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SPECIAL REPORT FOR SC B5 Protection and automation

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Session Papers

Session Papers focussed on a number of Subjects – referred to as 'Preferential Subjects' – selected in advance by the 16 Study Committees of CIGRE and available in the Call for Papers.
Session Papers are selected through a two-phase review process – abstracts and full Papers.
Have a look at the Technical Programme - the list of selected Papers for the Session, and so have an overview of subjects that will be discussed. It is updated as Full Papers review proceeds.

Format of CIGRE Sessions

At CIGRE Sessions authors are given the opportunity to present their Paper during half-day specific meetings – the Poster Sessions.
Four days are also dedicated to 'Group Discussion Meetings' organised by Study Committees. Four meetings run simultaneously each day from Tuesday to Friday, under the presidency of the Study Committee Chairs. The purpose of these meetings is the discussion of the Session Papers on the basis of "Special Reports" which incorporate the gist of the Session Papers and raise a number of questions for discussion.
For fruitful discussions delegates are strongly encouraged to read the Papers before the Session.
The set of Session Papers is made available for downloading to all duly registered delegates before the Session through their private account on the registration's portal. Papers are also readable on the Session smartphones application on site in Paris.
Follow our Session latest news and General Programme - by regularly visiting our website.

Introduction to SC B5

The CIGRE Study Committee B5 – Protection and Automation - or SC B5 for short, focuses on Protection, Control, Monitoring and Metering, and aims to cover the whole Power system, end to end related to this topic, from transmission, to distribution systems, including generation.

Two Preferential Subjects are presented in this Special Report:

- PS1 - Practical experiences and new developments of process bus
- PS2 - Acceptance, Commissioning, and Field Testing for Protection, Automation and Control Systems

Participating in the 2024 Paris session

All registered delegates are invited to participate in the discussion of the topics in this Special Report at the B5 Group Discussion Meeting on Tuesday 27th of August 2024 in the Grand Amphitheatre (Level 1) at the Palais de Congress de Paris.

The reporters have compiled 21 questions, these are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified in across the papers. This provides the opportunity for a broader response and participation in the discussion session.

We encourage you to share your views or experiences *in response to the specific questions* in this report.

Procedure for contributions.

1. Contributors should **upload your contribution** on the **registrations portal** – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials **before 10th August 2024, 18.00 CET** for a prior screening and a good organization of the Group Discussion Meeting. **Important points;**
    - Access to contribution uploading is given only to duly registered delegates.
    - As a consequence, **registration to CIGRE Session** should be finalized before uploading contribution(s) online.
    - Register now for the Session **registrations**
    - Contributions uploading will be open at beginning of June.
2. Special Reporters will review the prepared contributions (Power point presentation with max 3 slides and a written word file with max 1000 words per contribution). A guide for contributors as well as templates and sample pages will be available on the Paris session 2024 webpage. Any recommendations or changes to the contributions will be provided to the contributors by the Special reporters directly on the Registration platform between **10th of August and 16th of August 2024**. Contributors are encouraged to visit their account on the **registrations** portal to see the result of this review.
3. All contributors with accepted/finalised contributions will be contacted by the Special reporters of SC B5 by email between **10th of August and 16th of August 2024**, to finalize the presentation and receive the instructions regarding the session. There will be a limit of about 30 contributions for each Preferential Subject (PS1 and PS2) of SC B5.
4. Deadline for sending the poster for your paper is **10th of August 2024**

There might be the opportunity for spontaneous contributions during the session, which will only be verbal with no slides. Attendees who make a spontaneous contribution, are encouraged to summarise their contribution as a short, written response for the Proceedings. This text is required to be forwarded within two weeks after the SC B5 Session by **Tuesday September 10th 2024** to be considered in the proceedings.

No new contributions will be accepted after the 10th August 2024.

Authors of SC B5 Session papers are required to present their papers during the **SC B5 Poster Session scheduled for Monday 26th August 2024, (**14.30-18:00). Template and instructions on poster preparation are available on the CIGRE 2024 Session website. Posters will be displayed on digital screens. **A draft copy of the poster must be uploaded to the ConfTool platform by Wednesday 31st July** for review by the poster session convener. A final version, incorporating any requested changes, must be uploaded by **Friday 16th August 2024**. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session, he/she or the relevant National Committee is requested to send a substitute.

Key dates for SC B5

- **Saturday 10th August 2024, 18.00 CET** – Latest date for prepared contributions to be submitted for review.
- **Thursday 22nd August 2024:** Authors informed that their contributions will be included in the Discussion session, with a time slot.
- **Monday 26th August 2024,** 14.30-18:00: SC B5 Poster Session. All paper authors are invited to present a digital e-poster. This is an opportunity for you to meet authors and discuss papers.
- **Tuesday 27th August 2024,** 08.45 – 18.00: **SC B5** Group Discussion Meeting - Grand Amphitheatre (Level 1). Prepared contributions and this Special Report will be presented and discussed.
- **Wednesday 28th of August 2024,** 08.30-10.20: SC B5 Tutorial - Protecting a changing power system

1. PS1 - Practical experiences and new developments of process bus

1.1 Introduction

The preferential subject PS1 of CIGRE B5 Paris session 2024 is entitled "Practical experiences and new developments of process bus", which is the same preferential subject as the 2018 Paris session. Due to an increasing number of developments and projects of process bus related solutions, SC B5 decided to focus on the same topic again in the 2024 Paris session. Instead of the 17 papers written for the 2018 session, this special report covers 45 papers from 22 different countries. Roughly half of the papers focus on real-world implementations, while the remaining half present findings from laboratory or university studies.

