PROTECTION AND AUTOMATION
B5 - 00

SPECIAL REPORT FOR SC B5

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Special Reporters

Summary

The CIGRE Study Committee B5 – Protection and Automation - covers within its scope - principles, design, application and management of power system protection, substation control, automation, monitoring and recording - including associated internal and external communications, substation metering systems and interfacing for remote control and monitoring.

Two Preferential Subjects are presented in this Special Report:

- PS1 - Protection under System Emergency Conditions
- PS2 - User Experience and Current Practice with IEC 61850 Process Bus.

Contributions of 3-4 minutes are requested, to be presented during the Paris session, to answer the questions below from the authors of the papers, and from the Protection and Control community around the world.

The SC B5 Session is scheduled for Wednesday, August 29th, in Grand Amphithéâtre. The Special reporter meeting where the Special Reporters will meet the contributors will take place in rooms 233, 234, 235 and 237 on level 2 mezzanine of the Palais des Congrès de Paris on Tuesday 28th of August 2018, between 08.30 and 12.30.

The deadline for sending contributions to the Special Reporters is 8th of August 2018, 15.00 CET.

Keywords:
Under Frequency Load Shedding (UFLS), Intentional Islanding, Pole-Slipping Protection, PMU Aided Protection & Automation Schemes, Power Swing Blocking Protection, Novel Fault Location Schemes, Process Bus, IEC 61850, Site Trials and Real Installations, Design and Development, Testing and Commissioning Methodologies, Tools and Facilities to Support Design, Development and Testing, Costs and Benefits Analyses.

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1. PS1 - Protection under System Emergency Conditions

1.1. Introduction

This special report reviews 24 papers submitted by authors from 21 countries. These papers are broadly classified into eight categories for discussion:

1. Load shedding Schemes (USA, JO, CN, KR, NZ, TH)
2. Large/Transmission System Islanding (IN, JP)
3. Distribution and Isolated Power System related (PT, ES, GI)
4. Generator protection schemes (RO, GB, IN)
5. System Protection schemes (BR, CA, HR, RU)
6. Thermal protection (ZA)
7. Fault location (AT, EG, EG)
8. Conceptual System-Wide Protection Architecture (SA, RU)

1.2. Load Shedding Schemes

In power systems, the load and generation if not balanced causes the frequency to fall below nominal value. This causes the tripping of major transmission lines. To prevent the whole system from collapsing, protection schemes like Under Frequency Load Shedding (UFLS) are employed. In this section six papers from different countries study UFLS schemes to ensure the frequency stability of their power grid. The papers below either propose or showcase the performance, of the developed UFLS schemes.

Paper B5-102 proposes the use of R-GOOSE and GOOSE messaging in load shedding. R-GOOSE, unlike TCP, uses UDP multicast as the transport mechanism and also has enhanced security features to enable communication amongst different substations in a network. GOOSE is primarily used within particular substations. In the case of load shedding, the R-GOOSE will be sent upon determination from the grid operator after which an algorithm will be used to determine the best load shedding blocks and sequences. These messages will then be used by individual substations and their respective feeders.

Paper B5-104 provides a detailed description of a case study involving incorrect operation of under-frequency relaying scheme. It was envisioned during UFLS relay setting that the interconnection between Jordan and Egypt would be available but, in this case, it was lost thus triggering extreme load shedding. Apart from incorrect settings on some of the underfrequency relays, there was mis-coordination between the generator frequency protection scheme with the network underfrequency load shedding scheme and this led to loss of some generating units. The rate of change of frequency threshold should be determined from the available loading conditions as in some instances, some feeders with no substantial load to influence the frequency were tripped.

Paper B5-111 proposes off-line optimization model for under frequency load shedding scheme to ensure frequency stability of power grid during extreme contingent event. This scheme coordinates the settings of under frequency load shedding scheme with the generator over frequency tripping following system split. This model is currently applied in Central and Southwest China power grids. The methodology of the scheme is explained in detail in this paper.

Paper B5-112 discusses the new UFLS for Jeju island power system developed by KPX (Korean System operator). The Jeju island power system has experienced rapid changes to its existing system which required re-evaluation of the existing scheme. The new scheme takes into consideration, the new assets such as 200 MW of wind energy system, 400 MW of HVDC link installed between Jeju and Mainland. The various schemes considered for this system are discussed in the paper. The current scheme's UFLS amount is decreased from 52% to 49%.

