

**Study Committee C4
 Power System Technical Performance
 C4 - 00**

SPECIAL REPORT FOR SC C4

Special Reporters	Poster Session Conveners
PS1: T. LUND, A. HARJULA	PS1: P. DATTARAY
PS2: P. MUNHOZ-ROJAS, T. BROWNE	PS2 & PS3: M. MARTINEZ DURO
PS3: A. ROCHA, L. SCHWALT	

SC C4 Chair: M. VAL ESCUDERO; SC C4 Secretary: G. LIETZ

A few words about Session Papers...

Session papers are focussed on a number of subjects – referred to as ‘Preferential Subjects’ – selected in advance by CIGRE’s 16 Study Committees and published in the [Call for Papers](#).

Session papers are selected through a two-phase review process – abstracts and full papers.

It is recommended to have a look through the [Technical Programme](#) (specifically, the list of selected papers for the Session) to get an overview of subjects that will be discussed. This list is updated as the review of full papers proceeds.

...and specificity of CIGRE Sessions

At CIGRE Sessions, authors are given the opportunity to present their paper during half-day specific meetings – the Poster Sessions.

Four days are also dedicated to ‘Group Discussion Meetings’ organised by Study Committees. Four meetings run simultaneously each day from Tuesday to Friday, under the presidency of the Study Committee Chairs. The purpose of these meetings is the discussion of the Session papers on the basis of “Special Reports” which consolidate the themes covered by the Session papers and raise a number of questions for discussion.

The Special Reports are freely available to all from the end of May on the CIGRE website and the dedicated [Session website](#).

For fruitful discussions, delegates are strongly encouraged to read the papers before the Session.

The Session papers are made available for download to all duly registered delegates before the Session through their private account on the [registrations](#) portal. Papers will also be available on the Session smartphone app, for use on-site in Paris.

Follow our Session latest news and General Programme - by regularly visiting our [website](#)!

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CIGRE STUDY COMMITTEE C4 is responsible for advanced methods and tools for analysis related to end-to-end power systems, with particular reference to dynamic and transient conditions and to the interaction between the power system and its apparatus/sub-systems (including external causes of stress, other installations and non-standardised waveforms). The scope of SC C4 covers power system technical performance phenomena that range from nanoseconds to many hours. Areas of attention include:

- Power System Dynamics.
- Power Quality.
- Electromagnetic Compatibility and Interference (EMC/EMI).
- Lightning.
- Insulation Co-ordination.

Inherent in all activities of SC C4 is the investigation and development of new tools, models, methods and techniques for the assessment and analysis of relevant issues. Of special interest is the identification of power system needs, scarcities, technical envelope and design requirements, and new power system phenomena caused or accelerated by the energy transition.

SC C4 has selected **83 papers** aligning with the three Preferential Subjects (PS) for the 2024 CIGRE Session:

- **PS1:** Power system dynamic analysis in the energy transition: challenges, opportunities and advances.
- **PS2:** Power quality (PQ) and electromagnetic compatibility (EMC) analysis in the energy transition: challenges, opportunities and advances.
- **PS3:** Insulation co-ordination and lightning interference analysis: challenges, opportunities and advances.

Two out of the 83 selected papers were submitted as part of Next Generation Network (NGN) Young Member showcase competition.

Important information about the Session

1. Group Discussion Meeting

You are invited to participate in discussing this Special Report at the Study Committee C4 Group Discussion Meeting (GDM) on **Friday 30th August, 2024, in the Bordeaux Lecture Theatre** at the Palais de Congress de Paris.

In the following sections, a summary of each PS is presented along with corresponding discussion questions that have been prepared by the Special Reporters. A summary of each paper is provided at the end of the report for completeness. Responses and contributions to the questions offered throughout this Special Report are invited for presentation during the SC C4 GDM. The questions compiled by the reporters are not specifically aimed at the papers' authors but are synthesised from common issues and trends identified across the papers. This provides the opportunity for a broader response and participation in the discussion session. We encourage you to share your views or experiences in response to the specific questions in this report.

Intending contributors are encouraged to submit proposed presentation material by Saturday 10th August 2024. The Special Reporters will review the submissions and may request updates. **Final versions of the contributions must be submitted by Friday 16th August.** Prepared contributions which are received after the deadline will not be considered for presentation at the GDM.

Proposed contributions should be uploaded on the [Registrations platform](#) – “Contributions to Group Discussion Meetings” section - via the user’s existing account and credentials. It is important to note that:

- *Access to the uploading of contributions is given only to duly registered delegates.*
- *As a consequence, [registration to the CIGRE 2024 Session](#) should be finalized before uploading contribution(s) online.*
- *The system will be open for uploading contributions from early June 2024.*

A guide for contributors as well as templates and sample pages is available on the [CIGRE 2024 Session website](#) - see Group Discussion Meetings in the top menu bar. During the GDM, each prepared contribution will be allocated a time slot of three to four minutes for a presentation, therefore **the number of slides should not exceed four (including the title slide)**.

Special Reporters will review the prepared contributions for readability, technical/scientific content (no commercial information is allowed) and relevance to the questions posed in this Special Report. It is expected that the questions relevant to the three Preferential Subjects will attract many contributions, as a result the number of accepted contributions may need to be limited. The selection will be based on relevance and quality. Final acceptance of prepared contributions will be notified by **Saturday 24th August**.

Please note that accepted contributors will be required to attend a short pre-session meeting with the Special Reporters, SC Chair and SC Secretary on **Wednesday 28th August**. You can meet them **anytime between 08:30 and 10:30** in the SC C4 Poster Session area (Halle Ternes) at the Palais des Congrès to finalise presentation arrangements. The purpose of this short meeting is to review the final details of their contribution and to receive the latest instructions (such as schedule).

During the GDM session the SC Chair may call for **spontaneous contributions**, which will only be verbal with no slides. All attendees are eligible to make such a contribution. Attendees who provide a spontaneous contribution are allowed to deliver a written contribution which will be included in the Session Proceedings. This text is required to be forwarded within a maximum delay of two weeks after the SC C4 GDM Session (i.e. by **Friday 13th September, 2024**) to the SC C4 Secretary (g.lietz@ieee.org).

2. Poster session

Authors of SC C4 Session papers are required to present their papers during the **SC C4 Poster Session scheduled for Wednesday 28th August (08:30 to 10:30)** in Halle Ternes on level 1. Template and instructions on poster preparation are available on the [CIGRE 2024 Session website](#). Posters will be displayed on digital screens. **A draft copy of the poster must be uploaded to the [ConfTool platform](#) by Wednesday 31st July** for review by the poster session convener. A final version, incorporating any requested changes, must be uploaded by **Friday 16th August 2024**. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session he/she or the relevant National Committee is requested to send a substitute.

