SPECIAL REPORT FOR SC C4
Power System Technical Performance

Special Reporters	Poster Session Conveners
PS1: J. MATEVOSYAN (US), D. RAMASUBRAMANIAN (US)	PS1: Y. VERNAY (FR)
PS2: A. LOBATO CASTRO (ES), Z. EMIN (UK)	PS2 & PS3: K. VELITSIKAKIS (NL)
PS3: C. LETH BAK (DK), J. HE (CN)	

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' (PS), selected in advance by the 16 Study Committees of CIGRE and available in the Call for Papers.

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

To gain an overview of subjects that will be discussed during the week, please have a look at the Technical Programme.

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**' (GDM) 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 "**Special Reports**" which incorporate the gist of the Session Papers and pose a number of questions to the general audience for discussion: the questions and how to respond them are included below.

The Special Reports are available to all (from the start of June) on the Session page of the CIGRE website.

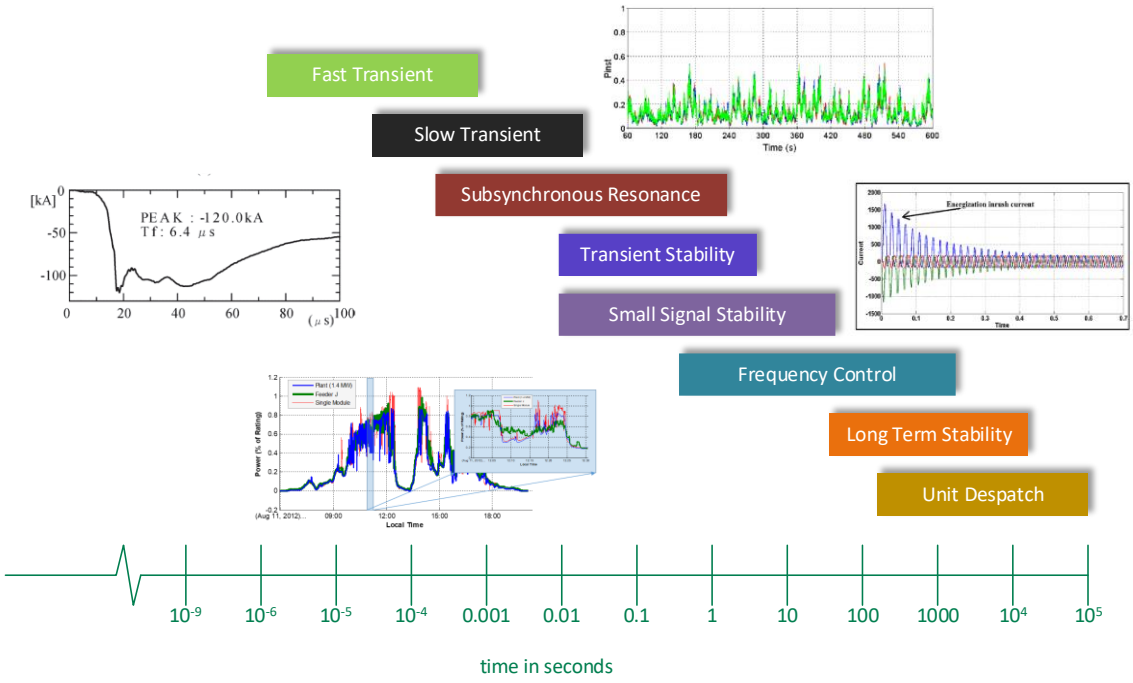
For fruitful discussions delegates are strongly encouraged to read the Special Report and Papers before the Session.

The Session Papers are made available for downloading to all duly registered delegates before the Session through their private account on the registrations portal. Papers are also readable on the Session smartphone application while on site in Paris.

Follow the latest Session news and General Programme by regularly visiting our website!

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.

Within the above scope, SC C4 has selected **126 papers** aligning with the three Preferential Subjects (PS) for the 2026 CIGRE Session:

- **PS1:** Power system stability aspects of decarbonisation of power systems and the road to net-zero (77 papers).
- **PS2:** Power quality (PQ) and electromagnetic compatibility/interference (EMC/EMI) aspects of decarbonisation of power systems and the road to net-zero (30 papers).
- **PS3:** Insulation co-ordination and lightning research: paving the way to net-zero in decarbonised power systems (19 papers).

Three (3) of the 126 selected papers were Next Generation Network (NGN) nominations for the Young Member showcase competition and one successful author will present the paper at the GDM.

PARTICIPATING IN THE 2026 PARIS SESSION – SC C4 ACTIVITIES

1. GROUP DISCUSSION MEETING (GDM)

You are invited to participate in discussing this special report at the SC C4 GDM to be held on **Tuesday 25th August in the BLEU Amphitheatre at the Palais de Congress de Paris, starting at 08:15.**

In the following sections, a summary of each PS is presented along with corresponding discussion questions that have been prepared by the Special Reporters. 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 Special Reporters are not specifically aimed at the papers' authors but are synthesised from common issues and trends identified across all the papers. This provides the opportunity for a broader response and participation in the discussion session. A summary of each paper is provided at the end of the report for completeness.

We encourage you to share your views and experiences in response to the specific questions in this special report. During the GDM, each prepared contribution will be allocated a time slot of **three minutes** for a presentation (therefore **the number of slides, including the title slide, should not exceed three**).

2. PROCEDURE FOR CONTRIBUTIONS TO THE GDM

i. Contributors should upload their contribution(s) on the registrations portal – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials **before 7th August 2026**, for a prior screening and a good organization of the GDM.

ii. 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.
- Register now for the Session registrations.
- Contributions uploading will be open at start of June.

iii. A guide for contributors as well as templates and sample pages are available on the Paris Session webpage. Important note: **No commercial names are to be included in presentation or the written summary** (even TSO/DSO names).

iv. Special Reporters will review the uploaded contributions for readability, technical/scientific content (**no commercial information is allowed**) and relevance to the questions posed in this Special Report.

v. Any requests for changes to the uploaded contributions will be submitted by the Special Reporters to the contributors directly on the registrations platform. Contributors are encouraged to visit their account to check the result of this review. Updated final contributions (when required) shall be uploaded to the registrations portal **by Friday 14th August**.

vi. It is expected that the questions relevant to the PSs will attract many prepared contributions. Consequently, the number of accepted contributions may need to be limited. The selection will be made by the Special Reporters and the SC Chair based on relevance and quality. Final acceptance of prepared contributions will be notified **by Friday 21st August**.

vii. Important note:
- All contributions must be finalised and uploaded to the portal prior to the start of the Conference in Paris.
- Last minute changes to the contributions will not be facilitated.

viii. Detailed instructions related to the presentation during the GDM (e.g. scheduling) will be shared via email the week before the start of the Conference. For SC C4, the Special Reporters will not meet the contributors before the GDM. **All contributors are required to attend the BLEU**

Amphitheatre 30 minutes before the start of the GDM (i.e. at 07:45 for PS1 and 14:00 for PS2/PS3) on Tuesday 25th August and introduce themselves to the Special Reporters.

ix. During the GDM the Study Committee 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 invited to submit a written contribution after the GDM, which will be included in the Session Proceedings. This text is required to be forwarded within two weeks of the Study Committee GDM Session (i.e. **by 8th September**) to the SC Secretary (g.lietz@ieee.org).

3. POSTER SESSION

Authors of accepted SC C4 Session papers are required to present their posters during the SC C4 Poster Session scheduled for **Wednesday 26th August (10:30 to 12:30) in Halle Ternes on level 1**. Posters will be displayed on digital screens.

Template and instructions on poster preparation are available on the registrations platform. Poster presentations must be uploaded on the ConfTool platform **between 18th May and 29th June** for review by the Poster Session Convener. Poster Conveners may ask the authors for a revised version, incorporating any requested changes. The final version must be uploaded **by Friday 14th August**. 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.

4. TUTORIAL AND WORKSHOPS

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

- Joint B4/C4 workshop on **Grid Forming**, co-chaired by Julia Matevosyan and Dechao Kong. Monday 24th August (14:00 to 18:00).
- Joint C4/C1/C2 workshop on **Large Inverter-Based Loads**, chaired by Julia Matevosyan. Tuesday 25th August (16:10 to 18:00).
- C4 tutorial on **Modelling and Simulation of Electromagnetic Transients in Lines, Cables, and Gas-Insulated Substations**, chaired by Haoyan Xue. Wednesday 26th August (16:10 to 18:00).
- C4 workshop on **Generic EMT-Type Modelling of Inverter-Based Resources for Long-Term Planning Studies**, chaired by Jean Mahseredjian. Wednesday 26th August (14:00 to 18:00).
- C4 workshop on **Wide Area EMT Simulations for Stability Analysis in Modern Power Systems**, chaired by Babak Badrzadeh**.** Thursday 27th August (08:30 to 12:30).

5. JOINT PREFERENTIAL SUBJECT SESSION WITH SC C2

SC C4 will support SC C2 with PS3 "**Power System Dynamics and Control in Operations**". The GDM and Poster Session will be jointly managed between SC C2 and SC C4, with Oscar Lennerhag serving as Special Reporter from SC C4.

- The C2 Poster Session will take place on Tuesday 25th August from 14:00 to 18:00.
- The C2 GDM will take on Thursday 27th August (PS3 will run in the afternoon) in the Bleue Amphitheatre.

SUMMARY OF KEY DATES

Date	Time	Action	Location
Monday 29th June 2026	End of day	Deadline for submission of posters for all accepted paper authors	ConfTool
Friday 7th August 2026	End of day	Deadline for uploading prepared contributions for the GDM	registrations portal
Friday 14th August 2026	End of day	Deadline for submission of final versions of posters for all accepted paper authors (if changes are required)	ConfTool
		Deadline for uploading final prepared contributions for the GDM (if changes are required)	registrations portal
Friday 21st August 2026	End of day	Notification of acceptance for prepared contributions for the GDM	Registrations platform
Sunday 23rd August	10:00 to 13:00	SC C4 AG meeting	111-112-113
Monday 24th August 2026	14:00 to 18:00	Joint B4/C4 workshop on Grid Forming	BLEU
Tuesday 25th August 2026	08:15 to 18:00	SC C4 Group Discussion Meeting (PS1 will start at 08:15 and PS2 & PS3 will start at 14:30)	BLEU
	16:10 to 18:00	Joint C4/C1/C2 workshop on Large Inverter Based Loads	BORDEAUX
	14:00 to 18:00	Joint C2 (PS3) / C4 Poster session	Halle Ternes
Wednesday 26th August 2026	10:30 to 12:30	SC C4 Poster session	Halle Ternes
	16:10 to 18:00	C4 Tutorial “Modelling and Simulation of Electromagnetic Transients in Lines, Cables, and Gas-Insulated Substations”	MAILLOT
	14:00 to 18:00	C4 workshop on “Generic EMT-Type Modelling of Inverter-Based Resources for Long-Term Planning Studies	BORDEAUX
Thursday 27th August 2026	08:30 to 12:30	C4 workshop on “Wide Area EMT Simulations for Stability Analysis in Modern Power Systems”	BORDEAUX
	PM	Joint C2 (PS3) / C4 GDM	BLEU
Friday 28th August 2026	09:00 to 17:00	SC C4 meeting	351
Tuesday 8th September 2026	End of day	Deadline for submission of spontaneous contributions to be included in the Session Proceedings	Email to SC C4 Secretary

CONTACT DETAILS

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PREFERENTIAL SUBJECT 1

The primary subject for PS1 is **Power system stability aspects of decarbonisation of power systems and the road to net-zero** and includes:

- Emerging tools and methods for plant and system-wide stability analysis, model validation, advanced data analytics, screening and performance monitoring.
- Power system stability impact of new technologies including storage, large scale inverter-based generators, inverter-based loads, network elements and control methods (e.g. grid forming). Development of appropriate specifications.
- Dynamic phenomena impacting power systems stability - e.g. wide-area, local interactions and forced oscillations.
- Demystifying system strength: definition, metrics, impact on power systems, experiences, challenges and solutions

Seventy-seven (77) papers were accepted, including one NGN successful paper under the NGN showcase competition which will be presented at the GDM:

- "A benchmark model and KPI framework for studying power system restoration of modern grids", by T. SKRJANC (SI)

The global transition toward low-carbon power systems is fundamentally changing the dynamic behaviour of electric grids. Rapid growth of inverter-based generation, storage, HVDC systems, emerging industrial loads, and advanced power-electronic technologies is challenging traditional assumptions regarding system strength, inertia, fault behaviour, oscillatory stability, and system restoration. At the same time, these technologies are creating new opportunities to enhance system performance through advanced controls, and grid services. The papers submitted under PS1 reflect the industry's growing focus on understanding these evolving dynamics, developing advanced modelling and simulation tools, and deploying new technologies capable of maintaining reliable and resilient operation in increasingly converter-dominated power systems. Together, they provide valuable insights into the technical challenges and practical solutions associated with achieving a secure and stable pathway toward decarbonized electricity systems.

