Special Report
Your guide to the Session 2

POWER QUALITY AND SAFETY

Britta HEIMBACH
Switzerland
britta.heimbach@ewz.ch

Jan DESMET
Belgium
janj.desmet@ugent.be

Jan MEYER
Germany
jan.meyer@tu-dresden.de

Herwig RENNER
Austria
herwig.renner@tugraz.at

Introduction

The scope of Session 2 has been jointly defined by the Session Advisory Group and the Technical Committee. It covers Power Quality (PQ), supply reliability and the general concept of Electromagnetic Compatibility (EMC) including related safety issues in electricity distribution systems.

In this sense, Session 2 deals with any phenomena related to PQ. This includes flicker, unbalance, distortion in the frequency range from DC up to 500 kHz as well as events like under- and overvoltage phenomenon. Furthermore, new technologies and their impact are discussed, both from equipment-related and system-related perspective. The session also covers all aspects of EMC including emission, immunity, its coordination and the related standardization. Conducted and radiated electromagnetic interferences, electric and magnetic fields as well as grounding issues are addressed. Finally, this session discusses PQ-related activities in standardization and regulation, the impact of interruptions on supply reliability as well as PQ system monitoring, PQ measurement methods and PQ data analysis techniques.

The aim of this special report is to present a summary of the present challenges, future needs and forward-looking approaches in PQ and EMC, based on all selected papers of Session 2 (92 papers). The papers reflect latest insights of the involved different stakeholders, in particular distribution system operators, manufacturers, regulators, standardisation bodies, industry and academia. The session and consequently this report are divided in the following four blocks:

Block 1: Electromagnetic Compatibility, earthing and safety
Block 2: Equipment-related Power Quality aspects
Block 3: System-related Power Quality aspects and measurement methods
Block 4: Standards, regulation, monitoring and advanced data analysis

However, as topical overlapping may appear to some extent between the blocks, a clear allocation is not possible for each contribution. Over the years, a shift of interests is observed. Especially the interest in Block 1 (EMC including immunity, earthing and safety) has considerably increased from 17 % of the papers submitted to Session 2 in 2023 to 30 % this year. On the other hand, the number of papers on equipment- and system-related PQ-aspects (Block 2 and Block 3) has significantly reduced with the reasons being unclear.

The transformation of the energy system entails fundamental changes. In this context, PQ and EMC aspects are of great importance for the reliable functioning of the distribution grids as well as customer appliances. Consequently, future work in this domain is strongly encouraged.

Based on the most relevant topics and recent developments, three Round Tables are organized within Session 2:

RT7: Power Quality Challenges in Networks with 100% Inverter-Based Resources
Chair: Jan Meyer
RT9: Industry experiences with Power Quality requirements in the process of connecting large customer installations
Chair: Mark Halpin
RT11: Power Quality experiences due to the massive integration of e-mobility
Chair: Jan Desmet

Research as well as standardization in the frequency range 2 kHz-150 kHz/500 kHz have significantly developed during the last years. In particular, methods for measuring disturbance levels in the grid as well as the measurement of frequency-dependent impedance gained significant importance. Therefore, the RIF (research & innovation forum) at this CIRED is dedicated to that topic.

Block 1: "EMC, Earthing and Safety"

Earthing (grounding) is crucial for both electrical safety and Electromagnetic Compatibility (EMC). In principle, EMC protection or mitigation provides a low-impedance path for fault currents, protecting people and equipment from electric shock and damage. In the context of EMC, earthing creates an equipotential point, minimizing electromagnetic interference. In this block, grounding systems and related safety aspects form one major group. Interference and EMC are further topics covered by Block 1.

Grounding systems and touch voltages

Grounding systems are designed to safely conduct fault currents back to the source of power, minimizing the system's touch voltage during a fault. Several papers in this year's conference deal with grounding system design and analysis.

In [1034(AU)], risk-based electrical safety standards, with a history dating back 30 years, are emphasized. Risk-based targets result in different earthing requirements for different installation conditions. This paper considers those developments and the associated implications, using case studies from diverse system and installation configurations to demonstrate pitfalls and opportunities. Application for the evaluation of grounding systems can range from relatively basic system design by utilities through to more complex applications designed for commercial use. The latter needs more advanced applications that will not only determine touch voltages but also determine risk levels associated with those touch voltages.

An example of open-source software for grounding system analysis is introduced in [114(DE)]. Buses with their earthing impedances and connecting branches like earthing wires, cable shields or PEN conductors, including mutual coupling, are considered. Through validation with a test network, the program's capability to quantify reduction factors in mixed cable and overhead line structures and assess the significant impact of harmonics on earth fault currents is shown.

Soil resistivity is an important parameter in the evaluation of grounding systems. However, this value will alter with weather conditions. Exemplary measurements were performed by the authors of [413(AT)]. The long-term seasonal trend of apparent soil resistivity seems to follow air temperature, whereas distinctive short-term variations are caused by changes in soil moisture (cf. Fig. [413(AT)]). Therefore, applying correction curves for seasonal variations may be inaccurate, especially during droughts or after heavy rainfalls.

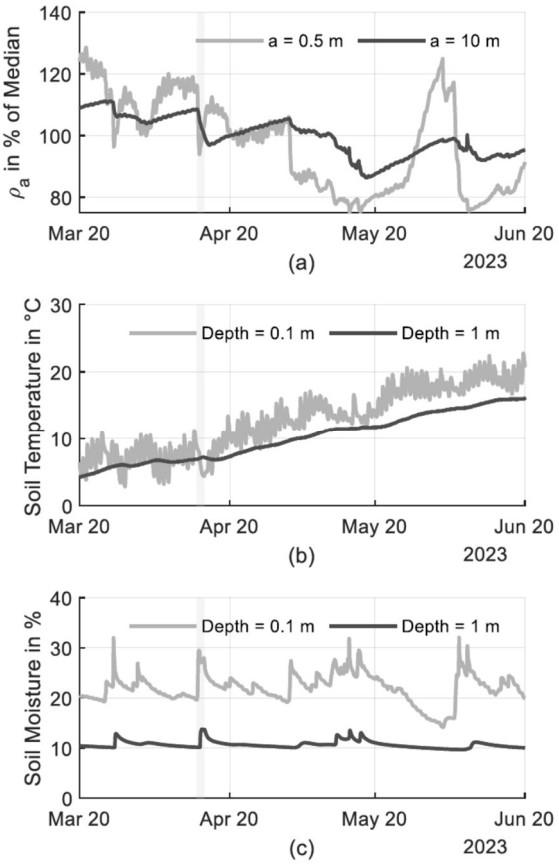

Fig. [413(AT)] Measurement results in spring 2023
(a) Apparent soil resistivity in % of the median value of each electrode spacing; (b) Soil temperature in depths of 0.1 m and 1 m; (c) Soil moisture in depths of 0.1 m and 1 m

In general, the assessment of earth resistivity is prone to many factors. While the configuration of electrodes for different methods, soil structure and other aspects have been addressed thoroughly, [892(CZ)] provides a discussion on the effect on the injected current magnitude. Increasing of fault current could be possibly helpful to overcome the contact resistance of the electrode with the soil. However, an unambiguous dependency was not proven by the performed measurements.