The prominence of discussions surrounding centralized, virtualized, and wide-area Protection, Automation and Control (PAC) applications indicates a significant trend. Specifically, the adoption of the IEC 61850 standard plays a pivotal role in enabling these applications, with the necessary technology infrastructure already established.

While the practical experience and developments of process bus cover multiple different domains, this special report groups these papers in:

1. Reference projects (18 papers)
2. Centralized and virtualized PAC (11 papers)
3. Wide area process bus applications (5 papers)
4. Time synchronization (4 papers)
5. Process level data acquisition (7 papers)

1.2 Reference projects (18 papers)

(Non-)economic drivers

All across the world, an increasing number of (fully) digital substations is being commissioned, utilizing IEC 61850 process bus. The **increasing commercial availability** of Intelligent Electronic Devices (IED), Process Interface Units (PIU) and Low-Power Instrument Transformers (LPIT) connecting to the process bus sustains this trend. No less than 18 papers describing a variety of projects and explaining the (non-)economic drivers confirmes this fact.

Commencing with **Paper B5- 10265** (FR), this article partially previews the outcomes of CIGRE WG B5.69. The working group specifically focuses on the topic of PS1. The paper provides a comprehensive overview of **60 reference process bus projects**, all meticulously analysed by the working group. While most of these projects pertain to TSO substations, there is also a **noticeable upward trend** in process bus applications at the DSO level. In addition to other findings, the paper outlines the (non-) economic drivers. Interestingly, numerous non-economic drivers can be seen as a translation of the **diverse anticipated benefits** offered by process bus solutions.

Paper B5- 10844 (BR) outlines four real-world implementations, offering valuable insights into practical lessons learned and potential benefits. For instance, it discusses the potential **reduction of CT cores** through the utilization of process bus technology. Additionally, the paper highlights the significantly **simplified busbar protection** (relying on ANSI 87B) achieved by leveraging station-wide available Sampled Values (SV) streams.

Several papers explore the impact on capital expenditures (CAPEX). **Paper B5- 11146** (UK) offers a comparative overview of CAPEX in projects between Vietnam and Australia. Meanwhile, **Paper B5- 11669** (IN) presents a case study and uniquely emphasizes **sustainability benefits**, which could be significant. Additionally, **Paper B5- 10746** (CH) and **Paper B5- 10262** (FR) delve into process bus applications, specifically addressing space constraints.

Interoperability & time synchronization
Practical implementations demonstrate that **technological interoperability has reached maturity**. Surprisingly, no papers address communication protocol interoperability issues. However, at the (protection) application level, there is room for improvement. Six specific papers - **Paper B5- 10367** (IT), **Paper B5- 10504** (PT), **Paper B5- 10708** (BE), **Paper B5- 10746** (CH), **Paper B5- 10846** (BR), and **Paper B5- 11788** (ID) - highlight time synchronization and related interoperability issues. These issues range from **unexpected blocking of protection functions** to false tripping. The extensive research on this topic highlights its importance and emphasizes the need for **further improvements**. Interestingly, the unpredictability of behaviour makes users and asset managers slightly nervous. Chapter 1.5 delves into time synchronization specifics. Notably, **Paper B5- 10745** (CH) utilizes IEC 61850-9-2 Edition 2.1 with an updated SmpSynch implementation, resulting in a **stable application**.

Architecture & performance
Most papers also show the used or proposed architecture. For redundancy purposes, the Parallel Redundancy Protocol (**PRP**) **is commonly used**, instead of using High-availability Seamless Redundancy (HSR)-rings. Both **Paper B5- 10708** (BE) and **Paper B5- 11666** (IN) show a critical analysis on PRP and HSR redundancy protocols.

Both Virtual LAN (VLAN) and MAC address filtering are commonly used to perform sophisticated network traffic management. These techniques are of significant importance in order to create a stable network architecture, **preventing overloading the network**. Due to this importance and in order to optimize the engineering workflow, **Paper B5- 10708** (BE) proposes to include switch port configuration in the IEC 61850 Substation Configuration Language (SCL). A rare example of a process bus network without this kind of network traffic management solutions is **Paper B5- 10304** (FR).

Paper B5- 10504 (PT) suggests using synchrophasor data utilizing the GOOSE protocol for inter-bay functions to conserve bandwidth. Other research papers have also explored this topic (see chapters 1.3 and 1.4).

Low power instrument transformers
Surprisingly, only two papers are dedicated to low power instrument transformers. **Paper B5- 10421** (US) refers to a quiet revolution, provides a **very complete summary** of the recent standardization effort and provides an overview of benefits. It covers both HV and MV applications. **Paper B5- 10969** (NO) is the only paper which is dedicated to practical LPIT experiences. It starts off with an introduction to optical current transformers (OCT). It is advisable for utilities starting with OCTs to read this paper. Requiring OCTs needs a different way of specification, testing and commissioning.

Case studies
Three papers, namely **Paper B5- 11387** (JO), **Paper B5- 11650** (IN) and **Paper B5- 11669** (IN) describe specific case studies, as a starting point to attain towards a fully digital substation. These case studies can be beneficial for utilities which consider moving towards fully digital substations.

Question 1.01 – What are the best practices in network traffic management for fully digital substations, e.g., in combining process bus and station bus?

Question 1.02 – How to ensure predictable protection and automation behaviour in case of time synchronization issues?

Question 1.03 – What are the possibilities for enabling new functions in process bus based substations, e.g., advanced Disturbance Analysis, PQ and Asset Monitoring?

Question 1.04 – What are the best practices on IEC 61850 system configuration management for process bus-based substations, during the project- and operational phases?

