Testing of Distributed Fault and Disturbance Recording Systems

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I. INTRODUCTION

The power system automation community is going through a period of transition from the world of hard wired systems and proprietary centralized disturbance recording systems into the world of distributed IEC 61850 communications based systems. This requires the development of a new set of methods and tools for the testing of such systems.

In order to define the requirements for the testing of Distributed fault and disturbance Recording Systems (DRS) we need to first understand what are the components and the architecture of such a system in an IEC 61850 based digital substation.

The first half of the paper presents the components of the distributed fault and disturbance recording system. They include two types:

- Hardware – PIUs (Process Interface Units), multifunctional IEDs, SCs (substation computers), communication devices, time synchronization devices
- Software – MUs (Merging Units), PMUs (Phasor Measurement Units), fault detectors, protection function elements, recording elements

The second part of the paper describes the methods and tools required to test all above listed components of the distributed fault and disturbance recording system, as well as the system as a whole.

II. IEC 61850 ARCHITECTURE

IEC 61850 is being implemented gradually by starting with adaptation of existing IEDs to support the new communications standard over the station bus and at the same time introducing some first process bus based solutions. The distributed disturbance recording system can also cover multiple substations. For example in the case of inter-tripping due to a breaker failure following a bus fault it may be necessary to trigger the recording in the remote substation with the GOOSE message delivering the Inter-trip signal.

Full advantage of all the features available in the new communications standard can be taken if both the station and process bus are used.

IEC 61850 communications based distributed applications involve several different devices connected to a substation local area network as shown in the simplified block diagram in Figure 1.

A Merging Unit (MU) will process the sensor inputs, generate the sampled values for the 3 phase currents and voltages, format a communications message and multicast it on the substation LAN.

A binary input/output unit (IOU) can be used to monitor the status of the breaker and trip or close it when necessary based on the GOOSE messages it receives from the different IEDs.

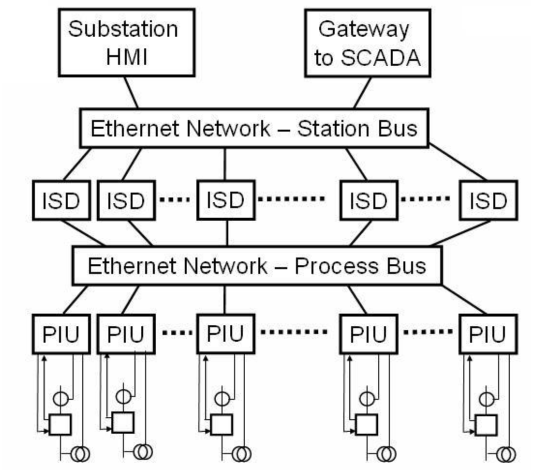

Fig. 1 Station and Process bus functional architecture

The merging unit and the input/output unit can be combined in a single device – a process interface unit (PIU) as shown in Figure 1.

All multifunctional IEDs will then receive sampled values messages and binary status messages, the ones that have subscribed to this data then process the data (including re-sampling in most of the cases), make a decision and operate by sending a GSE message to the IOU to trip the breaker or perform any other required action.

Figure 2 is an illustration of how the substation design changes when the full implementation of IEC 61850 takes place. All copper cables used for analogue and binary signals exchange between devices are replaced by communication messages over fiber. If the DC circuits between the substation battery and the IEDs or breakers are put aside, "copper-less" substation is a fact.

