Study Committee C4

SPECIAL REPORT FOR SC 4
(System Technical Performance)

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General Introduction:

CIGRE Study Committee C4 is responsible for methods and tools for analysis related to power systems, with particular reference to dynamic and transient conditions and to the interaction between the power system and its apparatus/sub-systems, between the power system and external causes of stress and between the power system and other installations. Specific issues related to the design and manufacturing of components and apparatus are not in the scopes of SC C4, as well as those specifically related to planning, operation and control, apart from those cases in which a component, apparatus, or subsystem behaviour depends on, or significantly interacts with, the performance of the nearby power system.

Study Committee C4 has selected three Preferential Subjects for the CIGRE Session 2014 in Paris, which represents the wide scope of the group and take into account the technical progress in different fields such as power quality, electromagnetic compatibility and interference, insulation coordination, lightning and power system performance models and numerical methods.

- **Preferential Subject 1 –** Power system technical performance in the advent of large deployment of power converter connected generation technologies
- **Preferential Subject 2** – Methods and techniques for the evaluation of lightning performance and insulation coordination
- **Preferential Subject 3** – Advanced methods, models and tools for the analysis of power system technical performance

Preferential Subject (PS) 1 has attracted 15 papers, PS2 has attracted 7 papers and PS3 has attracted 10 papers, for a total of 32 papers. The following pages each PS is dealt with separately in detail.

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1.0 Preferential Subject 1

The theme for Preferential Subject 1 is "Power System Technical Performance in the Advent of Large Deployment of Power Converter Connected Generation Technologies", including:

- Impact on stability and reliability of the power system due to large amounts of inverter based wind and photovoltaic (PV) generation, and large amounts of HVDC (wind plants and interconnectors);
- Impact of wind, PV and tidal generation on power quality;
- EMC and power quality impact of large scale voltage source converter (VSC) based technology.

<u>Papers for PS1</u>

Fifteen papers were accepted in response to this preferential subject. The papers originated from 12 countries reflecting a wide and international interest in this topic. The papers present concepts and results that may be categorized into 3 subgroups:

- Impact of renewable energy sources (wind and PV generation) integration on power quality – Papers 101, 102, 103, 109, 113, 114 and 115
- Impact on power system stability and reliability due to the connection of large amounts of inverter based wind and PV generation – Papers 104, 107, 108, 110 and 111
- Impact of HVDC links and grids on system performance and EMC – Papers 105, 106 and 112

Subgroup 1 - Impact of renewable energy source (wind and solar-PV generation) integration on power quality

C4-101: Flicker Assessment and Mitigation in Wind Farms Connected to Distribution Grids
This paper addresses the mitigation of flicker produced by wind farms connected to distribution feeders, particularly if embedded in long and weak feeders. It demonstrates that fast response supplementary controllers can be implemented either at the Point of Common Coupling (PCC) or at individuals wind generators. The proposed solution will perform the required functions if the converter power ratings are sufficient. The supplementary control loops discussed in this paper are designed to mitigate voltage flicker and operate only in the flicker frequency range. They include reactive and active power controllers.

C4-102: Impact of large wind farms on Power Quality. First experiences gained in the Argentinian Power System
This paper deals with the Argentinian experience regarding field measurements of flicker and harmonics in two sites where wind power plants were deployed, using EFS/MFS – based measurement method. The current regulatory Argentinian framework, in terms of Power Quality aspects is also addressed. The reported results showed that the recorded values were lower than the established limits. This naturally means either that during the measuring periods the harmonic emissions were not significant or that the main grid is powerful enough to absorb such harmonic emissions.

C4-103: Considerations on power quality requirements for integration of renewable sources (photovoltaic and wind power) into the transmission grid
The paper analyses several grid codes and suggests different requirements that may be adopted by the transmission system regarding the connection of large wind power and PV power plants to medium and high voltage grids. The main idea is to harmonize the requirements for renewable energy sources with an electronic interface and also take into consideration the characteristics of each single point of connection, based on the stiffness and other relevant issues such as background distortion and hosting capacity.

C4-109: Short-Term Fluctuations of PV Output in Japan - Evaluation Method of Fluctuations in Case of Large-Scale Integration

This paper presents a proposed method of estimating the short-term fluctuations of PVs in a control area in Japan. The short-term fluctuation characteristics were examined for kW-scale PVs distributed over a control area. Through the analysis of short-term fluctuations of solar irradiance, it was found that smoothing effects for solar irradiances are observed in the kilometre scale. Then, it is proposed an estimation method for short-term fluctuations of PVs in a control area. The results of sample studies showed that fluctuations of aggregated PV output are 1 to 2 % for the minimum demand capacity on weekdays in a control area.

C4-113: The Impact of Wind and Solar Power Generation on Romanian Power Quality
This paper addresses the Romanian experience on establishing regulation and monitoring system regarding power quality management in the transmission and distribution systems, taking into account the increase of wind and photovoltaic power plants connection into its national system. The focus in 2013 was flicker and it is foreseen to deal with harmonics in 2014. Several challenges are reported considering the deployment of PQMS (Power Quality Measurement System), mainly focusing on power quality management aspects.

C4-114: Impact of first wind farm in the Kingdom of Thailand on power quality and mitigation solution.
This paper presents the impact of the first utility scale wind farms and the largest in South East Asia on power quality (PQ) and a mitigation solution in the Kingdom of Thailand. The monitoring results show that the voltage fluctuation is not an issue for wind turbine generators decoupled by a fully rated converter. The wind turbine generators can maintain the voltage, power factor, frequency, voltage fluctuation, and DC current within acceptable levels. However, harmonic current emissions and harmonic voltage distortion sometimes do not comply with the limits in the regulations. A harmonic filter design study has been presented, and the installation of the filters to mitigate the harmonics is expected to be completed by April 2014.

C4-115: Guidelines for monitoring power quality in contemporary and future power networks – results from CIGRE/CIRED JWG C4.112
This paper summarizes major results of the JWG C4.112 “Guidelines for Power quality monitoring – measurement locations, processing and presentation of data” achieved from February 2011 to December 2013. This JWG was created aiming at addressing the application aspects of power-quality monitoring, in particular regarding what to measure, how to measure and how to handle recorded data. It provides guidelines for power quality monitoring depending on the monitoring objectives and identifies the areas requiring further development and research in order to address comprehensively the issue of power quality monitoring in contemporary and future power networks.

