TESTING OF INTERLOCKINGS IN SUBSTATION AUTOMATION SYSTEMS

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***Abstract* - During the engineering, commissioning and maintenance of Substation Automation Systems (SAS) with Protection, Automation and Control (PAC) tasks, testing the correct functionality of the subsystems represent a significant share of the project execution time as well as total implementation cost of the SAS. In the recent years, Automation systems became increasingly complex and the efforts for testing communication and proper operation of all signals transmitted to Supervisory Control and Data Acquisition (SCADA) systems grew dramatically. A general testing approach was introduced some years ago. This paper describes possibilities of testing interlocking functions within SAS. Considering typical challenges in logic testing an evaluation method is applied for testing in SAS. A typical example for logics in SAS is interlockings. Testing them is safety related and very time consuming. The paper collects different possibilities for the realization of interlockings and compares the advantages and disadvantages. Decentral and centralized solutions will be compared, especially taking into account extension and testing efforts. On the testing the first approach was using the information in IEC 61850 logical node CILO and apply this for testing. This allows testing of centralized as well as decentralized interlockings and can be repeated after an update. The approach developed can be extended for "end to end" testing for complete SCADA testing. This includes automatic setup of test cases, their test execution and assessment. Advanced possibilities and the application fully digital substations finalize the paper.**

Keywords - interlocking, IEC61850, testing, SAS, SCL

I. INTRODUCTION

Testing the protection element settings of Intelligent Electronic Devices (IEDs) and testing protection schemes are well established practices for a long time already. With the introduction of combined protection and control devices testing a Protection, Automation and Control (PAC) system became the task. This is covered during the lifecycle of SAS and described already in the IEC 61850 standard. It describes the distinct phases of a project, like Factory Acceptance Tests (FAT), Commissioning, Site Acceptance Tests (SAT) and Maintenance or Routine testing. For protection tools and methods are available to support standardized and automated testing routines.

On the other hand, testing the SAS, which involves Automation, Control and SCADA functionalities, is usually performed in a manual fashion. When looking at the time spent during commissioning, for example, testing the automation and communication system nowadays consumes even more time than testing the protection. Automation systems became increasingly complex and the efforts for testing communication, interlocking logics and proper operation of all signals transmitted to SCADA system as well the local HMI grew dramatically.

In substations with conventional hardwired interfaces, all wiring and cabling connections between IEDs need to be checked as part of the FAT and SAT. This is performed one-by-one in a manual process of "green marking" all interfaces at printed functional and wiring diagrams ("bit-testing"). For testing the relay logics, the physical inputs need to be forced and logics verified either by monitoring LEDs, outputs or with assistance of the IED software. For testing the HMI signaling, an end-to-end (also refereed as point-to-point) check is performed by stimulating the signals directly at the equipment level in the switchyard or by forcing them at the IEDs. Additional documentation is usually needed, like a spreadsheet with RTU signal and mappings list ("data point list").

In a substation with IEC 61850 communication-based interfaces, the process of testing the automation and control can be improved by using software to replace some of the manual steps applied before. This process can be even more efficient if some optional features defined by the standard are used as well as the capabilities of the System Configuration Language (SCL) is fully exploited.

A test system utilizing this approach was introduced in [1] and [2]. This paper focuses on new aspects.

II. TESTING THE SUBSTATION AUTOMATION SYSTEM

A. *Test Approach*

As mentioned previously in this paper, testing of the automation and control functionality are usually performed in a manual way. Tools are available offering testing capabilities on a per IED basis, allowing test and simulation of IEDs individually.

The test method presented here extends the test from single IED testing and simulation to test the entire Substation Automation System. The test is entirely based on the Substation Configuration Description (SCD) configuration file of the system. By importing the SCD file, the entire system can be visualized and all information available in the SCD is used.

The method proposed is suitable for testing the SAS during its entire project lifecycle, which project phases are described at IEC 61850 4 and illustrated in Figure 1. The tool using this method should support both monitoring as well as simulation of the system. When testing the system, the test set should have access to the network traffic and an MMS connection to the IEDs.

