Cost-optimized Protection & Control System Testing and Commissioning Process in Turnkey HV Substation Project Business

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Abstract

Major project phases in international turnkey substation business are described. Digitalization, increasing system complexity, new possibilities in testing and a very competitive environment are identified to be the main drivers for the last years' changes in substation testing and commissioning. An optimized testing process is presented, permitting to reduce cost and delay while increasing quality and reliability. A result comparison of two projects in Algeria [1] shows the efficiency of the approach. Finally a special example for anticipated testing, the "mobile substation" project, is presented.

Introduction

Siemens Transmission & Distribution is a French company within the Siemens Energy Division. Based in Grenoble, the company has a long experience in building GIS and AIS substations in France and all over the world, particularly in Africa, Asia and Middle East. Around 1000 employees, active in the local GIS factory, the HV or MV project management, energy automation and the service business are working closely together. They quote, sell, plan, manufacture, test, deliver, erect and commission turnkey substations or rehabilitation projects.

Figure 1: Example GIS Turnkey Indoor Substation

A turnkey project scope normally covers the complete responsibility from civil works, over the substations HV, MV and LV installation up to the protection and control system and their communication interfaces to the grid and to remote dispatching centers.

In a highly competitive environment with permanently rising technical complexity but reduced project delivery delays, well organized and optimized processes are a key success factor in order to insure high quality and reliability at a competitive price level.

One of the most important processes in the overall project schedule is the testing and commissioning of the substation elements at different stages. Potential system errors have to be excluded and total man hour cost to be reduced to a minimum. The duration of this process should be shortened where it is impacting the overall project delay but might even be extended, if advantageous, where being on a "non critical path" for the project delay.

In the Siemens Grenoble Service Division a dedicated team of about 20 specialized engineers is preparing, supervising and partially executing the testing and commissioning on site [2]. The team could significantly improve testing and commissioning results in the last years by combining already in extended factory tests the most important systems, by anticipated involvement of a site test coordination engineer to these tests, by reducing the number of external specialists on site and by the use of modern automatic test equipment.

Changes and history in substation testing and commissioning during the last 20 years

<u>Changes in testing and commissioning</u>

Imagine and compare three situations:

Some fifteen or twenty years ago an experienced protection test engineer could still leave for his site commissioning job, just equipped with the latest folder of setting notes, single line and detailed wiring diagram in his hand and some bulky test equipment in his luggage. After having probably studied his exact task not earlier than in the plane he would have arrived on site for a long mission abroad and the first thing he would have done is probably to wait because some necessary installation works would not have been finished yet.

Then, some ten years later, i.e. about 5-7 years ago, there would have probably sat several experts from the project company and different subcontractors in the plane: one for a specific protection, at least one for the digital control system, one for the meters, one for the telecommunication system, etc.

Probably the installation works would have been ready when they arrived, as project management had improved a lot, but very likely one of these experts would have certainly discovered a problem on site and suddenly the other experts would have had to wait or could at least not have worked in an optimal way as everything was interconnected.

Today, the man who is sitting in the plane looks probably a bit younger. His job is commissioning coordination engineer. Before entering into the plane he has already checked, that he has loaded the latest versions and drivers for the software of the different suppliers' equipment. He has saved the different systems' setting and configuration files and the corresponding test templates. And he knows that he has at least the possibility for remote access and hotline support on site. As he is a polyvalent engineer he is normally doing the protection testing and other tests himself, depending on the size of the project. He supervises the local testing personnel and when some few other experts may to come on site under his control, for a shot, exactly planned period, normally everything will be running correctly because the complete interconnected system has been pre-tested in the factory.

Which were the main drivers for these changes?

In the early nineties many of the protection and control panels were still of electromechanical or electronic type. In the mid nineties the first digital protection devices appeared in the substations. At that time a typical HV turnkey project duration was still around 26 to 28 months.

Around the year 2000, at least in HV, one "main protection" was equipped with a digital device and a redundant "main 2 protection" often remained electromechanical, on demand of the end-customer.