The papers have been grouped into three themes. A brief description of each theme and the associated questions are presented below:

PS1 Theme 1 System Strength, Stability and Oscillatory Interactions in Converter-Dominated Power Systems

The industry is confronting the rapid rise of inverter-based resources, which erodes traditional notions of system strength, inertia, fault behaviour, oscillatory stability, and dynamic performance. As inverter-based generation, large inverter-based loads, hydrogen production facilities, HVDC systems, and other power-electronic-interfaced technologies proliferate, traditional planning and operational metrics are increasingly insufficient to predict emerging stability challenges. New approaches and metrics are being developed to assess system strength, including impedance-based, and machine-learning-assisted metrics that capture complex interactions between converters and the network beyond conventional SCR-based indices. At the same time, power systems are experiencing new forms of oscillatory behaviour, ranging from subsynchronous control interactions and converter-driven resonances to evolving inter-area oscillation characteristics associated with changing resource mixes and declining inertia and damping.

The papers in this theme highlight the growing importance of advanced monitoring, frequency-domain analysis, high-resolution measurements, and data-driven techniques for identifying, localizing, and mitigating stability risks. They also examine the stability impacts of emerging technologies such as data centres, electrolyzers, grid-forming resources, and advanced protection systems, as well as lessons learned from real-world disturbance events. Across the papers a common need emerges for practical and scalable methods to assess stability, quantify system strength, understand converter

interactions, and guide the deployment of mitigation measures and operational strategies. Together, these contributions provide new insights into maintaining reliable and resilient operation of power systems as they evolve toward increasingly converter-dominated futures.

The following papers are related to this theme: 10102, 10154, 10487, 10492, 10507, 10508, 10509, 10676, 10682, 10903, 10905, 10938, 10993, 11132, 11261, 11262, 11445, 11446, 11521, 11553, 11641, 11764, 11769, 11784, 12039, 12063, 12325, 12435, 12540, 12541, 12542, 12625.

Q1.01: What are the advantages and limitations of emerging dynamic strength metrics (dSCR, IMR, AEI) compared to traditional SCR based indicators?

Q1.02: In what ways does the increasing penetration of inverter-based resources alter inter-area mode frequencies and damping ratios?

Q1.03: What are the most effective strategies for detecting and localizing sub-synchronous oscillations in real-time operation?

Q1.04: How should calculation methods and protection settings be redefined to accommodate the diverse fault-current characteristics of grid-forming and grid-following inverters?

Q1.05: What lessons from recent disturbance events can inform the development of more resilient system-wide automation and protection schemes?

Q1.06: Should low frequency inter-area oscillations, such as 0.2 Hz, be categorized as sub-synchronous oscillations? If yes, then why. If no, then what should be the basis to distinguish between types of oscillations?

PS1 Theme 2 Modelling and Advanced Simulation Methods

The rapid transition toward converter-dominated power systems is driving unprecedented demands on modelling, simulation, and stability assessment methodologies. Traditional analysis approaches are increasingly challenged by the scale and dynamic complexity of networks containing large numbers of inverter-based resources, inverter-based loads and HVDC systems. In response, the industry is advancing a broad suite of tools ranging from high-fidelity electromagnetic transient (EMT) models and digital twins to scalable screening techniques that support both planning and operational decision-making.

Many contributions in this theme focus on improving the fidelity, interoperability, and practical usability of dynamic models throughout the asset lifecycle. Advances in CHIL and digital-twin methodologies are reducing commissioning effort and hardware dependence, while new approaches to EMT model exchange, validation, benchmarking, and intellectual property protection are enabling more effective collaboration between system operators, developers, and equipment manufacturers. Large-scale EMT simulations, equivalent network representations, GPU-accelerated solvers, restoration benchmarks, and co-simulation frameworks are extending the range of phenomena that can be studied while maintaining practical computational requirements.

At the same time, frequency-domain and impedance-based methods are emerging as essential complements to traditional time-domain simulations. Techniques such as impedance identification, Nyquist-based stability assessment, and uncertainty-aware screening provide efficient means of assessing converter interactions, resonance risks, and system strength limitations before detailed EMT studies are required. Benchmarking efforts and open-source tools are helping establish common practices and improve consistency across organizations.

Collectively, the papers illustrate the industry's transition toward integrated modelling frameworks that combine high-fidelity simulation, scalable screening methods, real-world validation, and advanced analytical techniques to support the reliable evolution of increasingly complex power systems.

The following papers are related to this theme: 10134, 10155, 10350, 10506, 10511, 10564, 10724, 10781, 10859, 10904, 10915, 10920, 11091, 11432, 11609, 11610, 11618, 11753, 11773, 11814, 11859, 11860, 12258, 12265, 12317, 12543, 12602, 12646.

Q1.07: What validation strategies are most effective for ensuring that high-fidelity EMT models accurately reflect field behaviour across diverse assets?

Q1.08: How can frequency-domain impedance screening be standardized to reduce inconsistencies among different tools and utilities?

Q1.09: How can the industry balance the protection of OEM intellectual property with the need for transparent, high-resolution EMT models?

Q1.10: What criteria should be used to decide between phasor-domain and EMT modelling for studying inverter-based load interactions?

Q1.11: In what ways can CHIL and digital-twin methodologies replace or complement traditional hardware-in-the-loop testing for DER integration?

PS1 Theme 3 Grid Forming and Grid Enhancing Technologies for Stability and Resilience

The rapid growth of inverter-based resources is transforming how power systems maintain system strength, frequency stability, voltage support, and resilience. As conventional synchronous generation retires, grid-forming (GFM) converters are emerging as a key technology capable of providing many of the stability services traditionally supplied by synchronous machines, including voltage regulation, synthetic inertia, oscillation damping, fault-ride-through capability, and black-start support. At the same time, a broader portfolio of grid-enhancing technologies—including battery energy storage systems (BESS), STATCOMs, synchronous condensers, and advanced converter controls—is being deployed to address emerging stability challenges and enable reliable operation under high penetrations of inverter-based resources.

The papers in this theme examine how these technologies can improve system strength, enhance damping of local and inter-area oscillations, support frequency and voltage recovery following disturbances, and reduce reliance on costly network reinforcements and conventional generation. Several contributions investigate performance, optimal placement, and control of grid-forming and grid-supporting technologies, while others explore practical applications such as supporting highly dynamic data centre loads, hybrid diesel-BESS power stations, and system restoration following major outages.

As GFM technologies move from demonstration projects to large-scale deployment, significant attention is being given to practical implementation challenges, including fault-ride-through performance, synchronization under severe disturbances, current-limiting and negative-sequence control strategies, interoperability among multiple grid-forming devices, and compliance with evolving technical standards. Real-world operating experience, post-commissioning validation, and large-scale EMT studies demonstrate the growing maturity of these technologies and their ability to provide commercial stability services. Collectively, these contributions illustrate the increasingly important role of grid-forming and grid-enhancing technologies in maintaining reliable, secure, and economically efficient operation of modern power systems undergoing rapid transformation.

The following papers are related to this theme: 10162, 10183, 10348, 10396, 10397, 10715, 11251, 11702, 11713, 11772, 11826, 11856, 12227, 12320, 12328, 12466, 12578.

Q1.12: How can grid-forming converters be optimally positioned within a network to maximize their damping contribution while preserving system strength?

Q1.13: What are the trade-offs between using STATCOMs, synchronous condensers, and BESS for providing fast frequency response and voltage support in high-RES scenarios?

Q1.14: Does tuning of fault-ride-through (FRT) performance play a role in preventing loss-of-synchronism for GFM converters during severe, long-duration faults?

Q1.15: How can real-world post-commissioning validation data be integrated into simulation models to reduce uncertainty in performance predictions of GFM devices?

Q1.16: How can coordinated deployment of grid-enhancing technologies be incorporated into transmission planning tools to address both steady-state and dynamic stability challenges?

PREFERENTIAL SUBJECT 2

Preferential Subject 2 covers **power quality (PQ) and electromagnetic compatibility/interference (EMC/EMI) aspects of de-carbonisation of power systems and the road to net-zero**.

PS2 session provides a comprehensive overview of emerging power-quality and electromagnetic compatibility challenges in transmission and distribution systems undergoing rapid decarbonisation. It covers three themes:

- Modelling and simulation for assessment of PQ and EMC phenomena and mitigation strategies in meshed transmission systems
- Experiences with PQ issues in IBR-dominated systems and advanced data analytics, including allocation and compliance
- Experiences with EMI for large inverter-based generators and loads and interference between the power system (AC or DC) and pipelines and telecom systems

In total, thirty (30) papers were accepted. The contributions cover voltage fluctuations and flicker in modern loads such as LED lighting and PV installations, the growing influence of inverter-based resources on harmonics, supraharmonics, and voltage dips, and the difficulties of harmonic allocation, background amplification, and resonance assessment in increasingly cable-rich and converter-dominated networks. Several papers present advanced measurement-based and optimisation-based methods to improve harmonic modelling, allocation, and monitoring, alongside long-term analyses of voltage dips and harmonic behaviour from wind parks and transmission monitoring systems. System-integration challenges are further explored through studies on offshore wind, HVDC links, underground cables, and shared infrastructure corridors, highlighting risks related to resonance, earth-potential rise, and electromagnetic interference with pipelines and telecommunication systems. The session also addresses extreme-event phenomena, including geomagnetically induced currents, and demonstrates the need for adaptive control, online monitoring, and coordinated mitigation strategies. Collectively, the papers emphasise that ensuring power-quality compliance and system robustness in the net-zero transition demands holistic, measurement-validated approaches that integrate planning, design, operation, and resilience considerations.

Papers are grouped within the three thematic areas with further subdivision:

PS2 Theme 1: Modelling and simulation for assessment of PQ and EMC phenomena and mitigation strategies in meshed transmission systems

12 papers present concepts and results that are assigned to PS2 Theme 1. The papers within this theme can be grouped under two areas:

Papers 10908, 10967, 11540, 11776, 11777, 11811 and 12329 focus on advanced modelling and simulation techniques required to assess harmonic propagation, resonance, and amplification risks in increasingly meshed, cable-rich transmission networks. They highlight the limitations of traditional deterministic approaches when faced with multiple, uncertain harmonic sources and demonstrate the value of measurement-validated models, optimisation-based estimation of equivalent injections, frequency scanning, and online resonance monitoring. Collectively, they emphasise that accurate harmonic assessment and effective mitigation in modern transmission systems depend on combining detailed network modelling with real-world data, adaptive tools, and system-wide visibility of impedance and resonance conditions.

Papers 10304, 10906, 10969 and 11555 and 11556 focus on electromagnetic transient studies addressing switching phenomena, transformer energisation, resonance effects, and voltage-dip propagation. The papers show that realistic equipment modelling, statistical behaviour, and validation against long-term monitoring data are crucial for accurately assessing transient-driven power-quality impacts and supporting reliable planning and operation.

Q2.01: What challenges have been encountered in applying traditional deterministic approaches to managing harmonics? Can you provide examples of case studies with specific challenges on project execution (for example assuming the wrong background distortion or multiple projects interacting with each other)?

Q2.02: What alternative approaches have been developed (such as adaptive analytical approaches or introduction of optimization-based tools) to overcome the challenges in harmonic assessments and how do these alternative approaches fare in the management of harmonics? Can you provide specific success stories when applying these alternative approaches?

Q2.03: What has been the experience with assessment methods for rapid voltage changes based on simulation analysis and/or long-term monitoring data? Can you provide examples of specific study cases? Can you provide examples of validated assessments based on alternative approaches?

PS2 Theme 2: Experiences with PQ issues in IBR-dominated systems and advanced data analytics, including allocation and compliance

12 papers present concepts and results that are assigned to PS2 Theme 2.

Papers 10394, 10968, 11541 and 11781 report operational experience showing that inverter-based resources significantly influence harmonics, supraharmonics, and voltage fluctuations through control behavior and aggregation effects.

