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SPECIAL REPORT FOR SC B3
(Substations)

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Special Reporters

CIGRE Substation Study Committee B3 (SC B3) is responsible for activities which cover the design, construction, maintenance and life-time management of substations and other similar electrical installations 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 practice.

The major objectives of SC 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, through providing access to the network, fault isolation and facilitating expansion. This is evident all round the world as energy networks adapt to meet the challenges placed on them.

The Preferential Subjects (PS) for the 2018 Session aim to develop thinking and discussion around the following topical developments and challenges:

PS 1 Advances in substation technology and design
- GIS and GIL developments including HVDC.
- Adapting substations to meet emerging power system requirements and optimised availability including modular, fast deployment substations and live working.
- Changing roles and opportunities for substations including challenges for medium voltage and integration of storage systems.

PS 2 Evolution in substation management
- Advanced technologies for substation management, new information technologies, robotics and the application of 3D techniques.
- Risk quantification and optimised asset decision making, substation economics, maintenance management and life cycle management.
- Substation asset performance, residual life, health and condition metrics.
- Operations and maintenance of offshore substations.

PS3 Health, safety, environmental and quality assurance considerations in substations
- Customer and stakeholder interaction to reduce substation impact including aesthetics, noise and fire management.
- Design for safety, eco-design / recycling and product development
- Physical and cyber-security considerations for substations.
- Managing the implementation of health, safety and environmental requirements for substations, including training.

Executive Summary

This year a total of 42 papers from 23 countries addressing the 3 preferential subjects have been accepted for the 2018 CIGRE Session. As always, this material provides a valuable contribution to the active work of Study Committee B3 and a snap shot of the key issues on utilities minds during this period. The effort and time afforded by the authors and their supporting organisations in producing these papers is greatly appreciated. CIGRE aims to encourage discussion and involvement in the Paris session through stimulating discussion and participation around the material reported in the submitted papers.

The papers cover a broad scope of issues and all the preferential criteria have been addressed to some degree, the key themes which authors have highlighted are;

- Growing attitude to using risk as a deciding factor in determining maintenance and asset replacement priorities, moving away from the more traditional time-based methodologies of the past. While this may still be used in the initial planning stage, it is relegated nearer to time where the intervention is more subject to 'priority clash' between departments and a limited budget which needs to be strategically invested.
- There is also an undercurrent around improving network resilience through substation design and construction innovation, typically associated with being able to respond more quickly to opportunities or threats, using either more compact and agile solutions, but also improving cyber vigilance.
- The 'digitalization' of the substation is continuing at pace as more applications for the process bus along with wider application of merging units in both the transmission and distribution sector to facilitate faster refurbishments and smaller footprints.
- Facilitating the low carbon agenda and associated risks with the industry's key CO_2 emissions is driving more development and application of alternatives to SF_6 for insulation, but also looking at how losses can be reduced.
- Typical with other industrial sectors, there is a growing role for analytics around substation optimisation and operational decision making.

Participating in the 2018 Paris session

You are invited to participate in discussing this Special Report at the Study Committee B3 discussion meeting on **Thursday 30 August 2018** in the Grand Amphitheatre (Level 1) at the Palais des Congrès in Paris.

The reporters have compiled 11 questions below. These are not specifically aimed at the papers' authors but are synthesised from some common issues and trends identified in the papers. This provides the opportunity for a broader response and participation in the discussion session.

You should prepare and submit your contribution *in response to the specific questions* in this report. Prepared contributions must be submitted for review by **Friday 10th August 2018** to the Special Reporters and must address the questions in this report (see following review).

Each prepared contribution will have a time slot of four to five minutes, so that the number of slides should be no more than five, including the title slide, succinctly summarising your contribution to the discussion. The Special Reporters will review the size and readability of the power point presentation and confirm the final time slot is available. They will give recommendations to the contribution authors and inform them whether the prepared contribution will be accepted and is suitable by **Friday August 17th 2018**.

