2024 Paris Session

Revised on 6th June 2024

B3 - 00

# SPECIAL REPORT FOR STUDY COMMITTEE B3
# (Substations and electrical installations)

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**Special Reporters**

**K. KAWAKITA B3 Chair and S. NGUEFEU Secretary**

CIGRE Substation Study Committee B3 is responsible for activities, which cover the design, construction, maintenance and management of substations and the electrical installation in power stations excluding generators. The aim is to bring value to the engineering community through highlighting state-of-the-art practices, establishing recommendations and reporting best practices.

The major objectives of B3 are to facilitate technical guidance, which enables the electrical supply community to increase reliability and availability, encourage cost effective engineering solutions, manage environmental impact, support effective asset management and encourage the adoption of appropriate technological advances in equipment and systems to achieve these objectives.

Substations are integral parts of the power system and central to the safe, reliable transmission and distribution of power by providing access to the network, fault isolation, and facilitating expansion. This is evident worldwide as energy networks adapt to meet the challenges placed on them.

The Preferential Subjects (PS) for the 2024 Session are:

**PS1 Challenges & new solutions in T&D substation design and construction for energy transition:**

- Design impacts on substations from on-offshore wind, PV, hydrogen, small modular reactors, EV charging infrastructure, etc.
- New functions in substations (energy storage, synchronous compensators, etc.).
- HV-MV DC substation and GIS/GIL application for a DC network.

**PS2: Return on operational experiences for substation management:**

- Challenges of managing assets: Initiatives to strengthen resilience, reliability and security, best practice and end-of-life management considering sustainability aspects.
- Lessons learned from operational experience from $SF_6$ alternatives solutions, digital transformation solutions and digital substation.
- New competencies for new technologies, knowledge transfer methods and high standards of education in engineering skills.

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A total of 65 papers including one NGN showcase paper from 23 countries addressing the 2 preferential subjects were submitted to the 2024 CIGRE Session. This material is central to the active work of Study Committee B3 and provides a very informative snapshot of the key issues across the world during this period. The effort and time afforded by the authors and their supporting organisations in producing these papers are greatly appreciated. CIGRE's aim is to encourage participation and contributions in the Paris Group Discussion Meeting (GDM). To this end, we have prepared 10 questions based on content to the papers and the B3 community is invited to share their thoughts, ideas and observations.

As always within the T&D Substations and similar installations, the papers cover a broad scope of issues and all the preferential subject criteria was addressed to some degree, highlighting the following key themes;

- The challenges in meeting net zero ambitions and maintaining security of supply.
- The impact of $SF_6$ alternatives on substation construction and operation.
- Modularity and containerisation – solutions to meet the demand at distribution level of RES generation and power electronic applications.
- Impact of Digitalisation across all aspects of the substation lifecycle.

**Participating in the 2024 Paris session**

You are invited to participate in discussing this Special Report at the Study Committee B3 Group Discussion Meeting on **Wednesday, 28th August 2024** in the Grand Amphitheatre (Level 1) at the Palais de Congress de Paris.

The reporters have compiled 10 questions, which are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified and raised in the papers. These questions provide an 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. Prepared contributions can only be made by registered attendees, who will attend the GDM in person. These must be uploaded to the CIGRE Session platform by **Saturday 10th August 2024** for review by the Special Reporters and must address the questions in this report (see following review). **No new contributions will be accepted after the 10th August 2024.**

Each prepared contribution will have a time slot of three to four minutes, so we suggest that the number of slides shall not exceed five, including the title slide (please do not make the slide too busy), it needs to be easily read and clearly illustrate your message. The Special Reporters will review the size and readability of the power point presentation and confirm the final time slot available via the portal. They will give recommendations to the contribution authors and inform them whether the prepared contribution will be accepted and is suitable by **Friday 16th August 2024**. All communication will be via the web portal.

There will be the opportunity for spontaneous contributions during the session, which will only be verbal with no slides. Attendees who provide a spontaneous contribution, are encouraged to summarise their contribution as a short written response for the Proceedings. This contribution text is required to be forwarded within two weeks after the SC B3 Session by **Monday September 9th 2024** to be considered in the proceedings, the contribution should be sent to mark.osborne@nationalgrid.com.

Delegates who join the GDM remotely will not be allowed to contribute either via prepared or spontaneous questions.

**Poster session**

Authors must prepare their posters, which will be shown on fixed monitor screens at the event. The files shall be uploaded to the 2024 Paris Session ConfTool directly by authors according to the 2024 CIGRE e-Poster Session Guide, which authors received from CIGRE Central Office beforehand. B3 Poster Session Convener PS1: Jeff Camden (cam08529@sbcglobal.net) or PS2: Michael Weixelbraun

(michael.weixelbraun@apg.at) will check uploaded the files in advance of the event and ask authors revision if they need.

**Key dates**

- **Saturday 10th August 2024** – Latest date for prepared contributions to be submitted for review. No contributions for presentation will be accepted after this date, contributors will have to use the spontaneous contribution option.
- **Friday 16th August 2024 –** Authors to be informed that their contributions will be included in the Discussion session, with a time slot.
- **Tuesday 27th August 2024 -** 14:30 – 18.00. B3 Poster Session. All paper authors are invited to present an e-poster. This is an opportunity for you to meet authors and discuss papers.
- **Wednesday 28th August 2024** – B3 Group Discussion Meeting - Grand Amphitheatre (Level 1). Prepared contributions and this Special Report will be presented and discussed.

