C4 - 00

SPECIAL REPORT FOR SC C4

David JACOBSON (Canada)
Special Reporter PS1 & PS2

F. Faria da SILVA (Denmark)
Special Reporter PS3

The Special Report, prepared by Study Committee C4, has been updated with the new requirements for the CIGRE 2021 Virtual Centennial Session.
Revised parts are indicated in red and crossed through to easily identify the changes.

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 61 papers aligning with the three Preferential Subjects (PS) for the 2021 CIGRE Session. In addition to the papers selected, SC C4 invited five presentations from internationally acknowledged researchers to provide talks that align with the preferential subjects.

- PS 1: Improving power system technical performance through the use of advanced methods, models and tools.
- PS 2: Modelling of the future grid based on lessons learned from system events.
- PS 3: Methods, models, and techniques for evaluating lightning, power quality, and insulation co-ordination to enhance the performance of the evolving grid.

In the following sections grouped by preferential subject and its subcategories, a summary of each subcategory is presented along with corresponding discussion questions that have been identified by each of the Special Reporters. Summary of each paper is provided at the end of the report for completeness. Responses to the questions offered throughout this Special Report are invited for presentation during the **SC C4 Group Discussion Meeting** which will occur on **Monday August 23rd** in the Bordeaux Lecture Theatre.

Intending contributors are encouraged to submit proposed presentation material to the Special Reporters by no later than Wednesday 4th August. Proposed contributions should be uploaded on

dajacobson@hydro.mb.ca & ffs@et.aau.dk

the *Registrations platform* – "Contributions to Group Discussion Meetings" section - using their existing account and own credentials. It is important to note that:

- *Access to contribution uploading is given only to duly registered delegates.*
- *As a consequence, registration to CIGRE Session should be finalized before uploading contribution(s) online.*
- *Contributions uploading are open ~~will be open at the beginning of May~~.*

A guide for contributors as well as templates and sample pages will be available on the CIGRE Centennial website - see Group Discussion Meetings in the top menu bar.

Special Reporters will review the prepared contributions (PowerPoint presentation and Word document written contribution) and will provide any recommendations or changes to the contributions directly on the Registration platform. Final decisions on acceptance will be made by **15th August 2021**. ~~Final acceptance of contributions will be made on **21st August 2021.**~~

No poster session will be scheduled at the Virtual Centennial Session.

~~Please note that accepted contributors will be required to attend a **pre-session meeting** with the Special Reporters, SC Chair and Secretary on **Sunday August 22nd morning** in the SC C4 Poster Session area (Halle Ternes) at the Palais des Congrès to finalise presentation arrangements~~

~~The authors of the SC C4 session papers are required to present their papers during the SC C4 Poster Session scheduled for Monday morning August 22nd 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 Emil Hillberg (emil.hillberg@ri.se) with a copy to the SC Chairman (zia.emin@cigre.org) and Secretary (g.lietz@ieee.org) by no later than **Wednesday 4th August.**~~

Preferential Subject 1

The theme for PS1 is "Improving Power System Technical Performance Through the Use of Advanced Methods, Models and Tools" which includes:

- The assessment of frequency stability, system strength, or power quality using Big Data analytics.
- The analysis of widespread dynamic security issues including [intentional] electromagnetic interference, weather, and geomagnetically induced currents.
- Development of emerging metrics and tools for quantifying power system reliability, resiliency, and flexibility.

Twenty-eight (28) papers from fifteen countries were accepted plus two invited presentations. The papers present concepts and results that broadly align with the three subgroups defined by Study Committee C4 as follows:

1. Assessment of frequency stability, system strength using Big Data analytics.
    - Using Big Data to improve models – Papers 101, 102 and 103
    - Using Big Data for risk assessment – Paper 104
    - Using Big Data to assess frequency stability or system strength - Papers105, 106, 107, 108, 109, 110 and 111.

These papers examined some of the benefits gained by mining data from various sources (e.g. weather data, SCADA data, PMU data) to improve the modelling of losses, corona, fault current, loads and generators as well as some of the challenges.

Question 1: ***Are there any other examples of using Big Data analytics to improve power system technical performance?***

2. The analysis of widespread dynamic security issues including [intentional] electromagnetic interference, weather, and geomagnetically induced currents (GIC).
    - Improved electromagnetic performance through advanced methods -Paper 112
    - Widespread dynamic security – GIC - Papers 113, 114 and 115
    - Widespread dynamic security – weather - Papers 122 and 123.

Voltage stability assessments could benefit from more accurate transformer models. GMD assessments need accurate earth models. The NERC TPL-007 standard is being considered for use outside of North America. Transformer owners may wish to determine their own risk tolerance level for when to conduct thermal assessments.

Question 2: ***What are the biggest risks of Geomagnetic Disturbances?***

Question 3: ***Are there any other recent examples of widespread events causing dynamic security issues (eg. cold weather events, energy scarcity events)?***

3. Development of emerging metrics and tools for quantifying power system reliability, resiliency, and flexibility.
    - Emerging reliability metrics - Papers 116, 117, 118, 119 and 120
    - Emerging resiliency metrics - Paper 121
    - Emerging tools for quantifying reliability - Papers 124, 125, 127, 128 and 129

Systems with high penetration of IBR are starting to rely on monitoring of system inertia and Short Circuit Ratio to ensure reliability in real time operations. Redispatch of generation and synchronous condensers are used to ensure minimum levels of inertia are being maintained. Deployment of fast frequency response in IBR is also being used. Monitoring of inertia is more accurate than estimating inertia based on summing the MWs from each online generator as it could underestimate actual values if there are large amounts of embedded generation and motor load, for example.