Paper B5-124 systematically reviews the changes in the Automatic Under-Frequency Load Shedding (AUFLS) scheme being proposed in New Zealand for emergency conditions, and how the distribution utilities have to revisit their protection settings to implement these changes. Operating in an electricity market environment, a new product called as extended reserves is designed to be valued similar to other ancillary services.

Paper B5-212 presents the experiences on the under-frequency load shedding scheme including case studies on the successful and unsuccessful operation. The first case study shows advantage of the under-frequency load shedding scheme under the emergency unbalance power condition in the system. On the other hand, the second case illustrates unsuccessful operation of the scheme caused by inadequate disconnected loads due to under-frequency relays not ready during system emergency.

Question 1.1 - With the integration of renewable source to the existing power grid, what are some of the practical challenges to apply newer and more granular AUFLS schemes for national or continental scale power systems?

Question 1.2 - Are there countries where Automatic Under Voltage Load Shedding (AUVLS) or other specialized schemes are being used or planned to be implemented alongside AUFLS?

1.3. Large/Transmission System Islanding

In power system, severe faults might cause transient instability of a large number of generators which may lead to excessive loss of generation triggering the frequency fluctuation or dynamic instability which finally results in power system separation. In order to maintain the stability of the power supply even under such an emergency, several approaches can be selected. The first paper presents a controlled System Separation method before the system disintegrates to smaller islands considering frequency drop while the second paper focuses on introducing recent examples of stabilization system for power system emergency.

Paper B5-113 proposes system separation scheme for southern regional grid in India. Formation of two larger islands following drop in the system frequency to 47.9Hz arrests the frequency from falling further. The frequency stability in the two large islands will be better. This is verified using the dynamic frequency stability studies conducted on the islanded networks following contingent event using PSS/E software.

Paper B5-121 examines the transient and frequency stability of transmission lines in Japan and proposes Integrated Stability Control (ISC) to replace the traditional transient stability Control (TSC) and System Stability Control (SSC). The adaptability of the system is enhanced by the configuration of Circuit Breakers (CBs) and Disconnecting Switches (DSs). To decrease the probability of outage, Urban Power System Stabilizer (UPSS) which is an automatic islanding operation, is developed and applied. The paper also gives an overview of UPSS and Islanding System Automatic Synchronizer (ISAS).

Question 1.3 - Are there other existing examples for managing controlled separation schemes?

1.4. Distribution and Isolated Power System Related

Some smaller power systems are designed to operate in isolation. Such systems typically have low inertia and are very sensitive to the load-generation balance. On the other hand, some systems are mostly operated in grid-connected mode but have the capability of off-grid operation. Electrical distribution system operators are willing to develop the islanding operation capabilities for different reasons.

Paper B5-120 focuses on performance of MV Energy Storage System (ESS) in both islanding mode and grid connected mode in EDP Distribução distribution grid. Before the deployment, the inverters response time was tested when the system needed to rapidly commute between PQ (Active/Reactive) control mode, used in grid connection operation, to VF (Voltage/Frequency) control mode, used in

islanding mode, thus ensuring a successful island formation. Some adjustments are made to the inverter controller to speed up the recovery of voltage and frequency so that the tripping due to under frequency or under voltage relay operation is avoided.

Paper B5-118 focuses on an optimized under frequency load-shedding (UFLS) schemes for isolated power systems. Isolated power systems are sensitive to load-generation balance for their low inertia. A tool for design, simulation, and analysis of UFLS is presented. This tool is developed based on many operating and contingency (OC) scenarios which are selected using clustering techniques such k-means, fuzzy c-means or KSOM. The optimization problem is solved by either deterministic or heuristic optimization algorithms. The impact of varying step sizes and non-responding turbine-governor systems is studied by an MC approach.

Paper B5-122 describes a case study of the project initiated by Gibraltar Electricity Authority (GEA) to expand the HV grid while significantly reducing the SAIDI and SAIFI. And making the grid flexible to integrate renewables sources. The project involves retrofit and upgrade the existing devices. Upgradation of the automation, control and protection schemes and communication system upgraded to IEC 61850. In the end the paper summarizes the impact of the project, lesson learned and potential future work.

Question 1.4 - What key points need to be considered for Protection & Automation while developing islanding schemes using energy storage within distribution network?

Question 1.5 - What is the recommended ratio between the size of a storage system and the overall generation capacity of a distribution network to operate effectively in an islanding mode?

1.5. Generator protection Schemes

Electrical generators are subjected to both internal and external faults which should be cleared from the generator as soon as possible to prevent any permanent damage. This should be differentiated from emergency conditions that the generator might be required to operate in. The available generator protection schemes should be able to detect and differentiate the different conditions. Great care is to be taken in coordinating the systems used and the settings adopted, so that the sensitive, selective and discriminative generator protection scheme is achieved.

