Final Report of the 2019 CIGRE Symposium in Aalborg

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FINAL REPORT of the 2019 CIGRE Symposium in Aalborg

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by the Technical Organizing Committee

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Henk Sanders, Chair SC C3; and Christine Schwaegerl, Chair SC C6

Introduction

The CIGRE Danish National Committee working with eight Study Committees hosted a symposium in Aalborg Culture and Congress Centre, Aalborg, Denmark. The symposium's main focus was to provide a forum for recent research results and system operations experience related to the rapid transformation of power networks and markets and the challenges imposed on such networks by the introduction of increased amounts of renewable energy. A wide variety of papers, ranging from academia to industry and from conceptual to practical, implemented solutions were presented during the symposium. Moreover, a number of Northern European countries are at the forefront of introducing increasing amounts of renewables into their respective electric power systems and this large share is further increased by the introduction of offshore wind energy and interconnectors. This is necessitating a need to re-think how transmission and distribution networks are coupled and co-ordinated together from planning to operation while overcoming all the necessary technical, operational and environmental challenges.

The two-day symposium attracted over 325 delegates from more than 30 countries. More than 110 papers were accepted and presented during the 24 sessions. Papers originating from Young Members (YM) were also displayed as posters in addition to being presented. In total there were 18 Young Member papers. There were eight tutorials, presented the day before the symposium by all the supporting Study Committees. The symposium was supported by Study Committees B1, B2, B4, C1, C2, C4, C3, and C6 with SC C4 leading it.

Symposium Programme

The symposium was located in Aalborg City and hosted by Aalborg Congress and Culture Centre using one large session room (Europahallen) for common sessions and three session rooms (Musiksalen, Radiosalen and Det lille teater) for technical sessions. Lunches for delegates were served in the congress centre. The overall program consisted of:

- Three SC meetings and more than 30 WG meetings
- A welcome reception in NORDKRAFT (a former coal fired power plant) with three welcome speeches and two technical speeches. A light dinner and drinks were served. The Raggedy Ann's entertained the delegates during the evening.

- An opening session in Europahallen featuring an opening speech by the chairman of the organizing committee, a keynote speech, CIGRE TC Chair's address and sponsors presentations.
- A set of 24 technical sessions for the eight study committees in three parallel tracks.
- A student poster session where YM presented their work for more intensive discussions. YM papers were also presented in the sessions.
- Gala Dinner in Musikkens Hus with a welcome speech and some light snacks and drinks followed by a musical performance by the Piazzolla Orchestra. A three-course dinner was served in the upper foyer enjoying the view of the sun setting over the Limfjord.
- A closing session with an address from each SC chair summarizing the findings of the symposium and wrapped up by symposium technical chair. Best and runner-up YM paper awards were given. The closing speech was given by chairman of the organizing committee.
- A technical visit to offshore wind power plant ANHOLT by specially chartered ferryboat. The vessel visited the offshore turbines and transformer platform as close as possible with delegates being able to observe the technical installations. During the voyage 5 lectures related to offshore wind power were given.

Student Poster Session

The Technical Organizing Committee was particularly impressed by the very high standard of the Young Member papers. Prizes were awarded for the top two student submissions based on the quality of the paper, the clarity of presentation, young member's interaction with the audience during paper presentation, poster and the judges' discussions with the authors. First prize was awarded to Christina Brantl from the Institute for High Voltage Technology, RWTH Aachen University, Germany for her paper and poster titled "Impact of the HVDC system configuration on DC line protection". The runner-up was Juan-Andrés Pérez-Rúa from the Technical University of Denmark, Department of Wind Energy, Denmark, whose paper was titled "Improved Method for Calculating Power-Transfer Capability Curves of Offshore Wind Farms Cables".

Key Learning Points

The following sections provide key learning points per study committee in a concentrated form. More detailed summary of each session is given at the end.

Study Committee B1:

The main takeaways for SC B1 can be summarised under three heading: 1- intelligence is the future, 2- experience helps innovation and 3- future needs cables.

Condition monitoring provides valuable information about the state of the assets, this improves reliability and drives down costs across the whole cable life.

Innovation always fosters improvements: extension of range, increase of resolution, interpretation or collection of vital information which was not thought important initially. Overall, lessons learnt, and coordination are vital to improve designs, practices and standards.

DC systems need cables to be sustainable and integrated in the wide network. Hence importance of points like insulation coordination, coordination between sub-systems, and overall cost reduction etc

need to be considered. New cable applications for renewables are improving their resilience with more robustness in design, more focus on testing and operation and more experience being gathered from installations.

Study Committee B2:

The main learning and discussion point for SC B2 was the optimization of overhead lines by new tower design to increase the public acceptance, and also considering costs and maintenance, and new composite materials for towers. Much interest exists in DC and AC/DC hybrid overhead lines to transport bulk energy and to overcome bottlenecks in the existing transmission grid. Hybrid line means one circuit AC and one circuit DC on the same tower. Such lines can be created by the transition of existing double circuit AC overhead lines to an AC/DC hybrid line, or they can be built as new AC/DC hybrid lines to have a point-to point DC connection and to enable tie offs from the AC circuit.

Study Committee B4:

A key learning point from SC B4 was that most of the DC grids in the future will be formed as PtP links initially and later extended gradually to become multiterminal. This would most likely result in multi-vendor VSC systems. Interoperability among such converters is therefore a major concern which becomes all the more urgent with the perspective of future DC grids.

Another key discussion point was that a full-scale development of a meshed HVDC grid needs input from all areas. This is because the phenomena in such a grid are complex and difficult to estimate. Studies are required together with developments both with suppliers and with future users.

It was once again confirmed that there is a strong need for DC breakers, the technology, and the requirements in control and protection of DC grids. Further discussions were held on fault detection in mixed circuit with new converter topologies providing dc fault suppression capabilities. There was also confirmation of innovations in VSC technology leading to economic solutions for the integration of distributed renewables in the MVDC networks.

Study Committee C1:

The main learning points on the system planning side were that planners need to be aware of and quantify uncertainties at many levels, in many models and tools, and that trade-offs need to be made explicit. Many decision makers need to align in order for the system to be developed as needed, for which cooperation is key in general, and in particular for dealing with trade-offs.

On the planning of offshore wind connection, the choice of regulatory regime can influence choice of technology (HVAC, HVDC, storage) and that there is a need for long term offshore and onshore planning to be coordinated to minimize CAPEX and improve public support. Furthermore, dynamic loading enables increase in wind capacity per network capacity but requires forecasting, modelling, monitoring, and increased collaboration between OEM-developer-TSO.

Various innovative solutions for a long-term future, climate-neutral electricity and energy supply system based on strong contributions of renewable energy including much higher offshore wind

capacities than we have today were explored on the long-term side. The scale of decarbonisation of energy and the very large role for electricity mean that bold concepts (e.g. North Sea Wind Power Hub, global grid, Power-to-Gas) need to be considered and flexibility must be fully utilised, much of it in distribution networks. Increased number of concepts for balancing demand and supply even in those parts of the year where RES are most challenged is seen from accelerated research that shows climate neutrality will raise major political, regulatory and societal questions which will require cooperation across different decision makers, and that for flexibility, market price signals will be very important.

Study Committee C2:

It is worth noting that the papers covered all three technical directions of the study committee, i.e. (1) real-time system operation and control, (2) system operational planning and performance analysis and (3) control centre infrastructure and human resources for system operation. The contributions presented in the SC C2 paper sessions focused around enhanced and coordinated system operation. From transmission system operator's perspective this essentially evolves around three main requirements: flexibility, observability and controllability. With increasing power electronics interfaced devices (PEID), (e.g. offshore windfarms and energy storage systems), a high level of flexibility will be required for delivering ancillary services such as frequency and voltage support, congestion management and restoration. Majority of these new PEID are dispersed, requiring increased observability. As the output of these devices is volatile, increased observability will create the possibility for enhanced and more effective power flow control, which under all circumstances need to be coordinated. Lots of innovative solutions are being developed with the aim of increasing the operator's observability and controllability: wide area control systems, inertia estimation, dynamic security assessment and AC line emulation strategies are a few to name. At the end, the ongoing developments all contribute to the same goal: how can we achieve the same level of operational reliability, while making the energy transition in the power system.

Study Committee C3:

SC C3 topics were mainly on the definition of sustainability; people, planet, profit. The key learning point on these were:

Engagement of people (externally and internally) is crucial for being successful in all the challenges that the power sector is facing. Objection from public is still one of the major problems the power sector faces. Papers presented several ideas to improve public acceptance: from taking care of safety of all our workers to measurements for improving visual impact and from new methods for reducing environmental effects to the use of modern communication techniques.

Importance of sharing even bad examples and/or failures was highlighted along with the importance of data and collaboration between different stakeholders.

There is still a shortage of accurate data, our sector needs more involvement from academia as well as from practical experiences of the sector itself.

Working with the sustainable development goals (SDG's) presented by the United Nations, is helping with organizing and structuring the approach from the sector.

Study Committee C4:

A key learning point for SC C4 was that there are still many challenges with the analysis and control of power quality (PQ) in power systems, particularly with large deployment of wind and PV generation and with the advent of cables installed into the system. Main issues revolve around applicability of standards in complex interactive cases, application of analysis methods and the introduction of cables This final report provides a summary for all the 24 sessions that focus on the planning of power networks to accommodate offshore renewables and interconnectors, technological advanced that makes help this integration less onerous, issues associated with environmental and system technical performance aspects and they are operated in a wider scheme of TSO-DSO interaction.

into the transmission system can bring the natural resonant frequencies to lower orders. The latter brigs further issues in terms of TOVs and delayed current zeroes to name some of the technical issues. There are ongoing challenges that need to be addressed to adequately represent intermittent, converter interfaced generation in power system simulations and network security analysis tools.

Technologies that are now readily available bring certain challenges, but also create new opportunities to improve the performance and reliability of the power system. These include active filtering of harmonics from STATCOMs and wind turbine converters. Combining off shore wind developments with increased interconnection between neighbouring power systems utilising advances in both AC and HVDC designs.