Question 1.1: Paper C4-113 presented in figure 2 a correlation between power delivered by photovoltaic power plant installation and flicker measured by PQ meter. This figure shows high levels of long term voltage fluctuation Plt following changes in power production. Paper C4-114 presents measurement results for Pst indicator showing values around 5 p.u. on a 115 kV system. As discussed in the paper, these values are associated with the operation of an asynchronous generator connected to the grid via a fully rated frequency converter. Such values seem too high. Are there other measurement results indicating high levels of Pst or Plt in the context of wind or PV power plants? Do other utilities have similar experience?

Question 1.2: Papers C4-101, C4-102 and C4-114 deal with the need for flicker mitigation. Was this need simply based on compliance of established limits? Were there any real customer complaints or electrical problems related to this subject? In recent years, many countries established a policy to gradually substitute incandescent lamps by other types of technology mainly light emitting diode (LED) and compact fluorescent (CFL) lamps. Considering this new scenario is voltage fluctuations associated with flicker effects still a concern? Can wind and PV plant integration affect substantially the flicker level in the transmission and distribution systems? What types of wind power plants can have greater impact on flicker levels?

Question 1.3: Paper C4-101 refers to several mitigation techniques to reduce flicker, such as feeder upgrade, relocation of the point of connection to the main grid, active or reactive power modulation at the wind plant converters. Are there many wind parks connected to distribution grids with similar characteristics? Is there any practical experience comprising the application of similar measures? Considering the active or reactive power modulation either at the wind plant converters or at the wind generator converters, is the speed of response adequate for all the flicker frequencies from 0.05 Hz to 45 Hz? Could some interaction occur between the flicker control and other functions within the wind generation controllers or other active devices on the transmission/distribution system?

Question 1.4: Paper C4-103 considers that the short-circuit ratio defined as the ratio between the grid's short-circuit power and the rated power of the renewable energy source at the PCC, is a useful tool to estimate the grid stiffness. However, this parameter does not take into account the profile of system harmonic impedance seen from the point of common coupling, which could be an important feature for harmonic distortion analysis. Is it possible to identify practical guidelines resulting from this or similar concept and how could it be adapted to verify the PQ compliments? Are there other approaches that can be reported on this aspect?

Question 1.5: Figure 1 of Paper C4-103 shows a proposed flowchart for investigation and corrections of problems related to harmonics. Is there any experience with the application of such a procedure? With such a procedure, how can the harmonic content be evaluated for the generated current and how can one be assured that this content is really only from the current injected by the disturbing installation?

Question 1.6: Paper C4-114 reports harmonic distortion above the acceptable limits in the Kingdom of Thailand, due to the connection of wind farm plants in the transmission system. The evaluation of harmonics distortion levels was done through measurements while the harmonic filter design through simulations. The simulation has indicated the existence of a parallel resonance condition near the fifth harmonic order. How were background harmonics considered in these simulations? How was the harmonic impedance of the system beyond the PCC assessed, calculated and represented in the simulations? Is there any similar experience in other countries regarding this problem? What actions are usually taken during the feasibility studies of wind farms regarding power quality aspects? Are previous simulation studies and / or measurements usually carried out in order to assess the level of disturbances? In the case of measurements, are they performed before and after the wind farm connection?

Question 1.7: Paper C4-102 reports harmonic distortion and flicker measurements undertaken in two wind power plant sites in Argentina, using EFS/MFS– based measurement method. These sensors receive a signal from the wind park AC line wires similar to a ground mode component of the wire voltages or currents. Was some method implemented to get the sequence components of the three phases from simultaneous measurements in different transversal positions? Would these types of measurements represent a global trend? What is the level of uncertainty of these measurements compared to standard techniques based on direct current and voltage transducers? As can be verified from Figures 5 and 7, the 5th harmonics profile shows a trend for increasing while the active power decreases. Has the same trend been observed in other measurements? What are the possible causes for this trend?

Question 1.8: Paper C4-115 deals with the monitoring of power quality. This is a very important discussion on what voltage should be considered in these measurements: phase-to-neutral or phase-to-phase voltages. Existing standards and recommendations around the world consider limits for the various phenomena associated with power quality regardless of whether the considered voltage is phase-to-phase or phase-to-neutral. However, the PQ indices related to zero sequence components of voltage (such as third harmonic) will be attenuated when considering phase-to-phase voltages. Thus, should this aspect be considered in the measurement guidelines?

Question 1.9: Papers C4-103, C4-113 and C4-115 deal with PQ monitoring in existing and in future electric systems characterized by higher penetration of renewables sources, energy storage devices, Advanced Metering Infrastructure (AMI) and many forms of new devices and controllers. Paper C4-113 points out that the Romanian TSO has developed a methodology for monitoring the PQ at TSO/DSO or TSO/significant users interface using PQ monitors certified according to IEC-61000-4-30 class A. Paper C4-115 also comments that the actual trend is to deploy hundreds of thousands of these meters worldwide. Is there any analysis about the trade-off between accuracy gain vs cost of class A PQ analyzers that can be reported? Paper C4-115 points out that presently PQ monitoring embedded in AMI data are able to detect a limited set of voltage disturbances. Are there reports on the usage of AMI data for PQ purposes? What could be done as a future step in this area?

Question 1.10: Is there any similar experience in other systems with high penetration of PV (Germany, USA and Italy, for example) on statistical analysis of short-term fluctuations of PV in a control area, as that presented in paper C4-109? The depicted results in Japan showed that short-term fluctuations of aggregated PV output are 1 to 2 % for the minimum demand capacity on weekdays in a control area. Are these results compatible with experience in other countries?

Subgroup 2 - Impact on power system stability and reliability due to the connection of large amounts of inverter based wind and PV generation

C4-104: New challenges caused by the new energy sources in the Brazilian power system
The paper presents several actions, which have been developed by the Brazilian Operator in order to assure power system security and performance due to the integration of large-scale wind power plants into the Brazilian system. Aspects related to dynamic and voltage stability and control, electromagnetic transient studies and improvements in the technical requirements for connections of these types of power plants are dealt.