Resilience is an emerging topic area needing clear metrics. The resilience of specific equipment (eg. IBR) and the power system are being examined. Weather is being monitored and forecast to help make the network more resilient to possible outages.

Hardware in the loop testing is one method being proposed to help validate models and hardware performance.

Synchronous condensers with or without flywheels as well as IBR with fast frequency response are options being used to mitigate concerns with lowering inertia levels. Flywheels can reasonably increase the inertia of a synchronous machine by 300% but could go to 400-500% with careful analysis of subsynchronous resonance.

Question 4: ***How are TSO's managing the short circuit level in weak systems?***

Question 5: ***What resilience is desired by TSO's and what can OEM's reasonably develop and deliver; what is the value of the added resilience?***

Question 6: ***Are there any other emerging metrics such as flexibility metrics?***

Preferential Subject 2

The theme for PS2 is "Modelling of the Future grid Based on Lessons Learned from System Events" which includes:

- Experience gained from Smart Grid projects;
- High penetration levels of inverter-based devices.
- Deployment of energy storage systems.

Nine (9) papers from six (6) countries were accepted along with one invited presentation. The papers present concepts and results that broadly align with the three subgroups defined by the SC as follows:

1. Modelling of the Future grid Based on Lessons Learned from System Events
    - Modelling subsynchronous resonance (SSR) - Papers 210 and 211

Lessons learned from experience with SSR between series capacitors and wind plants in China and between series capacitors and turbine generators in Chile were presented. The main conclusions from the papers:

- Interaction between series capacitors and wind plants are possible and require careful study.
- Models can be setup to predict SSR and Torsional Interactions. Generator dispatch can impact results and should be considered in assessment studies.

Question 7: *Any other lessons learned from system events?*

2. Experience gained from Smart Grid projects – No Papers

No papers were submitted. Smart grid typically refers to non-traditional distribution grids that have characteristics like:

- Increased use of digital information and control technology to improve reliability, security and efficiency;
- Deployment of and integration of distributed resources and generation, including renewables (potential for bi-directional flow);
- Development of demand response;
- Deployment of smart technologies for metering, status and automation (improved fault detection and self-healing);
- Integration of smart appliances and other consumer devices (potential for demand side management);
- Integration of storage technologies, including electric vehicles.

Study Committee C4 is interested in the effect of such technology and projects on the transmission grid. Air-conditioning load, for example, could be responsive to price signals. Dynamic load models should reflect the correct amount of air-conditioning motor load to correctly reflect the risk of fault-induced delayed voltage recovery, for example.

Question 8: *Any recent experience gained from Smart Grid projects (such as aggregate modelling of load and distributed generation)?*

3. High penetration levels of inverter-based devices – Papers 201, 202, 203, 206, 207, 208 and 209

Lessons learned from systems with high penetration levels of IBR were shared, including solar installations in US and Egypt and Australian experience with IBR. Momentary cessation has been seen in large inverter-based resources that cause reliability issues and needs to be clarified in grid codes. Rate

of change of frequency is being calculated by different sliding window sizes (50 ms to 500 ms). It's unclear whether there could be a reliability gap if generator ride through capability and utility ROCOF management use different assumptions. Loss of large-scale solar plants (eg. due to clouds, solar eclipse) can impact primary reserves and needs to be considered in both planning and operations. Grid forming controls can aid in improving IBR performance in weak systems. Grid codes need adjustment to permit this mode of operation.

There was a strong message delivered that accurate models are needed to address the challenge of high penetration levels of inverter-based resources. RMS models currently are not accurate enough to assess phase locked loop stability or control interaction between IBRs – especially in weak systems. At minimum, RMS models of IBR need to be benchmarked against EMT models and field tests. EMT models of IBR are needed during the interconnection process to ensure no adverse impacts. In some cases, EMT models are also needed and being used in operational studies.

Question 9: ***What are recent examples of grid code modification to prepare for the energy transition?***

4. Deployment of energy storage systems – Papers 110 and 203

Two examples are given above of battery energy systems providing synthetic inertia or fast frequency response. Energy Storage is being used to provide ancillary services like fast frequency response, but the ability is technology dependent. BESS, in some cases, has limited ability to effect rate of change of frequency (ROCOF). BESS has been used to inject power quickly to improve stability. Hybrid schemes (BESS plus ultracaps) are being considered to offer multiple ancillary services.

Question 10: ***Are there any other different application examples of battery storage systems (eg. respond to automatic generation control signal to reduce area control error)? What are the lessons learned?***

Preferential Subject 3

The theme for PS3 is "Methods, models, and techniques for evaluating lightning, power quality, and insulation co-ordination to enhance the performance of the evolving grid" which includes:

- UHV AC and/or DC systems
- Renewable generation, inverter-oriented power systems, and traction loads
- Harmful interactions between power system components.