**Summary of the 2024 papers**

Firstly, we would like to express our gratitude to the Substation community world-wide who have continued supporting B3 either via the Working Group activities or through the virtual conferences over the last couple of years. The papers this year, were reviewed by the Study Committee Special Reporters along with **49** Study Committee volunteers. We would like to express our appreciations to all B3 reviewers. Each paper was reviewed and summarised. A set of accompanying questions was produced with the aim to address aspects highlighted in the preferential subjects and authored papers.

**Preferential Subject 1: Challenges & new solutions in T&D substation design and construction for energy transition:**

- Design impacts on substations from on-offshore wind, PV, hydrogen, small modular reactors, EV charging infrastructure etc.
- New functions in substations (energy storage, synchronous compensators, etc.).
- HV-MV DC substation and GIS/GIL application for a DC network.

There were 18 papers reviewed and accepted for this preferential subject. We received a broad cross section of contributions, as would be expected for the substation, we are also pleased to see increasing participation from the Distribution sector. There are some common aspects to both preferential subjects around GIS, modularity and digitalisation which are also touched on from different perspectives in the second preferential subject, highlighting the significance of these topics in the substation category.

**New substation concepts**

One of the major impacts of Net Zero was the emergence of new or alternative sources for energy provision, particularly to feed the heating and transport sectors. The production of Hydrogen is going to be a key feature in the Net Zero world, whether to fuel manufacturing processes e.g., steel production or facilitate transportation. The generation of Hydrogen from more readily available sources such as water will require substation interfaces to the network. Paper **10337** outlines how a Small Modular Reactor (SMR) concept can be co-located with a Hydrogen facility to address this ambition. Noting this is a modular nuclear application initially at distribution voltages, as scalability is required along with security, necessary for this type of application.

While we were constructing offshore substations for a decade, the challenge to move into deeper water, drives innovation. Two papers focus on how the capability development of floating offshore substations (FOSS) is progressing. Paper **10737** focuses on how the dynamic forces due to the movement and vibration of the GIS module in the floating marine environment are assessed and validated in the equipment solution (66kV GIS). While a second paper **10338** outlines how their whole design process went through two phases: numerical concept design and analysis, which is then validated with a wave basin model test.

Network expansion will require both new substations and the extension of existing substations to connect new customer and circuits. These additions will require auxiliary power to supply the services, especially since most applications utilise power electronics and digital systems. Paper **11816** introduces a method being piloted in Thailand to provide site auxiliary supplies from the transmission network using a line or busbar tapped Station Service Voltage Transformer (SSVT) rated for the supply duties (approx. 150-300kVA). is the new application is contrasted with the traditional methods and implemented to improve reliability. It will be interesting to understand to what extent this concept will be applied and how the concept of tariff metering is addressed.

The traditional vertical power system hierarchy is changing under the facilitation of renewables and Net Zero is turning the system on its head, specifically applications evolving within distribution networks. The power source inversion requires Grid Code rules to be re-evaluated. Paper **10362** outlines Italy's development of a new 36kV grid park connection to address the twin challenges of grid congestion and rapid network expansion to connect renewable energy sources (RES). The RES grid park connection provides a standard 36kV metal clad $SF_6$ free substation design suitable for RES clusters up to 100MW of capacity.

***Question PS1.1*** ***Is the philosophy of clustering new connections and technologies into a Distribution Grid Park or similar being considered elsewhere? What are the emerging key substation standardisation factors (e.g. voltage, rating, acceptable technologies etc..)***

**Evolution in modular and containerised substations**

Meanwhile, paper **10322** explains how the demand at distribution has driven the development of a standardised design for a 34kV 9MVA Distributed Centre in a Box (DCIAB). This is a containerised solution suitable for pad mount installation, inclusive of a 34/13kV step down transformer with OLTC, switchgear and cable connections. Undergrounding the circuits and connections also facilitates a smaller footprint, better visual amenity and higher reliability due to less risk from environmental and wildlife related faults. Standardised design allows a faster deployment and components are interchangeable between suppliers optimising spares and procurement risks.

Along similar lines, paper **10903** describes the upgrade of the Irish 38kV distribution network, and how standard modular substations play a role in meeting the growth. Furthermore, the 38kV indoor AIS footprint is used to accommodate 110kV GIS modules where land is difficult to acquire. Offline fabrication coupled with a standardised protection & control solution to accommodate either overhead line or cable enables efficiencies in delivery. This enables most testing and commissioning to be carried out in the factory, accelerating the roll out programme.

Further to this rollout at scale is the challenge around commercial aspects like metering and utilisation. Paper **11552** highlights the approach in India to wide scale EV charging for public transport networks. The paper describes how compact package EV charging infrastructure can be efficiently installed and rolled out across India from an end to end service provider perspective including base stations and customer billing. IoT is employed to monitor the distributed equipment condition and facilitate higher utilisation.

Large scale Battery Energy Storage Systems (BESS) implementation in South Africa is discussed in paper **10781**. The focus is around optimising renewable generation integration. It outlines how the substation is designed, rated and dimensioned to accommodate the required battery performance. Aspects are highlighted regarding the DC fault current management, cable sizing, earth fault protection and the interfacing of auxiliary power with a battery scheme. Operation and maintenance activities are outlined along with a detailed description of the Grid Compliance testing program.