More complex interaction phenomena are emerging as the ratio of synchronous to inverter-based resources is gradually declining in the system, and as different types of inverter-based resources and associated control systems are being connected in close proximity of each other. Diverse range of interaction issues including sub-synchronous control and torsional interactions, super-synchronous resonances, and weak grid instabilities are being observed. Different solutions including modifications of converter control systems, development of special protection schemes at the network level, and installation of passive harmonic filters are proposed and implemented. Further work on identifying these new and emerging interaction phenomena is required in addition to frequency domain analysis techniques as a screening method.

Another key theme is that the industry appears to have moved to ‘the next phase’ where commercially available solutions for harnessing wind (and solar) are now being ‘rapidly scaled up’, bringing with them new technical challenges for design engineers as well as network operators. This is particularly the case where HVAC is utilised to connect new generation and/or strengthen onshore networks to cope with significant increases in generation capacity.

Study Committee C6:

A key learning point was the elevated coordination required for TSO-DSO interaction with key challenges on the DSO side being the use of huge data (smart meters, aggregators etc), the need for commercial interaction among these players and the technical challenges that exists in the grid management with more fluctuating generators.

Grid forming provided by inverters in storage units and renewable generation units helps to improve overall stability and resilience, to provide ramp rate control and smoothing, to reduce wear and tear

on generators, to avoid load shedding and to reduce frequency deviation, to have frequency and voltage ride-through capabilities

In terms of strategies for active distribution network operation it is important to realize application of novel schemes and methods for realising active distribution system planning and operation, and enabling integration of flexible demand and regulation reserves in electricity markets. Thereby, the hosting capacity of the renewable units in local electricity grids are increased and economic benefits for the stakeholders are maximised.

Detailed Session Summaries

Detailed summary of the 24 sessions is given below under each study committee.

SC	Session
B1	13: Cable monitoring 16: Cable system design 22: Offshore network of the future: wind farms and HVDC grid
B2	17: OHL tower design, optimization of costs, public acceptance, EMF, AC/DC coupling effects
B4	3: DC Grids and multi-terminal dc systems 6: Innovative solutions in FACTS and HVDC technology 9: Control and protection of dc grids 21: Off-shore system integration 24: Analysis and modelling of DC and FACTS
C1	4: System planning including offshore networks 12: Offshore wind connection planning 15: Long-term and sector-coupled decarbonized energy system planning
C2	2: Assessment and study tools for system operation 5: Operation of hybrid and low inertia power systems 11: Support from VSC HVDC for system operation 14: Frequency support from power electronics interfaced devices
C3	8: Eco-design and environmental concerns, the social aspect (people) 23: Eco-design and environmental concerns, the environmental aspects (planet)
C4	1: Electromagnetic transient aspects 7: Power quality challenges 10: SSR, control interactions and instabilities 19: System technical aspects of wind generation
C6	18: Challenges for DSOs and improved TSO-DSO interoperability 20: Innovative strategies for active distribution network operation

SC B1, Session 13 “Cable Monitoring”

Chair: Roman Svoma

This session covered a wide range of monitoring technologies and innovation avenues for OHL as well as submarine cables including fault detection techniques, algorithms and the use of fibre optic condition monitoring.

Paper 005 introduces a novel way of fault finding on HVDC cables based on modal analysis and the Hilbert-Huang Transform (HHT). The advantages of HHT versus Fourier and Wavelet transform is discussed and theory for the methodology developed. The CIGRE DC system given in references is modelled and suggests an error of 0.2% which is very promising, however further studies and analyses have to be carried out to evaluate the sensitivities to system parameter variation such as bonding resistances, high impedance faults and different HVDC systems.

Paper 009 reviews the use of Distributed Temperature Sensing (DTS) in submarine cables and discusses the principles, applications and capabilities of the Brillouin systems available. Range of over 100km can be achieved and the advantages and disadvantages of greater resolution are illustrated. Two case studies show how such systems can be implemented and how soil conditions can be integrated into the Real Time Temperature Rating (RTTR) to give a greater accuracy.

Paper 016 sets out how a new fault location algorithm can be incorporated into the protection system. This can provide a much greater accuracy of locating a fault when it occurs by using the Bergeron transmission line model. System modelling is used to provide evidence that the proposed algorithm can achieve much greater accuracy especially for faults at large distances as compared to the conventional Takagi method.

Paper 112 considers the use and experience of DTS in Germany. One of the conclusions drawn is that the technology is not mature at the moment with regard to long length HV cables. Interesting case studies are reported relating to hot spots in joint bays, pre-failure associated with fibre optic interaction with the power cores and issues and de-burial. Comparison between Brillouin and Raman are illustrated and strain related issues affecting the Brillouin system highlighted. The evaluations lead to the TSO developing a strategy which is outlined at the end of the paper.

SC B1, Session 16 “Cable System Design”

Chair: Danijela Palmgren

This session covers a wide range of topics related to cable system design, such as measurements of electrical characteristics of HVAC cables, ground current calculations in power networks with OHL and underground cables and overvoltages in HVDC systems.

Paper 113 emphasizes that when using measurements to verify theoretical models or characterise cable designs it is important to be aware of sources for inaccuracy and minimise their impact on the measurement results. Except for the instrumentation itself other factors such as sample preparation, ambient conditions, test set-up and connections shall be thoroughly evaluated before application.

Paper 117 reviews methods for ground return current calculations according to two existing standards/recommendations. Different factors affecting the ground return current in OHL and cable networks, as well as the limitations of the methods are discussed. A practical case study has been performed assuming a system with both OHL and underground cables. The conclusion is that though the evaluated standards give good guidelines on the subject, they propose simplified calculation methods which do not cover all real scenarios and which due to conservative approach lead to over-designed and expensive earthing systems. For optimised solutions software methods are recommended.

Paper 134 deals with overvoltages in symmetric monopolar HVDC cable systems. After initial comparison of two different EMT tools a parametric study has been presented. The conclusion of the study is that the pole-to-ground fault in HVDC cable systems is the most relevant for further considerations. The overvoltages that the system experiences due to this fault mode differ both in shape and duration compared to standard overvoltages. Thus, even if the maximum amplitude of the overvoltage seems to be covered in the standard procedures further considerations are needed to conclude if new test procedures need to be adopted to cover the shape and duration of these overvoltages. The work in this paper is used to support discussions on this topic in the ongoing CIGRE Working Groups.

SC B1, Session 22 "Offshore network of the future: wind farms and HVDC grid"

Chair: Roland Zhang

Session 22 comprised of six papers with the main topic of offshore network of the future: wind farm and HVDC grid.

Paper 039 with the title of insulation coordination for DC cable grids: expected challenges of network development from point-to-point links to HVDC grids. This paper aims to raise the awareness i.e. "Be conscious. Think early". The extension of point-to-point links towards MTDC grids, possibly including HVDC circuit breakers and/or line energization switches, introduces potentially novel types of overvoltage, which have hitherto not been considered. In order to enable the cost-effective development of such MTDC grids, a holistic approach towards determining the insulation levels of all primary HVDC equipment is required, to define suitable standardized insulation levels and test waveforms. It is suggested to establish standardized representative waveform, especially for testing the DC cable systems and not experience the difficult scenario with "n" different waveforms emerging from "n" different project specific conditions

Paper 053 Installation engineering of the export cable for the Kriegers Flak offshore wind farm connection: The objective of this paper was to present the installation engineering of a high-voltage cable system to transfer power from offshore wind platforms to land, the so-called export cables. The paper aimed to motivate early cable installation engineering in order to reduce risk in the execution phase. This by describing the export power cable installation engineering at the offshore substation platforms during the Kriegers Flak AC project. The experience and findings regarding engineering, interface, communications etc. throughout the project has been presented.

Paper 115 Technical considerations for optimized design of AC HV submarine cables: This paper gave an overview of optimization possibilities and measurement method of three-core cable losses by single sample method. Best construction comprises the layup direction of the cores and the optimum design of the armoring. Stainless steel wires, or wires made with composite materials give the possibility to increase the rating of the cable. It was also discussed about the progressive reduction of armoring length.

Paper YM 119 DC cable systems aspects for future offshore windfarms cost reduction. This paper described DC transmission from the economical and delivery point of view. Improvements on cable

systems can help the offshore wind market to sustainably grow following the expected trends while reducing the CAPEX needed for DC systems. There are mainly four areas where cable system improvements can bring an overall economic advantage:

- Increase the maximum transmittable power by using larger conductor cross sections;
- Increase the maximum transmittable power by going to higher voltage levels;
- Improve insulation performances and reliability;
- Reduce system delivery time;

The latest achievements in these fields were analyzed with a specific focus to submarine cables. Technology gaps and challenges already solved were described. Finally, economic benefits of these developments have been presented.

Paper 128 Importance of mechanical design and testing of cable systems for floating offshore wind: This paper includes descriptions of analysis and testing activities and important aspects to be considered of cable systems for floating offshore wind. The final step of the qualification of a dynamic cable is the full-scale fatigue test which is part of the type test regime for dynamic cables according to CIGRE TB 623. The full-scale fatigue test uses input from all preceding analysis and testing activities and combines it into a test that simulates the expected fatigue loads that the cable will experience during service life. The full-scale fatigue test functions as an important robustness test of the cable and can contribute to finding unexpected failure modes resulting from fatigue loading. This paper gave a more detailed description of the full-scale fatigue test and aspects that should be consider when designing the block program.

Paper 133 Design and operation of three-core submarine cables with integrated optical fibres: The paper described two typical submarine cable designs in use summarizing their main features, advantages and drawbacks. Some case studies were presented, including simulations of normal and abnormal operating conditions. Voltages, currents and heat generated in the FOC are calculated for the two designs. The most critical operating conditions have been found when the FOC metallic tube is not properly earthed at both ends or interrupted along the route. A large electromotive force builds-up in the FOC metallic sheath owing to current flowing in the power core conductors. As a consequence, large current density flows through the FOC semiconducting sheath which undergoes premature ageing. Some failures occurred in recent years have clearly been related to improper FO tube earthing.