Measurement of each substation's grounding resistance test for safety compliance means a huge effort. To perform this task efficiently in a consistent way, a practical guide was developed by the Portuguese Distribution System Operator, which is presented in [463(PT)]. In a second paper [792(PT)], the authors analyse remedial measures in case of the grounding resistance measurement exceeds the limit. Two existing substation grounding systems were modelled to apply different measures to reduce touch voltages. The used models were evaluated by measurements. The simulation results show that surface mitigation techniques, particularly concrete pavement with an electro-welded steel mesh, were the most effective in

minimizing touch voltages. A new standard procedure outlining all the rules and required steps to meet regulatory requirements was established.

By low-ohmic connection of local grounding systems, a global grounding is formed, representing a kind of equipotential layer. Within this area, no hazardous touch voltages should arise. Safety requirements can be met with minimal additional testing, especially in medium and low voltage grids. The authors of [113(DE)] present effective assessment methods for global earthing systems, examining their applicability in diverse network configurations and fault types. By clustering local networks and applying statistical simulations, the model simplifies complex earthing structures without sacrificing reliability.

A special case of grounding of street light poles in the vicinity of a canal is presented in [529(TH)]. The authors conclude that the combined neutral and ground wire with a separate connection to the lamp neutral and the pole and no additional local grounding of the pole (TNC-S) is most effective as it prevents electrical currents from leaking into the canal.

Large ground-mounted PV installations in the vicinity of high-voltage (HV) lines require proper design of the grounding system to avoid hazardous touch and step voltages. Rammed steel profiles are often used for the installation of large ground-mounted PV systems. These driven steel profiles act like natural earth electrodes and can therefore contribute to the earthing system. The results of studies in [106(AT)] show that these natural earth electrodes, together with equipotential bonding, are already sufficient to ensure personal safety. This was tested for earth faults at the HV line and direct lightning strikes.

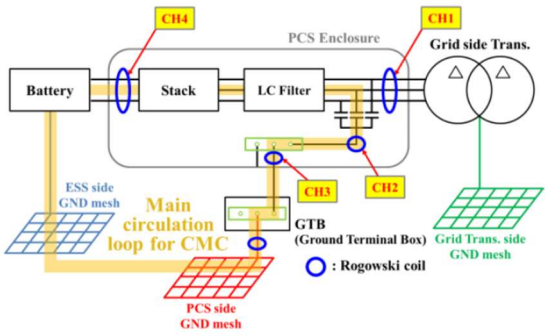

Fig. [669(KR)] Simple circuit configuration including CMC measurement setup

Not only fault currents but also circulating common mode currents (CMC) can cause trouble. This case is reported by the authors of [669(KR)] in a large-scale energy storage system, causing IGBT damage and sporadic shutdowns. The principal path is shown in figure [669(KR)]. Measurements, simulations and tests with a hardware-in-the-loop (HIL) simulation revealed Y-connected capacitors as a relevant part of the current path. Eliminating those capacitors significantly reduced the circulating CMCs.

An important measure to guarantee personal safety is the periodic verification of installations. In [134(AT)], specific test cases for the safety evaluation of DC charging stations are presented. The practicability of those test cases was demonstrated in field tests.

Interference and electromagnetic fields

Electromagnetic interference (EMI) is the unwanted interaction or disruption of devices caused by electromagnetic fields (EMF) or conducted disturbances from other sources. EMI can lead to hazards, malfunctions or prevent devices from working properly.

The voltage induced in pipelines by neighbouring distribution cables is simulated by the authors of [21(EG)]. While normal operation causes no problems, unbalanced load currents and short circuit currents lead to induced voltages up to several hundred volts.

Inductive and capacitive coupling between 400 kV and 110 kV overhead lines on common towers is analysed in [254(DE)]. Induced currents and influenced voltages can have a significant impact on the disconnected respectively grounded 110 kV line. Also, ferroresonance can be an issue in the case of the disconnected 110 kV line.

During construction and maintenance activities, site personal may need to bring vehicles and machinery within close proximity of energised high voltage overhead lines. These live conductors will cause capacitive and inductive coupling effects onto nearby conductive items. The authors of [369(GB)] analysed those effects by simulation studies, applying the limit of 50 V for the safety extra-low voltage (SELV). For worst case assumptions regarding voltage level and line current, the results show that the limit can be exceeded in 90 m distance. It is recommended that where work activities are carried out within the calculated minimum distances, studies are conducted to identify whether mitigation actions such as field earths applied, are required to ensure safety of workers.

[1143(RS)] addresses the reduction of magnetic field exposure by passive shielding. Using aluminium shields with a thickness between 3 and 6 mm and different geometric configurations, shielding factors between 7 and 44 were achieved.

While the previous papers addressed phenomena related to the mains frequency, [1294(AT)] presents key findings of the 4th EMI study report with conducted interference in the frequency range from 2 kHz up to 500 kHz. The report provides recent results and findings from academia and

industry, comprehensively covering all major aspects of EMC, namely emission, immunity, disturbance levels, impedance and related measurement methods. Regarding emission limits, it is recommended to consider the cumulative effect of pieces of the same type of mass-market equipment. When connected at the same location, it may result in significantly higher disturbance levels.

Voltage dip immunity

Voltage dip responsibility sharing typically involves a collaborative effort between the network operator and the customer. The network operator is responsible for maintaining the quality of the power supply, including mitigating the impact of voltage dips, while the customer is responsible for ensuring their equipment is compatible with the IEC61000-4-X standards.

Among others, the inrush current due to the switching of transformers can cause voltage dips. The authors of [406(IN)] describe a method to limit the inrush current by using a pre-magnetizing transformer. The power rating of this transformer is typically around 0.5% ~1% of that of the main transformer.

The impact of voltage sags on devices is investigated in [243(CN)], [804(MY)] and [1120(BR)]. Air conditioning usage is projected to increase significantly in the coming years, driven by rising global temperatures. Dip immunity tests for air conditioners were performed by the authors of [243(CN)]. The peak current during automatic restart after the dip reached almost 4 times the normal operating current. On a large scale, this might affect grid stability.

In [1120(BR)], the analysis of the dip sensitivity of an industrial customer is presented. During one year, 1258 voltage dips were registered and classified concerning their effect on the industry process, as shown in figure [1120(BR)]. As a remedial measure, reconfiguration of protection devices (pick-up current, delay time) in the distribution grid is considered. However, reconfiguration of protection relays within the customer area, especially under- and overvoltage settings, was also taken into account. After implementing the proposed measures, there was a clear reduction in the number of shutdowns.