***Question PS1.2*** ***Is there any return on experience to date, regarding the compact design and maintenance requirements for containerised and modular H&D applications (e.g. EV charging infrastructure, BESS, distribution substations etc..)***

**Developments in GIS technology**

There are a number of opposing challenges facing GIS at this time, namely the focus around the suitability of alternatives to $SF_6$, the evolution into HVDC applications and the legacy challenge around space optimisation. The $SF_6$ alternatives aspects which are relative to both GIS and AIS are also covered in preferential subject 2.

Paper **10738** discusses the design and testing of a C4-FN gas mixture development for GIS at 420kV. The analysis focuses on the disconnector and earth switch duties under short circuit making duties, showing how the same performance is achieved with a similar GIS footprint to the $SF_6$ version. The LCA is also included to compare the new C4-FN mixture with $SF_6$, showing a greater than 80% reduction in the CO2 equivalent for the same footprint.

As more HVDC GIS is required, not only is the DC element been a challenge, but this is further complicated with the need to migrate to $SF_6$ alternatives. Paper **11036** shares the operational experiences and design challenges facing DC-GIS applications on both offshore and onshore applications. The benefit of a robust and reliable field-testing capability is emphasised as we rapidly roll out HVDC GIS at increasing voltages with relatively unknown insulation media performance compared to $SF_6$. The units were commissioned in line with the CIGRE TB 842 guidance and highlight issues around the evolving IEC standards and testing for partial discharge (PD) in a DC environment. The experience so far is limited to 400kVDC and as the DC operational voltages for new installations increase to 525kV and beyond, testing will become more critical as alternatives to $SF_6$ are implemented.

Complimentary to the development of the DC GIS is the cable required to evacuate the power onto shore and the AC network. The interfacing between the GIS and cable is not a new challenge, but made no less easier by DC. Paper **11646** outlines the design studies performed to establish the internal physical and insulation characteristics for standard HVDC Gas Insulated CSEs (GISE) at 320kV and 525kV DC. The paper describes how this is validated through testing in line with IEC and CIGRE guidelines.

Although there is a lot of effort going into replacement and developing the technology itself, the substation logistics and configurations remain a key design factor. Paper **11605** describes key features required in new GIS substation build in India. The discussion centres on how the constrained footprint benefits from layout optimisation to ensure access for maintenance and future build.

The construction of GIS today, will invariably have a number of constraining factors, whether the environment, the logistics or in the case of hydro, typically the topology. Paper **11598** outlines the challenges faced during the construction of the GIS inside a tunnel. The logistics are very restrictive at all stages of the project, including the longer-term operational and maintenance aspects, which need to be carefully considered, e.g. the risks to personnel, expanding on the safety aspects of working in this constrained environment with $SF_6$ and oil posing health risks to personnel (the overhead crane and accessibility to marshalling cubicles).

Every project aims to find cost savings compared to the traditional delivery models. In most cases reduced installation time, fast and simpler construction techniques can help to achieve these ambitions. Paper **11537** describes the development of a prefabricated compact transition station for DC and AC cable transition where undergrounding is required within an overhead line circuit. The CAD layout is explained and how compact design uses GIS technology in a multi-tier construction to facilitate an optimised solution for the cable terminations to enter under the GIS bay.

***Question PS1.3*** ***How is the use of $SF_6$ alternative gases going to impact on the GIS design philosophy and utility GIS ownership perspective (e.g. extensions, accessibility, gas handling, interpreting test results, etc..)***

**The role for Digitalisation in the substation development**

The Digital narrative is expanding into all aspects of our lives and that is no different in the substation sector. One of the big questions being asked, particularly by organisations external to our industry and senior management is how to accelerate the pace towards Digital substations, while addressing the Net Zero growth. In some quarters this is also a way to address the scale and resource challenges facing the sector.

One of the key enablers is the role of the Low Power Instrument Transformer (LPIT), paper **11143** highlights how the benefits of a test block and its role in injection testing were adapted for LPIT protection and calibration testing. The adoption of the fully digital substation is still uncertain, so a design which can accommodate a hybrid approach utilising test blocks and the Merging Unit is required. The LPIT offers several benefits including safety features and reduced wiring.

Paper **11604** describes how the application of Building Information Modelling (BIM) tools were used to help redesign a breaker and half substation busbar layout. Most applications focus on its use in the initial design aspects, support during construction. The paper attempts to articulate around how the tool can be used in various lifecycle aspects of the substation.

***Question PS1.4*** ***How are utilities addressing the combined risks of innovation and digitalisation while at the same time significantly expanding their networks to accommodate net zero?***

**Preferential Subject 2: Return on operational experiences for substation management:**

- Challenges of managing assets: Initiatives to strengthen resilience, reliability and security, best practice and end-of-life management considering sustainability aspects.
- Lessons learned from operational experience from $SF_6$ alternatives solutions, digital transformation solutions and digital substation.
- New competencies for new technologies, knowledge transfer methods and high standards of education in engineering skills.

The 2024 session received 47 papers, including one NGN showcase paper covering this preferential subject which focused on asset management experiences. It is quite evident from these submissions, that changes in environmental and regulatory drivers and evolution of digitalisation within the grid have focused engineers on new concepts and ideas.

