CIGRE 2018

C4-00

SPECIAL REPORT FOR STUDY COMMITTEE C4

SYSTEM TECHNICAL PERFORMANCE

Igor Papič (Slovenia) **Alberto Borghetti (Italy)** **Andrew Halley (Australia)**

Special Reporter PS1 **Special Reporter PS2** **Special Reporter PS3**

General Introduction:

The scope of Study Committee (SC) C4 incorporates a variety of system technical performance issues which span a broad range of phenomena and time frames. To better delineate activities within the SC, the following primary topics have been defined:

- Power quality.
- Electromagnetic Compatibility and Electromagnetic Interference (EMC/EMI).
- Insulation co-ordination.
- Lightning and its impact on power system equipment.
- Power system dynamics and numerical analysis.

Inherent in all activities is the investigation and development of new tools, models, methods and techniques for the assessment and analysis of relevant issues. The specific interests of SC C4 relate to the dynamic behaviour of equipment, when considered uniquely and when operated as part of an interconnected power system, including issues which arise from the application of various types of disturbances and external forces.

SC C4 has selected 53 papers aligning with the three Preferential Subjects (PS) for the 2018 CIGRE Session.

- **PS 1:** System technical performance issues focusing on the effects of high level integration of power electronic (PE) based technologies.
- **PS 2:** Developments and advances in modelling and evaluation of lightning performance and insulation coordination.
- **PS 3:** Computational advances in tools, models, methodology and analysis of power system technical performance related issues.

In the following sections grouped by PS, a summary of each paper is presented along with corresponding discussion questions that have been identified by each of the Special Reporters. Responses to the questions offered throughout this Special Report are invited for presentation during the **SC C4 Group Discussion Meeting** which will occur on **Tuesday August 28th** in the Bordeaux Lecture Theatre.

Intending contributors are encouraged to submit proposed presentation material to the Special Reporters by no later than Friday 27 July. Proposed contributions should be emailed directly to the appropriate Special Reporter with a copy to the SC Chairman Zia Emin (zia.emin@ieee.org) and SC Secretary Hideki Motoyama (hideki.motoyama@ieee.org). Guidance, template and sample pages will be made available on the relevant Session parts of www.cigre.org.

Please note that contributors will be required to attend a **pre-session meeting** with the Special Reporters, SC Chair and Secretary on **Monday August 27th** in one of Rooms 233, 234, 235 or 237 on Level 2 Mezzanine at the Palais des Congrès to finalise presentation arrangements. Selected contributors will be notified during this meeting.

igor.papic@fe.uni-lj.si alberto.borghetti@unibo.it andrew.halley@tasnetworks.com.au

The authors of the SC C4 session papers are required to present their papers during the SC C4 Poster Session scheduled for Friday morning August 31st in Halle Ternes. Instructions on preparation will be available on the CIGRE website. Posters will be displayed on digital screens. A final copy will need to be forwarded to the SC C4 Poster Session convener Filipe Faria Da Silva (ffs@et.aau.dk) with a copy to the SC Chairman and Secretary by no later than **Friday 27 July**.

Preferential Subject 1

The theme for PS1 is "*System technical performance issues focusing on the effects of high level integration of power electronic based technologies*" which includes:

- Power system stability control, with particular emphasis on frequency and voltage control systems of converter based energy sources including their modelling and performance and challenges on series compensation and impact of microgrids.
- Analysis, measurement, benchmarking and standardisation of power quality.
- EMC aspects of future power networks including ELF exposures.

Summary of submitted papers

Twenty six (26) papers were accepted in response to PS1. The papers originated from seventeen (17) countries reflecting a wide and international interest in the topics. The papers present concepts and results that broadly align with the three subgroups defined by the SC as follows:

- Subcategory one: 12 papers 102, 105, 106, 112, 115, 117, 118, 119, 120, 121, 124 and 125.
- Subcategory two: 12 papers 101, 104, 107, 108, 109, 110, 111, 113, 114, 122, 126 and 127.
- Subcategory three: 2 papers 103 and 116.

PS1: Subcategory one

Power system stability control with particular emphasis on frequency and voltage control systems of converter based energy sources including their modelling and performance and challenges on series compensation and impact of microgrids.

C4-102: On steady-state voltage standards with high-penetration of distributed energy resources.

This paper describes some common U.S. and European standards that define voltage magnitude ranges. Standards were developed for distribution systems that were characterised by limited visibility and unidirectional power flows. These characteristics are rapidly changing with the on-going roll out of advanced metering infrastructure (AMI) and increasing penetration of distributed energy resources (DER). Addressing this issue requires improved understanding of how changing system operations, and increasing visibility are accounted for or how they may impact existing voltage range standards. This review examines differences in how these standards address voltage range magnitudes as well as the frequency of excursions. Also summarised are some of the known impacts that steady-state voltage excursions have on electrical equipment, as well as identifying the need for further testing and analysis of new and emerging end-use technologies.

C4-105: Investigation of processes during single-phase auto reclosing on transmission lines with controlled shunt reactors.

This paper describes magnetically controlled shunt reactors (MCSR) that are used in the power systems of many countries for voltage stabilisation and for increasing the throughput capacity of transmission lines. The paper discusses the sizing of parameters according to the secondary arc current limitation and the required rate of response of MCSR's. Also presented are analyses of MCSR phase currents during the reclosing dead time, faulted phase current dependence on the reactance of the neutral reactor and its operating modes. A mathematical expression is obtained for determining the reactance of the neutral reactor as a function of the degree of compensation of power line charging capacity. The paper also presents the results of an investigation into the impact of the reactance of the neutral reactor on MCSR response time for a typical 500 kV, 400 km transmission line equipped with fixed and controlled reactors.

C4-106: Updating reactive power compensation calculation required at Badr Converter Station in view of generation capabilities expected to be in service.

This paper presents an overview of the state-of-the-art in reactive power compensation technologies. As part of the Egyptian and Saudi Arabian electrical interconnection project, which has been planned as a High Voltage Direct Current (HVDC) link, the aim of this work is to update the reactive power compensation required to be provided at Badr 500/220 kV Substation, being the electrical connection point on the Egyptian side. Updating of reactive power compensation is implemented to preserve the operating standards of the Egyptian national network considering the loading and voltage operating criteria, which are included in the Egyptian National Grid Code. Short-circuit ratio (SCR) and effective SCR (ESCR) have been important indicators for basic HVDC performance analysis. SCR has been calculated at Badr 500/220 kV substation to investigate the ability of Badr to be the HVDC interconnection point.

C4-112: Inverter dominated UK Grid

This paper describes simulation studies that have been carried out using a reduced grid model of Great Britain (GB). The model is comprised of a detailed network representation for the area of interest (the South East region), with zonal equivalents used for the outlying regions. PSCAD was used in conjunction with DigSilent PowerFactory simulations, the latter utilised to undertake load-flow calculations to obtain the parameters required to initialise the EMT model. An indicative harmonic background representation for the initial operating conditions was also developed. Finally, EMT simulations using an extended representation of the southern GB grid are assessed for a particular study case. The analysis illustrates a potential set of operating conditions for which “inverter induced” instability phenomena may occur. The paper describes how these may be identified and evaluated and the extent to which the deployment of synchronous compensation or other mitigation measures may be used to maintain system stability.

C4-115: Application of fast frequency response to improve primary frequency control in Tasmania.

