

Commissioning test of IEC 6188 based substation automation systems

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1 INTRODUCTION

The electric power industry is experiencing important changes in the implementation of new SAS (Substation Automation System), with worldwide acceptance of the IEC 61.850 standard by many utilities, in several scopes of applications. It provides many solutions for the exchange of information, standardization, engineering and integration. Meanwhile, many legacy IEDs (Intelligent Electronic Devices) and legacy SAS still exist, but they will certainly need to be retrofitted or expanded later, requiring such solutions as well.

Important lessons have been learned with the adoption of these new implementations. Practical applications provide useful tips and help build testing guidelines, which can lead to the best practices. Expertise is being built with this state-in-the-art technology. It can avoid some initial difficulties and produce important feedbacks.

This paper aims to provide a return on experience of IEC 61850 based SAS testing practices, highlighting strategies and methods for commissioning tests. Additional network communication and redundancy tests are also described, considering redundancy, topologies, port switching for link failures, time synchronization and other services.

2 THE USE OF IEC 61.850 AT CHESF

The use of IEC 61.850 standard at Chesf (Companhia Hidroeletrica do Sao Francisco) started in 2006, with the technical specification of new SAS for its electrical grid comprised by high voltage power plants and transmission substations. The first one of them was successfully integrated to the electrical system in 2007. It has then been adopted in all new SAS specifications for the station bus, including integration to legacy SAS in some applications.

So far, IEC 61.850 has been used at SAS station bus level, for status exchange, interlocking, disturbance recordings start, protection schemes, intertrip, redundancy and supervision. In addition, process bus has recently been considered in specifications, as merging units and compatible IEDs become available. There is a shift in the technology applied to SAS, with impacts on testing approaches.

3 TESTING APPROACHES, MESSAGES AND NETWORK ARCHITECTURES

3.1 Test Requirements

Test requirements are determined mainly by the expected functionality of the installation and its documentation. In IEC 61850 this includes: functional specification (FICS file) supplemented optionally by other UML artifacts, system specification (SCD file), IEDs configuration (CID files) and conformance declarations (PICS, MICS and PIXIT). Commissioning tests, being directed to final users, shall comply with several additional requirements typical of software testing: they must be

simple, repeatable, documented, automatable, human readable, customer oriented, tool independent, supplier independent, extensible, systematic and standardized. In addition, the test plan shall attain an established goal or measure of completeness, expressed by the set of features tested, like possible failures discovered or functions tested. FMEA and HAZOP are two methods standardized by IEC and suggested by CIGRÉ to analyze possible failures a system may present, and to avail the fault coverage of any proposed test plan. In special, testing tools must have the capability to exercise specific functional requirements of IEC 61850 based systems and support the principles of Black Box testing, where the details of the internal logic of the components is not known. They should also support tests performed in a top-down or bottom-up approach, to address the needs of integration and factory acceptance testing. So, in addition to input and output signals, they should be able to monitor and generate messages between the different components of a distributed function.

3.2 Test Chain

In the SAS life cycle, different test stages are necessary to check functional specifications. From type tests down to FATs (Factory Acceptance Tests), functional design specifications and customer expectations are checked, using lab environment and simulated scenarios. Commissioning testing or SAT (Site Acceptance Test) has always been an important stage, representing a path from the off-line factory acceptance tests to the real time operational condition. Besides covering assemblage and physical connections on site, it is also a great opportunity to learn and check the integrated system with final settings and to overcome eventual lacks from earlier tests.

Within the IEC 61850 environment, SAT testing turns out to be more complex. Virtualization is intense, functions may be distributed. Traditional physical connections are substituted by logical connections, most of the times sharing the same network with other applications. Loading conditions could be critical. Very important protection and control functions now depend on the network reliability and performance. Therefore, commissioning tests must also cover shared virtual connections and specific network functionalities such as redundancy and addressing. Extra care must be taken to harmonize commissioning testing activities with the operational parts of the network and the SAS.

FAT can have good coverage, when the SAS is supplied by only one vendor. SAT can become much more important, when there is a composition of more than one supplier' SAS, an integration to a legacy SAS or different utilities sharing a system.

Figure 1 shows an example of a test chain, with such different agents.