As utilities struggle to deliver more work with fewer engineering resources, options around working smarter and adapt new concepts are addressed by the wide variety of substation papers.

**Safety through Design**

The first priority in any industry and organisation is safety, this touches on all aspects of the design, construction and operation. Ensuring working conditions and equipment is safe to work on is an essential part of modern maintenance and construction.

Net Zero is driving an unprecedented scale of rollout across the world of high voltage switchgear to connect RES and electrification of traditional fossil fuel-based services such as transport and heating. This sheer volume introduces an inherent risk to personnel involved in this work. As an industry the safety record is good compared to other sector and many of the issues are well understood and managed by everyone involved. One particular issue at MV is that of arc flash, paper **11475** provides experience on arc flash evaluations focusing on best utility practices. It outlines a proactive process to identify arc flash hazards for both engineering and field operators. It introduces the arc flash KPIs and states that this proactive means of identifying Arc Flash assessment program gaps or hazards by operating

organizations will greatly improve implementation. Moreover, this will help to safeguard the employees themselves and others against the hazards of arc flash.

There are a large number of operating environments, such as HVDC converter halls, cable tunnels, etc which are routinely inaccessible for visual inspections or testing by humans during operation due to the risk of electrical clearance and electromagnetic fields. Paper **11435** discusses the use of robots for inspection of HVDC Converter Hall while in service. The integration of robots and automated dynamic monitoring in high-voltage switchyards and HVDC installations presents a promising solution to the inherent challenges associated with maintenance and inspection in these critical environments.
Paper **10341** describes the testing and application of different robot configurations for use in substation applications. The paper provides test experience and recommendations for the choice of technologies based on the use case requirements. This supports the work in CIGRE brochure 807. Four types of robots were tested in a real-life substation environment with the objective of asset inspection in mind. This paper highlights improvements that vendors can make to provide better solutions to substation owners.

The evolving power system is impacting on the nature of electromagnetic phenomena being experienced by substation assets. It is therefore vital to identify and minimise the likelihood of introducing conditions which will cause faults or overstress transmission and distribution (T&D) assets. Paper **11547** describes controlled switching of transformers using an Intelligent Electronic Device (IED), which is used to reduce stress on equipment and prevent false tripping due to magnetic remanence in the core. The return of experience with ongoing improvement of parameters used for controlled switching of power transformers to minimize inrush currents for various configurations. The paper contains some technical details, and results gathered in commissioning tests of different configurations are presented to demonstrate the technical approach. Alternatives that are used such as pre insertion impedance or harmonic restraint of modern digital relays to prevent false tripping.

Earthing and grounding is probably the single-most risk to human safety when operating in a substation environment, since it is a key part of the protection effectiveness and making equipment safe to work on. Paper **10582** presents the monitoring strategy of earthing loop impedance and the criteria to be applied to verify the compliance of step and touch voltages in distribution networks interconnected by insulated cable and equipped with earth loop impedance monitoring systems. developed a method using simulation software that allows estimating the touch and step voltage values based on the measured earth resistances of the MV/LV substations.
This is further exacerbated in the management of high frequency transients in GIS, which although is reasonably well understood, however if the mitigation isn't implemented at the design stage major issues can plague the Asset Managers.

Composite insulators are increasing in popularity and usage, as porcelain usage wanes, so it's vital for correct design application using grading rings or otherwise. Now that cost is no longer a differential factor, non-ceramics are being more widely utilised. Paper **10795** provides testing and study feedback of non-ceramic insulators installed in the field. The paper discusses methods for testing and analysis based on field experience. Composite post and apparatus insulators at 220kV and 420 kV without grading rings are experiencing excessive degradation and overheating from electrical discharge. Based upon these findings, the utility is replacing composite post insulators that don't have grading rings, installing grading rings on apparatus of concern, updating technical requirements, and continuing inspection and investigation. The industry standards need to address design limitations for electric field and publish acceptance criteria for substation composite insulators.

***PS2.1*** ***What efforts and concepts are being applied, including the Distribution Substation sector, to ensure the safe and reliable rollout of new infrastructure, taking into considerations limited experience of new technology and the limited engineering resource pool?***

**Digitalisation in Substations**

Digital covers so many different aspects within the sphere of substations, ranging from capturing measurements and signals for protection automation and control (PAC)purposes, how holistic design and analysis tools are employed for decision making to the way condition data is collected and asset interventions are made.

Paper **10343** describes the reasons behind a utility's reluctance towards digital transformation in electrical substation projects. While we hear about all the benefits, it is the challenges that utilities are facing in adopting these technologies that tends to delay its implementation. Typical issues being familiarity with the traditional processes, limited knowledge of new technologies, cyber security concerns, and a few others. The strategies and solutions to overcome those hurdles are discussed in detail. Through a comprehensive analysis of challenges and a forward-looking exploration of potential solutions, this paper aims to illuminate the transformative path that lies ahead for electrical substations in the era of digitalisation for a more resilient, intelligent, and sustainable future.
It should not be understated that the economics are a big stumbling block to digitization as the initial cost is hard to justify a return on investment to regulators as this is an enabler, rather than a cost efficiency.