This paper investigates the use of fast frequency response (FFR) sources to support a high penetration of renewable energy systems (RES) which rely on power electronic (PE) interfaces to connect to the AC network. Specific focus is given to the potential application of a Frequency Stabiliser (FS) device within the Tasmanian power system which utilises supercapacitors for energy storage. The FS device also has significant reactive power capability which helps control voltage in localities having low fault levels. In Tasmania, additional inertia and reactive power services can be supplied by hydro plant operating in synchronous condenser (SC) mode. Although the FS only has a relatively small energy storage capability (of approximately 400 MW.s), the speed of its injection is an excellent complement to the slow responding governing capability of hydro units making for an elegant solution in a predominantly hydro based system.

C4-117: Minimum system strength for secure operation of large-scale power systems with a high penetration of non-synchronous generation.

This paper investigates system strength adequacy for a large-scale power system having a high penetration of non-synchronous generation. The South Australian (SA) power system has been chosen as an example to demonstrate the types of studies that need to be undertaken for any large-scale network to determine the minimum number of synchronous machines necessary to satisfy power system security criteria. In addition to determining the acceptable combinations of synchronous generators necessary to deliver sufficient system strength, the work identified an efficiency breakpoint, which is the largest overall capacity of non-synchronous generation that can be online for the least number of dispatched synchronous generators. The acceptable combinations were chosen such that the propensity for major generating systems to disconnect on the occurrence of credible faults was eliminated.

C4-118: Battery storage for enhancing the performance of transmission grids.

This paper describes Battery Energy Storage Systems (BESS) as a technically and economically viable technology for integration into high voltage transmission networks. Transmission utilities in Australia have been investigating the potential use of BESS and have identified a number of opportunities where the technology can be effectively and economically utilised to increase supply reliability of areas where transmission capacity is constrained due to network limitations. Additionally, it can be used to improve power system stability and thereby increase inter-regional transmission capacities. Potential improvements to frequency stability within the Australian interconnected power system are also discussed. The application of BESS to address each of the above scenarios, the level of improvements the technology can provide, and the resulting performance of the power system are presented.

C4-119: Risk assessment and reserve requirements for power systems with high wind power penetration.

This paper proposes a risk assessment approach to the quantitative evaluation of security of power systems with significant wind power generation (WPG). The proposed risk assessment approach is concerned with steady-state voltage and overload evaluations, as well as frequency response (control) adequacy. In the case study presented, the proposed approach was used to evaluate operational risks of a nine-bus power system having characteristics similar to Tasmania, Australia. The results show that the integration of WPG significantly affects system operational risks, especially frequency control. The impacts of different factors on system security including load and WPG forecasting uncertainties, wind power penetration levels, and operating reserves were investigated. It also shown that the proposed approach could assist system operators during operational planning activities, including the setting of curtailment levels for wind generation and determining operating reserves.

C4-120: Novel mechanism explanation and mitigation study of SSR in DFIG based on separate stator and rotor torque analysis.

Starting from the expression of electromagnetic torque for a doubly fed induction generator (DFIG), this paper describes a novel interpretation of sub synchronous resonance (SSR) mechanisms which affect these machines when operating in series compensated networks. The method involves dividing the electromagnetic torque variation into two parts, i.e. rotor torque variation and stator torque variation. Firstly, the relationship of stator and rotor torque with rotor speed is derived. Then the impacts of stator and rotor torque on SSR are examined by analysing amplitude-frequency and phase-frequency responses. By way of analysis, a double closed-loop control strategy with supplementary damping controls on the rotor side converter (RSC) is proposed. This strategy offers significant damping effects on SSR and can ensure stable operation of DFIGs. The validity and effectiveness of the proposed solution is verified through extensive simulation studies.

C4-121: Determination of wind farm performance.

This paper describes a performance baseline for wind turbine generators (WTG) and an annual assessment to monitor the performance deterioration of WTG's. The objective is to identify WTG's which require immediate attention due to underperformance outside of what could be considered an acceptable variance. The paper describes the creation of WTG power curves for the years 2015 and 2016. The reference wind speed distribution was used as a reference wind speed base with which to generate so-called 'normalised' energy curves for each WTG for each reference year; this was done to eliminate the bias of large length scale seasonality in the wind quality. The area under each WTG's normalised energy curve was used to output a reference energy production, thereby offering a single key-performance-figure which could be used to track and compare changes over each reference year.

C4-124: Utilising advanced resiliency planning within the electrical sector.

This paper describes several initiatives to safeguard critical infrastructure. The classical reliability perspective is that the utility engineer is able to plan, design, maintain and operate power systems within prescribed safety thresholds/margins for a predefined range of threats which can impact on stability and the continuity of supply. This context has changed with the exposure to extreme incidents that push beyond safety margins typically considered during the planning and design of infrastructure. A comparison is tabulated for two key engineering disciplines (namely: reliability and resilience) that may inform risk decision making. The paper also explores the different resilience strategies that can frame decision making and discusses the different time frames for decision making. The paper concludes with case studies to demonstrate the application of different types of resilience thinking adopted.

C4-125: The application of series compensation to the existing Scottish 400 kV transmission system.

This paper describes the first application of series compensation equipment in GB, designed to increase the onshore Scotland to England transfer capability from 3300 MW to 4400 MW in the most economic and efficient manner. The objectives in doing so are to reduce generation constraint (congestion) costs incurred by customers, to facilitate new generation connections in Scotland and to help achieve Government renewable energy targets. One of the solutions that enabled the capacity of the interconnection to be increased to the thermal limit of the existing overhead line conductor systems was to install series compensation equipment in all four interconnecting circuits. The installation of series capacitors introduced a considerable risk of sub-synchronous resonance (SSR). The development of an SSR performance-based specification to encourage a range of mitigation options led to the first installation of series capacitor banks with passive damping filters worldwide.

Question 1.1:

Revisions to the steady-state voltage ranges have consequences from utility distribution system planning and operation to the design and manufacturing of electrical equipment in networks with increased number of power electronics devices and changed structure. How may this impact existing voltage range standards?

Question 1.2:

Battery Energy Storage Systems (BESS) are now being considered as a technically and economically viable technology for integrating into electric power networks.

(a) Can we expect large-scale implementation to finally occur?
(b) What network services / functions are currently being delivered by such equipment?
(c) What roles do people see BESS fulfilling in electric power networks of the future?

Question 1.3:

(a) What are the world-wide experiences with magnetically controlled shunt reactors for voltage stabilisation and for increasing the throughput capacity of transmission lines?
(b) What other recent experiences are available with new transmission or generation technologies that have been specifically designed to deal with sub-synchronous resonance (SSR) or sub synchronous control interaction (SSCI) issues in series compensated transmission systems?

Question 1.4:

(a) How important are fast frequency response (FFR) resources to support high penetrations of Renewable Energy Systems (RES)? What is the experience in other countries in relation to the benefits (or drawbacks) of very fast acting frequency control capabilities coming from FACTS devices (including BESS), HVDC and PE connected generating systems?

(b) Is there a need (are there sufficient drivers) to utilise advanced risk assessment and resiliency planning going forward?

PS1: Subcategory two

Analysis, measurement, benchmarking and standardisation of power quality.

C4-101: The difficulties faced in the filters design versus the low harmonic voltages generated by wind farms.