At that time also the first digital control systems (DCS) appeared but only 1 out of 10 turnkey projects was equipped with DCS. The other 90% used traditional control and remote terminal unit (RTU) communication.

Only some few years later, about 5 years back from now, almost all protections used in these projects were digital, but often main 1 and main 2 protections used to be from different manufacturers and/or at least they used a different protection principle in parallel for the same protected device. Digital meters and other Intelligent Electronic Devices (IED) were standard. DCS were used at that time in 90% of the substations in different configurations and all the IEDs had to be integrated via various protocol interfaces into the DCS.

Protocol standardization started already 10 years ago on different levels, from proprietary to national, up to international standards and interfered more and more with the world of a protection engineer.

Today almost every turnkey project is fully digital on station and bay level (DCS and IEDs including protections and bay controllers). Fiber optic and digital interlocking replaced many hardwired copper connections and permit therefore to "shift" connection efforts and testing from the site to the factory. Driven by competition and due to standardization and other improvements, the project duration of a typical HV turnkey project is now reduced to 14 to 18 month (i.e. almost half the time in less than 20 years).

The first projects using the international communication standard IEC 61850 on station level appear in the commissioning phase. The link to the process level (CT, VT, CB, etc.) remains today traditionally hardwired. First pilot projects with non-conventional sensors, merging units and IEC 61850 based process bus exist already and also new tools to test them.

Major phases and milestones of a turnkey project with focus on testing and commissioning

Projects and their organization vary of course depending on the scope and technical, financial or environmental circumstances. Also first projects with a new customer or in a new country are not planned and executed in the same way as repetitive projects or as for example complete power grid renovation programs, where several substations are tendered in one lot.

Nevertheless some major phases can be identified, that exist to a certain extend in any project.

The most important ones are listed and roughly described below, concerning their importance for the testing and commissioning process. It is not the aim to give a complete picture of the project.

Tendering, offer and sales phase

Given the size and importance of HV substations most of the projects are tendered by the customer in a public or private, international tender. Sometimes such a tender is issued with the support of consultants, sometimes by the customer alone after comparison of different suppliers' sales presentations. A more or less detailed specification, sometimes functional, sometimes being very device specific, is then the basis for potential suppliers' and contractors' quotations. These quotations are based, of course, on a cost calculation of the total proposed material, on the total man hour cost estimation for the different execution steps (e.g. the testing and commissioning) and on some other factors.

The evaluation process of an offer on technical conformance and price competiveness is very important but very different from customer to customer.

Very often precise technical issues and solutions are fixed already in this phase, e.g. in our case specific relay types, control system structures or test procedures, having an impact on project organization and price. Such points are later on often difficult to change or require at least a negotiation.

Therefore the proposal of the most competitive solution already on sales level and the involvement, together with the offer team, of different experts and operational managers in this early stage is often a first decisive factor for a successful project execution.

Project management and planning

The task of the project management is to establish a realistic project schedule fitting to the contract conditions and being in accordance with the different project members' and suppliers' capacities and commitments. Nowadays very often "internal contracts" concerning hour-estimations and commitments are signed between the project manager having a transverse responsibility and the different line departments. The project manager's task is also to seize opportunities for improvement and to avoid and manage risks. Anticipation and permanent optimization are here a key issue.
An always updated project plan helps to identify, which activities are on track and which are not. It helps to identify alternative options during project execution.

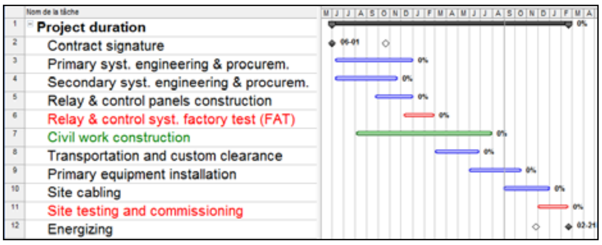

Figure 2: Simplified HV project planning (main tasks) (red: factory & site testing, green: civil works)

As figure 2 shows, the main tasks after contract signature and coming into force are:
- Engineering & procurement of primary and secondary equipment,
- relay and control panel construction,
- combined relay and control system test and FAT (Factory Acceptance Test),
- civil work and construction,
- transport and customs clearance,
- primary equipment installation,
- site cabling,
- site testing and commissioning,
- energizing.