C4-107: Methods for Risk Assessment of SSCI Stability Issues between Renewable Generation and Series Compensated Transmission
This paper provides an overview on some basic methods of assessing the risks of subsynchronous control interactions (SSCI) between the series capacitors in high-voltage transmission lines and renewable energy sources such as wind or solar generation and an evaluation of various SSCI mitigation strategies. It shows how some techniques were used to assess and mitigate the risk of SSCI stability issues identified in an actual series compensated transmission system project in Texas, where seven different transmission systems owners (TSO) constructed 345 kV transmission systems with 18 series capacitor banks to integrate up to 18,456 MW of wind power.

C4-108: Frequency Response of the US Eastern Interconnection under Conditions of High Wind Generation
This paper reports the results of a study that was specifically designed to investigate the frequency response of the USA Eastern Interconnection due to large loss-of-generation events, under possible future system conditions with high levels of wind generation. These investigations show that frequency sensitive controls in wind plants can have a substantial beneficial impact on system performance. Inertial controls from wind generation provide fast transient support, via controlled inertial response from wind turbines, which can significantly improve the system frequency nadir. Participation of wind plants in providing primary frequency response, i.e., plants with governor-like controls will have significant beneficial impact on frequency profile.

C4-110: Reliability Assessment of Power Generation Systems with Interconnections of Isolated Islands Incorporating Large Wind Parks and Photovoltaic Plants
This paper describes a computational probabilistic methodology that has been developed for assessing the operational performance of power generation systems with increased penetration levels of RES generation and interconnections with neighbouring smaller scale isolated power systems. The developed methodology is based on the Monte Carlo sequential simulation approach and simulates realistically the most important features of the involved systems. It is used for assessing the

operational performance of a typical power system incorporating interconnections with various power systems located on neighbouring isolated islands by using the HVDC VSC technology. Several PVs and wind plants are taken into consideration by including all the relative equipment while soiling and overcasting features of the PV parks are also considered. Alternative operational scenarios are examined and the obtained results are presented.

C4-111: Medium-term dynamic studies for a large island power system with high levels of wind
The paper presents the methodology and results of the main dynamic studies that were conducted in the Irish power system considering the high degree of wind power penetration (scenario with SNSP up to 79%) in its system. These studies considered a 5 year horizon (2018), having as main objective evaluating the boundary conditions of dynamic stability in the occurrence of three-phase faults, by means of determining the critical clearance time. The work also aimed at investigating the influence of the connection of wind sources connected to the distribution system through circuits with high resistance.

Question 1.11: What is the typical scope of the studies related to voltage and transient stability, power system frequency control and electromagnetic transient that are conducted by TSOs for wind power plant integration? In these studies, how are wind power plants represented? Are they represented by means of generic wind turbine generators models? Have the manufacturers somehow provided dedicated models? Or are they based on the experience of planners and operators? Which simulation tools are commonly used? In what kind of study is it mandatory that a detailed model (electromagnetic software type) of the wind power plant (generators, controls, connection grid etc.) be used?

Question 1.12: Paper C4-104 mentions the necessity to perform electromagnetic transient studies (EMT) with detailed models to analyze the performance of transmission line and transformer circuit breakers with the presence of wind generation. Is there any other experience to be reported on this subject? In this case, what were the problems experienced and solutions that have been applied?

Question 1.13: Paper C4-111 defines the SNSP factor – System Non-Synchronous Penetration (Wind + HVDC imports / system load + exports) to represent the degree of inclusion of non-synchronous sources on system performance and states that it is possible to obtain secure grid operation with SNSP up to 50%. For values up to 75%, the operation can be assured by adopting some special measures. How is the penetration degree of non-synchronous sources considered in other countries? Could we say that these maximum levels are a common point of view? What are the procedures usually adopted in countries with a high penetration of renewables to ensure an adequate system dynamic performance? What other experience may be reported?

Question 1.14: In paper C4-111, it is reported that doubly-fed asynchronous generator wind plants trip in 40 ms if voltage surpasses 1.135 p.u. Paper C4- 104 reports that in Brazil a high voltage ride through capability requirement was established so that wind plants should remain in operation for at least 2.5 s for voltage levels from 1.10 to 1.20 p.u. What is the experience of other TSOs related to this point? How can the establishment of high voltage ride through capability requirement minimize wind power plant interruptions in case of overvoltage? It is also reported on paper C4-111 that some wind power plants seem to have difficulties in riding through voltage dips unless they go into zero power mode. Could wind turbine manufacturers or other systems operators comment on this subject?

Question 1.15: What are the SCR values in the Irish system with SNSP above 50%? Have any wind power plants or HVDC control stability problems been observed under these circumstances? In the simulations mentioned on paper C4-111, how did the HVDC system recover after the elimination of the three-phase faults? Is there any experience to be reported regarding problems of wind power plants stability control in places with low SCR? What is the SCR range at the PCC that ensures proper performance of wind plants controls?

Question 1.16: Paper C4-111 mentions the lack of convergence in studies of wind generation connected to distribution networks. Could this fact indicate the proximity of voltage instability, mainly in degraded conditions, with low SCR? What is the minimum SCR accepted for radial feeders without backup interconnection? What is the minimum SCR accepted for meshed networks under n-1 conditions? In case of wind plants connected in several points along a radial feeder, how is the SCR concept applied, considering that the SCR is different at each point? Is it possible to use an equivalent SCR for several wind generators along a radial feeder, considering the different individual SCRs and positions? Could the voltage control mode at the PCC indicated in paper C4-114 (figure 6) improve the overall system performance regardless if the wind parks are connected in transmission or distribution networks?

Question 1.17: Paper C4-110 makes considerations on the allocation of system spinning reserve capacity considering the integration of wind and solar power plants. Taking into account that there are several countries with a high level of intermittent power sources penetration into the system and the importance of the spinning reserve for the system security, could TSOs comment on their experiences in dealing with this issue?