This paper describes the difficulties faced in defining harmonic and reactive compensation devices used to reduce voltage distortions generated by wind farms in Brazil. The methodology and process of harmonic performance evaluation for Brazilian wind parks is presented. The paper discusses the importance of improving analysis procedures used to assess voltage distortions caused by wind farms and the need to apply operational experiences versus study results. Such improvements are necessary due to (i) the expansion and importance of wind power in the Brazilian energy matrix, (ii) the cost of the filters involved, and (iii) project complexity and operational difficulties. Finally, the paper concludes that the study methodology required in Brazil must be reviewed since it has been demonstrated to be inadequate for achieving a realistic diagnosis of voltage distortions caused by wind farms.

C4-104: Measurement and analysis of harmonic data to assess the impact of installations connected to high voltage systems.

This paper analyses a harmonic study case using actual measurements from high and extra high voltage systems where inverter-based technologies are increasingly applied. In addition, due to the spatial planning needs of society, overhead lines are being replaced by underground cables. The use of more underground cables causes changes in the resonant frequencies of the power supply system which can result in either amplification or reductions of harmonic levels. A harmonic assessment analysing the impact of a distorting installation on an extra high voltage grid is in practice complicated. Articles are published on the methods, but not many describe real world cases dealing with high voltage grids. The analysis is based on the non-invasive method. In this particular case, when the disturbance originates from the grid, an assessment can be performed with known filter states and calculated filter impedances.

C4-107: Improvement of power system harmonics level generated from the electric arc furnaces (EAF) to the acceptable level by using shunt passive filters.

This paper describes a filter design to improve the power system harmonic levels generated by an electric arc furnace (EAF) used in the Arabian Company for Steel Manufacturing, Sadat City, Egypt. The factory uses two tuned harmonic filters at the second and third harmonic orders. Despite the existence of two passive filters, it is found from power quality measurements that the total harmonic distortion (THD) of current greatly exceeds the IEEE-519 standard limits. From the current measurements available, the value of the fifth harmonic current is found to be very high and it is necessary to design an additional tuned filter at the fifth harmonic frequency. By using Matlab-Simulink simulations, the EAF with three filters is simulated and the improvement in power system harmonic levels is verified. An important aspect which must be considered is the outage of one filter branch.

C4-108: Harmonic responsibilities determination at the point of common coupling.

This paper describes a method to evaluate the responsibilities of harmonic distortion between the utility and customer at the point of common coupling (PCC). The proposed method is based on the analytical study of three-phase instantaneous power flows of both fundamental and all harmonics signals. An important advantage of the method is that the voltages and currents measured at the PCC are sufficient for determining the magnitude and direction of power for each harmonic order. The method can be implemented in any power quality measurement device which monitors voltage and current harmonics (amplitudes and phase angles) simultaneously. It is possible to produce revenue meters that measure the correct quantities to determine the responsibilities for harmonic pollution exchanged between utilities and customers. The performance of the proposed method is verified using simulation studies for different cases.

C4-109: Power quality monitoring as a valuable tool for assessing system technical performance.

This paper describes the Romanian regulations regarding power quality (PQ) that are reflected in the new (2016) TSO Standard of Performance and the technical norms regarding the limitations of voltage fluctuations. The second part of the paper presents an overview of the PQ parameters recorded during 2017 by permanent monitoring systems. Measurements made using portable PQ instruments are also presented. The influence of fault level on the propagation of voltage fluctuations across the power grid represents a challenging issue. Several mitigation measures for long and short-term flicker are considered. Using data mining techniques on the collected data, the paper presents a first draft for clustering and long term memory processing methods for event extraction. Different metrics for distance and initial configuration are considered. In the end, a decision is made regarding the best data processing option.

C4-110: Technical challenges associated with the integration of long HVAC cables and inverter based renewable generation in weak transmission networks: the Irish experience.

This paper discusses the most critical challenges associated with the integration of large amounts of HVAC cables and inverter based generation into a weak transmission network based on the experience gained by the Irish Transmission System Operator (TSO) EirGrid over recent years. The integration of large amounts of HVAC cables introduces new technical challenges compared to the use of equivalent overhead line (OHL) circuits. In particular, large cable capacitance interacts with the predominately inductive power system and can introduce issues such as harmonic resonances at low frequencies. A case study is presented illustrating the technical analysis and solutions adopted for the connection of a large cluster of wind farms using HVAC cables in a weak part of the 110 kV transmission system. Simulations and field measurements are presented and key learnings discussed.

C4-111: International comparison of harmonic assessment approaches and implications.

This paper describes the emphasis placed on power quality and in particular on harmonic voltage distortion compliance in transmission systems. Voltage distortion continues to grow as an issue due to the increased penetration of nonlinear connections and the increased use of cabling. This is contributing to a shifting of resonant frequencies and a decrease of load that provides a dampening effect for harmonic voltage distortions. This paper summarises the approach taken by various countries in assessing such issues and the subsequent treatment of the analysis in terms of setting emission requirements. A simple case study is provided in order to illustrate the different approaches and to highlight the implications on both the System Operator and connecting parties.

C4-113: Investigation into the transmission system modelling for the effective assessment of voltage unbalance due to AC railway operation: Evaluation using on-site measurement data.

This paper investigates the importance of modelling the network's inherent asymmetries when estimating the voltage unbalance contributed by loads. To support the analysis, on-site measurements were performed in the Danish grid, with results used to evaluate network model calculations. In transmission grids where electric train systems are connected, un-transposed lines are the main source of a network's inherent unbalance. The question is raised 'how necessary is the accurate representation of transmission lines when calculating the unbalance contributed by load connections?' Although this study refers to unbalanced loads in general, it finds great application when considering electric railways as this is a dominant unbalanced customer connected to many transmission systems. For analysis purposes, the grid model of the western Danish transmission system is used. Comparisons between the measurement data and load flow results show very good agreement.

C4-114: Power quality analysis and IEC Standard evaluation using measurements and simulations in a STATCOM application.

A modular multi-level STATCOM was installed at an electric arc furnace plant to keep power quality within specified limits. A flicker evaluation using both measured and simulated values has been performed to assess its performance. An investigation of the general summation law and the exponent (α) shows that a lower exponent value of around two, or a lower probability level (95%), can produce good agreement with the background measurements in the studied case. The study shows how a chain-link STATCOM installed at a medium voltage level to mitigate interference from one specific source can at the same time improve the capability and the flexibility of the surrounding high voltage network. Production capacity benefits resulting from the STATCOM being able to maintain a high and stable voltage on the furnace bus are noted.

C4-122: Power quality monitoring in power grids focusing on accuracy of high frequency harmonics.

This paper presents an overview of established voltage transducer technologies and their suitability for high frequency measurements from 2 – 150 kHz. The voltage measurement using capacitance graded bushings is presented in detail including bandwidth measurements, temperature dependency and long-term stability. The results indicate that this technology is particularly suited to harmonic and transient measurements. Additionally, the necessary properties of the power quality measurement device are discussed with particular attention to the sample rate and the vertical resolution of the A/D-converter. Finally, two measurement installations are presented. One was conducted directly at an electric vehicle charging station and shows that harmonic distortion occurs at frequencies up to at least 50 kHz. The other was a test installation at a 380 kV transformer using the aforementioned capacitance graded bushings, where high frequency harmonics are measurable up to 9 kHz.

C4-126: Intermittent voltage unbalance and its impact on large power asynchronous motor operating modes.