Successful contributors will be invited to meet the Special Reporters on **Wednesday 29th August 2018** in room 234 to finalise the intended contribution to the session. More details will be available before the event. **No prepared contributions will be accepted after the 10th August 2018.**

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 to be included in the session Proceedings. This text is required to be forwarded within two weeks after the SC B3 Session by **Thursday September 13th 2018** by email to mark.osborne@nationalgrid.com to be considered in the proceedings.

Key dates

- **Friday 10th August 2018** – 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 17th August 2018 -** Authors informed that their contributions will be included in the Discussion session.
- **Wednesday 29th August 2018** – All contributors are requested to meet with Special Reporters to check their prepared contributions meet the required standard for uploading into the session presentation - Room 234 of the Palais des Congrès. Contributors should check the room allocation in Paris and will be ask to register to a specific timeslot prior to the event.
- **Wednesday 29th August 2018** 9-12:30 – B3 Poster Session Halle Ternes (Level 1). All paper authors are invited to present an e-poster. This is an opportunity for you to meet authors and discuss papers.
- **Thursday 30th August 2018** – B3 Discussion meeting - Grand Amphitheatre (Level 1). Prepared contributions and this Special Report will be presented and discussed.

Summary of the papers

The following summary and accompanying questions prepared by the Special Reporters, aim to address aspects highlighted in the preferential subjects and authored papers.

PS1: Advances in substation technology and design

This preferential subject was very popular and 19 papers were accepted for this year's session. The subject matter is broad covering all the subsets, in particular demonstrating the multifaceted nature of substation technology.

The application of Compact Substation designs has allowed utilities to explore new bus designs and concepts that were not previously practical due to required substation location or economic constraints. Paper B3-102 provides a methodology for evaluating substation bus designs using GIS or GIL to improve reliability and reduce space required for installation and operation. The use of GIS is just one possible solution.

B3-101 explains the Brazilian strategy to integrate a more compact substation design into existing sites as part of its regulated replacement strategy. Compact switchgear and preconstruction installation techniques with skid design reduce the installation time. The development of the compact substation and greater use of IEC 61850 provides new challenges, particularly where new technology is introduced in to the utility, requiring training and procedures to be developed and implemented.

Standard application designs of AIS substations have typically been predicated on a configuration using a horizontal bus design with some use of string bus to reduce layout site foot print. Two dimensional thinking has been predominately the norm in substations until the recent development of GIS which allows smaller electrical equipment with smaller electrical clearances. Paper B3-113 explores the use of vertical AIS design in India and implementation to reduce clearance, fault exposure and the need for construction space. Reduction in available substation land space helps significantly in many countries with permits or obtaining right of way. Locating the substation in the right place is the key to resilient operation with the most economic benefit.

Paper B3-106 reports on an increase in substation reliability and availability by the recently introduced new concept of "bus-node" substation. A complete 3D-model of a 245 kV double bus-node AIS is established for the verification and optimization of the mechanical and electrical design. Improvements in the switching and short-circuit conditions in bus-node substations have resulted in higher safety margins compared to the IEC requirements.

Three papers (B3-108, B3-109, B3-119) present solutions and examples using mobile substations including transformers, which represent a promising approach to improve grid resilience. Compact and highly mobile designs are described for fast-deployable prefabricated substations and plug & play installation on-site in paper B3-119. Paper B3-108 also describes the application of new insulation materials to minimize size and weight of mobile transformers. While, paper B3-109 focuses on the development of a 400 kV mobile substation bay and addresses in detail the challenges on bay integration into utility operation.