1.3 Centralized and virtualized PAC (11 papers)

Introduction
We are on the eve of the introduction of a new technological trend: Centralized Protection and Control (CPC) and Virtualized Protection and Control Systems (VPC). No less than 11 papers related to this topic have been written for the 2024 Paris session. Many papers describing CPC clearly state that this evolution is **the only way forward to leverage the maximum benefits** from IEC 61850 based process bus. The boundaries of CPC and VPC are from the different authors point of view **varying from a couple of bays to wide area protection** and automation system, see also chapter 1.4.

To gain the understanding of CPC concepts, **Paper B5- 11439** (DE) provides an **excellent introduction in CPC**. It describes the benefits, hard- and software constraints and highlights the impact on future Asset Management related topics. Furthermore, a comprehensive overview of the different possibilities in virtualizing is provided with explaining the differences between Virtual Machines and a Containerized approach.

(Non-)economic drivers
Paper B5- 10809 (RU) states clearly that CPC or VPC solutions are **necessary to gain maximum CAPEX and OPEX reduction**. The worldwide ongoing electrification needs simple, cheap but also flexible systems. This is underlined by **Paper B5- 11142** (DE), which describes the economic viability of CPC in medium voltage substations, with the use of cost-efficient Process Interface Units (PIU) without protection functions. **Paper B5- 10628** (ES) mentioned that the implementation of (backup) protection functions in the PIU means losing many benefits the CPC or VPC can offer.

Technical viability
No less than nine papers, namely **Paper B5- 10100** (FI), **Paper B5- 10106** (FI), **Paper B5- 10420** (US), **Paper B5- 10503** (PT), **Paper B5- 10532** (SE), **Paper B5- 11220** (CO), **Paper B5- 10628** (ES), **Paper B5- 10632** (ES) and **Paper B5- 11439** (DE) from universities and vendors are highlighting studies and laboratory trials. All papers confirmed the technical viability of CPC solutions. **Operating times are mostly in line with state-of-the-art distributed PAC systems**. Increased performance is measured in **Paper B5- 10628** (ES) and **Paper B5- 11220** (CO).

With the introduction of CPC solutions, it is most likely that in future also different instrument transformers have to be connected. **Paper B5- 10532** (SE) elaborates on combining three different data acquisition methods: 1) direct CT/VT, 2) SAMU connected CT/VT and 3) LPIT connected via a MU. It highlights the good dependability and security without any incorrect operations, also in special conditions.

Engineering & Testing
When moving towards CPC or VPC solutions, a good understanding of IEC 61850 and its beneficial features is necessary. It all begins with a stable basis, namely the engineering phase. A good overview of implementing a **top-down engineering** process into a utility is provided in **Paper B5- 11142** (DE). A stable SCL file as basis could help the testing process. **Paper B5- 10100** (FI) elaborates on the design and specification of a CPC solution, with **taking unknown future extensions into account**. This paper also provides a good explanation of the **IEC 61850 test mode handling**.

Next steps
There are however remaining challenges ahead. E.g., a standardized way for enabling redundancy concepts seems to be missing. The scalability limits of CPC solutions are mostly based on the implementation of basic overcurrent protection schemes, while in real implementations at least differential and the complicated distance protections algorithms need to be running. **Paper B5- 10503** (PT) indicates that built-in cybersecurity can be considered as a key advantage of centralized solutions.

Question 1.05 – What are the constraints and the simplification strategies for enabling large-scale CPC and VPC solutions, e.g., regarding system architecture, engineering, commissioning and testing?

Question 1.06 – What is the proposed strategy for future CPC and VPC replacements, both for MV distribution and HV transmission substations?

1.4 Wide area process bus applications (5 papers)

Wide area process bus applications could be tightly related to Centralized protection. Both are utilizing IEC 61850 process bus enabling the solutions. Wide area applications however do rely heavily on wide-area time synchronisation and wide area networking capabilities. A simple, but an extremely beneficial and applicable wide area process bus application is **vendor-independent line differential protection**. **Paper B5- 10807** (RU) considers such a line differential protection, providing a time synchronization solution where one IED is defined as time source. An artificial short-circuit has been created on a 220 kV overhead line to verify the behaviour of this protection in practice.
Paper B5- 11112 (DE) wrote also about this topic, where the complete chain is described starting from the utility's point of view with the aim of **avoiding proprietary protocols** and vendor lock-in and leveraging maximum benefits from installed PIUs. The installed time synchronisation mechanism, the engineering process and even the organizational impact are evaluated. It has to be stated that **utilities can demand this functionality** as it seems that in principle the technology is in place.

Paper B5- 10427 (US) elaborates on an Inverter Based Resources (IBR) dominated distribution grid, utilizing a wide area protection system. With a node-based architecture, providing different nodes working together with a master node, an state estimation based protection scheme is enabled. The aim of this scheme is to provide a protection scheme, which is immune to the characteristics of a modern, IBR-dominated distribution grid. Introducing also fault location, isolation, and service restauration schemes (FLISR), it moves towards an Automatic Distribution Management System (ADMS). For this wide area application, it is proposed to **convert the Sampled Value (SV) streams into synchrophasors** to limit the needed bandwidth. This synchrophasor approach is in line with the **Paper B5- 10813** (RU), however comparative numbers are not provided.

A wide area, virtualized protection scheme utilizing process bus in combination with 5G telecommunication networks is considered in **Paper B5- 11094** (UK). This paper combines techniques described in **Paper B5- 10106** (FI) regarding GOOSE over 5G using VxLAN technology and different other papers in relation to protection virtualization. Hardware in the Loop tests using a Real-Time Simulator shows promising results, which are in line with current available literature.

Question 1.07 – What are the benefits and constraints of implementing vendor-independent line differential protection schemes based on Sampled Value streams or Synchrophasor data?