This paper describes the determination of electromagnetic interferences which can affect electric motor outages. There are methods to estimate possible interference levels and develop protective measures. The first part of the research work is related to the investigation of possible causes of large power motor vibrations. The second part is related to the research of intermittent voltage unbalance at traction substations and the propagation of this unbalance to the other parts of the power network. Research results have helped determine how the number, power demand and power factor of passing trains can impact on the amplitude of the negative sequence voltage component and the angle between the symmetrical components of positive and negative sequences. The third part of the research deals with the development of methods for measuring intermittent voltage unbalance.

C4-127: Assessment of the impact of power electronic devices on harmonic levels in transmission networks

This paper focuses on harmonic issues that arise from the massive proliferation of power electronic (PE) devices in transmission systems. When considering harmonics in the transmission system, it is necessary to consider the injections of individual PE devices, as well as the susceptibility of all elements in the network, including transmission lines and cables. They are often one of the major causes of increased harmonic contribution due to poorly damped network resonances. The "scanned" Norton equivalent models of the PE devices are utilised for steady-state simulations in time or frequency-domain and tend to simplify the simulation complexity and simulation-time. Such equivalent models are an optimal solution for comprehensive impedance-based system analyses as well as the harmonic load-flow studies, which cover the steady-state conditions.

Question 1.5:

The importance of improving the analysis procedures to assess voltage distortions caused by wind farms in Brazil is suggested, where many unnecessary filters have been installed.

(a) What are the practices, experiences and network operator requirements in other countries which have large numbers of wind farms already installed or proposed?

(b) What have been the recent experiences elsewhere with harmonics (particularly even harmonics) produced by PE interfaced generation including measurement versus simulated results, any observable impacts on the network and methods used to mitigate those impacts?

A passive filter design to improve harmonic levels generated from an electric arc furnace (EAF) is presented. The same solution is often used in wind farm applications.

(c) Are there any examples of other available technologies now being used at such scale for power quality improvements, e.g. active or hybrid filters?

Question 1.6:

What are the current experiences with the use of "data mining" or other novel approaches to extract useful information from large volumes of power quality measurements? How easy are the techniques to implement (from a network operator perspective) and what examples can be offered to demonstrate the use of such activities to assist with network operation and design?

Question 1.7:

(a) What are the experiences with voltage unbalance in other countries? What level of unbalance is considered acceptable and are there plans to review / revise existing limits in your network?

(b) How severe are any observed problems and what have been the practical impacts of significant voltage unbalance on the operation of your network?

(c) Have increasing levels of PE connected generation played any significant role in changing the levels of voltage unbalance observed in electric power networks? If so, what have been the mechanisms for this in your network?

Question 1.8:

An overview of established voltage transducer technologies and their suitability for high frequency measurements from 2 to 150 kHz is presented. What opinions exist on the need for such high frequency measurements to become part of 'regular' (routine) power quality monitoring programs in the future? What technical issues could drive such a need and do examples already exist in some networks?

PS1: Subcategory three

EMC aspects of future power networks including ELF exposures.

C4-103: Zero sequence currents in the high voltage grid in the Netherlands.

This paper focusses on a possible source of electromagnetic interference: zero-sequence currents in high voltage transmission systems. The objective of the paper is to investigate the levels of zero-sequence currents and the behaviour of those currents as a function of time. To this end, measurements on two 150 kV branches in the Netherlands were performed over a period of 245 hours. During the measurement time, three modes of operation were observed: normal daily oscillations, switching off of one of the branches, and switching events elsewhere in the network. The ratio between zero-sequence and positive sequence current can change quite heavily when there is load changing within the network. This is mainly due to the decrease in positive-sequence current and to a lesser extent due to the increase in zero-sequence current.

C4-116: Cost effective EMC/EMI management for transmission and distribution substation control buildings.

This paper focuses on cost effective EMC design for electric power transmission and distribution substation control buildings and high voltage yards. Due to the rapid technological development, modern protection, control and telecommunications equipment are exclusively microprocessor driven. Although these systems provide significant benefits, they are also susceptible and vulnerable to various threats. Poor electromagnetic compatibility (EMC) specification, design and construction can result in significant costs to users of electrical energy due to rework requirements, general under-performance and unreliability of plant and equipment. Considering that mal-operation of transmission and distribution protection, control and telecommunication devices will have a direct impact on the reliability and availability of the power system, it is imperative that the equipment contained in substation control buildings are adequately protected from EMI.

Question 1.9:

(a) Based on the measurement of zero-sequence currents in the high voltage transmission system of the Netherlands, are there any special measures foreseen or required to reduce electromagnetic interference? What are the experiences from other countries?

(b) What are the estimated annual costs related to the malfunction of secondary equipment due to poor EMC design? Are other network businesses able to easily justify robust EMC designs and what criteria / evidence are being used to defend the associated costs?

Preferential Subject 2

The theme for preferential subject two is "*Developments and advances in modelling and evaluation of lightning performance and insulation coordination*" which includes:

- Estimation of lightning performance of transmission lines including detection, evaluation of shielding analysis methods and effectiveness of line surge arresters.
- Lightning protection of renewable and nuclear power plants including seasonal variations and risk management.
- Evaluation of surges and overvoltages on OHL / cable systems and the impact of harmonic resonances on temporary overvoltages.

Summary of submitted papers

Thirteen (13) papers were submitted to PS2, coming from eleven (11) different countries. The papers broadly align with the three subgroups defined by the SC as follows:

- Subcategory one: 6 papers, 201, 202, 206, 207, 209, 212.
- Subcategory two: 1 paper, 213.
- Subcategory three: 6 papers, 203, 204, 205, 208, 210, 211.

Several papers describe the use of information provided by lightning location systems and meteorological models for the characterisation of lightning incidence, severity and for the estimation of the effects of pollution to the flashover failure rates of insulators. The spatial and temporal correlation of lightning, weather, and outage data requires the adoption of modern algorithms. Moreover, some papers describe recent experiences relevant to the development and use of improved measurement systems for voltage fast transients. Overvoltage problems associated with the use of HVDC systems as well as classical studies, such as the advantages of the adoption of shield wires or gapped line arrester, the analysis of ferroresonance phenomena and the evaluation of the lateral attractive distance are addressed. This is accomplished thanks to the help of new field data, as well as by comparing computer or analytical models and experimental test results. Finally, some new examples of the adoption of numerical electromagnetic analysis (NEA) methods for the accurate evaluation of overvoltages are documented.

A summary of each paper, as well as the Special Reporter questions, are provided below.

PS2: Subcategory one

Estimation of lightning performance of transmission lines including detection, evaluation of shielding analysis methods and effectiveness of line surge arresters.

C4-201: Development of outdoor insulation pollution maps for IECo (Israel Electric Co) power grid.

The paper presents pollution maps obtained by using both continuous monitoring and computer models. These maps are an important result since the pollution-related line outages reach 18-20% of the total line outages in the Israeli power grid mainly due to Saharan dust. The data presented in the paper are related to the subjects of two international standards, namely IEC 60721 "*Classification of environmental conditions*" and IEC TS 60815 "*Selection and dimensioning of high-voltage insulators intended for use in polluted conditions".*

C4-202: Optimal placement of line surge arresters based on predictive risk framework using spatiotemporally correlated big data.