Twenty-four (24) papers were accepted in response to PS3 and additionally two presentation were invited. The papers originated from fifteen (15) countries plus a Working Group, 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, but it should be noticed that overlaps between subcategories exists:

1. UHV AC and/or DC systems – Papers 309 and 321

The modelling of the armour of submarine cables is challenging and a source of inaccuracy. It is possible to adjust the simulation models to match the measurements with a higher accuracy, but this is a topic where more work is necessary, in order to have both better models and better guidelines.

Question 11: ***Are there examples of transient measurements and comparative simulations of submarine cables? What recommendations exist for estimating armour permeability for simulations and which phenomena are mostly impacted by a change in this parameter?***

2. Renewable generation, inverter-oriented power systems, and traction loads – Papers 301, 302, 303, 311, 312, 315, 319 and 322.

The increasing number of converters at generating units and other auxiliary devices has a key impact on the system performance, and good simulation models are required. Guidelines and proposals of converter models for different types of the studies are proposed, with the respective advantages, disadvantages and limitations. In general, the topic has many open questions and it is a work-in-progress, with future contributions from CIGRE WGs expected.

The increase in inverter-connected generation also increases the usage of EMT simulations, in order to account the behaviour of the converters. Highly accurate and detailed models are becoming significantly preponderant and even essential, for simulating very large-scale power grids with the increased integration of renewable energy sources

Mismatches between simulations and field measurement at large wind parks is becoming usual leading to the installation of unnecessary filtering equipment. The attribution of responsibility for harmonic emission among multiple sources can be done via PQ measurement at the PCC and frequency-dependent models of the connections.

It is proposed that the standard for the voltage withstand capability of PE devices should be evaluated, as the existing requirements might be unsuitable for PE devices and lead to higher costs.

Question 12: ***What criteria are used when choosing a simulation model and how are the different stakeholders managing model validation? What future needs can we foresee in terms of research and development (for example, is compatibility of the models over a large period of years and multiple software versions an issue or to be)?***

Question 13: ***What is the experience from operators/owners on discrepancies between expected and measured harmonic levels for large inverter-based generation parks? What strategies exists to minimise these differences and to avoid the installation of unnecessary mitigation measures?***

Question 14: ***What proposals exist or are being studied for the insulation coordination of power-electronic devices directly connected to the grid considering testing of insulation, waveforms being used, possible reactions during some overvoltages? How can we achieve a balance between cost and risk?***

3. Harmful interactions between power system components - Papers 305, 306, 307, 308, 310, 314, 317, 318, 320, 323, 324, 325, 326, and 327

Power Quality: Harmonic issues are being raised at several locations due to increasing system undergrounding and usage of radial connections for wind/PV generation, and current simulation models are often unable to provide an accurate estimation.

A 20-years long power quality survey in Australia shows a decreasing tendency for the emissions of different PQ disturbances.

It is clear that the major ongoing trends in production, in the grid and in consumption (generation, transmission and distribution) introduce both new challenges and new opportunities related to power quality.

Insulation Coordination: VFTO can lead to faster aging or destruction of transformers. Attenuation of the very high frequency components of the VFTO via devices using skin effect might help, but it still requires demonstration.

The standard simulation approach and the IEC recommended impulse tests might not be fully adequate for GIS-transformer interactions, as switching overvoltages from a GIS circuit breaker might be more

severe than overvoltages from standard lightning impulses. Proper simulation requires a detailed manufacturer model.

Several presentations on the impact of series reactors and capacitor banks on transient phenomena indicating study examples and solutions for different unwanted behaviours.

Lightning: Increasing computational power, more measurements and additional control options can proactively change the power flow from areas with lightning and thereby reducing interruption times.

A considerable amount of wind turbines have the down-conductors disconnected. Different approaches are able to detect the disconnected conductors.

The EGM continues to be a popular tool, but it is an empirical method and several new tower configurations are being built, which might affect its accuracy

Protection: Traditional protection settings will not operate as desired for overcompensated lines. TRVs and fault current also show noticeable increase for these lines.

Question 15: ***How is modelling uncertainty being accounted for in power quality studies as the trend seems to be a conservative one in dealing with emission limit setting whilst violation of limits does not lead to noticeable complaints? Should a revision of allowable limits be considered as a way forward?***

Question 16: ***Are there examples of insulation coordination studies where the existing waveshapes were unable to properly account the existing stresses including possible insulation failures due to limitations in the waveshapes? Do we need to rethink the waveshapes by creating new divisions or by having sub-cases?***

Question 17: ***With emphasis on new tower designs (e.g. with the goal of minimising visual impacts and/or rights-of-way) and increasing voltages, how acceptable is it to continue using the EGM for lightning studies? Are there examples of configurations leading to a larger estimation error for the EGM and requiring other methods?***

Question 18: ***What steps are being taken to improve the sensing and monitoring of lightning, and how can this extra data be used to improve both the system design and the development of preventive strategies? Can we apply a proactive approach in small grids or are these only useful in locations with multiple large load centres?***

PS1 Paper Summaries:

Paper 101: A method is proposed to improve modelling of losses on distribution feeder via analysing SCADA data. Embedded generation is shown to increase losses rather than reduce losses as wind typically blows when the loads are low. Radial and meshed networks in Wales and Scotland are analysed.