Fig. 1. Project lifecicle

During specification, the SCD file can be validated and used to support the configuration of devices. Development and testing of SCADA RTUs and HMIs can start by simulating the communication behavior of all IEDs in the system. During the Factory Acceptance Test (FAT), IEDs that are not yet present can be simulated to test the ones already installed and available. As the project moves into the commissioning stage, more monitoring and testing of the real IEDs is done instead of simulation.

One of the key factors for an efficient approach is the option to create test plans. A test procedure can be documented and reused throughout the SAS lifecycle. Test sequences can be performed and assessed automatically as in *Fig. 2*.

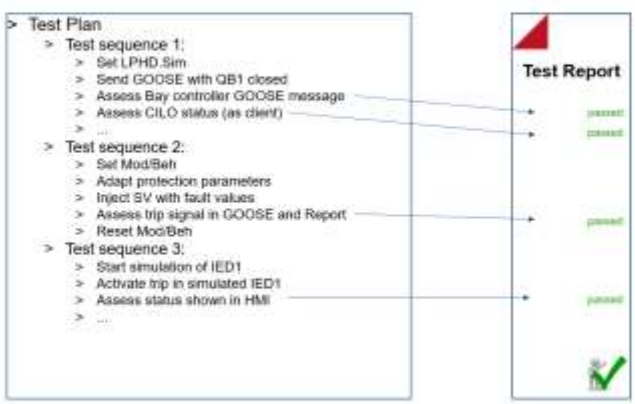


Fig. 2. Example of test plan

Detailed test cases related to the SAS system are discussed in the following sections of the paper.

B. *Testing Interlocking Logics[2]*

1) Introduction: Logics are implemented in IEDs to cover many automation functions. They can automatically be tested using this approach by simulating the inputs of the logic (either via IED simulation or real switchgear status) and the result of the logic can be assessed. One application example is the use of logics for interlocking schemes to ensure proper operation sequence of disconnect and grounding switches. To represent the result of interlocking logic conditions, IEC 61850 represents the status of the release in the logical node CILO. For testing, all combination of inputs can be tested, and the logic output assessed by reading the CILO status values automatically. This approach does not demand definitions of the logic conditions within the test set since the result is checked in the CILO logical node as in *Fig. 3*.

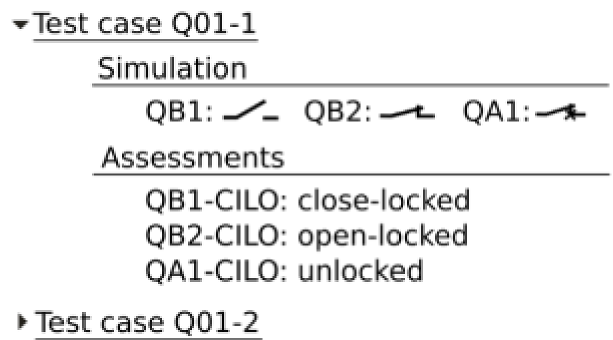


Fig. 3. Testing of interlocking schemes

2) Command Interlocking: In addition to remote control and monitoring of the primary installation, command interlocking is a standard function that can be found in almost every substation automation system. The command interlocking ensures that the control of a primary equipment does not lead to damage to the electrical equipment or to endangering individuals. For ex-ample, the command interlocking prevents the opening of a disconnector under load. Which equipment is to be inter-locked, and how, is often specified by the owner of the sub-station in the form of an interlocking concept? Not just the specific properties of the primary equipment but also operational requirements play a role here. For example, switching from the control center is usually only permitted in the "re-mote" operating mode (switching hierarchy) and all further commands must be blocked as long as a switching operation has not been clearly completed (1-out-of-n interlocking).