The paper addresses the important topic of choosing the most efficient placement of surge arresters in a transmission network by the development of a fully automated decision-making risk model based on a linear regression algorithm. At first, the parts of the network with the highest probability of faults caused by lightning are identified. Then, an optimisation procedure is adopted for the placement strategy of a limited number of surge arresters considering economic factors.

C4-206: A simplified approach for use of a lightning attachment model to assess exposure of EHV and UHV transmission lines to direct strikes.

The paper describes an analytical method able to provide the lateral attractive distance of any conductor of a multi-conductor transmission line from the lateral distance evaluated for a single free conductor. The accuracy of the method is verified against the results provided by a more detailed model for different types of EHV and UHV lines.

C4-207: Shield wire or not – experiences from the Swedish 130 kV grid.

The paper reviews the lightning protection design of 132 kV overhead transmission lines in the Scandinavian country of Sweden which has an annual flash density of only 0.20 - 0.25 flashes/km^2/year and a high soil resistivity (average value equal to 3 kΩm). The paper focuses on the cost-benefit analysis of adding a second overhead ground wire to lines with H-frame towers that could guarantee the absence of shielding failures.

C4-209: Analysis of lightning performance for 154/345 kV transmission lines with externally gapped line arrester in South Korea.

The paper discusses the advantages of installing line surge arresters in 154 kV and 345 kV multi-circuit lines. Arrester test results, EMTP analysis, practical application cases, and a comparison of the lightning performance with and without line surge arresters are described. No multi circuit trip has been reported since the installation of external gapped line arresters.

C4-212: Evaluation of insulation coordination of substations by advanced approaches.

The paper provides a review of the authors experience in Japan on insulation coordination studies in ultra-high-voltage (UHV) transmission systems. The applied approaches are based on measurements of lighting return stroke currents (to towers and to phase conductors) and lightning originated overvoltages, as well as the use of finite-difference time-domain (FDTD) computer simulations.

Questions 2.1:

Concerning performance analysis:

(a) What are the international experiences with pollution maps beyond the activity in Israel described by paper C4-201? What are the characteristics of insulators that can comply with high Site Pollution Severity (SPS) indices and that could limit the Saharan dust effects? What is the international experience for the operation of medium voltage or high voltage overhead lines in countries seriously affected by dust storms?

(b) Since the location accuracy of the lightning location system is typically described by 50% error ellipses with major axis of some hundreds of meters, according to the international practice what is the required area around transmission lines and towers that is sufficient to guarantee that all dangerous events are considered in the lighting performance analysis? Is there a standard methodology for this purpose, based on the characteristics of the lightning location system and of the overhead line? What is the relationship between the hazard map mentioned in paper C4-202 and the typical map of N_G values (mean number of cloud-to-ground flashes per unit area per unit time)? According to international experience, is the N_G map sufficient for lightning performance analysis or is the use of density maps of striking points (provided by modern lightning location systems) more appropriate?

Concerning shielding analysis and surge arresters:

(c) According to international experience, are the attachment models adopted for HVDC lines similar to those adopted for HVAC lines? Is the method proposed in paper C4-206 also valid for DC lines?

(d) What are the international practices and experience on the application of shield wires in overhead lines below 130 kV, besides the Swedish study reported in paper C4-207? What are the experiences with the use of shielding wires in medium voltage overhead lines? What is the international experiences on the application of a Leader Propagation Model for the lightning performance estimation of 130 kV lines, with or without shielding wires, instead of the electro-geometric model?

(e) Paper C4-209 mentions the interesting topic of surge arrester in failure mode. According to international experience, what is the typical rate of line surge arresters in failure mode and the most common causes for the surge arrester failure? Is there any experience of unusual high failure of surge arresters in specific lines?

Concerning the use of numerical electromagnetic analysis (NEA) methods:

(f) The application of NEA methods is traditionally limited to benchmark cases with limited space domain. Both papers C4-212 and C4-213, in addition to those already presented in CIGRE Technical Brochure 543 and references therein, describe some examples that appear to show an increasing application of NEA methods. Are there other experiences relevant to the application of NEA methods in insulation coordination studies?

PS2: Subcategory two

Lightning protection of renewable and nuclear power plants including seasonal variations and risk management.

C4-213: Evolution of lightning protection of nuclear power plants: an overview of EDF's experience.

The paper reviews the evolution of lightning protection design for nuclear power plants based on the experience of the authors. The review includes a description of how the lightning location system (with a focus on striking point density and current distribution) is used and mentions a new procedure for the calculation of the overvoltages in cables connected to buildings struck by lightning.

Question 2.2:

In reference [15] of paper C4-213, the adoption of the FDTD calculation approach delivers induced voltages in cables that are, in general, significantly higher than those obtained by using the procedure in the German standard KTA 2206. How much would these new results potentially affect the protection design in nuclear power plants? Are there studies or experiences in the nuclear power industry that may confirm these concerns?

PS2: Subcategory three

Evaluation of surges and overvoltages on OHL / cable systems, impact of harmonic resonances on temporary overvoltages.

C4-203: Merits and challenges of a differentiating-integrating measurement methodology with air capacitors for high-frequency transients.

The paper presents a detailed description of the implemented measuring system for the acquisition of high frequency voltage transients in substations and in the transition points between a cable and an overhead line. The effects of several formulations of the decoupling matrix are examined. The comparison between measurement and computer simulation results is particularly interesting.

C4-204: Application of C-type harmonic filters as remedial measure against temporary overvoltages in transmission systems due to harmonic resonances.

The paper presents a rather comprehensive analysis of the temporary overvoltage limitation that can be achieved by the installation of C-type filters.

C4-205: Voltage transient measurements using electric field sensors and ATP modelling of a 500 kV GIS station

The paper describes the practical experience of measuring very fast transients in a 500-kV gas insulated switchgear station using a portable electric field sensor. The measurements are successfully compared with computer simulations.

C4-208: Field measurement of lightning transient voltage in substations using optical electric field sensors.

The paper describes a measurement system that uses optical electric field sensors based on the Pockels effect. The system has a response time not higher than 9 ns and a flat amplitude-frequency curve from 5 Hz to 100 MHz. These characteristics are appropriate for the accurate measurement of lightning originated voltage transients. The paper also describes measurement results recorded over an eight-month period showing that 307 events of a total of 832 recorded transients have been correlated with ground flashes detected by a lightning location system.

C4-210: A novel approach to statistical analysis of slow front overvoltages in HVDC converter stations.

The paper presents an analysis of the statistical characteristics of slow-front overvoltages typically originated by earth faults. The analysis is carried out for both faults in the AC side and DC side (bus and pole faults). The statistical distribution of these overvoltages is not well described by the normal distribution. The highest overvoltages are caused by DC pole bus faults.

C4-211: Ferroresonance in inductive voltage transformers or power voltage transformers: analysis, laboratory tests and solutions.

The paper presents analysis of ferroresonance phenomena in solidly earthed neutral systems where a network section, which contains a station service transformer (SST), remains coupled to the rest of the system through the grading capacitance of an open circuit breaker. Analogous results are obtained for inductive voltage transformers (IVT), whilst capacitive transformers that include anti-ferroresonance circuits are not affected by these phenomena. The paper presents the results of laboratory tests and computer simulations. The analysis confirms the need for damping solutions different from a simple uncontrolled switched resistor.