Paper B5-108 presents a generator protection system arrangement. Moreover, it proposes some certain details on the distance protection function and highlights the methods used to detect and trip the generator under pole slip conditions. To support the document a case study for a small size hydropower generating plant is included and some calculations are presented along with a testing method for the out-of-step function.

Paper B5-110 is first and foremost a follow-up to the paper J.L.H. Goody, “Overcoming Problems associated with impedance measurement in pole slip protection for Dinorwig”, IEE Proceedings, Vol. 133, No.1, January 1986 and has been written to confirm some of the conclusions in the 1986 paper. It also covers several developments since 1986, including most notably the separation of the Central Electricity Generating Board (CEGB), closure of nearby nuclear power plants, penetration of renewables, advances in modelling of asynchronous operation of salient pole generators, and new methods for detection of pole slip. These developments are enough to justify the review of pole slip protection settings supported by system studies. This paper also includes topics associated with future power system developments and how this will affect system stability in North Wales and more generally the distribution network. Lastly, the paper explores how these developments could drive changes in the application of pole slip protection.

Paper B5-114 proposes a practical guide for improving the coordination of under excitation limiter with loss of excitation protection schemes during abnormal system conditions. This will prevent outage of generators due to lack of coordination of these 2 systems. The machine capability is matched with

protection relay functionality. The load angle limiter operating curve, and the PQ limiter operating curve is coordinated with protection relay curve.

Question 1.6 - Have other countries had experiences in reviewing their existing pole slip protection settings of synchronous plants either because of changing technology or due to increasing penetration of large-scale wind and solar generation into their network?

Question 1.7 - Are there experiences of abnormality affecting the coordination between the AVR limiters and generator relay settings or practices of using adaptive generator protection settings to handle wider range of system disturbances?

1.6. System Protection Schemes

Analyzing the system stability as a whole rather than focusing on specific generators is useful to assess the capability of the system to maintain integrity. System stability analysis specifically helps to adjust power swing protection and arrangements. By use of phasor measurements from different points of the network, characterization of the different disturbances can aid us in prediction of system instability.

Paper B5-101 provides 2 case studies in relation to operation and performance of large scale oscillation operation after fault occurrences. The first experience entails the non-detection of stable power swings/oscillations that led to mal-operation of distance relays. By use of PMU data through predictive analysis, protection mal-operation would have been avoided. Proof of this was observed in the second case study in which the PMU was used to ensure the desired operation of the oscillation operation. This paper demonstrates the application of WAMPAC from the research field to the practical field.

Paper B5-109 presents the development, implementation and testing challenges of a new modern Special Protection Schemes for loss of synchronism detection, which has been developed inside Hydro-Québec's innovation program in automation and control. The design and functionality of the advanced algorithm solution are first presented followed by the description of the closed-loop hardware integration on the Hypersim real-time digital simulator at Hydro-Québec's research institute. Finally, real-time simulation results and evaluation of the solution is presented to highlight the utility benefits and encouraging outcome of the project.

Paper B5-117 focuses on the angular stability of a power system. Maintaining the angular stability of the system is a must for transmission system operators. Small active power oscillations are tolerable but medium and large oscillations should be detected and isolated from the rest of the system. This paper shares experiences of the progress on Wide Area Monitoring Protection and Control (WAMPAC) in Croatian Transmission Network Operator (HOPS) as an out of step protection based on synchrophasor measurements

Paper B5-123 proposes the implementation and development of a tool to identify the Low Frequency Oscillation (LFO) of a synchronous generator. The method used to dampen the LFO is Automatic Voltage Regulators (AVR) and the results are tested on a real time digital simulator (RTDS). Furthermore, the risk of transition of LFO to asynchronous operations is also eliminated.

Question 1.8 - Are PMU based stability assessment techniques cost beneficial, considering their dependence on an effective and stable communication system?

Question 1.9 - Are there other experiences where establishing the on-line stability or wide-area protection application is constrained by the number of PMU's available in their network?

Thermal Protection

This section focuses on the thermal protection of conducting materials. During network fault, the fault current if stayed for a long period of time can heat up the conductor causing conductor damage (Plastic

deformation). It is proposed to speed up the Inverse Definite Minimum Time (IDMT) elements and apply instantaneous curves to protect the feeders and improve network availability.