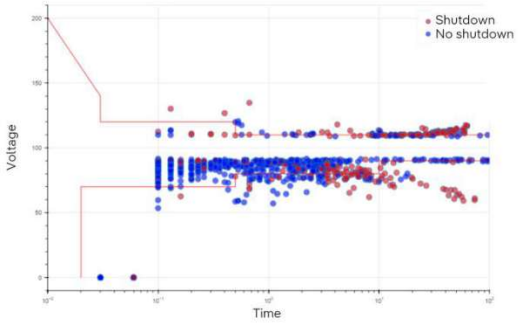

Fig. [1120(BR)] Client's Sensibility for voltage sags

Contactors are essential devices for controlling industrial processes. Contactor sensitivity refers to the ability to reliably operate when subjected to variations in voltage without becoming unstable or unreliable. Besides voltage amplitude, the point-on-wave at which a dip occurs plays a crucial role. This sensitivity is analysed in [804(MY)]. This study confirms that the point-on-wave has a significant impact on the immunity levels of the tested equipment, with the best immunity at 90° switching angle.

Mains frequency and transient overvoltages

A single-phase fault, particularly a fault to ground, can lead to overvoltages in an electrical system. These overvoltages can be temporary or sustained, depending on the system's grounding configuration and the fault characteristics. Paper [623(FR)] provides a parametric study of the overvoltage levels, varying grounding methods, capacitive currents, short circuit capacity and fault impedance. Static calculations as well as electromagnetic transient (EMT) simulations were performed. Highest overvoltages occur for special combinations of short circuit impedance, grounding method and capacitive current, obviously due to resonance effects.

Overvoltage protection is essential for the safe operation of a distribution system. In that field, surge arc suppressors (SAS) are an alternative to conventional metal oxide arresters. Paper [1017(CH)] describes the development of the new IEC 63518-1 standard, dealing with those devices in systems operating above 1 kV. The standard gives guidance in classification, application and type tests. The IEC 60099-8 standard for the external gapped line arresters was taken as the basis for a new standard, as it is a similar device to SAS in terms of applicability.

In [1018(CH)], the review of line lightning protection technology, required equipment and accessories, and the specific requirement for installation on bare MV overhead lines was carried out. To find the optimum number of devices required for installation on 4 selected sections of the lines, several simulations were performed with different amounts of devices?. A reduction of line tripping rate by 52% to 78%, depending on the line section, is expected. This kind of analysis can be performed, for instance, by GROZA, a software dedicated to the lightning performance of overhead lines and presented in [1022(CH)]. It allows the evaluation of the number of expected outages per year with and without the installation of protection devices.

The electrical performance of polymer insulating materials can be improved by adding inorganic fillers. In paper [0468(EG)], the influence of the amount of silica filler on the flashover voltage under different conditions (wet, dry, polluted) is analysed. Experimental results are used to train an artificial neural network. The trained network is useful

to estimate the flashover voltage for different conditions and recommend the optimal filler concentration.

Large renewable energy generation sites require sophisticated protection systems. In those installations, vacuum circuit breakers are often used. However, the overvoltage that occurs during the switching of vacuum circuit breakers jeopardises the insulation of power equipment. To analyse the effect of transient overvoltages on transformers, the authors of [1144(BR)] modelled a PV plant in LTSpice. Evaluating numerous scenarios, it can be stated that surge arresters are essential to limit the transient voltage amplitudes. Increased distance between modules reduces reignitions due to the cable impedance. Transformers at the beginning and the end of each feeder tend to experience more severe transients.

Flashovers and faults

Vegetation contact with medium voltage conductors is a major problem for many distribution network operators. Field tests with branches were performed by the authors of [539(US)]. Results from high current tests show that after energization of the branch, charring and scintillation were observed at both ends and progressed toward the middle of the branch. Ultimately, the charred paths connected, resulting in a high-current flashover. The initial current remains low, often below 1 Amp, until just before a high-current flashover occurs (figure [539(US)]). These findings suggest that detecting early-stage vegetation faults will be difficult.

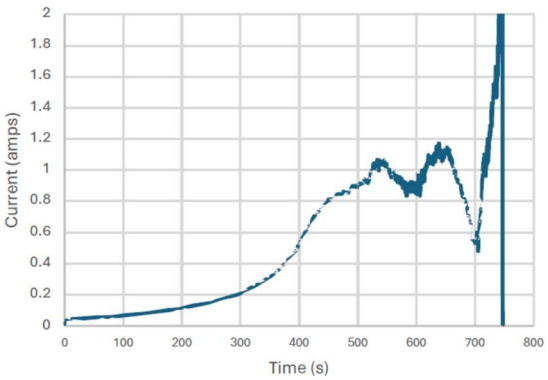

Fig. [539(US)] Current levels for exemplar vegetation test

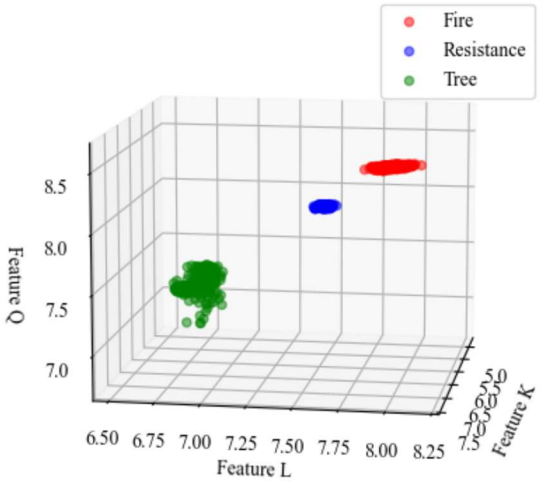

Fig. [677(CN)] Schematic distribution of eigenvalues for different faults

However, authors of [677(CN)] present a method to identify vegetation-related high-impedance faults using a bidirectional long-short-term memory model. Similar experiments as in [539(US)] were performed, and voltage and current signals were recorded. With the help of feature extraction applied on the zero-sequence voltage, a discrimination between different fault types (fire, resistance, tree) seems to be possible (cf. figure [677(CN)].

Potential scope of discussion

Although the definition of global earthing systems is well established, there is still a lack of harmonised and practicable methods to verify the required characteristics.

Risk-based safety standards are ?accepted in Australia, while the rest of the world seems to be rather reluctant. Will this, in the long run, lead to increased investment costs for grounding systems, or is it irrelevant due to significantly higher population density?

More and more power electronic devices are installed in distribution and in transmission systems (HVDC). Can we expect an increase in circulating DC stray currents in grounding systems, and what will be their effect?