Question 2.3:

(a) Modern monitoring systems allow improved comparisons between measurement and computer simulations (interesting examples are presented in papers C4-203 and C4-205). These comparisons require suitable identification of computer model parameter values. What are the methods typically applied and the experience in this regard?

(b) What is the international practice and experience relevant to the application of C-type filters at the terminals of long HVAC cables, as suggested in paper C4-204? As C-type filters are used in some HVDC systems, what are the main differences between the design and application of these filters in HVDC and HVAC systems? What experiences can be offered from the industry in this regard?

(c) Paper C4-208 describes a measurement system of high frequency voltage transients. What are the reasons for installing this kind of measurement systems in the network, e.g. are they installed for protection purposes or to improve the accuracy of the lightning location system? Do other utilities have experiences with similar measurement systems and what are the intended uses?

(d) What is the experience of slow front overvoltages in HVDC links with converter configurations different from the symmetrical monopole VSC arrangement assumed in paper C4-210? What are the configurations less affected by this type of overvoltage? What are the opinions on the countermeasures that can be implemented in existing and new HVDC systems?

(e) What are the more promising anti-ferroresonance methods currently applied in substations, other than switched resistors? What is the industry experience and protection practice with ferroresonance phenomena in substations, including phenomena different from those originated by islanding manoeuvres of transformers analysed in paper C4-211?

Preferential Subject 3

Fourteen papers were submitted for PS3 which is titled "*Computational advances in tools, models, methodology and analysis of power system technical performance related issues.*"

The proposed subject matter included the following topics:

- Frequency dependent modelling techniques for high frequency electrical transients and power quality assessments.
- Developments in lightning surge studies with particular emphasis on finite-difference time-domain (FDTD) method and advances in grounding electrode modelling.
- Hybrid and real time simulation of system dynamic behaviour.

Summary of submitted papers

Fourteen (14) papers were submitted to PS3, coming from ten (10) different countries. The papers broadly align with the three subgroups defined by the SC as follows:

- Subcategory one: 6 papers, 301, 304, 306, 309, 310, 311
- Subcategory two: No papers were received on this topic.
- Subcategory three: 5 papers, 303, 305, 307, 313, 314.

A number of authors chose to address the main theme of the preferential subject without direct reference to a specific subtopic.

- Aligned with overall theme of PS3: 3 papers, 302, 308, 312

A summary of each paper and common subgroup themes, as well as the Special Reporter questions, are provided below

PS3: Subcategory one

Frequency dependent modelling techniques for high frequency electrical transients and power quality assessments.

C4-301: Comparison between measured and simulated VFTO in 525 kV GIS.

Following successive transformer failures in a hydro power plant in Brazil, investigations were initiated into the effect of GIS disconnector switching and the resulting impacts of very fast transient overvoltages (VFTO) on transformer insulation life. The paper describes development of a detailed model of the GIS, including disconnector switch opening and closing, as well as the tuning and verification of simulation results using measurements coming from an experimental GIS facility. The development and calibration of VFTO sensors is described. Field measurements generally showed good agreement with simulation results noting the complex physics of the equipment to be represented at the frequency range of interest.

C4-304: Impact of uncertainties in HVAC cable modelling on transmission system harmonic behaviour.

The paper explores the impacts of design uncertainties associated with long HVAC cables when calculating harmonic impedance and harmonic voltage amplification factors for a transmission network. Uncertainties are identified for both the pre and post installation cases. The 600 MW Kriegers Flak wind power plant is used as a case study. It is demonstrated through the application of Monte Carlo analysis that feasible variations in cable length, insulation thickness, insulation permittivity, core radius and core resistivity can have a significant impact on network harmonic behaviour. Furthermore, it is also demonstrated that the commonly used approach of assessing harmonic amplification via positive sequence voltage may be insufficient when dealing with asymmetrical cable systems where the harmonic performance can vary across individual phases. Methods for dealing with differences between phases are discussed, as are guidelines for considering safety factors in harmonic studies involving HVAC cable systems.

C4-306: Computation of power losses in HV submarine three-core armoured cables: a 3D multi-conductor cell analysis along with subdivision techniques.

This paper describes the use of three dimension multi-conductor cell analysis (MCA) for the calculation of positive sequence impedance and the resulting power losses in a 29.5 km submarine cable running between Capri and the Italian mainland. Theoretical analysis is well supported by field measurement, allowing the methodology to be validated. Results show that positive sequence resistance (and hence power losses) are within approximately 7% of measured values, with positive sequence reactance simulated with an error of approximately 10%. A key advantage of MCA when compared to finite element method (FEM) analysis is the dramatically reduced computation time to perform simulations. With a cable model length of 49.4m, the authors report a simulation time of approximately 32 minutes. Existing FEM software is reported to be limited to models of 3m or less. Direct comparison between MCA and FEM techniques were also performed on a 2.6m submarine cable, with MCA producing comparable results with a simulation time some 4200x faster. An observation from this analysis is that MCA cannot consider eddy (Focault) currents which produced a notable difference in power losses calculated in the cable armouring. This largely accounts for the 7% error observed. The authors note that the computed losses using MCA (and FEM) are well less than that estimated from application of IEC 60287-1-1.

C4-309: Impact of cable impedance modelling assumptions on harmonic losses in offshore wind power plants.

The paper compares calculated positive sequence cable impedances over a range of frequencies for a number of different cable models and presents the differences. It demonstrates how the total harmonic losses and distortion in a wind farm can be either underestimated or overestimated depending on the cable model selected and outlines the practical implications of this discrepancy.

C4-310: Development of improved aggregated load models for power system network planning in the Nordic power system – Part 2: Method verification.

In the paper, the authors share their experiences from the development of load models for the Nordic power system. It is well known that the response of load to voltage and frequency changes could have a substantial impact on the performance of the power system, especially during transient operating periods. However this work, as many others conducted previously, confirms that there is no simple and fast solution to address the load modelling challenge. While modelling outcomes are preliminary at this stage of the project, with validation of the methodology given priority, initial results suggest that optimised ZIP model parameters may be quite different from that currently being used by the respective TSO's. The load response to frequency changes has only been addressed in a coarse fashion thus far and alternate measurement approaches are to be considered. The authors reached the conclusions, which align with the experiences of others, that: 'there will be large uncertainties in the development load models and that the models can only be validated to a limited extent'.

C4-311: A high frequency power transformer model for network studies and TDSF monitoring.

The paper presents a high frequency power transformer model for network study purposes. The model combines white and black box representations in a package implemented as "compiled foreign model" of the MODELS language within the EMTP/ATP program. Time domain severity factor (TDSF) monitoring is integrated into the model package which offers valuable information to examine the risk level of the inner points of the power transformer windings when the unit interacts with the network during fast transient conditions. The proposed white plus black box model of a 50/50/16.67 MVA transformer is illustrated for simulating lightning overvoltages when it is connected to a 220 kV gas insulated substation (GIS).

Question 3.1:

(a) Given that detailed modelling of the physical GIS arrangements is required to achieve accurate simulation results, are there alternate methods that can be used to determine critical locations or GIS configurations that give rise to the most severe VFTO that may be detrimental to connected equipment?

(b) What is the experience of other organisations in relation to VFTO introduced by GIS operations and has this phenomena been identified or suspected as a potential root cause of failures of nearby connected equipment?

Question 3.2:

A number of papers have described how credible variances in model parameters can have a material impact on the outcomes of various analysis including network harmonic studies. In particular, the challenges associated with the accurate representation of high voltage cable systems in harmonic studies have been discussed.