SC B2, Session 17 “OHL Tower Design, Optimization of Costs, Public Acceptance, EMF, AC/DC Coupling Effects”

Chair: Herbert Lugschitz

Paper 29 presented newly designed “T-pylons” for a 380kV double line, based on tubular steel poles and tubular crossarms. The conductors are mounted in the form of a diamond. The towers´ height is 35 metre above normal ground, this is smaller than standard lattice structures with two or three crossarms. If maintenance work is necessary, it can be done using cranes. The structures are galvanized and coated, it is expected that maintenance coating will become necessary not before 80 years.

T-pylon

Paper 54 showed two other new designs for 380kV double lines. “Eagle” towers have been erected in Denmark in 506 locations, and several more are presently under construction. They consist of tubular steel poles and two crossarms, building the form of an eagle. The “Thor” towers are designed like lattice steel towers with one crossarm but uses tubes for the bracings. This allows the reduction of the number of bracings and leads to a more “open” appearance. Based on a survey it is assumed that the Thor-design will be less visible in open country, also because of only one crossarm. It is expected, that Thor costs only little more than standard towers if used in lines with long straight sections in flat countries.

Eagle tower

Thor tower

Paper 62 presents the project of a pylon where the tower body and the crossarms are made of composite material. Due to the insulating crossarms, no extra insulators are necessary. The principle electric properties of the material have been tested successfully, details are pending. More investigations need to be done, e.g. mechanical test to ensure, that the structures can take the high forces from the conductors, and the connection of the ground wires with the ground earthing system needs to be clarified.

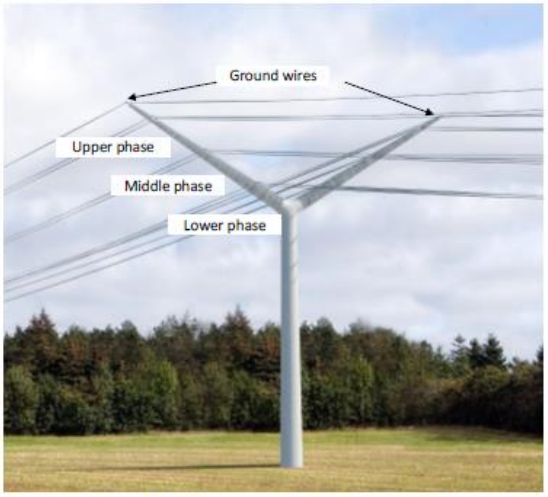

Fig.1 A fully composite pylon proposed in PoPyFu

Paper 67 presents calculations of the electric and magnetic fields, audible noise, radio interference voltages, induced voltages and currents, saturation effects and the air ion concentration and ion current flows from i) separate AC and DC overhead lines on parallel routes and ii) on AC and DC systems on the same structure (hybrid lines). It comes out that the least influences will be for AC and DC lines on separate routes. For hybrid lines the optimised transposition is essential to reduce coupling effects.

SC B4, Session 3 "DC Grids and Multi-terminal DC Systems"

Chair: Ting An

There were five papers presented in Session 3 and two important themes were covered: multi-vendor HVDC systems/grids and HVDC grid protection. The challenges to expand a point to point link into a multi-vendor MTDC system, interoperability issues and interactions of multi-vendor HVDC systems, and measures without knowing the internal structure of converters from different suppliers and accessing their control and protection logics to improve interoperability were addressed in three of the five papers. The guidelines for constructing performance indicators for protection algorithms on HVDC grids and the applicability of different voltage rebalancing schemes in multi-terminal HVDC systems protected by full bridge converters were provided and investigated respectively in the other two papers.

Paper 77 presents the interoperability issues witnessed between VSC HVDC converters from different manufacturers and observed with both EMT with VSC models provided by different vendors and real-time simulation with vendors' converter control cubicles. Actual interoperability issues (e.g. low-frequency DC voltage and active power oscillations around 3.5 Hz) were witnessed between VSC HVDC converters from different manufacturers and fixed using a dedicated organization which is likely to suit for any multi-vendor interoperability issue. In addition, a real-time set-up connecting industrial VSC control cubicles from different suppliers was operated and proved to be a most effective tool to fix interoperability issues. The paper also indicates that it was possible to implement a DC Power Oscillation Damping (DC-POD) control similar to the ones currently implemented in HVDC converters to damp inter-area oscillations of the AC networks.

Paper 83 aims to provide some guidelines on how analytical methods can be applied to mitigate interactions between multi-vendor HVDC grids and improve interoperability without requiring

knowledge of the internal structure of converters. The responsibility is clearly on the system operator to keep the system behaviour acceptable at all times during operation. Therefore, this paper is devoted to system-level analysis and control design to improve robustness to disturbances, based on system-level input-output behaviour without requiring internal knowledge of converters. The conclusions drawn from the paper are: high-level supplementary controllers overlooking the network from an external view can be designed and adapted as required, for an impedance-based design, the problem reduces to an impedance-matching procedure and finally supplementary controllers are not required for each terminal in the network.

Paper 105 proposes an intelligent frequency control (IFC) which can be used to implement the MTDC-related control without the need to change the existing converter control. Furthermore, it also simplifies the implementation of the advanced converter control. In addition to the above, the response of the existing converter control can be adjusted as well with this component. The integration of the auxiliary converter controls (e.g.: power oscillation damping and frequency control) has also been made possible. Therefore, the IFC helps the realization of a multi-vendor MTDC system.

The paper concludes that steady-state DC voltage operating range of the MTDC system can redesign the range of the existing PtP link by limiting of the hub DC voltage in order to reflect the limits of the additional converter and that the implementation of the proposed IFC for DC grid control system translate the reference from the secondary control (in the form of droop slope) into the appropriate DC voltage reference used by the existing UdcCtrl, solving the interoperability between various vendors.

Paper 45 provides guidelines for constructing performance indicators for protection algorithms on HVDC grids and for designing tests considering relevant parameters. A case study of a selection of existing algorithms and considering the impact of voltage and current measurements and digital filtering, demonstrates the performance indicators and tests. In addition, based on the test outputs, this paper proposes an alternative algorithm for directional comparison protection.

Paper 93 assesses the problem regarding voltage rebalancing in multi-terminal HVDC systems protected by full bridge converters (FBCs), investigates the applicability of different schemes to rebalance the pole voltages during the DC voltage restoration process (i.e. dynamic braking and AC grounding systems) and evaluates the impact on the performance of the protection strategy, analyses existing strategies and proposes a new rebalancing method. The rebalancing method, which does not rely on specific equipment, but only on the control of the fault blocking converters appears to be a feasible alternative. The paper also points out that the rebalancing can also be accomplished using AC grounding schemes providing a sufficient zero-sequence current path, such as zig-zag grounding transformers.

Based on the papers presented in this session the questions to be further considered by CIGRE SC B4 are raised as below:

- Provisions of standardized converter design procedures to be considered across all vendors.
- Providing clearer definition on interoperability.
- Guidelines on the need to provide public recommendations for standardization bodies and TSOs to maximize interoperability in future multi-vendor VSC systems.
- Availability of assessment procedures of interoperability in multi-vendor VSC-HVDC systems based on existing technology as supplied by major manufacturers.

SC B4, Session 6 "Innovative Solutions in FACTS and HVDC Technology"

Chair: Mohamed Rashwan

Five papers were presented and discussed in Session 6; three of the papers addressed STATCOMs and two papers were related to HVDC.

Paper 19 addressed the advantages of 3rd harmonic injection in improving the utilization of the dc voltage. It explains the STATCOM control strategy including the method for injecting the 3rd harmonic. It also describes the method to suppress the generated 5th harmonic current. The strategy was verified through testing. The paper's main objective was the elimination of the 5th harmonic.

Paper 61 deals with the application of a STATCOM in the Indian power network. It describes the overall control and protection system as well as the verification of the control and protection utilizing an RTDS that incorporated a large ac equivalent network. This was important for the Dynamic Performance Testing (DPT). The DPT results and the site commissioning results were compared and were shown to match closely.

Paper 97 investigated the impact of the midpoint STATCOM on the loss of field (LOF) protection of a synchronous generator. The simulations were performed utilizing an RTDS. The results showed that a conventional LOF relay needs additional time to detect LOF failures in the presence of the STATCOM. The additional delay depends on the generator initial loading and the type of LOF failure.

Paper 73 addressed the application of the travelling waves to identify, locate and clear faults in a multi-terminal HVDC system. The paper compares the behaviour in a high impedance grounded symmetrical monopole to a bipolar configuration with a dedicated metallic return. The results show that the system configuration has small impact on the current and voltage profiles in the time period relevant for the detection of the fault in a multi-terminal grid. The behaviour is predominantly defined by the travelling wave effects. Although the fault detection and fault clearing are similar for both the symmetrical monopole and bipole with dedicated metallic return, the system recovery is different and should be considered.

Paper 136 presented a new novel submodule topology referred to as Modified Half Bridge (MHB). It utilizes the number of semiconductor devices of a half bridge submodule but can suppress the dc fault current. The performance of the MHB was demonstrated by simulation for the various dc faults. Both the magnitude of the fault current as well as the time to suppress the fault current were demonstrated. The paper stated that the MHB offers lower cost and losses than a FB.

SC B4, Session 9 "Control and Protection of DC Grids"

Chair: Kees Koreman

The five papers presented in Session 9 were very diverse but all related to DC grids. The entire area from studies to hardware was covered. It became clear that a full-scale development of a meshed HVDC grid needs input from all areas. This is because the phenomena in such a grid are complex and difficult to estimate. Studies are required together with developments both with suppliers and with future users.

Paper 4 investigates the impact of mixed cable and overhead line systems on the performance of protection systems. Due to the differences in travelling wave impedance, multiple reflections and refractions can be expected that make an accurate fault detection and location very difficult if not

impossible. The authors make use of models developed in the past. These models show a good and stable behaviour. Main question is “what is the effect of ground impedance in overhead lines?”. In underground cables the "ground current" will predominantly run in the screens of the cable but this effect is difficult to model for overhead lines. Additionally, the high impedance of the grounding system in a symmetrical monopole system will have a dominant effect on the measured currents. The latter may have a dominant effect in overhead line parts. As mentioned the introduction of a DC reactance in series with the lines may give a positive effect but the authors recommend using more sophisticated methods specifically adapted to the transmission line type.

