission line protection relays, are fairly easy to understand and group together in order to build the object model. That is not the case for more complex devices like a multifunctional transformer differential protection. Even more complex to model are distributed functions based on high-speed peer-to-peer communications between multiple IEDs.

IEC 61850 defines not only the object models of IEDs and functions in a substation automation system, but also the communications between the components of the system and the different system requirements. It is very important to understand that the fact that one can model a function in a device or substation automation system does not mean that the standard attempts to standardize the functions.

With today's state-of-the-art Intelligent Electronic Devices (IEDs) there is a significant overlapping of the functionality between devices of different types. Typically different groups within a utility will install in the substation their own devices, such as:

- Protective relays
- Measuring devices
- Metering devices
- Control devices
- Monitoring devices
- Disturbance recorders
- Event recorders
- Power Quality Monitoring devices
- Remote Terminal Units (RTU)

Each of the above needs to be installed, wired to the substation equipment that it interfaces, tested and maintained. Considering the requirements for redundancy, many of these devices need a primary and backup, which doubles all of the above costs.

The interface requirements of the relays are quite different from the metering devices. As a result they need their own instrument transformers that allow accurate metering of the energy or other system parameters.

A significant improvement in the functionality and some reduction of the cost of integrated substation protection, control, monitoring and recording systems can be achieved based on the modern devices (existing or under development) as described below.

Non-conventional instrument transformers with digital interface based on IEC 61850-9-2 eliminate some of the issues related to the conflicting requirements of protection and metering IEDs.

It is important to be able to interface with conventional and non-conventional sensors in order to allow the implementation of the system in different substation environment.

A simplified diagram with the communications architecture of an IEC 61850 Process Bus based substation automation system is shown in Fig. 1.

The Merging Unit (MU) multicasts sets of measured sampled values to multiple IEDs in the substation over the substation local area network. In some cases it is called the “process bus”. Status information for breakers and switches is available through an input/output unit (IOU). In some cases the merging unit and the input/output unit can be combined in a single device.

The receiving devices then process the data, make decisions and take action based on their functionality. The action of protection and control devices in this case will be to operate their relay outputs or to send a high-speed peer-to-peer communications message to other IEDs in order to trip a breaker or initiate some other control function.

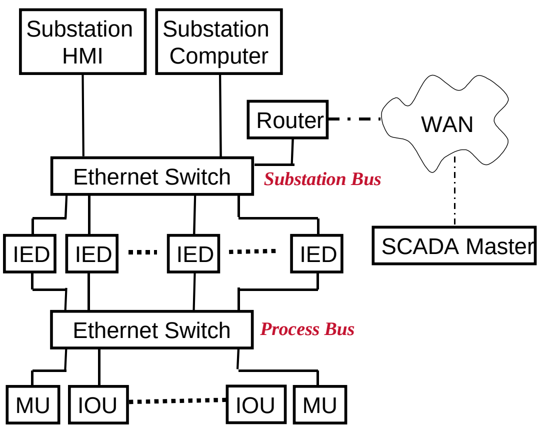

Figure 1: Simplified IEC 61850 based communications architecture

The modeling of complex multifunctional IEDs from different vendors that are also part of distributed functions requires the definition of basic elements that can function by themselves or communicate with each other. These communications can be between the elements within the same physical device or in the case of distributed functions between multiple devices over the substation local area network. The basic functional elements defined in IEC 61850 are the Logical Nodes.

A Logical Node is “the smallest part of a function that exchanges data” [1]. It is an object that is defined by its data and methods. When instantiated, it becomes a Logical Node Object. Multiple instances of different logical nodes become components of different protection, control, monitoring and other functions in a substation automation system.

2.1 Distribution and modeling of functions in physical devices

The functional hierarchy of a modern protective relay to a great extent is dependent on the application and the main protection function of the device. A very simple low-end device may have a very limited functionality, while an IED that supports IEC 61850 will typically have a more complex functional hierarchy. For protective relays used at high voltage and extra high voltage transmission level the model has to also consider the availability of multiple analog inputs – for example in the case of dual breakers, breaker-and-a-half or ring bus configurations.

A more complex example are the relays protecting transformers between the substation transmission and distribution buses that will interface the device with two or more voltage levels.

The modeling of protection relays in IEC 61850 is in a way similar to the design of a protection panel (Fig. 2) with electromechanical or solid state relays. In this case each individual relay performs a specific function and hard-wiring between the relays is used to achieve more complex schemes.