One of the key elements underpinning the digital substation is the method that current and voltage is measured and processed for the PAC functions. Paper **11029** introduces the operational experience of the technology for digital conversion of measured values by utilising low power instrument transformers (LPIT) in order to accommodate future digital substations. The report discusses signal processing from the introduction of the equipment perspective and an insight to the commissioning of a non-$SF_6$ GIS substation using non-standard instrument transformers.

Paper **10960** highlights the end-user evaluation and experience in Norway commissioning a 132 kV non $SF_6$ GIS substation employing LPITs and IEC61850 interoperability. A clear, well-structured article, both on factory and on-site acceptance test phases and on various areas covered including instrument transformers, interoperability of different vendor equipment, gas mixture and partial discharge monitoring.

There is a rich source of asset data performance in the SCADA and protection IEDs, Paper **11093** outlines a method employed in Japan for the condition based monitoring (CBM) of equipment of substations by combining data stored in IEDs with existing equipment data from substations. The effectiveness of this method was verified through test results. This method can be implemented by providing a programmable device for condition monitoring that complies with IEC 61850 standard in presence of IEDs. As a condition monitoring device, SCADA was verified as a programmable device in this paper.

Data collection was made much simpler and easier as digitalisation tools become more accessible and common place. CBM is also being facilitated by the growth and application of IoT technologies.
IoT is a major growth area as third-party developers identify opportunities in the Energy sector. It is vital that utilities consider their needs when specifying these tools. Paper **10796** outlines the adoption of analytics to asset management and the automation of the process through digitization. The paper proposes how to structure the digitized asset management with monitoring and calculated indices.

One of the main benefits seen in utilities for digitalisation is the modernisation of legacy maintenance documentation and record keeping, makes the review and access more effective. Paper **11800** describes the journey of a Malaysian utility towards a digital platform replacing manual data collection methods for data recording of maintenance and inspections for substations and lines. Some of the methods were accelerated by needs identified during the COVID years. Highlighting how digital applications make data immediately accessible to operators and key personnel.

Paper **11556** discusses the application and value of a visual monitoring system for operation and maintenance in principally unmanned substations in India. The narrative focuses on how it can be applied remotely to basic inspection activities and during periods of poor weather. It also mentions the evolution to interactive work with operatives connecting them to centralised coordinators.

Paper **10769** describes the process of substation digitization in Brazil to develop a digital twin. The paper discusses the use of laser scanning and promotion of Building Information Modelling (BIM) workflows. Several practical case studies are provided. This is further illustrated in paper **10771** which outlines the advantages of a digital twin of the substation in BIM, integrated to the Asset Registry, Operating System and Geographic Information System (GIS), containing the three-dimensional, functional and georeferenced representation of all the equipment in the substation. The paper provides a case study of the circuit breakers monitored by the predictive system in real time and how the digitization enhances asset management real time. One of the longer-term challenges to our industry is to make the legacy asset data compatible or at least accessible with these new systems and tools.

***PS2.2*** ***With regard to new resources and skills, how prepared is the Energy sector to manage the impact that Digitalisation and Net Zero will place on it. Is this a threat or opportunity to the skills gap within the sector?***

**Substation Asset Health Metrics**

Asset health metrics are becoming an increasingly important measure of the condition and risk associated with the continued use of substation equipment, The challenge to the asset manager is how to condense all the various individual asset health measure into a singular or representative value for the substation. Paper **10684** introduces asset management methods from a Regional Transmission Operator's perspective. The paper provides quantitative analyses for asset reliability and end of life assessment. presents an asset management methodology for quantification of risk in decision-making and optimal replacement periods for transmission asset investment. The paper is based on ENSTO-E TSO experience but is applicable to any major power system assets. Finding an optimal replacement period for high value assets has often been considered the "holy grail" of asset management practice and this paper advances thinking and clarifies some theory in regard to optimisation.
The question remains how this method can easily be adopted and integrated into asset management practice, but the work clearly demonstrates how asset decision-making and risks assessment must be supported by robust asset condition information.

The reliable prediction of the End of Life (EoL) is a very powerful tool in the asset replacement arsenal. It is the key aim for most utilities, so they can replace assets in a timely manner. Paper **10340** presents cases to cover aspects of asset management which rely on a combination of condition data, contextual assessment and analyses, resulting in planned interventions. The cases studies demonstrate a need for an understanding of both technical knowledge and the asset management. These include condition and risk assessment to make the best use of assets near end of life, illustrated for 3 use-cases: 400kV air blast circuit breaker, 48MVA Transformer experiencing Dissolved Gas Analysis (DGA) and an ageing 66 kV cable.

Paper **11499** provides an in-depth focus on developing an asset management program and provides examples with a case study across 2395 transformers. It makes a connection between previous CIGRE B3 work and other sources of theory, practice and standards on reliability-based maintenance (RBM), resulting in a clear visualisation of the risk map, based on the use case in Indonesia. This is further expanded in paper **11725**, which provides an insight to the Indonesian asset management methodology for GIS by developing a calculated priority index. The method of calculation is explained with additional factors complicated by factors such as operational constraints. This illustrates the importance of the Cigre technical brochure (TB 858) and examples of its application.

The increasing external pressures on power systems is making time-based intervention become more difficult and expensive. Paper **11088** discusses a utility's transition from Time Based asset management to Condition Based Maintenance (CBM) system utilising IoT applications. It describes how the use of sensor technology was addressed through the evaluation in conjunction with intelligent algorithms.