1.5 Time synchronization (4 papers)

Process bus applications heavily rely on the availability of high-precision time synchronization. Four papers wrote specifically about this topic. **Paper B5- 10801** (RU) is considering the impact of **lost GNSS signal** and the impact on the short-term protection availability. It proposes changes to the PTP standard, but also bigger SAMUs are proposed to keep the protection functionality available with loss of synchronization. **Paper B5- 11445** (DE) evaluates different **time synchronization concepts, both for local and wide-area applications**. The main goal is to have a **predictable protection blocking behaviour**: protection blocking is a particularly good mechanism to prevent false tripping.
It must be mentioned that **Paper B5- 10708** (BE), discussed in chapter 1.2, described a situation of a blocked trip signal in case of lost time synchronization.

The results of extensive PTP time synchronization testing and **profile compatibility** are reported in **Paper B5- 11457** (CO). It confirms that compliance testing is necessary considering the diversity of

profiles. **Paper B5- 11778** (TW) provides a solution for holdover time optimization and compares the stand-alone behaviour of different crystal oscillators.

Question 1.08 – What are the alternatives to obtaining and distributing a reliable time source in the event of a non-reliable GNSS signal?

Question 1.09 – What is the risk-based impact on protection blocking due to re-synchronisation, and what are the proposed solutions to mitigate the operational risk?

1.6 Process level data acquisition (7 papers)

The introduction of the different **IEC 61869 standards** is a **cornerstone** in the further introduction of process bus applications. Seven papers are evaluating (Standalone) Merging Units and/or Process Interface Units (PIU), with topics varying from engineering considerations until data modelling proposals.

Paper B5- 10204 (CN) considers the combination of MU and Binary I/O into a PIU to limit the number of different devices in 220 kV and 500 kV substations. The main consideration is the **combination of SV and GOOSE** and the impact on transmission delays in SV streams in the case of a burst of GOOSE messages. Strict response time requirements need to be met and the paper shows positive results. In China, already 60,000 PIUs are installed at 110 kV level, which has stable operation and fully meets the requirements. **Paper B5- 11231** (JP) is closely related to this work, with a comprehensive study to process bus operating times.

Paper B5- 10514 (NL) is providing considerations of IEC 61869-9 compatible SV stream implementations, where this standard provides **SV stream flexibility**, some incompatibility is recognized in subscribing IEDs. The paper proposes a remerging application to convert SV streams into IEC 61850-9-2LE profile. Both **Paper B5- 11003** (BR) and **Paper B5- 11656** (IN) are concerning IEC 61869-9 compatible SV streams, in relation to the legacy IEC 61850-9-2LE profile. The papers are providing a **comprehensive overview of bandwidth usage using different profiles**. In line with **Paper B5- 11445** (DE) described in chapter 1.5, **Paper B5- 11003** (BR) also confirmed that no information about **protection blocking** times is being found in IED manuals. The paper concluded (in contradiction with the **Paper B5- 10628** (ES) and **Paper B5- 11142** (DE)) with the recommendation to include basic protection functionality in PIUs, making them IEDs again.

Paper B5- 10261 (FR) describes the PIU requirements in order to **support a large-scale rollout**. The paper describes the utility's considerations towards the introduction of PIUs and provides a good introduction to the term Process Interface Unit. There are constraints related to the large-scale rollout, from the **IEC 61850 engineering process** point of view, where PIUs are proposed as modular units. A common Application Programming Interface (API) has been developed to support seamless configuration and administration. The paper also provides data modelling suggestions for PIUs. This is in line with **Paper B5- 10349** (US), which is an excellent description of the elementary elements of **IEC 61850 based data modelling**. It provides principles which can be used for several types of process-near intelligent interfaces.

Question 1.10 – How does the IEC 61850 engineering process support modular PIUs to enable standardized solutions?

2. PS2 - Acceptance, Commissioning, and Field Testing for Protection, Automation and Control Systems

2.1 Introduction

The preferential subject PS2 of CIGRE B5 Paris session 2024 is entitled “Acceptance, Commissioning, and Field Testing for Protection, Automation and Control Systems”, which is the same preferential subject as the 2013 Study Committee B5 Colloquium Belo Horizonte, Brazil. In the last decade, Protection, Automation and Control systems (PAC) have evolved technologically, driven by the IEC 61850 standard and the evolution of electronics and communication networks, enhancing the capacity of IEDs, Wide Area Monitoring, Protection, and Control (WANPAC) solutions and virtualization.

This evolution also requires a new testing strategy, especially software, virtualized environments, and Real time simulator for WAMPAC. Testing is a fundamental part of the implementation, operation, and maintenance process.

This special report reviews a total of 59 papers on PS2 from 25 different countries. These papers can be broadly classified into five groups:

1. Engineering process and tools in Digital Substation (15 papers)
2. Aplication Tests in Digital Substation (10 papers)
3. Tests associated with inverter-based generation sources - IBR (7 papers)
4. Wide Area Monitoring, Protection, and Control (WAMPAC), including Travelling Waves (TW) and Synchrophasor (20 papers)
5. General testing applications (7 papers)

2.2 Engineering process and tools in Digital Substation

The increase in the application of the IEC 61850 standard in Protection, Automation and Control Systems (PACS), especially with the application of the Process Bus, motivated its implementation by utilities in order to guarantee the security, scalability and cost improvement of PACS in implementation and maintenance. This involves the engineering process and tools for all stages of PAC system.

Paper B5- 10713 (BE) highlights the value of top-down engineering process that gives real opportunities to globally enforce the PACS test process and makes it more reliable, starting in the specification stage while creating templates until realization of projects to verify user profile and conformance of chosen IEDs. Testing during all stages of the engineering process and development of automatic testing leads to more reliable PACS that can be deployed in an efficient and industrial way.