3. Tutorial and Workshops

The following C4 tutorial and workshops will take place during the week:

- Joint C1/C4 workshop: “**Resilience by design**”, presented by Emanuele Ciapessoni and Mathaios Panteli. Tuesday 27th August (08:30 to 12:30)

- C4 workshop: **C4 Green Book “Power system dynamic modelling and analysis in evolving networks”**, presented by Babak Badrzadeh, David Jacobson, Marta Val Escudero, Deepak Ramasubramanian and Zia Emin. Wednesday 28th August (14:00 to 18:00)
- C4 tutorial: **“EMC issues in modern and future power systems”**, presented by Patricio Munhoz-Rojas. Thursday 29th August (14:00 to 15:50)

SUMMARY OF KEY DATES

Date	Time	Action	Location
Wednesday, 31 st July 2024	End of day	Deadline for submission of posters for all accepted paper authors	ConfTool platform
Saturday 10 th August, 2024	End of day	Deadline for uploading prepared contributions for the GDM	Registrations platform
Friday 16 th August, 2024	End of day	Deadline for submission of final versions of posters for all accepted paper authors (if changes are required)	ConfTool platform
		Deadline for uploading final prepared contributions for the GDM (if changes are required)	Registrations platform
Saturday 24 th August, 2024	End of day	Notification of acceptance for prepared contributions	Registrations platform
Tuesday 27 th August, 2024	08:30 to 12:30	Joint C1/C4 workshop “Resilience by design”	TBA
Wednesday 28 th August, 2024	08:30 to 10:30	SC C4 Poster session	Halle Ternes (level 1)
		Authors of accepted prepared contributions to meet Special Reporters, SC Chair and SC Secretary	
	14:00 to 18:00	SC C4 Workshop: C4 Green Book “Power system dynamic modelling and analysis in evolving networks”	TBA
Thursday 29 th August, 2024	14:00 to 15:50	SC C4 Tutorial “EMC issues in modern and future power systems”	TBA
Friday 30 th August, 2024	08:45 to 18:00	SC C4 Group Discussion Meeting	Bordeaux Lecture Theatre
Friday 13 th September, 2024	End of day	Deadline for submission of spontaneous contributions to be included in the Session Proceedings	Email to SC C4 Secretary

PREFERENTIAL SUBJECT 1

Modern power systems worldwide are undergoing massive transformation due to the high penetration of Inverter-Based Resources (IBRs), decentralizing energy generation and consumption. This includes numerous smaller units such as distributed energy resources (DERs) and electric vehicle (EV) chargers, and also significant loads like gigawatt scale data centres and hydrogen electrolyzers. Challenges of the future power system include reduced inertia and system strength, scaling the connection process, and managing the new complex and nonlinear power transmission systems. The task of ensuring transmission system dynamic stability is becoming increasingly complicated, and deregulated markets require Transmission System Operators (TSOs) to justify reinforcement costs and allocate them correctly. Thus, advanced tools and robust analytics are vital for addressing these challenges and capitalizing on new opportunities.

The primary subject for PS1 is “Power system dynamic analysis in the energy transition: challenges, opportunities and advances” and includes:

- Methodologies including modelling tools and techniques, model validation, metrics and data analytics.
- Technologies including storage, large scale electrification and advanced control methods.
- Phenomena including control interactions, system needs and required equipment capabilities for planning and operation of secure power systems.

Forty one (41) papers were accepted, which includes one NGN paper from Denmark entitled “EMT-Based Machine Learning Model for Fault Ride-Through Assessment in Type IV Offshore Wind Turbine Generators”, by G. M. Gomes Guerreiro.

A brief description of each theme and the associated questions are presented below.

PS1 Theme 1 Methodologies including modelling tools and techniques, model validation, metrics and data analytics.

Effectively managing the changes seen in the power system requires advanced methods and tools for modelling, simulation and data analysis for operation and planning. Until recently, most analyses of full transmission systems were conducted with load flow and RMS/PDT tools to limit the computational burden, and very detailed EMT studies were carried out on only limited parts of the system, because high frequency phenomena were considered local issues. Today, there is a need to combine the two analysis methods to assess interactions across larger distances. The combination of the availability of high-resolution data from Phasor Measurement Units (PMUs) and the advances in various artificial intelligence (AI) methods can be utilized for aspects of model generation, model validation, system planning and system operation.

The following papers present such new methods: 10289, 10291, 10383, 10456, 10458, 10461, 10837, 10907, 10910, 10911, 11096, 11099, 11119, 11163, 11302, 11408, 11448, 11490, 11502, 11503, 11639, 11731, 11748, 11762, 11871.

Question 1.1: What is the experience with EMT analysis of large power systems? How to determine the scale and boundaries of EMT model needed for analysis of large IBR-dominated networks? How to derive accurate network equivalents?

Question 1.2: How should data centres, which have both stochastic and time-synchronized load patterns, be represented in power system models? What is the experience with modelling this type of load (inverter based) in different type of studies (e.g. loadflow, short-circuit, RMS/PDT dynamics and EMT)?

Question 1.3: How should distributed resources like the millions of EV chargers and rooftop PV plants of different brands and generations be represented in different type of power system analysis (e.g. loadflow, short-circuit, RMS/PDT dynamics and EMT)?

Question 1.4: What methods are adopted in industry to ensure fidelity of the models used in power system analysis throughout the lifetime of a generation or demand facility?

Question 1.5: Are the existing tools and models adequate to assess new IBR-driven phenomena? What are the gaps? Are there emerging new tools and models available to address those gaps?

PS1 Theme 2 Technologies including storage, large scale electrification and advanced control methods.

The development of the performance and price of Battery Energy Storage Systems (BESS) opens the possibility for new services such as replacement of synchronous condensers by grid forming BESS, delivery of frequency control services and acting as virtual power lines. Other emerging technologies are load resistors for system stabilization, power oscillation damping (POD) with reactive power and ultra-fast load demand response. The studies presented in this session show that the configuration and location of the units have a significant influence on the efficiency of the solutions.

The following papers present such new technologies: 10383, 10384, 10386, 10456, 10457, 10463, 10495, 10800, 11030, 11060, 11122, 11247, 11520.

Question 1.6: How can AI support operational and planning actions from large quantities of measured, simulated, or combined power system data? What are the risks, pitfalls, and impediments? What is the experience in the use of AI to date?

Question 1.7: What are the most critical aspects to consider from a power system performance perspective in large scale electrification of society (large scale electrolyzers, CO₂-free smelters etc.)?

Question 1.8: What services are (or can be) provided by new technologies like storage, large scale electrification and advanced control methods? What is the experience with these technologies?

Question 1.9: How should large scale BESS and hybrid load and renewable generation plants be configured, controlled, and incentivised to benefit power system performance? Is it necessary to consider all combinations of operational states and power balances in large scale power system analysis?

PS1 Theme 3 Phenomena including control interactions, system needs and required equipment capabilities for planning and operation of secure power systems.

IBR-dominated grids are facing new and more complex stability issues including converter-driven stability, resonance stability and IBRs shifting between control modes. Traditional

phenomena like electromechanical oscillations will still exist as long as there are synchronous machines in the system, at least under some conditions. Also, frequency stability remains even more critical than before. As IBRs increasingly dominate the system response from time to time, their capabilities become ever more critical.

The following papers discuss these challenges and capabilities: 10102, 10292, 10459, 10837, 10910, 11096, 11099, 11119, 11302, 11448, 11521, 11639, 11732.

Question 1.10: Is the short circuit ratio (SCR) still a valid measure for system strength and stability in high IBR penetration networks, or is there a better metric? How should grid forming (GFM) and grid following (GFL) inverter technologies be considered in SCR calculations or other system strength or stability metrics?

Question 1.11: What is the experience with new phenomena driven by integration of high shares of IBRs? How is it assessed during planning phases? What mitigation options are preferred? How are they managed in real-time operations?

Question 1.12: What is the experience with performance specifications for new stability enhancing technologies (e.g. Grid Forming controls)? How is the compliance process defined? Are there real life experiences to share?

PREFERENTIAL SUBJECT 2

The primary subject for PS2 is “Power quality (PQ) and electromagnetic compatibility (EMC) analysis in the energy transition: challenges, opportunities and advances” and it covers three themes:

- New tools and methods for the assessment and the mitigation of PQ issues for low-carbon grids.
- EMC related challenges arising from large penetration of renewable energy plants and electric vehicles (EV) charging networks.
- Evaluation and mitigation of high-altitude electromagnetic pulse (HEMP), intentional electromagnetic interference (IEMI) and geomagnetically induced current (GIC) in modern power systems.