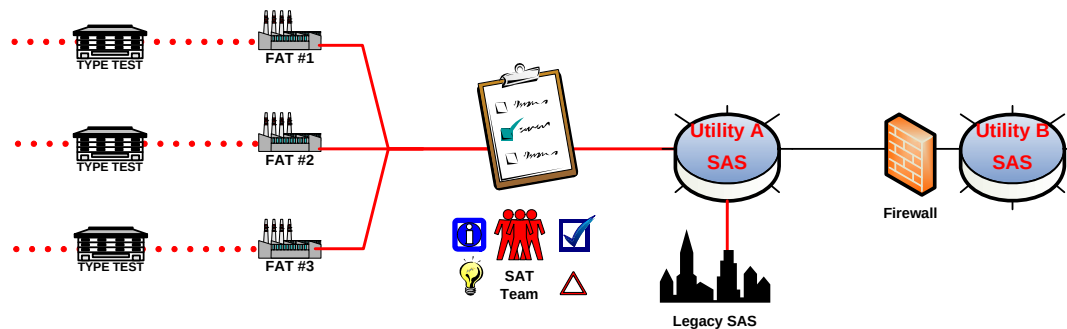


Figure 1: An example of a test chain

SATs are very important in the test chain, because it is necessary to test assembling, cabling, wiring etc on site, for the real operational condition, although it is not in the worst case scenario. Moreover, there are usually additional reasons present on site, resulting from:

- New firmware versions, configuration adjustments, final settings and customized applications, occurred from FATs to SATs;
- Real network operational conditions, with new shared environment, multiple applications, other protocols, wrong configuration in switches (paper...), excessive sensitive analogue deadbands etc;
- Unexpected bugs, side effects and new behavior from later changes that can happen;
- Eventual human errors and test limitations from earlier stages test coverage;

- Definitive integration to operational SCADA/EMS architecture and network backbone, with preparation for future expansions or retrofits.

Nonetheless, SAT usually faces tight schedule times.

The SAS test chain should be simplified in the future, the same stages are necessary but solving problems could be anticipated and simple test repetition has to be avoided. Test coverage must complement each other.

As to methodology, new procedures are expected to apply extensive automate tests, based on models, fulfilling all test requirements. CIGRÉ WG-B5.32 published a very interesting Brochure on Functional Testing of IEC 61850 Based Systems.

3.3 IEC 61850 based messages

The IEC 61850 standard offers several flavors of structured message types, like Report, Goose and Sampled Values. They are basically related to 2 communication models. Report messages are based on the “Client x Server” model, while GOOSE and Sampled Values messages are based on the “Publisher x Subscriber” new model.

The “Publisher x Subscriber” model messages are considered time critical, for they are structured for real time control, protection schemes and measurement purposes. Therefore, they are very much influenced by the network performance, which must have specific tests as well.

All messages of an SAS should be contained in the signal list of the SAS and tested as well, considering aspects like structure, semantics, addressing, Human Machine Interface display and behavior etc.

Later, in the chapter 4, more testing details are presented, relating to messages and network.

3.4 Network architectures

The SAS can be implemented in many different topologies and communication protocols. In order to achieve redundancy, a ring of switches is usually adopted, but some applications also include the IEDs network interfaces as part of the ring, with RSTP protocol. Recent successful applications start using PRP.

All functionalities must be tested. However those so much important messages also rely on the network reliability and availability that might have been checked in earlier stages tests. At first, the network itself should not be tested. But, after final assemblage on site, the real network must be checked against connections as well as its particular protocols and redundancy features adopted according to the chosen topology.

The network technology as a means for the message flow is already indirectly tested by the application. The focus is never on fully testing well approved network functionalities, but the application itself, relying on the network and its relevant configurations.

Figure 2 below shows the architecture of a typical SAS used by Chesf.