Papers 10303, 11284 and 12539 highlight practical challenges in maintaining power-quality compliance for large renewable plants, particularly offshore wind, requiring coordinated onshore and offshore mitigation and continuous reassessment as system conditions evolve.

Papers 10843, 12103 and 12456 address the growing complexity of PQ allocation and grid-code compliance, demonstrating that traditional limit-setting approaches can become overly conservative under contingency-driven and low-emission constraints

Finally, papers 10175 and 11135 focus on the increasing role of large-scale monitoring and advanced data analytics to identify long-term PQ trends and support evidence-based planning and operational decisions.

Q2.04: What has been the observed impact of increased IBR penetration (including increased use of underground circuits) on power quality beyond a shift in resonant frequencies and harmonic distortion)? The question is looking on impact in areas such as voltage unbalance, rapid voltage changes, voltage fluctuations (flicker) and voltage dips/swells.

Q2.05: What has been the experience with measurements of power quality metrics (harmonics, unbalance, flicker, voltage dips, rapid voltage changes etc.)? Can you provide examples of validated assessments, usage in investigation of system event or damages to assets, correlation with specified emission limits or dispute resolution?

Q2.06: What are the risks of considering too many scenarios (for example extreme grid conditions) in the assessment of power quality compliance and allow them to establish somewhat unrealistic worst-case conditions? How should these risks be managed and mitigated?

PS2 Theme 3: Experiences with EMI for large inverter-based generators and loads and interference between the power system (AC or DC) and pipelines and telecom systems.

6 papers present concepts and results that are assigned to PS2 Theme 3.

Three papers, 10571, 11882 and 11905 report practical experience with electromagnetic interference between AC/DC power systems and nearby pipelines or telecommunication networks, highlighting safety, corrosion, and coexistence challenges in shared corridors.

Papers 10575 and 11557 focus on EMI and power-quality issues arising from inverter-dominated generation, inverter-duty transformers, and instrument transformers, emphasizing interaction effects and measurement limitations.

Finally, Paper 12547 addresses power-quality impacts from extreme external phenomena such as geomagnetically induced currents, demonstrating their influence on harmonic distortion and system vulnerability.

Q2.07: Can you provide real examples of EMI interference associated with AC/DC power systems or nearby pipelines or telecom networks and how did these issues got resolved? What are the observed trends when aiming to minimize such issues?

PREFERENTIAL SUBJECT 3

The primary subject for PS3 is "**Insulation co-ordination and lightning research: paving the way to net-zero in decarbonised power systems**" and it covers three themes:

- Future of insulation co-ordination for AC, DC and hybrid systems.
- Improvement of lightning detection systems with a focus to enhance power system reliability.
- Lightning protection strategies for transmission lines and hybrid systems, including the impact of thunderstorms and extreme weather events.

In total, nineteen (19) papers were accepted. A brief description of each theme and the associated questions are presented below.

PS3 Theme 1: Future of insulation co-ordination for AC, DC and hybrid systems

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

Papers 10305, 10907, 11085, 11086, and 11622 address overvoltage analysis, insulation coordination, and system studies. Paper 10305 presents continuous transient voltage measurements on a 110 kV transformer, confirming robust insulation coordination. Paper 10907 investigates ferroresonance during a blackout test on a 400 kV isolated network using EMT simulations. Paper 11085 examines HVDC insulation coordination for VSC and Dedicated Metallic Return (DMR), showing full-bridge converters produce lower overvoltages. Paper 11086 proposes a screening method for transformer energization using Transformer Short Circuit Ratio (TSCR) and harmonic impedance metrics, validated on 51 cases. Paper 11622 studies sustained overvoltages in offshore wind 66 kV cables under islanding, identifying converter blocking as an effective mitigation.

Papers 11249 and 11582 address contamination mapping and fault diagnosis. Paper 11249 presents CIGRE work on pollution severity maps with correction factors for AC/DC, insulator geometry, and material. Paper 11582 presents a fault identification method using traveling wave data and deep learning, achieving 96.2% accuracy on 500 kV line faults.

Q3.01: What are the challenges and experiences in transient overvoltage simulation in HVAC, HVDC, offshore wind, and distribution systems? What mitigation strategies (e.g., converter blocking, strategic arrester placement, screening methods for transformer energization, statistical risk-based design, and grounding system design) have proven effective, and how can continuous monitoring and measurement data (e.g., transient voltage recordings) improve EMT model validation and insulation coordination?

Q3.02: What advancements have been made in modelling and diagnostic techniques for insulation coordination and system reliability, including contamination mapping, fault cause identification using distributed traveling wave data with deep learning, and sample balancing methods? How can these tools be applied to optimise maintenance, reduce study workloads, and support the secure integration of renewable and offshore wind energy sources?

PS3 Theme 2 Improvement of lightning detection systems with a focus to enhance power system reliability.

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

Papers 10970, 10971, and 11919 address advancements in lightning detection systems and performance assessment methodologies. Paper 10970 analyses 40+ years of Japanese outage data, demonstrating that the use of externally gapped line arresters (EGLAs) on 66/77 kV lines significantly reduces lightning outages, with dual-circuit installation nearly eliminating all events. Paper 10971 presents a new lightning location system with ~40 m accuracy, capable of estimating charge amount

(>50 C), peak current, and steepness, validated using a 634 m tower. Paper 11919 proposes an hourly lightning risk assessment framework incorporating wind-induced insulator swing and DBSCAN clustering, showing that wind can increase shielding failure flashover rate by up to 400%.

Q3.03: What location accuracy and detection efficiency must modern lightning location systems achieve to enable the integration of high-resolution stroke data (peak current, steepness, charge, polarity)?

PS3 Theme 3 Lightning protection strategies for transmission lines and hybrid systems, including the impact of thunderstorms and extreme weather events.

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

Papers 11087 and 11089 investigate lightning performance assessment methods for extra high voltage and hybrid lines. Paper 11087 evaluates the relative impact of negative first, subsequent, and positive strokes on 500 kV HVAC and ±500 kV HVDC lines, revealing that positive strokes significantly affect HVDC performance while negative first strokes dominate overall outage rates. Paper 11089 examines overvoltages on hybrid overhead lines (138 kV, 13.8 kV, 220 V) via EMT simulations validated by scale model testing, demonstrating that longer current front times and lower grounding impedance reduce overvoltages, with the low-voltage circuit providing additional attenuation.

Papers 10327, 10930, and 11799 present assessment methods for specialized applications. Paper 10327 quantifies differential insulation using arcing horns on 500 kV double-circuit lines, showing reduced double-circuit backflashover but increased single-circuit rates, highlighting coordinated gap design. Paper 10930 develops a probabilistic risk model for subsoil arcing and pipeline damage from lightning- or fault-initiated arcs, with fault-initiated events dominating. Paper 11799 presents real-time monitoring of lightning currents on a 110 kV tower with line arresters, using Rogowski coils and 5G communication, successfully recording multiple events and validating measurements against LLS data with Kalman filtering.

Papers 10936 and 11088 present assessment methods for grounding design. Paper 10936 introduces a probabilistic framework using Markov Chain Monte Carlo to quantify uncertainty in fall-of-potential grounding resistance measurements, the approach supports risk-based lightning performance assessment by propagating grounding resistance uncertainty into backflashover rate calculations and acceptance criteria. Paper 11088 presents a statistical methodology for grounding design of transmission line and wind farm towers, using geometric averaging of apparent resistivity curves to derive standard curves and grounding phases, improving efficiency over traditional site-by-site inversion.

Paper 11775 challenges the 10 m bonding lead standard for cross-bonded cable systems through EMT simulations, demonstrating that fault scenarios allow leads up to 50 m, while lightning strikes limit safe lengths to 15–20 m depending on strike magnitude.

Paper 10702 addresses work safety on overhead lines by using EMT simulations to design a temporary protection grounding (TPG) protocol for a 400 kV double-circuit line, confirming that a TPG with equipotential bonding ensures operator safety during distant lightning without additional grounding on adjacent towers.

Q3.04: What is the experience with EMT analyses in simulating lightning-related transients and developing effective countermeasures for overvoltage suppression to prevent insulation failures and power system malfunctions?

Q3.05: What are the best practices and challenges in grounding design, cable bonding, and temporary protection grounding for transmission lines, wind farms, and cable systems? How can statistical resistivity methods improve grounding efficiency, what are the safe limits for bonding lead lengths under lightning strikes, and how can EMT simulations ensure operator safety during maintenance?

PAPER SUMMARIES

PS1: POWER SYSTEM STABILITY ASPECTS OF DECARBONIZATION OF POWER SYSTEMS AND THE ROAD TO NET-ZERO

10102 - Physics-Informed Neural Networks (PINN) for Enhanced Power System Strength Assessment: This paper introduces a novel machine learning-based approach that captures the physics of complex power systems and aims to predict power system stability outcomes based on previously defined metrics and advanced AI algorithms.

10134 - Open-source tools for frequency-domain stability analysis of black-box and white-box AC/DC grids: This paper presents a framework for frequency-domain stability assessment of converter-dominated AC/DC systems by combining black-box impedance identification with analytical modelling tools. The authors propose a methodology to extract, integrate, and interpolate black box converter frequency responses and demonstrate its effectiveness through a validated HVDC case study.

10154 - Design of an Energy Hub for Stable Large-Scale Green Hydrogen Production: This paper addresses the design and dynamic performance of a large-scale off-grid renewable energy system intended for green hydrogen and ammonia production. The concept involves the conversion of multi-gigawatt wind generated power into hydrogen through electrolysis and synthesizing ammonia for export. The objective of the study is to validate the feasibility of an off-grid architecture dominated by converter-based resources (CBRs) and to define principles for frequency and voltage control. The work focuses on electrical architecture screening, stability assessment, and dynamic simulations to ensure robustness against severe disturbances and operational uncertainties.

10155 - Application of Passivity-Based Control Interaction Assessment and Mitigation in AC/DC Power Systems with Black-Box Models: This paper shows that stability assessment based solely on AC-side impedance or passivity criteria can lead to incorrect conclusions in AC/DC hybrid systems. Using a black-box admittance approach for an MMC with DC-voltage droop control, the study shows that changes in DC-side dynamics primarily affect AC/DC coupling terms, which can significantly alter system stability even when the AC-side admittance remains unchanged. The AC only passivity-based design is highlighted, and the findings are validated through EMT simulations under weak DC grid conditions. An equivalent AC admittance formulation incorporating AC/DC coupling is proposed to enable more accurate frequency-domain stability assessment.

10162 - Mitigation of Low-Frequency Inter-Area Oscillation Using Grid-Forming Inverters: This paper assesses the intrinsic damping contribution provided by GFM inverters in the frequency range of inter-area modes and compares them to GFL converters with- and without- a dedicated POD-P or POD-Q controller. Initially, several sensitivities are unveiled for a benchmark two-area four-machine system. Further, a representation of the Continental Europe synchronous area system with a past oscillation event is investigated. The paper highlights the effect of GFM controllability (related to its position in the power system) on its damping contribution.

10183 - Dynamic Impact Assessment of High IBR Penetration and Grid Enhancement Technologies on Power Systems: This paper presents a practical study on the dynamic impacts of increasing IBR penetration on power system stability and on the evaluation of mitigation strategies using Grid Enhancing Technologies (GETs). Using reduced, standard positive-sequence simulation models (WECC 240-bus) divided into 14 zones, the study analyses locational differences in system strength, frequency response, and voltage recovery under different IBR penetration scenarios. The work evaluates mitigation solutions, including STATCOMs, shunts, and BESS, providing fast frequency response and synthetic inertia. The results highlight that IBR integration impacts vary significantly across regions and demonstrate that coordinated deployment of GETs can improve voltage recovery, frequency response, and accommodating capacity while potentially reducing the need for transmission expansion.

10348 - Stabilisation of Subsynchronous Controller Interactions using a Robust Data-driven Grid-forming Control in e-STATCOM: This paper presents a data-driven voltage controller design for a GFM e-STATCOM to achieve effective SSO mitigation across a range of resonance frequencies. The identification of system dynamics and the development of respective control objectives in the frequency domain eliminates the need for detailed system information, making it well-suited for large-scale networks. The proposed controller design is evaluated with respect to stability, damping performance, and robustness through a number of assessments, which showed substantial improvements in comparison to a baseline PI controller.