Figure 2: Protection panel with electromechanical relays

The modeling of complex protection devices can be done in different ways. One option is to model them as servers with a single logical device and multiple logical nodes. In this case certain functional elements have to be grouped together using the available object hierarchy and the naming conventions for the data objects. A simplified block diagram of this approach is given in Fig. 3.

One of the most important concepts that needs to be understood at the very beginning of the IED modeling process is that the model includes only objects that are visible to the communications. The relay may contain a lot of data internal to the device, such as data exchanged between elements of a fixed scheme logic. If this logic is represented to the outside world as a black box with certain inputs and outputs, these internal signals are not visible and as a result they are not included in the model.

In order for the logical nodes to interoperate over the substation LAN, it is necessary to standardize the data objects that are included in each of them. IEC 61850 considers three levels of data and services for the modeling of different substation automation functions.

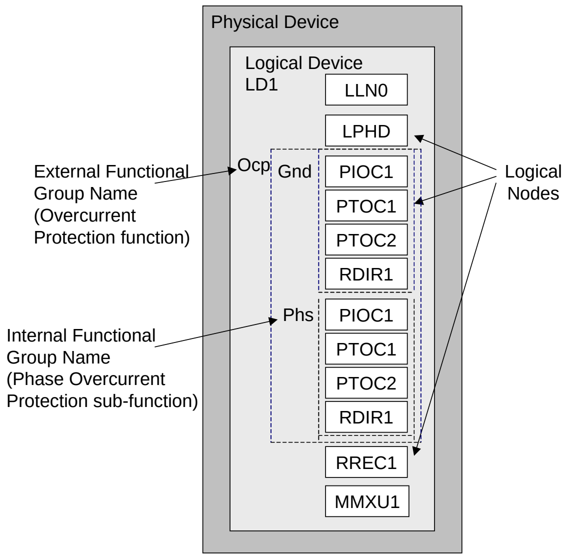

Figure 3: Object model of IED as a single Logical Device

The first level is the Abstract Communication Service Interface (ACSI). It specifies the models and services for access to the elements of the specific object model, such as reading and writing object values or controlling primary substation equipment.

The second level defines Common Data Classes (CDC) and common data attribute types. A CDC specifies a structure that includes one or more data attributes.

The third level defines compatible logical node classes and data classes that are specialization's of the common data classes based on their application.

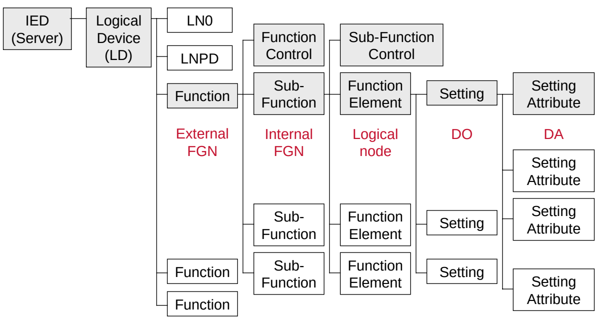

Figure 4: Object hierarchy

Part 5 [2] of IEC 61850 defines the logical node concept and the communications requirements for different functions and device models. Part 7-2 [3] specifies the first level of modeling – ACSI. Part 7-3 [4] covers the CDC, while Part 7-4 [5] defines the compatible logical node and data classes.

The object hierarchy can be represented in a simplified way as shown in Fig. 4. A Server typically is any physical device that is being modeled as part of a substation automation system. Usually an IED will be modeled as server with a single Logical Device (Fig. 3).

The server represents the communications visible behavior of the IED. Each logical device is defined as a "virtual device that exists to enable aggregation of related logical nodes and data sets". Multifunctional devices are modeled using several types of logical nodes depending on the specific application of the IED.

The logical nodes contain the information required by a specific function, such as a function setting or measurements being calculated by an IED. A Logical Device has a single Logical Node Zero, a single Logical Node Physical Device, plus one or more other logical nodes.

In case of protective relays with more complex functional hierarchy it might be necessary to group together several logical nodes in a functional group such as Overcurrent protection. The fact that a logical node belongs to a functional group of logical nodes can be represented by a functional group name. If the device has a very complex functional hierarchy, it is possible to use External Functional Group Name (EFGN) or Internal Functional Group Name (IFGN) as shown in Fig. 3 and Fig. 4.