Engineering and design phase & panel construction

Calculations, plans and documents are produced in this phase. Good processes, standardized working methods, and optimally shared information are here important for all involved parties. Concerning the secondary design, the single line, functional and detailed diagrams are produced. Here two important interfaces are fixed and require a good collaboration and anticipation:
- First, the wiring connection to inputs & outputs of all IEDs (relays, control system, meters...), which has to be coordinated closely with the system configuration teams, if not yet being standardized.
- Second, the diagrams which are the work basis for the subcontracting panel-builders who integrate and wire the devices into the panels and who execute a complete point-to-point wiring check in order to guarantee every connection is conform. Any later correction costs time and money.

More and more functions are today done digitally in IEDs, which were still "hard wired" some years before (e.g. generation of residual voltage or current). Hence, the wiring has become much simpler and the manufacturing process more flexible. In case of necessary correction, software changes are easier to do than the change of interposing relays or wiring.

Factory tests and FAT

A differentiation should be made between "factory tests" and "factory acceptance tests" (FAT):
"Factory tests" are internal tests within a company having built or configured a device or a system. It is verified that the tested part is working correctly, conform to the specification and documentation. If necessary, corrections can still be implemented.
In "factory acceptance tests" an internal or external witness attends and certifies to the supplier whether the delivered part is accepted or rejected. It is also possible to accept with remarks or with a list of certain minor pending items to be resolved later at specified deadlines. These witnesses are often the end-customers, sometimes external certification companies or consultants. It can also be a member or a quality inspector of the contracting company's project department itself, confirming the conform reception of a subsystem manufactured by an internal neighbor department (e.g. control & automation system supplier) or from an external subcontractor (e.g. panel-builder).

Figure 3: Factory test: control system (a.l.), protection panel test (a.r.), control-protection-metering interconnection (below)

Factory Tests and FATs exist for all main components and, as will be discussed later, at least the secondary system (Control, Protection, Metering, Communication, etc ...) are nowadays regrouped to one combined test of a complete system. Injection tests are carried out on bay level and corresponding event and fault recording, interlocking as well alarm logging and clearance at the station control system are checked.
Such tests can be carried out in the main factory, at subcontractors' locations or sometimes abroad. An evaluation of practical reasons, experts' travel cost, local labor cost and expected quality is the reason for often choosing a panel-builder's location close to the main factory.

Figure 4: Factory Acceptance Tests with the End-customer

Site tests, commissioning

Once all primary and secondary equipment has been shipped, cleared in the customs, installed and wired on site, the site tests can start.
The target of the site testing is to control each device and to test primary and secondary systems connected together.

- HV devices are tested individually after mounting by dielectric tests.
- Site cabling is checked by primary injection.
- Automation, protection and reclosing cycles are controlled now for the first time with the real primary devices' time constants.
- Data exchange between IEDs and substation control is checked including the information on HV devices statuses.

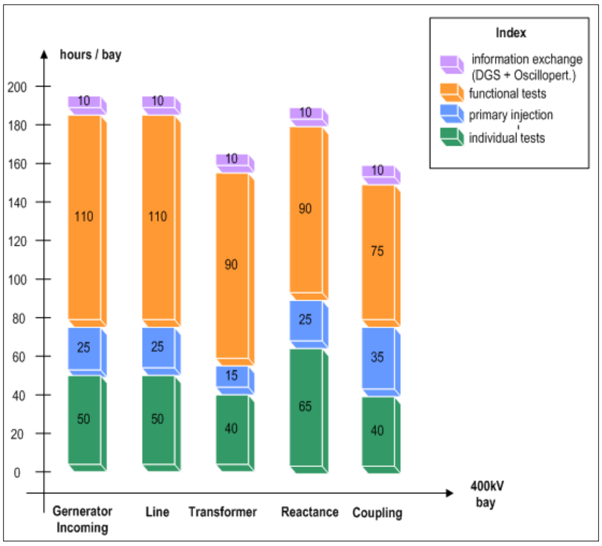

Figure 5: Site test times / bay & task (optimized 400kV project)

Figure 5 gives an overview on the time spent for each task per bay in an optimized and well prepared project.