Table 1: Papers of Block 1 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
21	Influences of unbalanced AC underground distribution cables on their neighboring metal pipelines and safety of operators			X
106	Touch Voltages in Ground Mounted PV Power Plants Caused by Earth Faults or Lightning Strikes			X
113	Modeling and evaluation of global earthing systems using earth potential rise criteria	X		X

114	GroundInsight: Open-Source Software for modeling and analyzing earthing systems			X
134	Periodic Verification of DC EVCS: Results of the ProSafE² (Protection, Safety and Efficiency of Electric Vehicle Charging Stations) Research Project			X
243	Analysis of the influence of voltage sag on residential air conditioning load			X
254	Impact of inductive and capacitive coupling on common high voltage/extra high voltage overhead lines on a 110 kV grid			X
369	Effect of distances from aerial HV energised conductors have on electrostatic coupling onto vehicles and machinery			X
406	Limiting Inrush Current in Power Transformers by using a Pre-Magnetizing Transformer			X
413	Practical Impact of Measured Seasonal Variations in Soil Resistivity	X		
463	E-REDES | A new model, based on EN 50522, to manage earthing systems in Secondary Substations			X
468	Estimate flashover voltage for polyester Insulators by using feed-forward neural network			X
529	Enhancing Grounding Systems for Canal-Side Street Lighting: Preventing Electrical Leakage Hazards by the MEA, Thailand			X
539	Electrical phenomena associated with vegetation in contact with medium voltage conductors: summary of field experiments	X		X
623	Parametric analysis of overvoltage phenomenon during a single-phase to earth fault in MV distribution grid			X
669	Analysis and Mitigation of Common Mode Circulating Current in Large-Scale PCS-Integrated ESS Sites			X
677	Identification of Tree-Related High-Impedance Faults Using BiLSTM Model	X		X
792	E-REDES adopts EN50522 | Touch Voltages on Secondary Substations Measurement – Observability & Mitigation Solutions			X
804	Voltage Sag Point-on-Wave Impact on AC Contactor Sensitivity: A Comparative Study			X
892	Comparison and Recommendations on Earthing System Measurement and Simulation Techniques Including Staged Fault Method	X		X
1017	The development of a new International Standard IEC 63518-1: Surge Arc Suppressor (SAS) devices to Protect Power Line Insulation of systems > 1kV			X
1018	Lightning Protection for Overhead Distribution Lines on a Wind Farm Power Plant: Implementation and Expected Performance			X
1022	GROZA – lightning performance software for overhead lines			X
1034	Thirty years of learning about distribution earthing design in Australia			X
1120	GODEL PQA 900 - Case Study for reducing voltage sag impacts in industrial clients			X
1143	Analysis of influence of low voltage cable terminal boxes on magnetic field levels in the apartment and shielding solutions			X
1144	Effects and suppression of fast transient overvoltages on transformers applied to solar photovoltaic and BESS			X
1294	Electromagnetic interference in the frequency range 2 kHz to 500 kHz – Key findings of the 4th EMI study report prepared by CENELEC TC219/WG11	X		X

Block 2: "Equipment related power quality aspects"

Block 2 focusses on the contributions related to the impact of new technologies, including control systems and their effects on the grid quality.

In contrast to the last CIRED conference, a significantly smaller number of papers is allocated to this block, which can lead to the conclusion that more accurate solutions for power quality related issues are addressed.

Also the submitted papers for Block 2 of Session 2 are more diverse (an average of two or three contributions each topic). This is a sign that multiple disciplines and points of major interest start to occur in terms of mitigation of decreased power quality and more focused on the integration of low carbon technologies (LCT) in both public and island grids.

PV integration

Current PV interconnection limits in Japan are determined solely by the thermal capacity and does not consider the voltage stability. A novel evaluation method that incorporates the voltage stability to assess the PV hosting capacity (HC) is done by the authors of Paper [82(JP)] by quantitatively analysing the effects of thicker power lines on the HC. It is shown that when the PV interconnection capacity exceeds the line thermal capacity, it can be solved by increasing cable cross section. However, for some interconnection capacities over longer distances, the HC decreases. As a conclusion, it can be stated that the change in the line impedance caused by the thicker wires degrades the voltage stability index VSI.

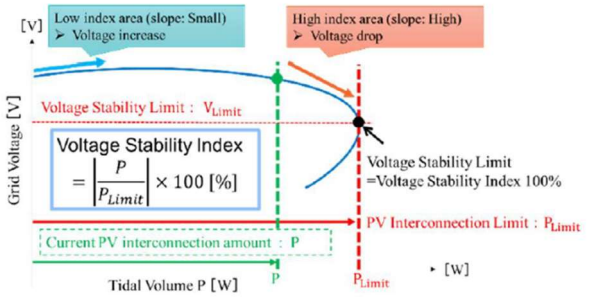

Fig. [82(JP)] Definition of the VSI based on voltage characteristics

Paper [185(DE)] investigates the power quality disturbances caused by PV installations using dynamic modelling and Matlab/Simulink simulations. By evaluating different parameters, including (partial) shading, harmonics, voltage sags, swells, and flicker as well as bidirectional active power flow, the impact on voltage and frequency stability in microgrids is analysed and discussed under varying grid conditions. A household PV system is modelled to explore these effects in a weak grid, emphasizing transient events like weather fluctuations and faults. By addressing these challenges, the study contributes to the development of robust PQ management, supporting the reliable and efficient integration of PV systems into microgrids. It can be concluded that weak grids exhibit higher susceptibility to these issues, with slower recovery and greater instability compared to strong grids.

Paper [187(AT)] discusses the integrating of PV systems into MV industrial grids linked the transmission networks from both power quality and grid stability perspective. The study investigates an industrial grid with and without PV a park on a 6 kV grid power grid under pre- and post-installation. Analytical assessments and hardware-in-line (HIL) testing were performed to evaluate system behaviour in both steady state and transient conditions. On-site tests were performed to validate both planning assumptions and standardization compliance. It is found that the PV park doesn't introduce significant stability or harmonic issues, ensuring compatibility with industrial operation.

Electric vehicles and heat pumps

Paper [47(SE)] investigates the impact of EV charging installations from both EMC, research perspective and measurements. At least two concerns are their effect of radiated emissions (on nearby equipment and living creatures) and their influence of conducted emissions on the grid and nearby equipment. Time-domain measurements are executed on a bus charging station. As a conclusion it will be very difficult to predict future emission levels and thus to guarantee a sufficiently low risk of interference. Therefore, only through more studies and measurements, it will be possible to standardize these sub-systems from the EMC perspective.

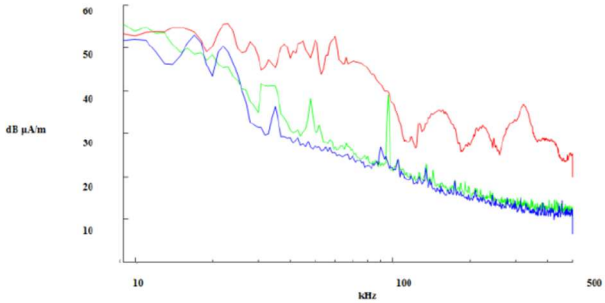

Fig. [47(SE)] Comparison between the maximum spectrums: before and during start of charging (red colour), during charging (green colour), and after charging (blue colour)

Paper [132(CN)] analyses the behaviour of a fast charging station for EVs and its impact on the power quality parameters of the grid due to their non-linear behaviour and impulsive load characteristics. The analysis is performed based on field measurements. Based on measured data the paper describes the individual

characteristics of fast-chargers and their aggregated integration characteristics in distribution networks. Out of this analysis, it is concluded that the characteristics of fast-charging stations exhibit significant variations depending on different combinations of chargers and EVs. Also, a close coupling with the background distortion of the distribution grid is found.