Paper **10139** describes the in -situ monitoring system developed in France to identify change in Capacitive Voltage Transformer (CVT) performance, as an indicator a faulty CVT. The diagnostics continuously measure the three phases using a Merging Unit (MU). This data can then be analysed remotely to detect a failing unit. This is a good example of how power system measurements from SCADA could also be used to identify poorly performing assets.

A topic not frequently discussed is reactive compensation which was widely implemented across most networks for more than 20 years.Many assets are starting to demonstrate age related issues. Paper **11210** introduces the development in Columbia of a health index for capacitor end of life. There are a few factors missing that should be added in the evaluation. The configuration of the bank such as fuseless, externally fused or unfused is an important design factor. Sync switching operation can fail and provide a 2 PU switching surge that magnifies to an 8 PU transient at points in a fuseless bank in many configurations. The design of the case terminal to case insulation is critical to the life of the capacitor to prevent catastrophic failure. The polymer thickness also plays a role. The internal design of the can from MVAR to voltage rating of the bank is significant to insure reliability.

***PS2.3*** ***The application of Asset Health Indices to lead assets is quite well practiced, but how are aspects associated with the substation infrastructure and services to support the primary equipment assessed and considered? Is there information from the SCADA that can be used to help identify these issues?***

**Service Continuity**

There is a large volume of GIS already installed in power systems, and it will continue to grow and be in service for many decades. As the world focuses on the elimination of greenhouse gases, how is the remaining legacy of $SF_6$ filled equipment being managed so as to staisfy the legislators and environmentalists?

Paper **11089** describes how, in Japan, through effective $SF_6$ gas leakage monitoring, estimates are made where leakage repair is needed before equipment gas level alarms are triggered, or before equipment can be replaced. A new repair method is presented, and two repair cases explained that were successful. Overall gas leak rates are maintained below required levels. The example gives an insight on the actual operational experience of HV GIS equipment regarding the leakage issues and methods that were developed to repair the equipment so that operational safety is restored.

Paper **11090** describes an advanced approach to the maintenance, management and prioritisation of replacement of ageing substation equipment. The paper examines methods of strategic investment decision-making based on a significant data set from Japanese utilities. Case studies are described where the methodology is utilised. This paper has significance for any utility with ageing substation assets.

GIS Modules are reliant on external measurements to understand the nature of any issues or evolving failure modes within the equipment. Paper **11801** describes activities in Malaysia to manage $SF_6$ leaks on GIS, providing a commentary on how statical data is collected and can be used to illustrate the issue.

Paper **11538** is a good example of how a utility can struggle in a commercially led world when introducing GIS technology. The paper places significant emphasis on contractual obligations of the manufacturer with minimal focus on design changes or focus on developing organizational expertise on technologies. This paper outlines in detail the specific need for spares and contingency plans for GIS failures. It also identifies the need for in-house expertise to address GIS failures and it highlights the need for a strong maintenance program. It also identifies the need for subject matter experts to be on site during installation to help avoid installation problems or quality issues that could lead to later failures.

The recent publication of TB 870 *Service Continuity Guide for HV GIS above 52 kV* addresses all the relevant topics during Maintenance, Repair, Extension (MRE) or on-site dielectric testing for GIS above 52 kV. In particular, it enhances the need for effective cooperation of users and manufacturers.
Papers **10739** & **10741** provide an overview of the IEC62271-203 about service continuity and CIGRE TB870 for service continuity of GIS. While **10739** also describes the magnitude of the impact of the GIS accident that occurred on the 220 kV system in Switzerland and the service continuity will be improved by examining the equipment specifications with considering MRE code at the planning stage.

Paper **11560** provides experience and practical design considerations to enhance service continuity during all phases of green field and brown field GIS applications in India. The philosophy covers Maintenance, Repair and Extension (MRE). The authors first time applied their newly defined service continuity requirement code and discussing the importance and relevance of this topic to our industry.

Paper **11087** summarises the requirements for design, operation, maintenance and end of life strategies for outdoor GIS. It is a collection of common sense and good practice in engineering and operational practice taking into account the prevailing conditions, based on generic observation.

Paper **11097** introduces an OEM perspective of a different but logical life cycle assessment (LCA) solution. Changing a complete substation is not easy, especially when directly connected to overhead lines. If connected by cables, the cables can be re-routed and connected to a new GIS. It provides experience on the retrofit GIS switchgear to extend the substation equipment useful life. With the exchange of the arcing chamber the CB-part of the GIS the lifetime of the complete GIS can be extended, while the CB being the most critical part.

Paper **11555** reports on two recent extension projects for 420 kV GIS by using GIBs to the existing GIS at two hydro power stations in India. One is an integration of reactor bay to the existing GIS, and the other is an integration of gas-to-oil bushing. The narrative includes design and commissioning experience.

Paper **10716** provides a philosophy and method for asset management of spare parts. The paper explains information on automating the spare equipment management using an automated software program based on best utility practice. It adopts a system risk approach using software management tools to optimize mean time to repair (MTTR) and spare parts warehousing.

***PS2.4*** ***What strategies are being considered by utilities and solution providers to manage the lead time issues associated with the procurement and construction of new bays or substations?***

**Introduction of $SF_6$ alternatives**
This is a major topic of interest and is likely to be popular for a few years to come. There were 6 papers that focus both on $SF_6$ management and evaluation of alternatives gases.