Question 1.18: Paper C4-108 mentions that it is possible to program the wind plant controls to provide emulated inertial response so that for large underfrequency events, the inertial control temporarily increases the power output of the wind turbine. The paper also comments governor-like-controls mentioning that they respond to significant deviations in grid frequency by increasing or decreasing power output in response to low or high frequency events, respectively. Both effects can have a potential benefit on the system frequency performance during generation or large load loss disturbances. A case is studied where the wind generation is curtailed by 5% of the available wind power, and the governor-like-controls were enabled. What tool was used in order to perform the simulations and how were these controls modelled? As this procedure can have commercial impacts on wind generation, is there any practical experience where this feature has been adopted? How have the commercial arrangements been settled in those cases?

Question 1.19: Paper C4-110 presents the results of a reliability computational methodology to simulate the operational performance of electric power systems with renewable generation using Monte Carlo techniques. Was the reliability of the primary energy sources (wind and solar radiation) simulated in the models? Or did the reliability models compute only the electric components of generators, transmission system and PV blocks? Figure 7 of paper C4-110 presents an average increase of 14.4 % in renewable generation when the interconnection links with the three isolated power systems are considered. Could authors comment if any cost vs benefit analysis was carried out in order to justify the economic feasibility of the respective investments? The annual availability levels of HVDC VSC interconnection links shown in table 3 of Paper C4-110 seem to be low. Could authors and experts comment on this aspect?

Question 1.20: Paper C4-107 shows an experience in Texas on the treatment of sub-synchronous control interaction (SSCI) between the series capacitors in high-voltage transmission lines and renewable energy sources. Is there any other experience to be reported on this problem? Is it a good choice to solve SSCI problem by means of wind power plants controls, even considering that such approach could limit the choice of wind generation technology to a particular type, instead of others? Would it not be preferable to adopt a more robust solution (for example, the addition of passive damping filters in the capacitor banks, or thyristor controlled series compensation, etc.) in order to mitigate the SSCI problems? What are the thoughts and experience of experts in Texas and other regions/countries on this issue?

Subgroup 3 - Impact of HVDC links and grids on system performance and EMC

C4-105: Aspects to arranging the test conditions under challenging electricity market situation and the AC-DC system performance during the site acceptance tests of Fenno-Skan 1 upgrade and Fenno-Skan bipole controls

The paper presents the arrangements of the tests of higher level controls performed when commissioning the HVDC Fenno-Skan 2 system along with the upgrade of the Fenno-Skan 1 system control, enabling to carry out tests of the bipolar operation of two systems operating jointly. It is reported the measures to manage the challenge presented by the prevailing electricity Market conditions for the operational planning, that had the task to facilitate the system operations to ensure feasible DC transmission schedules for the commissioning tests.

C4-106: Impact of multi-terminal HVDC grids on AC system stability and operation
Paper C4-106 presents the gains obtained by integrating an inland AC grid to an offshore DC grid with renewable generation. The aspects examined were: ancillary services (fault through capability and system frequency control); operation and security of an AC system (helped by DC grid); and use of offshore wind farms for system restoration under major contingency. Alternative configurations for DC grid performance (H frame, three leg backbone and meshed) were investigated in a DC grid (2 or 3 terminals) connected to an AC system (with 39 busses). The DC grid control capability showed very useful in the operation of the combined system.

C4-112: EMC Considerations and Planning for an Offshore HVDC
The paper describes the EMC considerations and planning for the High Voltage Direct Current (HVDC) platform DolWin β, where a complete voltage source converter station is installed. The Dolwin β platform is located outside the 12 mile zone and the current EMC-directive is formally not applicable to platform equipment and installations. The authors of this paper recommend that the current applicable DNV and IEC standards should be modified and/or extended with this new offshore application.

Question 1.21: To reduce possible problems to the AC network during bipole tests, would it be possible to perform some tests with maximum DC power going through one pole and returning through the other? In general, what are the facilities provided by HVDC systems to perform commissioning tests under power system constraints?

Question 1.22: There is a wealth of literature related to observed inter-area oscillations (rotor modes of electromechanical oscillation) with frequencies close to 0.3 Hz, similar to that shown in paper C4-105. Can others share their experience on utilizing power oscillation damping controls on FACTS and HVDC systems for enhancing the damping of inter-area modes?

Question 1.23: Considering the new system conception involving DC Grids, what are the methods, tools and models mostly recommended for the study of these systems? Is there any advantage in using RTS simulators (Real Time Simulator) compared to traditional software? Is there any experience regarding the validation of simulation results through field tests? Is there any integrated AC/DC system in operation or under design/planning? What can be expected concerning the application of meshed DC grids in connection to renewable generation and other installations?

Question 1.24: Is there any other experience concerning offshore platforms project regarding EMC aspects, particularly with the installation of voltage source converters, besides that reported in paper C4-112? Has there ever been any EMC problems involving offshore platforms? What is the opinion of EMC experts regarding the standards application in zones 1-5 proposed in paper C4-112? For this kind of application, could ANSI also be used, besides IEC? What are the major concerns when onshore standards are applied to offshore plants?

2.0 Preferential Subject 2

The theme for Preferential Subject 2 is "Methods and Techniques for the Evaluation of Lightning Performance and Insulation Coordination", including

- Evaluation of lightning performance and models (e.g. leader-progression versus EGM) for EHV and UHV AC and DC lines; ·
- Protection of other exposed structures such as wind turbines.

- Insulation coordination for EHV and UHV AC systems including adequate modelling of apparatus.

Papers for PS2

Seven papers were accepted in response to this preferential subject, which can be assigned to the following subgroups:

- Evaluation of lightning performance and models (e.g. leader-progression versus EGM) for EHV and UHV AC and DC lines (papers 201, 204, 207)
- Protection of other exposed structures such as wind turbines
- Insulation coordination for EHV and UHV AC systems including adequate modelling of apparatus (papers 202, 203, 205, 206)

Paper C4-201 "Evaluation of leader progression model and EGM for analysing lightning performance of transmission line" studies the suitability of leader progression models for the shielding failure analysis of EHV/UHV transmission lines as an alternative to the Electro Geometric Model (EGM). The existing methods for shielding failure analysis from the literature were critically assessed and experiments at an UHV test field were carried out additionally. Operation data of actual AC transmission lines were collected and compared with results of analytical models. The authors found that the operation voltage above a given limit (e.g. 500kV) plays a major role on the suitability of the applied model and promote further actions in the standardisation that will provide suitable procedures for shielding failure analysis dependent on the operational voltage level.