(a) How are other organisations managing parameter uncertainty when performing harmonic studies for new or modified network connections?

(b) What typical safety margins are being applied when dealing with HVAC cable systems in particular?

(c) Is there a potential for unnecessary investment in mitigation measures if sensitivity studies are not undertaken as part of the analysis methodology and are there any practical examples of this being the case?

(d) Do other organisations assess harmonic amplification across individual phases as standard practice or is there a general reliance on the positive sequence with safety margin applied?

(e) In Paper C4-306, the authors note that the computed losses using MCA (and FEM) are well less than that estimated from application of IEC 60287-1-1: '*Current rating equations (100 % load factor) and calculation of losses – General'*. What is the experience of others? Is there enough evidence to suggest that modifications to this Standard are required?

Question 3.3:

The issue of uncertainty is also relevant to load modelling parameters. While it is widely recognised that no practical load model can be a perfect representation of all equipment downstream of the aggregation point, it is unclear whether load modelling errors are a more significant risk for the power system now than they have been in the past.

(a) Given that networks are typically being operated closer to their technical limits and the generation mix is evolving to include more PE interfaced generation equipment (thereby contributing to a reduction of system fault levels and inertia, effectively reducing overall 'system strength'), are the risks associated with inadequate / inappropriate load models increasing? Can organisations offer any practical experiences or opinions on this, especially those operators from smaller power systems with an increasing mix of PE interfaced renewable generation?

(b) How common is it for system operators to evaluate stability limitations using a range of load model parameters rather than a single fixed set? What have been the historical practices and are these likely to change going forward if there is a perceived increase in risk?

(c) Recognising the efforts of the Joint Working Group C4-C6.35/CIRED "*Modelling of inverter based generation for power system dynamic studies",* are system operators updating their existing load models to include the characteristics of embedded generating systems, most notably rooftop PV (where it is significant)? What are the recent practical experiences of attempting to modify / determine model topologies or parameter sets to cater for such equipment?

(d) If yes, have such models included non-linear behaviours (under and over voltage protection for example) or simply represented the basic voltage/frequency dependence of the inverters in aggregate? How are the initial conditions for the load model being estimated, i.e. the level of PV generation at any given time? What has been the general approach to implement a 'practical' load model inclusive of embedded generation?

PS3: Subcategory two

No papers were submitted for this subcategory.

PS3: Subcategory three

Hybrid and real time simulation of system dynamic behaviour.

C4-303: Hardware in the loop platform for testing the wind turbine type 4 ability of improving frequency stability of power systems.

The paper presents a Control Hardware In the Loop (CHIL) platform which is used for the testing and validation of wind turbine generators (WTG) and also to demonstrate new control methodologies for PE interfaced generation. The paper focuses on Type 4 WTGs but notes that hardware in the loop investigations have been completed by others on different technologies. The platform includes an RTDS simulator to represent the wind turbine and power system, a signalling interface, and external hardware to replicate the machine side converter (MSC) controller which is configured with the algorithms being examined. The paper investigates the feasibility of Type 4 WTGs providing primary frequency regulation using an algorithm based on frequency containment reserves. The impact on Low Voltage Ride Through (LVRT) was also investigated. The results demonstrate that the primary frequency control design can improve post-disturbance frequency dynamics in terms of both nadir and final steady state frequency. The CHIL platform is shown to be able to demonstrate and test other control algorithms for Type 4 WTGs including LVRT.

C4-305: Requirements for models to study and prevent system separation and collapse.

The paper draws on published work from CIGRE JWG A3/B5/C4.37 "*System conditions for and probability of out-of-phase*" and elaborates on specific aspects related to modelling requirements. It is noted that modelling 'power systems in distress' following unforeseen events is not an easy task when the consequential interaction between primary plant and various control and protection systems needs to be adequately captured. The JWG identified three main causes of large disturbances; (i) lack of situational awareness, (ii) 'common' causes (weather, vegetation management, natural disasters etc) and (iii) homogeneity of control and protection settings (especially on dispersed generation technologies which can be identical across many individual units). It is noted that the latter should be correctly modelled to understand how system wide or region wide variables such as voltage, frequency and power swings can impact on equipment having homogeneous response characteristics. The use of real time simulations to test the behaviour of protection relays during unstable power swings is also noted along with the need to include feedback loops to represent resulting changes in the network after relay operation. The need for multi-disciplinary evaluation of models to study the effects of certain technological developments has been deemed necessary by the authors.

C4-307: A review of dynamic model equivalents in emerging electrical grids.

This paper categorizes power system dynamic model equivalents (DME) into (i) low-frequency (0.2-2 Hz) (LFE); (ii) high-frequency (60 Hz – 3 kHz) (HFE); and (iii) wide-band (WBE) equivalents. It summarises the purpose and application of each category of DME. The particular emphasis of the authors is on DMEs for systems or sub-systems having a significant penetration of power-electronic equipment, i.e. asynchronously connected sources. The paper summarises methods employed to develop DMEs in each category as well as a number of technical difficulties and challenges to be overcome. It is noted that existing LFE techniques are not well equipped to represent the ranges of control systems that can have a significant impact on dynamic performance and that existing HFE techniques have not been widely applied in practice. Development of WBEs remains to a significant extent, in a research phase. The authors state that future research and development work is needed to develop more general approaches to the formulation of DMEs which address the challenges listed in the paper. The bibliography of the paper is extensive and very useful.

C4-313: Benchmarking standard power system test systems for real time simulation studies.

This paper describes the development of models for standard power systems, including the IEEE benchmark systems, for use in real time simulation studies. Comparisons of simulation results are made against corresponding transient stability models for a selection of benchmark systems and balanced disturbances. The main objective of the paper is to show that with the use of appropriate data and models, a close match between results coming from a real time simulator (RTS) and transient stability analysis (TSA) tool (such as PSS/E) can be achieved when the system under study does not contain high frequency switching devices such as HVDC or FACTS. The paper describes how the data conversion program in RTS was used to convert PSS/E files and create corresponding real time simulation models. A number of key recommendations are offered to help align data sets (and resulting simulations) when using this process. Due to the lack of reliable zero sequence data for the benchmark systems at this point in time, a comparison of unsymmetrical fault events is to be pursued in the future, along with the inclusion of renewable generation sources.

C4-314: System dynamic studies of power electronics devices with real time simulation – A TSO operational experience.

In 2011, RTE (TSO, France) established a real-time simulator (RTS) laboratory where physical replicas of control and protection equipment associated with power electronic devices such as HVDC converter stations and static var compensators (SVC) can be connected to RTDS and/or Hypersim real-time network simulators. The paper describes the use of this facility to investigate system events, to perform parametric studies to assist in optimum tuning of the control and protection systems in the field, to provide opportunities for operator training, as well as research and development. It is stated that off-line EMT studies are still essential for performing certain types of analysis, however RTS platforms using physical replicas of control and protection hardware provide additional features, accurate validation and a reliable tool for performing longer term studies.

Question 3.4:

While computing power continues to increase, becoming more affordable at the same time, the complexities associated with power system modelling are also increasing. A number of papers have discussed evolving simulation techniques which still ultimately result in the need for some trade-off between accuracy (needing to capture the phenomena of interest) and practicality (recognising that it is very difficult to include all characteristics of every piece of equipment, especially when dealing with large networks).