Paper 102: Actual fault current is being monitored in an 11 kV network and correlated across a radial network to correct fault models. Conservative methods are resulting in a high range between min and max short circuit levels, which may limit DG penetration. With a limited number of active fault level measurement devices installed at lower voltages and the data recorded with existing protection relays, it is possible to estimate the fault level throughout a full grid area.

Paper 103: Paper discusses 500 kV corona loss measurement and reduction. Both PMU data and weather data are signal processed to calculate corona losses in real time. Voltage levels in the grid are optimized and automatically adjusted to reduce corona losses. Total corona losses are shown to decrease from 15-40% using this method.

Paper 104: Weather data is used to predict the fault probability and take real-time actions. Limitations of big data analytics are discussed. Three parameters are used to predict line flashover.

Paper 105: This paper focuses on dynamic model validation of generators with an emphasis on primary frequency control. The paper proposes hardware in the loop simulator to test frequency control capability.

Paper 106: Inertia measurements are made by changing system load and measuring the resulting change in frequency.

Paper 107: Common mode frequency oscillations (0.03-0.08 Hz) are measured and correlated against the maximum system non-synchronous generation penetration level.

Paper 108: Australian studies are presented on how to determine short circuit dispatch decisions to maintain inertia requirements in high inverter penetration scenarios. In Australia, inverter-based resources are currently 150% of local demand.

Paper 109: The paper discusses a method to extract the load frequency static response slope based on PMU measurements of frequency and voltage as well as SCADA measurements of total load.

Paper 110: The Romanian power system is analysed based on phasor measurement unit (PMU) measurements. Frequency variations were examined. Simulation of a battery energy storage system (BESS) is included. BESS is providing synthetic inertia.

Paper 111: The Georgian power system is analysed. An automatic emergency response is modelled to help maintain frequency within limits following large disturbances. The real time inertia is monitored and underfrequency load shed (UFLS) programs are adjusted.

Paper 112: Electromagnetic compatibility (EMC) measurements and calculations made. Surge arresters are applied to mitigate overvoltage in switchgear drive cabinets. The authors want to ensure protection and control have enough EMC to withstand transients from lightning and switching.

Paper 113: A finite element method is used to assess the thermal impact of GIC on transformers. The paper provides a critical review of current assessment practices. The current practice of using 75 A as a threshold for triggering a detailed thermal assessment may be too high.

Paper 114: The paper describes GIC monitoring equipment applied in the Australian network. 3D earth models are noted as providing more accurate results.

Paper 115: A Korean GIC study is presented based on the approach in NERC TPL-007.

Paper 116: EMT modelling of inverter-based resources (IBR) are often needed for stability studies in weak systems but the simulation time is long. RMS models being used today can't predict IBR controller instability. Screening indices developed based on weighted SCR has been proposed but is not detailed enough to reflect controller tuning. A transient stability margin index is proposed based on critical

clearing time and loss of PLL synchronism. The gain of PLL and voltage regulator influences IBR stability.

Paper 117: Multi-infeed interaction between HVDC converters are calculated using frequency dependent network equivalents (FDNE) and detailed converter models. Modelling the network up to 25th harmonic doesn't seem to be enough. No clear guidance is given on how to ensure passivity in the model.

Paper 118: The impact of PV penetration levels on distribution systems are analysed. The authors propose a method to calculate feeder hosting capacity considering PV size and location, operating mode, protection coordination, voltage regulation, feeder configuration, equipment ratings. Simple limits result in 15-30% of peak load penetration levels. Penetration levels can increase to 50% and up to 200% with smart inverters.

Paper 119: The fault current injection requirements, as dictated by current grid codes, are carefully analysed for inverter-based generation. Australian rules require 4% capacitive current for each 1% drop in voltage (based on X' of synch generators). The IBR requirement is 2% capacitive current for each 1% drop in voltage. The Q/P ratio is roughly equal to the X/R ratio of network.

Paper 120: The Indian grid code is being changed as high levels of renewables are expected (40% by 2030). The new version adds a short circuit ratio (SCR) requirement (eg. SCR at PCC >5). A system inertia index of 128 GWs is specified.

Paper 121: The paper focuses on the resilience in existing and future inverter-based resource designs.

Paper 122: The impact of weather (fire, lightning, wind, ice) causing faults on China's UHVDC system and subsequent impacts on the China grid are analysed. If the risk is high, operating modes may change such as lowering of the dc voltage, lowering the loading on the line or increasing the amount of spinning reserves.

Paper 123: The risk of voltage collapse, as a result of lightning-induced outages, is determined.

Paper 124: The paper talks about a method to forecast loads and avoid masking by distributed generation, such as solar PV. ComEd plans for 90/10 load forecast with the largest generator offline.

Paper 127: The paper highlights performance issues between EMT and phasor-based simulations tools. It recommends guidelines and procedures for modelling and performance testing be developed to ensure the performance of IBR.

Paper 128: A generic VSC model is analysed in the IEEE second benchmark system. This could represent a Type-4 wind turbine connected radially through a series compensated line. Both small signal analysis and hardware-in-the-loop tests show the development of unstable subsynchronous oscillations. A virtual conductance algorithm is added to the control and is shown to improve damping.

Paper 129: Synchronous condensers are considered as a new tool to provide inertia, fast frequency response, primary frequency response and reactive power. The paper covers design aspects (A1) and applications aspects (C4).