In total, nineteen (19) papers were accepted, including one NGN paper from Australia entitled “Background Harmonics: Quantifying network assumptions and impacts”, by I. Zheng.

A brief description of each theme and the associated questions are presented below.

PS2 Theme 1: New tools and methods for the assessment and the mitigation of PQ issues for low-carbon grids.

Reflecting the increasing penetration of inverter-based resources in low-carbon grids, along with reduced synchronous generation and rapid transmission development, new and enhanced power system modelling methods for harmonic distortion have received considerable attention. In particular, the increasing uncertainty and variability inherent in models of grids, loads, and other connected equipment has prompted closer attention to harmonic modelling techniques and their underlying methodologies, as considered in papers 10452, 10462, 10464, 11238, 11651, 11760. Similarly, managing amplification of existing background harmonic voltages by

new connections, typically heavily based on inverter-based resources, is an emerging issue for low-carbon grids, and is examined in papers 10293, 10947, 11238, 11651 and 11876.

Beyond harmonic distortion, other power quality issues continue to generate focus. Reductions and increased variability in short-circuit levels in low-carbon grids see renewed attention on modelling and measurement of voltage dips. Similarly, increasingly bidirectional power flows challenge existing approaches to management of voltage unbalance and thus to line transposition. Papers 10509, 10598 and 10678 examine disturbance types beyond harmonic distortion.

Power quality measurements, both at the network level and for individual plant, also receive attention, in papers 10595, 10898, 11649 and 11760. New methods of obtaining power quality measurements in the field are described. A range of measurement topics is encompassed, including alternate transducers, trends in and methodologies for wide-area harmonic measurements, and validation via hardware-in-the-loop testing.

Question 2.1: What trends in power quality disturbance levels – both harmonic distortion and other power quality disturbance types – have been observed or predicted in the transition to low-carbon grids, and why?

Question 2.2: To what extent do the quantities and values selected for existing power quality limits require revisiting to be suitable for application to low-carbon grids?

Question 2.3: In what ways can approaches to modelling and measurement of power quality disturbances be simplified, while accommodating uncertainty in power quality models and measurement data, in order to remove impediments to the development of low-carbon grids?

PS2 Theme 2: EMC related challenges arising from large penetration of renewable energy plants and electric vehicles (EV) charging networks.

Three papers were received that refer to EMC challenges: one deals with the problem of EMC testing of some power electronics equipment and the other two deal with the EMC of the power supply system that feeds modern control systems.

Paper 10794 refers to a method to test, in-situ, the radio frequency fields emitted by some modern equipment, for which it is impractical and/or impossible to make the type test in an EMC chamber, that is based on the near-field properties of a point source to distinguish them from the ambient noise, without the need for a separate measurement of it.

Papers 11070 and 11440 refer to the need for proper design and maintenance of the EMC of the auxiliary DC power supply system that feeds the control system of HVDC converter stations or substations. The last paper found that the waveform of disturbances in the field differs from the standardized waveform that represents fast transients.

Question 2.4: Are there other practical experiences showing that the waveform of the fast transient disturbances really existing in modern power systems is not a damped wave, as supposed in the standards, but a high frequency oscillation modulated by a pulse?

PS2 Theme 3: Evaluation and mitigation of high-altitude electromagnetic pulse (HEMP), intentional electromagnetic interference (IEMI) and geomagnetically induced current (GIC) in modern power systems.

The study of these low-probability events that can have a high impact on power systems is still progressing, and papers 10455 and 10678 refer to GICs.

The first paper presents an improved method, which utilizes maps of the one-minute averaged geoelectric field as inputs to estimate in near real-time the value of the electromagnetic disturbance impacting the power system, that is the voltage induced along the conductors of a transmission line. The second paper presents an analysis of the effects of GICs on power system stability and discusses the possibility of their mitigation, starting with the assumption that the voltage induced along the conductors has a step waveform.

Question 2.5: Are there any practical experiences of validation of the assumption that the local value of the geoelectric field has approximately a step waveform? Are there any practical experiences of validation of the entire calculation of the GIC?

Question 2.6: Is there new measured data of GICs from the recent geomagnetic storms?

PREFERENTIAL SUBJECT 3

The primary subject for PS3 is “Insulation co-ordination and lightning interference analysis: challenges, opportunities and advances” and it covers three themes:

- Overvoltage stress of future HVDC and HVAC transmission and distribution systems, including new characteristic waveforms.
- Advancements in lightning detection systems and lightning performance assessment methods including advanced data analytics of AC and DC high voltage, medium voltage, hybrid overhead lines and other exposed structures.
- Impact of extreme weather events, such as wind, fires, flooding, lightning, icing, snow, etc, on insulation co-ordination including practical solutions.

In total, twenty three (23) papers were accepted. A brief description of each theme and the associated questions are presented below.

PS3 Theme 1 Overvoltage stress of future HVDC and HVAC transmission and distribution systems, including new characteristic waveforms.

13 papers present concepts and results that are assigned to PS3 Theme 1.

Papers 10294, 10382, 10531, 10550, 10949 and 11473 address the importance of the analysis of transient and temporary overvoltages, including non-standard waveforms, in open air and gases and their effects on equipment reliability. Simulations that utilize state-of-the art modelling techniques, field measurements and methodologies based on test data are presented.

Analyses that cover the monitoring of equipment and the evaluation of failures in operation due to system events as well as transient overvoltages are described in papers 10326, 10751, 10955, 11596 and 11787.

Calculations of switching overvoltages on transmission lines, including effects of corona discharges and methods of measuring, modelling, and simulating high frequency grounding impedances with emphasis on the frequency dependence of grounding systems are discussed in papers 10575 and 10881.

Question 3.1: What are the challenges and experiences in the analysis of equipment performance related to temporary and/or high frequency transient overvoltages, including failures in operation? What are the state-of-art mitigation procedures to improve equipment reliability especially in HVAC and HVDC transmission and distribution systems?

Question 3.2: What new experiences have been gained in the area of modelling switching and lightning-related transient overvoltages as well as regarding the frequency dependence of grounding systems? Which improvements have been implemented in power system grid operation?

PS3 Theme 2 Advancements in lightning detection systems and lightning performance assessment methods including advanced data analytics of AC and DC high voltage, medium voltage, hybrid overhead lines and other exposed structures.

8 papers present concepts and results that are assigned to PS3 Theme 2.

The variation of the lightning density along a transmission line and the continuous monitoring including the prediction of the lightning threat on transmission lines are presented in papers 10953 and 11736. The effects of metallic cable sheaths on the high-frequency grounding performance of wind farm grounding structures during lightning strikes to wind turbines, as well as the effect of the frequency content on the effective area of grounding grids at uniform soil resistivity, are discussed in papers 10278 and 11118. Measurements and evaluations of lightning currents in line arresters and through transmission line towers, as well as the impact of underbuilt wires on flashovers and the modelling thereof on insulator strings of overhead lines have been discussed in papers 11224, 11707 and 11711. Recent progress in simulating transients using Finite Difference Time Domain (FDTD) methods is presented in paper 11062.

Question 3.3: What is the experience with EMT analyses in relation to the simulation of lightning-related transients and the development of effective countermeasures for the suppression of overvoltages to prevent failures and malfunctions of power systems?