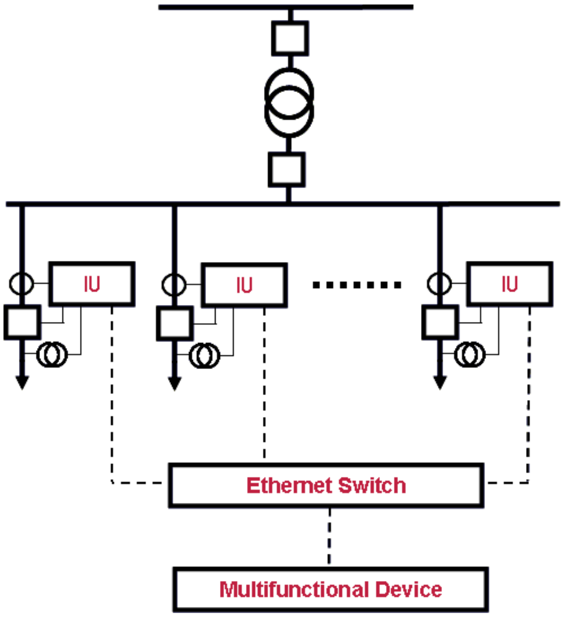

Fig. 2 Substation design with process and station bus

All of the above devices can be components of the distributed fault and disturbance recording system. Since in a fully digital substation the allocation of functions can vary significantly between different implementations, it is important to identify the functions available in such a system. From this point of view we have:

- Analog interface – current and voltage signals available directly from non-conventional sensors as IEC 61850 9-2 LE or in the near future IEC 61869-9 streaming sampled values
- Binary interface – status of primary switching devices available through IEC 61850 GOOSE messages
- Triggering functions – protection or monitoring functions that identify the need for recording of system parameters available through IEC 61850 GOOSE messages
- Recording functions – the functions performing the actual recording of the different types of abnormal system conditions identified by the triggering functions based on the subscribed sampled values and GOOSE messages.

All of the above functions and more specifically the function elements used in their implementation need to be properly tested in order to ensure the correct operation of the distributed recording system.

III. CROSS-TRIGGERING OF DISTURBANCE RECORDING

The peer-to-peer communications in an integrated substation protection and control system are based on what is defined as a GOOSE. This is a Generic Object Oriented Substation Event and is based on the asynchronous reporting of an IED's functional elements status to other peer devices enrolled to receive it during the configuration stages of the system integration process. It is used to replace the hard wired control signal exchange between IED's for interlocking, protection and recording purposes. As a result they are mission sensitive, time critical and must be highly reliable.

The associated devices receiving the message use the contained information to determine what recording function should be executed.

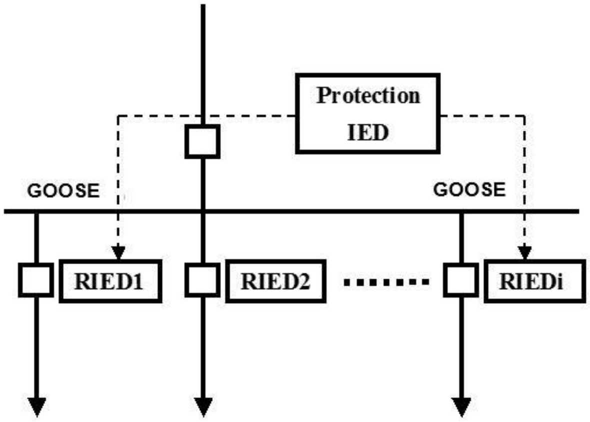

Fig. 3 Cross-triggering of disturbance recording

Each recording device will have to subscribe to GOOSE messages from multiple IEDs which contain the function elements used to trigger the recording. An example of the cross-triggered recording is the case when the protection IED acts as the Publisher and the recording IEDs (RIED) are the Subscribers. The protection IED will detect the fault or other abnormal system condition and send a GSSE message to the RIEDs (see Figure 3) that need to record it. In the subscribing RIEDs it will trigger a waveform recording with a high-sampling rate (for example 128 samples/cycle) to record the fault for future replay during testing. At the same time this may trigger high-speed disturbance recording (for example one or more cycles/sample of the rms voltage profile) for analysis of the voltage sag caused by the fault.

IV. WAVEFORM RECORDING BASED ON SAMPLED ANALOG VALUES

The introduction and wide spread of microprocessor based protection devices, combined with the advancements in non-conventional instrument transformers resulted in the development of digital interface between the sensors and the IEDs.

Digital analog interface in a point-to-point communications scheme was defined by IEC in the IEC 60044-8 standard. The development of Merging Units that convert the optical signal into a digital message containing sampled values and protection devices with a digital interface that perform multiple protection functions resulted in demonstration projects that showed the advantages of this technology.

