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2026 Paris Session

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

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Special Reporters

M. McVEY B3 Chair and S. NGUEFEU Secretary

CIGRE Study Committee B3 'Substation & Electrical Installations' is responsible for activities, which cover the design, construction, maintenance and management of substations and the electrical installation element 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 2026 Session are:

PS1 Innovative Concepts, Designs and Operation Experience in Substations:
- Experience with Digital design, Training Tools Using 3D Software, AI and Machine Learning
- Modular Substations and Prefabricated Material Design Methods for all Voltage Classes
- Operational Experience with Renewable Substations for Onshore and Offshore UHV or HVDC

PS2: Life Cycle & Asset Management in Substations:
- Monitoring, Diagnostics and Testing Equipment to Improve Energy Efficiency and Functionality to Reduce Carbon Footprint as well as Improve Resiliency
- Substation Up-Rating, Upgrading Experience and Operation Concepts
- Asset Management Strategies Including Optimised Maintenance and Substation LCA

PS3: Impacts of Grid Transformation and New Reliability Threats in Substations
- Physical Security Designs and Experience for Substations
- Substation Designs, Upgrades and Concepts to Mitigate Severe Weather effects

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- Experience Building Substations to Connect Large Customers such as Data Centres, Reliably and Safely

A total of 85 papers including one NGN showcase paper, have been accepted from 23 countries addressing the 3 preferential subjects for the 2026 CIGRE Session. This material is substantive to the active work of Study Committee B3 and provides a very informative snapshot of the key issues around the world during this period. The effort and time afforded by the authors and their supporting organisations in producing these papers is greatly appreciated, along with the reviewers, who have assessed the papers' suitability for publication. This aligns with CIGRE's objective to encourage participation and contributions in the Paris Group Discussion Meeting (GDM). Following a comprehensive review, we have prepared 15 questions based on observations across the papers submitted. The B3 community is cordially invited to share their thoughts, ideas and observations.

The papers cover a broad scope of issues covering all the preferential subject criteria, highlighting the following key trends;

- Increasing focus on substation resilience, to address the impact of network growth as the industry accommodates the decarbonisation agenda.
- The progression of SF_6 alternatives across all levels of switchgear. This is also supplemented with an increased focus around decarbonisation in the construction and operational phases.
- Uptake of modularity and ambition for more standardisation in the substation sector to meet the construction ambition across the industry.
- The increasing exposure and growth in substation related digital applications, across all stages of the substation life-cycle.

Participating in the 2026 Paris session

You are invited to participate in discussing this Special Report at the Study Committee B3 Group Discussion Meeting on Thursday **27th August 2026** in the Grand Amphitheatre (Level 1) at the Palais de Congress de Paris.

The reporters have compiled 15 questions, which are not specific to 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 **Friday 7th August 2026** 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 7th August 2026.**

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 14th August 2026**. 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 text is required to be forwarded within two weeks after the SC B3 Session by **Monday September 7th 2026** to be considered in the proceedings, this should be sent to mark.osborne@nationalgrid.com.

Delegates who join the GDM remotely are not 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 sent to the relevant preferential session Poster Session Convener PS1: Jeff Camden (cam08529@sbcglobal.net) or PS2: Michael Weixelbraun (michael.weixelbraun@apg.at) who will upload the files in advance of the event. Authors will not have the possibility to upload their own file on the very day of the meeting. Only Conveners will have access to the Poster Sessions preview room.

Key dates
- **Friday 7th August 2026** – 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 14th August 2026 –** Authors to be informed that their contributions will be included in the Discussion session, with a time slot.
- **Wednesday 26th August 2026 -** 14:00 – 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.
- **Thursday 27th August 2026** – B3 Group Discussion Meeting - Grand Amphitheatre (Level 1). Prepared contributions and this Special Report will be presented and discussed.

Summary of the 2026 papers

The B3 Substations and HV installations is a growing world-wide community and the continued support and participation in B3 activities via Working Groups, Webinars, Colloquia or Symposia is more important than ever. The papers this year, have been reviewed by the Study Committee, Special Reporters and over 50 Study Committee volunteers. We would like to express our appreciation to all B3 whether they were the authors or reviewers. Each paper has been summarised in this Special Report. A set of accompanying questions has been produced with the aim to address aspects highlighted in the preferential subjects and authored papers.

We received 85 papers covering a broad cross section of items addressing aspects of all three preferential subjects. around resilience, digitalisation and upgrading challenges.

Preferential Subject 1: Innovative Concepts, Designs and Operation Experience in Substations:
- Experience with Digital design, Training Tools Using 3D Software, AI and Machine Learning
- Modular Substations and Prefabricated Material Design Methods for all Voltage Classes
- Operational Experience with Renewable Substations for Onshore and Offshore UHV or HVDC

For PS1 we received 32 papers. The papers can be clustered into four main themes.

Substation design challenges under dynamic electrical, environmental, and operational conditions
This category consolidates insights from eight technical papers (10164, 10748, 11030, 12209, 10542, 12279, and 10835) to present a unified view on how modern substations must be designed, analysed, and delivered to remain safe, reliable, and resilient under increasingly dynamic conditions.

Across grounding, transient overvoltage's, switchyard topology, and construction methods, the studies consistently demonstrate that static, nominal condition design approaches are no longer sufficient. Instead, substation performance is governed by a combination of transient electrical phenomena, environmental variability, operational stresses, spatial constraints, and execution realities that interact throughout the asset lifecycle.