(a) Paper C4-307 mentions that frequency dependent network equivalents (being one high frequency equivalent (HFE) model type) can be derived from measured or calculated frequency responses. Are there any practical examples from industry where HFE models of this type have been developed using the measurement approach and what measurement facilities have been employed to record the necessary signals?

(b) Paper C4-312 (below) discusses a method for optimal placement of PMU's to identify electromechanical modes, while Paper C4-307 states that measurement methods to develop low frequency equivalent models are still relatively new in literature, with more work required 'on real systems'. What are the most recent experiences with the use of PMU's for developing or verifying power system dynamic models, including determining dynamic model equivalents? How common is the deployment of PMU units specifically for model development / validation purposes or is this generally a bi-product of needing to increase 'situational awareness' as discussed in Paper C4-305?

(c) Where multiple groupings of PE interfaced equipment is connected in reasonably close electrical proximity, there may be a requirement for a multi-port dynamic network equivalent. What are the recent practical experiences with the use of multi-port dynamic network equivalents?

<u>Question 3.5:</u>

The use of real time simulators (RTS) for design and planning activities associated with HVDC and other power electronic based equipment is now relatively commonplace. The ability to integrate physical replicas into network simulations running in real time brings with it obvious advantages for control tuning and protection testing, as well as for validating the overall performance of equipment (and network) during commissioning. The ability to analyse subsequent network events and identify the origin of any unexpected issues has also been noted.

(a) Looking forward, what role might RTS platforms be able to fulfil in a control room environment to replace or complement existing Dynamic Stability Assessment (DSA) tools?

(b) How confident are we that existing DSA tools which typically focus on transient stability, voltage stability and oscillatory stability based on RMS (positive sequence) modelling, will continue to be adequate as power systems continue to evolve with ever higher penetrations of PE interfaced equipment?

<u>Question 3.6:</u>

It is reported in C4-314 that for each new HV power electronics project, RTE (the French Transmission System Operator) acquire and install hardware replicas of control and protection systems that are to be installed on site. It is not clear from the paper whether RTE also require this from large wind and solar farms as the real time laboratory is only reported to include replicas of HVDC and SVC installations at present.

(a) Is RTE's approach becoming more common around the world? What are the current experiences / expectations in other countries and are changes being considered (or are they imminent)?

(b) What has been asked of large scale wind and solar generators to date noting that hardware in the loop testing of type 4 wind turbine controls is described in Paper C4-303? What is the recent experience of manufacturers in terms of requests to provide physical replicas for system integration studies (in addition to RMS and EMT offline models)?

(c) What processes are equipment owners / manufacturers putting in place to ensure that firmware revisions as well as control and protection settings in physical replicas remain consistent with that installed on site?

<u>PS3: General</u>

Computational advances in tools, models, methodology and analysis of power system technical performance related issues.

C4-302: Full-frequency dependant models for variable time-step simulations.

The authors have described a novel numerical method whereby the time-step of an electromagnetic transient (EMT) simulation can be altered part way through without introducing inaccuracies or discontinuities at the time step transition. The advantage of such an approach is that simulation time steps can be reduced when high frequency transients are present, as may occur at and/or immediately following switching or fault events, but can then be extended as low frequency phenomena begin to dominate the network response. Validation of the methodology has been demonstrated using an academic RLC network, a 24 kV rural distribution network represented as a frequency dependent network equivalent (FDNE), and a 132 kV overhead transmission line. The variable time step approach reduced the overall simulation times by approximately 50% for test case one and approximately 35% for test cases two and three when compared to a fixed time step model implemented in a commercially available EMT program. The authors believe that the methodology could be incorporated into existing EMT software packages to improve simulation efficiencies.

C4-308: Utilising EMT for benchmarking and assessing short circuit calculation methods.

This paper describes some of the assumptions used for various power system short circuit calculation methods including IEC 60909, IEEE C37.010 and Engineering Recommendation G74. It identifies that commonly, the X/R ratio used is calculated at the point of fault inception, however in reality this ratio varies as the reactance of generators increase during the time frame of a network fault (sub-transient to transient period). The authors use EMT software to model this variation during a fault and show that when the X/R ratio is calculated at the time of fault breaking, the DC component can be higher than if the X/R ratio was not re-calculated. The EMT model is benchmarked against an actual fault recording (of a 110 kV busbar fault) with quite good agreement. A sensitivity analysis is included on the input parameters of the EMT model and indicates that credible variations do not greatly impact the final results. The authors demonstrate that faults located close to large synchronous generators can have a notably higher DC component at the time of breaker opening if the X/R ratio is recalculated whereas remote fault locations are less affected because of the dominating impedance of the network.

C4-312: PMU placement in a 110-330 kV AC network for identification of the mathematical model of the Kalingrad Region power system mode.

The authors observe that with the advent of Phasor Measurement Units (PMUs), accurate time-synchronised wide-area measurements of power system electrical quantities (node voltages and device current flows) are now feasible. It is noted that with such wide-area measurement-systems (WAMS), the problem of identifying power system dynamic models (for various purposes) has also become one of research and development into appropriate signal processing techniques, mathematical algorithms and efficient computational methods. The particular problem considered in the paper is the optimal placement of PMUs within the modestly sized Kaliningrad power system. The PMU placement algorithm is based on a linearized three-phase model of the power system which is implemented in Matlab. A genetic algorithm that aims to minimise the number of PMUs required to achieve complete observability is proposed. The paper presents the results of the PMU placement algorithm when applied to the Kaliningrad power system and shows that for the identification of the electromechanical modes, at least three PMUs are required (for what is a 12^{th} order system).

Question 3.7:

Paper C4-308 has discussed fault current calculations from the perspective of a classical synchronous machine based power system.

With the increasing penetration of PE connected generating systems:

(a) Is there a perceived need to rely more heavily on EMT simulations to perform accurate fault current calculations (especially for protection studies)? What opinions exist on this, especially for networks experiencing high non-synchronous penetration levels?

(b) What assumptions are being applied to represent transmission connected wind and solar farms in load flow based short circuit studies (noting the proposed assumptions documented in CIGRE Technical Brochure 671 – '*Connection of Wind Farms to Weak AC Networks*')? Are comparisons from RTS / EMT simulations and load flow based calculations available for discussion?

(c) What approaches have been adopted for calculating short circuit ratio (SCR) at the terminals of HVDC converter stations or the connection points of wind and solar farms? Should the calculated fault level be comprised only of synchronous machine contributions in this scenario using sub-transient (Xd'') or transient (Xd') reactance? What is common practice in your network?

(d) When calculating the 'available' fault level at a connection point in a network that is shared by multiple PE interfaced devices (HVDC converter stations, wind farms, solar farms etc), the approach is generally to multiply the SCR required by each device (that ensures stable operation when not being influenced by other PE equipment) by the MW rating and then sum the individual requirements existing at that network location. This summated figure is then compared with the actual three phase fault level (in MVA) to assess what remains 'available'. A negative result infers insufficient system strength to support all of the PE connections at that point in the network.

Noting that diversity is taken into account in various other types of analysis including harmonic assessments, is there merit in refining this methodology to include 'diversity factors'? Is it too conservative to assume that all PE devices 'consume (require)' the available system strength at exactly the same point in time? What opinions exist on this concept? Can the basic methodology be refined any further allowing for better estimates of network capability before having to resort to detailed offline EMT analysis?