Paper 33 focusses on the interface between the DCCB and the IED that covers the algorithms to determine operation. O-C-O operation is indicated to put constraints on the recharging of the capacitor, but it will give also constraints on the thermal performance of the energy absorption branch. The paper identifies additional functions, called auxiliary functions, that support the operation of the grid. It can be questioned whether these functions are nice to haves or might in future become essential due to the increased utilisation of the HVDC grid. The entire paper is focussing on new functions that may be implemented to control the system during disturbances. It may be questioned whether that is a necessity in future. It may be more interesting to apply a "Keep it simple" concept. The concept of automatic reclosing of a hybrid circuit breaker was given as an example during the presentation. Limiting the reclosing action to the power electronics part and only reclose the mechanical part after some additional delay could be an interesting approach to speed up the entire process.

Paper 35 describes the development of a 535 kV DCCB with a mechanical interrupter. The development and engineering of the various components in the DCCB are described. The mechanical switches comprise of a limited number of vacuum switches (10) with voltage sharing technology. The performance is verified with a 1000 kV switching impulse test applied 2 ms after opening. Due to the design of the DCCB it is necessary to have an external power supply to feed the different processes. The upper levels of the control system are in a control room. Only the lower submodule control devices are in the DCCB itself. The development of the DCCB is entirely fine-tuned to the proposed application. Various components need to be designed to the application so there is currently no common design possible. This raised a long discussion during the session. It was generally accepted that in future the procurement of a HVDC circuit breaker should be comparable to the procurement of a HVAC breaker. So, without the need of detailed studies and fine-tuning to the application.

Paper 36 describes the design of a DC-DC converter. It reflects the work of CIGRE WG B4.76 that focusses on DC-DC technology. The principle is a so called non-insulated converter design. The application of DC-DC converters will be essential in the development of DC grids in Europe. Mainly because it is very difficult or even impossible to take a decision on standardised voltage levels. The described technology is promising and can also be used to limit DC fault currents. This because the design effectively blocks DC fault current migration from one HVDC grid into the other HVDC grid. It is not clear why the authors have chosen a non-insulated design over a transformer insulated system. The authors identify that the proposed system can be used for further studies. The first simulation results are very promising.

Paper 63 focusses on the activities performed in CIGRE WG B4-70 "Guide for EMT studies involving VSC converters". Several scenarios are described together with the required simulation studies and results from these simulations are presented. The main driver for the paper is to highlight the importance of simulation studies to increase the knowledge on dynamic performance of VSC systems in particular for system users and system owners. This knowledge is considered crucial when the contribution of HVDC technology to the AC power system increases for instance due to

the large-scale integration of renewables. Details are given about the requirements for the models to come to representative results. It is acknowledged that generic models, known from literature, might not be suitable for the various simulation studies and that more detailed information is required. It is assumed that manufacturers give detailed information about the protection and control systems. When multi-vendor systems are considered then suppliers will be reluctant to deliver the information to other suppliers but are less reluctant when the information is given to the user or owner of the system. The paper clearly describes the benefits of increased knowledge and simulation tools to investigate all kind of phenomena in AC grids and the behaviour of HVDC systems under these circumstances.

SC B4, Session 21 "Off-shore System Integration"

Chair: Joanne Hu

Session 21 focused on the integration of renewable energy into the system through VSC based HVDC system. These papers highlighted how the maturing and ongoing development of VSC HVDC system are enabling and offering more reliable and flexible interconnection of renewable power sources such as onshore/offshore wind farm and solar into existing network. Four papers were covered in this session.

Paper 7 summarizes and highlights the advantages and challenges on increased application of VSC based HVDC on integration and transmission of large-scale offshore wind farm to onshore grid. VSC technology offers more reliable performance of HVDC system with great controllability. However, there are still challenges such as harmonics and oscillations caused by the natural network characteristics, control interaction and so on which are required to be resolved. CIGRE SC B4 has recently established two WGs to investigate SSR and control interactions associated with offshore windfarm integration using VSC technology to find the viable and reliable solutions to mitigate these issues.

Paper 40 demonstrates a good study case on utilization of VSC technology on supply power to offshore oil and gas platforms which has unique technical requirement such more stringent voltage control and reactive power supply. Parallel dc links are considered to offer greater reliability and availability. The challenges include the harmonic penetrations to the offshore network as well as instability associated with system disturbance. In order to design a reliable and robust system, it requires the accurate understanding of VSC converter and control characteristics, detailed modelling of converters and its controls, offshore load models and so on. Another challenge is the interoperability between various technologies providers which requires the sharing of information of between the vendors. What would be the best approach on sharing the information so that the studies can be carried out with accurate system models without losing the protection of vendor's proprietary information?

Paper 164 describes a study case of a hybrid HVDC system with LCC at sending end and mixed FB/HB VSC at receiving end with equivalent performance as FB MMC converter. The challenges associated with mixed operation of FB/HB converter have been successfully tackled through the proper control strategy. Hybrid HVDC technology opens the door for more flexible interconnection of existing AC system with existing and new LCC, VSC DC system under various system conditions such as weak system and renewable energy. There are still more known and unknown potential issues with hybrid technologies such as control interactions, harmonics and so on which are and would be researched and resolved in the near future.

Paper 165 covers a few key design studies to implement some design functions such as EPC and

frequency control to improve the system performance of NL and NS in case of any system disturbance such as instability and large frequency changes as identified during stability studies. It also demonstrates the actual performance tested during commissioning such as step response and dc line fault. This is another milestone of VSC technologies applied in a combined OHL and cable system using bipolar scheme with electrodes.

SC B4, Session 24 "Analysis and Modelling of DC and FACTS"

Chair: Chandana Karawita

This session included a well-balanced representation of the modelling and analyses techniques related to the DC and FACTS. In addition to the software-based simulation technique, there is a trend that the industry is moving towards hardware-based testing. This is mainly to identify the behaviours of power electronic devices, which are not modelled in software-based simulation models. Furthermore, there was a good discussion on vendor provided detailed simulation models and the expectations from the utilities/consultants in terms of simulation models.

Paper 018 discusses how to adapt Lyapunov energy functions for evaluating the large signal stability of the voltage source converters connected to a weak grid. The concept of the stability of the synchronous machine connected to the infinite bus is used in order to find the energy function related to VSC. It is shown that the system works in its stable mode with positive value of the energy function, while its derivative with respect to the time is negative. Based on the discussions, it was found that further investigations are required in order to capture the complex dynamic behaviour of the VSCs.

Paper 020 presents an analysis on grounding electrode circulating current in NBGS overcurrent test for HVDC transmission based on RTDS simulation system. In this paper, a test case of station grounding overcurrent protection malfunction is analysed in details. This is a very good example that the simulation models may produce inaccurate results when the system is not modelled adequately. In this test, the inaccurate modelling of the grounding electrode conductivity was the reason for the maloperation of the relay.

Paper 037 addresses the need for and requirements of vendor provided project specific models and the models application for the AC system related studies performed by the TSO both prior, during and after finalization of an HVDC interconnector's lifetime. The authors have proposed a generic performance type HVDC model to be developed in addition to the vendor's project specific model. Such non-restricted model alleviates application difficulties and uncertainties of precompiled, black-boxed deliverables from vendors for the power system stability studies. It furthermore enables exchange of power system models between TSOs for bilateral studies within ENTSO-E framework which is a requirement imposed by the EU. This presentation initiated a good discussion during the session and the proposed methodology was greatly appreciated.

Paper 043 presents a laboratory prototype for series LC DC circuit breaker. A new concept of series LC DC circuit breaker was presented and experimental results on 1200 V, 200 A hardware demonstrator were discussed. This mechanical DC CB topology converts DC fault current into AC current by inserting a series capacitor. The AC current can be interrupted by a conventional AC CB at one of the zero crossings and will not be increasing because of series capacitor. Only mechanical switches are used including the commutation switch. The commutation switch has design with lateral contact overlap which facilitates current commutation without arcing. The experimental tests have verified that DC current commutation into a parallel capacitor using a mechanical switch is possible without arcing. The main advantage of the proposed topology is the high operating

speed.

Paper 108 discusses a test-bench setup for AC-side-grid-interaction analysis of MMC-based HVDC systems. This has been primarily designed for the evaluation of the first full-bridge multi-terminal project: “Ultranet”. It has been discussed how the Ultranet test bench was extended by adding more components including a synchronous generator, four power-electronic converters representing wind-turbine generation and a configurable grid representation to investigate the AC-side grid-interaction phenomena between MMC-based HVDC converters and other power-electronic equipment. All components can be arranged in a flexible way depending on the phenomena to be analysed. It has been demonstrated that a variation of the parametrization of a control algorithm – which is stable under normal grid conditions – may lead to stable or unstable grid conditions in case of converter-dominated grids.

SC C1, Session 4 “System Planning Including Offshore Networks”

Chair: Konstantin Staschus

Paper 68 from Iran and Denmark suggests a two-stage method for optimally placing of phase shifting transformers based on combinations of technical and economic system performance indices, analyzed with OPFs and multi-attribute decision making.

Paper 72 describes the development of offshore wind farms in France in general, and with view on various possible designs of platforms for the offshore substations and for the laying of subsea cables.

Paper 102 from the European Union-funded R&D project PROMOTioN describes a methodology for societal cost-benefit analysis of meshed offshore grids, with which different large offshore wind farms can be connected with each other and with different countries’ onshore grids around the North Sea. Dimensions of the CBA include scenarios, project alternatives, KPIs, and tools for the assessment framework.

Paper 146 is an intermediate report of CIGRE WG C4.47 about its international survey on the adoption of resilience within the electricity sector. One result is that the risk landscape highlights four extreme threats (national blackout, seismic, load shedding and cyberattack). While these do not occur frequently, the significant adverse impact and consequence to the economy and society require focused attention. The survey also addressed definitions of resilience in distinction from reliability, methods and metrics, and how to boost resilience.