10350 - The Journey of Commissioning a Large-scale Solar Plant and the Lessons Learnt: Role of Pre-commissioning Platform: This paper presents the use of a pre-commissioning platform developed for a solar plant. It is based on CHIL testing and is the first of its kind in Australia, in that it facilitates a holistic analysis and assessment of plant operation. Commissioning time is shown to be reduced as a result of earlier identification of potential issues, therefore requiring fewer back and forth iterations between plant owner and system operator.

10396 - Grid-Forming Inverter Capabilities for System Restoration in 100% IBR Power Systems: This paper examines the role of GFM inverters in the system restoration process. The authors address the topic on a holistic manner covering a wide range of factors including the GFM/GFL ratio required for stable restoration, the influence of the black start source on DER protection, and the impact of DER penetration on stability. Guidance is provided on practical implementations of black-start capability in inverter dominated systems, based on simulations using generic models in a small system. The paper concludes that GFM BESS can be considered as a basic solution for black starts, offering an additional or alternative path for future grid restoration in IBR-dominated systems.

10397 - Fault-Ride-Through Performance of Grid-Forming Battery Energy Storage Systems: Observations and Analysis of Synchronisation: This paper presents an EMT study conducted with OEM models aimed to investigate the synchronisation performance of GFM BESS during fault conditions. It is shown that FRT control strategies and specific parameter tuning affect the synchronisation (or loss-of-synchronism LoS) performance. The study shows that GFM BESS can exhibit better synchronisation performance than equivalent synchronous generators, especially for severe long duration faults. Finally, it highlights that GFM BESS are also susceptible to LoS and emphasises the need for adequate tuning of FRT controls.

10487 - Dynamic Modelling of Coordinated UFLS and DER Shedding in Wide Area RMS Studies of Non-credible Events: This paper illustrates the performance degradation of Under-Frequency Load Shedding (UFLS) schemes in the presence of large volumes of Distributed Energy Resources (DER) and distributed photovoltaic (DPV). The authors introduce an augmented UFLS relay model designed for large-scale phasor-domain studies and demonstrate its effectiveness and scalability against a severe non-credible contingency event experienced in Australia. The authors show that dynamic arming relay functionality (i.e. ability to disarm during periods of reverse flow) can significantly improve the retention of DER generation while maintaining frequency stability. This work provides a detailed and scalable framework for assessing UFLS responses in broader applications.

10492 - Frequency Stability Challenges and Solutions in Low-Inertia Power Systems with Hyperscale Data Centres: This paper examines how utility-scale data centre operation, driven by AI training and inferencing workloads, may introduce sudden large active power mismatches and thus pose risk to frequency stability in low-inertia power systems. A modelling framework is proposed to represent key data centre behaviours relevant to frequency control studies, including voltage-driven uninterruptable power supply (UPS) switching strategy and high-magnitude server load fluctuations. The approach is illustrated with a representative model of the Australian transmission system, showing that data centre operation can introduce high RoCoFs and nadir/zeniths, and sustained frequency

oscillations which may evolve into generation tripping. The effectiveness of utility-scale GFM BESS as a potential mitigation option is examined via simulation.

10506 - Dynamic Modelling of Large Inverter-Based Loads: A Data Centre Perspective: This paper describes the complex dynamic behaviour of data centres (which differs from traditional loads and IBRs) and proposes a framework for accurate modelling in phasor domain and EMT, with appropriate treatment of control and protection logic. The paper clearly describes the architecture of a typical Data Centre and outlines the key components that determine its dynamic performance during system disturbances and the deficiencies of "conventional" load models. The paper emphasises key behaviours that need to be captured in the models, including FRT capability, response to unbalanced faults and phase-jump conditions, DC voltage and current stability, reactive power dynamics, and post-disturbance recovery trajectories, including conditional transfer to internal supply and staged reconnection.

10507 - Protection System Challenges with Inverter-Based Resources: Insights, Modelling Needs, and Performance Recommendations: This paper documents an international survey on protection relay misoperation in systems with high IBR penetration and examines technical and operational issues that arise as the energy transition accelerates. The paper considers both GFL and GFM inverters, discusses how their operating principles interact with protection functions during faults, and contrasts their behaviour with that of synchronous generation. A practical framework is introduced for defining and evaluating "protection-quality fault response" for inverter-based resources. The authors highlight six measurable fault-current characteristics and suggest initial performance benchmarks to create more consistent expectations for both grid-following (GFL) and grid-forming (GFM) inverters.

10508 - Sizing grid-forming inverters to support grid-following inverters using frequency scan approach: This paper introduces a novel, frequency-domain approach to quantify system strength support provided by a GFM resource using frequency scans. The proposed method uses transfer functions from the grid voltage magnitude and phase, respectively, to the reactive and active power output of a GFM resource for quantifying its contribution to system strength. The authors demonstrate that these transfer functions provide a direct measure of the ability of a GFM resource to behave as a stiff voltage source behind a reactance over a specified frequency range, enabling robust quantification of its system strength contribution. The paper also demonstrates how frequency scans could identify if an unstable condition observed during weak grid conditions is a result of the lack active or reactive power support or both.

10509 - Analysis, Modelling, and Mitigation of Sub-synchronous Oscillations in a Weak Grid with High Inverter-Based Resources: A practical case study of the 17 Hz oscillations experienced in the West Murray area of Australia is presented in this paper. The base case model is developed and shown to successfully replicate field measurements of the oscillations. Several remedial actions are tested, including re-tuning the inverter control system, installing synchronous condensers, using grid forming (GFM) inverters, and constraining the number of online inverters of the contributing IBRs.

10511 - System Services in an Inverter-Dominated Grid: Insights from EMT Modelling of the NEM through to 2034: This paper presents an investigation conducted with EMT into the feasibility of operation of the Australian power system without synchronous machines. The work focuses on understanding the technical needs of Australia's evolving power system for system services and identifies a minimum requirement for 30% grid-forming IBR in order to preserve stability with a fully inverter-based system. The paper also highlights new phenomena observed at 100% IBR penetration level requiring further investigation: widespread phase angle jumps during faults and overvoltages during remote faults.

10564 - Load Characteristics of Emerging Bulk Loads – Electrolysers and Data Centres in the Renewable Energy Era: This paper examines the dynamic behaviour of new Inverter-Based-Loads (IBL), namely electrolysers and data centres, from a power system integration perspective. EMT

simulations with the generic PERC1 model in a SMIB setup illustrate the dynamic behaviour of IBLs during voltage dips and the subsequent effect on system voltage due to the load disconnection.

10676 - Subsynchronous Neutrality of Series Compensated Lines: This paper introduces the concept of subsynchronous neutrality for series-compensated networks and proposes a screening process to identify and mitigate potential SSR risks. The authors evaluate mitigation approaches, including passive damping filters, thyristor-controlled series capacitors (TCSC), and static synchronous series compensators (SSSC), using frequency-domain scans based on the IEEE SSR benchmark model.

10682 - Synchrophasor Data-Driven Investigation of Real-World Unstable Controller Dynamics: This paper illustrates the use of spectral analysis and system identification for synchrophasor data to successfully diagnose root causes of unstable controller dynamics across three real-life incidents: (1): Data Center UPS Instability (14.7 Hz); (2) PV Controller Delay (0.05 Hz); (3) Abnormal PV plant dynamic behaviour during low active power operation (0.07 Hz).

10715 - Leveraging Energy Storage to Accelerate Integration of Data Center Loads: This paper examines the application of behind-the-meter BESS to mitigate negative impacts of AI data centre loads on the host power system (i.e. fast and large power fluctuations). The authors describe HIL tests conducted to evaluate the BESS performance with different system strength conditions. Test results demonstrate that behind-the-meter BESS can reduce upstream transformer overload and buffer the grid from rapid load swings, but the benefit is limited by the controller–inverter communication delays.

10724 - EMT Modelling and Simulation of Grid Following Converters in Modelica Integrating the IEEE/CIGRE 'Real Code'/DLL Modelling Guidelines: This paper deals with portability and interoperability of OEM EMT models using the CIGRE/IEEE DLL interface format. The authors demonstrate proof of concept implementation of a CIGRE/IEEE DLL based controller model in a non-vendor specific, open-source platform such as Modelica, and validate the approach against an equivalent implementation in a commercial EMT software package.

10781 – France-Italy HVDC Link Offline EMT Model Based on Partially Open Control and Protection Software: This paper describes a collaborative approach between a TSO and an OEM for modelling and validating a partially white box EMT model of a VSC HVDC link. The authors present a validated, lifecycle-compatible EMT modelling framework for MMC-HVDC systems that combines open high-level controls for TSO flexibility with protected low-level OEM control, enabling accurate, adaptable, and IP-secure offline studies. The modelling approach has been applied to the France-Italy VSC-HVDC link and validated against Factory Acceptance Tests (FAT), Dynamic Performance Tests, real-time replica simulations, and field measurements from actual events.

10859 - Stability Assessment of Large Electronic Loads: Insights from Impedance and Eigenvalue Analyses: This paper examines the stability impact of large power-electronic loads on power systems using a UPS EMT model as a representative case. The authors combine impedance scanning and small-signal eigenvalue analysis as fast screening tools, and cross-check their indications against time-domain EMT simulations while varying grid strength (SCR) and key control-loop settings to verify when damping degrades or oscillations emerge. The paper also discusses when phasor-domain models may be adequate versus when EMT modelling is required, with the stated intent of guiding efficient study workflows for converter-dominated systems.

10903 - A Case Study on the Impact of Electrolyser Behaviour During Faults on Transient Stability: This paper examines the impact of thyristor-based electrolyser power recovery behaviour on rotor angle stability. The key aspect is the coupling of active and reactive power. Studies are conducted using a 2040 scenario of the French transmission grid including a large electrolyser in close proximity of synchronous generators. The results show that, for this type of thyristor-based installations, a fast power recovery can be detrimental to rotor-angle stability. It is concluded that

converter technologies for which reactive power is intrinsically tied to active power, such as thyristor-based rectifiers, require slower or conditioned active power recovery. Conversely, technologies allowing independent behaviour of active and reactive power, such as IGBT-based converters, can accommodate faster active power recovery without degrading stability. The key recommendation is that connection codes need to account for the diversity of electrolyser converter technologies when defining future grid connection requirements to ensure robust integration and power system stability.

10904 - EMT Generic Wind Turbine Model for Offshore Substation Design: This paper proposes and validates a grid-code-compliant generic EMT model of Type-4 grid-following wind turbines intended for early-stage offshore substation design, when OEM models are not yet available. The proposed model provides a more realistic representation of the converter-based wind turbine generator behaviour than the Thevenin equivalents commonly used in early-stage offshore wind studies. Notably, it can accurately reproduce the positive- and negative-sequence components of the fault current, which are governed by converter control and reactive current injection during faults. Preliminary analysis using the generic model allow early identification of potential overvoltages issues during fault clearing and compromised performance of protection systems.

10905 - Analysis of Classical SISO POD Controller Robustness for Inter-Area Oscillations Damping: This paper examines the robustness and effectiveness of SISO POD controllers to changes in location and operating conditions. By comparing eigenvalue sensitivities across multiple scenarios, the study aims to identify the limits of standard POD designs and to clarify how suitable they are for widespread deployment in modern, highly dynamic power systems.

10915 - Dynamic Impedance Method (DZM) Stability Screening for Large Systems: This paper discusses approaches for assessing power transfer limitations in converter-dominated power systems using impedance-based indicators. A voltage modulation method implemented in EMT is proposed to derive frequency-dependent characteristics intended to provide insight into dynamic interaction effects between converters and the grid. The authors introduce the Dynamic Impedance Method (DZM) as a practical screening tool for assessing system strength and stability margin and compare outcomes against EMT and Positive Sequence Dynamic Simulation (PSDS) over a large number of scenarios showing statistical correlation between the methods.

10920 - Impedance-Based Screening for Control Interaction Risk using Harmonic Impedance Sectors: This paper proposes a frequency-domain screening method for identifying potential control interaction and harmonic instability risks in converter-dominated power systems using the concept of harmonic impedance sectors. The approach aggregates frequency-dependent variations in grid impedance into sector envelopes intended to represent uncertainty due to changing operating conditions and future system developments. Screening criteria based on impedance magnitude/phase intersections, voltage amplification, and Nyquist-based considerations are combined to shortlist scenarios that require further detailed EMT analysis.

10938 - Mitigating Oscillations in the Victorian Transmission Network: A Structured Remediation Approach: This paper presents a structured approach to detect, localise, reproduce, and mitigate sub-synchronous voltage oscillations (SSCI, roughly 5–25 Hz) experienced in the Australian transmission network. The proposed approach combines PMU-based oscillation source location (modified CDEF, applied consistently to PMU and EMT outputs) with wide-area EMT studies. It then tests mitigation options in EMT, concluding that a grid-forming BESS plus a local dynamic voltage control (DVC) loop can reduce the observed oscillation magnitude to the acceptance threshold.