Question 2.1a: Considering the importance of the shielding failure analysis of EHV/UHV transmission lines as mentioned in paper C4-201, which further activities should be taken into account to develop improved standards that will provide suitable procedures for shielding failure analysis of both standard-height and UHV/EHV transmission lines? What kind of specific leader models will be required to improve the shielding failure analysis?

Question 2.1b: The authors of paper C4-201 have carried out shielding failure experiments in an UHV test field by using an impulse voltage 200/2000µs to evaluate the application ranges of EGM and leader progression model. The lightning withstand tests are related to the wave shape 1.2/50µs. Which influence on the experimental results can be estimated when using much longer impulse shapes, especially for of EHV/UHV distances?

Paper C4-202 "VFTO simulation and testing for 500kV and 800kV GIS disconnectors" analysis the generation of Very Fast Transient Overvoltages (VFTO) caused by disconnector operations in a Gas Insulated Switchgear (GIS) considering the trapped charge at the busbar. VFTO are high frequency transients with very short and steep wave fronts and become the focus of attention in GIS at a voltage level of 800kV and above. Their impact at these levels may over-stress the insulation of the GIS and the connected equipment. In the paper the authors present electromagnetic transient simulations for bus-charging current switching test and compare them with measurements at a 550kV gas-insulated disconnector operation. Based on these results a compact 765kV GIS layout was numerically evaluated to compare the conservative maximal trapped charge with a more realistic prospective trapped charge. This is of major interest for the insulation coordination entering the UHV levels.

Question 2.2a: Considering the trapped charge on the busbar of a Gas Insulated Switchgear (GIS) during disconnector operation the authors of paper C4-202 suggest that the commonly used value for the trapped charge leads to an overestimation of the magnitudes of the Very Fast Transient Overvoltages (VFTO). Is there any other experience available in the UHV level related to the magnitude of VFTO depending on the trapped charge on the busbar? Which effects can be expected from reducing the trapped charge values and furthermore which advantages, disadvantages, benefits or risks imply such a reduction?

Question 2.2b: As it is mentioned in paper C4-202, the trapped charge can be an important aspect in GIS in the UHV levels during bus-charging current switching tests. Which activities have to be carried out to in the future to make progress in the field of insulation coordination for UHV levels and to avoid an overdesign in general?

Paper C4-203 “High energy line surge arresters to improve reliability and protection against switching surges on a 500 kV transmission line” raises the issue of the application of special designed transmission line arresters (TLA) for switching duty. For this purpose the switching surge factors and the transmission line energization overvoltages were evaluated. In cooperation with a utility a 500kV transmission line was analysed and equipped with special designed line arresters (e.g. switching surge energy test). The paper describes the mechanical and electrical design and setup of the arresters and gives some information about an arrester condition monitoring device. The project is guided by transient computer simulations to evaluate the appropriate number and location for the TLAs.

Question 2.3: The authors of paper C4-203 show, that modern TLAs can reduce effectively switching surge overvoltages on a 500kV transmission line system. The application was prepared by using an electromagnetic computer program and guided by a monitoring device to record the switching transients. Is there any other practical experience available for the application of line arresters to limit the transient stress caused by switching? Are these protection technologies applicable on high voltage systems with levels over 500kV (UHV)?

Paper C4-204 “New technologies of lightning currents registration with high resolution” describes a pilot operation of a new lightning current recorder (LCR) to measure the transient current distribution on a 220kV transmission line system directly, placed on transmission line towers or on ground wires. This former developed LCR is not presented in detail in this paper, the paper presents the application and first measurement results for a period of more than one year. The system is called up by the lightning radiation of the upcoming storm due to optimized power consumption. Three measurement results were shown in the paper consisting of the first and the subsequent component of the lightning current in the tower shaft. The author’s point out, that the LCR allows the collection of statistical data of lightning currents affecting OHL.

Question 2.4: To evaluate the transient current caused by lightning in transmission systems, a number of measurement systems are in use. Paper C4-204 deals with a lightning current measurement system at power transmission lines and describes the application of a so called “Next-generation lightning current recorder”. Are there any waveforms of other measurement systems collected in transmission lines available and how do these results correspond?

Paper C4-205 “Protection of power transformers connected to GIS against lightning overvoltages” examines the modelling to be used to simulate the electromagnetic transients due to lightning occurring in 132kV and 220kV substations. A typical GIS (double busbar) with two transmission line bays, two transformer bays and one coupling bay was analysed by varying the connection to the transformer (using GIL or cable) and the connection to the overhead line (using GIL or cable). Surge arresters were set at the overhead line connection points only. The paper concludes that additional surge arresters are needed in the substation, if the GIS are connected to the overhead line with GIL or cable. No additional protection is needed, if both, transformer and overhead line are connected via insulated high voltage cables.

Question 2.5a: Paper C4-205 compares three different configurations of connections between GIS and transformers and overhead lines. Beside the modelling of the investigated substation it is well known, that the length of the cable or the GIL, the rise time of the lightning source and the peak value have a significant influence on the transient stress and on the number of the needed arresters. Is there any other experience available including a wider parameter variation to apply an appropriate number of surge arresters in substations?

Question 2.5b: Numerical investigations like in paper C4-205 are mainly based on the effort in modelling the transformers, the GIS and the surge arresters. Additionally the time step and the details of the model have an influence. Would it be possible to define a more general numerical model of substations for the calculation of the arrester application in such an often used configuration?

Paper C4-206 "Principles of insulation coordination and recent activity on reduction of insulation level in Japan" looks at the latest situation of the insulation coordination in Japan, describes its principles and recent activities of insulation rationalizations. The test voltages were reduced in a coordinated manner to a rational insulation level for engineering, economy and operation, and were standardized for systems in the range of 66/77kV up to Ultra High Voltage Systems (UHV) of 1100kV. For the range of 66/77kV to 550kV reduced test voltages for lightning impulse withstand voltage tests have been standardized and a high-performance metal oxide arrester was applied. For the UHV level new techniques for surge suppression during switching were applied and high-performance metal oxide arresters were used, based on the latest knowledge such as lightning conditions for lightning overvoltage analysis. A guide giving a technical explanation of these Japanese activities toward insulation coordination has been published.