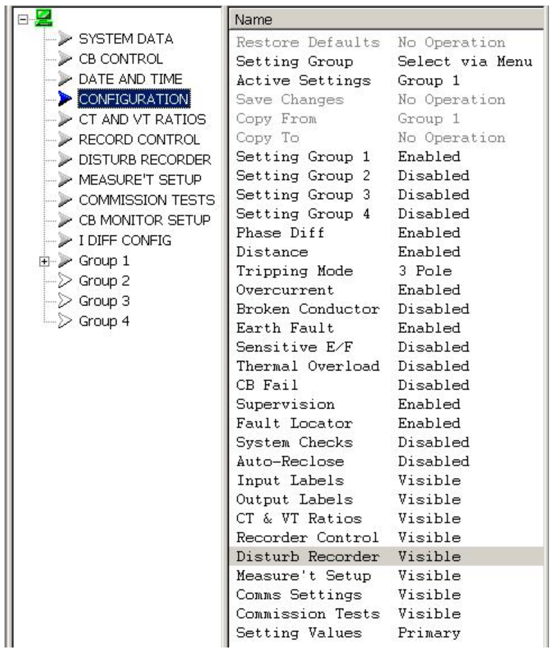

Figure 5: Transmission line protection relay configuration

Fig. 5 shows the functional configuration of a transmission line protection relay. The model of such device in IEC 61850 can be done by mapping the different substation functions supported by the relay to different logical devices. One logical device will represent the primary protection functions. Another will define the Measuring function and a third – the Disturbance recorder. A Fault Locator and a Circuit Breaker Monitor will be modeled with additional Logical Devices.

If we go further down in the functional hierarchy from Fig. 4, the Protection Logical Device will include multiple protection functions. As can be seen from Fig. 5 each of these protection functions can be Enabled or Disabled. For the relay in Fig. 5 the Distance, Phase Differential, Phase and Ground (Earth) Overcurrent protection functions are enabled, while the Breaker Failure, Broken Conductor and some others are Disabled. When a protection function is Disabled, it means that all Functional elements (Logical Nodes) included in it become Disabled as well. This is one of the reasons that require the functional grouping of multiple logical nodes as described above.

The functional hierarchy becomes even more complicated in the case of an advanced transformer protection relay. As can be seen from Fig. 6 below, the relay is connected to current and voltage transformers at different voltage levels and in some cases different breakers at the same voltage level.

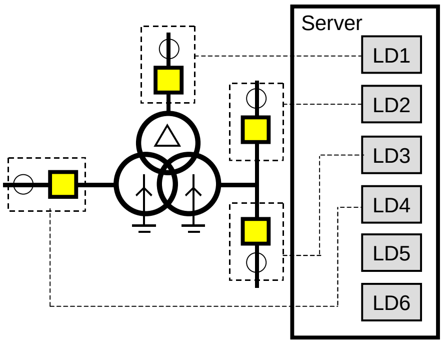

Figure 6: Transformer protection relay object model

One way of modeling this device is to use a Logical Device for each different physical interface (shown with dotted lines in Fig. 6) and for some Transformer level functions. Then each of these Logical Devices will include Protection, Measuring and Monitoring functions. The transformer level LD will also contain the Disturbance recorder function.

Another approach will be similar to the one described earlier for the Transmission Line protection relay – have a logical device for Protection, Measurements, Monitoring and Recording and then different functional groupings per voltage level and further down the functional hierarchy.

2.2 Data object hierarchy

Logical nodes typically include not only data, but also data sets, different control blocks, logs and others as defined by the standard.

The DATA represents domain specific information that is available in the devices integrated in a substation automation system. It can be simple or complex and can be grouped in data sets as required by the application.

Any DATA should comply with the structure defined in the standard [3] and should include DataName, DataRef, Presence and multiple DataAttribute's.

The DataName is the instance name of the data object, while the DataRef is the object reference that defines the path name of the DATA object instance.

The Presence is a Boolean type attribute that states if the data object is Mandatory or Optional.

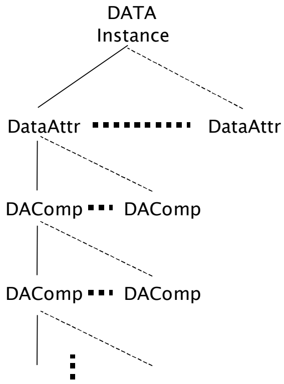

Figure 7: Nested data attributes

Each instance of a DATA class object must contain at least one DataAttribute. Instead of a DataAttribute it is possible to have a SimpleCDC or Composite CDC (both are specialization's of the DATA class). DataAttribute's can be simple or nested. If they are nested, at each nesting level other than the first the DataAttributeName is called DAComponentName (see Fig. 7). The DataAttribute's are of certain data type that can be primitive (BasicType) or composite (DAType).