Paper **10309** describes how France examines the use of three different LCA alternatives to $SF_6$ for insulating electrical equipment. The paper provides data on the of the alternatives to $SF_6$. Three alternative gas technologies are being tested in labs and substations at equipment ratings up to 145 kV. Vacuum technology is already in service with experience shared at 72kV, in addition to X-ray measurement, switching tests and EMTP modelling. For C4-FN gas mixtures, experience is shared regarding on-site mixing and analysing, including CO detection. Lab tests for filling at low temperatures address humidity concerns, and electrical wear tests are planned for 2024, also looking for CO by-products and oxidation. For the $CO_2$ mixture alternative, the permeation issue is presented along with the challenge of on-site mixing to correct the gas ratio. Mechanical and electrical endurance tests are planned for installations in 2025.

The integrity of voltage transformer measurement accuracy with alternative gases is covered in paper **11757**. It describes how for the alternative gases, voltages transformer designs were optimised for the

corresponding GIS at 72kV and 145kV rated voltage levels. This paper considers dielectric, thermal and material compatibility factors.

Paper **10740** provides experience of a 420 KV GIS retrofill using a C4-FN/$N_2$/$O_2$ gas mixture to replace $SF_6$. The paper details a utility effort to reduce $SF_6$ in the equipment inventory by providing good utility practice. It showcases a retrofill of a 420 KV GIS substituting the $SF_6$ gas in installed equipment. A complete list of modification and type testes to retrofill for 420 kV gas-insulated line design was well presented. This paper shows a big step forward for economic replacement of $SF_6$ in existing equipment for high voltages than previous papers.

Reporting on 'in service' experience is invaluable when introducing new technology or concepts. Paper **11306** provides experience in the UK gained on gas handling with C4-FN gas mixtures, from the perspective of users, high-voltage equipment manufacturers and gas handling equipment manufacturers. The paper indicates lesson learned that will help utilities and asset managers to optimise the use of these alternative gases, including process improvement, tools and equipment, training and spares.

Partial Discharge Measurement is a central part of understanding the state of gas filled equipment. Paper **11334** discusses in detail experience in Partial Discharge monitoring (PD) of GIS using non $SF_6$ gas. This paper presents some of the challenges performing field measurement and difficulty to compare S-parameter as recommended in the CIGRE TB 654 on a C4-FN gas mixture. This study suggests technical viability of applying the same procedure for sensitivity study as adopted for $SF_6$ GIS. A modified approach was suggested in this study derived from the concepts of the TB 654 sensitivity recommendation.

A novel approach for the measurement of $SO_2$ in GIS, based on the photoacoustic detection of gases is introduced in paper **11444**. The paper introduces Photoacoustic spectroscopy and discusses several advantages compared to conventional gas sensing techniques. Potentially a good option for real time decomp measurement to determine possible nozzle damage.

Utilities on the whole are taking a cautious, comprehensive approach to implementing alternative gas technologies. It is the role of CIGRE to further synthesise best practice from the around the world. The key is how testing and experience findings are reflected back to suppliers for development of reliable and effective solutions. Best practise should be incorporated into regulations.

***PS2.5*** ***What strategies are being implemented to aid the transition away from $SF_6$? Is there an emerging direction regarding the re-use of GIS with an alternative or replacing the GIS in its entirety?***

**Substation Resilience**

The definition of resilience is subjective; however, the essence is about the ability of the substation to withstand and ride through issues associated with external pressures, such as natural events and actions affecting the network integrity. Paper **10342** comprehensively addresses some of the threats to the resilience of substations in the United States, including both traditional natural hazards and the recently emerging human-caused threats. It outlines the status of the response to these threats, providing a very helpful organization for the reader's understanding. The sometimes extremely high cost of responding to threats, and the fact that one threat countermeasure may conflict with or create challenges for other constraints, suggest the need for a comprehensive study, sharing the concerns of power companies. It consists of a list of actions that are taken at substations in the USA to protect them from weather and vandalism.

Paper **11824** describes issues experienced with a 23/4kV MV substation in USA and the case study of a substation mitigation event for failed retaining wall and substation foundation collapse, due to soil erosion and sink holes. The resolution requires the temporary reinforcement of the foundations to be

adapted to deal with the hydraulic nature of the ground to provide reliable power supply to the local service area, until a longer-term replacement can be built.

Building resilience into the substation and the network is central to providing a secure and recoverable power system, NGN paper **11893** provides a real-world case study of countermeasures for protection of substation assets employed in Japan, focusing on lightning protection.

Paper **10339** describes a comprehensive research program in the US to characterize the role of interconnection by flexible conductors for seismic design of substation equipment. It reports on tests and computer simulations to investigate the dynamic design aspects under normal operating conditions. It gathers extensive data and compares various analysis options, making it a highly valuable and sophisticated paper on seismic design for substations. This paper also introduces the development of analysis tools that allow users to examine the linear or nonlinear mode classification of interconnecting conductors obtained through experiments, which will be useful in assisting the design of future substations and investigating the causes of earthquake damage.