10993 - NEM Inter-Area Modes Dependencies: This paper presents a comprehensive analysis of the changes observed in the three inter-area modes of the Australian transmission system (I20, I25, and I35) as more IBRs come online and synchronous units retire. Using measured data from 2008 to 2024, the authors show that mode behaviour and damping now depend on a wider set of variables sometimes in unexpected ways. This highlights the need for ongoing, data-driven stability assessment as the grid

decarbonises. The findings help to address emerging damping scarcities and inform the need to retune the existing PODs and/or install new damping devices at various strategic locations.

11091 - Dynamic Analysis of the August 15th, 2023 Partial Blackout in the Brazilian Interconnected Power System: The Brazil 2023 partial blackout exposed weaknesses in the modelling and dynamic performance of inverter-based resources (IBR). Post-event investigations revealed that the simulation models available to the system operator overestimated the dynamic power support capability of wind and PV generation plants. This paper describes the incident, subsequent dynamic analysis and actions adopted to improve modelling, including a review of technical requirements for IBR, improvement of verification and compliance processes, introduction of requirements for EMT model submission, and enhancement to performance monitoring.

11132 – Dynamic and Frequency-Domain Assessment of Power System Strength in Grids Dominated by Inverter-Based Resources: This paper challenges the traditional understanding of system strength based on fault current contribution from synchronous machines and proposes a new framework combining traditional static indicators (MISCR) with advanced dynamic analysis techniques. The novelty introduced in this work is the application of the Impedance Margin Ratio (IMR) – a frequency-domain metric that evaluates the ratio between the allowable impedance variation and the original inverter impedance at the point of interconnection. The outcomes of this methodology are compared against time-domain simulations in a reduced model of the Italian power system, showing good agreement.

11251 - Compliance and Model Validation of a Grid Forming BESS Replacing Synchronous Generation: Real-World Integration into Australia's Northern Grid: This paper presents the real-life post-commissioning model validation (RMS and EMT models) of a 35 MVA GFM-BESS, including capability envelope verification, overload management, and frequency/voltage control performance. It proposes a new synthesized waveform EMT playback as a practical technique to avoid artefacts from noisy field waveforms. Further, it discusses the impact of metering/frequency meter latency (≈0.3 s).

11261 - Quantitative Assessment of Grid-Forming BESS and Synchronous Condensers for System Strength Support: This paper presents a study aimed to compare and quantify the System Strength Support (SSS) provided by GFM BESS and Synchronous Condensers to enable stable operation of GFL IBRs under a range of operating conditions. The authors argue that SCR-type metrics are no longer suitable system strength indicators and propose an alternative metric in the form of quantification of the SSS capacity (in MVA) required to stabilize GFL IBRs. The analysis presented in the paper reveals key dependencies on the GFL IBR capacity, the electrical distance, and the technology providing SSS. It is shown that the capacity requirements for both GFM BESS and SC increase with electrical distance to the GFL resources. It is also shown that SSS provided by GFM BESS is more sensitive to electrical distance than that provided by SCs.

11262 - Technical Challenges Related to the Synchronization Process of the Baltic States' Power System with the Continental Europe Synchronous Area: This paper describes simulation studies conducted to assess the feasibility of synchronisation of the Baltic States to the Continental European System. The studies focus of frequency stability, transient stability and inter-area oscillations. The paper also addresses modelling gaps and measurement campaign conducted in conventional power plants to validate the dynamic models (especially PSSs).

11432 - State-Space Models of Virtual Control and Protection Systems for Stability Analysis: This paper introduces the use of linear time-invariant modelling and discusses how it can be best used to complement traditional modelling approaches in more complex systems with higher penetrations of HVDC and inverter-based technology.

11445 - Guidelines for the Implementation of Power Oscillation Damping Controllers in Power Converters: This paper provides practical guidelines for the implementation of Power Oscillation

Damping (POD) controllers in power converters, especially in grid-following (GFL) devices. The authors include numerical examples to illustrate the proposed criteria for POD using the synthetic two-area system used in Spanish technical standard for monitoring compliance (NTS). A generic power converter model is used for simulation analysis where POD controllers using modulation of active-power injection (POD-P), reactive power injection (POD-Q) or both simultaneously (POD-PQ) are investigated. Results are validated in a large-scale power system.

11446 - Impact of Plant Controls of Large-Scale Inverter-based Generation on Inter-Area Oscillations in the Continental Europe Power System: This paper analyses the impact of plant-level voltage and reactive power control of large-scale inverter-based resources on low-frequency inter-area oscillations in the Continental European Power System under high renewable penetration. Study results suggest that IBR electrical and plant controls can have significant impact on low-frequency inter-area modes. This is particularly true for wind and solar energy sources which constitute most of the inverter-based generation, and concern both, the type of voltage/reactive power control implemented and the specific control settings. It was shown that fast voltage regulation in a power plant control model, in areas participating in the low-frequency inter-area oscillations, can significantly reduce the damping of this mode. Increased damping can be achieved by using other regulation strategies, such as power factor or reactive power control. If voltage regulation is used, it should not be excessively fast.

11521 - Improvement of LVRT Behaviour of Variable Speed Pumped Storage Units to Enhance the Transient Stability of the Power System. A Case Study: This paper provides a comprehensive analysis of Variable Speed Pump Storage Units (based on doubly fed induction machines), and investigates their impact on the power angle stability of a nearby hybrid Pump Storage Power Plant (PSPP) using both, mathematical analysis and simulation. The authors propose two possible methods to increase stability margins: increase the fault ride through current limit of VSPSUs (method A) and voltage threshold (method B). The proposed approaches are illustrated in a real project in China, showing that the export capacity could be increased by 200 MW by means of optimised control parameters, thus reducing the need for operational constraints to maintain power system stability.

11553 – A New Index for Quantifying Stability Adaptation Effort in Power Electronics-Dominated Power Systems Based on Frequency-Domain Impedance Identification: This paper introduces a new metric called the “Adaptation Effort Index” (AEI) that measures the sensitivity of dominant modes to parameter variations and quantifies the effort required for a converter to “reconfigure itself” under unstable operating conditions. The AEI combines the Nyquist Stability Margin obtained from frequency-domain screening with a modal-sensitivity index derived from fitted state-space models synthesized from black-box impedance data. Application of the new index is illustrated in a simple benchmark system with one GFM and one GFL converters. The key contribution of this paper is a novel, practical and model-agnostic tool for identifying which converter should be reconfigured in converter-dominated grids, offering valuable guidance for system operators and manufacturers.

11609 - Co-Simulation for Nuclear Power Plant and Power Electronic Interfaced Devices Interaction Studies: The paper demonstrates a co-simulation framework based on the Open Platform Communication (OPC) protocol that couples the thermomechanical dynamics of a nuclear power plant (NPP) with electrical grid dynamics modelled in the root mean square (RMS) domain. The framework is validated through simulations of a grid frequency step disturbance and frequency modulation. The results highlight the importance of properly selecting the simulation step size to accurately capture the frequency range of interest. Future work will investigate interactions between the nuclear power plant and inverter-based resources.

11610 - Immittance-Based Frequency-Domain Method for Sub-Synchronous Torsional Resonance Analysis: This paper extends an immittance-based frequency-domain method, originally developed for electrical resonance studies, to the assessment of torsional resonance stability, with the objective of providing a unified framework for both electrical and mechanical resonance phenomena.

The authors present the theoretical foundation and methodological steps of the approach and validate it through case studies based on the Swedish transmission system. EMT simulations are used to verify the stability predictions obtained from the frequency-domain analysis showing good agreement.

11618 - Comparison of Impedance-based Tools for Sub/Super Synchronous Oscillation Analysis: This paper provides a clear and useful discussion of different reference frames used in power system and converter impedance studies and explains how impedance data from different toolboxes can be transformed consistently across domains. Simulations results are presented comparing several tools, providing the industry with a useful perspective and confidence regarding their reliability.

11641 - Analysis of the Large Disturbance in Georgian Power System: Stability Challenges and Lessons Learnt: This paper presents a detailed analysis of a major power system failure in Georgia, which led to a blackout. The authors demonstrate that the primary cause of the incident was the malfunction of hydropower plant regulators, which, instead of stabilizing the system, led to increasing frequency oscillations. The research highlights the importance of properly configuring control systems and the need to develop monitoring and system automation systems to prevent similar events in the future. The importance of the ancillary services market for generating better incentives for participation in regulatory processes is also emphasized.

11702 - Grid Forming Preserving Control Current Limitation Strategies and Impacts on Grid Support: This paper discuses current limitation methods for HVDC GFM converters. Methods to preserve GFM property during fault while also limiting current are also discussed. Based on a phasor approach, the paper illustrates how the converter current could be limited by limiting the converter internal voltage (phase and magnitude or only magnitude). Assuming that the magnitude and the phase of the converter internal voltage are kept constant, the paper shows the impact of the operating point on the unsaturated currents for different grid events. EMT simulation results are also included in the paper to verify the phasor domain approach.

11713 - A Comparative Study of Negative Sequence Support of Grid-Forming Voltage Source Converters with Current Prioritization Schemes: This paper investigates negative sequence support (NSS) for grid-forming voltage source converters during unbalanced grid faults. The authors conduct a comparative study of various control strategies, specifically evaluating how different current limiting controls (CLC) impact fault-ride through performance. They demonstrate that choosing a negative sequence priority (NSP) is essential for meeting international grid standards like IEEE 2800 and VDE 4120. The research further highlights that the dual current reference saturation limiter provides more reliable protection than the elliptic alternative across varying fault severities. The paper underscores the high level of co-dependency between sequence injection functions, current limits, and overall converter stability.

11753 - Enhancing Power System Stability: Integrating High-Fidelity Plant Controller Models for Distributed Energy Resources: This paper demonstrates that a high-fidelity digital twin controller model that runs the same code as the physical DER controller and can be integrated directly with standard power system simulation tools. By validating this model against HIL tests, the authors show that it reproduces real controller behaviour with high accuracy while eliminating the cost and complexity of real time simulator hardware. Overall, the paper demonstrates that digital twins are a reliable and cost-effective way to assess grid stability, check compliance with connection standards, and support the transition to a low-carbon power system.

11764 - Explainable Machine Learning for Real-Time Frequency Stability Assessment: This paper proposes a machine learning (ML)-based methodology to assess frequency stability in power systems. The proposed ML framework provides near-real-time visibility and explainability of (locational) frequency stability metrics. A deep neural network surrogate is trained using 5,040 RMS simulation scenarios of a reduced GB system to predict the system-wide minimum frequency nadir following the loss of the largest generation unit. The proposed approach significantly reduces computation time compared with conventional time-domain simulation while maintaining good

accuracy (RMSE ≈ 0.003–0.007 Hz). In addition, SHAP-based explainability is used to identify the operating variables that most influence the predicted frequency response, improving transparency and supporting operational interpretation. The method is demonstrated for applications such as rapid scenario screening and minimum inertia assessment.

11769 - Sub-Synchronous Control Interaction in a Utility-Scale Solar PV Plant: First Evidence and Countermeasures in Vietnam's Power Grid: This paper presents a detailed analysis of a real-life SSCI event observed in a 600 MW solar PV plant connected to a series-compensated 500 kV transmission corridor in Vietnam and offers practical insights for the detection, analysis, and mitigation of sub-synchronous oscillations. The event produced sustained oscillations around 33 Hz following line energization under weak-grid conditions. The study combines high-resolution fault recorder measurements (16 kHz), analytical screening methods, impedance-based stability analysis, and EMT time-domain simulations to identify the root cause and confirm the presence of SSCI interactions between the converter-based plant and the series-compensated network. The authors discuss operational mitigation measures adopted by the Vietnamese SO, including switching restrictions, plant-side control actions, and monitoring improvements.

11772 - ROCOF Incident Study and Stability Enhancement by Grid-Forming Technology in Danish Power System: This paper describes a system incident that occurred in Denmark in 2024 where the loss of an exporting HVDC link resulted in high RoCoF and subsequent loss of significant amount of generation. EMT studies conducted with OEM models successfully reproduced the incident and were used to validate phasor-domain models, evaluate and compare two stability enhancement technologies, namely GFM BESS and SynCon. A range of studies are presented in the paper illustrating the stability enhancing capabilities of GFM BESS, with a commentary on the effect of various control parameters on their dynamic response.