Question 3.4: What possibilities do newly available products from the fields of meteorology and lightning location systems offer in terms of power system operation and control? What location accuracy and detection efficiency should be achieved to enable integration of forecasts and detection system data?

PS3 Theme 3 Impact of extreme weather events, such as wind, fires, flooding, lightning, icing, snow, etc, on insulation co-ordination including practical solutions.

2 papers present concepts and results that are assigned to PS3 Theme 3.

Considerations of the influence of extreme weather events on the isolation coordination related to high-voltage substations as well as the integration of contamination maps regarding an optimization of the design of components to increase power system reliability are discussed in paper 10385 and 11513.

Question 3.5: How can the effects of extreme weather events be incorporated into system planning and operations? What is the experience regarding contamination effects in the insulation coordination studies?

PAPER SUMMARIES

PS1: POWER SYSTEM DYNAMIC ANALYSIS IN THE ENERGY TRANSITION: CHALLENGES, OPPORTUNITIES AND ADVANCES

10102 - Changes in Nordic Power System Dynamics due to Massive Introduction of Wind and Solar Power: This paper presents the consequences of high Renewable Energy Source (RES) penetration in Nordic Transmission System Operator (TSO)-operated systems, highlighting new challenges to power system stability. It illustrates three severe, unforeseen events with waveform examples, emphasizing the need for innovative solutions. The paper defines technical objectives aimed at ensuring Nordic grid stability amidst changing power systems.

10289 - An Open-Source Tool for the Validation of Power Park Modules Generic Models: This paper introduces a new open-source tool that simplifies the RMS/PDT model validation for Power Park Modules, as per the IEC 61400-27-2:2020 standard. It offers an automated, clear, and quantitative method for model accuracy assessment, aiding TSOs in managing power system stability with increasing power electronic connections. The tool also helps in selecting and verifying compliance of dynamic models and is adaptable to changing grid requirements.

10291 - Parallel Simulation of a Wide-Area EMT Model with High Penetration of Power Electronic Converters Using Co-Simulation: A Real Case Study: This paper focuses on speeding up the simulation of Electro Magnetic Transients (EMT) for studying potential interactions between power electronic converters on the French grid. The authors employ delay-based parallelization techniques, co-simulation using the Functional Mock-up Interface (FMI) standard and manual decoupling into subnetworks, resulting in faster EMT simulation.

10292 - Study of New Types of Dynamic Interactions in Power Systems with Mixed Conventional and Renewable Generation: This paper analyses the stability challenges in power systems with increased inverter-based resources (IBRs), focusing on dynamic interactions between IBRs and synchronous machines that may lead to oscillations. It highlights the impact of communication delays of IBRs on stability, presents a case study of a French island power system, and proposes solutions including the tuning of Power System Stabilizer (PSS) and introduction of Power Oscillation Damping (POD) controller to mitigate identified oscillation modes.

10383 - Dynamic Assessment of Power System Strength in Systems with a Large Share of Generation from Renewable Sources: This paper discusses the inadequacy of traditional short-circuit based system strength methods in the face of high IBR integration and explores the role of HVDC systems with voltage source technology in enhancing grid stability.

10384 - System Stability in Dynamic Analysis of Large Power Systems Enhanced with HVDC Reinforcement: HVDC Foggia-Forlì: This paper focuses on the development of the Italian transmission grid, with a particular emphasis on High Voltage Direct Current (HVDC) connections. It presents dynamic stability study results, demonstrating improved grid performance with planned reinforcements. The paper highlights the role of the HVDC Foggia-Forlì project in enhancing renewable energy integration, long-distance power transmission, and grid stability. Additionally, it provides an overview of the Hypergrid project, utilizing Terna's in-house simulator for technical assessment. Dynamic simulations emphasize improved voltage

stability, congestion mitigation, and interarea oscillation control, showcasing Hypergrid's importance in ensuring grid stability and facilitating renewable energy integration.

10386 - Regulating Resistors: an Advanced Control Strategy to Achieve Overall System Stability in the Italian Transmission Grid: This paper shows the effects of regulating resistors on the transient stability of the Italian power system. The results show that regulating resistors are a promising technology to increase power system stability margins. Special focus is on the optimal location of the devices. The installation plan on the Italian grid has been demonstrated to improve system stability, dampen power oscillations and control power on tie sections, which produces economic, energy and environmental benefits.

10456 - Location and Sizing of Grid Forming Devices in Transmission Power Networks: This paper proposes a method for locating grid-forming (GFM) converters in power grids. It presents a screening approach using available short-circuit strength-based analysis to identify the optimal GFM location and size. The paper demonstrates verification studies in both positive sequence and electromagnetic transient (EMT) domains. This research provides a crucial first step in identifying candidate locations for GFM deployment, ensuring grid stability post-retirement of synchronous condenser resources.

10457 - Unlocking Capability in Transmission Connected Inverters for Improved Reliability of Transmission Power Networks: This paper addresses the underutilization of inverter-based resources (IBRs) in transmission power networks, emphasizing the locked capabilities due to existing interconnection requirements. It demonstrates through electromagnetic transient (EMT) simulations that grid-following (GFL) PV and BESS systems, aligned with IEE2800-2022 specifications, can support the grid with voltage and frequency control. Additionally, it shows that with 11% of generation from new grid-forming (GFM) IBR units, a grid can operate in island mode. The paper provides a comparative analysis of control strategies for IBRs, validating their effectiveness across positive sequence and EMT simulation domains. It also offers practical insights into using commercial software packages for IBR simulation and provides useful guidelines for the applicability of RMS/PDT models.

10458 - Collector System Equivalent with Frequency-Dependent Representation for Electromagnetic Transient Models: This paper proposes an equivalent collector system model for wind power plants, capturing frequency-dependent behaviour and resistive damping. It offers an efficient alternative to frequency-dependent line modelling, reducing simulation time and computational load. The model integrates seamlessly with aggregated single-machine models, streamlining simulation processes. This provides a practical solution for accurately representing wind power plant dynamics in power system studies.

10459 - Grid Forming Functional Specifications and Verification Tests for North American Bulk Power System Connected Battery Energy Storage Systems: This paper is proposing test procedures for transmission planners to ensure Grid-Forming Mode (GFM) functionality in Battery Energy Storage Systems (BESS) connections. The tests and criteria are designed to be simple, agnostic to control topologies, and not overly prescriptive. Using OEM-provided EMT models, the paper illustrates test implementation and result assessment against proposed success criteria. Example tests differentiate the unique characteristics of GFM BESS from Grid-Following Mode (GFL) BESS.

10461 - Inertia Trend Analysis in the U.S. Eastern Interconnection with Field Measurement Data: This paper utilizes field-synchronized measurements from the U.S. Eastern Interconnection to evaluate interconnection-level inertia. It processes data from over

200 locations in North America using the FNET/GridEye system. The paper presents detailed considerations for processing field measurement data and choosing the optimal Rate of Change of Frequency (RoCoF) time window for large interconnections. It analyses the inertia trend, indicating that the Eastern Interconnection's inertia remains largely steady from 2012 to 2022. Additionally, it discusses the potential impact of changes in the system's primary frequency response, considering a chosen RoCoF time window of 3 seconds.

10463 - Evaluation of Primary Frequency Response from Inverter-Based Resources with 1% Droop Setting: This paper provides the summary of a risk analysis used to evaluate a proposed change to rules surrounding frequency response services in the ERCOT system. It provides a good overview of the value of Battery Energy Storage Systems with different frequency droop settings and different locations in the ERCOT system. It concludes that 1 % droop for the inverters would provide the best frequency stability.