Question 2.6a: In paper C4-206 the authors present the recent activity in Japan on reduction of the insulation level of standard high voltage systems and ultra-high voltage systems. The discussion of insulation rationalization is a well-known one since many years and has been stimulated again based on UHV systems. Can other delegates share their experience in the field of reduced test voltages (e.g. system performance data), in general and in the field of UHV systems? Furthermore, which benefits and which risks are expected based on the reduction of the test voltages with special regard to the system reliability?

Question 2.6b: The authors of paper C4-206 expect, that these practice in Japan will contribute to the activities of CIGRE and IEC in future. Which implications can be expected for the international standardisation?

Paper C4-207 "Effectiveness of line surge arrester application on the 132 kV Kuala Krai - Gua Musang Line" deals with the situation and application of Transmission Line Arresters on a particular power transmission line under lightning stress. Malaysia is well known as one of the highest Ground Flash Density (GFD) areas in the world. At this particular 113km long line an unacceptable number of 55 tripping events (including 11 single circuit tripping and 22 double circuit tripping) were registered in 12 years. Since 2007 the line was equipped with 120 units of Transmission Line Arresters (TLA) without any significant effectiveness of this measure. From the results of the experience presented some conclusions were made regarding the application of TLA. The paper shows that insulation coordination strategies have to be made on actual line data with approved numerical parameters to find the needed number and efficient position for the installation of TLA. Beside the work a high GFD value influence the line performance significantly and the lightning peak current affects the type of failure.

Question 2.7: As it is pointed out in paper C4-207, the strategy for the application of transmission line arresters is always based on actual line data like geometrical data, footing resistance, insulator and arrester types, and on sophisticated numerical tools. What is the state-of-the-art in the development of line arrester application strategies with respect to maximizing effectiveness and efficiency?

3.0 Preferential Subject 3

The theme for Preferential Subject 2 is "Advanced Methods, Models and Tools for the Analysis of Power System Technical Performance", including

- Application of hybrid tools for 3-phase and positive sequence modelling of power systems, and hybrid EMT and finite-difference time-domain analysis;
- Characterization and modelling of geomagnetically induced currents;
- Analysis of system performance with a large number of long AC cables, such as the potential for harmonic resonance.

Papers for PS3

Ten papers were accepted in response to this preferential subject. These are discussed below, together with the proposed special report questions, within the three subcategories.

PS 3.1 - Application of hybrid tools for 3-phase and positive sequence modelling of power systems, and hybrid EMT and finite-difference time-domain analysis.

Only one paper was submitted that potentially falls into this subtopic namely "Involvement of electric utilities in the development of EMT simulation tools" [C4-304] however a number of papers in PS3.3 deal with the use of various EMT type tools.

Paper C4-304 deals with practice and experience at CRIEPI, EDF, Hydro-Quebec and RTE on the simulation of electromagnetic transients (EMT's) in power systems.

Firstly, it looks at the offline simulation tool EMTP-RV and its usage by the aforementioned utilities in addressing the strategic issues of studying very large networks with complex components such as Modular Multilevel Convertors for HVDC transmission and power production sources. These utilities are actively involved in the development of EMPT-RV.

Secondly, it looks at the aforementioned utilities involvement in real time simulation of EMT's with the Hypersim simulator to test protection relays and HVDC/FACTS control systems. The Hypersim software is a real time loop simulation platform originally developed by Hydro-Quebec for the simulation and testing of control systems.

The paper also presents research activities related to the field of EMT simulation in general. These include Cable modelling, High frequency transformer modelling, Stochastic simulations with EMTP-RV, Sparse matrices solver and parallelization and Co-simulation.

EMT tools are very complex in nature, but are increasing needed by modern utilities. These tools need to be developed and maintained to keep up with the ever changing type's power system equipment being developed and used. This requires high levels of technical collaboration and commitment between both the utilities and the developers. The utility commitment is essential to ensuring that they have the appropriate skills and required system model and tools to manage the complex networks we are already seeing.

Question 3.1.1: Some utilities have shown active commitment and involvement in the development of power system EMT type tools. How committed/involved or otherwise are the utilities in your country and what benefits or pitfalls have you seen from this involvement or lack thereof?

PS 3.2 - Characterization and modelling of geomagnetically induced currents.

Geomagnetic Storms and their associated induced geomagnetic current have been identified as potential threat to electrical networks, especially those with significant long lines located at higher latitudes. These very low frequency Geomagnetic Disturbances (GMD) have been known to cause damage on the electrical power system and hence have been identified as a potential risk that needs to be modelled and understood. The induced low frequency "quasi DC" currents may result in damage to the network installed equipment (particularly transformers/reactors) or incorrect tripping of other equipment (particularly SVC or Capacitor Banks) but more significantly could cause voltage collapse and thus result in a significant network blackout.

Four papers were submitted that related to this topic namely, "Simulation of Voltage Collapse by GMDs – Problems and Solution" [C4-301], "Development of advanced GIC analysis tools for Manitoba Power Grid" [C4-302], "Modelling and Evaluation of Geomagnetic Storms in the Electric Power System" [C4-306] and "Application of Geomagnetic Disturbance Vulnerability Assessments using Eskom Main Transmission System Model" [C4-307].

All four papers focused on the potential reactive power losses due to transformer saturation, the consequential possible voltage collapse and the impact on network stability rather than on damage caused to the equipment itself.

The first paper "Simulation of Voltage Collapse by GMDs – Problems and Solution" [C4-301] looks at providing a benchmark for simulating the effect of Geomagnetic Disturbances (GMD's) on voltage regulation in the power system.

It uses a modified version of the IEEE39-Bus as its base and EMPT-RV as the simulation tool. It further looks at the effectiveness of using line series capacitors in avoiding voltage collapse. The constant parameter line model (CP-Line) is used with the zero sequence resistance being equal to the positive sequence resistance, the lines are transposed and the line orientations are arbitrarily set. The transformer magnetising curves are obtained and calibrated with field test measurements and the various single and three models are used. All transformers are grounded using 0.2 Ohm resistance and include tap changer functionality. Synchronous machines are modelled with corresponding d and q-axis impedances and time constants, to accurately represent their transient performance.