IEC 61850 further developed the sampled analog values interface at the process level of the substation automation system. This is the logical interface 4 defined in IEC 61850 between the process and the bay levels.

The frame format from IEC 60044-8 is reused, but the IEC 61850 standard defines the transmission of sampled analog values over the Ethernet in both a point-to-point (unicast) or multicast mode.

The transmission of sampled values requires special attention with regard to the time constraints. The model provides transmission of sampled values in an organized and time controlled way so that the combined jitter of sampling and transmission is minimized to a degree that an unambiguous allocation of the samples, times, and sequence is provided.

Similar to the GOOSE model, the sampled analog values model applies to the exchange of values of a DATA-SET. The difference in this case is that the data of the data set are of the common data class SAV (sampled analogue value as defined in part IEC 61850-7-3). A buffer structure is defined for the transmission of the sampled values that are the output from the instrument transformer logical nodes TCTR and TVTR (Figure 4).

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 (see Figure 4), 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.

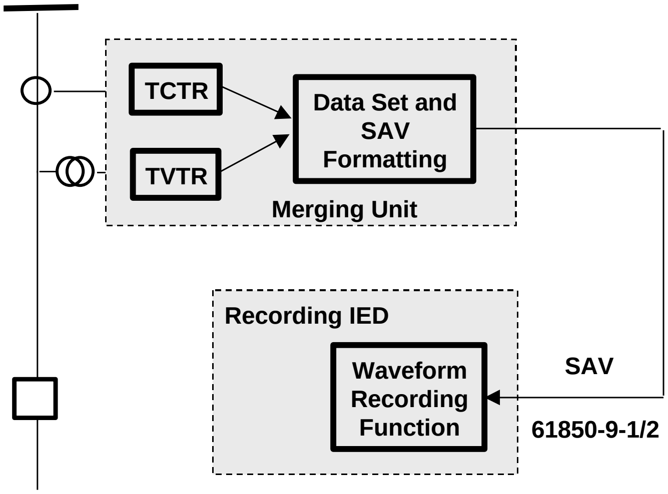

Fig. 4 Waveform recording based on Sampled Analog Values

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".

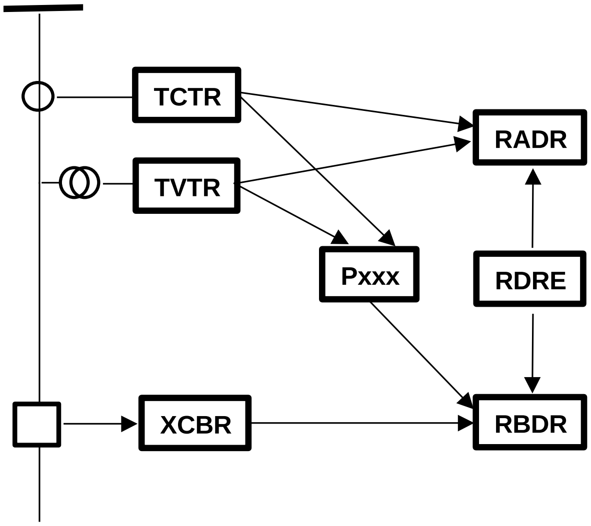

Fig. 5 Logical Nodes for waveform recording

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 used by the recording system. Figure 5 shows a simplified block diagram of the logical nodes used to model the different components of the distributed recording function. **Pxxx** is used to indicate any protection functional element whose status is recorded in the waveform record. The logical nodes from the P class may also provide

Start or Operate information that is included in the recording. **RDRE** is the logical node representing the acquisition functions for voltage and current waveforms from the power process (CTs, VTs), and for position indications of binary inputs. Calculated values such as frequency, power and calculated binary signals may also be recorded by this function if applicable. RDRE is used also to define the trigger mode, pre-fault, post-fault etc. attributes of the disturbance recording function.

The logical node class **RADR** is used to represent a single analog channel, while **RBDR** is used for the binary channels. Thus the disturbance recording function is modeled as a logical device with as many instances of RADR and RBDR logical nodes as analog and binary channels are available.