The different DataAttribute's can be grouped based on their specific use. For example some indicate the status of the logical node, while other are used for configuration or measurements. The property of DataAttribute that shows its use is a Functional Constraint (FC). The standard defines many different functional constraints [3], Some more commonly used are:

CO – control
SP – set point
CF – configuration
DC – description
SG – setting group
MX – measurements

The SP functional constraint is used for settings that are global to the IED, while SG applies to settings that may have different values in the different setting groups. The SP and SG data attributes can be read and set.

The MX functional constraint is used to indicate that the data attribute represents measurand information. The value of this data object can be read, substituted, logged or reported. The values of these DataAttribute's are normally based on processed data from the IED. After describing some of the typical data objects used to model measured values, we are finally at a point when we can give an example of a data path (the DAComponentRef) for a single phase measurement of the current in phase B represented as a floating point:

MMXU1.A.phsB.cVal.mag.f

where:

MMXU1 is an instance of the Compatible LN class MMXU defined in Part 7-4 [5]

A is an instantiation of the Composite DATA class WYE (defined in 7-3 [4]) used to represent the three phase currents and the neutral current

phsB is the value of the current in phase B as a Simple Common DATA class of type CMV (defined in 7-3 [4])

cVal is the complex value of the current in phase B (of the Common DataAttribute type Vector

mag indicates that this object represents the magnitude of the complex value (of type AnalogValue - defined in 7-3 [4])

f is a DataAttributeComponent which is of the basic type FLOATING POINT (defined in 7-2 [3])

All measurements in multifunctional IEDs are modeled in a similar way and grouped into special logical nodes described in the next section of the paper.

3 HIGH SPEED PEER-TO-PEER COMMUNICATIONS

One of the important differences between IEC 61850 and UCA 2.0 GOMSFE is the IEC GOOSE.

GOOSE message		
Parameter Name	**Parameter Type**	**Value / Value Range / Explanation**
DatSet	ObjectReference	Value from the instance of GoCB
AppID	VISIBLE STRING65	Value from the instance of GoCB
GoCBRef	ObjectReference	Value from the instance of GoCB
T	EntryTime	
SqNum	INT32U	
StNum	INT32U	
Test	BOOLEAN	(TRUE) test | (FALSE) no-test
ConfRev	INT32U	Value from the instance of GoCB
NdsCom	BOOLEAN	Value from the instance of GoCB
GOOSE-Data [1..n]		
Value	(*)	(*) type depends on the common data classes defined in part IEC 61850-7-3. The parameter shall be derived from GOOSE control

While in GOMSFE it is defined as a set of bit pairs that represent the state of logic elements in the modeled device, IEC 61850 defines the GOOSE message used for the exchange of a wide range of possible common data organized by a DATA-SET. The GOOSE messages are multicast the same way as the GSSE with a repeat time for the initial GOOSE message being short followed by an increase in repeat and hold times of subsequent messages until a maximum is reached. The GOOSE message contains information that will allow the receiving IED to know that a message has been missed, a status has changed and the time since the last status change (see the table above).

The table includes the common components used to facilitate the IEC 61850 GOOSE Class Object. There is no equivalent in UCA 2.0.

In the table above the different parameters are defined as follows:

DatSet: The data set parameter contains the ObjectReference of the DATA-SET (taken from the GOOSE Control Block GoCB) whose values of the members shall be transmitted.

AppID: This is the identifier of the LOGICAL-DEVICE (taken from the GoCB) in which the GoCB is located.

T: The timestamp contains the time at which the attribute StNum was incremented.

StNum: The state number parameter contains the counter that increments each time a value change has been detected within the DATA-SET specified by DatSet and a GOOSE message has been sent.**SqNum**: The sequence number parameter SqNum contains the counter that increments each time a GOOSE message has been sent.

Test: The test parameter indicates with the value of TRUE that the values of the message shall not be used for operational purposes, but only for testing.