Paper 162 describes the impacts of such high-impact/low-frequency (HILF) events and the lessons learned from them for the Indian power system, in the context of India’s topography and climate. Natural hazards analysed include in particular tropical cyclones and tsunamis, earthquakes, floods and landslides. Examples of dangerous cyclones, earthquakes and floods over the years are given, showing an improvement in the resilience of the power system, through systematic attention to anticipation, preparedness, response, and restoration/recovery.

SC C1, Session 12 “Offshore Wind Connection Planning”

Chair: Cornelis Plet

This session addressed a wide range of topics regarding the planning of offshore wind farm export links, such as the impact of regulatory regime on the choice of technology, the necessity to upgrade the onshore transmission system to accommodate the offshore wind connections, the ability of new technologies such as battery storage to deliver ancillary services, and how the performance of

power equipment can be enhanced by considering the dynamic nature of offshore wind generation.

Paper 84 from the United Kingdom discusses how the choice of regulatory regime can influence the choice of technology (AC or DC) for offshore wind farm export links. Guided by an example of a 1,2 GW windfarm 100 km from shore, the paper compares different ownership structures (i.e. developer, third-party or onshore TSO owned). By considering the return-on-investment, several selection criteria are used to select the optimal combination of ownership structure and export link technology under 'severe' uncertainty in capacity factor and wholesale price. It was noted by the audience that apart from CAPEX there are many more aspects to be considered in the selection of technology, not in the least how the cost of the losses over the projects lifetime is allocated.

Paper 142 from Denmark analyses the techno-economic feasibility of a STATCOM with integrated battery energy storage for application to offshore wind power plants. An overview is given of various converter topologies and battery technologies and how these could be technically integrated. The main body of the paper focusses on the ancillary services which could be delivered by such a system such as black start capability, grid frequency response, intraday balancing, active filtering and voltage regulation. Each service is discussed in some detailed and prioritised based on a comparative analysis. The power and energy ratings that would be necessary for each service are discussed to arrive at a proposal for standardised modular ratings. It was noted by the audience that the regulatory aspects of such a system, especially regarding ownership and operation, should be consider as in some countries storage is considered similarly as generation and can therefore not be owned or operated by a TSO or OFTO.

Paper 109 from Poland presented the long-term onshore power system planning to facilitate the closure of thermal power plants in the south and to integrate 10 GW of offshore wind energy into the north of the Polish transmission system by 2030. Several different AC grid reinforcement options required by 2020 and 2030 were discussed for two scenarios and compared on the basis of the necessary network investment. It was shown that significant investment is required to avoid overloading existing lines, especially in case of emergency states, and that substantial effort must be placed to maintain the cross-border exchange balance with Germany. In the discussion following the presentation, it was concluded that also the transmission losses, variability of offshore wind, but most importantly public acceptance of infrastructure works were decisive factors in selecting different network reinforcement options.

Paper 21 from Denmark introduced a method to increase the power-transfer capability curve for offshore wind farm export cables by considering the fluctuation in offshore wind farm power production and the thermal inertia of the export cable and its environment. The analysis suggests that the increase in cable capacity that can be achieved increases with cable length. Following a discussion in the audience, it appeared that the model takes into account the temperature dependence of conductor resistance, and that the actual generation time series of offshore wind farms were considered rather than only a statistical solution, to ensure a full generation maximum duration period did not exceed permissible temperature limits. However, detailed information such as seabed soil temperature and thermal properties must be known to optimally exploit the dynamic rating capability of a cable.

Similarly, Paper 81 from Denmark analyses the attainable increase in transformer loading capacity when taking into account the cyclical generation of offshore windfarms. Considering a validated hot spot temperature model and realistic loading timeseries, the impact of an increase in cyclical transformer loading on transformer thermal lifetime utilisation and violations of normal and emergency loading limits is studied. It is shown that the considered transformers in Anholt windfarm could potentially handle a 50% increase dynamic loading, providing options for future wind farm expansion and redundancy improvement. It was noted that in order to achieve this increased

loading, also peripheral equipment such as instrumentation and switchgear would have to be upgraded.

SC C1, Session 15 "Long-term and Sector-coupled Decarbonized Energy System Planning"

Chair: Keith Bell

Paper 25, by a global set of authors, describes the work in the IEA's International Smart Grid Action Network's (ISGAN) Annex 6 cooperation under the auspices of the International Energy Agency (IEA), and structures the need for 'flexibility' in four categories:

- Flexibility for Power (short-term equilibrium supply-demand, required for frequency stability)
- Flexibility for Energy (medium- to long-term equilibrium supply-demand)
- Flexibility for Transfer Capacity (short- to medium-term ability to transfer power between supply and demand, subject to congestion and bottlenecks), and
- Flexibility for Voltage (short-term ability to keep bus voltages within predefined limits)

In the discussion the question was addressed how we ensure that sufficient 'flexibility' capability is going to be available in future:

- Is there a role for the system planner to define needs and to have something like ancillary service market that operates with a procurement horizon of a year or more?
- How much 'flexibility' can or should be provided by a TSO and how much invited from 'the market' (and could be delivered by generators, interconnectors, flexible demand, etc.)?

Further points raised from the floor addressed whether DER might displace 'the supergrid', and the role of local energy. A tentative conclusion was that both will be required for future secure system operation with ever more fluctuating RES and the above four flexibility needs.

Paper 34 from the Netherlands discusses electrolysers as a source of flexibility and notes a pilot power-to-gas facility with a 1-MW electrolyser that is installed in the northern part of the Netherlands. Because of their fast ramping capabilities, electrolysers are argued to be more effective in providing frequency containment reserve than conventional generators.

One question concerns the potential impact on the electrolyser itself – the management of inputs, outputs, heat etc. – of rapid modification of the current? Are there any constraints that we should take account of in the power system modelling and operation? According to the speaker, there are no impacts on the electrolyser and no constraints that need to be taken into account when using an electrolyser as a source of flexibility aside from maximum current rating.

Paper 143 from the Netherlands and Denmark looked into scenarios and designs of the North Sea Wind Power Hub, i.e. one or several artificial islands (of different kinds) which connect thousands of MW of offshore wind energy, and through connections with each other and with the countries surrounding the North Sea create an offshore grid. It describes currently considered design choices proposed for the electrical infrastructure, necessary for the overall transmission system. Power ratings and voltage levels for all sections of the transmission chain, HVDC scheme configurations, and systems' interconnectivity are addressed in detail.

The scale of what is being considered is tremendous, with very many cables, transformers, etc. There is much further detail still to be worked out to fully establish the feasibility, including in respect of

commercial/regulatory arrangements and a comparison of cost-effectiveness with power to gas on an artificial island and transport of the gas back to shore.

Paper 147 by CIGRE WG C1.35 describes the concept of a global electricity network which has been imagined in order to take advantage of the diversity from different time zones, seasons, load patterns and the intermittency of renewable generation, thus supporting a balanced coordination of power supply of all interconnected countries. CIGRE WG C1.35 has undertaken a feasibility study on this concept of a global electricity network. The main results were presented.

Some questions from the floor concerned the detail of ratings, etc. The presenter emphasised that, in such a conceptual study with many details, only high-level assumptions can be made and details neglected. Among the other points of discussion were:

Has the WG explored the counterfactual of meeting the projected demand without interconnection? Yes. This results in 850 MtCO2/yr and an average cost of energy of €54/MWh. This compares with, in the global grid scenario 343 MtCO2/yr and €48/MWh, i.e. a global grid has the potential to save significant CO2-emissions while also saving money.

What assumptions were made about global CO2/-emissions constraints? A certain number of tonnes of CO2-emissions per person per year in each scenario studied.

An extension to the study is planned (CIGRE WG C1.44), factoring in possible use of storage and flexible demand, and also addressing trading rules.

SC C2, Session 2 "Assessment and Study Tools for System Operation"

Chair: Todd Ramey

Session 2 dealt with developments and research into various analytic and decision support tools of potentially high value to power system operators. In summary, key take-away from the session included:

- a methodology for measuring total system inertia in real-time exists, thereby allowing higher levels of renewable penetration;
- the challenging and complex process of system restoration can be greatly simplified by use of a flexible platform utilizing an algorithm to find the optimum restoration path on any system;
- the Full Line Decomposition method allows flow type identification and source/sink mapping enabling efficient cost sharing of coordinated congestion management actions;
- future control system monitoring applications may produce continuous dynamic state assessments thereby enabling extensive control action automation;
- and finally, that there exist alternatives to eliminate the need for open-loop, intrusive governor response testing to qualify hydro units for providing frequency containment reserve service.

Paper 49 explained that as non-synchronous, distributed generation becomes an increasing proportion of the energy mix, power grid inertia estimation methodologies used by Transmission System Operators (TSO) become increasingly inaccurate. Various methodologies for inertia monitoring were compared. A newer inertia measurement methodology was demonstrated, and case study findings were provided.

Paper 51 discusses the development of a flexible simulation platform for a decision-support tool of

power system restoration. The platform adopts a path searching algorithm based on electric distances to find the direct path from the black-start unit to the bus with shortest electric distance. During the restoration, the grid regulations regarding frequency and voltage at each substation are quickly checked by time-domain simulations, i.e. either in the root mean square (RMS) or electromagnetic transient (EMT) mode. A flexible close-loop decision-support tool is implemented to recalculate the path of energization when necessary, e.g. in case of unavailability of components or violation of grid regulations.

Paper 78 demonstrated Full Line Decomposition is a method to decompose the flow on each network element in an intuitive and transparent way, according to the laws of physics. In the method the contribution of every generator to every load is determined. The flows in the network can be traced back to these node-to-node exchanges, and can be aggregated to zone-to-zone exchanges. Via the ENTSO-E flow definitions these flows are assigned to their respective flow type. Together with the PST flows (i.e. flows induced by phase shifting transformers) this results in an exact decomposition of the total power flow.