The grounding and earthing studies (10164, 10748, 11030, 12209) show that Ground Potential Rise (GPR), touch and step voltages, and transferred potentials are strongly influenced by lightning impulses, soil ionization, seasonal freezing or drying, industrial congestion, and complex subsurface structures. These papers clearly indicate that conventional grounding assumptions based on uniform soil resistivity

and steady state conditions can significantly underestimate risk. Robust grounding design therefore requires accurate site characterization, advanced soil and geophysical modelling, and adaptive mitigation solutions that explicitly address worst case transient and environmental scenarios rather than average conditions.

Paper 10542 considers on very fast transient overvoltages (VFTO) and transient enclosure voltage (TEV) in Gas Insulated Switchgear (GIS), further highlighting this dynamic perspective to EHV/UHV substations, demonstrating that disconnector switching, particularly under trapped charge conditions, can generate very fast transient overvoltage's approaching insulation limits and induce significant transient enclosure and ground potential rises. Importantly, these effects are shown to be operationally realistic and repeatable, not rare anomalies. Field measurements and electromagnetic transient simulations confirm that effective risk reduction can often be achieved through operational and design optimization, such as improved switching sequences, targeted earthing enhancements, controlled delays, and modest insulation coordination adjustments, without major equipment redesign.

At the system configuration level, paper 12279 highlights that resilience is not solely a matter of component robustness, but also of topology choice. Busbar less HVAC configurations such as the Moebius Strip and Crossed Ring demonstrate superior feeder availability, fault containment, maintenance flexibility, and extendibility when compared with traditional 'Breaker and a Half' arrangements, even when the number of circuit breakers per feeder is unchanged. These layouts inherently reduce exposure to single points of failure, distribute short circuit stresses, and simplify expansion, illustrating that inherent resilience can be "designed in" rather than added through complexity.

Complementing the electrical and operational findings, paper 10835 addresses substation delivery and constructability, showing that precast reinforced concrete foundations can significantly reduce construction time, labour dependency, and on-site variability by shifting critical activities to controlled factory environments. This demonstrates that construction methodology is itself a resilience factor, directly influencing schedule certainty, quality, and overall project risk. This is particularly relevant for large, fast tracked, or resource constrained projects.

Collectively, these papers lead to a clear overarching conclusion: substation resilience emerges from the coordinated integration of grounding design, transient behaviour management, system topology, operational philosophy, and construction strategy. Treating these aspects in isolation increases the likelihood of hidden vulnerabilities, cost escalation, or reduced lifecycle performance.

The report therefore underscores the need for:

- Early, cross disciplinary integration of electrical, geotechnical, operational, and construction considerations,
- Explicit treatment of dynamic and worst-case conditions in both design studies and standards,
- Balanced use of standardized solutions and site-specific modelling, driven by risk rather than convention,
- And a shift from purely compliance-based design toward lifecycle oriented, resilience-based decision making.

In an environment of higher voltages, denser networks, more extreme climates, tighter schedules, and rising availability expectations, the lessons synthesized here provide a coherent framework for designing and delivering substations that remain safe, reliable, and adaptable throughout their operational life.

Q1.01 ***From practical experience, how can grounding, transient overvoltages, switchyard topology, operations, and construction be better integrated into substation design and delivery to achieve safe, resilient performance under worst case conditions, while remaining cost effective and scalable?***

Substation Decarbonisation and SF_6-free evolution

Five papers (11997, 12004, 10436, 10686, 10691) collectively demonstrate a major transformation in high voltage substation design and operation, driven by decarbonisation, environmental regulation, and the need for flexible and resilient grid infrastructure. A central theme is the transition away from SF_6 based technologies toward greenhouse-gas free insulation and environmentally neutral solutions, while maintaining, or even improving, technical performance and reliability.

Several contributions confirm that SF_6 free technologies are no longer conceptual, even for transmission level. Developments and products in operation demonstrated performance comparable to high global warming SF_6 systems, with zero greenhouse gas impact and successful field operation. Early operational experience indicates stable electrical behaviour, robust fault clearing capability, and manageable maintenance requirements, positioning these solutions as replacements for legacy SF_6 equipment. The use of LPIT technology further reduces material usage, size, and transport constraints, supporting compact and modular designs which enable easier digital substation concepts.

Another key aspect is flexibility and sustainability beyond primary switching equipment. The deployment of Battery Energy Storage Systems (BESS) as replacements for diesel generator sets at transmission receiving stations demonstrates how auxiliary power systems can evolve from purely passive backup assets into cleaner, faster, and more reliable support systems. When combined with rooftop solar and tariff optimisation, BESS solutions significantly reduce emissions, operational costs, and response times, contributing directly to grid decarbonisation.

Finally, the paper on HVDC Floating Offshore Substations (FOSS) highlights how innovative platform concepts, such as Tension Leg Platforms, which enable reliable offshore HVDC integration in deep water environments previously considered impractical. Through detailed numerical analysis and physical model testing, the study confirms that such solutions can meet stringent requirements for structural integrity, dynamic cable fatigue, and equipment qualification, supporting the large-scale expansion of offshore wind generation.

Taken together, the papers illustrate that sustainability, resilience, and flexibility are increasingly addressed holistically, from primary switching technology and auxiliary power systems to onshore as well as offshore transmission infrastructure.