<u>Invited Presentation – The biggest risks of Geomagnetic Disturbances by T. Gaunt</u>

The biggest risks posed by GMDs and GICs in power systems arise from differences between the physical performance of real systems and our coupled simulation models based on inconsistent assumptions. When our analytical methods, models and tools mislead us, there is a hidden risk of making wrong decisions about possible failure and mitigation.
Resilience and reliability are not assured by ticking a Regulator's procedures boxes but by understanding the systems and making informed decisions. Many researchers of GICs are contributing to our understanding of the physical and engineering sciences, and bringing new data, approaches and tools.
The "GIC system" can be conceived as three physical sub-systems, and four if we include the people. I will describe my view of some recent developments and their implications.

1) <u>The environment</u>. GICs are induced by space weather driven disturbances of the geomagnetic field and shaped by the frequency-weighted filters of ground resistivity and the power system.

The newest developments are in GMD forecasting, geomagnetic field measurement and a statistically based transform from B-field measurements to the GICs in transformers.
2) The transformers. Combining FEM analysis and physical measurements improves our understanding of transformer inductance, unbalance and harmonics generation, guiding transformer design and leading to more representative equivalent circuit models for power system simulation. In the meantime, existing transformers must be managed.
3) The system. Harmonics and unbalance increase line losses, reducing the efficiency of energy delivery and increasing the possibility of voltage instability. New tools for this analysis are promising and power electronics offers some interesting possibilities. Understanding the effects of harmonics and unbalance on system protection, which can also threaten stability, remains a challenge.
4) People and decision-making. Optimum combinations of hardware and operational mitigation depend on models of possible GMD severity and duration, the uncertainty of the power system response, and the costs incurred. Risk perception is incomplete. Decision support modelling is improving but do the underlying models represent reality? Although the sub-systems are mostly useful for managing complexity, the interconnected system is an active model that does not distinguish where one sub-system ends and another begins. The recent research suggests simplistic models, inappropriate thresholds of assessment parameters, and uncertainties in present mitigation responses all leave unknown gaps between representation and reality. A new solar cycle is starting. Even as we implement known approaches, we need to continue reducing the hidden risk.

Invited Presentation – Managing the short circuit level in weak systems by B. Badrzadeh

Many regions worldwide are experiencing rapid uptakes of inverter-based resources (IBR) concurrent with the retirement of conventional synchronous generation. Commonly new IBR, such as wind and solar farms, are in remote locations with limited network capacity. They are also often far from large synchronous generators, which have traditionally provided system strength support to these IBR. Even when there are large synchronous generators physically nearby, they tend to dispatch much less often due to higher marginal prices. The global power industry is continuously developing state-of-the-art assessment methods and solutions to address the complex and new power system challenges presented by this rapid transition. The term 'system strength' has emerged to encompass these trends and their implications on power system operability in terms of system stability, protection system operation and quality of power supply.
This presentation first provides an overview of the constituting components of system strength in terms of associated power system phenomena and key determining factors, allowing to establish an overarching definition of this concept.
Various tools and techniques for assessing and monitoring system strength are then discussed. These range from tools used by power system planners and study Engineers to those more suitable for integration into the control room environments or at least providing support to making judicious decisions for minutes-hours ahead. Relative advantages and disadvantages of each tool, and their complementary benefits are then discussed.
Tools with the potential to use as decision support tools for actual power system operation include direct measurements of power system quantities, and the use of simplified analytical methods. Methods based on measurements of power system quantities are, in turn, divided into two categories which are online measurements and the use of staged system testing. Practical examples of the use of each method is overviewed in this presentation. Lastly, examples of screening methods based on both the steady-state and dynamic calculations are then provided, and their relative merits and limitations are explored further.

PS2 Paper Summaries:
Paper 201: NERC summarizes the latest lessons learned from field cases. Momentary cessation, where the IBR controls the output current to zero for relatively small voltage drops (10%) is noted to cause significant reliability issues. EMT studies are recommended to be performed at time of interconnection studies along with benchmarking with RMS models.

Paper 202: A large solar park (1465 MW) in Egypt is analysed. Large events (eg. loss of plant due to cloud cover) are compared against model results.

Paper 203: Based on other systems experiences at high penetration levels, the European system was modelled and tested along with various potential solutions. The effect of synchronous condenser, BESS and SVCs are compared against VSC with improved grid forming controls is tested. BESS provides FFR.

Paper 206: The Australian experience is presented. EMT models are being used and have been developed for all five regions in Australia. Includes effect of BESS used as part of a SPS, injected power improves stability. The paper focuses on EMT model validation.

Paper 207: Simulation results related to 50% VRE in order to study frequency stability in Europe. The results indicate generator disconnection risk if ROCOF is in the range of 1-2 Hz/sec and blackout risk if the ROCOF is greater than 2-2.5 Hz/ sec. During an overfrequency event, 50% of generation has limited frequency sensitivity (only applies to new generators) and is activated at 50.2 Hz with 5% droop.

Paper 208: Discusses hardware in the loop testing of HVDC converters in RTDS. Real tests are compared against simulations. The benchmarked model is then tested. Changes to gamma control and point on wave switching is tested for converter transformer energization with and without remnant flux being considered.