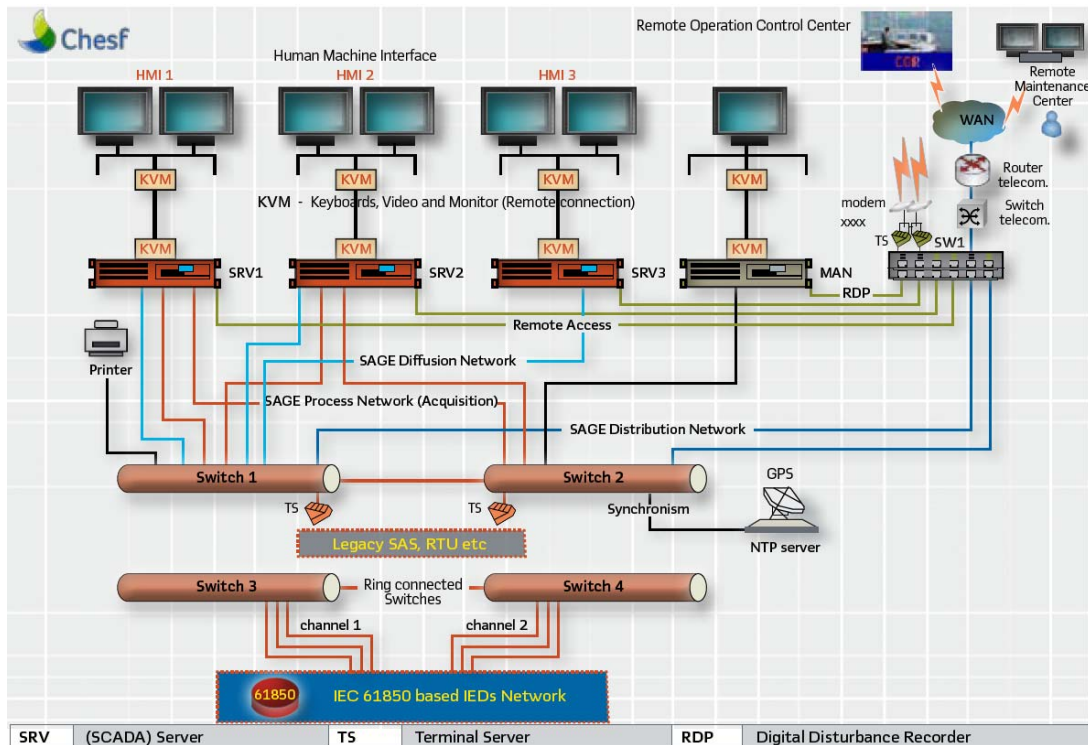


Figure 2: The SAS typical architecture

The SAS network plays an important role for the success of the communication among the IEDs as well as between the several hierarchical automation levels like the process bus, station bus and SCADA systems. It brings new concerns about latency, traffic delays, data storms, switch recovering(grace) times, topologies, filtering, Goose repetition times etc, altogether in the real environment.

4 COMMISSIONING TESTS OF PROTECTION AND AUTOMATION SYSTEMS

4.1

SAT is a very important stage to check the SAS messages and related functionalities, after the final settings applied to the IEDs that are networked together into the real architecture environment. Actually, it is the last chance before the SAS integration to operation.

4.2 Strategies

At first, all previous checks from earlier test stages should be considered and not repeated at all, except when there is a special reason.

Main focus must be on physical connections, installations and the general functionalities of the SAS with the final settings, in the real scenario. The main goal is to check the inputs and outputs of the SAS, while the middle pathway may be seen as a black box.

Different approaches can be considered for SATs, whether aiming for functional tests performing or for hidden failures search. Anyhow, the test coverage definition is used to define in advance the scope of the tests and which tests are enough. Figure 3 shows an example of a test coverage definition model, based on functional tests.

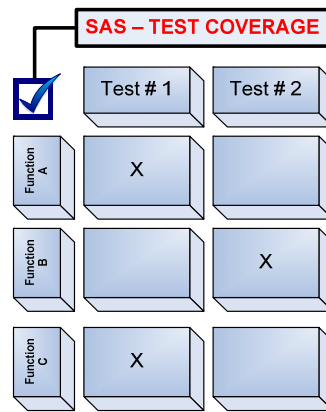


Figure 3: Test coverage model

Thorough planning is very useful and specifies procedures and the minimum inputs or previous conditions for SAT start, for example:

- An important input is the detailed signal lists and its appropriate management related to modifications. It contains all physical and logical connections of the SAS, with the corresponding expected behavior;
- A very obvious but frequently forgotten previous condition is the full assemblage of the field components.

Other important strategies are related to testing Cyber security functions according to specifications, a strategy for integration to legacy SAS and the generation of the overall documentation.

4.3 Methodologies and Procedures

SAT is aimed to test the functionality of the SAS, according to the specifications and standards. SAT procedures are generally set to check the following basic features:

- Visual inspection on identification, assemblage, structured cabling, grounding, painting, cooling, sealing, cleanliness, locks etc;
- Checks on cabling, functional and logical electrical drawings;
- Functional tests on Measurements, Protection schemes, Control, Interlock and Supervision, with the final settings;
- Functional tests on signals, alarms, displays, blockings, synchronization and communication links related to the Human Machine Interface – HMI, SCADA system and integration to other hierarchic levels;
- Software and documentation inventory with software, firmware, system data bases, manuals, technical instructions, check-lists, non-conformities list and reports.