10495 - Simultaneous Voltage and Power Oscillation Damping Control: Towards Robust and Scalable Grid Requirements and Control Solutions: This paper presents design and analysis of a decentralized IBR control scheme that provides both fast voltage control and Power Oscillation Damping (POD) by modulating the reactive power injection. Instead of switching between modes, the proposed control scheme always prioritizes local voltage stability during large voltage excursions by using a deadband activated voltage controller. It is shown that the standard frequency response test can be extended to also assess the effect of the nonlinear deadband function, using the describing function method.

10800 - Impact on Frequency Stability of the Feedback in the Active Power Control for Synchronous Generation: This paper compares active power feedback and guide vane opening feedback in terms of dynamic properties and regulatory compliance for hydro plants. To mitigate the negative impact of active power feedback, adjustments to the guide vane opening feedback governor are proposed. These adjustments include varying droop with load and water head or adding extra slow feedback using active power. The paper recommends that the Requirements for Generators (RfG) should allow motivated deviations in droop for frequency control while not permitting governors that counteract a production unit's inertial response.

10837 - Impact of Active Distribution Networks on Power System Stability – A Case Study: This paper investigates the impact of active distribution networks (ADNs) and their behaviour on transmission grid stability in Scotland. The paper shows how different components of the composite load model, including ADNs, impact the results. This also includes impacts from legacy distributed energy resources without fault ride-through capability.

10907 - Impact of Converter-Based Demand on Frequency Quality in the Ireland and Northern Ireland Power Systems: This paper analyses the impact of large data centres (DCs) on grid frequency quality, focusing on DC demand behaviour and its effect on parameters such as standard deviation, nadir, and zenith. It identifies two types of demand behaviour: (i) regular, cyclical fluctuations causing ongoing frequency issues, and (ii) the demand response during and after transmission system faults. Using actual data and system events, the analysis underscores the importance of data provision and DC modelling in dynamic stability assessment tools. Finally, the paper offers recommendations and next steps to address converter-based demand-driven frequency quality issues alongside the fault ride-through challenge.

10910 - Development of Look Ahead Reactive Power Resource Optimisation Tool for Voltage Security in IBR Dominated Systems: This paper introduces the Voltage Trajectory Tool (VTT), designed to address voltage management challenges with numerous Inverter-Based Resources (IBRs) in the power systems of Ireland and Northern Ireland. Developed for control room environments, the tool optimizes setpoint selection and commands for reactive power sources, aiming for smoother voltage trajectories and reduced control actions. It minimizes the total number of controller actions in the near time horizon and enforces inter-temporal constraints on device settings changes and grid resource setpoint movements.

10911 - Enhancing the Evaluation of Rate of Change of Frequency During Fault Contingencies Simulated in Phasor-Domain Tools: This paper presents the development of a toolkit aimed at improving the evaluation of Rate of Change of Frequency (RoCoF) during fault contingencies for offline studies. It addresses the need to handle large step changes in frequency to avoid unrealistic RoCoF assessment, particularly when using RMS/PDT simulation tools. The toolkit aims to smooth the data to improve the accuracy of RoCoF evaluation. Additionally, it acknowledges the blocking behaviour of certain RoCoF relays during low voltage conditions.

11030 - Energy Storage to Enhance Transmission Capacity - A Case Study on the Swedish Transmission Grid: This paper presents a case study on the Swedish transmission grid, analysing the benefits of energy storage to enhance grid capacity. It investigates the placement of energy storage systems to relieve over-congestion on critical lines after N-1 contingencies. The study includes different implementation strategies and a thorough load-flow analysis to identify the most suitable locations for storage systems. Focusing on critical operating conditions, the methodology explores how energy storage solutions can lower the loading on critical grid elements during grid contingencies.

11060 - Experimental Evaluation of Lighting Device's Potential for Securing Frequency Control Reserve Using Demand-Side Devices: This paper explores the use of air conditioning and lighting devices for frequency control, particularly Frequency Containment Reserve (FCR). It proposes a discrete controller to modulate lighting device energy consumption following grid frequency events, enabling lighting to act as a demand response mechanism. It presents a prototype using inexpensive microcontrollers and infrared expansion boards, validated through laboratory power system simulations. The prototype demonstrated quick response capabilities equivalent to Japanese frequency containment reserve, contributing to improving frequency nadir in the event of generation loss.

11096 - Automatic Detection of Subsynchronous Oscillations: The paper introduces a novel hybrid approach combining signal processing and machine learning (ML) to efficiently detect sub-synchronous oscillations (SSOs). This methodology allows for the automatic classification of SSO-containing regions in time-domain signals, leveraging the strengths of both analytical and data-driven techniques.

11099 - Framework for Identification of Subsynchronous Oscillation Risks: This paper analyses the impacts of poorly damped oscillatory modes on sub-synchronous oscillations in power systems characterized by a massive penetration of inverter-based generators. The paper proposes a mathematical framework integrating frequency-domain methods, time-domain simulation, and machine learning techniques for analysing sub-synchronous oscillations in multiple operating scenarios.

11119 - Identifying Potential Sub-Synchronous Oscillations using Impedance Scan Approach: This paper presents a systematic approach for using impedance scans for large power system oscillation studies. It utilizes scanned impedance models of inverters to assess the risk of sub-synchronous oscillations, supported by case studies from Australia. The case study identifies poorly damped resonance modes around 17 Hz in some Inverter-Based Resources (IBRs), which become unstable under specific operating conditions. Additionally, it discovers that certain IBRs increase the effective grid impedance seen by others in close proximity under specific operating conditions.

11122 - Large Scale Grid Forming BESS Replaces Synchronous Generation Enabling High Renewable Penetration & Low System Load in Australia's Major Northern Grid: This paper discusses experiences from a generator connection process, focusing on modelling and applying grid-forming (GFM) technology in high renewable energy penetration networks. It examines the implementation and development of GFM technology and innovative control systems to meet grid codes. Additionally, it evaluates the performance of the Darwin-Katherine Battery Energy Storage System (BESS) in GFM mode in the Northern Territory, Australia, emphasizing the complexities of integrating a grid-scale BESS to fully replace gas turbines and presenting novel solutions to address integration challenges.

11163 - On the Use of the Congestion Forecast Processes for Early Warning of Possibly Tensed Situations: This paper proposes a congestion forecast approach to identify situations that may present an increased risk of disturbance by considering voltage phase angle differences. It discusses using congestion data to detect potential major disturbances in highly-loaded corridors. Preliminary results include statistical analysis of voltage angles and investigations into the suitability of existing congestion forecast processes to predict such increased risk situations. Analyses involve comparing phase angle differences from forecast models with PMU measurements and geographical analysis to identify critical corridors. These insights could lead to valuable dispatcher support tools.

11247 - Impact of Grid-Forming Solutions on North-Western Victorian Network in Australia: This paper presents findings from using a large electromagnetic transient (EMT) model to replicate specific conditions in the Victorian region of Australia. It presents large-scale EMT analysis, demonstrating the ability of grid-forming (GFM) Battery Energy Storage Systems (BESS) to dampen oscillations and prevent voltage collapse. Detailed simulations compare the effectiveness of GFM inverter-based resources (IBRs) to synchronous condensers in mitigating sub-synchronous oscillations (SSOs). The results show that even though the GFM inverters are designed to emulate the characteristics of synchronous machines, they are not a direct substitute.