Paper B5-116 focuses on IDMT as the backup protection on HV feeders and highlights the problem of delayed operation that can cause a conductor damage. The suggested solution is to use speed up the backup relay operation as well as using instantaneous curves where possible.

Question 1.10 - Are there implementation experiences where time difference between the main and the backup operation have been made adaptive to cater to dynamic line rating or generation run-back schemes?

1.7. Fault location

The need of accurate location of the fault facilitated the development of fault location algorithms and their subsequent implementation in relays. Their use in the transmission system has been proven to be accurate but their use in sub-transmission and distribution is still undergoing some challenges due to network structure. Increased penetration of DGs have also introduced bidirectional power flows thus it becomes necessary to first identify the feeder in which the fault has occurred after which the exact location can be pinpointed. These papers provide some insights on some of the solutions to fault location and fault feeder identification.

Paper B5-105 provides results of a field tests with regards to fault location under single phase to ground faults in a series compensated network. They are the most difficult to detect. Conventional techniques of fault locations are difficult to predict the location of the fault as the magnitude of fault current is approximately similar to the value of load current. A comparison between an improved impedance-based fault location scheme and travelling wave-based scheme was done. Capacitive sensors, as compared to the standard inductive sensors, produce accurate voltage measurement results for fault location analysis. Determination of the faulted feeder was accurate, but it was still challenging to locate the exact position of the fault. Nevertheless, the travelling wave-based scheme was more accurate as compared to the improved impedance-based fault location.

Paper B5-107 presents a statistical evaluation of different techniques for estimating the fault location for parallel-circuit distribution feeders concerning the current transformer (CT) saturation. Two different fault location algorithms are selected using the sequence networks and the apparent impedance methods and they are tested via simulating a real 11-kV parallel-circuit distribution feeder in Egyptian distribution network. These algorithms have been examined under fault condition as fault locations, fault resistance, and high impedance faults. Other conditions such as the CT saturation are considered in the study. A proposed technique is used to avoid the error for fault location determination due to the CT saturation. This highlights the required further consideration for realizing practical and efficient fault detection with the aid of correction methodologies for current CT before calculating the fault distance.

Paper B5-106 investigates a novel directional relaying technique that only require current measurement from the current transformers; hence the use of bulky and costly potential transformers associated with this type of protection in the traditional directional relays are eliminated. Novel directional protection algorithms are presented, that use only pre-fault and post fault current signals for determining fault direction excluding the need of voltage signals. An exhaustive literature review and a comparative study between the suggested techniques illustrating the advantages and limitations of these techniques for the different study cases are provided in this paper.

Question 1.11 - Impedance based and travelling-wave based schemes are reported as the two common fault location techniques. Are there any other known fault location techniques used in practice globally?

Question 1.12 - Are there any experiences and challenges experienced in implementation of fault location algorithms at sub-transmission levels?

1.8. Conceptual System-Wide Protection Architecture

Constructing a consolidated, system-wide protection philosophy is a key step in the development of the Unified Protection Setting Philosophy. Emergency automatics is one of the main factors for on-time detection of emergency disturbances, prevention and elimination of the evolving dangerous emergency modes in power system.

Paper B5-103 provides an experience on the development of a common protection philosophy for the National Grid of Saudi Arabia. This is after the individual operators managing the 380-kV, 230-kV, 132-kV, 115-kV, and 110-kV were amalgamated into 1 state owned operator, National Grid Saudi Arabia. This involved a lot of data collection on all the field relays, their particular functions and their respective settings. Protection coordination studies were then performed to determine if there were any required modifications. Benefits and challenges of such an undertaking are recorded in this paper.

Paper B5-119 analyses the application of emergency automatics systems (EA) widely used in Unified Power System (UPS) of Russian Federation. EA is a necessity in a power system to assure the system integrity during the emergency conditions. Classification of EA systems in Russian UPS, design principles, analyzes of application experience and operation of EA systems are presented. Design principles of preventive automatics for stability control schemes (PASCS) is the focus of this paper since it is the most complex type of EA. Information about development and implementation of centralized emergency automation systems (CEAS) in power systems of Russian Federation is also given here. It is also shown that the implementation of the large-scale solutions of EA is accepted in Russia.

Question 1.13 - How do countries manage coordination of protection functions and their respective settings across their generation, transmission, distribution operators?

1.9. Summary for PS1

Protection and automation under emergency situation covers several interesting directions as have been identified through the contributions received from this Special Report. The contributions and discussions thereof does cover a range of existing and known issues like AUFLS practices and generator pole-slipping through to changes posed due to renewable energy/battery storage into distribution and identifying newer methods for fault identification to help quicker restoration. New technologies like PMU through to establishing nation-wide protection system philosophies have also emerged as key interest areas from some countries.