Paper [764(CH)] investigated the Zurich's tramway network which is supplied with DC voltage through solid-state rectifier systems via MV to LV 6-pulse rectifiers. By combining two 6-pulse rectifier systems, a 12-pulse rectifier system is created, offering lower harmonic emissions. Both configurations are installed in the distribution grid of the city of Zurich and were subject of this study from the perspective if future concepts should be changed towards only 12-pulse rectifiers form power quality perspective issues. It is found that the emission of harmonic currents by both the 6- and the 12-pulse rectifier are within the limits, however, the difference of the current waveform shape between the two configurations is pronounced.

Paper [810(NO)] discusses the grow of EV-technologies especially related to smart charging and vehicle to grid (V2G) applications. The impact of bidirectional charging on power quality, using experimental data from an EV connected to a single-phase bidirectional charger are presented. Both voltage variations and unbalances, as well as harmonic current distortion are observed for different power levels and compared with the grid standards. It can be concluded that the voltage drops of the loaded phases during charging and inversely swells during discharging are noticeable. However, they remain within LV grid standards. Voltage unbalance is more pronounced suggesting that V2G technology could help stabilize the grid. It is concluded that harmonic current emissions in that case exceed the limits of the IEC 61000-3-12 standard, particularly at power levels well below nominal power.

Other power electronic based equipment

Paper [119(EG)] discusses a performance evaluation of inverter control strategies for a 1 MW grid-connected wind turbine system based on double-fed induction generator (DFIG) where the rotor is connected to the grid via a 3-phase rectifier and a 3-level inverter. In order to reduce harmonic current injection, a detailed investigation of the interfacing inverter switching techniques is performed for four different new developed switching techniques. The system is simulated using Matlab/Simulink. Results showed that the standard PWM-switched inverter produces the highest THD(I) and consequently highest THD(U) while three-level PWM-switched inverters produces the lowest harmonic grid injection.

Paper [153(CZ)] describes a passive filter design for weak distribution network using EMT modelling. Therefore, a load of two 5.5 MW inverter driven motors, supplied by a 24th pulse rectifier is analysed from harmonic emission perspective. The EMT model is developed in order to calculate the emitted harmonic content including the THD and TDD. Finally, the results were compared with the IEEE-519 standard and the IEC/TR 61000-3-6. The modelling also included a filter optimization to mitigate harmonics with minimum of reactive power consumption and power losses. The shunt passive filter for harmonics elimination was recommended.

Paper [347(DE)] highlights the droop control of grid-forming inverters for managing the power system's voltage and frequency stability. The authors suggest the integration of virtual impedance (VI) to adjust the R/X ratio and achieve decoupling between active and reactive power. Three different VI-configurations and their effects on the frequency and voltage dynamics under varying grid conditions are analysed. The dynamic response of each of these configurations to load changes is evaluated on a test bench. The results reveal that while inner and outer VIs maintain stable dynamics, the parallel VI introduces additional oscillations and longer settling times. It can be concluded that a further investigations on R/X ratio must be performed in order to replicate an R/X ratio similar to that seen in real high-voltage systems.

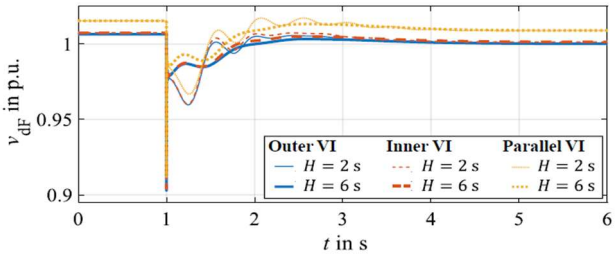

Fig. [347(DE)] Variation of the inertia of the SG: distribution generating unit filter voltage.

Paper [658(BE)] investigates the relationship between the power rating of a boost converter used as an active power factor corrector (APFC) and its own generated supraharmonic emission. This work is done by exploring the modelling of converters with focus on both low-frequency and high-frequency harmonic emissions. The converter model, which functions also as an APFC, is analysed with the objective to determinate the parameters, which influence the supraharmonic emissions. The added value of this contribution is that the different approaches analytical, numerical and experimental are presented and compared.

Paper [255(EG)] analyses the influence of the DC link capacitor and inductor on the performance of the grid-connected Double-Fed Induction generator based wind turbine (DFIG-WT) during 3-phase symmetrical grid

faults. For this analysis, a Matlab/Simulink model is used to analyse 3-phase voltage sags, swells and ground faults. The transient peaks of the stator current, rotor current, rotor voltage, and DC link current and voltage are observed for different values of the DC link capacitor and inductance. It can be concluded that the DC-link capacitor and inductance will improve fault ride through without the need of other fault ride through devices.

Paper [1199(FI)] presents the droop-based coordination for active and reactive power sharing between grid forming (GFM) and grid following (GFL) inverters based on a 12 MVA 100% inverter-based microgrid with two PV systems. The impact of different inverter control strategies on power-sharing and frequency response is analysed using a PSCAD/EMTDC software model. Three different cases are studied based on different GFM and GFL power limits. It can be concluded that a fully GFM-based microgrid offers the most stable response, but proper reactive power droop tuning is crucial for balanced power sharing between inverters located at a distance.

Harmonic emissions and standard compliance

Paper [49(NL)] elaborates the harmonic current emission limits (in the grid) in the Netherlands using 2 case studies. Basically the harmonic emission from the customer's installation needs to be restricted so that the Distribution System Operator (DSO) can meet the harmonic voltage requirements for all customers as indicated in the EN 50160. Furthermore, in the Netherlands, additional requirements are stipulated. The harmonic limits are more than 25 years old, are not applicable anymore, and consequently need an update. Two cases are discussed: A customer with large pumping equipment was producing a big share of 5th harmonic voltage emissions as well as a big milk production company that operates with frequency controllers and is connected to the MV grid. It is concluded that the emissions limits should be fair for each customer, meaning they should not depend on the neighbouring connections.

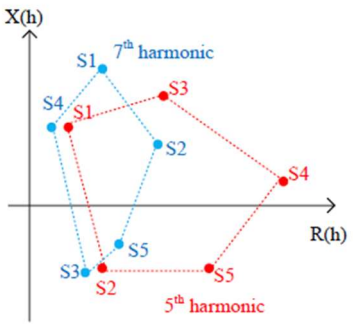

Fig. [59(CA)] Grid impedance in the form of impedance polygons

Paper [59(CA)] presents the research findings on harmonic interconnection studies of Inverter Based Resources (IBR) plants. The presented examples include the need for probabilistic summation of the harmonics generated by the IBR units including a range of grid impedances, and a method how to quantify the severity of harmonic resonance. Assessing the severity of the resonance when interconnecting an IBR plant with respect to background distortion is done. It is concluded that harmonic resonance is a more important concern than current harmonic limit violation when interconnecting IBR plants.