Question PS1.1 **How does compaction and modularity affect substation resilience? How is this defined and measured? What are the key issues and logistics that influence resilience?**

Application of alternative gases to SF_6 is discussed in three papers. A 123 kV GIS pilot installation with fluoronitrile gas (mixture with CO_2/O_2) in Switzerland is described by Paper B3-107. The SF_6-free switchgear has the same dimensions and technical characteristics as the standard SF_6-filled product. A significant reduction in CO_2 footprint is reported. Paper B3-111 deals with the application and use of SF_6/N_2 gas mixture in China. The main driver for SF_6 reduction in China is the high number of GIS installations and an average growth rate of more than 15% per year. Eight substations with compartments filled with the gas mixture were placed into operation. Operational experience from a 72.5 kV GIS with clean air insulation and vacuum switching technology is reported in Paper B3-115. The SF_6-free GIS is optimized for on- and offshore wind-turbine application and the overall GWP is reduced by 94%.

On a different tangent, B3-302 argues transparency is required in environmental impact assessment when considering alternatives to global warming potential (GWP) contributors such as SF_6 and mineral oils in transformers. It is important to consider the whole-of-life cycle analysis. The paper considers a typical substation and that the total energy losses which contribute to the lifetime CO_2 equivalent are not just due to material but also the actual operational losses. Focussing on environmentally friendly alternatives alone will not solve the problem.

Question PS1.2 **With the drive to decarbonise generation in the energy sector, what is the anticipated future for SF_6 applications? What role does economics or legislation play in the future of substation design?**

Paper B3-104 highlights test results for HVDC station insulators at very harsh environment and under heavy icing conditions. The insulator design approach for a new ±350 kV HVDC transmission system requires full scale icing tests on contaminated insulators and the test results indicate the need for improved standards.

Paper B3-118 discusses the switching surge insulation coordination process for substations when uprating the nominal voltage from 275 kV to 400 kV. A concept of relating the switching surge time-to-crest to the network configuration and the transmission line geometry is described to ensure the equipment will remain within acceptable operating conditions following the uprating.

Paper B3-110 reports on an UHV double-circuit 1100 kV AC GIL tunnel project with a system length of 5.7 km. The technical specification is discussed in comparison with 1100 kV GIS. Paper B3-114 describes the benefits when upgrading of air-insulated substations is realized by GIS. Return of experience from three projects shows the challenges and solutions of such upgrading projects.

Question PS1.3 **What examples of substations reinforcement or upgrading have been carried out to increase power transfer capability or improve access for new customers?**

Digitalisation of the substation is considered in a few papers. B3-103 highlights how the low power instrument transformer (LPIT) is being used with the intelligent merging units (IMU) in distribution applications to facilitate the move towards implementation of IEC 61850 and 'digitalization' of the substation. This is enabling the key function of the process bus to support the move to a fully digital protection and control solution.

Paper B3-117 describes the LPIT technology integrated in GIS. The passive sensors for a combined I/U measurement are introduced in a 110 kV GIS pilot installation. Information about design, manufacturing, and type testing are given. First results from the pilot installation and customer benefits like environmental-friendly design and realization of digital substation are reported.

Paper B3-116 looks into digitalization of station level and process level and application of IEC 61850 and non-conventional instrument transformers (NCIT or LPIT). Potential benefits for TSO have been identified for the increasing needs of asset management and grid operation support. In addition some aspects of cyber security for digital substations are discussed.

Integrating new technology into the network or even a substation, requires a high degree of assessment. Korea reports on the Hub substation in paper B3-112, which has been designed exclusively to assist in the connection of smaller renewable energy sources, which are traditionally "below the radar" of transmission system operators, yet in sufficient numbers, may contribute to network instability if not correctly managed. This facility aims to use an energy storage solution (ESS) to help stabilize the network perturbations resulting from faults and interactions using the Hub to compensate for these new renewable connections.

Question PS1.4 **What impact are distributed resources such as embedded generation and energy storage having on substation design and operation? What changes at the substation level are necessary to accommodate these into the power network? How can digitalization help achieve these goals?**

Preferential Subject 2: Evolution in substation management

This PS was also very popular and 18 papers were accepted. The subject matter attracted many utility contributions showing that good asset management is a growing issue across the sector.