The contributions and discussion during this preferential subject during the 47th CIGRE session in Paris will directly feed into informing the ongoing working group document of CIGRE WG B5. 54 Protection and Automation Issues of Islanded Systems during System Restoration/ Black Start, whose technical brochure is likely to be released by the end of this year.

PS2 - User Experience and Current Practice with IEC 61850 Process Bus

1.10. Introduction

Preferential Subject 2 for Paris Session 2018 is "User Experience and Current Practice with IEC 61850 Process Bus", particularly associated with the following topics:

- Interoperability between merging units, stand alone and associated to NCIT, and Protection functions,
- Experience from FAT, SAT, commissioning and maintenance of process bus- based equipment and functions,
- Use of process bus for metering and monitoring of HV equipment.

A total of 16 papers from 15 different countries (including joint papers) have been received for this Preferential Subject. These papers can be broadly divided into 5 groups, most papers covering more than one topic:

- Site trials and real installations (8 papers, Section 2)
- Design and Development (3 papers, Section 3)
- Testing and commissioning methodologies (2 papers, Section 4)
- Tools and facilities to support design, development and testing (3 papers, Section 5)
- Costs and Benefits (1 paper, Section 6)

1.11. Site Trials and Real Installations

It is rather encouraging to receive eight good quality papers about site trials and real installations of Protection, Automation and Control (PAC) systems using IEC61850 process bus. Three papers presented "Piggy-Back" pilot schemes (with tripping and control outputs disabled) in parallel with existing protection and control functions; and 5 papers described real installations of digital PAC systems either for a bay or a whole substation. It is particularly exciting to learn (Paper B5-209 in Section 3) that there have been over 1500 digital substations in service in China. All the papers shared experiences gained from the design, configuration, testing and commissioning of their projects covering almost the full range of topics under this preferential subject.

Paper B5-203 presented a pilot project within Statnett to explore the Digital Substation Automation and Protection System (DSAS) using IEC 61850 9-2 process bus. The "pilot project" was a "piggy back" trial, installed in a live 300kV feeder bay. The objective is to gain experience with Non-Conventional Instrument Transformers (NCIT) and process bus installations including equipment from multiple vendors. The project also challenged traditional design principles by investigating the feasibility and practicality of some new ideas including the use of one common IED to protect and control two transmission lines, and a single computer (Linux) for the PAC functions for multiple transmission lines. Topics such as tests and simulations, time synchronization, network structure and traffic management were discussed in the paper. To achieve good vendor interoperability, the paper believes that users should produce an application specification with sufficient details of requirements for function implementation, tests and simulations.

Paper B5-207 presented a site trial of a multi-vendor digital substation and automation system – FITNESS project, aimed to test vendor interoperability at station, bay and process bus level. It is being installed as a "piggy-back" trial at the Wishaw 275kV substation in Scotland, with two feeder bay PAC solutions from different suppliers. The project also examines the impacts of mixing technologies, which is very likely to occur during the transition phase from traditional hardwired schemes to new modern fiber optic-based schemes and demonstrates that the designed architecture is capable of supporting all the application needs. This paper focused on a series of off-site tests and provided findings and suggestions to improve/optimize the performance of a PAC system.

Paper B5-204 describes real installations of IEC61850 based digital substations as part of the Smart Grid Project within the Helen Electricity Distribution Network. It is a further stage of "digitization" based on previous experience, deploying process bus for the PAC functions at the substations for the whole Medium Voltage ring in Kalasatama. The applications include Digital Switchgears with NCITs (both Current and Voltage Sensors), combined Station Bus and Process Bus with Sampled Values (SV) and GOOSE message applications for full digital PAC functions including busbar protection. The main objective of this project is to achieve high reliability of power supply on the MV distribution network, and also to test new technologies for future applications. The project was successfully commissioned in January 2018, the detailed experience on the system design, project execution and commissioning were discussed.

Paper B5-211 presents another real installation of process bus-based PAC functions. A digital PAC solution was installed for a feeder bay at Bhiwadi 400/220 kV substation with an NCIT (Optical CT) and Switchgear Controllers installed in the switchyard. This was a pilot project to evaluate the architecture design, engineering process, and device performance of the process bus applications under different configurations. The outcome was used to leverage the specifications and test requirements for India's first full scale commercial implementation of a digital substation at Malerkotla. A dedicated station bus and process bus with VLAN engineering are recommended by the paper to optimize the network traffic, and issues with duplicated GOOSE messages in the network were raised as a particular concern for cyber security.