11773 - Frequency-Domain Screening Methods and Benchmarking for Converter-Based Systems: This paper provides an overview of frequency-domain screening practices for converter-based systems and presents benchmarking studies comparing frequency-scan implementations across different tools. The authors identify a lack of standardisation and limited cross tool validation among existing frequency scan methodologies, which hinders consistent application across projects. This work aims to support the development of a common understanding of frequency-scan methodologies among TSOs and proposes practical guidance for deriving impedance representations suitable for stability screening. Based on the benchmarking results, recommendations are provided regarding scan parameter selection, modelling assumptions, and workflow design for single-device impedance identification.

11784 - Impact of BESS-based Power Oscillation Damper (POD) on Inter-area Oscillation Damping in the Argentine Power System: This paper considers how inter-area modes can be managed as conventional forms of PSS-based damping become less available through retirement of synchronous generation plants. The paper demonstrates via simulation that BESS distributed through a large power system and equipped with POD controller can improve damping of inter-area oscillations (via active power modulation). In this study, the authors integrate the POD functionality in generic WECC models using python scripting. The findings of this study support the use of BESS POD as a system level damping service, reducing reliance on synchronous units kept online solely for stability.

11814 - Advanced Large-Scale EMT Modelling for the Scottish Transmission System – Capabilities & Experiences: This paper shares the authors' experience with setting up a large EMT model of the Scottish Network. The paper presents a method of modelling for building a relatively large EMT model, so that it is scalable and repeatable. The paper also discusses what could be done with the model in terms of contingency studies for planning and operation as well as impedance calculation for small signal studies, and in what timeframe using this EMT modelling for a 20 second simulation.

11826 - Experience with Commercial Stability Service Provision of the UK Blackhillock Large Scale Grid-forming BESS: The paper presents real world operational experience from the Blackhillock 200 MW/400 MWh grid forming BESS, which is the UK's first large-scale plant delivering commercial, firm inertia and short circuit level (SCL) services under the Stability Pathfinder (SP2) framework. It validates GFM performance using measured data from real grid events (generator trip, unbalanced fault) compared with EMT simulations, demonstrating accurate matching and proving the maturity of GFM BESS for stability services. The paper also provides practical guidance on plant level design, controls, and compliance.

11856 - Suppression of Interactions of Parallel Grid Forming Converters using Decoupled Grid Forming Control: The paper proposes a new synchronization mechanism for a GFM control scheme based on the combination of vector current control and power synchronization, and shows improved performance with respect to interaction between different GFM converters. The proposed GFM control implementation is applied to a MMC HVDC that delivers PLL like synchronization by forcing Vq to 0, eliminates virtual impedance, and shows robust EMT performance from SCR = 10 to SCR = 1 (and islanded), with current limiting and improved PQ decoupling. The theory is verified through simulations.

11859 - The Role of EMT Simulation Tools in Operation and Control of Synchronous Generators: This paper presents a high-fidelity electromagnetic (EMT) transient model of a synchronous generator based on a phase-domain embedded modelling approach. Unlike the classical d-q axis model, the phase-domain model explicitly represents the stator and field windings, making it particularly suitable for representing space harmonics and simulating internal machine faults. As a result, the model is well suited for offline and real-time EMT simulation, enabling detailed analysis of the operation, control and protection of synchronous generators. The paper validates the developed EMT model through several practical simulation tests, comparing simulation results with field measurements under various operational scenarios. The validation includes AVR response test with and without PSS, fault ride-through (FRT) performance, Rate-of-Change -of-Frequency (ROCOF) events, and black-start procedures.

11860 - Enhancing Grid Stability: A Novel Methodology to Maximize Ride-Through Capability of IBR Inverter Based Resources: The paper provides a methodology for IBR owners to maximise IBR ride through capability to help meet grid codes, and practical steps that can be taken to improve the IBR/BOP plant capabilities. The proposed method seeks optimisation of the IBR and BoP protection settings to maximise ride-through performance while still protecting the equipment. The proposed method is illustrated with ERCOT NOGRR 245 requirements.

12039 - Oscillation Damping Requirements for Inverter-Based Generation in the Colombian Power System: This paper reviews POD characteristics and proposes an implementation strategy for PODs in IBRs to provide damping to conventional electromechanical oscillations in the Colombian power system. The authors also provide guidance on how to define POD input signals based on observability criteria and a correlation analysis to assess the impact of selected signals on oscillation damping.

12063 - Real-Time Identification of Power System Oscillation Sources Using DEF Method with WAMS Data. A Case Study in Thailand: This paper presents a real-time oscillation source identification method based on Dissipating Energy Flow (DEF) analysis using Wide Area Monitoring System (WAMS) data. The approach has been deployed in Thailand's real-time system, providing oscillation source identification within 30 seconds to 1 minute after event occurrence.

12227 - Application of Grid-Enhancing Technologies for Stability Improvement in Low-Inertia Power Systems. A Case Study from Egypt: The paper presents a system planning study for the future Egyptian transmission network, evaluating the stability challenges associated with large-scale RES integration and the application of grid-enhancing technologies (GET). The study combines steady-state analysis, voltage stability (V-Q), short-circuit assessment, and transient stability

simulations to identify stability challenges under high-RES-penetration conditions. The results show that sustained oscillations under high-RES, low-load scenarios can be effectively mitigated with dynamic reactive support and energy storage, with strategically placed STATCOM devices combined with large-scale BESS providing fast frequency response and synthetic inertia.

12258 - A Scalable Framework for Stability Assessment at the Grid Interface of Power Electronic Interfaced Devices: This paper presents a scalable and practical framework for assessing small signal stability at the grid interface of power electronic interfaced devices (PEIDs) such as wind, solar, HVDC links, batteries, and large industrial loads. The proposed methodology uses immittance based analysis, supported by the Single Input Single Output (SISO) Nyquist criterion, capturing both positive and negative sequence behaviour as well as frequency coupling effects between converters and the grid. The method also defines validity conditions and robustness margins to ensure consistent and transparent application in grid connection studies.

12265 - Electromagnetic Transients-Based Stability Analysis of the Colombian Power System with High IBR Penetration by 2030: This paper presents a wide-area electromagnetic transient (EMT) model of the Colombian power system for a projected 2030 operating scenario with high penetration of inverter-based resources (IBRs). The EMT model has been built from an existing phasor-domain model (using a combination of "manual work" and some bespoke scripting) and expanded for validity at higher frequencies. The use of this model is illustrated under scenarios of increasing IBR penetration, with focus on stability issues and FRT. A penetration limit of 60% IBR is identified and the effectiveness of SynCon as mitigation option is evaluated.

12317 - Enabling EMT and HIL Simulations for IBR-Dominated Grids. An Equivalent Model of the Chilean Power System: This paper discusses the development and use of a dynamic equivalent model of the Chilean power system for conducting EMT and HIL real-time simulation. This technique is used for both the EMT and the RMS models for validation purposes. The main objective of the equivalent model is for use in advanced EMT and HIL simulations for the design studies of an HVDC link. The paper illustrates the challenges associated with the development of EMT dynamic equivalents.

12320 - PV Plant Black-Start Supported by Grid-Forming BESS: A Real EMT Study Based on OEM Models: This paper presents an EMT study conducted with OEM models to demonstrate the black-start capabilities of a hybrid PV+BESS plant. Results demonstrate stable voltage and frequency control through droop-based GFM operation, maintaining frequency within 0.1% and voltage within 0.3%, while keeping harmonic distortion below operational limits (THDv < 3%, THDi < 10%). Sensitivity studies considering residual transformer flux and voltage ramp rates further illustrate how controlled energization strategies mitigate inrush currents and maintain power-quality compliance.

12325 - System Strength and Grid-Forming Technologies. A Comprehensive Assessment of the Chilean Power System Towards High IBR Penetration: This paper examines challenges and solutions for the Chilean National Electric System (SEN) as it transitions to high penetration of inverter-based resources (IBRs) to achieve carbon neutrality by 2050. The authors use a system strength and inertia framework combining long-term economic dispatch, Effective Short-Circuit Ratio (ESCR) screening, RMS dynamic simulations, and detailed electromagnetic transient (EMT) studies to assess the system's robustness under high IBR conditions. The study identifies scenarios that fall below the minimum system strength and inertia thresholds and investigates mitigation options including synchronous condensers, GFM BESS and IBR curtailment. The paper emphasizes the importance of grid-strengthening strategies, regulatory updates, and accelerated BESS deployment to ensure stable and reliable operation of the SEN under high IBR penetration.

12328 - Demonstrating Stability Enhancement in the Danish Grid through Grid Forming STATCOM and BESS Solutions: This paper presents a comparative analysis of different grid supporting technologies as to how they can support the power system ride through major events in periods of high inverter dominance. Using a test case based on an actual event in the Danish grid, this

paper illustrates the damping limitations of SynCons and describes the structure of a modern GFM control explaining how the key control loops and parameters contribute to improved damping performance. Small-signal analysis and time-domain simulation are provided to illustrate the effect of various GFM parameters, with focus on low frequency damping. The key control loops responsible for the damping of different modes are identified.

12435 - Influence of Inverter-Based Resources on the Planning of Short-Circuit Withstand and Breaking Capability in Transmission Grids: This paper provides insights into the current challenges that European TSOs face in forecasting, calculating, and mitigating a rising maximum Short Circuit Level (SCL) due to grid development and increasing use of inverter based resources with implications on the rating requirements equipment for equipment. Various countermeasures are discussed, including increased equipment ratings, topological modifications such as busbar decoupling, current-limiting reactors, reduction of short-circuit contributions from IBRs through specification and control. The paper also discusses gaps in the IEC 60909-0 standard for short-circuit calculations in IBR-dominated systems.

12466 - Comparative Analysis of Voltage Stability in Offshore Power-from-Shore Systems with Fast-Switching On-Load Tap-Changers and STATCOM/TCSC Technologies: This paper discusses dynamic voltage control requirements for long HVAC submarine cables for voltage stability purposes. As an alternative to installation of STATCOMs, the paper proposes a configuration using fast-switching on-load transformer tap-changer. The associated Volt/Var control strategy is evaluated under challenging dynamic scenarios. The simulation results show acceptable performance, albeit observed temporary overvoltages may require re-assessment of insulation co-ordination.

12540 - Geographic Mapping of Minimum Fault Levels to Identify Weak Areas on the Irish Grid and the Assessment of New technologies for System Performances Enhancement: This paper presents an overview of stability challenges of the power system in Ireland during the energy transition. The authors demonstrate that the increasing share of renewable energy sources leads to a decrease in short-circuit power and a weakening of the system. A valuable aspect is the geographic analysis. The developed method of geographically mapping short-circuit power levels allows for the identification of weak areas in the grid and supports network development planning. The authors emphasise the need to examine the impact of technologies that could play a key role in maintaining system stability in the future and provide practical recommendations in this regard.

12541 – Reducing the Number of Must-Run, Conventional Sets in Northern Ireland to Enhance RES Penetration, while Maintaining System Stability: This paper outlines stability challenges faced by the system operator in Northern Ireland due to increase IBR intake and describes the process of performing hundreds of studies to demonstrate that frequency and voltage stability criteria can be satisfied under lower inertia operating regimes. The authors illustrate the use of python scripts to automate scenario construction for bulk power systems analysis simulations in order to assess the feasibility of reducing the number of must-run gas units in Northern Island from 3 to 2 units.

12542 – System Strength Evaluation Framework for the Irish Power System: This paper presents the All-Island system strength evaluation framework that moves beyond using fault level, SCR, SNSP, and MUON alone, discussing that these become insufficient as inverter-based resources (and their interactions) dominate. The authors review a wide range of candidate metrics, group them into families (short-circuit based, interaction-factor based, and impedance-based), then shortlist a subset for planning and operations. The paper demonstrates the shortlisting with small-scale phasor-domain and RMS studies, with thresholds still to be established later using validated EMT models.

12543 – Development of a Roadmap to Integrate System Wide EMT Study Capabilities in Ireland: This paper presents a roadmap for the phased implementation of wide-area EMT capabilities in the planning and operations teams of the associated system operators in Ireland and Northern Ireland. The outcomes of a global benchmark investigation into the integration of EMT in similar organisations are provided, detailing key learnings and recommendations.