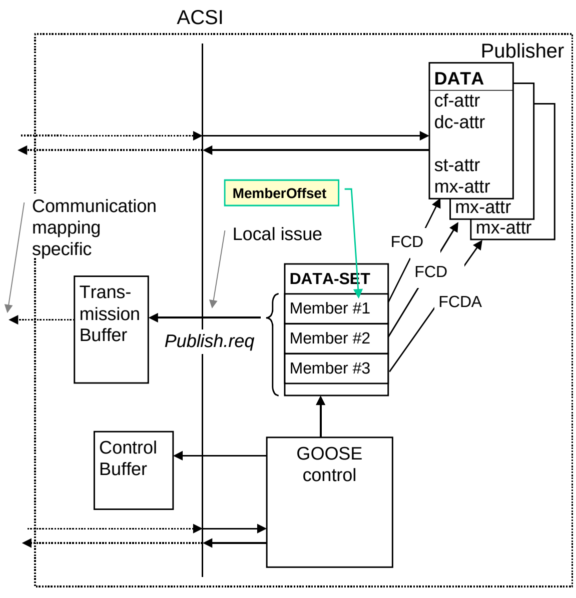

Figure 8: GOOSE control model

ConfRev: The configuration revision parameter ConfRev (taken from the GoCB) contains the count of the number of times that the configuration of the DATA-SET referenced by DatSet has been changed.

NdsCom: The parameter needs commissioning contains the attribute NdsCom (taken from the GoCB) of the GoCB and is used to indicate that the GoCB re quires further configuration.**GOOSEData [1..n]**: GOOSEData contains the user defined information (of the members of DATA-SET) to be included in a GOOSE message.

The parameter **Value** contains the value of a member of the **DATA-SET** referenced in the **GoCB**.

The information exchange is based on a publisher/ subscriber mechanism. The publisher writes the values in a local buffer at the sending IED (see Fig. 8), while the receiver reads the values from a local buffer at the receiving IED. A GOOSE event control in the publisher is used to control the procedure. In order to achieve high speed performance and at the same time reduce the network traffic during severe fault conditions, the GOOSE message has been designed based on the idea to have a single message that conveys all required analog values and binary information regarding an individual protection IED.

The number **n** of members of the GOOSEData set may vary as a function of the analog inputs of the IED interfacing with the power system.

4 IED CONFIGURATION REQUIREMENTS

The basic configuration of any IEC 61850 based relay is achieved by writing into the data objects of the SP and SG functional constraint for the individual Logical Nodes that represent the different protection function elements.

Since relays with relay-to-relay communications within the substation require configuration in order to map the incoming signals into the relay logic, as well as to map relay logic outputs to outgoing communications messages, it is important to support Virtual Inputs and Outputs. They are treated in a similar way as the opto inputs and relay outputs of the protection IED being configured.

Fig. 9 shows a detail of programmable scheme logic with a Virtual Input signal to be inverted as an input to an AND logic gate. The output of the 1 (OR) gate is used to operate a relay output, a latched LED and a Virtual Output that is mapped to an outgoing GOOSE message

IEC 61850 based IEDs have a combination of physical inputs and outputs, as well as the high speed peer-to-peer communications based signals that get mapped to virtual inputs and outputs. The users of such devices need tools to configure the IED to receive and send GSE (Generic Substation Event) messages from at least one IED in order to provide functionality similar to the wiring of physical inputs and outputs between the relays.

To achieve this goal, the configuration tools should allow the "Subscription" for receiving of GOOSE or GSSE messages and their processing and "Configuration" of outgoing GOOSE messages. After an IED has been added to the subscription list, the user has to select which bit pairs from the received GOOSE messages will be monitored and when changed mapped to the virtual inputs of the IED's programmable scheme logic.

Since GOOSE messages can be used to provide information, for example of the status of a breaker or other switching device in the substation, if the IED monitoring the breaker is out of service, this may result in loss of information. In order to provide a solution for that kind of problem, there are several different options for the mapping of each bit pair in the received GOOSE message. The GOOSE configuration tool should allow the user to specify the Default and Pre-Set values for the bit pairs of interest.

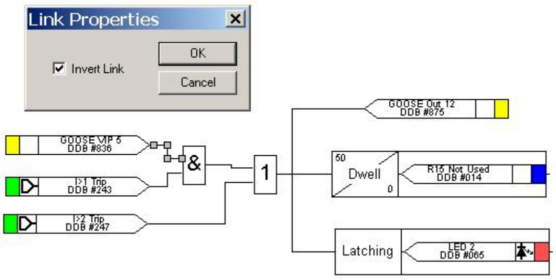

Figure 9: Virtual Inputs and Outputs configuration

The incoming messages might be of a type that requires the combination of several signals into a logic gate that is then mapped to a Virtual Input in the programmable scheme logic of the IED. AND and OR gates should be available to allow such input logic.