"Commissioning" is the site acceptance test, normally in presence of a consultant and/or the end customer. Each detailed device-test and overall function is explained, demonstrated and submitted to the customer for written approval of the results.
Depending on the availability of the customer, cultural aspects or other parameters, this approval process can be more or less difficult and time consuming. Therefore it is very important to have validated the correct function of the system before by internal site tests [3].

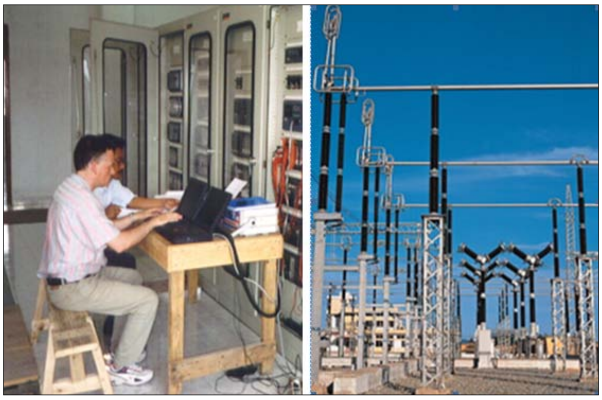

Figure 6: Protection commissioning with the end-customer

Specific tests after commissioning - Energizing

When the substation itself has been tested and commissioned completely, there are often still some tests to be done, before final energizing:
Transmission lines linking the new substation to the grid are most often tendered in a separate lot and the lines are finalized a bit later than the substation. When lines are ready, exact line parameters (line, earth and mutual impedance) can be measured by primary injection devices, in order to obtain the final settings of the distance protections [4].

Once the lines are connected to the substations, an end-to-end testing of the line protections can be done. Primary or secondary injection devices on both ends are synchronized via GPS and apply fault specific conditions to the respective protections [5]. The correct transmission of protection signals via fiber or PLC and the overall protection function can be tested that way.
When the lines are ready and the link of the new substation control system to the above dispatching center control system has been established, the correct remote transmission of commands, device statuses, interlocking, regrouping of alarms and events have to be tested.

Once all tests have successfully been carried out, the substation can be energized.

Trouble shooting – fault analysis – revisions

Not being anymore a part of the project, fault analysis and trouble-shooting are typical tasks for a project being still under warranty or for a service later on. The possibility to collect fault and event recording permits for example to explain why a protection has tripped or not. Modern test equipment offers also the possibility to replay recorded data and to re-inject for example into sample relays on an internal test platform, which facilitates the analysis of specific cases.
When regular revisions are carried out by the customer, the possibility exists to replay exactly the original test routines for the respective devices and to detect by comparison a possible variation in time of a device's performance [6].

Optimization strategies for the testing and commissioning process

The previously described steps of testing can be optimized in order to avoid risks, reduce total cost, shorten the total delay, and increase quality of a project. The most important point is to see the project as a whole and not to optimize simply subparts. To keep this in mind is especially important when different business divisions are involved or where responsibilities are split between Mother Company and Local Setup.

Anticipation and common, extended factory tests

A first key element for optimization of planning is the identification and permanent supervision of the "critical path". The "critical path" is defined as the one sequence of tasks, where a delay in any of these tasks directly causes a delay of the complete project. Other tasks being not on the "critical path" may be shifted, delayed or even increased in volume of work without any impact on the overall project delay.