12578 - Analysis of the Robust Operation of a Hybrid Power Station Incorporating Diesel Generators and Battery Energy Storage Systems in a Novel Data Center Electrical Topology: This paper addresses islanded operation of a generative AI Data Centre, which is supplied by a combination of diesel generator units and BESS. The main focus of the paper is on modelling aspects using EMT and validation against SAT measurements for each key component. Simulation studies cover a case study with loss of load, loss of generation, and performance in case of load fluctuations. The paper reveals that operating the BESS in grid-forming (GFM) mode provides superior frequency stabilization and more effective damping of oscillations compared to traditional diesel-led configurations, highlighting the critical role of high-fidelity modelling in optimizing data centre electrical infrastructure.

12602 - Large Scale EMT Simulation using General Purpose GPUs for better Speedup: This paper employs Graphics Processing Units (GPUs) to solve the network equations, achieving significant speedup compared to existing methods. It also presents a complete GPU-based EMT simulator demonstrated on a synthetic grid example.

12625 – Fault Ride Through Issues and Evaluation of Mitigation Techniques in a Converter-Dominated Power System: This paper investigates PLL loss of synchronism in wind power plants in an area with high penetration of converter-based generation. Using EMT simulations on a large network model with OEM IBR black-box models, it is shown that, in addition to the well-known close-in faults, loss of PLL synchronism can also occur for remote faults in weak areas of the grid. Mitigation measures, including IBR re-tuning, Synchronous Condensers and GFM BESS, are discussed.

12646 - A Benchmark Model and KPI Framework for Studying Power System Restoration of Modern Grids: This paper introduces a benchmark restoration model together with a structured set of key performance indicators designed to support consistent evaluation of system restoration performance. The framework captures transformer energisation, sympathetic inrush, and cold load pick-up, and is made openly available to facilitate reproducibility.

PS2: POWER QUALITY (PQ) AND ELECTROMAGNETIC COMPATIBILITY/INTERFERENCE (EMC/EMI) ASPECTS OF DECARBONIZATION OF POWER SYSTEMS AND THE ROAD TO NET-ZERO

10175 - News regarding the power quality monitoring system in the Romanian transmission grid: This paper presents the 2024–2027 modernization of Romania's transmission-level Power Quality Monitoring System (PQMS), deploying class-A analysers across HV and selected MV/UHV substations and a centralized, cyber-secure analytics platform. The upgraded system enables real-time waveform analysis, automated event classification, and standardized percentile reporting, improving detection of disturbances such as voltage fluctuations from renewables. The authors conclude that the new PQMS significantly enhances grid observability, regulatory compliance, and resilience in a renewable-rich transmission system.

10303 - Large, moderately rapid voltage fluctuations due to a PV farm: an additional limit on how much PV fits in the medium-voltage grid: The paper analyses a 60 MW PV farm connected to a weak Dutch MV grid and shows that cloud-driven power ramps cause large voltage deviations that are too slow to be classified as rapid voltage changes, yet too large for existing grid-code limits and tap-changer control. Simulations demonstrate that these "moderately rapid" voltage fluctuations can create voltage violations elsewhere in the MV network and excessive tap-changer operation. The authors conclude that current standards do not address this phenomenon and recommend new grid-code provisions and mitigation measures such as STATCOMs or advanced voltage control at the connection point.

10304 - Point-on-Wave performance when considering the statistical switching behaviour of the circuit breaker: This paper evaluates Point-on-Wave switching in the Dutch HV grid using EMT simulations that explicitly account for the statistical behaviour of circuit breakers, including pole scatter and dielectric strength. It shows that while PoW switching generally reduces inrush currents and rapid voltage changes, its effectiveness is not guaranteed for larger capacitor banks, motivating a more probabilistic, risk-based approach in power-quality policy.

10394 - Case study of converter control improving on-site harmonics performance: The paper presents a wind-farm case study where measured 6th-order harmonic voltage distortion exceeded site compliance limits, despite a strong grid, and investigates root causes through extensive on-site measurements and seasonal analysis. It demonstrates that targeted converter control modifications—particularly active harmonic suppression—can reduce harmonic currents, while highlighting the strong influence of background network conditions and the gap between theoretical studies and real-world performance.

10571 - Harmonious co-existence of Power and Telecommunication networks: A study on Low Frequency Induction (LFI) risks and Mitigation measures: This paper examines Low Frequency Induction (LFI) and Earth Potential Rise (EPR) risks arising from the co-location of power transmission and telecommunication networks, particularly under fault conditions in renewable-driven grid expansions. It presents analytical methods, international standards, and practical mitigation measures—such as corridor separation, grounding coordination, and use of fibre-optic cables—to ensure safe and reliable coexistence of power and telecom systems.

10575 - Power Quality Issues Associated with Inverter Duty Transformers: This paper investigates recurring failures of inverter-duty transformers in grid-connected solar PV plants, linking them to severe power-quality stresses such as high dv/dt switching transients, harmonics, DC injection, unbalance, and resonant effects from inverter operation. Using surveys and three detailed case studies with site measurements, it shows that existing standards and design practices often underestimate these stresses, leading to insulation breakdown and premature transformer failures, and concludes that continuous power-quality and condition monitoring, improved design requirements, and updated standards are essential for reliable renewable integration.

10843 - Harmonic emission assessment within the constraints of the metrological performance of the instrumentation chain: This paper shows that strict harmonic emission limits for renewable power plants can appear non-compliant largely due to measurement uncertainty rather than true network impact. It demonstrates that current transformer accuracy dominates this uncertainty and, when properly accounted for, marginal exceedances may be regarded as "sufficiently compliant," avoiding unnecessary mitigation costs while still protecting grid power quality.

10906 – Effects of Multi-Cycle Symmetrical Control (MCSC) Loads on the Feeding MV/LV Distribution Transformers: This paper shows that MCSC loads, which generate asymmetric currents with DC components, can drive MV/LV distribution transformers into saturation, increasing losses, magnetizing currents, and harmonic injection upstream. EMT simulations indicate that saturation severity depends mainly on the duration of same-polarity cycles, load magnitude, phase distribution, and transformer magnetizing characteristics, while short MCSC patterns (e.g. four cycles) generally avoid harmful saturation.

10908 – New Approach for Assessing the Risk of Harmonic Amplification on the French Network: This paper introduces a methodology that uses large-scale EMT-based network models to pre-screen harmonic amplification risks from long radial underground cable connections across the French transmission grid. By building a database of harmonic amplification gains and critical cable lengths by substation and harmonic order, the approach enables early identification of projects requiring detailed harmonic studies and targeted monitoring.

10967 – Voltage Fluctuation Test for LED Lighting: Assessment of Relations between ΔV10

Flicker Index and Illuminance Change: This paper investigates flicker in LED lighting caused by low-frequency voltage fluctuations from PV inverter anti-islanding controls, combining subjective visual tests with frequency-domain analysis of illuminance signals. Results show a clear correlation between the ΔV10 index and illuminance fluctuation, with LEDs generally exhibiting much higher flicker resistance than incandescent lamps, although sensitivity varies by fixture design and flicker becomes noticeable mainly for $\Delta V10 \geq 3$.

10968 – Experimental Study of the Impacts on 2–9 kHz Harmonics Due to IBRs Connected to a Distribution Line: This experimental study demonstrates that high-order (2–9 kHz) harmonic voltage distortion from inverter-based resources is strongly driven by series resonance between inverter switching frequencies and grid impedance. When multiple inverters are connected, the inverter located closer to the grid dominates the harmonic amplification, showing that inverter connection location and status are as critical as switching frequency and grid impedance.

10969 – A Practical Evaluation Method for Inrush Currents and Voltage Dips during Transformer Energization: The authors present a web-based analytical calculation tool that rapidly and accurately estimates transformer energization inrush currents and associated voltage dips without full EMT simulation. Validation against sixteen real Japanese system cases shows errors below 1%, and the study clarifies how worst-case inrush and voltage dip conditions depend on transformer winding configuration and grounding method.

11135 – Voltage Dips Propagation in the Transmission System: Analysis of the Voltage Events Monitored in the Period 2009–2024 by the QuEEN System: This paper analyses fifteen years of Italian power-quality data from the QuEEN wide-area monitoring system to assess the propagation of voltage dips in the context of increasing inverter-based generation. The results show a clear increase in dip propagation—particularly in southern Italy where wind penetration is highest—and confirm, through cluster and geographical analyses, a growing spatial extent of voltage dips as system short-circuit power decreases.

11284 – Online Monitoring of Power Quality Indicators in Renewable Power Plants Using the Synchronized Phasor Measurement System of the Brazilian National Grid: This paper presents a PMU-based online monitoring framework for voltage and current THD in wind and photovoltaic plants in the Brazilian Interconnected Power System, leveraging existing synchrophasor infrastructure. Results show that, despite small deviations from IEC 61000-4-7 compliant analysers, PMU-based THD provides a reliable basis for continuous monitoring and early detection of potential PCC limit violations, reducing reliance on offline measurement campaigns.

11540 – Challenges in Estimating Amplification of Background Harmonic Voltage Distortion: This paper evaluates the accuracy of simplified background harmonic amplification methods when new grid elements are connected, distinguishing between shunt connections and point-to-point connections between existing buses. Using the IEEE 39-bus system and a large real transmission model, it shows that impedance-based amplification factors are reasonably reliable for shunt connections but can lead to large errors (often >50%) for meshed, point-to-point developments, indicating their unsuitability for such cases.

11541 – Impact of Replacing Synchronous Generation with Inverter-Based Generation on Voltage Fluctuations: This paper investigates how replacing synchronous generators with inverter-based PV resources reduces system strength and increases voltage fluctuations and flicker near highly variable loads such as electric arc furnaces. EMT simulations show that flicker severity increases significantly with reduced short-circuit capacity, while mitigation using STATCOMs or synchronous condensers—particularly the latter—can effectively restore voltage quality.

11555 – Assessment of an Electrical Resonance Issue in a Fast Electronic On-Load Tap-Changer Transformer Based Test-Bench During Renewable Energy Source Tests: This paper analyses a high-frequency resonance problem observed in a test-bench with cascaded electronic OLTC

transformers used for renewable generator validation. It demonstrates that simplified single-phase transformer T-models and cable π-models are sufficient to identify the resonance mechanism and that adding an appropriately sized length of MV cable effectively shifts resonance away from converter switching harmonics.

11556 – Voltage Balancing by Magnetically Controlled Reactors in Electric Grids Containing Unbalanced Loads: This paper demonstrates the use of magnetically controlled shunt reactor-based filter-balancing units for mitigating voltage unbalance caused by large single-phase and traction loads. EMT simulations show that phase-wise controlled reactors can restore voltage symmetry within ~100 ms, achieving performance comparable to STATCOMs with lower complexity and cost.

11557 – Harmonics and High-Frequency Characterization of Capacitive Voltage Transformer and HVMAC Device: This paper presents experimental validation of a reference high-voltage test setup for harmonic characterization of capacitive voltage transformers equipped with a high-voltage measurement adapter card (HVMAC). Results show that the HVMAC enables accurate harmonic voltage measurements up to 5 kHz, maintaining ratio errors within 3% near resonance and within 1% in linear frequency regions, supporting IEC 61869-1 wideband requirements.

11776 – Harmonic Assessment of Transmission Grid Expansion with Underground Cables via Measurement-Validated Simulation Model: This paper presents a deterministic, measurement-validated harmonic simulation framework for assessing transmission grid expansions with extensive 400 kV underground cable integration in Denmark. Case studies show that harmonic behaviour in meshed grids depends on vector superposition of magnitude and phase angle—rather than scalar impedance alone—with meshed UGC configurations sometimes reducing distortion while radial configurations tend to increase it.

11777 – Estimation of Harmonic Injections for Harmonic Propagation Studies in Meshed Transmission Grids: This paper presents an optimisation-based method to estimate equivalent harmonic current injections in large, meshed transmission grids using long-term harmonic voltage measurements and detailed grid models. Applied to Danish transmission system, the approach improves the accuracy of harmonic propagation studies and supports more robust planning of mitigation measures, particularly under evolving grid conditions.

11781 – Comprehensive Data Investigation of Harmonic Measurements from Wind Parks for Assessing Mechanisms and Long-Term Variations: This paper analyses one year of harmonic voltage and current measurements at the PCC of a 90 MW wind park using advanced statistical methods and unsupervised machine learning. The results show that dominant harmonics (notably 5th and 7th) are largely driven by background distortion and grid impedance, while lower-order components correlate more strongly with wind park operating conditions.