Q1.02: ***Which proven use cases and near-term innovations in SF_6-free equipment, LPITs, mobile substations, BESS solutions, and HVDC substations are most critical for scaling reliable solutions that support the energy transition and achieve Net Zero targets?***

Q1.03 ***Are there any significant failures, challenges, or lessons learned from field operation or investigation that you would be willing to share to help the industry collectively progress towards reliable and effective SF_6-free solutions?***

Modular and Prefabricated Substations

The three papers (11813, 12201, and 12603) collectively indicate that modular and prefabricated substations have progressed beyond pilot implementations and are increasingly being adopted as scalable, utility grade solutions. This development is particularly relevant for DSOs and TSOs addressing reinvestment backlogs, accelerated renewable integration, and constraints on skilled resources.

The papers consistently report measurable benefits, including reduced project costs, shorter delivery times, and improved resource efficiency, while identifying no fundamental technical barriers to wider deployment. A key recurring message is that long term success depends less on fully standardised, single vendor solutions and more on the standardisation of interfaces across electrical, civil, protection, and communication domains.

Such an interface-based approach supports supplier flexibility and lifecycle adaptability, but also introduces new challenges related to asset governance, compatibility, and version management over multiple generations of installations. Overall, the session highlights that modular substations should be viewed as long term product platforms rather than project specific solutions, requiring both technical and organisational alignment to fully realise their potential.

Q1.04 ***Based on practical experience, which interface areas and primary equipment innovations have delivered the greatest benefits from standardisation and prefabrication in modular and mobile substations - including the use of SF_6 free technology - and what key challenges and lessons learned should be addressed to further improve efficiency, operation, and maintenance?***

Digital, AI Enabled, and Human Centric Substation Engineering, Operations, and Knowledge Systems

This category captures the accelerating transformation of substation engineering, delivery, operation, and workforce development through data driven, AI supported, and lifecycle-oriented methodologies, as evidenced by papers 10389, 10438, 10443, 10445, 10692, 10684, 10808, 10834, 10877, 11300, 11302, 11616, 12059, 12057, 12207, 12272 and 12635.

Collectively, the contributions demonstrate a decisive shift away from document based, geometry centric, and discipline siloed practices toward integrated digital ecosystems built around structured data, BIM and GeoBIM, Digital Twins, generative and AI based optimisation, automation, and advanced simulation. Across both greenfield and brownfield substations, these approaches consistently deliver measurable benefits, including reduced engineering effort and rework, improved spatial and layout optimisation, enhanced safety and constructability, shortened time to energisation, and lower lifecycle cost.

A central finding is that the value of digitalisation lies not in 3D visualisation or automation alone, but in improved decision-making quality, coordination, and transparency across the asset lifecycle. Interoperable data models, robust data governance, and semantic consistency – often supported by OEM provided digital asset information – enable engineers to evaluate multiple design options, manage constraints more effectively, and make better informed trade-offs earlier in the project. AI based optimisation and generative design are shown to be particularly effective when applied with clearly defined objectives and constraints, supported by experienced engineers who remain accountable for final decisions.

The category further demonstrates that digitalisation extends well beyond design into operation, maintenance, and organisational capability. Digital twins, simulation environments, and AI enabled analytics support condition-based maintenance, predictive insights, and safer operation. Inspection robots and automated data capture increase inspection coverage and consistency in both AIS and GIS substations, freeing specialist staff from repetitive tasks while improving asset visibility.

Equally important, the papers highlight the role of AI and digital platforms in training, skills development, and knowledge transfer. High fidelity simulation environments enriched by adaptive AI scenarios and generative AI based virtual mentoring enhance emergency response realism, accelerate competence development for less experienced engineers and operators, and help preserve critical tacit knowledge as experienced personnel retire. These systems consistently outperform static simulators and informal knowledge sharing methods, while reinforcing that human expertise, judgment, and accountability remain essential.

Across all contributions, a consistent principle emerges: AI and digital tools are most effective as human support systems, not autonomous replacements. Trust, explainability, regulatory compliance, cybersecurity, and workforce readiness are repeatedly identified as critical success factors. As a result, the transformation described is as much organisational and cultural as it is technological, requiring new

skill profiles, updated standards, and closer collaboration between utilities, OEMs, and digital solution providers.

In summary, this category shows that future ready substations will be defined by the convergence of digital design, AI enabled optimisation, intelligent operations, and continuous learning systems. When implemented in a structured, interoperable, and human centric manner, these capabilities enable utilities to deliver safer, faster, more resilient, and more sustainable substations – capable of supporting accelerated grid expansion, electrification, and Net Zero objectives.

Q1.05 ***Based on current experience, how can digital and AI enabled approaches be scaled and evolve as the technology matures (e.g. BIM/GeoBIM, Digital Twins, generative design, automation, and intelligent operations). How can these innovations deliver step changes in substation safety, performance, skills, and lifecycle value, while retaining human accountability, trust, and regulatory compliance? What role can a digital product passport play?***

Preferential Subject 2: Life Cycle & Asset Management in Substations:

- Monitoring, Diagnostics and Testing Equipment to Improve Energy Efficiency and Functionality to Reduce Carbon Footprint as well as Improve Resiliency
- Substation Up-Rating, Upgrading Experience and Operation Concepts
- Asset Management Strategies Including Optimised Maintenance and Substation LCA

The 2026 session received 37 papers, covering this preferential subject which is focused on substation asset management experiences.