5 FUNCTIONAL TESTING

The testing of conventional functions in substation protection and control systems has some similarities and some differences with the IEC 61850 communications based solutions. In the case of the conventional testing the test device has to simulate the substation process through hard-wired interface between the analog and binary outputs of the test device and the analog and binary inputs of the test object.

At the same time the test device has to monitor the closing of relay outputs of the tested device in order to detect the operation of the IED and analyze it to determine if the performance meets the specification.

The operating time of the tested function is usually measured from the simulated by the test device process change of state that has to trigger the tested function until the moment when it will detect the operation of the IED relay output controlled by the tested function [6].

Fig. 10 shows the testing configuration for a partial implementation of IEC 61850 communications based solution. In this case the multifunctional IED interfaces with the process in a similar way to the conventional method described above, i.e. hard-wired analog signals between the test object and the test device.

The communications based distributed functions in this case use the IEC 61850 GSSE or GOOSE messages. All devices with communications interface have to be connected to the substation network switch as shown in Fig. 10.

Since the expected communications based performance should be similar to the conventional hard-wired interface, it is a good idea to compare the operation of a relay output and a GSSE message driven by the same functional element in the IED logic.

Another difference between the conventional testing and the IEC 61850 GSE based functional testing is that the state-of-change part of the process simulation is achieved by GSE messages sent from the test device to the test object. An example is to indicate the opening of the auxiliary contact 52a of the circuit breaker monitored by the tested IED.

The test setup in Fig. 10 can also be used for the testing of a distributed application based on IEC 61850 Merging Units that send sampled values over the substation LAN.

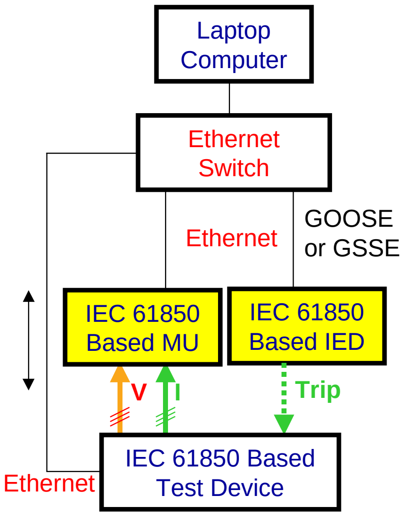

Figure 10: IEC 61850 based IEDs functional testing setup diagram

In this case the analog signals from the test device will be hardwired to the Merging Unit. The distributed function will be performed by the IEC 61850 based IED that will send a GSSE message to an Input/Output Unit that will operate a relay output to control the process, for example to trip the breaker.

The test device monitors different elements of the distributed function and can analyze their performance, as well as the overall function operating time.

When the multifunctional IED with the tested function operates, it will send a GSSE message to the interface unit that will control the process. The test device will subscribe and capture this message and also detect the operation of the binary output of the interface unit.

The difference between these two times can be used to calculate the required time to send a GSSE message over the network, process it in the interface unit and operate the binary output.

If the tested 61850 based IED also has a binary output, it can be monitored by the test device as well. This can provide valuable information on the overall performance evaluation process. The operation of a binary output of the IED will provide the time of a partial implementation of the communications based function. The binary output of the interface unit (IOU) will give the total distributed function operating time for the case of a complete IEC 61850 communications based solution.

6 CONCLUSIONS

The modeling of IEC 61850 based multifunctional protective relays requires good understanding of their functional hierarchy, as well as the modeling principles defined in the standard.

Complex devices, such as transmission line protection relays and transformer protection relays are modeled as servers with multiple Logical Devices that correspond to typical substation functions, such as Protection, Control, Measurements, Monitoring and Recording.

The IEC 61850 high-speed peer-to-peer communications are based on GSE (GSSE and GOOSE) messages. They can be used for different distributed protection and control applications. They require specific configuration tools in order to define the subscription to GSE messages from other IEDs, as well as to map between incoming and outgoing messages and the Virtual Inputs and Outputs of the device programmable scheme logic.

The functional testing of IEC 61850 based relays requires the use of specialized test devices that support the standard in order to simulate the substation environment and sense and analyze the operation of the test object.

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