Paper 91 discusses the applicability of a dynamic power system mirror, here referred to as dynamic digital mirror (DDM) in the control room. The DDM approach combines dynamic simulations and sensor data analysis, thus builds a new foundation for model dependent and data driven applications in future control centres. The DDM concept allows substitution of measurement data and online predictive calculations, augmenting power system observability. Benefits of a dynamically mirrored power system are the possibility to continuously compare monitored and simulated grid behaviour (pattern recognition), fast detection of anomalies in system operation and automated pretesting of preventive and corrective actions.

Paper 126 presented an alternative approach for checking the new draft requirements on frequency containment reserves (FCR). The alternative approach uses PMU measurements while the plant is in normal operation in contrast to the new draft requirements, which proposes ten sine tests while the plant is operating in open loop. The approach is validated and compared to the approach presented in the new draft requirements. It is also demonstrated that only one test is needed if using the approach in the new draft requirements.

SC C2, Session 5 "Operation of Hybrid and Low Inertia Power Systems"

Chair: Enrico Carlini

Session 5 consisted five papers focusing on the operation of hybrid and low inertia power systems. Two papers focused on mathematical approaches in system operation: one on the optimization of hybrid systems and another on the use of preventive and curative control for N-1 operation. One paper investigated the impact of increasing levels of wind generation on short-term frequency variations in the Irish power system. Another paper addressed the increasing need for reactive power in the Danish power system, whereas the last paper focused on a regional blackout in the Brazilian power system.

Paper 2 addresses implementation, verification and application examples of an optimization approach for HVDC-systems from grid operations' viewpoint. Different types of HVDC-systems (back-to-back, point-to-point, and multi-terminal) are introduced and their respective modelling and implementation in a power system optimization is shown, incl. a study case representing a multi-terminal HVDC with offshore DC-grid and offshore wind farms is presented using real world generation and load data from Germany and Norway.

Paper 47 investigates an approach to include the determination of curative actions into the

consideration while computing preventive measures. By doing so, N-1 security does not have to be established solely by preventive measures alone but can also be guaranteed by pre-calculated curative actions, like Special Protection Schemes. The approach consists of a Preventive Security Constraint Optimal Power Flow (PSCOPF) method, utilizing VSCs or generating units, and an incorporated Corrective SCOPF algorithm. To validate the proposed method, it is tested on a dedicated case study.

Papers 60 presents the developments of the Danish transmission system enabling larger shifts in power flow, while the share of HVAC cables in the system is increasing. These changes increase the need for reactive power- and voltage control in the Danish transmission system. This paper presents two reactive power- and automatic voltage control (RPC/AVC) schemes that have been designed to secure stable operation and minimisation of operational costs. Through real implemented cases, the benefits, limitations and challenges of automatic control of reactive power assets are discussed.

Paper 120 analyses the challenges European transmission systems face in integrating increasing shares of wind power and other renewable energy sources (RES). In this paper, system frequency variations caused by variable wind power generation are investigated. For that purpose, two use cases are simulated in a generic model based on the Irish transmission system. From the results of the analysis, it can be shown that frequency variations increase with a higher PE penetration level, primarily because of higher active power variations and a lower system inertia as well as a lower primary control reserve in the system.

Paper 122 deals with how to improve the performance of the Northeast Brazilian subsystem when isolated from the remaining interconnected system during major disturbances. This paper discusses the events that lead to the regional blackout of March 2018 in Northeast Brazil. Several mitigation solutions are presented to reduce the likelihood of such events in the future.

SC C2, Session 11 “Support from VSC HVDC for System Operation”

Chair: Francois Boulet

Session 11 contained five papers that discussed operational support provided by VSC HVDC systems. Two papers presented control strategies for damping of electromechanical oscillations using a power oscillation damping controller in the VSC. One paper presented a hardware-in-the-loop test setup for investigation of undesired tripping of synchronous condensers. The last paper showed the successful execution of a black-start test using a VSC HVDC system between Denmark and Norway.

Paper 15 discusses the modulation of the control strategy of a point to point HVDC link with the aim of damping interarea electromechanical oscillations, caused by a three-phase fault in the AC grid. A power oscillation damping controller was tuned based on the residue-based method, providing adequate damping. The HVDC link was expanded by adding an offshore wind farm and its behaviour was examined for various operating conditions.

Paper 104 investigates the possible undesired trip of a synchronous condenser (SC) by reverse power and over-frequency protection under certain grid configurations, through hardware-in-the-loop (HiL) tests. The tests have identified that, when there are two transmission lines emanating from the substation and the VSC-HVDC station is operating under inverter mode, the trip of the line that exports active power from the substation may lead to an undesired trip of the SC due to the power swings. In this regard, the paper provides insights for grid operators and engineers regarding the planning of power dispatches and the settings of generator relays for synchronous condensers.

Paper 129 is a basic review paper that discusses ancillary services that can be offered by HVDC

systems to support a certain level of operational reliability. Among others, synthetic inertia, ac line emulation and restoration support can be provided by HVDC systems and contribute to enhanced operation of hybrid power systems.

Paper 139 proposes coordinated controls for a VSC connected to a weak system, with the aim of maintaining system stability. The system voltage is maintained by having a fast-acting voltage controller. The frequency can be regulated by a frequency controller. An energy storage mechanism in the converter submodules is proposed to supplement the frequency control action. The electromechanical oscillations produced by the small generators in the weak system can be controlled by having a properly tuned damping controller. The performance of the coordinated controllers has been demonstrated for a very weak network using EMT simulations.

Paper 140 describes the preparations, execution, results and lessons learned from a live black start test of an HVAC network using soft start capability of the voltage source HVDC converter of the Skagerrak4 link between Denmark and Norway. The test was performed to verify the general functionality of the black start capability of the link and its ability to energize several network components in one sequence using the AC-voltage ramp of the HVDC converter. The test, which was performed successfully, also demonstrated that the AC-voltage ramp of a VSC based HVDC converter is another valuable feature of the technology that can be used to energize networks where harmful voltages could occur, when energized from a weak AC-source via AC-breakers.

SC C2, Session 14 "Frequency Support from Power Electronics Interfaced Devices"

Chair: Greg Hesse

Session 14 had four papers all grouped around techniques for providing frequency support from power electronics interfaced devices. Three of the papers focussed on the development of control philosophies and their validation through simulations using test systems. The fourth paper assessed the current situation for the definition and use of Fast Frequency Response in power markets worldwide. Discussion centred around communication links and what might be the optimal mix of direct communication and HVDC link droop-based control schemes. It was also suggested that the current definitions of FFR derive from the technical capabilities of wind turbines and that other technologies might exhibit different characteristics that are still valuable, for example extracting kinetic energy from synchronous condensers.

Paper 13 examines the use of droop-based control (communication less) for point-to-point HVDC systems and extends this to a meshed HVDC grid connecting two off-shore wind farms to two separate on-shore AC grids. A signal flow model is developed to mathematically analyse this situation. The use of droop control results in DC voltage drops that might be unacceptable and compensating for this in the case of connections to multiple AC system is not readily achieved.

Paper 42 presents the concept of use diode rectifiers as the off-shore connection for a HVDC link and the ability of this configuration to provide FFR. Two different control strategies for the off-shore wind turbines response are studied through simulation. Both strategies extract kinetic energy from the rotating wind turbines to provide the provide response, slowing down the turbine rotational speed. An adaptive control strategy, where the wind turbine base power target adjusts dynamically as the turbine speed slows, is shown to reduce the size of the secondary frequency drop in the AC system when the wind turbine starts to recover speed, compared to a strategy of holding the base power target constant throughout the disturbance.

Paper 70 discusses a range of methodologies and techniques to address the challenges of operating power systems with decreasing levels of inertia caused by high levels of inverter-based generation. The paper demonstrates the trade-offs to be made by system operators in balancing frequency control reserves in different timeframes and how this impact the critical level of inertia needed to contain RoCoF within acceptable levels.

Paper 76 analyses various control philosophies to acquire FFR from offshore wind farms that are connected to on-shore AC grids by VSC HVDC links. In situation where the latency and/or reliability of direct communication links are issues then droop based schemes seem the most appropriate. A new method, which might be used in conjunction with droop-based schemes, is to extract the stored capacitive energy in the HVDC cable to provide an initial increment of power.

SC C3, Session 8 "Eco-design and Environmental Concerns, the Social Aspect (People)"

Chair: Henk Sanders

Session 8 had 5 presentations. Two of them mostly dealing with safety-aspects, the other three were focussed on public acceptance.

The five papers covered the following topic areas:

Paper 03 explained why and how the COBRAcable project developed a safety culture. It was an explicit choice of the board to create safe working conditions by ensuring the project's safety culture operated at a pro-active level as way of ensuring good working conditions. The relation was made with one of the 17 sustainable development goals (SDG's) of the UN. The paper describes the scientific background on which the program was based and the implementation of this background into operational means and actions. Most important lessons were good conversations in the whole organisation and start to involve all people in an early stage of the project.

Paper 56 also dealt with safety aspects, but more the technical details of safety. It gives an overview of the potential for major accidents, due to manning, helicopter and vessel impact, flammable fluids storage/handling and installed MV/HV electrical equipment in offshore substations. The paper highlights recommended practices for safety perspective based on knowledge, experience and lessons learned. Topics that were discussed are the use of risk-based approach, the methodologies and concepts of hazard identification, the hazardous classification for offshore substations.

Paper 28 presented a new design for transmission towers, in order to improve the public acceptance of it. The most significant environmental aspects of this design are the impacts on the landscape, land use and impacts on nature and biodiversity. But the main reason for this new design is that public acceptance must be present before permit applications and at the same time the public has become increasingly aware of the importance of protecting nature. For these reasons, having a tower design that takes into account the many environmental aspects, is crucial for future lines.

Paper 137 gave an overview of the way Argentina takes care of public acceptance in the planning of new electrical equipment. Although the constant increase of electrical demand makes it necessary to expand the electric network, this growth of the grid is not always socially acceptable. The paper presents mechanisms for public participation in the planning process. Interesting idea was shown about the inclusion of actors, teachers and educators, capable of explaining the situation on a didactic and clear way to the public; e.g. health aspects were explained by medical school teachers. The general public valued these informative talks very good.