Improving substation operational resilience

Following a number of high-profile networks events, resilience at both the network and substation level is emerging as a key priority in the drive towards Net-Zero. As more essential public services migrate towards using electricity as the main energy vector, the key concern is to maintain or increase the levels of reliability and availability typically associated with delivering these services.

Paper 10467 examines the lifetime impact of through faults on a 400/220kV inter-bus substation (predominantly from the LV averaging 80-100/yr). The transformers and switchgear experience a high number of events and associated stress, which has been made worse as the network has been reinforced. The increased stress ages the equipment, shortening the anticipated lifetime through degradation in transformer insulation, observed in the dissolved gas analysis (DGA) and elevated circuit breaker failure risk (early replacement of 400kV CBs). An auto-reclose automation scheme has been installed on to the 220kV to reduce the volume of switching seen through the site at 400kV. Series reactors have also been added to reduce the short circuit fault current seen on the substation infrastructure following the upgrades.

Paper 10655 correlates partial discharge (PD) monitoring with relay waveform data to detect early fault development, before it results in an unplanned outage. Specifically, the multi-source data analysis helps to validate and locate real events from noise and 'contextual blindness' that can be associated with condition monitoring data on its own. The example illustrates how a fault in a generating plant was identified at an early stage. There is an ambition to utilise AI to integrate multiple sources of data to synthesise results more quickly, however this is still in its infancy with training in the lab.

Paper 11425 Application of machine learning to determine distribution substation (24kV) reliability based on surface PD measurements using non outage remote measurements. Analysis considers the large population (over 500) substations to determine intervention priority managing precious resources. the concern is that most of the observed issues are with newer sites on or around cable terminations (87%). Indication that faults in adjacent substations are a major influence on the increase in PD activity.

Paper 10740 outlines how the continuous monitoring features in Controlled Switching Devices (CSD) can provide enduring asset performance data, in addition to their primary feature to reduce stress on the CB during switching and move towards a condition-based maintenance strategy. Furthermore, it will highlight if defects are developing, potentially avoiding in service failures.

Resilience is further considered in paper 11301, which outlines how automation is being introduced to improve 500kV circuit availability and consequently resilience, through the provision of a spare phase reactor, which can be reconfigured into service remotely, significantly reducing circuit downtime.

The nature of networks is changing, and dynamic compensation and FACTS devices are being used to help manage the complexities when increasing boundary power flows. Paper 12609 outlines South Korea's 2x500MVAr MMC VSC units with single phase transformers (plus one spare on standby). Modular approach using 4x250MVAr units to improve availability and reliability. Insight is provided to the longer-term operational strategy, with a priority towards condition-based maintenance, for the large items, however the cooling and aux systems still drive a time-based approach.

Finally, paper 12643 provides a techno-economic assessment of benefits of integrating BESS (and associated renewable energy sources), with the legacy substation auxiliary supply. A comparison between different battery technologies is used to outline the effectiveness of the options. It also considers extending the scope for the Aux supply to include vehicle charging. this increased complexity requires the short circuit level (SCL) and protection to be coordinated. There remains a question around the resilience and integrity of impacting this critical system

Q2.01 ***To what extent is resilience now driving substation design decisions, in these dynamic times. How is this impacting the traditional design vectors of reliability and availability. What are the key design elements that should be consistent in the enduring Asset Management stage?***

Managing the substation carbon footprint

The key driver behind movement towards Net-Zero is an increased awareness and commitment to reducing the carbon footprint associated with the wider electrification of our essential services. To this end the materials used in the substation contribute the most to the carbon agenda, whether through the choice of insulation medium employed in switchgear or the energy intensive materials used in the civil and support infrastructure.

Paper 10839 from Japan considers a more wider reaching LCA over 80yrs taking into account an entire GIS (275kV) and AIS (66kV) substation. The results are dominated by the raw material CO_2e, with operational losses from transformers contributing significantly, however the operational losses of FACTS is not insignificant. Replacing the SF_6 saw a 26% reduction in the LCA for the GIS. The conclusions emphasise that a combination of elements have the best impact and it will vary on site logistics.

Paper 11170 describes a case study looking at a sustainable decarbonisation option for switchgear support steelwork reuse. This has advantages with the embodied cost for steel production is taken into account. The key is to verify the condition of the steelwork and to what extent it can be modified. in-situ treatment is required for exposed elements and any fabrication.

Paper 12107 captures the challenges utilities face with the site assembly of GIS, especially in more remote or extreme climatic conditions. It highlights the controls required to manage site facilities to ensure good quality assembly. The availability of certified and experienced resource to do the assembly work are also a major constraint.

SF_6 Policy evolution

At the national level, countries are beginning to implement strategies to manage SF_6 within their own borders. Paper 10351 provides an overview of an Australian utility's SF_6 strategy for transmission

applications. Based on the principles of Monitor, Manage and Replace (where commercially feasible), they are rolling out an extensive on-line monitoring through wireless systems to provide a cost effect data collection network. Management techniques range from; implementing a value to leaks to incentivise repair or replacement, up to trialling of SF_6 alternatives in AIS applications, to understand the new asset management challenges.

Paper 10461 Introduces the emerging Indian utility strategy to SF_6 management; People - Process - Technology model. To date the key efforts are in the educating people regarding the concerns with SF_6 and handling. Leak detection measures are in progress. The target is to achieve less than 0.1% leakage rate by 28/29 (no base line data to date).