The paper [652(DE)] assesses the flicker emission of an existing electric arc furnace (EAF) and presents a possible procedure for a detailed connection assessment for a planned 200 MW EAF connected to the 220 kV network. It is observed that dynamic power consumption leads directly to a significant flicker emission. The case study is compared to the calculation of the flicker emission of a planned EAF. The study shows that based on the cooperation and effort of TSO and steel manufacturer sharing more detailed data and considering possible flexibilities in the assessment on both sides, the grid connection of EAFs without intolerable emission can be assured.

Paper [712(ES)] investigates impulse based events, such as spikes, supraharmonic emissions, and high-level transients due to inverter-based systems. These events may impact the correct working of protection equipment. Measures, which enable an accurate measurement of these events are necessary. A new approach for a more accurate assessment, based on a sample-by-sample analysis, including techniques for waveform reconstruction are presented. The proposed measurement techniques provide a better understanding of transient events occurring in the grid and valuable knowledge to design mitigation measures against these disturbances.

Paper [724(SE)] evaluates a microgrid consisting of two energy storage systems of 160 kW power and 336 kWh energy each. At one of the storage locations, a small PV system of 2 kW_p has been installed with the purpose of testing its control system in the microgrid. The normal operation is grid connected while the island operation is intended to be used only in case of grid outages. The voltage harmonics has been investigated during periods of island operations. Both THD and individual harmonics are compared between island and grid connected operation and related to limits of the EN 50160 standard. It can be concluded that during grid connected operation the microgrid doesn't has a noticeable negative effect on the harmonics while in island operation there is a noticeable increase in the THD but staying within the limits of EN 50160.

Paper [777(CN)] investigates the impact of changing position of both no-load and on-load tap changers

(NLTC/OLTC) of transformers supplying thyristor based inverter systems on an electrolyser. It is shown that to cope with the AC voltage variation as well as the DC operation range of electrolyser system, a transformer tap-changer is often required in combination with the thyristor rectifier to regulate voltage at different loads. Both, OLTC and NLTC solution in terms of reactive power consumption and harmonic currents are compared by theoretical calculations and simulations. It can be stated that in case of large AC variation the OLTC solution performs better than the NLTC. However, in case of smaller AC variations both give same advantages.

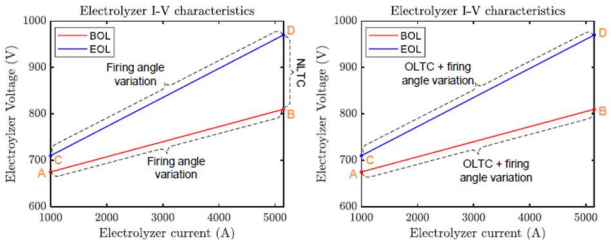

Fig. [777(CN)] (a) NLTC solution, (b) OLTC solution

Paper [841(DE)] presents the results of a survey of power quality disturbances caused by heat pumps (HP) in LV grids. The survey is focusing on harmonic current distortion and voltage changes especially during the switch-on process. The presented results of this analysis is based on field measurements of 14 HP-models under realistic operating conditions. The models represent various types and manufacturers of the German market. It is shown that a significant harmonic and supraharmonic current distortion occurs with magnitudes comparable to the fundamental current. Next to that, it is found that over a quarter of the models shows a high inrush current, causing significant voltage changes during switch-on. Finally, the paper highlights the need for a more in depth examination of HP behaviour and consequently a better standardization framework.

Paper [1125(BR)] presents the impact of a saturated core reactor used in an MV grid to mitigate power quality problems since the use of such a core is a good alternative for voltage stabilizers. In this study case the feeder is served by a low-level short-circuit system with a rated voltage of 34.5 kV with different end users such as industrial, residential, irrigation and distributed generation customers. Out of the proof of concept, it can be concluded that the integration of a saturated core reactor brings significant benefits to the network due to its mitigation of overvoltages in the network.

Potential scope of discussion

The submitted papers for Block 2 of Session 2 are quite diverse highlighting that multiple disciplines and points of interest are observed. The decreasing power quality due to massive integration of LCTs and consequently also the upcoming background distortion due to whether or not fast injection or retraction of (harmonic) currents seems to be an upcoming point of interest.

The massive integration of EVs is an important point of concern, especially in case of fast charging installations and V2G applications. Next to that, renewable energy sources combined with storage systems also win more interest. From the point of view energy market challenges dynamic power flows are observed in local grids. However, from the perspective of voltage and frequency variations, especially in grid systems with a high share of renewable energy sources power quality related problems are occurring.

Table 2: Papers of Block 2 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
47	A review on radiated and conducted emissions from E-roads, EVs, and charging installations			X
49	Considerations on harmonic current emission limits in the Netherlands illustrated with two case studies	X		X
59	Practical Solutions to Harmonic Impact Assessment of Inverter-Based Resource Plants			X
82	Development of simple determination method for available interconnection capacity of PV considering voltage stability	X		X
119	Performance Evaluation of Inverter Control Strategies for Grid-Connected Wind Energy System			X
132	Study on the Characteristics of Large-Scale Fast Charging Loads and their Impact on Power Quality in Distribution Networks based on Field Measurements			X
153	Passive Filter Design for Weak Distribution System with 24-pulse Converter Load using EMT Simulation			X

185	Enhancing Power Quality: Investigation of Photovoltaic systems in Microgrid Power Systems			X
187	A Pre- and Post-Installation Analysis of the Impact of Industrial Photovoltaic Park Deployment on Power Quality Emissions	X		X
255	Influence of DC link parameters on the Fault Ride Through of Wind-Driven Grid-Connected DFIG			X
347	Influence of a virtual impedance on the dynamic behavior of the grid-forming control of inverter-based generation plants			X
652	Assessing the Flicker Emission of Electric Arc Furnaces in CO2-Neutral Steel Production: A Case Study			X
658	Investigation of the Relationship Between Power of a Boost-Type Converter Used as an Active Power Factor Corrector and its Supraharmonic Emissions			X
712	On the need of uncertainty computation of electrical waveforms on a sample-by-sample basis			X
724	Comparison of Harmonics in a Microgrid When Operating in Island and Mainland Mode	X		X
764	Optimizing Rectifier Systems for Zurich's Tramway: Assessing Harmonic Impact on the Medium Voltage Grid	X		X
777	Implication of transformer configurations on power quality performance in thyristor-based electrolyzer plant			X
810	Power quality measurements reveal vehicle-to-grid (V2G) influence from charging and discharging			X
841	Survey of power quality disturbances caused by heat pumps connected to low voltage networks	X		X
1125	Saturated Core Reactor Applied to Medium Voltage Distribution Networks			X
1199	Droop-based Co-ordination of Grid-Forming and Grid-Following Inverters Ensuring Stability in a Microgrid			X

Block 3: “System-related Power Quality aspects”

This block is dedicated to papers studying PQ in the context of system behaviour as well as methods for the measurement of PQ parameters.