Paper B5-213 also reported a real scheme of a process bus application installed at an EPCOR substation in Canada. The scheme was for a Circuit Breaker Fail protection, however the architecture for the entire substation PAC system was evaluated as part of this project. As it was the first process bus application, only products from a single vendor were used. The application used the Parallel Redundancy Protocol (PRP) for physically segregated process bus and station bus with IEEE 1588 (PRP) time synchronization mechanism, and VLANs are also deployed for the benefit of cyber security and bandwidth reduction of the communication network. The device health monitoring via GOOSE was discussed in the paper, and the "GOOSE single line" diagram was used in the project as a useful reference for deciding which relays need to be blocked during testing and maintenance.

Paper B5-214 described a "piggy-back" trial project within Red Eléctrica de España (REE) to prove the "interoperability" between the process bus application and conventional technology. The trial was installed for the line differential protection of the 220 kV Mudarra-Montearenas overhead line, with one conventional end and the other end using Process Bus (PB) fed by an NCIT to the IEC61869-9 standard. The key challenges discovered from the hybrid scheme include the resilience to lost SV (errors resulting from communications), hardware issues as well as the time compensation for the Process Bus delay. The protection remained stable under various fault scenarios such as loss of time signal, communications and power supply; however, the loss of time synchronization actually resulted in the differential protection to block. The experience gained from the engineering, testing, commissioning as well as cyber security considerations were also discussed in the paper.

Paper B5-215 reported experience from RTE's "Postes Intelligents" project, which was to design, test and commission a completely digital, IEC61850 based PAC System. The paper focused on the challenges from testing and commissioning of the project, including tests of functions using Sampled Values (SV), the FAT and SAT Strategies for the NCITs as well as interoperability and time synchronization issues. As the merging units and switchgear control IEDs may be located in outdoor cubicles near the primary plant and the protection equipment in the relay rooms for a digital PAC system, the authors suggested that there might be benefitting to split the testing between the "outdoor" and the indoor equipment. With support by appropriate simulation tools for the part of the system that is not under test, this testing methodology should make the tests much simpler prior to the end to end testing on site. The paper also shared some practical experience of working on the outdoor devices such as Merging Units under adverse weather conditions. The importance of Basic Application Profiles (BAP) was emphasized as a key to achieving vendor interoperability, and the use of the built-in features within

the IEC61850 Ed 2 standards to test individual functions during maintenance whilst retaining other functions in service was also discussed in the paper.

Paper B5-216 presented a digital PAC pilot scheme for a full generator unit (including the step-up transformer) at Nizhegorodskaya hydropower plant, Russia. The project was to evaluate the operability and conformance of the IEC 61850 digital system under real operating conditions, in order to establish the requirements for commissioning, testing and maintenance of the new technology. The system used physically separated process bus and station bus with both NCITs (current and voltage) and Standalone Merging Units for a whole set of PAC functions for the generator-transformer bay, including energy meters. The IEEE 1588 PTP was also used in this application, and a special information security "complex" was developed to monitor the traffic quality and activities of the communication network. The detailed findings from the FAT and SAT of the pilot were discussed.

Question 2.1 - What are the benefits and drawbacks of a PAC system architecture with physically segregated or VLAN segregated process bus and station bus? What are your views and experiences on the PRP and HSR applications?

Question 2.2 - With a staged approach to implement process bus-based PAC systems, initially restricted to limited functions/bays, how is the interface to be managed with the existing conventional protection systems and how is the migration to a full digital substation going to be approached?

Question 2.3 - What cyber security measures should be considered in an IEC61850 digital PAC system to detect and prevent security threats, especially for the functions (e.g. Time Synchronization) using GPS signals which can be maliciously corrupted or "spoofed" as cyber-attacks?

1.12. Design and Development

To address the challenges from the implementation of IEC 61850 process bus-based PAC solutions, three papers particularly focused on the methodology and process for the design, development and engineering of the digital solutions.

Paper B5-201 shared the experience of implementing an IEC61850 DSAS based on surveys carried out by Brazil Cigré B5. It described different implementation processes, methodologies and architectures for delivering the DSAS projects with main strengths and weaknesses. Key principles to specify, design and engineer a DSAS were discussed. The concept of "more or less digitized process interfaces" was introduced to enable the combination of conventional and digital technology for process bus applications. Although the IEC 61850 station bus-based PAC functions have been widely used within Brazilian utilities, the process bus applications were still "little explored". A number of development strategies for the DSAS was discussed, including options using a utility company's own resources, partially out-sourced, and fully out-sourced, however the paper pointed out that utilities should at least have sufficient knowledge to specify, evaluate and supervise the delivery of a DSAS project. It was pointed out that one limiting factor to the successful implementation of the new technology was the organizational structure.