Return on experience from early deployments of C4FN SF_6 free alternative gas in 420 kV GIS in Scotland are described in paper 10738. The existing GIS was retrofitted and extended using the alternative gas, with the exception of the circuit breaker. This was also combined with an increase in the thermal rating from 4000A to 5000A to cater for growing network demand. This technology shift is necessary for the significant network expansion required to meet UK government net zero targets. The paper describes the retrofitting process, including commissioning and testing.

The experiences in Japan are outlined in paper 10837, which provide a summary of the current status surrounding natural origin gas utilisation as an alternative to SF_6 in Japan. Cross industry activity including OEMs, Academia and the Utilities. New application guidelines have been established, along with a Roadmap. The paper reviews the operational performance of 72/84kV equipment which has successfully been operating since 2006 using VCB and dry insulation in so called cubicle type GIS (C-GIS) at low pressure. Higher voltage applications using this combination are being developed with 245kV and 550kV applications in mind.

There is a lot of pressure on the manufacturing sector to respond to this challenge. Paper 12281 outlines service experience to date with retrofill activity on GIS up to 420kV and GIL up to 550kV. Achieving a 75% reduction in the SF_6 volume. OEMs continue to maintain their solutions are very low leak through design, but will continue to address the SF_6 removal, through using a gas mixture with 10% C4-FN 90% air with a GWP reduction of 99%. While retro-filling works for back-parts and some of the switchgear, it is not yet suitable for the circuit breaker.

Operational mitigation for SF_6 and GIS

Paper 10278 outlines how a range of different SF_6 leak fixing solutions, have been compared using a common test environment to prove the concept, these are then considered in field tests. The work concludes, that on the whole, most of the methods work well providing it is applied correctly and there is reasonable accessibility to the point of work. Where sealing is applied to higher pressure vessels (AIS) then solutions with release valves or fittings are advised.

Paper 11075 advocates for the application of continuous monitoring to understand where and when conditions that could contribute to SF_6 degradation or leakage can be identified early and mitigation put in place sooner. One measure is in-line gas dialysis creating a closed loop system to manage the issue.

Digitising the on-line GIS conditioning monitoring to determine remaining useful life is covered in paper 10836. Anomaly detection via the collection and analysis of different data sources provides insight to the utility. Operational data is used to establish baseline equipment performance such that abnormalities can be detected through machine learning. The paper outlines how the learning in SF_6 filled GIS is being adapted for dry alternatives, this also requires adaptation of the UHF sensors down to 100MHz and distance of the sensor from the object.

Experimental investigations (paper 12441) have identified the adaptations required in UHF PD testing techniques on 420kV and 245kV GIS modules to cater for different types of dielectrics; SF_6 and clean air in this case. Sensitivity of sensor type and distance of sensors has an impact on the accuracy and effectiveness to suitably calibrate equipment to determine anomalies inside the GIS.

Q2.02 ***As the use of SF_6 becomes increasingly restricted or prohibited in the electricity industry, to what extent does the electricity industry sector see the wider uptake in on-line monitoring and data driven supervisory methods to manage the SF_6 risk?***

The evolution in substation asset management

Asset management is a constantly evolving field in the substation sector. Many utilities still employ traditional maintenance methodologies and decision-making philosophies, however as digital tools become more common place and embedded with the industry, newer strategies can be employed using intelligence-based decision making, derived from greater asset status insight and the optimisation of different constraints to make the most efficient decisions.

The digitalisation journey of an element of a utility's asset management system is described in paper 11175. The emphasis here is about optimising the maintenance of most substation assets away from a time-based system. This can only be achieved if the asset data and any condition is accurately captured. In turn, this needs to be considered in respect of what impact any intervention has on the asset lifetime.

A high level six stage Asset Management model employed in Columbia. Paper 12123 illustrates how to improve utility operational reliability, by focusing on the impact on operations of traditional reliability indicators. Emphasis is made around Cost- Risk-Performance model, addressing the fact that cost is one of the biggest drivers in decision making.

Paper 10158 provides some valuable insight from a substation service provider, which illustrates how different asset strategy processes still require significant experience and engineering perseverance to achieve a reasonable resolution. This philosophy is demonstrated through a number of case studies, which include determining circuit breaker spare volumes, management of cracked bushings, the use of condition monitoring and diagnosis tools to detect deterioration.

Spares

Managing the supply chain lead time is a major concern in these times. One way risk can be managed is via focussing on strategic components. Paper 11959 concludes, how this is applied in an offshore substation and generation context, such that an initial spares stock needs to be backed up with a risk-based approach to replenishment to manage the resilience risk. Stock-up when the spend is capital driven and employ risk-based management during the operational phase. The paper provides examples for each type of method considering the total cost of ownership.

Implementation of an asset health and risk framework (Paper 10483) to manage critical asset spares inventory which in turn supports equipment availability (circuit breakers in this case). This incorporates failure mode & effect analysis (FMEA), spare part availability, faults and defect history. Used to determine the ageing impact and risk prioritisation.

As many assets reach their end of life at the same time (50 years in this case), they cannot be replaced in a timely manner, due to outage and resource constraints. In Japan paper 10840, explains how a collaborative framework between utilities and OEMs has been established to support legacy and obsolete equipment designs, until they can be replaced. A simulation tool was established to map the renewal plan. Four aspects are considered along with possible counter measures, such as lack of spare parts, no OEM technical support, grey spares and lack of technical expertise.