The advances in computer aided design and technology are beginning to gain acceptance in the industry and across the world. The evolution of three-dimensional (3D) models are leading to exploration of alternatives for preparation of more effective bus designs as outlined in detail in paper B3-210. The use of 3D modelling effectively improves computation in the design process for the ability to evaluate changing standards and environments in design. The ability to create models for existing as well as new substation equipment and layouts can take significant time and effort.

Paper B3-214 evaluates and explores the use of 3D scanning to improve speed and accuracy for substation design. Examples are helpful and instructive to the new engineers to show the value in time and prevent costly construction design changes during implementation. The use of 3D technology has the potential to shift the paradigm of computer aided design in the future industry. Application of substation design is not the singular advantage for cost effective substations. The development of special equipment enhancements and virtual training of employees are the ultimate benefits. Designs for components using through additive management allow for enhanced equipment parts not readily available with conventional manufacturing techniques. Paper B3-216 is an introduction into a new way of thinking and provides examples of ancillary benefits of new 3D design technics for the substation world.

Paper B3-301, shows how this can be put into practice to demonstrate the mechanical integrity of substation enclosures, which is a major safety concern during an internal fault. Software modelling is used to replicate the dynamics during faults to validate structural integrity of switchgear enclosures.

Question PS2.1 **What role are new software design tools and techniques such as 3D modelling and printing playing in the management of substation design and construction? How can these tools be easily applied to legacy substations and made accessible to the engineering staff, what are the challenges and opportunities?**

The use of Asset Health Indices (AHI) is not new, however these are now increasingly being used to justify risk-based decision making. Paper B3-201 discusses some of the flaws in using AHIs in the wrong context, particularly around calibration and in considering consequence. It reports the application of the concept of 'equivalent probability' across a population of different aged assets to identify the urgency around intervention within National Grid in the US.

A paper from Australia reports on how they are developing an asset management risk framework to identify the best timing for equipment replacement. This uses risk models along with AHI to determine the optimal intervention for substation protection & control systems B3-205. This enables the utility to quantify the trade off in investment against protection and control reliability and availability.

Korea have provided two papers on asset management topics. The first on reliability Centred Maintenance (RCM) is used to establish the inspection and replacement strategy for GIS B3-207. Fault tree analysis, service fault data is combined with Failure mode effects and criticality analysis (FMECA) to estimate future reliability and the timing of necessary interventions. The second paper, B3-208 details their Asset Health Management System (AHMS). This is a holistic end to end data collection and analysis system, which encapsulates all the information necessary to make asset health decisions and determine the maintenance strategy for specific asset, in particular the timing and priority around maintenance actions. In the short duration of its implementation it has reduced the failure rate significantly and costs by up to 30% at an oil refinery substation.

In Thailand, MEA have developed an importance index for key assets B3-209 such as power transformers. This evaluation program takes into account multiple determining factors including system security, network conditions, and asset condition to establish the grouped risk associated with each transformer. This in turn determines the risks associated with unit and the appropriate maintenance strategy for that asset. This enables all the transformers to be categorised such that prioritised intervention can be assigned to the more critical units.

The Chilean utility, Transelec describes a roadmap to 'digitalization' of its operation and asset condition data B3-213. Much of the effort resides in automating the collection of data, developing new analytical tools and information models to support the asset management strategy. The scale of work is large; digitalisation of historical data, establishing processes requiring reliable communication services to gather remote data, database platform to store the data and analytics to optimise the decision making. Finally, success will only be possible if establishing the processes and cultural change are embedded into the business.

Question PS2.2 **How are data analytics and risk management being used and are they becoming more common place in substation intervention decision making? How is this being reflected into substation maintenance policy? What evidence is there to show that these strategies are delivering value?**

Changing asset management practices with the utility is not very easy. Japan reports, in B3-215, how three utilities have approached this. As costs are challenged due to stable network demands, more efficient utilisation of equipment needs to be considered. The paper focuses on changes in GIS maintenance strategies, towards shortening the un-availability of the GIS, through faster data collection, less site inspections, more thinking around the priorities for refurbishment or repair. This takes into account the age, utilisation and deterioration factors associated with the GIS.