A second key element is the fact, that the later a system error is detected in a project, the more its modification will cost.
These two points are what all is about in project optimization:
The target is to shift as much work as possible from "critical path tasks" in the end of the project to "uncritical tasks" in the beginning of the project.
Of course there are tasks can almost not be shifted or compressed as typically the civil work and construction.
As shows the simplified project planning (fig. 2) very clearly, the "uncritical" relay and control system factory testing takes place during a long period in which the civil works are on the "critical path". However the site testing and commissioning is always on the "critical path" the end of a project. Therefore in an optimized testing strategy some additional time and money should reasonably be invested in extended, interconnected factory testing, in order to save afterwards many expensive hours on site.
In an extended factory test will be done:

- Combine tests for all important subsystems (i.e. DCS, Protection, Metering, fault recording, clock...).
- Complete individual performance test on 1 device for each TYPICAL protection or IED.
- Complete functional test of every TYPICAL bay panel, interconnected to DCS, using breaker simulators for checking complete reclosing cycles.
- Communication interface and grouped signal test between DCS level and above dispatching level.

Once all "typical" bays and devices have been checked in detail the configurations are copied & uploaded to the protections / IEDs of all "duplicated" bays and devices. This saves time and reduces manual errors. While uploading, it is automatically checked and excluded that one of the duplicated IED doesn't work at all.

On site the complete system should work from the beginning and the preparative site tests can concentrate on all new parameters, which are really site dependant: CT, VT connection, wiring, HV device time constants etc., as described before.

Another example for anticipation in very tight projects is to start certain engineering tasks and specific tests (e.g. anticipated lab test of a completely new relay type or configuration) very early, sometimes even before the signature of the contract. This represents on the one hand a certain risk, as costs are envolved, but gives on the other hand the possibility to immediately identify and eliminate technical risks in the beginning.

One commissioning coordination engineer instead of many specialists

An important point is to maintain specific "knowledge" during all important phases of testing and not to re-discover points on site, which were already known by others before, who tested in factory.

In the same time it should be avoided to send too many experts on site. They all cost a lot of money and are difficult to coordinate.

For these two reasons the new function of a "commissioning coordination engineer" was created. He manages the complete testing process. He is already deeply involved in the FAT of all important sub-systems, he will do site testing of the main functions on site by himself and he coordinates short interventions of some very few specialists on site.

Modern automated test devices and tools

Today modern, multifunctional test devices and tools exist [7] for secondary and primary testing, which permit to anticipate work, to save time and to avoid errors by:

- preparation of test sequences already in the office,
- automatic or step-by-step injection (factory / site),
- standardization of tests,
- use of same test in factory, site and revision,
- automatic generation of personalized test reports,
- replay & injection of fault records for fault analysis,
- synchronized injection of several devices
- remote access and control,
- multifunctionality when testing protections, meters, IEC 61850 communication, primary devices.

Here it is important, to invest some time in good standardized test methods and to train the testing personnel correspondingly.

Of course it is important, that the factory and site testing is done with the same equipment. And it is an advantage for efficient support and good longterm relationship, if also the end customer is already familiar with the test equipment or continues to maintain his substation with the same test routines and tools.