Each utility needs to have a comprehensive and robust Asset Management strategy for their installed asset base. Paper 12392 highlights the impact that spares management has on network resilience, through minimising the un-availability of transmission equipment. This requires closer upfront collaboration between the utility and OEMs to identify and determine the logistics to source key components in a time effective manner. While failures are rare, they significantly impact the utility availability. Fast recovery typically requires simple modular replacement avoiding the need for special tools, tests or engineering

services. Utilities need to cater for the specific spares, especially interfacing with legacy equipment is a common challenge.

Q2.03 ***How do utilities adapt their maintenance strategies to cater for evidence-based insights from condition monitoring or AI? How is this prioritised against constrained system access and a supplier driven supply chain. How is the work planned around an outage, or is every optimised intervention based on the asset category? Is the recovery and refurbishment of obsolete equipment increasingly being considered and are there any examples of grey spares strategies or 'spares clubs' supporting this wider practice?***

Extracting substation insight from substation data

The impact of Digitalisation on the substation sector has been significant over the last few years, principally due to the general adoption of these tools to provide better insight and recognize tends and patterns. Compared to other data mining applications, the utility sector is still relatively basic, it is important to note that the role of the subject matter experts is still key in managing decisions around the unknown. This is even more pertinent today in the context of Substations, given the variation of technology, resources and external drivers impacting on the day-to-day operation.

There is a mass of latent information hiding within existing Control Room applications, protection and control relays. Paper 10344 outlines how data available within the SCADA from the bay controllers can be used to prioritise maintenance, especially in distribution networks with large volumes of circuit breakers. It can provide an indication of factors like contact timing, phase opening sequence and fault current duty. This is only for indication and not a replacement for more accurate testing but helps to prioritise interventions. This can then be applied to options like extending the interval between maintenance activities.

An approach employed in Slovenia (Paper 10696) utilises smart meters in the LV network to provide a real-time network monitoring. The analysis is achieved through edge computing to provide substation and circuit information to interface with the existing SCADA. The wide availability of 4G and IoT makes this feasible and easily deployable.

The application of QR codes and a digital platform to aid and simplify substation inspections has long been the desire form many Asset Managers. Paper 10512 from India reports how augmented reality headsets have been developed and introduced to help field engineers, by facilitating remote access for expert engineers to 'see the issues' that the field engineer sees. This has a secondary benefit, in that this can also be used to speeds up training and maximises the use of the experts and enables issues to be resolved more effectively.

Substation upgrading

Paper 12214 from Columbia, provides a broad examination and the structure to address the factors which can impact on the substation upgrade decision making. The focus is on how legacy substation uprating requirements can be addressed considering the impact of increasing fault levels and the range of options including digital tools and topologies to optimise and enhance the substation modernisation process. It also provides a summary of the wider international legislative factors driving decision uncertainty.

Brazil presents an optioneering analysis paper (11303) highlighting the challenges facing utilities from network expansion. Legacy substation refurbishment is complicated trying to increase capacity and complexity. Challenges in agreeing the regulatory perspective. Utilities need to work closely with Regulators, to encourage anticipatory investments to facilitate the 'build it once' concept, rather than long complex outage sequences.

Geographic Building Information Modelling (GeoBIM) has been used in Brazil since 2024, principally in the construction phase (Paper 11300). This is a large process so requires careful management. This

also captures the 'as is' information via point cloud LIDAR and then is coupled with other operational mode factors to move towards an Operational Digital Twin. This is reliant on having common data platform to share and access different data sets.

Paper 12076 provides a comparison of the additional seismic elements necessary in Chile with the IEEE 693 standard. It focuses on the local issue for subduction earthquakes which are more common in Chile. These are generally more onerous and last longer, necessitating longer duration testing and accepting larger displacements. The Chilean standard also considers the wider infrastructure, particularly the foundational contribution, compared to the IEEE. The Chilean standard also considers the immediate post-quake availability.

Paper 10518 discusses the use of 3D modelling in the modernising & uprating design process of a 132kV hydro-plant commissioned in the 1980s from 144MW to 156MW. Utilise 3D modelling to check short circuit fault level withstand capacity (replaced porcelain with polymeric and uprated busbar conductors). Modelling also optimised the location of bay marshalling Kiosks (BMK) and relocation of ITs and new station transformer. The paper also highlights the interfacing challenges between new and legacy systems, new fibres installed for IEC61850 Control and comms channels.

Paper 10537 outlines efforts in India to double the capacity of 400kV shunt reactor compensation, while constrained to the same footprint. The old unit had reached end of life based on DGA and oil contamination issues (furans). Review of existing foundations was required to ensure the larger unit, inclusive of tank mounted coolers plus its dynamic forces during switching are supported. Updated the fire management system (water spray). Additional protection logic updates to integrate the new plant into the legacy network design. It would have been interesting to see how Digital design tools such as GeoBIM would have helped deliver the project.

Paper 11171 examines the challenges associated with applying IEC 60865 short-circuit force models to the structural assessment of substation gantries. It highlights the disconnect between peak electromagnetic force calculations and actual structural behaviour under dynamic loading. Relevant experimental evidence from CIGRÉ is reviewed and current practice is contrasted with fundamental concepts of structural dynamics, including dynamic amplification and equivalent static loading. Provides some direction around when calculation can be used or whether FEA or other digital tools will help to provide a most realistic option.