This article is mostly focused on IEC 61850 based SAS. Despite huge engineering benefits, testing approaches are necessary to harmonize with new features, mechanisms and resources. Data models, peculiar messages, network use and other services call for extra checks, as listed below:

- Signal list based checks against semantics, syntax, addressing, routing and behavior;
- Goose, SV and report messages monitoring, failure alarms, quality bits checks;
- Network inspection, monitoring, analysis, security, synchronization and redundancy checks.

Figure 4 shows a compacted example of a test list used in SAS.

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 SUBSTATION AUTOMATION SYSTEM TESTS & CHECKS		Area:	
		Process: Commissioning Tests	
		Procedure:	
INSTALLATION:		DATE:	
Item	Tests and Checks	A	NA
General Functionalities			
1	Minimum inputs and requirements to start SAS commissioning, such as: - Documentation (Project, detailed signal lists, FAT report etc); - Full assemblage of the field components: installation, identification, cabling structure, addressing, AC/CC supply;	☒	☐
3	DC potential distribution check	☒	☐
4	General checks of alarms and statuses of switchyard equipments: <u>transformers, circuit breakers, disconnectors etc</u>	☒	☐
5	General functional checks and drawing updates of the SAS: - check auxiliary relays, timers, mini circuit breakers, circuits etc	☒	☐
6	Primary analog injection and checks for eventual drifts in control, <u>measurement, protection and disturbance recording IEDs</u>	☒	☐
7	Update and issue of 2(two) printed collections of "As commissioned" Drawings for Engineering and Maintenance teams	☒	☐
Automation System - Levels 1, 2 and 3			
9	SAS communication cables and connection checks	☒	☐
10	Optical Fiber attenuation test (Cords and cables)	☒	☐
11	Human Machine Interface functional checks (Levels 1, 2 and 3): <u>Menus, buttons, displays, sounds, events and alarms lists</u>	☒	☐
12	Control Units inputs and outputs	☒	☐
13	Signal simulation of alarms, positions and commands (Levels 1, 3 and 2)	☒	☐
17	Secondary analog injection and checks for eventual drifts in Control Units and Human Machine Interfaces (Levels 1, 2 and 3)	☒	☐
18	Checks in Control Units logical and interlockings	☒	☐
19	Remote access to sequence of events	☒	☐
20	Circuit breaker closing with Synchronization check	☐	☐
21	Time synchronization in IEDs and Human Machine Interfaces	☒	☐
Protection System			
22	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
23	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
24	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
25	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
26	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
27	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
28	Simulation of protection functions: overcurrent, differential, distance, etc.	☒	☐
Disturbance Recordings System			
Remarks: A = APPROVED NA = NOT APPROVED		☐	☐
Performed by:		AREA:	
Revisio 0	Date:	Approved by	

Figure 4: An example of a test list

The use of test bits, simulation and behavior definitions, as from IEC 61850 Edition 1 and Edition 2, offers flexible options for testing.

The Edition 1 had offered an option for system testing, in order to handle isolation to the physical process. Edition 2 comes with many additional features and sophisticated details for implementations in products, with test bits, test modes and test behavior. Despite the current reluctance in trusting these new kinds of features, some day the implemented systems will be matured enough to exploit them. Therefore, testing the “test” functionality itself is very important, in order to be trusted by the users in future maintenance or integration tests

New applications and the development of the IEC 61850 Standard with new features require additional test approaches, to deal with:

- Process bus, Sampled Values, Synchrophasors and applications beyond the substation level, migrating to other Substations and to Control Centers;
- New specific network tests, considering new services and other topologies based on PRP and HSR redundancy protocols;
- New synchronization tests for SAS based on IEEE 1588 protocol;
- Interoperability “minimum” test, to check future compatibility with other systems, in advance;
- Automated tests or on-line applications to monitor information consistency, quality, versions and other features potentially offered by the standard.

4.4 Network communication and redundancy tests

SAS are more and more dependent on the network reliability and its redundancy features. That may be a new field for the SAT teams, although they may not feel much comfortable even in testing network specific features.