Compared to CIRED 2023 a significantly smaller number of papers is allocated to this block. While at former conferences studies related to harmonics (frequencies below 2 kHz) and supraharmonics (frequencies above 2 kHz) built the majority of papers, this CIRED a dominating share of papers (35%) is related to measurement methods, in particular for the supraharmonic frequency range. 20 % of the papers deal with small-signal stability and evaluation of inertia in AC- and DC-grids. This confirms that power electronic dominated AC networks as well as DC micogrids represent a recent topic of research. A remaining set of papers addresses studies related to the most common PQ phenomena, particularly harmonics, supraharmonics, slow voltage variations, voltage fluctuations and flicker. Despite the significantly reduced number of these papers compared to last CIRED, this should not serve as indicator that these are of less importance anymore.

Finally, some papers propose strategies to improve, either the hosting capacity for photovoltaics and electric vehicles in LV networks, or to reduce losses and improve voltage by optimal placement of shunt capacitors.

Measurement methods

IEC SC77A WG9 was required during the last years to define a grid measurement method for the frequency range 9-150 kHz. Discussion addressed particularly, if the CISPR 16 Quasi-Peak (QP) method intended for laboratory measurements is also suitable for grid measurements and if it can effectively capture the interference mechanisms that shall be protected by respective limits.

Paper [31(ES)] concludes after a comprehensive analysis of synthetic and field measurements, that CISPR 16 QP method is not suitable to capture the fast amplitude variations of narrowband Power Line Communication (PLC) signals appropriately as presented in Fig. [31(ES)]. Consequently, the authors propose alternative approaches applying combined time-frequency domain analysis for this issue.

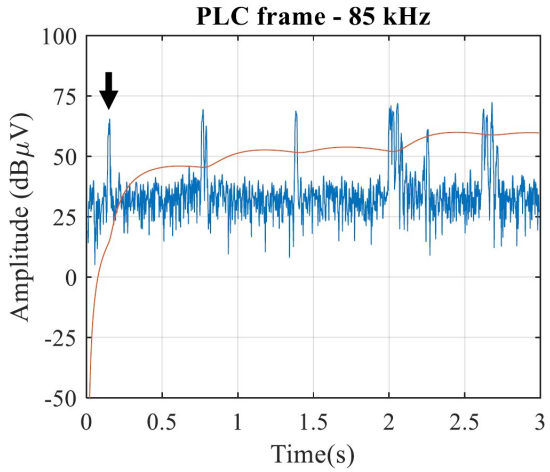

Fig. [31(ES)] Comparison of CISPR16 QP and an alternative analysis for a PLC frame at 85 kHz (black arrow indicates first PLC frame)

Paper [1176(CA)] studies a similar question as paper [31(ES)], where synthetic impulsive and non-impulsive (noise) signals with the same power spectrum in frequency domain are compared. The authors conclude that the very different time-domain characteristics cannot be captured by the amplitude spectrum in frequency domain. One reason is the different phase spectrum of the individual frequency components. In this sense, the question remains, if the frequency domain alone is sufficient for the appropriate characterization of supraharmonics.

Paper ([50(CA)] addresses the computational burden required by the QP computation. Based on implementations on a Field Programmable Gate Array (FPGA) and in the computer, eight methods are compared with the reference method defined in the recent draft of IEC 61000-4-30 Ed.4. The authors prove that efficient alternatives for the QP computation do exist that could be integrated into cost-efficient hardware platforms.

Papers [249(KR)] and [789(IN)] do also address the challenges of implementing the measurement methods as required by IEC 61000-4-30 into low cost equipment. Both papers address in particular the Fourier transform to obtain harmonic spectra, where IEC 61000-4-30 refers to IEC 61000-4-7. [249(KR)] proposes a combination of polynomial interpolation based resampling and Mixed Radix FFT, which reduced the computation time by a factor of 10 compared to the classic DFT algorithm maintaining the required accuracy.

[789(IN)] does not look into the sampling and Fourier transform algorithm at all, but proposes to shift the computation of the different input channels to reduce the computational burden for the CPU. However, performance comparisons based on processing times are not provided. The second part of [789(IN)] discusses also the aggregation of the harmonic spectra into 3-s- and 10-min-values and the subsequent percentile calculation for comparison with limits.

Paper [516(JP)] addresses the very timely topic of measuring impedance in the frequency range 2-9 kHz, which is closely linked to the ongoing activities of defining emission limits and the test impedances (AMN, artificial mains network) for this frequency range (e.g. in the upcoming IEC 61000-3-10). The authors prototyped a device based on triac-controlled resistance, which can actively inject harmonics into the grid (invasive method). Measurements have been performed a customer house connected to the LV side of a 6.6 kV/100 V/200 V pole transformer located about 1 km from the substation. The measurements confirm that the impedance is mainly determined by the type of equipment (i.e. its frequency-dependent input impedance) connected at the LV side. As example Fig. [516(JP)] presents the impact of a PV system.

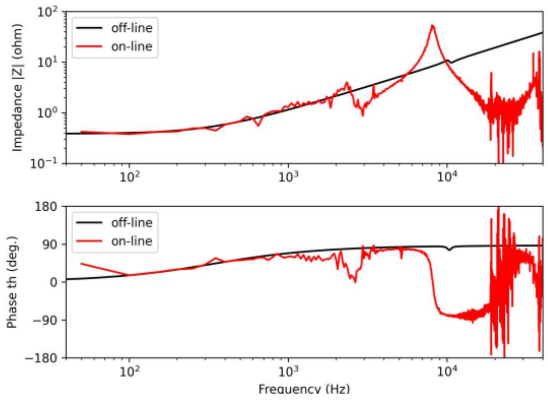

Fig. [516(JP)] Frequency-dependent network impedance with/without PV generation connected

The last paper related to this sub block ([126(US)]) addresses the important topic of the impact of sensors on measurement uncertainty, especially at higher frequencies. The authors develop a laboratory test setup to analyse the suitability of a capacitive voltage divider (Low Power Instrument Transformer, LPIT) to accurately measure at high frequencies. Lightning impulses are used for the test, which shall reflect the fast-switching pulses from modern IGBT-based power electronic devices. The LPIT proves to be accurate with magnitude differences below 3 dB up to 3 MHz.

Inertia and stability in AC and DC networks

Especially in power electronic dominated networks, inertia and small signal stability performance are essential for a stable grid-operation. This applies particular to DC networks, which are usually supplied by AC/DC converters. In this sense, paper [216(FR)] studies the small-signal stability of DC-microgrid consisting of a boost converter as DC source, a DC cable and a Buck converter as constant DC power load. The system has been modelled in time domain and stability analysis is

performed based on eigenvalue analysis. The authors concluded that each of the individual elements could be the root of an instability, both due to unsuitable element design (e.g. high boost converter inductance) or control design (e.g. low current loop control bandwidth). As example, Fig. [216(FR)] shows that when increasing the boost converters inductance, the system becomes instable at an inductance value of about 3.8 times the reference value, when the pair of eigenvalues shifts to positive values on the real axis.