Q2.04 ***Is there any evidence backed justification to show the impact of the proliferation of IBR and whether this actually increases the fault current contribution impacting the substation design? How is the increased or changing fault current profile assessed for ageing and legacy infrastructure?***

As the demand on networks to increase capacity and throughput on the existing system, reactive compensation is called into action to keep the system within operational limits, especially under periods of light load and the impact of more cable in the distribution networks pushing up the voltages on the transmission system.

Substation expansion is plagued by many constraints, working in a live environment, since you cannot switch out the whole site, so a programme of outages needs to be managed. Constrained space is probably one of the most common issues.

A utility in India highlights how demand growth within its region has increased three-fold over the last 20 years. Paper 10469 describes how the use of hybrid GIS modules and cables have facilitated site expansion in a constrained AIS site. This has also been helped in that cables are more forgiving at lower voltages such as 33kV and 66kV, compared to transmission voltages.

The modernization programme, as described in an Indian utility aims to upgrade and replace legacy AIS substations utilising GIS with double busbar config. Typical constraints include limited land availability (due to urban encroachment), construction within the existing substation boundary. An example of 66kV AIS substation with oil CBs upgrading to cater for increased generation capacity, is provided in paper 10482, which explains the logistics to manage space constraints, environmental challenges (industrial pollution, dust) and minimal downtime (5-day outage window). This required a compact offline solution, so a GIS option was chosen. The GIS Hall is a multilevel design with cable basement and GIS on the next floor above. The ground conditions were not ideal, so significant foundation reinforcement was required. The paper also includes narrative on the OHL upgrade and tower footing reinforcement.

Extending legacy or existing GIS is traditionally a very prescriptive activity. Paper (10473) outlines the process an Indian utility established to develop a GIS interface module to facilitate a substation extension with a different OEM GIS. The different bay dimensions required a complex augmentation piece to be designed, fabricated and tested (to IEC requirements) by the second OEM installing the new bays.

Q2.05 ***Where utilities continue to use SF_6 filled GIS to support rapid expansion, with no national legislation to restrict its use, is there any consideration being given to how this could be managed in a future where SF_6 use is restricted or at worse banned. Are any additional requirements being specified to protect the GIS seals, to prevent leakage, enhanced maintenance or on-line monitoring?***

Preferential Subject 3: Impacts of Grid Transformation and New Reliability Threats in Substations

- Physical Security Designs and Experience for Substations
- Substation Designs, Upgrades and Concepts to Mitigate Severe Weather effects
- Experience Building Substations to Connect Large Customers such as Data Centres, Reliably and Safely

For B3 PS3, we received 18 papers. The papers have been clustered into 6 categories addressing the topics authors have in PS 3.

Enhancement of physical access management using digital technologies

Physical access management for substations has historically relied on conventional keys, giving rise to issues including a lack of standardisation, the absence of auditable access logs, and risks associated with lost keys and unauthorised use. To address these issues, the introduction of a battery-free smart access control system utilising near field communication (NFC) technology has been proposed. By using a smartphone as a virtual key, real-time access logging (traceability) can be ensured and key handover time in emergencies can be reduced, thereby improving worker safety, operational efficiency, and physical security (Paper 11444).

Q3.01 ***How should physical access management for power facilities evolve as digitalisation progresses? What operational, institutional, and technical insights can early adopters provide regarding an optimal balance between security and business efficiency?***

Design of defensible space (clearance) and fire protection measures against external environmental hazards

Modern substation physical security must address not only malicious threats but also hazards arising from the surrounding environment. In particular, protecting substations from wildfires, wind turbines (e.g. ice projectiles) and battery energy storage system (BESS) fires requires provision of an appropriate defensible space (clearance) to prevent fire spread and escalation of damage (Paper 11534). Moreover, when integrating BESS in close proximity to substations, the risks of thermal runaway and fire necessitate specific thermal management design, using, for example, computational fluid dynamics

(CFD) analysis and appropriate siting and layout planning from a physical security perspective (Paper 10339).

Adaptive design for increasingly severe extreme weather (heatwaves, high winds, flooding)
Climate change is intensifying extreme weather, increasing the need for more resilient substation design and operation. For heatwaves and flooding, utilities are considering both infrastructure improvements and operational countermeasures to maintain equipment reliability and secure restoration capability under severe conditions. Recent experiences have also highlighted the importance of combining robust design with flexible emergency response and recovery strategies.

In Brazil, comparative assessments of differing technical standards for wind loading (e.g., ABNT NBR and IEEE 605) have been conducted to design substation busbar structures capable of withstanding extreme winds, seeking an optimal balance between cost and safety level (Paper 11314).

Q3.02 ***From a resilience perspective what design principles should be considered for substations with respect to external hazards (natural disasters, neighbouring facilities, new technologies, etc.)? Furthermore, what knowledge do specific examples of design, layout, and protective measures provide regarding the selection and limitations of standards and code-based approaches versus risk-based approaches?***

Dynamic response analysis of substation equipment for seismic risk and strengthening resilience
Seismic design of substations in earthquake-prone areas is directly linked to maintaining grid reliability. With respect to equipment seismic withstand, comparisons of requirements in international standards such as IEEE 693 and IEC 62271-207, and challenges in regional application, have been discussed (Paper 10882). In Italy, reinforcement solutions have been developed, such as new support feet and anchoring systems, to prevent transformer overturning during earthquakes (Paper 11074). For HVDC disconnectors, shake-table testing has demonstrated that adopting composite insulators can secure long creepage distances (pollution performance) while improving flexibility and seismic withstand (Paper 11101). For support-structure design, simulations using Dynamic Equivalency Models are considered effective for accurately evaluating seismic response by bridging differences between laboratory test conditions and actual installation environments (Paper 12120). Furthermore, for HV equipment on offshore wind platforms, a new approach has been proposed to derive Secondary Seismic Response spectra that account for transmission of seismic motions from the primary structure (Paper 11350).