Paper B5- 10263 (FR) gives an overview of the different tests and the associated approaches and tools implemented for R#SPACE project aiming at an industrial rollout of fully digital, IEC 61850 based multi-vendor PACS. This includes conformance and interoperability “pre-integration” tests of components, end-to-end integration tests covering the complete testing cycle: FAT, SAT, and commissioning tests.

Paper B5- 10869 (SE) describes a lab environment that has been established by a Swedish DSO to validate the test method and test routine for an IEC 61850 process bus based digital substation. Tests are created by applying a Hardware-in-the-Loop concept to make the lab environment as close as possible to the reality and meanwhile reduce the cost and space for the lab environment.

Paper B5- 10870 (SE) presents a user defined prototype of a consistency validation tool for IEC 61850 substation system integration configuration. Functional requirements have been listed and an

open- source IEC 61850 library is used as basis for the development. Consistency validation includes the commissioning phase, as well as operation and maintenance.

Paper B5- 10368 (IT) provides an overview of the SAS2021 project and its associated design and specification methodology, including tests, which guarantees standardization at several levels. The initial engineering effort is justified by numerous benefits over the whole PACS lifecycle.

Paper B5- 10798 (RU) presents the development of a Continuous Integration/Continuous Deployment (CI/CD) - inspired framework for the commissioning of protection, automation, and control systems (PACS). It considers the increase of software-based (or virtualized) protection and control devices, the increase of software updates for protection and control devices demanding frequent testing of updated devices.

Paper B5- 11162 (AT) proposes a pioneering model-based, service-oriented, and collaborative engineering and validation platform tailored for smart grid automation applications. The difference is in the discerning integration and advancement of existing methods, creating an integrated framework specifically designed for the power and energy domain.

Paper B5- 11403 (DE) shows the evolutions of a user-centric tool approach for engineering, commissioning, and operation of protection and automation IEDs. These tools enable power system engineers to configure typical via predefined libraries, optimized for standard applications. User-centric tools speed up FAT or SAT, offering automated configuration and early software verification through virtual copies that behave identically to real IEDs.

Paper B5- 10850 (BR) points out the need to monitor Process Bus communication traffic, in order to help substation operating teams to fully understand the causes leading to most of the malfunctions occurring in a PACS. A tool and test results are presented in order to meet the new requirements in accordance with the National Grid Code.

Paper B5- 10847 (BR) aims to conceive the usage of device management systems to be responsible for the secure remote connectivity with devices giving capabilities to reliably perform changes in firmware, configuration, setting, sending, and getting data which enables the capability to perform automate a series of activities, especially tests, reducing SAT tests or in-person maintenance.

Paper B5- 10851 (BR) presents different strategies that can be applied to monitor the PACS. Use of the resources provided in IEC 61850 standard in Logical Nodes, taking advantage of the information that the devices themselves can diagnose, involving physical conditions, quality, and absence of digital, analog and time synchronization signals, and monitoring the signals on the network, comparing with the project described in the SCD file.

Paper B5- 10852 (BR) considers that vPACS is at the forefront of the technological development of PAC systems. It explores the testing requirements in this new paradigm by comparing the requirements for testing physical IEDs with those for testing virtual IEDs (vIED). In addition, it presents testing in the vPACS context using both physical test sets and virtual test sets, comparing the differences of each testing method.

Paper B5- 10423 (US) describes the experience and perspective while in the interoperability tests (IOP). It presents work with the System Configuration Tool (SCT) vendors to develop the SCD file describing the substation, communications, and signal flows of the system under test in the IOP. The system developed was highly unique in that it incorporates a multi-vendor solution with devices from numerous vendors.

Paper B5- 11423 (FR) presents the development of IEC 61850-6-3 in TC57 WG10 task force, on a new standard part covering the use of the Object Constraint Language (OCL) to validate any IEC 61850 eXtensible Markup Language (XML)-based files, including System Configuration Language

(SCL) files. This standard and the associated tooling have the power to drastically improve the quality and interoperability of SCL files used during IEC 61850 substation procurement, engineering, and testing phases.

Paper B5- 11217 (CO) presents the advantages of using digital twin tools in detecting anomalies and solving problems in protection equipment that can speed up decision-making and improve response times. The impact on efficiency and cost is directly related to the time that protection experts dedicate to finding solutions for anomalies in the power system. Therefore, with the traditional methodology, physical equipment is required. In contrast, with the Digital Twin, the simulation is moved to a virtual environment where only a Digital Twin usage license and an internet connection are required.

Considering all of these approaches, we can formulate some questions:

Question 2.01 - The engineering process is fundamental in the application of IEC 61850. A Top-Down application has great value for Utilities. Is this effort actually taking place in companies, and are the solutions market-based or internal developments?

Question 2.02 - What is the maturity of the tools and systems capable of effectively testing a PACS, and what level of expertise does this require from teams?

Question 2.03 - The reliability of the PACS is associated with redundancy and monitoring of system conditions. Is this aspect being considered within the engineering process, including the application of tools?

Question 2.04 - Virtualization is an expected development process for PACS based on IEC 61850, advancing vPACS and Digital Twins applications. They are very powerful solutions, but how are we planning the future of these solutions to ensure they will be applicable to different vendors and work in an integrated way?

2.3 Application Tests in Digital Substation

Tests related to the PACS of an IEC 61850 substation are essential to ensure the correct operation of the system. Their application alone is not sufficient for success, it is also requires the procedures established at the various stages of the process. Furthermore, the qualification of the teams and the correct tools to carry out the tasks are essential. Experiences in pilot projects, simulated environments and real implemented projects are building knowledge to change and improve all testing processes involved.