11302 - PMU Applications for Voltage Stability Monitoring and Oscillation Analysis: This paper presents a computational platform with a graphical interface for real-time monitoring of voltage stability and electromechanical oscillations in transmission corridors. It utilizes information from previously installed PMUs, updating calculated indices every 4 seconds. Experimental results from the wide area monitoring System (WAMS) deployed at the National Control Center demonstrate the platform's effectiveness in monitoring voltage stability and oscillations, using data from a sudden generation outage event in the Crete interconnected island area.

11408 - A Novel Methodology for Grid Impact Studies of Photovoltaic Systems: The paper presents a new mathematical approach to help in reducing the turnaround time to accept or reject PV system connections to Jordan's distribution grid. This mathematical model is

compared to a conventional method used to accept or reject any new residential or industrial photovoltaic venture.

11448 - Oscillation Modes Identification Via Singular Value Decomposition and Principal Component Analysis: The paper discusses the use of dimensionality reduction techniques for post-mortem analysis of power oscillations in large systems using PMU data to identify dominant oscillation modes. Two dimensionality reduction techniques, Principal Component Analysis and Singular Value Decomposition, are employed in the paper and the results compared.

11490 - Load Model Evolution for the Colombian Power System: The paper details the refinement of Colombia's power system load model from static ZIP parameter-based model to a composite load model for an improved representation of the load dynamics. The paper emphasizes the use of actual measurements from the grid and laboratory tests together with optimization algorithms to create the improved load models.

11502 - EMT Modeling and Analysis of the Chile's Power Grid with High Penetration of Inverter-Based Renewable Energy Sources: This paper presents the process followed by the Chilean TSO (CEN) for the development of a large-scale EMT model of the Chilean transmission system. Generic EMT models are used and an innovative model parametrisation approach using AI is adopted. Results of two studies are illustrated and a comparison between EMT and RMS/PDT results is presented for one of them.

11503 - Real Time System Strength Monitoring in the Chilean National Electric System: This paper describes the implementation of on-line system strength monitoring in the Chilean transmission system using the Equivalent Short Circuit Ratio (EqSCR) metric. This tool is used for situational awareness to manage stability risks related to operation with a high share of IBRs.

11520 - STATCOM Modelling Assessment and Performance Analysis in Rajasthan Renewable Complex of India: The paper evaluates the impact from a STATCOM in a grid with growing penetration of inverter-based resources. The performance of the STATCOM in faults and oscillations is shown by simulation results and real measurements. The paper emphasizes the need for proper tuning of STATCOM dead band, droop settings, and control coordination with mechanically switched reactors and capacitors.

11521 - Strategies for Mitigation of Oscillations in IBR Penetrated Network in India: The paper examines voltage oscillations in India's Rajasthan RE complex, attributing them to controller issues and the rapid expansion of wind and solar power. It suggests solutions like adjusting reactive power control, tuning PPC parameters, and altering ride-through limits to improve grid stability and manage oscillations.

11639 - Enabling System-Level EMT Studies of Danish Power Systems: The Danish TSO has advanced its EMT network for power system stability studies, integrating automated data conversion and simulation processes. Verified by real incidents and future projections, this EMT environment is addressing stability challenges, especially in weak grid conditions, and is seen by the TSO as a vital tool for future stability analysis and management.

11731 - SSSC Model Validation Experience for the Colombian Power System: This paper presents the challenges and procedures to be followed when validating Static Series Synchronous Compensator (SSSC) models, with the aim to establish relatively accurate static

and dynamic (RMS/PDT) models to evaluate their performance and impact to the Colombian Power System and lead to more reliable analysis.

11732 - Comprehensive Analysis of Colombian Power System Oscillations: This paper outlines various measures taken to prevent, detect, and mitigate the impact of frequency and power oscillations in Colombia's power system. These efforts involve normative regulations, system operator actions, a wide-area monitoring system and regional coordination. The paper also presents impact of tuning the power system stabilizer to improve damping.

11748 - Evaluation of the Robust Operation of a Diesel Generator Pool in New Proposed Data Center Electrical Topology Considering Specific Generator Manufacturer: This paper examines the design of electrical systems in data centres for GenAI operations. It highlights the development of a centralized backup power system to handle dynamic GenAI workloads and the creation of a detailed simulation model for diesel generators. The study emphasizes the importance of accurate modelling for reliable data centre operations and suggests further research on the generators' response to fluctuating power demands.

11762 - Enhancing Dynamic Performance Validation of Transient Stability Models Using Argentina's Phasor Measurement Units: This paper proposes a practical method to validate and optimize generation parameters using PMU data, with the main contribution being the use of neural networks to identify model parameters during real system events. It suggests using Artificial Neural Networks (ANNs) to tune dynamic parameters of a generation unit by comparing PMU measurements to RMS/PDT playback simulation results. The study focuses on implementing an ANN in generator governor dynamic model parameter validation using PMU data, demonstrating significant improvement in model validation compared to conventional methods.

11871 - EMT-Based Machine Learning Model for Fault Ride-Through Assessment in Type IV Offshore Wind Turbine Generators: This paper proposes using feature extraction during fault ride-through (FRT) and an EMT-based Machine Learning (EMT-ML) model for grid compliance assessment. The EMT-ML model, employing a hybrid approach of long-short term memory (LSTM) and recurrent neural network (RNN), is trained using 6000 simulated scenarios and validated against real power system faults in offshore Wind Turbine Generators (WTGs). The study suggests that the EMT-ML method can enhance Wind Power Plant (WPP) reliability by providing preliminary assessments of a large fleet of WTGs, improving grid compliance and stability.

PS2: POWER QUALITY (PQ) AND ELECTROMAGNETIC COMPATIBILITY (EMC) ANALYSIS IN THE ENERGY TRANSITION: CHALLENGES, OPPORTUNITIES AND ADVANCES

10293 - Sensitivity Analysis Methods for Onshore Harmonic Studies: Recognising the uncertainty inherent in early-stage harmonic models of wind parks, the paper compares various sensitivity analysis tools in their application to windfarm parameters and the topology of connection and transmission networks, aiming to evaluate the most influential parameters in the amplification of background harmonics

10452 - Influence of Composition-Dependent Load Modelling on System-Wide Harmonic Impedance Characteristics: The paper examines the impact of different aggregated load

models on harmonic impedances within a transmission network, demonstrating the substantial changes to calculated impedances, and particularly the frequency and damping of resonances, that result from changes in load model topology and parameters.

10455 - Real Time Geomagnetic Disturbance Analysis of Bulk Power System Grid Using Geoelectric Field Grid Maps: The paper, using as input one-minute averaged 0.5x0.5-degree grid geoelectric field maps, introduces a method to estimate the voltage induced along the conductors of a transmission line by a geomagnetic disturbance, in near real-time.

10462 - Estimation of Harmonic Exponent Summation Factors for Type 3 DFIG Wind Turbines: The paper reviews, via simulation studies, the aggregation of harmonic current emissions at a single point from multiple wind turbines of the same type, aiming to revise the summation exponents in the IEC 61000 technical reports to be more suitable for wind farms and other inverter-based resources.

10464 - Harmonic and Supraharmonic Emission and Aggregation Characteristics of Some End Use Loads Sold in the US: With the increased penetration of power electronic equipment in end-use loads, the paper examines the changing spectrum of current emissions. Laboratory tests are used to benchmark emission levels, into the supra-harmonic frequency range, and to investigation aggregation of multiple items of equipment within a single residential customer's premises.

10509 - Voltage Unbalance in Overhead Lines with EHV and HV Circuits Combined in the Same Tower: Recognising increases in EHV network power flows and decreases in short-circuit levels arising from the energy transition, the paper investigates the impact of incomplete phase transposition upon voltage unbalance where HV and EHV circuits share common towers. The effects of short circuit level, length of coupling, tower geometry and direction of power flows are investigated, and validated via field measurements.