Manufacturers are also looking at the effect of asset management strategies and how they can provide an APM[1] using sensors, AHI and SCADA data in B3-217. This combines FMECA[2] and risk mitigation actions to help the utility address its ownership issues. The software produces a health model of the GIS, based on the knowledge across the OEMs world-wide population. This can provide an estimate of the probability of failure and residual life, which coupled with factors like criticality can calculate the Asset Risk Index.

The role of software and processes is already central in substation automation and will only increase in the coming years. Predictive maintenance for substation automation is considered in B3-218, it considers how redundancy can be achieved though different system architectures. The development of a predictive maintenance strategy needs to consider how to 'monitor' the automation and identifying points of weakness. Cyber security is discussed around the different architecture approaches and security features associated with different hardware access methods.

There is often a huge amount of very useful data idling within the utility's existing SCADA systems. The timely analysis and evaluation of this data could provide very useful asset management data, however this is all too frequently inaccessible to the asset management departments. The Croatian TSO[3] HOPS has developed a Smartgrid application described in B3-211 which takes the operational statistics (alarms and events) together with condition data and the Asset management policies to establish a proactive maintenance schedule for assets. This identifies specific assets and correlates it with system events. It can also test the availability of remote functions. It also highlights the need to establish reliable processes for data standardisation and the collection rules as new assets are added to the network.

Question PS2.3 **Legacy maintenance systems and databases are increasingly being interfaced with new analytics and web-based processes, what examples are there of how is this challenge being addressed to provide agile, efficient and flexible asset management systems?**

The design of offshore substations has been the subject of a number of B3 technical brochures, paper B3-204 reports on the operational experiences of 6 offshore facilities in the UK. It describes the issues in transitioning ownership from developer to OFTO[4] requirement in the UK. The differences between onshore and offshore approach to asset management are highlighted. Key points include preparation for the hostile marine environment, maritime regulations, reliance on remote systems and almost whole reliance on cables, which effect voltage, switching duty and resonance. The report summarises design improvements based on operational experience for an offshore environment. The reliability of auxiliary systems is a key problem, establishing settings and reactive voltage control. On the maintenance angle, issue around certification can be problematic as well as finding multidisciplinary resources to deliver more services while offshore.

Qatar reports in B3-105 on experience using various partial discharge detection methods to carry out annual inspections and determine whether there are issues developing across their large population of switchgear. This quickly helps the utility to determine where to focus more detailed inspections and is a key part of their predictive maintenance strategy.

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[1] Asset Performance Model
[2] Fault Mode Effect and Criticality Analysis
[3] Transmission System Operator
[4] Offshore Transmission Owner

The Russian utility PJSC FGC UES, describes the move towards outsourcing maintenance as a service in paper B3-219. It examines the factors which contribute to how a utility should structure contracts to ensure the supplier delivers a service which respects the utility's responsibilities. This translates many of the technical attributes into business related features which dictate the terms of contracts between the utility and service providers, typically the OEM.

Question PS2.4 **What examples are there in defining the health of the substation as a whole entity, rather than asset specific health indices? How significant is the substation infrastructure and auxiliary systems on the performance and reliability of the substation?**

PS3 Health, safety, environmental and quality assurance considerations in substations

Safety is the paramount driver behind the design and operation of the substation, while many of the papers in PS1 and PS 2 focus on the technical reasons behind design improvements, fundamentally much of this is driven by the need to meet either safety or environmental legislation within each country. Five papers have been submitted in this section, not as many as the other subjects, however increasingly the concept of resilience is being considered to underpin the design and construction assumptions. Nowhere else is this more evident than in the cyber sector.