Paper B5- 10422 (US) addresses testing of protection systems in digital substations which requires a good understanding of the architecture of the system and the functionality of each of its components. It describes two basic protection systems based on conventional and LPIT: Distributed system with multifunctional IEDs and centralized system with redundant substation protection and control devices.

Paper B5- 10428 (US) highlights aspects of the evolution of the electric power system to meet the demands and needs of customers so too the acceptance, commissioning, and field-testing practices. This evolution not only involves new equipment but also the introduction of advanced technology to provide more flexibility in operating and maintaining the grid.

Paper B5- 10631 (ES) presents a detailed analysis of the implementation of the IEC 61850 standard in electrical substations, with special emphasis on the benefits it provides in the laboratory testing phases of IEDs and its positive impact on the economic aspects of the companies.

Paper B5- 10797 (RU) presents, based on pilot Process Bus application projects, changes in the maintenance of the PACS. It highlights the change in documentation and procedures, the importance

of the state simulation mode (test mode) of the precision time source and requirements for the algorithms and logic of the IED.

Paper B5- 10849 (BR) identifies challenges and limitations in achieving interoperability and testing PTP time synchronization among diverse devices, particularly in Process Bus. It highlights the lack of standardized testing methods and the need for more comprehensive testing solutions. Standardizing testing methods, detailing PTP frame parameters, and establishing a comprehensive test set can address these challenges.

Paper B5- 10877 (KR) highlights the expectation to improve the reliability of digital substation operation, with a focus on reducing test time and cost, and driving the technological process for digital substation at interoperability test standards and test automation systems. Test automation system was applied to verify interoperability with all devices installed and operating in Korean digital substations.

Paper B5- 11451 (CO) emphasizes the need to assess the behaviour of IED during contingencies on information on the Process Bus. The test architecture involves a real-time simulation (ATP-RTS) capable of Hardware-in-theLoop testing, an IED, and network monitoring equipment. A packet loss model is implemented in the simulator to evaluate the IED's performance during contingencies.

Paper B5- 11807 (QA) proposes smart testing solutions for the digital transformation of power grids. It explores aspects of testing including compliance with communication protocols, protection automation and control, and asset performance with some practical examples. Testing solutions are integrated with central management systems.

Paper B5- 11821 (TH) presents the experiences related to the procedures and processes implemented in acceptance testing. It outlines the formats and methodologies used for testing and commissioning at substations. Electricity Generating Authority of Thailand (EGAT) has adopted the concept of digital substations and implemented four pilot projects by renovating existing conventional substations to study and evaluate their performance.

Paper B5- 11901 (CN) Gujarat Energy Transmission Corporation Limited (GETCO) has adopted IEC61850 standard based substation automation system and modernized the control and protection systems. Based upon above narrated findings during testing, it becomes evident that performing required conformity tests to identify and resolve protection and automation system problems.

Considering all of these approaches, we can formulate some questions:

Question 2.05 - Test procedures are changing in the different development stages of the IEC 61850 based PACS. One of the expectations is that they can be optimized by avoiding the repetition of all tests in the different stages of FAT, SAT, commissioning, and maintenance. Is this optimization really happening?

Question 2.06 - The IEC 61850 standard defines several features to perform tests safely and effectively. Are these resources being applied?

2.4 Tests associated with inverter-based generation sources (IBR)

The challenge of including inverter-based generation sources (IBR) in the power system brings enormous challenges, including protection and control aspects. One of the most critical functions is distance protection, especially on the lines that connect renewable wind and solar generation to the system. The effort to find better solutions also includes finding ways to test and simulate systemic conditions.

Paper B5-10104 (FI) shares experiences on the real events and false operation of distance protection due to the lack of awareness and coordination in new possible operational points and studies cases of

the effect of the reactive power capabilities of IBR in various operational points of the grid. It discusses different possibilities to mitigate the risk of an unintended trip of a distance protection.

Paper B5-10105 (FI) investigates the performance of distance protection in the Finnish power system when the share of converter-connected generation increases, and analyses potential challenges for distance protection for a small-scale and a large-scale simulation. The most challenging situations are also tested on physical relays to analyse the reliability of the simulation results.

Paper B5-10107 (FI) presents practical experiences on cases where harmonics have caused maloperations during power system faults in the Finnish transmission grid. There have been four different false operations where the distance protection has operated incorrectly. It shows that the transients of current and voltage measurements during the faults and the relation of the rms and fundamental frequency measurements values are important factors. It seems that when the fault current levels decrease the relative proportion of the harmonic frequencies can increase which might cause calculation inaccuracies and possible maloperations in the protection functions.

Paper B5- 10424 (US) describes a hardware-in-the-loop (HIL) test with a high-capacity real-time simulator to test six commonly used protection models from five vendors. The tested includes detailed RTDS electromagnetic transient (EMT) system models. Distance and overcurrent protections tested with the base case settings showed incorrect protection operations under Hi-IBR scenarios. The tests of setting/configuration adjustment mitigation solutions showed improvement but could not mitigate all incorrect protection operations.

Paper B5- 11322 (UK) offers general recommendations for configuring and testing distance and directional overcurrent protections in complex offshore wind collector networks. It highlights that the application of current typical setting recommendations are not the best option with non-conventional networks. For all these operating characteristics and polarization techniques, guidelines for properly setting their main parameters were established.

Paper B5- 11458 (CO) addresses the challenge of safely incorporating inverter-based generation sources (IBR) into transmission systems. To address this issue, an Electromagnetic Transient (EMT) dynamic model was developed in a simulation software to conduct fault analysis in transmission systems with unconventional renewable sources. The modelled control for the IBR considers the injection of reactive power and negative sequence current under fault.