Paper 153 describes a new technique for improving public participation in the planning process of building new assets. The use of AR/VR technology will help TSO's to better communicate with stakeholders/general public and thus improve public participation and acceptance. This tool helps planners to identify in a few seconds multiple paths for a new overhead line, to rank them, based on the impact on environment and population, to estimate the visual impact, to assess the costs and so on. The tool and solution on mobile devices are connected through cloud-based technologies and enables planners to decide which information of the selected paths to share with stakeholders. Through the application of AR/VR technology on mobile devices, citizen and authorities can experience a realistic interaction and perception with new planned projects.

SC C3, Session 23 "Eco-design and Environmental Concerns, the Environmental Aspects (Planet)"

Chair: Pedro Fernandes

The session had an average audience of forty people. During the session there were five questions of clarification and during the general debate that took place at the end of the session there was a good discussion with general questions and some comments.

The five papers covered the following topic areas:

Paper 121 describes how the nationwide strategic marine spatial planning process took place with the support of RTE in the stakeholder and public consultations organised in the maritime regions of France. The paper explained the impact of the information and shows that an integrated planning of grid and generation development, including enhancement of marine knowledge, is a key factor for cost reduction as well as for increasing local acceptability. Several connection design strategies for future floating and fixed bottom wind farms, based on standardisation and modular development, have been analysed and establishing a roadmap for optimized connection strategies.

Paper 125 examined different studies engaged to investigate the ecological incidents of increased turbidity on the benthic ecosystem using a living organism as a potential indicator of an ecosystem perturbation causes by the installation of submarine power cables. The paper also gave an overview of other ecological impacts on benthic ecosystem, such as artificial reef effect, heat and electromagnetic field emissions, reserve effect and the hierarchy of these interactions during the project phases. A set of recommendations for better monitoring and mitigation of the most significant impacts and the main knowledge gaps and needs for future research are also presented.

Paper 22 presented the new ideas related to offshore grid eco-design that settle in the cooperation with environmental organisations, the value of offshore data gathering, and the re-assessment of the offshore grid concept from a nature inclusive design perspective. Based on the experiences so far, this paper presents the importance of re-assessing the standardised offshore grid concept in terms of opportunities for nature enhancement and further ecological monitoring. The idea of using the offshore grid infrastructure to realise opportunities to increase nature diversity and to achieve additional societal benefits has evolved. The expectation is that if such measures are integrated in an early stage, they can be added against very limited cost and risk compared to the project investment.

Paper 92 provides an overview of the Visual Impact Provision- Landscape Enhancement Initiative in Great Britain and reports on progress to date. It also explores the potential that taking a landscape enhancement approach to reducing the landscape and visual impact of transmission infrastructure (including that associated with offshore generation) has to create a positive environmental impact

and increase in public acceptance. To achieve the maximum enhancement to the landscape from the available funds four major projects has been selected to replace existing transmission lines with underground solutions.

Paper 23 (YM) propose a species prioritization method aimed to identifying both species and areas with the potentially highest extinction risk due to collision risk. The method takes into account: species morphological, behavioural parameters, habitat selection and conservation status and the spatial exposure to collision with power lines. This method can be applied to any geographic area of the world, generating valuable lists of both priority species and areas in which collision risk with power lines can potentially produce local or even global extinctions.

Paper 95 explain how passive acoustic monitoring technology can provide species-specific estimates of population density and seasonal movements based on the simultaneously record and analyse vocalizations from multiple species, including cetaceans such as dolphins, whales, and porpoises. The sounds recorded can be analysed by a computer that compare the sound with a library sound allowing the reduction the lack in the quality of environmental data.

SC C4, Session 1 "Electromagnetic Transient Aspects"

Chair: David Jacobson

Session 1 had five papers that generally covered the topic of electromagnetic transients associated with integration of off shore wind plants into the grid. The first four papers in this session discussed the topic of low order harmonic resonance, as well as increases in temporary overvoltages and delayed current zeroes. The last paper in the session discussed a somewhat unrelated but very interesting topic of induced voltages on pipelines and helped to clarify the origin of the numbers used in different standards.

Paper 11 describes the expected challenges in Germany as more EHV underground cables get integrated into the transmission system. Many of these cables are expected to create hybrid lines that are a mixture of overhead and underground cables. The high level of cable charging current also requires the addition of shunt reactors to compensate. It is expected that high penetration levels of cables will lead to low order harmonic resonance, delayed current zeroes and high voltage stresses for equipment to name a few.

Paper 12 identifies the problem of delayed current zeroes in the case of tertiary connected shunt reactors connected in a weak network with high X/R. Representing the arcing behaviour of circuit breakers is shown to be an important consideration. Delayed switching of the line to allow for discharge is shown to be one feasible solution.

Paper 141 also tackles the topic of low order harmonic resonance and temporary overvoltages (TOVs) associated with the addition of long HV cables. Resonance near the 2^{nd} harmonic is considered to be the most onerous condition. TOVs associated with resonance conditions could damage equipment if they exceed the equipment withstand capability. The paper makes the important point that simply analysing the energy levels in surge arresters may not be sufficient as the surge arrester may not completely protect the equipment from TOVs.

Paper 161 describes an interesting electromagnetic transient case study at Kriegers Flak, where two different synchronous networks (i.e. Danish and German) are integrated via a back-back HVdc tie and also connect to four offshore wind interconnections. Point on wave switching is shown to be needed to help energize a large autotransformer that connects the two different offshore grid voltages.

Paper 116 provides the technical background behind the safe induced voltage limits on pipelines published in the British Standard (BS 50443-2011) and compares this value with IEEE standards. The 60 V value in the British Standard is quite different from the 15 V standard in IEEE 80-2013 and is a possible source of confusion. The paper does an excellent job describing the calculation methods and underlying assumptions. This paper would be very useful for a corrosion engineer.

As offshore wind increases and public opposition to overhead lines increase, it is expected that more underground ac cables will be added to the power system, including more lines that contain a mixture of overhead and underground cables. The additional shunt capacitance will require the addition of shunt reactors to compensate. The topic of low order harmonic resonance, as well as increases in temporary overvoltages and delayed current zeroes are some of the issues that need to be considered as the penetration level of ac cables increases.

Circuit breaker arcing characteristics has a major influence on the delayed current zero phenomenon. In some cases, access to this information is difficult due to intellectual property concerns.

Transformer energization can excite low order harmonic resonances and methods such as point on wave switching considering remnant flux should be considered to minimize the inrush current. The wound potential transformer should be located close to the transformer bank for accurate measurement of the voltage and calculation of switching times and remnant flux.

CIGRE WG C4.46 'Evaluation methods for TOVs due to low harmonic order resonances in power systems' has started and plans to address some of the issues raised in Session 1.

SC C4, Session 7 "Power Quality Challenges"

Chair: Dalton Brasil

Session 7 had five interesting presentations concerning power quality. Two of them deal with harmonic distortion calculation due to presence of underground cables in the power system. Another two also refer to harmonic distortion. The first compares two different methods for calculating the impact of new circuits on existing background harmonic distortion. The second looks into the challenges of establishing harmonic limits for multiple new customers in a meshed transmission network. The last presentation deals with the evaluation of the application of an energy storage system to overcome problems due to an AC Arc Furnace in a small isolated power system.

Paper 08 proposed guidelines and methodologies to evaluate the impact of underground cables on the harmonic voltage distortion levels in the system. For this purpose, a procedure along with the study methodology and applicable utility standards/criteria was presented. A real project was used to illustrate the application of the procedure, including the replacement of segments of one 240 kV and three 138 kV overhead lines with underground cables as part of a major road development in the city of Calgary.

Paper 44 investigated the grid resonance frequencies shift due to an increased number of cable section in the Southern Germany power system. The resonance frequencies were calculated using the harmonic resonance mode analysis (RMA) to show the behaviour of the parallel resonance frequencies. With the knowledge of the resonance frequencies, a probabilistic calculation was introduced to analyse the probabilities of harmonic voltages in the transmission grid. In this calculation, the cable share in the grid was varied. Using the probability density functions (PDFs) of the nodal voltages or currents, the nodal voltages in the modified transmission system could be

forecasted.

Paper 65 presented a comparison of two typical methods for determining the amplification of existing background harmonic distortion on the system, based on both a harmonic propagation study and using amplification factors from frequency scans. The analysis showed that neither method is suitable for all network topologies and/or reinforcement options. Careful consideration should be given to the method being followed when trying to estimate the amplification of existing harmonic distortion on a transmission or distribution network. In the case of a new radial connection from the node of interest either method is suitable. At other nodes on the system or for a new circuit connected within the system the preferred method is not clear.

Paper 66 showed that the direct implementation of the IEC TR 61000-3-6 methodology regarding harmonic limit allocation to multiple customer in a meshed network can result in very restrictive harmonic emission limits being provided to all customers. It is concluded that the current IEC method has practical limitations when considering multiple new connections in a highly meshed network. The interaction between the different customers and the selection of the minimum harmonic allocation results in very low emission limits to each customer. It is proposed that the method of calculation and allocation of emission be revised such that: it is based on an iterative approach taking into account customers interactions but also allows for a suitable apportioning method such that it does not delay customer connections; emission limits issued to connecting customers are realistic and within measurable levels and; consider the type of distorting equipment and whether any probabilistic assessment is appropriate to account for diversity in their operating level.

Paper 46 showed some voltage frequency fluctuation problems in a weak power system if an increase of AC arc furnace load were connected to the system. To overcome these problems the effect of a fast-acting energy storage system (battery storage) in operation together with the arc furnace was analysed. It was concluded that putting the new electric arc furnaces into operation should be made together with the battery or any kind of fast acting energy storage system of appropriate power and capacity.

In summary, there are still many challenges with the analysis and control of power quality (PQ) in power systems, particularly with large deployment of wind and PV generation and with the advent of cables installed into the system, such as:

- The harmonic distortion limit allocation to multiple customers comes at an appropriate time because it addresses a current issue that must be faced by operators worldwide in the management of harmonic distortion in the system due to the connection of generators through converters. Some effort is needed to improve IEC TR 61000-3-6.
- Several interesting methodologies, using fields measurements and simulations, were presented in order to evaluate the impact of underground cables and wind and PV generation installed into the system. Some of them have shown that further efforts are still necessary to remove restrictions and difficulties.
- The assessment of the background harmonic distortion in the system was the subject of some questions and discussion, showing that this point deserves further attention.
- It became evident that the introduction of cables into the transmission system can bring the natural resonant frequencies to lower orders and impact the levels of harmonic distortion in the system.