10595 - Advancing Power Quality Measurements in the Swedish Transmission Grid: The paper presents results of a power quality measurement campaign in which the use of the capacitive tap of a current transformer is shown to yield comparable harmonic measurements to those arising from a bandwidth-enhanced capacitive voltage transformer. Capacitive taps of current transformers are under consideration as a temporary source of harmonic measurements where no bandwidth-enhancing equipment is yet to be installed for capacitive voltage transformers.

10598 - Post-Energy Transition Voltage Dips Assessment: A Dutch Transmission Network Case Study: The paper investigates the impact of the energy transition, in particular the consequences of network changes and reductions in synchronous generator dispatch, upon the ability of an HV/EHV grid to continue meeting the voltage dip requirements set out in the grid code. Both the residual voltage and the extent to which the voltage dip propagates through the grid are examined.

10678 - Towards a Novel Approach to Voltage Magnitude, Harmonics, and Voltage Stability in the Presence of GICs: The paper presents a new approach to control electrical power flow that is based on a new average power theory, and discusses its application to situations that present distortion, unbalance and non-linearities, in particular, to the analysis of the effects of GICs on power system stability and the possibility of their mitigation.

10794 - A Methodology to Define Radiated High Frequency Emission of In-Situ Measurements in Harsh Environments: The paper proposes a methodology to distinguish the electromagnetic fields emitted by an Equipment Under Test from the ambient noise, in an in-situ measurement, without the need of a separate measurement of the ambient noise.

10898 - Voltage Harmonics Trends Based on Field Measurements on the Irish Transmission Network: To assess the impact of substantial increases in inverter-based resources, the paper examines harmonic voltage measurement in a transmission grid over an eight-year period, finding harmonic voltages to be broadly – but not universally – increasing in that time. The paper models background harmonic amplification issues arising from the prospective connection of four new offshore windfarms and their attendant transmission cables.

10947 - Reduction of the Influence of the Background Harmonic Voltage on the Assessment of Harmonic Current at WT Terminals by the Application of the Superposition Method: The paper uses the principle of superposition to present a method for decomposing a harmonic current measured or simulated at the terminals of a wind turbine into separate turbine-side and grid-side components, with a view to eliminating the influence of existing background harmonic distortion in the attribution of harmonic measurements to a wind farm.

11070 - Electromagnetic Compatibility in Auxiliary DC Power Supply System: After concluding that many costly power system failures in Russia were caused by electromagnetic disturbances in the auxiliary DC power supply systems of power plants or substations, the paper presents a diagnostic method that was developed to verify the proper design and to ensure the maintenance of the EMC of this vital auxiliary system.

11238 - Harmonic Assessment in Renewable Energy Zones: The paper examines the harmonic performance of a specific system area being developed to contain large quantities of inverter-based resources, in the network planning stages when detailed models of the plants are not available. It proposes a study methodology and examines the effects of modelling choices and other related sensitivities, confirming via modelling that aggregated harmonics models of generators within a REZ are unsuitable for harmonic filter selection.

11440 - EMC Issues within HVDC System under GIS Environment: The paper presents a case of interference in the control system of a modern HVDC converter station, due to the presence of fast transient disturbances in its auxiliary DC power supply system, during the operation of the HVAC Gas-Insulated Switchgear (GIS) that connects the HVDC system to the AC power grid; and outlines the mitigation measures utilized to solve the problem.

11649 - Exploratory Analyses of Power System Harmonic Measurements Using Principal Component Analysis: A method of analysing wide-area harmonic measurement data sets using multivariate statistics, via principal component analysis, is presented and explored, with practical measurements in the Western Danish 400 kV transmission grid used as an example. The paper recommends further work on development of electro-metrics across power system analysis fields.

11651 - Flexible Network Model to Study the Impact of Future Changes in Transmission Systems on Harmonic Levels and Impedance: The paper demonstrates application of a parametrised transmission network harmonic model which has been developed to be representative of meshed networks typical of those in Central Europe. The test network is used to examine the impact of inverter-based resources on the system harmonic impedance and propagation of harmonic distortion, including for zero-sequence harmonics.

11760 - Multi-Platform Analysis for Harmonic Emission Assessment of M-SSSC FACTS Devices in the Santa Marta Substation (Colombia): The paper describes the harmonic studies undertaken prior to the installation of a modular multilevel converter static synchronous series compensator, with validation via hardware-in-the-loop testing. Results of the studies indicate minimal increases in voltage distortion arising from the proposed equipment.

11876 - Background Harmonics: Quantifying Network Assumptions and Impacts: The paper identifies the amplification of background harmonic voltages as a key source of uncertainty when assessing pre-connection compliance of proposed inverter-based resources and demonstrates the volatility that can arise in amplification factor calculations. A graphical tool is developed for analysis and interpretation of background harmonic amplification, intended for use with project parameters from the concept design stage.

PS3: INSULATION CO-ORDINATION AND LIGHTNING INTERFERENCE ANALYSIS: CHALLENGES, OPPORTUNITIES AND ADVANCES

10278 - Effect of Frequency Content on the Effective Area of Grounding Grid at Uniform Soil Resistivity: Authors describe an approach to study the high frequency response of a grounding grid, taking the frequency dependency of the soil into account. Frequency dependency is depicted in the assessment of soil conductivity and permittivity that are used in calculation of unit R-L-C parameters of the transmission line model. Results indicate that frequency content greatly affects the decrease of the effective grounding grid area.

10294 - Transformer Withstand Capability to Temporary Overvoltages: A General Determination Method from Standard Input Data: A methodology is provided for determining transformer withstand capability against temporary overvoltages, based on available test data. The method accounts for the following key factors: the interdependence between withstand amplitude and duration, the fact that the amplitude of the actual overvoltages is time-varying, the presence of harmonics and the insulation ageing. The method utilizes the fact that the voltage distribution along windings is linear at low frequencies.

10326 - Utilizing Substation-Based Monitoring to Improve Condition Assessment of Distribution Networks: The condition-based maintenance of systems at distribution grid level has not yet been fully established. Three case studies give reasonable solutions for the event detection using waveform analytics techniques to identify, classify, and interpret electrical signatures associated with incipient failures. The developed algorithms that can anticipate and detect potential equipment failures such as insulation breakdown and arcing.

10382 - Long Tail Withstand Voltage Test (TOV) on the HVDC Cable and Accessories of the Italy-France Interconnection: A Comparison between Laboratory and Infield Results: This paper presents an overview of test voltage selection and testing activity performed on a 320 kV XLPE cable system with a typical length for type test loops, with presentation of test results. Additionally, the paper highlights the good correlation between the laboratory-obtained waveforms and those observed in the field during operational conditions.

10385 - Contamination Map and Design Optimization for Increased Transmission Reliability and Resilience: The Italian Experience: Illustrations of the mapping methodology for insulator surface contamination used in Italy are given for the years of 2016 to 2020 considering the design stage, the in-field samplings and data post processing analysis. Results of measurements of contamination for insulators installed in various locations are given

including a contamination map. The interpolation of the results highlights three main areas of contamination in Italy.

10531 - Enhancing Power Transformer Reliability: High-Frequency Modeling, Transient Interactions, and Overvoltage Protection Scheme: A complete procedure for simulating transient overvoltages on transformers in the system, using state-of-the art modelling techniques is presented. The models, integrated into electromagnetic transient software, enable the identification of vulnerabilities and examination of case studies involving lightning strikes and switching events. Furthermore, the details of a novel protection method applied to safeguard the transformer are discussed in this paper.