Paper 209: Results from OSMOSE are presented building on earlier results from MIGRATE. Results are validated in a hardware in loop environment – to improve confidence in final results. A 1 MW grid forming demonstrator project (batteries and ultracaps) is described. Power injected does not rely on measured grid frequency.

Paper 210: Interesting paper that analyses SSR in wind plants in China due to series capacitor interaction with nearby wind plants. The model has been adjusted to verify field measurements.

Paper 211: Real wide-spread SSR measurements (11 generators) are made and compared against model results.

Invited Presentation – Harmonizing Canadian Provincial Grid Codes for the Energy Transition by J. MacDowell

This presentation will provide an overview of the work undertaken for the Wind Energy Institute of Canada and the NRCan Utility Forum to evaluate existing Canadian and International grid codes, standards and planning practices across Canada and around the world. This work includes a comprehensive analysis to propose a common set of integration and interconnection guidelines not only in terms of technical requirements but also market rules including ancillary service markets. Canadian grid codes are reviewed, identifying technical gaps, and making suggestions for what they could contain and what they must contain. It will also address specific interconnection requirements for newer technologies such as utility-scale solar, battery energy storage and hybrid systems. It also covers the analysis of transmission-level codes accounting for distribution-level aspects that affect the bulk power system. Examples include how distribution-connected generation can contribute to system reliability given the growth of DERs and the changes required to achieve this. Additionally, this work highlights best-practices and experiences from around the world, including bulk-system and DER technical integration requirements, market design and harmonizing these aspects in grid codes and energy trading mechanisms across provinces.

One particular aspect that the presentation will focus on is how the requirements need to evolve to make the most of new technology capabilities through updated modelling techniques and assessment practices for planning and operations. The critical need to focus on interoperability of controls and capabilities of all resources is another key element. New technologies like grid forming controls will play a key role and updated requirements to unlock the value of this technology are needed. Other aspects of equipment and systems that are addressed includes momentary cessation and current injection during faults, ride-through, control stability and interactions, frequency and voltage support as well as modelling and data requirements.

PS3 Paper Summaries:

Paper 301: The paper presents a harmonic model of a Type 3 wind turbine and benchmarks it against laboratory measurements. The model consists in a Norton equivalent with a frequency-dependent current source and frequency-dependent impedance derived from a model implemented in EMT software. The derivation of the two parameters of the Norton equivalent model is demonstrated. Sensitivity analyses for short-circuit ratio and voltage unbalance are then done using the proposed model and it is shown that the latter might have a large impact on the harmonic current injection.

Paper 302: The paper presents a tuneable converter (type 4 WT) harmonic impedance model that can be used for early-stage harmonic studies when parameter uncertainty exists. The details of model itself are presented in other publications. The windfarm impedance and the amplification factors are calculated via a sensitivity study of different parameters, an approach that can be replicated for other wind farm studies. The results show that the converter impedance has a significant impact in low order harmonics ($h \leq 10$).

Paper 303: The paper presents a method that can be used to attribute responsibility for harmonic distortions among different sources; wind farms are used as example in the paper. The method is simple to use and it requires only the installation of PQ meters at the PCC, besides the frequency-dependent impedance of the grid and of connections between the PCC and the individual harmonic sources, which can be provided using an impedance loci. Multiple calculation examples are provided for validation using measurement data.

Paper 305: A substantial background harmonic amplification was measured in the 400kV Danish grid, after the commissioning of an 8km 400kV cable. This amplification was mainly on the 11th order harmonic voltage, which increased above the planning level on two substations at 80km and 90km in opposite geographic directions from the commissioned cable. The harmonic distortion was approximately 50% of the planning level before the energisation of the 8km cable.

It was concluded that the harmonic source was a HVDC-LCC substation and that the AC filters no longer filtered enough of the 11th harmonic after the commissioning of the 8km cable. This paper is of special relevance as it shows that a minor change in the grid can have a large impact in the harmonic distortion.

Paper 306: The paper investigates the interaction of harmonics generated by a Power Conditioning System with resonances caused by capacitor banks from an Energy Storage System in a large power plant. For this case, large harmonic distortion was simulated when multiple Energy Storage Systems were operated in parallel.

Paper 307: Japanese utilities noticed abnormal power outages due to the operation of earth leakage breakers, as well as abnormal acoustic noises, which were associated to usage of imported household electric appliances. The root cause being an overvoltage originating from harmonics and a resonance between pole transformer, the LV line and the capacitance of the appliances. This seems unique to Japan, because the impedance of the Japanese LV system is more likely to cause parallel resonance at 2-9kHz. The paper shows measurements and simulations of the phenomenon. A new Japanese standard limiting emission in the 2-9kHz range had a positive impact and new industrial standards are being prepared.

Paper 308: The paper discussed how to model transmission grids with higher penetration of power electronic devices: modelling depth, modelling of devices and determination of the converter impedance. The process for obtaining the latter is explained and validated via EMT software. Furthermore, the paper presents sensitivity studies for the impact of the line model (frequency dependent or load flow models), modelling depth and amount of power electronic assets.