3) Specific Interlocking Function: In the past, the interlocking functions had been realized in electromechanical relay technology in the respective (bay) control cabinets. Various signals such as "Busbar grounded" or "Switching operation in progress" must actually be hard-wired between the individual bays – a complex solution, especially for installations with multiple busbars. Fortunately, IEC 61850 provides a solution that is cost effective and more elegant: The required signals, such as for the switch positions, are exchanged by means of GOOSE services and the calculation of the command release information is implemented, for example, by means of a function plan ac-cording to IEC 61131-3. Over time, the following implementation concepts have been developed:

a) Centralized: Complete interlockings realized in a central unit (for example in the telecontrol gateway) All release information is calculated centrally in one de-vice and sent to the corresponding bay devices. Benefit: Simple and clearly structured. Disadvantage: No inter-locking if the central unit fails.

b) Decentralized: Calculation of Interlockings is fully distributed in each field device. Each bay controller processes all necessary switch positions of the other bays and thus calculates the release information of the switching commands in its bay. Disadvantage: Complex, all bay devices must be updated when the substation is expanded!

c) Mixed: The bay-related interlocks are implemented in the respective bay device. In addition, a dedicated de-vice (e.g. station controller) calculates the station-wide interlockings (Figure 4). To realize this, the bay devices send their switch positions via GOOSE to a “station controller”, which calculates topological information such as "busbar 1 grounded" and sends this information via GOOSE to the bay devices, where the actual command releases are formed. Benefit: If the central device fails, the bay-related interlocks remain available. Existing field devices are not affected by expansions of the substation!

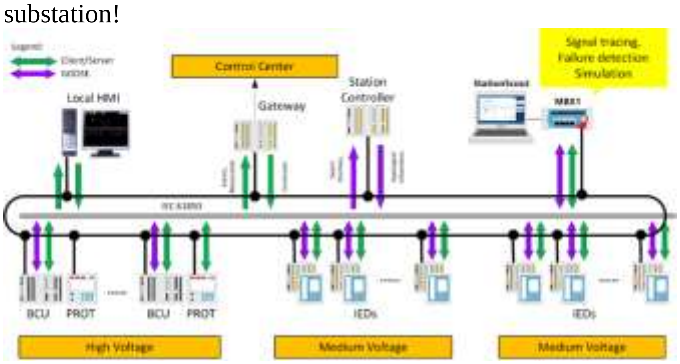


Fig. 4. Substation control, interlocking in station controller

In particular, the question "Do I have to re-parameterize all existing bay control devices when expanding the installation and therefore recommission the entire installation?" previously discouraged many operators from implementing interlockings using GOOSE instead of conventional wiring. In principle, the "mixed" implementation, therefore, allows subsequent extension without re-testing the existing bays and – when using modern testing tools such as OMICRON StationScout – also during operation. In addition, it makes sense to provide for a future extension by including future IEDs already in the initial parameterization of the system.

III. Test Cases

The test case concept was introduced in [2]. It is obvious that testing the interlocking conditions and functionality causes huge efforts and are time consuming. So, an approach to perform the tests and repeat if needed was developed. A test case itself is shown in *Fig. 5*.