Paper B5- 11599 (DK) utilization of Voltage Source Converter (VSC) HVDC links in weak or isolated HVAC grids has introduced some challenges for HVAC protection systems to detect HVAC system faults in traditional ways. This is particularly prevalent in the offshore wind industry for offshore HVAC grids in HVDC-connected wind farms.

Considering all of these approaches, we can formulate the following question:

Question 2.07 - There is an effort to adjust the distance protection to Inverter Based Ressources (IBR) by improving or creating new settings in the relays. Can this strategy really solve the problem or do we need new developments in protection algorithms?

2.5 Wide Area Monitoring, Protection, and Control (WAMPAC), including Travelling Waves (TW) and Synchrophasor

The evolution of Wide Area Monitoring, Protection, and Control (WAMPAC) as a system protection strategy advances due to the increase in the complexity of the power system and the difficulty of adequate performance without this vision. The application of Travelling Waves (TW) also contributes, both for fault location and protection functions. Synchrophasor has advanced in its application of system control and protection. For all these approaches, carrying out application testing is essential, which involves simulations supported by real time simulators.

Paper B5- 10429 (US) proposes a solution to implement the FLISR logic in a fully distributed manner, through peer-to-peer communications amongst distributed Intelligent Electronic Devices (IEDs). In addition to fault location and service restoration, the proposed solution offers fault detection in a coordinated manner.

Paper B5- 10505 (PT) presents the solution developed and discusses the Hardware-In-the-Loop (HIL) infrastructure used to test the performance of the centralized protection system. A distribution network and substation test model, based on the CIGRE MV benchmark network, was developed within the real-time simulator that connects to the CPC and to MV feeder physical Intelligent Electronic Devices (IEDs).

Paper B5- 10629 (ES) describes the application of current differential protections, that supports the change of configuration that i-DE is deploying in the 30 kV network. It presents the requirements, steps taken to design and select the algorithms to be used and their adjustment, the acceptance of the specific protection model through simulations carried out on RTDS to ensure that the functionality is adequate for said network, the installation and field tests in the network and the real cases of fault once under operation.

Paper B5- 10630 (ES) presents the development of a WAMPAC system in the Greek transmission system. Based on voltage and current synchrophasors, different algorithms have been designed and implemented. To evaluate this algorithm, it was deployed in a Real-Time Automation Controller (RTAC) that operates as a Phasor Data Concentrator (PDC). A real-time laboratory tested with a Real-Time Digital Simulator (RTDS) was used to debug the RTAC implementation.

Paper B5- 10806 (RU) contains recommendations for the commissioning of fault localization devices depending on the method being used. The possibility of using combined methods is addressed using two different combinations of impedance and spectral methods, topographic and two-way wave methods as examples. For each specific case, it is necessary to select a different fault localization method, taking into account all the specifics of commissioning.

Paper B5- 10815 (RU) presents development for emergency control (EC), relay protection (RP) and implementation of advanced technologies for monitoring the dynamic behavior of energy systems in real time based on phasor measurement units (PMU) and phasor data concentrators (PDC). It also shows four types of PACS tests.

Paper B5- 11019 (DE) presents a concept to integrate an adaptive protection system into the control system environment. The presented graphical user interface enables manual changes from protection engineers and visualizes results of an adaptive protection system performance analysis. The decision support tool is evaluated in a field test in northern Germany, where new protection devices are installed in a parallel operation mode to the already existing devices.

Paper B5- 11109 (AU) describes a wide-area broken conductor detection scheme under trial which uses thousands of voltage detection points across a distribution network rated at 11 kV. The aim of the trial is to detect broken conductors and wires-down faults for which traditional protection schemes perform poorly. It describes the scheme and summarize the acceptance and commissioning processes chosen, and high contrast with traditional schemes.

Paper B5- 11456 (CO) presents an EMT-based protection coordination study considering Modular Static Synchronous Series Compensator (M-SSSC) FACTS Technology in the Atlántico region of the Colombian Transmission System. It introduces a relay modelling approach and presents an adaptable automation framework for various protection manufacturers. This contributes to test of protection performance under diverse scenarios.

Paper B5- 11493 (JP) presents the development of a protection for Black Start (BS) situations, motivated by a strong earthquake which struck Hokkaido, Japan, in 2018 that caused a blackout. Analysis software was used to simulate these situations, and the specification required for the BS protection was defined, especially by dynamically changing the setting values in response to the grid voltage. Tests were carried out to confirm correct operation and determine the setting values, in addition to performance tests.

Paper B5- 11496 (JP) introduces a new Special Protection Scheme (SPS) for the stabilization control of pumped storage hydropower plants operating as a balancing power source in power system. It performs various controls based on its locally measured quantities like voltage and current after a fault clearance. To improve the efficiency of them algorithm, a tool was created that simulates the control action of new SPS.

Paper B5- 11497 (JP) proposes an N-1 Inter-trip Scheme that uses the installed capacity reserved for emergencies. This scheme uses power supply control to immediately stop or reduce the output of grid connected generators when a single equipment failure (N-1 failure) occurs in the power transmission. This promotes the possibility of the introduction of more renewable energy. The solution applies IEC 61850 MMS, using SBOw. Tests confirmed the adequate performance for the control system.

Paper B5- 11745 (GR) presents the methodology and results of the WAMPAC for transmission network of Albania TSO - OST. The systematic methodology covers all the stages of such a study, from data collection and system modelling to simulation-based analysis and definition of evaluation criteria. The importance of regularly reviewing relay settings in a transmission system is highlighted, showing that critical protection reliability issues may arise due to an out-of-date system model, or inconsistent relay setting calculations between different substations.