11811 – Online Harmonic Resonance Monitoring for Adaptive Control of HVDC Systems: This paper compares time-domain (SOGI-FLL) and frequency-domain (SWDFT, SWIFT) resonance detection methods for enabling adaptive damping control in HVDC systems. While SOGI-FLL offers the fastest and least computationally intensive detection under ideal conditions, frequency-domain methods provide greater robustness under complex and noisy transient harmonic events.

11882 – HVDC Cable–Pipeline Interaction Under Fault Conditions: Induced Currents, EPR, and Safety Implications: This paper investigates electromagnetic interactions between HVDC land cables and parallel gas pipelines under fault conditions using detailed EMT and FEM modelling. Results show that while inductive coupling generally produces manageable induced effects, earth potential rise at cable earthing points can dominate pipeline stress and must be explicitly included in safety and design assessments.

11905 – Holistic Approach for Managing and Mitigating Interference on Metallic Pipelines in Shared Utility Corridor: This paper proposes a lifecycle-based EMI management framework for

metallic pipelines co-located with high-voltage AC infrastructure, covering planning, design, mitigation, and operational monitoring. Case studies from Great Britain demonstrate that early risk screening, advanced modelling, optimised phasing, and real-time monitoring are essential to control AC corrosion risks and ensure personnel safety as transmission capacity increases.

12103 – Methodologies for Defining Harmonic Specifications in Transmission Systems at Future Points of Connection of Energy Resources: This paper compares deterministic and probabilistic methods for forecasting harmonic background levels at greenfield transmission Points of Connection where no measurements exist. A Polish TSO case study shows that probabilistic, impedance-weighted approaches better capture variability and resonance risk, while deterministic methods remain useful for conservative planning and sensitivity analysis.

12329 – Impact of Increasing Underground Cable Penetration in the Swiss Transmission Network: This paper assesses the system-wide impact of large-scale XLPE underground cable integration in the Swiss 220/380 kV transmission network using frequency-domain and EMT analysis. The results show major risks from shifted resonances, harmonic amplification, temporary overvoltages, increased reactive power demand, and black-start challenges, requiring coordinated mitigation and new restoration strategies.

12456 – Influence of Contingency Scenarios on the Allocation of Harmonic Emission Limits in Transmission Systems: This paper analyses how considering all transmission contingencies in IEC 61000-3-6 harmonic allocation leads to overly conservative emission limits and systematic underutilisation of planning levels. Simulation results show that a very small subset of rare contingencies drives the strictest limits, and excluding the most extreme cases can significantly improve utilisation with only marginal risk increase.

12539 – Investigating Implications of Offshore Wind Farm Connections Regarding Harmonic Distortion: This paper develops a coordinated harmonic assessment and mitigation framework for large-scale HVAC offshore wind connections to the Irish transmission system, addressing compliance at both onshore 220 kV GIPs and offshore 66 kV POCs. Results show that onshore passive filtering combined with selective offshore mitigation and, where necessary, WTG emission tuning is required to manage low-order harmonic risks and inter-OWF interactions.

12547 – Investigation into the Effects of GICs on Power System Harmonics: This paper analyses high-resolution measurements from the May 2024 solar storm in Ireland to quantify how geomagnetically induced currents drive harmonic distortion in transmission networks. Strong correlations are observed between GIC magnitude and increased even-order harmonics, highlighting transformer saturation, network topology, and regional geoelectric conditions as key factors for power-quality risk during geomagnetic events.

PS3: INSULATION CO-ORDINATION AND LIGHTNING RESEARCH: PAVING THE WAY TO NET-ZERO IN DECARBONISED POWER SYSTEMS

10305 - Results of continuous transient voltage measurement in the Dutch 110kV grid: This paper presents one year of continuous transient voltage measurements on a 110 kV transformer in the Dutch grid. Recorded events include transformer energization, switching operations, and faults. Overvoltages remain below surge arrester residual voltages, confirming robust insulation coordination. The study provides valuable data for refining electromagnetic transient models and insulation policies amid increasing grid changes and renewable integration.

10327 - Quantifying the effect of differential insulation on double circuit back flashover performance using the leader progression model: This paper investigates the use of arcing horns on one circuit of a 500 kV double-circuit line to reduce double-circuit backflashover rates via differential

insulation. EMT simulations with the leader progression model show that shorter arcing horn gaps increase the required stroke current for double-circuit flashover but also increase single-circuit rates. Results highlight the need for coordinated gap design.

10702 - OHL Work Safety. Use of EMT to Design the Protocol for Setting Up Temporary Grounding Protection: This paper uses EMT simulations to design a temporary protection grounding (TPG) protocol for a 400 kV double-circuit line with unconventional tower geometry. It evaluates operator safety during distant lightning strikes based on specific energy and IEC 60479-2 fibrillation thresholds. Results show that a dedicated TPG with equipotential bonding ensures safety without additional grounding on adjacent towers.

10907 - Blackout anticipation test: investigation of induced voltage and resonant event causing sustained high voltage at isolated network: This paper investigates a sustained high voltage event recorded during a blackout anticipation test on a 400 kV isolated network. Using EMT simulations and model tuning with field measurements, the study identifies the phenomenon as ferroresonance caused by autotransformer saturation and frequency differences at switching. The highly sensitive model exhibits three distinct states, validated against onsite measurements.

10930 - A Probabilistic Method for Estimating Rates of Pipeline Leaks and Ruptures due to Arc Faulting in Shared Utility Rights-of-Way: This paper presents a probabilistic risk model to estimate rates of subsoil arcing and damage to buried pipelines from lightning- or fault-initiated arcs near overhead conductors. Applied to a hypothetical 115 kV pole 3 m from a pipeline, fault-initiated arcs dominate (6.7×10^{-4} per year). Coating damage occurs at 2.0×10^{-4} per year, leaks at 2.7×10^{-10} per year.

10936 - Enhancing Lightning Performance Assessment Through Uncertainty Quantification in Grounding Resistance Measurements Using the Fall of Potential Method: This paper introduces a probabilistic framework using Markov Chain Monte Carlo to quantify uncertainty in fall-of-potential grounding resistance measurements. Applied to a synthetic 25 Ω target case, it shows that additional readings away from the 62% rule reduce uncertainty. The approach supports risk-based lightning performance assessment by propagating grounding resistance uncertainty into backflashover rate calculations and acceptance criteria.

10970 - Recent Use of Line Surge Arresters (EGLA) on overhead Transmission Lines in Japan and their Effect on Reducing Lightning Outages: This paper analyses 40+ years of lightning outage data from Japanese overhead transmission lines. Since 1989, nearly 500,000 externally gapped line arresters (EGLAs) have been installed, mainly on 66/77 kV lines. Case studies on double-circuit 77 kV lines show that EGLA on one circuit prevents its outages; EGLA on both circuits nearly eliminates all lightning outages, with failures only from arrester punctures.

10971 - Development of a new Lightning Location System designed for Parameter Estimation: This paper presents a newly developed lightning location system (LLS) designed for high accuracy (median error ~40 m) and estimation of charge amount, peak current, and current steepness. Validated using a 634 m tower with Rogowski coils, the system detects large charges (>50 C) crucial for ground wire damage assessment. It supports efficient maintenance and lightning-related outage analysis.

11085 - Main Issues Regarding HVDC Overhead Transmission Lines Insulation Coordination: VSC Technology and Dedicated Metallic Return: This paper examines HVDC overhead line insulation coordination challenges for VSC technology and dedicated metallic return (DMR). EMT simulations on a ±600 kV bipolar line show that full-bridge converters produce lower overvoltages than half-bridge. DMRs face higher backflashover risk due to shorter insulation. Pollution drives insulator dimensioning. The study provides recommendations for tower optimization, DMR protection, and statistical risk-based design.

11086 - Screening Method for EMT Studies of Border Transformers in the Brazilian Interconnected Power System: This paper proposes a screening method to determine when detailed

EMT studies for transformer energization are needed in the Brazilian grid. Using transformer short-circuit ratio (TSCR) and harmonic impedance up to 10th order, the method defines impedance envelopes and risk tables. Validated on 51 historical cases, it reduces study workload while maintaining security. It applies to 230 kV border transformers (≤225 MVA) and aligns with international TSO practices.

11087 - Investigation of the Relative Impact of Negative and Positive Lightning Strokes for Establishing the Lightning Performance of Extra High Voltage Transmission Lines: This paper assesses the impact of negative first, negative subsequent, and positive lightning strokes on backflashover rates for 500 kV HVAC and ±500 kV HVDC lines. Using electromagnetic simulations and leader progression models, results show negative first strokes dominate outage rates. Subsequent strokes matter for low grounding resistance (e.g., 10 Ω). Positive strokes significantly affect HVDC performance, especially under moderate-to-high ground flash density (Ng ≈ 5).

11088 - A new methodology for the grounding design of transmission lines and windfarm towers: This paper presents a statistical methodology for grounding design of transmission line and wind farm towers. Instead of individual 1D geoelectric models per tower, it uses geometric averaging of all apparent resistivity curves to derive up to five standard curves, one standard deviation apart. Applied to a 300 km, 345 kV line, four grounding phases were defined. The method improves design efficiency and reliability over traditional site-by-site inversion.

11089 - Analysis of Lightning Overvoltages Due to Direct Strikes on Hybrid Overhead Lines: This paper investigates lightning overvoltages on a hybrid overhead line (138 kV, 13.8 kV spacer cable, 220 V) using EMT simulations validated by a 1:20 scale model. Longer current front times and lower grounding impedance reduce overvoltages. The medium-voltage circuit outperforms conventional lines due to shielding by the overhead ground wire and coupling with the messenger wire. The low-voltage circuit and underbuilt shield wire provide additional attenuation, especially at higher grounding impedance.

11249 - Insulator contamination maps toward outdoor insulation coordination: This paper presents preliminary work from CIGRE JWG C4/A3/B2/B4.75 on creating contamination maps for outdoor insulation coordination. It reviews global mapping practices and proposes a practical approach: define a reference site pollution severity (SPS) map for non-energized standard cap-and-pin insulators, then apply correction factors for energization (AC/DC), insulator geometry, material (including HTM), orientation, and height. Italian mapping and future standardization needs are discussed.

11582 - Research on Fault Cause Identification Method for Transmission Lines Based on Distributed Transient Traveling Waves: This paper presents a fault cause identification method for transmission lines using distributed traveling wave data. A fused improved SMOTE algorithm balances imbalanced samples (423 lightning, 502 non-lightning faults). A CNN-BiLSTM-SelfAttention model extracts time, frequency, and time-frequency features. The method achieves 96.2% accuracy on 925 real 500+ kV line faults, improving from 82.6% without balancing. It supports lightning protection and insulation coordination.

11622 - Sustained Overvoltages in Offshore Wind Farm Array Cables under Islanding Conditions: This paper investigates sustained overvoltages in offshore wind farm 66 kV array cables following asymmetrical faults and islanding. EMT simulations show healthy-phase overvoltages up to 3.5 pu persisting for cycles, risking surge arresters and cables. Magnitude is driven by network and WTG control; duration by islanding detection and control deadbands. Converter blocking and strategic arrester placement are effective mitigations. Energy-only arrester checks are insufficient.

11775 - Why are bonding leads usually within 10m?: This paper challenges the 10 m bonding lead length standard for cross-bonded cable systems. Using EMT simulations of fault and lightning events on trefoil and flat 66 kV cables, fault scenarios allow leads up to 50 m safely. However, lightning

strikes pose greater risk: 20 m leads are safe only for strikes ≤13 kA, 15 m for ≤14 kA. Results inform flexible link box placement.

11799 - Real-time monitoring of lightning currents in transmission towers and line surge arresters: This paper presents a real-time lightning current monitoring system installed on a 110 kV transmission tower with line surge arresters in Croatia. Using Rogowski coils, solar power, and 5G communication, the system successfully recorded three lightning events (e.g., -17.8 kA tower current) and one switching transient over 1.5 years. Measurements correlate well with LLS data. Kalman filtering improves waveform quality, supporting EMT validation and insulation coordination.

11919 - A Dynamic Approach for Assessing Lightning Risk to Electricity Transmission Networks Considering Environmental Factors: This paper presents an hourly lightning risk assessment framework for UK transmission networks, incorporating wind-induced insulator swing and DBSCAN-clustered lightning data. The shielding failure flashover rate (SFFOR) is adjusted for environmental factors. A case study on July 8, 2023, shows wind can increase SFFOR by up to 400%. The approach improves dynamic risk evaluation for decarbonised power systems.

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