**Implementing Sustainability**

Similarly, to resilience, sustainability considers the internal and external impact that the substation life-cycle has in terms of its construction, operation and replacement, in particular, the circular economy aspects that are considered throughout its lifetime. Paper **11092** provides an introduction to the concept of sustainability and shares the experiences related to the construction of new substations and the replacement of equipment. While the goal is to enhance the resilience and reliability of the substation, the wider aim is to use eco-friendly transformers and circuit breakers. The authors focus on sustainable substation operations, aiming to reduce environmental impact while maximising the utilisation of existing substation assets. The article explains how a sustainability led improvement is achieved in field application through the application of natural esters in transformers and the application of synthetic air in combination with a vacuum CB in a dead tank. (replacement of an $SF_6$ dead tank CB).

One of the key issues for GIS, in particular flanges and joints, is exposure to the natural elements. Paper **11201** from Columbia outlines the types and effects of external conditions affecting the sealing properties of GIS. It also defines the specific degradation mechanisms that affect the reliability and operability of the GIS.

Paper **11202**, from Columbia, discusses the options of clean non $SF_6$ gas substation design for grid transformation in urban areas. It outlines the encapsulated substation, the first installation technology in Latin America, combining digital substation technology, sustainable design concepts such as green facades, self-generation from solar energy, rainwater collection and reuse, and the application of digital substations, together with $SF_6$-free technology, not only reducing space and environmental impact but also improving reliability. This is further supported through the maintenance process, benefitting the life cycle costs of the asset and facilitated community acceptance of the project.

An extendable philosophy of sustainability is the enhanced utilisation of assets. A couple of papers describe the use of dynamic ratings to improve utilisation. Paper **10141** outlines the experience of a Dutch DSO together with their service provider to manage network congestion. The paper explores dynamic equipment rating and how to utilise untapped asset capability to handle renewables and the proliferation of electric vehicles to reduce carbon emissions. The paper describes a detailed approach for the controlled overloading of substations and the MV switchgear as part of it for a better utilization of the network. Increased load and production creates bottlenecks and would classically require network upgrades. Initial results show that the system works and temperatures correspond to the model.

Paper **11159** provides an Austrian case study of operational experience with dynamic current rating of busbar systems in 220-kV substations. The method considers the calculated ampacity of the busbars, via temperature and current calculations, based on the available current measurements from the control system and temperature measurements of the busbars.

These are great real world practical example of how to get the most capacity out of the existing grid. The only caveat is to get the TSO to adopt a dynamic rating market allowing something besides a static rating.

***PS2.6*** ***A key aspect of resilience and sustainability is the ability to cater and absorb change. Should utilities be constructing substations ahead of need and create the network, or should they be more reactive and expand as the need appears? What are utilities doing in this respect?***

**Concluding Remarks**

The 2024 B3 Special Report reviews a collection of 65 papers, which covered a diverse and wide cross section of issues. This illustrates the challenges facing the substation engineers and operators around the world. The Special Reporters have combined these into a narrative which hopefully enables the reader to appreciate the headline issues and gets a flavour of what is happening across the world. Ten questions were synthesised from all the papers which hopefully provide some fruitful discussion at the Paris Group Discussion Meeting (GDM) on Wednesday28$^{th}$ August.

Net Zero is undoubtedly driving changes and impacting on substations at both transmission and especially distribution, in their role as facilitator of network expansion. This includes growing the flexibility to operate assets in a more dynamic and responsive manner. This comes about as the system becomes more volatile reacting to changes in generation and demand pattern associated with intermittent energy sources and people behaviour, especially within the distribution sector.

A number of papers articulated how sustainability and resilience metrics, can be used to reflect external threats and conditions we need to be incorporating into the design rules when developing, constructing and operating substations. The challenge will be to manage the global supply and engineering demand curve as the world adapts to net zero.

There are two big technical issues which were featured in the substation roadmap; alternatives to $SF_6$, which is environmentally driven and digitalisation, which is symptomatic of global technology evolution.

The expansion of the networks to accommodate Net Zero, creates a real juxtaposition, as we face probably one of the biggest threats to our sector; the potential banning of $SF_6$. This gas is critical to the safety and reliability of substations, and although T&D is not the biggest emitter by far, the extent of this threat is driving the development of alternatives, especially at the lower voltages. The developments are promising, however as with the introduction of $SF_6$ decades ago, it takes time to fully understand all the interactions and the full impact of these changes is still be seen.

The industry is responding quickly, in Transmission timescales, to develop and implement new ideas and technology to help facilitate the change to less reliance on $SF_6$ and ultimately its overall removal from the system. In the meantime, more effective measures will be necessary to manage the legacy installed volume, along with recently published GIS service continuity guidelines to optimise extendibility, maintainability and repair.

The other big game-changer is Digitalisation, which is penetrating into all aspects of the substation lifecycle, from design tools through to AI based asset management systems. Digital is a rapidly evolving world and T&D will have to adapt quickly to keep pace with the speed of change in the digital sector and adoption of digital solutions. Given our current resource shortage in the Electricity industry, how will these systems be integrated, proven and verified to ensure the outputs are safe, secure and effective.

A salient point, emphasised in a few papers, is the benefits the community gets from sharing experiences and best practices, underpinning the real value of CIGRE-membership and participation in the working

groups. On that note, in 2009 B3 WGB.11 published Technical Brochure 389 entitled Combining Innovation and Standardisation, its recommendations now are probably more relevant than ever!

The B3 Study Committee hopes you find this summary useful and the questions are representative. We look forward to reading your responses and contributions this summer at the group discussion meeting in Paris.