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

Any disturbance recording device has to be configured to perform this function. The available configuration parameters in a specific device are mapped to the mandatory or optional data objects in the different disturbance recording related logical nodes described above.

V. TESTING OF IEC 61850 DEVICES AND SYSTEMS

The testing of disturbance recording systems based on IEC 61850 sampled values requires a new range of tools that can be used to test the different components of such solutions.

The testing requirements depend on the functionality that is being tested, as well as on the purpose of the test:

- Type or acceptance testing
- Integration testing
- Factory acceptance testing
- Site acceptance testing
- Maintenance testing

A range of tools and simulators are required to perform these test. The configuration of the test relies on the ICD, CID and SCD files defined in the IEC 61850 standard.

Figure 6 also shows the Merging Units simulators required in the case of testing of IEDs with process bus implementation of IEC 61850.

A network simulator, a state sequence simulator or other simulation tool can be used to produce the sampled values with a sampling rate of 80 samples/cycle or 256 samples/cycle as required by the type of device or function being tested. The test device formats the Ethernet message according to IEC 61850 9-2 LE (or IEC 61869-9 in the future) and publishes the sampled analog values over the network for testing.

Testing of devices with hybrid or full implementation can be combined with the testing of a merging unit. In this case the analog signals from the test device will be hardwired to the Merging Unit. The process bus based function will be performed by the IEC 61850 based IED that will send a GOOSE message to an IO Unit that will operate a relay output to control the process (trip the breaker).

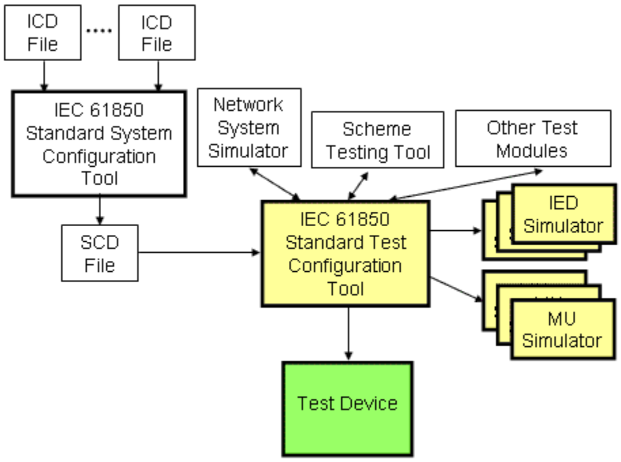

Fig. 6 IEC 61850 test configuration process

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

When the multifunctional IEDs with the tested function operate, they will send a GOOSE message to other IEDs or the DRS included in the test. The test device will subscribe and capture these messages and will use them in the test assessment.

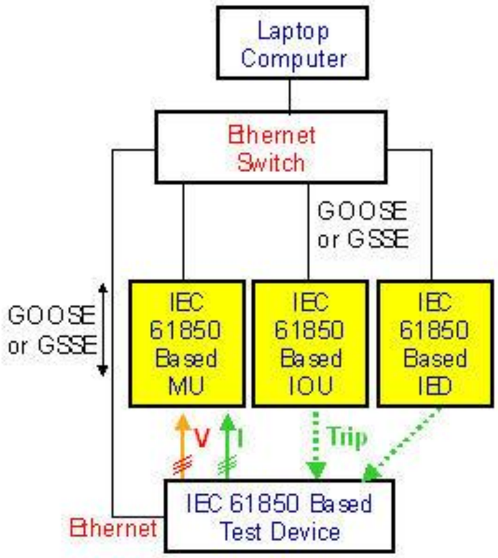

Fig. 7 IEC 61850 process and station bus test setup

The testing of the merging unit (MU) in this case will require comparison between the analog signal waveform applied to it and the IEC 61850 9-2 LE messages sent by the merging unit. The test device needs to subscribe to these messages and perform the comparison and evaluation. It should include not only the accuracy of representation of the waveform, but also any phase shift that may be the result of the processing of analog signals in the MU. The time stamps of the sampled values will be used for this purpose. Accurate time synchronization of both the test device and test object is essential for the testing of the merging unit.