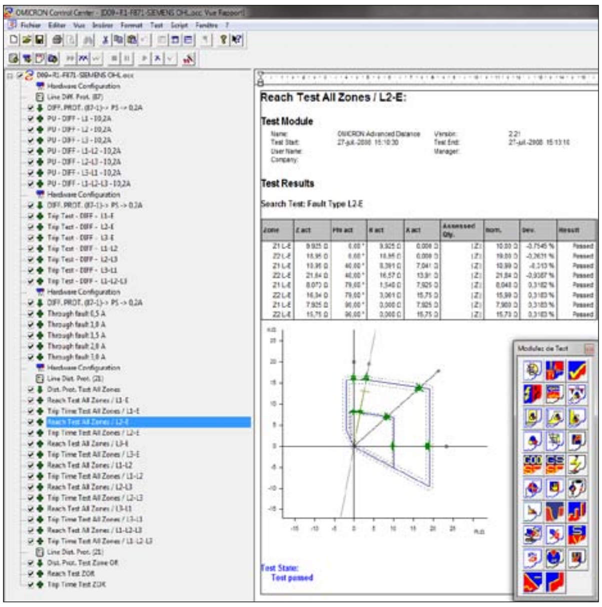

Figure 7: SIEMENS OMICRON Control Center test routine

Figure 7 shows an example for a completely predefined test routine (left) and automatic test protocol (right) for a 220 kV substation's line feeder panel including a main1 line differential protection and a main2 distance protection. This OMICRON Control Center (OCC) test routine is used here for secondary injection with the OMICRON CMC 256plus.

For primary testing, test devices as for example the CPC 100 or the CT Analyzer are used (fig. 8 right). Also here, innovative testing methods permit quick and efficient testing with multifunctional devices. Pre-prepared automated sequences and automatic test reports help to gain time, increase quality and therefore save cost.

Figure 8: CMC test on site (left). Primary test with CPC (right)

Standards for similar bays, projects or substation lots

When bays use the same devices, successive projects with the same customer are almost similar or even when in grid renovation projects many identical substations are tendered in one lot, the project organization has to be adapted in order to benefit of repetition effects.

Test routines in the OCC can easily be configured in a way that only some specific parameters are to be adapted once but all functional tests remain the same. All feeder specific setting parameters then are taken over automatically in the routine.

The time savings concerning testing and documentation are important and organized test preparation pays out as a real competitive advantage.

Result comparison: traditional vs. optimized testing processes of two 400kV turnkey projects for Algeria

Two real 400 kV turnkey projects (names changed) for Algeria are compared, both successfully terminated by Siemens T&D Grenoble.

The first one, here called "TRAD", was executed with the traditional testing organization:

- FAT focused on protection, not connected to DCS.
- Intervention of many specialists, no coordinator.
- Expatriated, and insufficiently trained site testers with "old fashioned" test equipment.

For the second project here called "OPTI" the new optimized testing strategy was applied:

- Extended FAT including DCS etc.
- Commissioning coordination engineer & local team.
- Modern test equipment with trained personnel.

The size of the "OPTI" project was: 11 bays 400 kV, 8 bays 220 kV, 2 transformers, 2 shunt reactors, 20 bay-controllers, 1 DCS, 93 protections of 4 suppliers.

Figure 9: 400 kV AIS Substation "OPTI" (name changed)

The result comparison shows that for obtaining the same good end-quality, 3 times more hours (+600 hrs) were invested in the OPTI project factory testing. However on site a reduction of 500 hours per bay was obtained (fig. 10). This corresponds in the OPTI project with 19 bays to saving of 9500 hours.

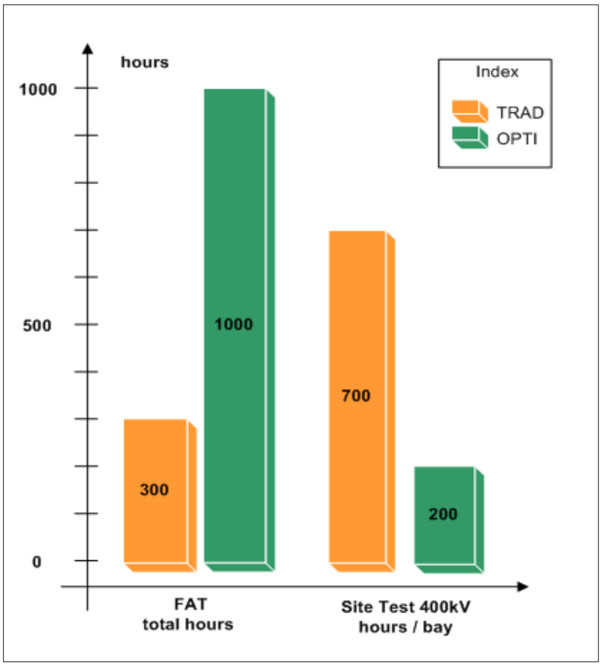

Figure 10: factory & site test time comparison of both projects

Special Project – Mobile Substations for Algeria

The following example shows that projects can be quite different, but that optimized testing processes can still be applied. In this exceptional case a customer ordered 4 mobile 220 kV substations for Algeria. These substations shall be positioned and connected to the grid by the end-customer, wherever a fast and flexible solution at optimized costs is needed, to provide a local MV distribution, fed by the HV transmission system.