SC C4, Session 10 "SSR, Control Interactions and Instabilities"

Chair: Babak Badrzadeh

Five papers were presented in Session 10 with presenters comprised of a wide range of organizations including academia, power system equipment manufacturers, wind power plant developers, and consultancies.

These papers discussed a diverse range of interaction issues including sub-synchronous control and torsional interactions, sub- and super-synchronous resonances, and weak grid instabilities. Different solutions including modifications of converter control systems, development of special protection schemes at the transmission network level, and installation of harmonic filters were proposed. Key points of each paper are summarized below.

Paper 14 proposed the use of a modified control system on a voltage source converter (VSC)-based offshore wind power plant to cancel out oscillations caused by sub-synchronous resonance (SSR) due to the interaction of a nearby series compensated line and masses of turbine-generator in a thermal power plant. This improved damping is achieved by modulating reactive power on the onshore converter station of the wind power plant. Time-domain electromagnetic transient (EMT) simulation studies were conducted for designing the proposed control system and demonstrating its effectiveness.

Paper 26 discussed the development and practical implementation of a remedial action scheme (RAS) to avoid the risk of sub-synchronous control interactions (SSCI) between a series compensated line and a wind power plant based on type 3 wind turbines during islanding events. The scheme uses rate of change of power and frequency and proven effective during an actual event. This scheme was implemented for an existing wind power plant where modifications in the wind turbine converter control system could not be readily implemented. Time-domain EMT simulation studies were carried out for designing the proposed RAS.

Paper 87 investigated weak grid instabilities for a grid connected VSC as the network to which the VSC is connected becomes weaker. The sensitivity of converter control to the variation of network short circuit ratio (SCR) was studied. Growing oscillations were observed and converter instability was experienced under low SCR conditions. Both sub- and super-synchronous resonances were observed. Time-domain and frequency-domain analysis techniques were used in this paper.

Paper 110 focused on super-synchronous resonances and high-frequency oscillations for a practical offshore wind farm. The paper investigated relative merit of different fileting techniques including the use of active and passive harmonic filters. Two different frequency-domain techniques including open-loop stability and eigenvalue analysis were applied.

Paper 127 discussed sub-synchronous torsional interactions (SSTI) between masses of turbine-generator in a thermal power plant and a modular multilevel converter (MMC) based VSC HVDC link. A control system design strategy was presented for mitigating the risk of SSTI. A two-staged study approach was presented with the frequency-domain Nyquist method as the first stage and detailed EMT simulation was used for the second stage of the study.

Key learnings from this session can be summarised as follows:

The use of frequency domain analysis techniques as a screening method and time-domain analysis as a more detailed and comprehensive analysis were discussed by various authors as a two-stage approach for identifying the risk of sub-synchronous interactions and developing mitigation measures.

Different solutions exist for addressing the risk of adverse sub- and super-synchronous interactions. However, the most appropriate solution would need to be determined on a case-by-case basis based on detailed studies.

SC C4, Session 19 "System Technical Aspects of Wind Generation"

Chair: Andrew Halley

Five papers were presented during Session 19. The broad theme for the session was "System Technical Aspects of Wind Generation". It was pleasing to note that two of the five papers were prepared and presented by CIGRE Young Members (YM). The five papers covered the following topic areas:

Paper 41 investigated the development of small signal (state space) models using frequency response methods based on a local 'd-q' axis reference frame. The paper acknowledged that obtaining detailed transfer functions (with corresponding parameters) for converter interfaced equipment can be difficult and it is often necessary to treat such equipment as a 'black box' in simulation studies. The methodology described in the paper aims to identify an acceptable linearized model using frequency response analysis techniques which preserve the key dynamic performance characteristics of the partitioned system.

Paper 48 investigated the impacts of inherent fluctuations in wind turbine power output on the pseudo steady state reactive power capability available to the connecting network. While other forms of generation also exhibit variable reactive power limits as a function of real power loading (as defined by traditional capability diagrams), the paper suggested that the more rapid changes in wind power output increased the level of uncertainty needing to be managed by network operators. Potential impacts on network voltage stability were discussed as part of the paper.

Paper 94 presented analysis of the HVAC/HVDC interconnector between Denmark and Germany known as the Kriegers Flak Combined Grid Solution (KF CGS). The simulation-based study focused on the impacts of unintended synchronisation of the Nordic and Continental European transmission systems and the potential outcomes should such an event ever occur in practice. While the presenter noted that significant procedural failures would be necessary for such an event to be realised, the chairman noted (to the amusement of the audience) that an event of this nature would be an excellent case study for presentation at the Power System Disturbance Workshop held at the CIGRE General Session in Paris.

Paper 155 summarised the numerous challenges associated with the design and construction of the two Hornsea Offshore Wind Projects which are the world's largest, totalling approximately 2600 MW. The paper focused mainly on network connection issues which included the propagation of low order harmonics, the mechanisms needed to manage switching events and the requirements for significant reactive power compensation. Many of the issues stem from the use of very long HVAC cables to connect the offshore assets back to the onshore network. The presentation prompted a variety of questions from the audience which were well answered by the presenter. It was noted that 'cost' was a significant contributor toward the decision to implement HVAC rather than HVDC to connect the offshore generation.

Paper 157 explored the potential use of doubly fed induction generator technology to provide active filtering of power system harmonics. Testing on a kilowatt scale machine indicated that the network side converter could be configured to perform this function with observable improvements in the condition of the AC test system. The paper complemented other discussions during the symposium where it was noted that active filtering has been incorporated into a STATCOM forming part of the

Hornsea Offshore Wind Projects. Both examples indicate that while the proliferation of power electronic converters bring certain challenges to the power system, their very fast speed of response and highly controllable nature also create opportunities which are still yet to be fully realised in commercially available designs.

The learnings and outcomes from Session 19 can be summarised as follows:

- There are ongoing challenges that need to be addressed to adequately represent intermittent, converter interfaced generation in power system simulations and network security analysis tools.
- Technologies that are now readily available bring with them certain challenges, but also create new opportunities to improve the performance and reliability of the power system.
- Active filtering of harmonics from STATCOMs and wind turbine converters.
- Combining off shore wind developments with increased interconnection between neighbouring power systems utilising advances in both HVAC and HVDC designs.

SC C6, Session 18 "Challenges for DSOs and Improved TSO-DSO Interoperability"

Chair: Christine Schwaegerl

This session addressed two main topics, TSO-DSO coordination and the application of storage technologies to stabilise/smooth fluctuating wind generation.

TSO-DSO coordination

Paper 64 suggested an advanced TSO-DSO interface for provision of ancillary services by distributed energy resources (DER) in distribution networks. This allows the TSO to purchase ancillary services from DER connected to medium-voltage distribution networks through the market for load balancing without causing congestions. The DSO receives the DER dispatch information (active power profile) from the TSO and runs an optimal power flow (OPF) routine based on semidefinite programming. If the activation of ancillary services may cause network congestions the DSO either sends the reactive power setpoints to the DER or requests the TSO to re-evaluate the DER dispatch accordingly.

Paper 107 discussed recommendations for improved TSO - DSO interoperability and their cooperation in smart grids. DSOs are facing several challenges, in particular using huge amounts of data due to presence of new actors (smart meters, aggregators, data security, etc.) or technical challenges in grid management due to active distribution networks with more fluctuating generations (e.g. congestion, voltage/frequency fluctuation, grid balance, protection/control, islanding etc.). Commercial interaction of these actors requires new market frameworks. Redefining data management, proper exchange of data between TSO-DSO (not only technical but also commercial), restructuring of market setup and revising the strategy to handle technical problems may provide opportunities for a reliable system operation.

Application of storage technologies to stabilise/smooth fluctuating wind generation

Paper 156 demonstrated how energy storage systems can improve grid stability with high renewable penetration or volatile loading. Setup and performance of two operational sites were discussed. A stability analysis showed the benefits of a Battery Energy Storage System (BESS) in severe events including generator trips, faults, and step-changes in the load. Grid forming provided by inverters in storage units and renewable generation units helps to improve overall stability and

resilience, to provide ramp rate control and smoothing, to reduce wear and tear on generators, to avoid load shedding and to reduce frequency deviation, and to have frequency and voltage ride-through capabilities.

SC C6, Session 20 "Innovative Strategies for Active Distribution Network Operation"

Chair: Jayakrishnan Pillai

Session 20 addressed the need for optimal mix of renewable energy systems, storage and conversion technologies, and distribution grid management systems to smarten the electricity grids and to earn economic benefits for the stakeholders from the existing and emerging electricity markets.

Paper 088 presented an investigation to find an optimal combination of 100% renewable electricity generation for the Faroese islands, considering 2030 scenario. Based on the technology characteristics, costs and resource availability, an optimal mix dominated by solar PV followed by wind generation, in combination with pumped hydro storage are found to be more economically feasible.

Paper 103 evaluated real-time network reconfiguration for mitigating distribution grid congestions and voltage issues caused by distributed renewable energy sources. Deep reinforcement learning approach is used in the study which is characterised by fast computation time when compared to other methods. The study also concludes that other solutions like storage systems and other dispersed energy resources are also necessary along with reconfiguration techniques to effectively operate the grid with large amounts of dispersed generation units.

Paper 132 evaluated flexible ramping products in electricity markets to realise upward and downward power regulation to tackle the unbalances caused by load fluctuations and variance in the wind power generation. Information gap decision theory-based scheduling of combined heat power units and wind generation is applied to find the minimal operating cost of the system.

Paper 130 focused on optimal energy trading strategy in electricity markets for the economic benefits of distribution systems operator through demand response. Options like increasing self-consumption, energy exchange between day ahead and real time markets, and load shedding under emergency situations are considered in the analysis.