Q3.03 ***In ensuring substation reliability under seismic risk, how should assessment methods and design philosophies evolve? Moreover, how do discrepancies among standards (e.g., IEEE 693 and IEC 62271-207), testing, simulation, and actual earthquake experience influence practical engineering design decisions?***

Rapid connection of large demand using mobile substations and modularisation technologies
With the rapid growth of data centres and the electrification of industry, power infrastructure must be expanded quickly. In this context, mobile substations constitute a strategic solution that can be deployed within days to weeks, providing bridging power to large loads until permanent substations are constructed, and supporting disaster recovery and peak-load conditions (Papers 10749 & 11078). Furthermore, by modularising and standardising GIS in defined dimensional steps and implementing a prefabricated, “building-block–type” platform that can be combined as needed, on-site assembly and testing time can be dramatically reduced, enabling safe and rapid responses to complex layout requirements (Paper 12284).

Q3.04 ***To respond to rapidly changing large-scale demand, how should substation design and construction approaches be transformed? What practical insights can the wider substation community provide, using project experiences with mobile***

substations and modularisation/standardisation, regarding trade-offs among speed, reliability and flexibility?

Ensuring safety and reliability for large-scale connections under specialised constraint environments

When connecting large customers or large-scale renewable energy, designs must address specialised physical and electrical environments. In an offshore wind project in India, advanced reactive power compensation has been designed and implemented, combining shunt reactors and STATCOMs at both onshore and offshore substations, to compensate capacitive reactive power generated by long HVAC submarine cables and to prevent overvoltage (Paper 10546).

Under extreme space constraints, such as underground hydropower plants in the Himalayas, facilities have been integrated while maintaining safety and maintainability by adopting distributed GIS arrangements and flexible EHV cables (Paper 10514). For large earthing systems spanning wind farms and BESS across extensive high-resistivity soils, conventional methods may underestimate ground potential rise (GPR) and touch/step voltages; therefore, accurate design using multi-layer soil models and dedicated simulation software capable of handling FEM is essential (Paper 12309). Finally, in an example of connecting a high-capacity short-circuit test laboratory to the grid, a "bypass arrangement" utilising a breaker-and-a-half configuration was introduced to prevent voltage dips at nearby power stations caused by rapid power draw during testing, achieving safe grid interconnection without costly additional equipment (Paper 10540).

Q3.05 ***Under special conditions such as offshore, underground, mountainous, and high-resistivity soils, how should substation design optimise reliability, safety, and economy in an integrated manner? Furthermore, what insights do specific design and operational examples provide regarding the limitations of conventional methods and the effectiveness of new design approaches?***

Concluding Remarks

This 2026 B3 Special Report has reviewed 85 papers. The diverse range of issues underpins the breadth of challenges facing the substation engineering community around the world. The Special Reporters have combined the papers into a narrative which hopefully brings together the issues, enabling the reader to get some insight to what is happening across the world. The Reporters have produced 15 questions, synthesised from all the papers which hopefully provide some fruitful discussion at the Paris Group Discussion Meeting (GDM) on Thursday 27th August.

Substation Decarbonisation is a priority on the agenda of most utilities and regulators around world. The transition away from SF_6 is progressing well, with more examples of migration to a lower carbon future. There is also an increased awareness and importantly, a commitment to reducing the carbon footprint associated with the wider electrification of essential services. To this end, there is a focus on the optimising the use of materials and activities within the substation sphere which contribute the most to the carbon agenda, whether through the choice of insulation medium employed in switchgear or the energy intensive materials used in the civil and support infrastructure.

The word 'resilience' has emerged in the recent years, following major disturbance events which have highlighted society's reliance on electricity. While it has always been important, it is now increasingly a priority in substation design and operational decision making, particularly where utilities are having to manage risks with resources, system access and the supply chain.

The pace of network expansion and demand for electricity is resulting in the need to build new infrastructure quickly and effectively. To this end, modularity and standardisation are forefront in the substation construction element of most utilities and connecting customers. The benefits are faster supply, construction and commissioning, if the issues are thought through. However, a key recurring

message is that long term success depends less on fully standardised, single vendor solutions and more on the standardisation of interfaces across electrical, civil, protection, and communication domains.

Digitalisation is heralding a shift away from document based and siloed practices toward integrated digital ecosystems built around structured data, using the evolving digital tools such as BIM, Digital Twins and AI based analysis. Utilities are embracing and embedding these tools into their Asset Management strategy as they discover the value of digitalisation lies in improved decision-making quality, coordination and transparency across the asset lifecycle.

In summary, this report has illustrated, that the challenges facing substations across the world have common threads, which through CIGRE, we can share best practice and learning. As electrification becomes more prominent in our lives, hopefully there is some insight the reader can take away, which helps to inform the evolution and innovation of ideas within their respective organisations.

The B3 Study Committee submits this report for your consideration and hopes you find this summary useful and that the questions are representative. We look forward to receiving your responses and contributions this summer at the Group Discussion Meeting in Paris.