Paper B5- 11756 (CO) analyses the impact of the integration of the Modular Static Synchronous Series Compensator (M-SSSC) by using real-time simulations with Hardware-in- the-Loop (HIL) technique, over the protection coordination schemes in the area of influence. The results show that it can be successfully coordinated with the protection schemes, mitigating overloads through the transmission lines during steady state and contingencies.

Paper B5-10103 (FI) presents Line differential protection tests to compare SDH, hybrid SDH / Multi-Protocol Label Switching Transport Profile (MPLS-TP) and native MPLS-TP inter-substation communications in a live telecommunication network with real protection and telecommunication devices, measuring real differences between the interfaces and telecommunications technologies. The test results prove that with a correct design, the teleprotection signal transfer times and line differential trip times can be reduced.

Paper B5- 10848 (BR) presents limitations of traditional commissioning methodologies in the current scenario of IBR-rich systems, pointing out the historical evolution of commissioning technologies. A special attention was given to TW-based functions, because they require commissioning strategies capable of reproducing signals with a wider frequency bandwidth, hence, electromagnetic transient simulations, real-time simulators and innovative commissioning playback solutions were discussed.

Paper B5- 11137 (DE) presents a short introduction of traveling wave fault location, followed by a discussion of possible source of inaccuracy for single ended and double ended traveling wave fault location. Factory acceptance test and site acceptance test are explained in detail using practical examples. It also exposes how to verify the settings, especially the propagation velocity of the line. This can be done after putting the system into operation, using data from the first external faults.

Paper B5- 11418 (DE) describes a method for characterizing and modelling the current and voltage instrument transformers for protection applications to especially improve the high-frequency models for applications like traveling waves. In this process, signal generators and methods typically used for well-known EMC tests to prove conformity with established standards have been applied.

Paper B5- 10425 (US) presents some testing recommendations and experiences reported in the brochure TB 843 of SC B5 WG B5.62 Life Cycle Testing of Synchrophasor Based Systems used for Protection, Monitoring and Control. It also adds new developments in the testing practices in recent years.

Paper B5- 10747 (CN) demonstrates the accuracy of the PMU-enhanced fault distance estimation approach. It is particularly relevant in distribution long feeders by the presence of laterals with two-phase or single-phase sections which is common on these feeders. Using EMTP-RV, a wide range of scenarios was simulated by varying the fault type, location, and resistance to give a realistic estimate of the errors that can be expected from a fault distance estimation solution that uses only PMU measurements.

Considering all of these approaches, we can formulate some questions:

Question 2.08 - The challenges of the power system of the future point to an intense WAMPAC application. What are the main difficulties in testing these systemic schemes?

Question 2.09 - The application of Travelling Waves for fault location and protection functions is advancing significantly. What are the main difficulties in testing these applications?

Question 2.10 - The tendency to apply Synchrophasor in system protection functions shows excellent potential. What requirements are needed to make this possible?

2.6 General testing applications

There are several other protection applications associated with Hydro Power, Retrofit, and LPIT that also have an implementation and testing process. Some of them are technologically new, and these procedures still need to mature.

Paper B5- 10419 (US) presents several advantages of LPIT over traditional instrument transformers including lower cost, smaller size, easier installation, no saturation, and challenges associated with using LPITs in field testing. Several techniques can be used to test LPIT, using specialized signal conditioning equipment, digital signal processing techniques, and software-based simulation tools.

Paper B5- 10887 (RS) presents a contribution to the application of LPIT - based and digital metering systems. The accuracy of the overall measuring chain for different metering system configurations including conventional Instrument Transformer, LPITs, Merging Units and digital meters is presented. The proposed measurement / testing concept for linearity verification is explained. Practical recommendations are given.

Paper B5- 10803 (RU) presents the experience in conducting studies to analyse the causes and eliminate the possibility of incorrect operation of the turbine governors of Serebryansky and a number of other HPPs. The required result means it is necessary to provide detailed modelling of hydraulic turbines, their automatic control systems, as well as local emergency control devices. As a result, the national standard GOST "Automatic frequency and active power control devices for hydraulic units of hydraulic and pumped-storage power plants" was developed.

Paper B5- 10816 (RU) discusses the problem of stable and efficient operation of generating equipment of power plants in various schemes and operating conditions with the quality of regulation and efficiency of operation of automatic voltage (excitation) regulators (AVR) of synchronous generators equipped with power system stabilizers (PSS). Certification tests are recognized as successful if correct operation of the AVR is demonstrated in all tests.

Paper B5- 10853 (BR) presents concepts, practices, and strategies that can contribute to asset acceptance activities, about PACS, highlighting the benefits of this application in carrying out FAT

and SAT more efficiently. It also emphasizes the importance that must be given to the issue of training and the level of technical knowledge necessary for the development of the implementation of a new asset by teams in the project execution and commissioning stages.

Paper B5- 11197 (UK) describes the design and customer approval testing of a retrofit kit for a utility which includes laboratory testing and an extensive field trial. Tests include functional and simulation tests of the protection, EMC and environmental. After successfully passing the lab tests a field trial was organized. This solution aligns with the need to replace old secondary assets while optimizing while limiting the outage time required.

Paper B5- 11676 (IN) presents a strategy to enable complete testing of the PACS including Control Center SCADA. It develops a Portable SCADA to use on the FAT and SAT tests. This approach eliminates complete point-to-point testing at site and Control Center, reducing the commissioning time of the PACS.

Considering all of these approaches, we can formulate the following question:

Question 2.11 - What are the main challenges in testing related to the application of LPIT in the different stages of implementation and maintenance?