Testing can be quite complex, considering the characteristic of the multicast Goose messages with transient publishing times, the redundant network topologies, priority tagging, VLAN use, IED internal processing, switch configuration and so on. There is a need to specify network minimum commissioning tests due to IEC 61850 based issues, like time delays, communication switching etc. A specific technical instruction designed to test basic functionalities and redundancy has been deployed. It provides practical procedures for such checks, followed by filling the appropriate forms. Figure 5 shows an example of a check list used in the referred instruction, with basis on the typical architecture presented in Figure 2.

REDUNDANCY AND COMMUNICATION TESTS (LEVEL 2)
SAGE ARCHITECTURE - 02 SERVERS AND 01 CLIENT

FUNCTION	TEST	BEHAVIOR			COMMENTS
		SRV 1	SRV 2	IHM	
DIFFUSION	Cable SRV 1(NIC eth_) - SW_				CHECKS: HMI displays, windows, analysis softwares, Ping, Protocols etc
PROCESS 1	Cable SRV 1(NIC eth_) - SW_				
PROCESS 2	Cable SRV 1(NIC eth_) - SW_				
PROC. 1 E 2	Cable SRV 1(eth_ & eth_) - SW_				
DIFF. & PROC.	Failover SRV 1 x SRV 2				
DIFFUSION	Cable SRV 1(NIC eth_) - SW_				
PROCESS 1	Cable SRV 1(NIC eth_) - SW_				
PROCESS 2	Cable SRV 1(NIC eth_) - SW_				
PROC. 1 E 2	Cable SRV 1(eth_ & eth_) - SW_				
DIFF. & PROC.	Failover SRV 1 x SRV 2				
DIFFUSION	Cable IHM (NIC eth_) - SW_				
REM. ACCESS	Router w/ Firewall				
SWITCH CONX	Cable Switch 1 x Switch 2				
LEVEL 1 x 2	Cable Switch 1 x Switch 3				
LEVEL 1 x 3	Cable Switch 2 x Switch 4				
REDUNDANCY	Turn off Switch # 1				
REDUNDANCY	Turn off Switch # 2				
RTU / LEG. SAS	IED / TS x SW_				
RTU / LEG. SAS	IED / TS x SW_				
CTRL CENTER	EXT. LINK x SW_				
CTRL CENTER	EXT. LINK x SW_				
SYNCH.	NTP SERVER Cable				
PRINTER	Print request				

LEGEND: SRV = Server SAGE IHM = IHM SAGE TS = Terminal Server SW = Switch
BEHAVIOR: OK = Normal P = Problem N/A = Not Available

Figure 5: An example of a Check-list

4.5 Tools

Vendor´ specific regular tools are used for configuration and loading of the IEDs and network integrated devices. Original and additional tools are used for special purposes like browsing, monitoring, tracing, signal forcing and temporary settings. At present, the SAT team usually uses specific vendor tools to perform the tests, but third party tools are becoming available and tend to be used more extensively. Future use could be in an automated way.

4.6 Documentation

Full test documentation is very important for SATs. Test coverage indicates the necessary tests and results must be registered, in a standardized way, so that it can be easy for later researching and for the maintenance team.

Besides traditional documentation, in the IEC 61850 world extra inputs have shown to be required as well. Goose messages are scattered through traditional insufficient documentation, different IED tools and specific descriptions. So, virtual wiring maps called “Goose Maps” have been developed, with the information flow, sources, destinations, descriptions, addresses etc, as shown in Figure 6. Goose Maps are very useful for tests, in checking messages, associations “publisher x subscriber”, links and descriptions.

Network data like IP addresses, MAC addresses and Port numbers are also very important. Special attention is needed to add on information to the signal lists, comprising all necessary data. The whole process is consolidated with a SAT report.

5 CONCLUSION

In the test chain of a Substation Automation System, SAT plays a very important role. Test requirements must be fulfilled in accordance with the specified functionalities and the adopted technologies.

This paper is a return on experience of IEC 61850 based SAS testing practices, highlighting strategies, methods and tools for commissioning tests. Additional network communication and redundancy testing procedures are described, considering redundancy, architectures, network port switching for link failures, time synchronization and other services.

Important lessons have been learned with practical applications. They provide useful tips and help build testing guidelines, which can lead to the best practices. Expertise is being built with this state-in-the-art technology. It can avoid some initial difficulties and give important feedback. Further work must be done to tackle new deployments and technology advances.

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