10550 - Service Experience in the Dutch Transmission Grid with Non-Standard Waveforms & their Impact on the Component Insulation: Based on the service experience gained in the Dutch transmission grid related to harmonic resonance TOVs and vacuum circuit breakers (VCB) re-ignition overvoltages that led to equipment failures, the paper aims to facilitate the discussion for the necessity to introduce new ways to characterize a component withstand against such non-standard waveforms, e.g., define new test waveforms, introduce new or updated testing procedures, online monitoring of transients etc.

10575 - A Methodology of Measuring, Modelling and Simulating of High Frequency Earthing Impedance: The paper presents a methodology for measurement and analysis of earthing impedance in a high frequency region. It discusses the results of measurements and provides insight into frequency dependence of grounding systems. The analysis can help to determine the quality of an earthing system for transient performance and can be used for real applications.

10751 - Overvoltages with High Harmonics when Connecting Step-Up Transformers in a Pumped-Storage Power Plant: A Case Study: The paper discusses the occurrence of temporary overvoltages (TOVs) resulting from inrush current due to transformer energization in the Swiss system. The TOVs presented a high degree of low-order harmonics. Detailed EMT simulations were performed together with the analysis of recorded oscillograms. Mitigation actions were recommended and implemented as a first measure to avoid the re-occurrence of TOVs.

10881 - Simplified Methods and Models for Calculation of Switching Overvoltages on Transmission Lines Including Effects of corona Discharges: Simplified models for the calculation of switching overvoltages on transmission lines including effects of corona discharges are presented. Furthermore, the importance of considering the influence of corona and surge arrester models in EMT simulations as well as the concept of the specific storm outage rate in the planning of new overhead lines is demonstrated. Estimated reduction rate of maximum overvoltage levels obtained for a 450 km line are given.

10949 - Very Fast Transient Overvoltage Analysis in Clean Air and SF6 Gas Insulated Substation Modules Using the Extended Transmission Line Theory: Simulations for a typical 138 kV gas insulated substation (GIS) are presented and the behaviour of SF6 and clean air filling in regard to Very Fast Transient Overvoltages (VFTO) is compared. The investigations were carried out with and without a transformer connected. Simulations show that GIS with clean air tends to generate VFTO with peak values comparable to those of a classical SF6 GIS, including lower frequency components.

10953 - Climate Characterization and Historical Changes in Density and Intensity of Lightning around the 500 kV Bacabeira-Parnaíba Transmission Line: The investigation of the lightning density along a transmission line (TL) in Brazil for the years 2013 – 2023 is presented and discussed. The study compares two approaches for calculating the TL's lightning performance: the traditional method using an average lightning density and a detailed method using data from a lightning detection system. Findings highlight the need to consider varying lightning patterns in the planning and operation of TL's to ensure safety and efficiency.

10955 - Voltage Scaling Phenomenon in Isolated Ground Systems - Approach and Proposal for Mitigation Analysis of a Real Case in Brazil: The main goal of this paper is to present the voltage scaling phenomenon (VSP) of a real case occurring at the 13.8 kV level of the auxiliary service system in a 500 kV substation in Brazil. The main contribution is the use of real oscillography records to show/discuss VSP as the existing literature doesn't present many real cases of the phenomenon. A simple mitigation method is also proposed.

11062 - Recent Progress in Three-Dimensional FDTD-Based Electromagnetic Transient Analysis of Electric Power Facilities: This paper deals with a full-wave simulation of electromagnetic transients in power facilities. Simulations have been performed using the hybrid technique of 3D Finite Difference Time Domain (FDTD) models and transmission line theory. Authors combined the Agrawal model to estimate the induced voltages for coaxial cables and twisted-wire pairs. Five examples of applications that compare simulation with experimental results are given.

11118 - Effect of Cable Sheaths on Grounding Performance of Wind Power Plants in High Frequency Region: The paper investigates the effect of the cable (metallic) sheaths on the high-frequency grounding performance of the wind farm grounding structure during lightning strikes to the wind turbine. The conclusion was that metallic sheaths give, in some situations, additional reduction of the (local) high-frequency impedance.

11224 - Evaluation of the Impact of Underbuilt Wire on Backflashover Critical Current in Transmission Line: Simulation studies were performed to evaluate the effect of an underbuilt wire (UW) on the back-flashover rate on transmission lines installed in areas showing high-resistivity soils. Three scenarios are analysed: no UW, UW on the entire line, and UW on a short line section. The focus is on reducing the back-flashover rate caused by direct lightning strikes and to identify optimal installation approaches.

11473 - Transient Switching Mitigation in 115kV Offshore Platforms Sensitive Loads by Introducing Controlled Switching Device in Three-Phase Gang-Operated Breakers: This paper discusses the use of point of wave (PoW) switching to mitigate the effect of transient inrush current during transformer energisations in an offshore platform. Simulations of three-pole simultaneous operation GIS circuit breakers, known as gang-operated circuit breakers, in a 115 kV ring bus substation are presented along with field data recorded during commissioning of the PoW controller showing effective mitigation.

11513 - POWERGRID Experience on Insulation Coordination of High Voltage Substations Located at High Terrain and Snow Bound Area: Experience and engineering approaches for the installation of 200 kV substations at altitudes of above 1000 m are presented. Special impulse type testing requirements, constraints faced by manufacturers in non-standard dielectric testing, increased air gap requirements due to decreased insulating property of air

with altitude, etc., are discussed. Findings show equipment design options for high altitudes based on IEC standards for insulation coordination.

11596 - Resonance in 765 KV Shunt Compensated Transmission Lines: Disturbance recordings and electromagnetic transient simulations of line resonances in 765 kV shunt compensated transmission lines are presented. Shunt compensation of transmission lines is applied to improve voltage profile and the use of a properly sized neutral grounding reactor is demonstrated to be an effective mitigation measure against resonant overvoltages. Recorded waveforms of two incidents are presented and reproduced with EMT simulations.

11707 - Measurement of Lightning Current Circulating in Line Arresters and Through the Transmission Line Tower: A strategic implementation of a line surge arrester monitoring system, with a deliberate focus on site selection and cost-effectiveness is given. The design, development and testing in a high voltage laboratory of a measurement system developed to record the lightning current circulating in line surge arresters and through transmission line towers are described.

11711 - Modelling of Flashover on Insulator Strings of Overhead Lines Due to Lightning Overvoltages: The paper presents integration-based and physical models, developed in electromagnetic transients (EMT) software according to CIGRE recommendations, for insulator strings of various voltage levels. To verify the accuracy of calculations, the obtained U-t flashover curves are compared with measurements performed in the HV laboratory. The influence of changes in front and time-to-half durations on the critical flashover voltage is observed.

11736 - Supervision and Forecast of Lightning Threat on Transmission Lines: Lightning data analytics, a correlation of lightning data with transmission line outages, a comparison of transmission line failure with present lightning density (real-time) and the combination of weather forecasts with lightning potential are analysed in comparison to real-time lightning occurrence. An expert system composed of information, monitoring and forecasting modules is introduced.

11787 – Analysis of Several Hypotheses that Caused the Explosion of a 500 kV Current Transformer During Disconnecter Operations: The authors investigate the explosion of a current transformer (CT) in a 500kV substation in Colombia. The explosion occurred when the disconnecter next to the CT operated, causing a large transient overvoltage. Forensic EMT analyses were conducted to identify the root-cause of failure. The paper provides detailed analysis of the incident and a set of operational recommendations to mitigate prospective transient overvoltage during disconnecter operations.