Geomagnetic Electric Field (GEF) data was obtained for both Northward and Eastward electric fields and the GEF as a function of time were then based on a look up table. DC sources are modelled based on the GEF data and injected at 34 line locations in the model.
Time domain simulations are used to determine the relationship between the DC currents (caused by the GEF) flowing in the transformer neutrals and the resultant reactive current (generated by the saturation) flowing into the system. Voltage collapse was then simulated, however, noting that in any given system this depends on many factors such as initial operating point, tap-changer ability, loss of var control devices (e.g. SVC, Capacitor banks, etc.) and operator actions in addition to the "var consumption" as a result of the GEF.
Using this benchmark model, it is possible to study the contribution made by DC blocking devices (such as series compensation) at various locations. A number of varied solution cases are shown in the paper for different GEF strengths. The paper concluded that the ratio of "incremental reactive current" to "dc current in the transformer neutral" stayed at about 0.47 and in most cases was in the range of 0.2 to 0.64 except for three legged core transformers where it became zero. It also concluded that GEF angle and magnitude have equivalent impacts and that automatic insertion of shunt capacitors help to avoid collapse was more effective than series compensating the transmission lines.

The second paper "Development of advanced GIC analysis tools for Manitoba Power Grid" [C4-302] rather than using a theoretical network model used the real Manitoba Power Grid. It too looked at voltage collapse as the most likely impact of a GMD. This paper focuses on the development of a

Geomagnetic Induced Current (GIC) analysis tool consisting of two parts, a GIC simulator and a voltage collapse calculator.

A dc resistance's model, an Earth conductivity model and the magnetometer data were used to calculate the GIC at each substation in the network. Alternatively a uniform GEF could be chosen for the model. These GIC's were converted to an equivalent shunt inductor at each substation using a simple single phase transformer model.

A conventional power flow program (PSSE) was then used to determine the risk of voltage collapse. The results of this tool were benchmarked against real world data with reasonable accuracy. It was further used to identify the impacts on the GIC's of adding series capacitors or neutral blocking devices.

The paper also talks about the categorisation of GMD's using a NERC contingency event model based on the size of the GEF and their impact on the power system.

The third paper "Modelling and Evaluation of Geomagnetic Storms in the Electric Power System" [C4-306] describes theoretical modelling methodologies that can be used for studying the effects of GIC's on the power network for various planning studies such as power flow, contingency and voltage stability analysis. It provides practical advice on how to reduce the power system to a dc resistive model for calculating GIC's using some assumptions for the various types of equipment (e.g. Lines, Single phase transformer or Auto transformer etc.). The paper also presents on how to model the additional reactive power losses due to the GIC's. A simple scaling model is proposed where the scaling is either based on the generic transformer type or calculated for the specific transformer. Like the previous approach the additional transformer reactive power losses are added to the base case power flow as constant reactive currents.
A uniform GEF of 1V/km is applied but it is rotated from 0 to 300 degrees to determine the maximum reactive power loss. With the GEF angle set at maximum impact the strength of the GEF is now varied to study the impact on the network voltages. Further network contingencies can be modelled to assess their impacts on the voltages on the network. Essentially by finding the GEF direction that results in the maximum reactive power loss and by ascertain the maximum GEF before voltage collapse the GMD limits for any network can be determined.

The final paper in this topic "Application of Geomagnetic Disturbance Vulnerability Assessments using Eskom Main Transmission System Model" [C4-307] once again discusses the development of a model, using simulation tools and component models, to evaluate the impact of GMD on the Eskom main transmission system. It describes a methodology or series of steps needed to perform the assessment to identify the system vulnerabilities. It notes that the unexpected loss of reactive power sources such as capacitor banks or SVC's (as a result of the transformer saturation and associated high harmonic levels) during any GMD will exacerbate the impact of the GMD on system stability. As GIC's are typically in the 0.0001 to 1 Hz they can be considered quasi DC currents and hence a dc model of the system is needed. As with the previous paper some guidance is described in determining this model. The substation grounding resistance was varied to assess their sensitivity on the results. Reactive power loss vs GIC's models of each transformer type were determined using assumptions however further research is proposed in improving these models. With the additional reactive power losses superimposed onto the base case power flow model, steady state analysis techniques can be used to analyse network voltages. As part of the vulnerability assessment, credible contingencies and potential mitigation actions should also be included for analysis. Some important issues noted during this assessment were that the introduction of series capacitors to reduce GICs associated with those lines can shift the GIC flow to other parts of the network with unintentional consequences and that intentional removal of lines seen as high GIC sources had a larger effect on reactive power margins than the GICs themselves. From the above papers it is fairly clear that although the timing, magnitude and orientation of GMD are unpredictable, the methods, tools and techniques used to model how they interact with the electrical systems, although complex, are available. It is clear that the biggest perceived risk of GMD is the possibility of voltage collapse or system instability as a result of the increased reactive power losses and not the risk of damage to the equipment itself. The chance of system voltage collapse is further compounded by possible incorrect protection/operating of plant especially var supporting equipment like SVC's, Capacitor Banks etc.

Question 3.2.1: Although incorrect operation of var supporting equipment can be simulated during a GMD vulnerability assessment has anyone done any work or analysis on the probability of a GMD causing this equipment to mal-function?

Question 3.2.2: All papers submitted used similar approaches for establishing the possible impact on system voltages and hence risk of system collapse. What in your view would be the best approach to use and why would you say this?

Question 3.2.3: Paper C4.302 talks about the categorisation of GMD's impact on the power system using a NERC contingency event model. Is anyone working on any other techniques or tools for the characterization or categorisation of the impact of GMD on the power system?

PS 3.3 - Analysis of system performance with a large number of long AC cables, such as the potential for harmonic resonance.

Traditional EHV or HV power networks consisted of generators (mainly synchronous machines), transformers, overhead lines and loads (induction machines and resistive loads) which after many decades of research have well established models that are well understood. However electricity networks have become much more complex with the introduction of more non-linear loads (e.g. variable speed drives), variable power sources that utilize complex power electronic interfaces (e.g. wind and PV generation), integrated HVDC and an ever increasing need to use AC cables to connect these new sources or load to the system.