These "mobile substations" (fig. 11) are a specific construction and consist of 4 trucks, which are interconnected with short removable line elements via their bushings. On one side the HV line is connected to the "incomer-truck" with lightning arresters and CCVT. Next is the GIS bay, which is mounted on a "GIS bay truck" with breaker and imbedded Digital Control System. Further follows the "power transformer truck", which is finally connected to the "MV switchboard truck", feeding the MV distribution cables.
In this project the protection panels and DCS system was supplied by another Siemens Unit in Belgium for internal organizational reasons. An extended factory test and FAT with interconnected protection, control, metering systems and other devices was organized in Belgium with full involvement of the commissioning coordination engineer from Grenoble.
Of course "civil works" and "cabling" in the traditional sense do not exist in this case. The critical path of this project was furthermore the manufacturing delay of the transformer and GIS manufacturing, the mounting of all devices on special trucks and of course the final testing and commissioning of the installed solution. Mounting and "site"-testing (fig. 8 left) was done at the container solution system integrator's site in France, some 100 km away from Siemens Grenoble. An external consultant attended to the testing. The final customer will come for 3 days for the reception.
The total project duration was reduced to about 1 year.
The contract ends after shipping and delivery of the mobile substations.
Then it will be the task of the end-customer to determine the correct parameters for the relay settings for each new location, to which the "mobile substations" will be connected.

As these projects are finally "highly standardized solutions", which will be ordered always in the same configuration, the big challenge for optimized testing is the use of standardized automatic test routines and reports.

Figure 11: Commissioning of 220 kV GIS mobile substation

Conclusion

With progressing substation digitalization and increased pressure on turnkey project prices and delivery times, an adaptation of testing and commissioning practices became necessary.

An efficient optimization of the substation testing process is possible by anticipated factory testing of interconnected sub-systems, early involvement of dedicated commissioning coordination managers and the use of modern automated test equipment.

The presented example comparison showed that by tripling the efforts in optimized factory testing, the total overall delay and cost of testing can be reduced to half compared to a traditional process.

However future challenges for substation testing and commissioning appear, as technology is continuously evolving. Today more and more substations are tendered with IEC 61850 station bus and the first ones have reached or even passed commissioning phase. Today the first IEC 61850 devices have been configured and tested, often with the help of a control system specialist or a very IT-interested protection expert. In near future complete teams of protection engineers have to adapt their habits and get used to this technology in their daily work.

The next big step, probably appearing on the horizon of future turnkey substation commissioning, could be the IEC 61850 process bus with special relays, merging units and non-conventional CTs and VTs.

Today high performance test equipment already exists for such applications. However people have to get used to it and test processes will have to be adapted and optimized again.

The direction is already visible today: the replacement of copper by fiber also on the process level will permit to extend anticipated factory testing even more and to deliver a completely pre-configured, almost "plug-and-play" secondary system to site.

Glossary of used abbreviations

GIS – Gas Insulated Substation
AIS – Air Insulated Substation
HV, MV, LV – High, Medium, Low Voltage
DCS – Digital Control System
RTU – Remote Terminal Unit
IED – Intelligent Electronic Device
CT, VT – Current, Voltage Transformer
CCVT – Coupling Capacitor Voltage Transformer
CB - Circuit Breaker
FAT – Factory Acceptance Test
PLC – Power Line Carrier
CMC – OMICRON Multifunctional Secondary Test Device
CPC – OMICRON Multifunctional Primary Test Device
CT Analyzer – OMICRON Current Transfomer Test Device
OCC – OMICRON Control Center

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