Paper 309: The paper presents impulse and wide-frequency impedance/admittance measurements on a 393km-500kV HVDC cable, as well as heir comparison with EMT simulations. These measurements are part of a campaign of measurements made by TERNA on high–voltage cables. Besides describing the measurement protocol and used equipment, so that others can perform similar measurements, the authors make the results available upon request. Impulse tests compare with EMT-type simulations using a Finite-Section model and a JMarti model. Both models match the measurements at high

frequencies with differences found at the magnitude of the resonance frequency. For the impulse test, the Finite-Section model exhibits oscillations and both models mismatch the propagation, while correctly representing the damping.

Paper 310: Australia has been doing power quality surveys of its distribution grids for 20 years. The paper summarises this data for steady-state voltage magnitude, voltage unbalance, harmonics, flicker and voltage sag. It concludes that there is a consistent report of overvoltages even prior to the introduction of rooftop PVs, but with a decrease tendency. Voltage unbalance is also over the limits, as well as flicker, but the latter shows large variations and the data is less reliable. Harmonics and voltage sags are beyond the limits. Additionally, the paper also discusses trends in immunity and compatibility for all parameters.

Paper 311: Measurements of voltage unbalance at different 400kV substations via PMUs and its relationship with PV generation are presented. The measurements show a relation between zero-sequence voltage unbalance and solar power generation, but the measured values were still much below the limit.

Paper 312: The paper shows measurements of harmonics, voltage unbalance and flicker in two traction substations, one having a Scott transformer and the other single-phase transformers. In both cases, the measured quantities were below the limits. A simulation model of the electrified railway was also developed and validated using the measurements.

Paper 314: Field measurements of a VFTO in a 525kV GIS are presented. The measurements show that the VFTO is a not a single overvoltage pulse, but train of pulses. As the attenuation in the GIS is very small, these pulses reach all connected transformers, even with circuit breakers open, due to the grading capacitors. This might accelerate insulation ageing, as the high frequency of the phenomenon means an overheating of the insulation around the first turns of the windings.

Additionally, the paper presents a device consisting of two hollow conductors that uses the Skin Effect principle to attenuate the components above 1MHz. By decreasing the heat in the insulation, the device might lead to a longer lifetime.

Paper 315: The paper discusses a shortcoming of the existing insulation coordination procedure when applied to power electronic apparatus. The authors propose that the capability of protection devices as surge arresters should be considered in the surge withstand capability of a power electronic device, because to design the devices to withstand the high voltages leads to prohibitive costs. A step-by-step procedure is proposed together with examples. In short, the paper proposes a new definition and a new test procedure for the BIL of power electronic devices, and it can be an important contribution for further advancements in this topic.

Paper 317: The paper proposes a simplified approach to estimate the extra shunt capacitance needed to avoid excessive TRV, due to the initial rate of rise of the recovery voltage from the interaction between a series reactor and an inherent small shunt capacitance. The method consists in defining the potential values of series reactors for the Dutch grid as well as grid conditions and then, to perform EMT simulations sweeping different values of extra shunt capacitances, with some assumptions. The proposed approach is conservative, but it allows a standardisation of the capacitance and an acceleration of the design in future projects.

Paper 318: The shielding performance of the new Wintrack lines (4x380kV) is estimate via three different methods: EGM, Angle Corrected EGM and lightning attachment model. The first two methods show a similar performance, but noticeable differences if the ground wires are moved closer to the centre of the tower. The lightning attachment model shows a better shielding performance with low SFR and SFFOR. This difference will be investigated further, and in the future, TenneT will use the EGM and the angle corrected EGM for internal studies.

Paper 319: The paper describes four technologies that can be used as lightning detection system in wind turbines and four methods to detect if down conductors are disconnected. The advantages, disadvantages and requirements of the former are explained. For the latter, the principles and example are provided. The paper allows a good overview of different options and it can help to take informed decisions.

Paper 320: The paper presents a real-time preventive approach against lightning outages that has been applied in Suzhou area (China). By tracking the lightning, the control centre adjusts the power flow, after a system stability calculation, to reduce the power flowing in the lightning areas. This is achieved via: regulation of the generating units, usage of Unified Power Flow Controllers (UPFC), reduce of power exchange with local grids that have enough distributed generation, and load shifting. The application of this solution lead to a reduction of the average system restoration time and of the average interruption time.

Paper 321: The paper considers a hybrid overhead line-cable 500kV LCC-HVDC link and simulations are performed for a lightning surge at 60m from the cable-overhead line junction. Different cable lengths are considered (10-40km), as well as the presence or not of a surge arrester at the cable-overhead line junction. Both shielding failure and back flashover are simulated. The simulations show that the voltage at the cable end closer to the lightning impulse does not depend on the cable length, but the voltage at the furthest end reduces steeply with the increase of the cable length.

Paper 322: The paper presents a detailed study estimating switching overvoltages, inrush currents and TRV for a wind power plant and its connection to the PCC. This specific wind power plant required capacitive reactive power compensation to fulfil the grid requirements, and thus, the evaluation of the mentioned phenomena. In this case, the used of controlled switching (opening and closing) and limiting reactors at the circuit breaker allowed to fulfil the requirements.

Paper 323: AltaLink transmission system (Canada) is observing an increase of the short-circuit level. The installation of line reactors in some locations was chosen as a cost-effective solution to reduce the fault levels. This solution raises concerns in regards to: Transient Recovery Voltage, Insulation Coordination and Harmonic Voltages. The paper investigates these issues via simulations and it presents the respective mitigation measures: the TRV via additional capacitance, the overvoltages via a new lightning mast in the substation and two surge arresters, the harmonic voltages at the 5th harmonic via filters.