Paper B5-209 summarized the issues and challenges associated with the engineering of process bus applications for IEC61850 PAC systems, based on the experiences from the large volume of digital substation projects in China. By studying the efficiency improvement requirements for system configuration, commissioning, fault diagnosis and maintenance, the paper proposed some specific solutions to improve the engineering efficiency and operational reliability, which included the use of the bay SCD file to improve system integration, the "multiple states" maintenance methodology, as well as monitoring and visualization tools to help fault diagnosis.

Paper B5-206 described a design methodology for IEC61850 digital substations, based on National Grid's Architecture for Substation Secondary Systems (AS^3). The methodology defines interoperability boundaries between device functions within a bay over process buses as well as functions distributed

across bays over the station bus, with the aim to achieve functional interoperability between solutions from different vendors whilst optimizing the engineering process and time. A lab-based Virtual Site Acceptance Testing and Training (VSATT) facility was presented in the paper for assessing the digital substation design. The VSATT consisted of a RTDS based testing platform to simulate substation primary systems, and the PAC solutions from five different suppliers. The facility also included an in-house developed monitoring tool to visualize data flows in the IEC 61850 network to validate the information exchanged. The findings of the interoperability testing were also discussed in the paper.

Question 2.4 – With consideration of functional performance and network traffic management, should the busbar protection, particularly a distributed scheme, be integrated into the same architecture with other PAC functions within an IEC 61850 digital system, and why?

Question 2.5 - What are the main contributing factors to the reliability and efficiency of the engineering design and implementation process for an IEC61850 based PAC system**? (e.g.** modification of SCD files as a result of a configuration change, configuration tools, etc.)?

1.13. Testing and Commissioning Methodologies

To ensure the design is fit for purpose, and system configurations and installations are properly executed, two papers are dedicated to the testing and commissioning methodology for process bus-based PAC functions/applications.

Paper B5-202 systematically discussed the requirements and methods for functional tests of a fully digital PAC system using the IEC 61850 Process Bus. The discussion covered the testing at different levels of a complex digital system, for both individual devices as well as the system as a whole. Typical testing methods such as "Black and White box testing", "Bottom-up and Top-down testing" were described for different types of tests. As a key principle, it was emphasized that once a digital PAC system was put in service, it should not mal-operate even if there are any problems in any of the components within the system. The paper proposed some particular methods to address the challenges associated with testing and commissioning of a digital substation with NCITs. Details regarding how to use testing features defined in Edition2 of IEC 61850 were also discussed.

Paper B5-205 presented the fundamental concepts and structures of numerical relays, with the methodology for testing and validation at various stages of relay life cycle. The contents covered design, development, production as well as the FAT, SAT and in-service tests for the equipment with both conventional technology as well as IEC61850 process bus and NCIT applications. The test philosophy and responsibility at different stages of the relay tests were also discussed in the paper.

Question 2.6 -What are your views and experience on the test and simulation features specified in the IEC61850 standard, especially use of the features to test and commission individual functions in an otherwise operational, in-service bay?

Question 2.7 - What characteristics and features should be tested for the functional chain with NCITs and digital protective IEDs?

1.14. Testing Tools and Facilities

To support the implementation of the digital substation with IEC 61850 process bus applications, three papers presented the tools and facilities for the design, engineering and testing of the digital systems.

Paper B5-210 presented a portable IEC61850-9 Sampled Value (SV) generation device with up to 20 channels, transmitting 80 SV frames/cycle per channel. It is capable of testing the basic operations and the performance of a process bus-based current differential busbar protection, without the need for voltage/current generation equipment or Merging Units. The device could provide a low cost and efficient facility for testing process bus-based busbar protection, which otherwise would be rather

complicated, costly and time consuming due to the larger number of digital and analogue signals required. As the device is also capable of generating fault-level currents and voltages, it could be used for development testing, the FAT, SAT as well as commissioning of process bus applications. The paper described the design, development and application of the device using a KEPCO 154kV substation supported by test results and further development discussions.