The testing of the merging unit can be combined with the testing of the recording function. In this case the simulation should also include a GOOSE message representing the operation of a triggering function element synchronized with the simulated analog signals. The output of the merging unit then will be compared by the recorded values in the COMTRADE file from the tested disturbance recording device.

Since the recording device also needs to capture the operation of the function elements required in the recording configuration, each of these elements need to be simulated by the test system by sending the corresponding GOOSE messages.

Testing Methods

For example the testing of a distributed recording function during the user acceptance phase may focus on the testing of the measuring element characteristic using search test methods, while during the commissioning the operating times for different system conditions be the important ones achieved through transient simulation methods.

The knowledge of the internal behavior of the test object or more specifically the logic or algorithms implemented determine how the tests are being executed. The most commonly used test methods from this point of view are:

- Black box testing
- White box testing

The following sections discuss in more detail the different testing methods listed above.

A. Black box testing

Black Box Testing is a very commonly used test method where the tester views the test object as a black box. This means that we are not interested in the internal behavior and structure of the tested function.

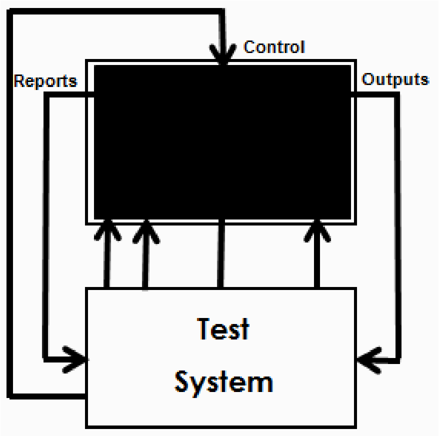

Fig. 8 Black Box Testing

In the case of black box testing the test system is only interested in finding conditions under which the test object does not behave according to its specifications. Test data are derived solely from the specifications without taking advantage of knowledge of the internal structure of the function.

Black box testing is typically used for:

- functional elements testing
- DRS factory acceptance testing
- DRS site acceptance testing

Since functional elements are defined as units that are the smallest that can exist independently and are testable, it is clear that black box testing is the only method that can be used for their testing.

The response of the test object to the stimuli can be monitored by the test system using the operation of physical outputs, communications messages, records or reports.

B. White box testing

White box testing is a method where the test system is not only concerned with the operation of the test object under the test conditions, but also views its internal behavior and structure.

In the case of DRS it means that it will not only monitor the operation of the system at its function boundary, but also monitor the exchange of signals between different components of the system.

The testing strategy allows us to examine the internal structure of the test object and is very useful in the case of analysis of the behavior of the test object, especially when the test failed.

In using this strategy, the test system derives test data from examination of the test object's logic without neglecting the requirements in the specification. The goal of this test method is to achieve high test coverage through examination of the operation of different components of a complex function and the exchange of signals or messages between them under the test conditions.

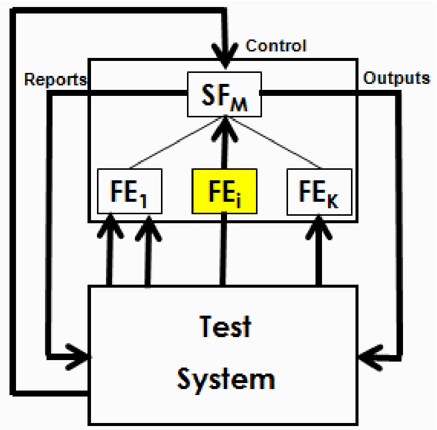

Fig. 9 White box Testing

This method is especially useful when we are testing distributed functions based on different logical interfaces. The observation of the behavior of the sub-functions or functional elements is achieved by the test system through monitoring of the exchange of messages between the components of the test object.

The test scenarios however do not have to be different from the ones used under black box testing.

C. Top-down testing

Top-down testing is a method that can be widely used for DRS, especially during site acceptance testing, when we can assume that all the components of the system have already been configured and tested.

Top-down testing can be performed using both a black box and a white box testing method.

The testing starts with the complete system, followed by function or sub-function testing and if necessary functional element testing.