Paper 324: The paper summarises the work from the JWG B5/C4.41 on the protection of series overcompensated lines, in regards to: Transient Recovery Voltages, Fault Current, and voltage/current inversion including the respective effects on protection schemes. The paper shows that the TRVs and fault currents increase substantially, which might pose a challenge to varistor and spark-gap design. Regarding voltage and current inversions, it is concluded that distance protection cannot be used in Zone 1 and that only differential protection can be used for primary protection. The use of distance protection as a backup protection is also affected by the overcompensation of the line. The paper presents multiple formulas and examples to support the definition of the protection settings for overcompensated lines.

Paper 325: A GSU transformer was damaged during a normal energisation. The observed damages were consistent with a transient overvoltage, but the simulations showed a peak voltage at the transformer terminals far below the BIL specification for 1.2x50 µs impulses. A white-box model of the transformer was provided by the manufacturer and the simulations redone. The new simulations show that the switching overvoltages from operating a GIS circuit breaker might be more severe than those from standard lightning impulses, at the first interturn of the transformer.

Multiple simulations are presented and it is seen that the overvoltage depends on the system-transformer interaction. The paper also suggests that the traditional IEC waveforms for impulse tests might be insufficient for transformer insulation in case of VFTO.

Paper 326: The paper presents the second part of a project with the goal of predicting the pollution levels of outdoor insulators when considering the Saharan dust and Mediterranean Sea salt aerosol. The first part presented in the 2018 session was dedicated to the Saharan dust deposit mapping, whereas this paper presents the results for the sea salt aerosol mapping. The develop maps were successfully validated against measurements at two locations: in Israel and in Italy. Besides showing the entire process behind the developments of the maps, the paper shows that the sea salt aerosols pose a marked contribution to the pollution level and should be considered when estimating the flashover rate.

Paper 327: A special setup was built for measuring the earth current of a three-core and a single-core cable, both of aluminium core for usage at 12/20kV. For this specific setup, the earth current magnitudes

were mostly function of the grounding resistors and such is concluded to be common for short cables. The comparison between the measurements and simulations did not give a good match, which will be investigated later.

Invited Presentation – The importance of Power Quality in the future grids by M. Bollen

The aim of the power grid is to transport, distribute and supply electricity of sufficient quality to customers and equipment connected to that grid. Through the years, big changes have occurred both in the quality of the electricity supply (power quality) and the way in which this quality is perceived by customers and equipment.
This presentation starts with an explanation of what power quality is, why it is so important and why it will remain important, as well as a brief overview of what has been on the agenda in the past and what is currently on the agenda concerning power quality.
Following the scene setting, the main part of the presentation will discuss the major ongoing trends in production, in the grid and in consumption (generation, transmission and distribution) , and how they are introducing both new challenges and new opportunities related to power quality. Some recommendations for research, development and standardization will be given, to be taken up within the next few years. A somewhat narrower definition of power quality is used, where voltage dips and harmonics are among the subjects to be taken up, but not just those.
The presentation concludes with a look further into the future, towards 2050, when the challenges introduced are expected (or rather hoped) to be addressed and largely resolved. Power quality will still be important, but the question is to which extent it will be visible in research, in development, in education and in the practical design and operation of the power grids

Invited Presentation – The future of electromagnetic transient simulations: needs, challenges and game changers for the future by J. Mahseredjian

This presentation is on future trends and applications related to the methodology used for the simulation of electromagnetic transients in power systems. Accurate simulation needs are growing faster with the advent of renewable energy sources and increased integration of power electronics-based components that justify migration towards EMT-type simulations, not only for smaller grids, but also for very large-scale systems traditionally simulated in phasor-domain. The EMT approach with its numerical kernel may soon become the only system transient performance simulation approach used by engineers.
The future trends in the EMT world are in fact aligned with those of power system performance simulation trends in general. The envisioned futures trends are: simulation of very large scale grids with all details reaching the level of grid electronic copy, advanced data management, data integration and unification, standardization, standardization of manufacturer model interfaces and contents, interoperability between applications and very fast computations. Other trends include high-level modelling techniques and languages that can be used by both software users and developers.
Network data, data standardization and compatibility are key ingredients for leaping the EMT simulation tools to higher levels and wider acceptance in the industry. Unified EMT computational kernel-based environments can accommodate a variety of studies comprising load-flow, short-circuit, protection, slow transients and fast transients. Reducing or eliminating approximations eliminates doubts and increases engineering productivity for designing robust power grids. Accuracy of models should become standardized. An accuracy navigator concept should be established that can automatically adjust itself to the frequency content of studied phenomenon. It means that the numerical methods with unified models should be able to benefit by accelerating for slow transients while remaining fast and accurate for faster transients.
Increased computational performance within powerful data management environments opens the door to the implementation of intelligent methods for analysing power systems and predicting abnormal modes or instabilities. It should become common practice to simulate huge numbers of scenarios that are automatically summarized with reports on potential problematic conditions. Significant research is required for developing intelligent numerical methods that minimize user-intervention while being capable of detecting problems and informing on system conditions and modes.