The value for utilities of participation in CIGRE, is the ability to be exposed to new ideas and technologies that have shown promise in the management of substations performance, health and condition. The subject of earthing is a major concern when considering this is the main function to manage the safety of both employees and the public. B3-206 considers the challenges to obtain accurate and meaningful measurements to demonstrate the effectiveness of the substation earthing grid. A particular concern is the growing complexity and overall interaction as networks become more complex and integrated. Essentially, understanding and proving the system efficiency is more difficult. Skills and knowledge are required to both design and test these systems and it should not be under-estimated.
Paper B3-304 describes the substation grounding assessment carried out on the Itaipu project for the health and safety of personnel in the substation, in particular the need to confirm the design is effective and is intact following construction or maintenance activities. The examples provide design criteria and methodologies of testing to prove that complex earthing design are achievable and can be maintained over time.

Question PS3.1 **What examples can be provided illustrating how customer and stakeholder influence is impacting on substation design, operations or management? E.g. safety, environmental impact, visual amenity etc..**

The emerging risk around cyber security is presenting utilities with a variety of issues. Increasingly, the resilience of power systems to non-environmental factors is becoming a serious threat. Understandably, there is a limited amount of detail published on the weaknesses and shortcomings of substations. However, paper B3-305 details experiences with substation automation systems, in particular, object control and approaches used to fix the problem, including industry and national standards outlining the resilience and expectations from critical network services like utilities.

The challenge in gathering condition data on assets is a long running issue. The improvement in wireless communication and the onset of the Internet of Things (IOT) is significantly improving the ability to achieve this. Paper B3-203 reports the practical experiences in Finland around how 68 sensors are being used to measure the acoustic emissions and establish the performance of legacy switchgear during normal operation without the need for off-line testing. The challenges are around data management and suitable processing environment. The threat of cyber security breaches is also highlighted and any potential on information validity.

Question PS3.2 **How are utilities addressing the dilemma between developing the Smartgrid and securing the substation infrastructure against cyber-attack? Are there examples of known cyber intrusion? Are there any further examples of how substation digitalisation is delivering value?**

In Russia the PJSC FGC UES utility with 933 substations has carried out an evaluation of its auxiliary system consumption and considered approaches to optimise the usage in B3-212. As energy costs increase, utilities are looking at deploying more energy efficient measures to control costs. Auxiliary energy consumption accounts for approx. 4% of losses. Of this transformer cooling and building heating are the largest. The 'Energy Efficient Substation' project has deployed a number of innovative approaches including transformer heat recovery to heat site buildings, automated control for transformer cooling to control the speed of cooling and finally thermostatic regulation of substation heating services. Together these initiatives will deliver an 80% reduction in auxiliary consumption for new substation facilities.

Japan describes in B3-303 how gas insulated equipment can be used to reduce the risks from locating substations in confined spaces or very close to public areas. Gas insulated transformers (GIT) are used to remove fire safety risks arising from mineral oil related fires. A second example illustrates how GIS is used in building to avoid affecting third party amenity. It shows how simple measures such as rubber pads can reduce the noise and vibrations emanating through building structures to neighbouring facilities. The technology is an enabler for compact and constrained locations such as indoors or underground facilities, removing the need for bunding and fire protection systems.

Question PS3.3 **What new safety and risk related aspects are emerging as new technology for substations, and is there adequate understanding of the associated issues?**

Concluding Remarks

This session's collection of papers covers a wide range of issues. As always the challenges facing the substation owners, engineers and operators are extensive, reinforcing the fact that bodies like CIGRE are an essential element to minimising the number of times a problem proliferates and adds value through having networks to quickly develop solutions and share best industry practice.

The key headline this session is about managing the risks associated with design, construction or operational activities to do with the substation, whether that is choice of technology, busbar configuration or data analysis to determine a policy. However, understanding the risks requires reliable information and processes to support the decision making and provide evidence of the assumptions upon which the decisions.

There is no one single solution, each utility must balance the issues specific to its own operation and business environment, but which ever approach is taken, the utility needs to be able to determine the appropriate level of resilience that is required.

We hope you find this summary useful and the questions representative. We look forward to reading your responses and contributions this summer at the discussion session in Paris.