In the case of factory acceptance testing, when not all components of a system or sub-system are available, it is necessary for the test system to be able to simulate their operation as expected under the test scenario conditions. In this case the test system creates the so called Stubs for functions or functional elements that are not yet available.

Top-down testing results in re-testing of higher level elements when additional lower level elements of the system are added. The adding of new elements one by one should not be taken too literarily. Sometimes a collection of elements will be included simultaneously, and the whole set of elements will serve as test harness for each functional element test.

Each functional element is tested according to a functional element test plan, with a top-down strategy.

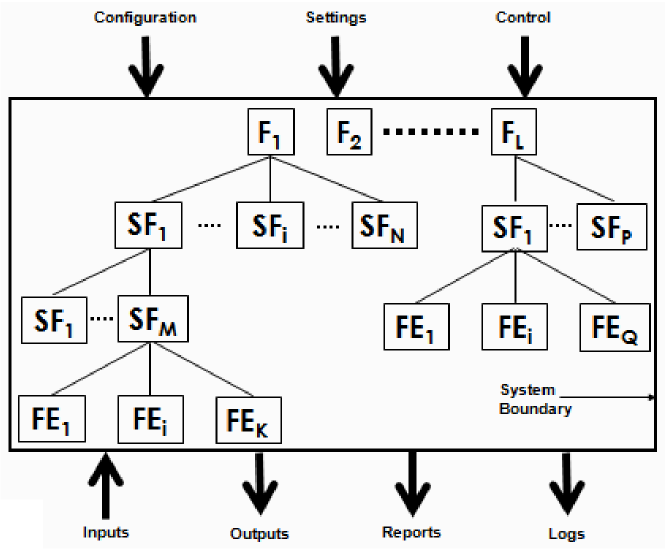

Fig. 10 Top-down testing of distribution automation system

If we consider a DRS implementation in IEC 61850 for testing using a top-down approach, we will start with the definition of the function boundary.

The testing of the individual components of a system function might be required in the case of failure of a specific test, which is shown in Fig. 10. The function boundary for each of these tests will be different and will require a different set of stimuli from the test system, as well as the monitoring of the behavior of the functional elements using different signals or communications messages.

For example if we are testing the recording at a remote substation that is triggered by the inter-tripping and the recording fails, we will need to know if the bus protection function failed, the breaker failure protection function failed or the recording function failed.

D. Bottom-up testing

Bottom-up testing is a method that starts with lower level functions – typically with the functional elements used in the system.

This method is more suitable for type testing by a manufacturer or acceptance testing by the user.

When testing complex multilevel functions or systems, driver functional elements must be created for the ones not available. The test system must be able to simulate any missing component of the system when performing for example factory acceptance testing.

There are many similarities in the test scenarios used in the bottom-up, compared to the top-down method. The main difference between the two methods is the order that the tests are performed and the number of tests required.

E. DRS Factory Acceptance Test (FAT)

The factory acceptance test (FAT) is a customer agreed functional tests of the specifically designed and implemented DRS. It is a subject of agreement between the final user and the system integrator and is highly recommended, since it allows the detection of potential problems in an earlier stage of the project, when it is less expensive and easier to fix them.

Factory acceptance testing should be performed using a top-down approach based on a test plan including test scenarios defined as part of the design of the system.

Black box testing methods can be used until any failure of the system for a specific test occurs. White box testing will then be used to determine the reason for the test failure.

One of the characteristics of factory acceptance testing is that not all components of the system are available. That requires from the test system the ability to simulate devices missing from the factory system, which is a part of the real DRS.

Another differentiating factor for the FAT is that all existing components of the system are configured and set according to the requirements of the real system application.

The factory acceptance test thus should be based on configuration of all devices using the IEC 61850 System Configuration Description (SCD) file for the project.

F. DRS Acceptance Test (DRSAT)

The DRS acceptance test corresponds to the common site acceptance test (SAT) of a substation protection, automation and control system, but covers to complete testing of the DRS which may be distributed in multiple sites. It is the verification of the correct functionality not only of the individual components of the system, but also the communications between the different devices and sites. The DRS acceptance test is a precondition for the DRS being put into operation.