Paper B5-208 theorized that PAC systems adopting a process bus network could be applied to any size of transmission substation. However further tests are necessary to prove the point. As such the paper presented a laboratorial assessment of a process bus network architecture using a testbed equipped with real and "virtual" IEDs as well as a simulated Portuguese transmission substation. The aim was to demonstrate the performance of IEC61850 process bus technology under "close to real" conditions. The latency, link utilization and trip time were the KPIs used for the assessment, and particular focus was on the differential busbar protection and breaker failure function which receive GOOSE and SV data from all the relevant bays. In addition, the tests were also designed to help understand how scalable the PAC system solution is, in order to define the Quality of Service requirement for the switches in the communication network.

Paper B5-217 described the development of an active testing field, capable of assessing the interoperability, conformance, as well as the quality of the communication network for IEC 61850 digital substations. The "Digital Substation Testing Field" (DSTF) was built on the basis of an existing 110/10 kV substation in Russia, consisting of a substation part and a laboratory part. The substation part provides the physical environment including a control center with IEDs, measurements, communication network, time synchronization equipment as well as NCITs and SAMUs. The laboratory part is mainly an RTDS with other testing software and hardware to simulate disturbances required to verify the designed functions and performance. In addition, a portable tool was developed within the facility to assess the traffic on the communication network (for GOOSE messages and SV streams etc.). Apart from the benefit to reduce the need and costs for site trials for the development of the digital substation, the DSTF could also be used for information security analyses and staff training.

Question 2.8 - As the process bus-based PAC systems do not have hardwired connections between IEDs, what methods/tools can be used (or are available) to test the GOOSE message, SV and MMS communication so that the "point to point" connections can be checked during site installations and commissioning tests?

Question 2.9 - Is there a size limitation to the application of process bus technology for a substation? What KPIs should be adopted to determine the performance of an IEC61850 process bus network?

1.15. Costs and Benefits

Paper B5-204 briefly touched upon the cost issue and expressed a reserved view on the economic viability for the implementation of digital PAC solutions, despite other benefits achieved from successful delivery of their "digitalization" projects.

Question 2.10 - What are your views and experience regarding the economic viability for deploying the IEC 61850 based PAC systems?

1.16. Summary for PS2

It can be clearly seen that the PAC functions using IEC61850 process bus have moved from the development phase to the "era" of real installations. Nearly half of the submitted papers under PS2 presented pilot schemes/practical projects of the digital solutions. Most of the reported projects were involved with process bus applications using both Non-Conventional Instrument Transformers (NCITs) and Standalone Merging Units (SAMUs), no major issues were reported regarding the interoperability between these devices. Generally, vendor interoperability at different levels of an IEC 61850 PAC system can be achieved by having a clear specification with sufficient level of technical details (data

modelling, configuration, testing requirements etc.), and it is the users' (utilities) responsibility to develop such a specification. However, the interoperability between the configuration tools from different venders tends to be a common problem for a multi-vendor digital system, and close collaborations between users and suppliers are needed to resolve the issue.

Time synchronization is recognized as one of the important aspects for the design of IEC61850 based PAC functions, especially for managing the time delay on the digitization chain of process bus applications. A common practice is to use the IEEE PTP with GPS signals as the source reference for the function. As GPS signals can be maliciously corrupted or "spoofed", it may be necessary to avoid GPS "dependence" in the design for the benefit of cyber security. Concerns have also been raised about the information security, particularly on the use of the GOOSE message within process bus applications. Some specific solutions have been proposed to mitigate the risks including the one using VLAN technology. With increasing concerns of the cyber threats to the power industry, the function of "intrusion" detection and protection is certainly a future development area for IEC 61850 based digital systems.

Functional testing, including the FAT, SAT, commissioning and maintenance tests, plays a crucial role for the successful implementation of an IEC 61850 based PAC solution, and the site testing and commissioning of a process bus application with NCITs presents a particular challenge. Some practical and effective methods have been proposed and trialed for testing both equipment and system as a whole. Experience shows that the built-in testing features defined in the IEC61850 Standard ED2 can be rather effective if deployed properly. To facilitate large scale rollout of IEC61850 PAC systems, some further development in the area of commissioning and site testing is deemed to be necessary.

To support design, development and delivery of the digital substation with IEC 61850 process bus applications, several testing devices and facilities were presented. The visualization function within some of the facilities to monitor the traffic and data flow on the network of the digital systems is particularly useful to validate the information exchanged between IEDs. It would be a great help if such a function can be further developed into a portable device for the purpose of site tests and commissioning.

Finally, as substantial user experience has been gained on the technical aspects of the IEC 61850 process bus applications, it is also the right time to examine the economic viability of such a system and remind us of a fundamental question: What are the main objectives and benefits we try to achieve with the digital solutions?