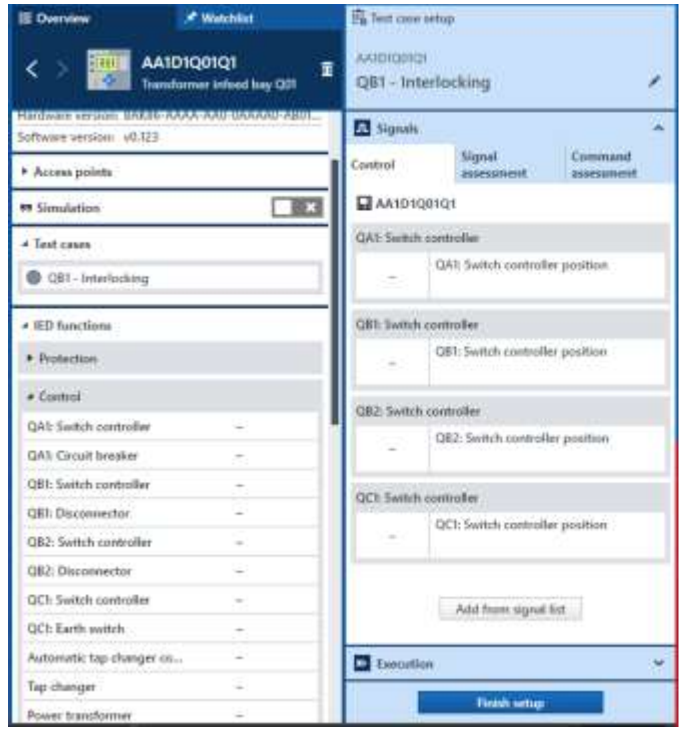


Fig. 5. Defining a test case for interlocking

Tests of logic and especially interlockings include a huge number of signals and test steps. In typical SAS configurations they are available as “data point lists”, very often in the Microsoft Excel format. The tool must be available to import such “signal lists” containing the IEC 61850 addresses (Logical Devices\Logical Nodes\ Data Objects\ Data Attributes.

Fig. 5 shows implementation proposal and result. Such signals can be controlled, can be used for signal assessment and the command can be assessed.

Assessment means the comparison with an expected value. *Fig. 6* [2] shows an example. Assessments can be done manually or automatically. In addition to the automated assessment of signal values like CILO logical nodes, the test system can issue command operations and check the command response from a switch or bay control unit. Using an enough timeout value this can be also done by assessing results from hard-wired interlocking logic, for example it can be used for the most real interlock cases we have in Mexico. The system will automatically issue the correct switching command based on the current position of the switch. The assessment depends on the selected result. If a command response according to IEC 61850-7-2 is selected (for example Blocked-by-interlocking), the system checks if the actual response matches the expected response and assesses the test step as Passed or Failed.

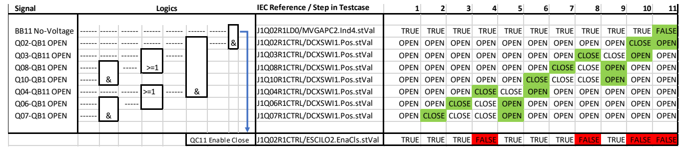
Fig. 6. Assessment of interlocking [2]

The test can be executed also automatically as in *Fig. 7*:

Fig. 7. Execute Interlocking test

IV. Extending the Approach

In a next step the testing approach was applied to test an entire SAS with interlocking. The interlocking conditions are available as logic conditions (*Fig. 10*). Every step in test case was defined and used for the calculation of interlocking conditions. The last row contains the expected status of CILO.stVal:



IEC Reference / Step in Testcase	1	2	3	4	5	6	7	8	9	10	11
J1Q02R1LD0/MVGAPC2.Ind4.stVal	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
J1Q02R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	OPEN
J1Q03R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	CLOSE	OPEN	OPEN
J1Q08R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	CLOSE	OPEN	OPEN	OPEN
J1Q10R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSE	CLOSE	CLOSE	OPEN	OPEN	OPEN
J1Q04R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	OPEN	CLOSE	CLOSE	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
J1Q06R1CTRL/DCXSWI1.Pos.stVal	OPEN	OPEN	CLOSE	CLOSE	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
J1Q07R1CTRL/DCXSWI1.Pos.stVal	OPEN	CLOSE	CLOSE	CLOSE	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN
J1Q02R1CTRL/ESCILO2.EnaCls.stVal	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE

Fig. 8. Interlocking definitions and test steps in spreadsheet

V. Extension for Signal Tests

FAT and SAT are not just on testing the different logics and interlockings.

Another very important topic are signal tests. Signals, available in the list mentioned, must be tested. The signal can differ (double point indication vs. single point) and demand different steps during the test. This results into different test steps (*Fig. 9*).

Fig. 9. Different test steps in signal testing

This results in test case again and allows automated testing.

Fig. 10. Signal testing test cases

VI. Extension for Fully Digital Substations and Additional Protocols

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VII. Conclusion

An innovative test approach was presented for testing the Communication, Automation, Control and SCADA part of the SAS system, which is based on the SCD file information. Test plans can now be created to document and automate test procedures that have been very time consuming until now. Automated test plans also enable a quick re-test after security patches and firmware updates, which are performed quite often

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