The DRSAT, similar to the FAT is a customer agreed functional tests of the specifically manufactured substation protection, automation and control system, performed with the complete system as installed.

It is also a subject of agreement between the final user and the system integrator from the point of view of the content of the test plan and the responsibilities of the involved parties.

There are no specific guidelines on what should be included in a DRS acceptance test. Development of such guidelines will be of great help to the industry in order to ensure the completeness of the testing process and reduce the probability for failure of the system when put in service.

DRS acceptance testing should be performed using a top-down approach based on a test plan including test scenarios defined as part of the design of the system.

Black box testing methods can be used until any failure of the system for a specific test occurs. White box testing will then be used to determine the reason for the test failure.

One of the main characteristics of DRS acceptance testing is that all components of the system are available. That requires from the test system the ability to simulate all required analog, binary or other signals required for the testing of any specific substation or electric power system condition that the real distributed recording system is designed to handle.

The DRS acceptance test should be based on configuration of all devices using the SCD file for the project.

The final stage of the DRS site acceptance test should be performed as end-to-end testing to ensure that all the wiring between the process and the devices included in the substation protection, automation and control system are properly done.

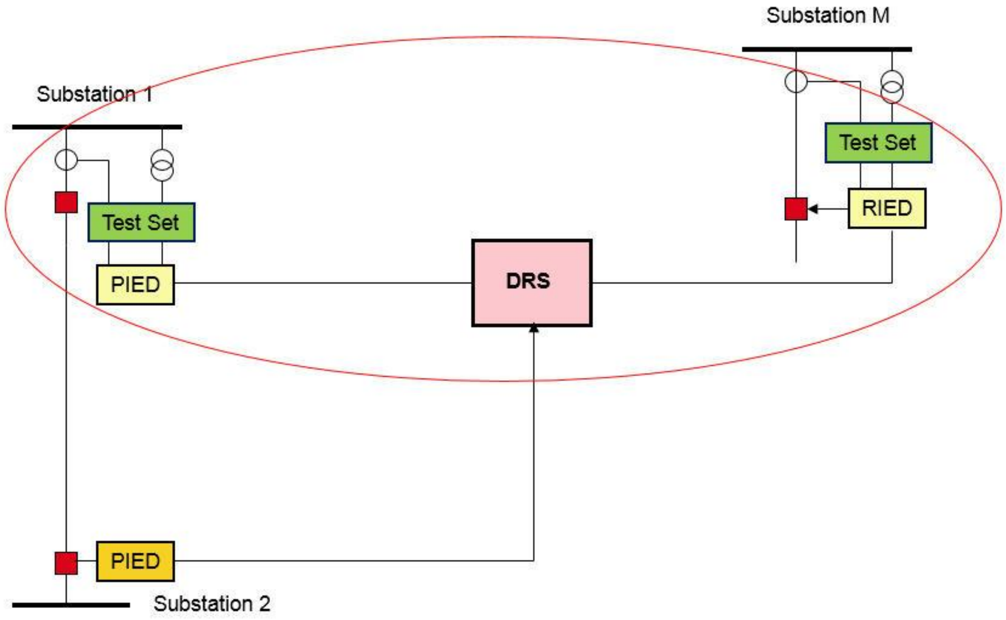

Fig. 11 DRS End-to-End test

To compare with the FAT, which is performed off site where the system was assembled and it has to prove that the complete system fulfils the properties specified in the contract between the manufacturer and the user before it leaves the factory, the DRS SAT concludes commissioning and proves that the system fulfils the contract before it goes into operation.

For the end-to-end testing of some DRS functions it may be necessary to GPS time synchronize the testing devices at all the sites.

VI. CONCLUSIONS

Testing of Distributed Recording Systems requires good understanding of the functionality and the hierarchy of the system.

Different methods are used for testing of the components of the system, as well as the distributed sub-functions and functions.

Bottom-up testing is used at the initial phases of development and implementation of the system and especially for the acceptance of merging units and IEDs to be used at the system protection and recording levels of the system.

Black box and top-down testing can be used during the factory and site acceptance testing stages.

End-to-end testing is required for the final acceptance test of the DRS before it can be put in service.