The introduction of the increasing number of long AC cables into our complex, but mainly inductive networks, create additional opportunities for phenomena such as LC resonance to occur on the network. This is exacerbated by the increased number of non-linear loads/sources and by the steeper switching transients produced by modern equipment (e.g. vacuum breakers). As stated, modern power systems are becoming increasingly complex and hence modelling them or analysing them correctly is very challenging. Papers in this subtopic deal with some of the complexity of introducing long AC cables into the network.

Five papers were submitted that related to this topic namely, "RTE experiences with the insertion of long EHVAC insulated cables" [C4-303], "Frequency domain studies for Malta-Sicily interconnector" [C4-305], "Harmonic Analysis of Wind Farm Clusters using HVAC Underground Cables in the Irish Transmission Network" [C4-308], "Frequency Domain Analysis of the influence of Compensating Wires and Earth Resistances in Mixed Overhead / Underground HV Transmission Lines" [C4-309] and "Influence of offshore wind farms layout on electrical resonances" [C4-310].

The first paper "RTE experiences with the insertion of long EHVAC insulated cables" [C4-303] focuses on the various phenomena that RTE have experienced with the introduction of EHVAC cables into their network. The paper deals with both the phenomena and the way in which RTE is dealing with them.
The phenomena include:

- Overvoltages during cable energization and De-energization with specific focus on re-energizing charged cables.
- Transient Recovery Voltages (TRV) on Circuit Breakers.
- Zero Miss Effect of Switching Currents.
- Background Harmonics.
- Transformer Energization, including Network Modelling, Network topologies to be studied and Frequency dependant network equivalent (FDNE).

RTE conclude that there is generally no need to conduct specific studies for slow fronted transient, such as cable energization or TRV's during a fault close to a cable, provided that there is no association of equipment like an insulated cable with a series reactor. They do believe that specific studies for each project need to be conducted for harmonic temporary overvoltages during transformer energization and for background harmonic amplification. It was also noted that the zero miss effect is a concern but does not require complex studies.

The second paper "Frequency domain studies for Malta-Sicily interconnector" [C4-305] deal with detailed frequency studies for the 118km long 245kV Malta-Sicily line being constructed. This line is actually a cable made up of underground cables and a submarine cable connecting the Maltese and Sicilian systems. This paper outlines the results of the frequency scan studies were conducted on an ATP-EMTP model.

The third paper "Harmonic Analysis of Wind Farm Clusters using HVAC Underground Cables in the Irish Transmission Network" [C4-308] looks at the effects of the proliferation of renewable generation sources and the associated AC cables on the harmonic levels in the Irish network. These harmonic distortions can exceed planning levels and have undesirable consequences if not managed. Hence there is a need to augment the traditional range of studies with an assessment of compliance against power quality technical requirements. This paper presents the methodology adopted by EirGrid to assess the impact of harmonics at transmission levels driven by the installation of HV/EHV cables associated with "clusters" of Wind Farm connections. This area based approach based approach helps EirGrid expedite the allocation of Harmonic Voltage Distortion limits to all wind farms in the cluster. It furthermore allows for single Transmission solutions to be assessed, as they may be more cost effective than individual wind farm filtering solutions. The methodology consists of two steps. One, assessment of the Transmission Infrastructure which included measuring background level, reproducing these in study models, running harmonic scans and harmonic load flows before and after new customer and equipment are added and identifying mitigation. And two, Allocation of Distortion Limits to Wind Farms which includes determining background distortion at PoC, calculating the available harmonic capacity (headroom), calculating the Influence Coefficients and Reduction Factors, apportioning the available harmonics using IEC methodology and calculating harmonic impedance loci.

The fourth paper "Frequency Domain Analysis of the influence of Compensating Wires and Earth Resistances in Mixed Overhead / Underground HV Transmission Lines" [C4-309] looks at the electromagnetic transient behaviour in an extension to the Dutch 380kV network, a complex network comprising of multiple mixed overhead and cable segments with compensating wires. It uses a frequency domain approach tailored to analyses the influence of the compensating wire as well as the effects of earthing resistance on both the overhead and cable segments. This paper makes some conclusions on both influences of the compensating wire and the earthing resistance on the network transient response.

The last paper in this sub-topic "Influence of offshore wind farms layout on electrical resonances" [C4-310] looks at how the topology of the collection grid of offshore wind farms influences the occurrence of electrical resonance within the wind farm in the medium to high frequency region.
It uses broad band models for the main components. Travelling wave type models are used for the cables taking into account the frequency dependency of all cable parameters. Transformers are modelled using a lumped representation including leakage inductance, winding resistance and winding capacitance. Breakers and Capacitors are modelled as ideal components. The wind farm layout, or model, chosen included both simple radials and branched structures. The analysis included admittance frequency sweeps and time domain simulations. Considerable overvoltages were shown to occur in certain frequency ranges. The analysis also showed that cable lengths and transformer characteristics had a significant impact on the results. It notes that during the design stage of the offshore wind farm a method of systematic parametric variation can be used for detailed sensitivity studies to assess if resonance dependant on certain parameters (e.g. cable length) could result in severe consequences.

From the above papers it is fairly clear that there are many potential problems and complex phenomena resulting from the uses of a large number of AC cables in any given high voltage network and that developing methodologies and models for these networks and phenomena is not an easy task.

Question 3.3.1: There are many phenomena described in the papers above, as well as methods to model/analyse these phenomena and their impact. What phenomena have you encountered with the introduction of long AC cables into your networks, how have you approached modelling/analysing them and how have you mitigated the problems?

Question 3.3.2: One of the papers [C4-308] used an approach of analysing the impact of a "cluster of wind farms" as a more efficient/optimal approach than dealing with them individually? Is anyone else using a similar or different grouping approach in dealing with the integration of multiple variable sources of generation?

Question 3.3.3: The use of compensating wires to ensure step and touch potential along any given line or cable changes the frequency dependant behaviour of these elements? Is anyone else doing work or analysis on how these compensating wires affect the frequency/transient behaviour of networks?

Question 3.3.4: The number of and the size of wind farms is continuously growing. The layout or topology of these wind farms is often dependant on the "geography" of where they are situated and the components used, hence each layout will vary. Is anyone developing tools/techniques to optimize these layouts for both the steady state and resonant/transient behaviour?