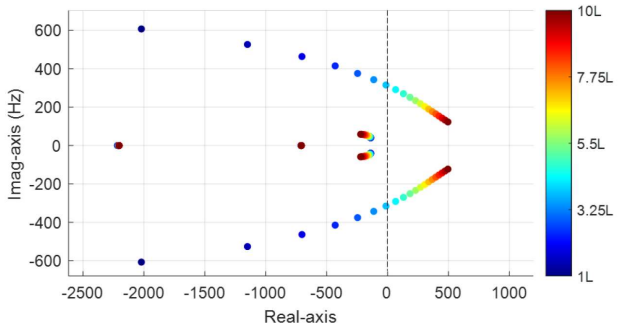

Fig. [31(ES)] Sensitivity map of the boost converters inductance

Paper [183(DE)] explores the potential of Topology Adaptive Graph Convolutional Networks (TAGCN), which combines the advantages of model-based and measurement-based determination of system inertia. The IEEE 39 bus system consists of six synchronous generators and five supply points based on Inverter Based Resources (IBR). Based on 55 disturbance scenarios four different neural network architectures including TAGCN are explored. TAGCN outperformed the other architectures and can provide an effective alternative to estimate inertia and damping in electrical grids. Amongst others, more comprehensive datasets, including real-world scenarios, are required to improve robustness of the method.

Power Quality improvement strategies

Paper [1142(IR)] addresses the challenges of voltage band utilization and THD due to the increasing penetration of distribution networks with EV charging and PV generation and how their coordinated integration and operation can improve it. Based on the radial, single-fed IEEE 33-bus-system, the proposed two-stage-optimization algorithm is analysed. The impact of EV charging on the voltage profile is reduced by integrating distributed PV generation and coordinating the EV charging with it. The second stage considers harmonic distortion and identifies an optimal allocation of active filters in order to ensure that target limits of THD are not exceeded.

Paper [1059(FR)] reports the efficiency of measures to increase the hosting capacity of LV networks for PV generation in particular by improving voltage band management and reducing their automatic disconnection due to overvoltage. Therefore smart meter data of an LV distribution network with a high penetration of PV generation are analysed before and after applying a data-driven optimization method for phase balancing by switching selected customers between phases. Finally, 20 out of 23 recommended phase changes of customers in four LV networks have been implemented. The results of field measurements over three months show the effectiveness of the method for balancing both, power injection and consumption. This way, the average injected power for four different MV/LV substations could be increased in the range of 17 % up to 32 %. Fig. [1059(FR)] illustrates the improvement for the injected power, which is especially significant for the substation Maronne.

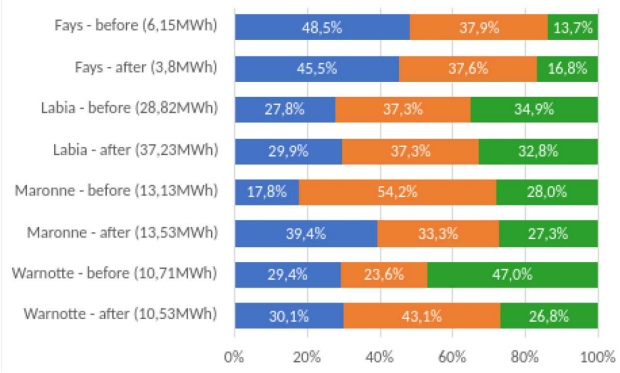

Fig. [1059(FR)] Change in power injection before and after balancing measures for four different substations

Paper [242(EG)] studies the optimal placement and sizing of capacitor banks based on a Particle Swarm Optimization (PSO) algorithm in order to minimize losses in MV networks. The application of the algorithm is illustrated for an IEEE radial 34-bus system and a real radial 135-bus distribution system in Egypt. For the IEEE test network the PSO-based method achieved less active power losses requiring less reactive power (capacitor banks) compared to a conventional placement method. Next to the reduction of power losses, also the voltage band utilization and the THD could be reduced. However, the analysis of the THD is simplified by considering only one harmonic source in the network and does not consider possible impact of capacitor banks on resonances.

A more detailed study of harmonic mitigation and influence on resonances due to high-pass filters and detuned capacitor banks is presented for the case of a 70 bus network of a water treatment plant in paper [368(JO)]. The study analyses three simulation scenarios: non-detuned capacitor banks, detuned capacitor banks as well as detuned capacitor banks with high pass filters. The simulation results show that detuned capacitor banks shift the resonance frequency away from characteristic harmonics. High-pass filters effectively mitigate residual harmonics. In this way, improvements in THD by factors between 2 and 142 with most of them around 10 could be

achieved compared to the case with non-detuned capacitor banks. Exemplarily, Fig. [368(JO)] shows the improvement of voltage waveform at one bus between the three scenarios.

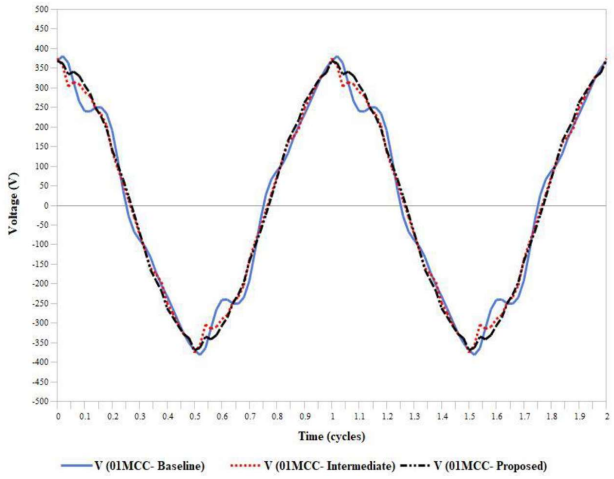

Fig. [368(JO)] Voltage waveform at bus 01MCC for three scenarios

Studies on harmonics, supraharmonics, voltage changes and flicker

Paper [496(IE)] develops simplified equations to evaluate the required short circuit level (SCL) of an MV network (system strength) and its X/R ratio at the Point of Common Coupling (PCC) to minimize the risk of adverse voltage variations. In a second stage, the method considers the impact of the length of supply cable with regard to the risk of resonances. The equations are easy to apply and require only commonly known knowledge about the connected installation and the grid. The authors apply the method to study the connection of a 30 MW exporting customer and conclude that in terms of voltage variations a SCL larger 250 MVA at a X/R ratio larger than 3 limits the voltage rise to below 2 %. Fig. [496(IE)] exemplarily presents a heatmap plot showing the voltage variation of the customer at a power factor of 0.95 lagging. Resonance frequency and resonance rise reduce with increasing cable length. At cable length of 20 km, the resonance is expected around the 7th harmonic. To reduce the risk of resonance excitations a cable length less than 5 km is recommended. The paper concludes that short-circuit level and X/R ratio are of major importance to minimize the risk of voltage fluctuations and resonances caused by customers being connected to the network.

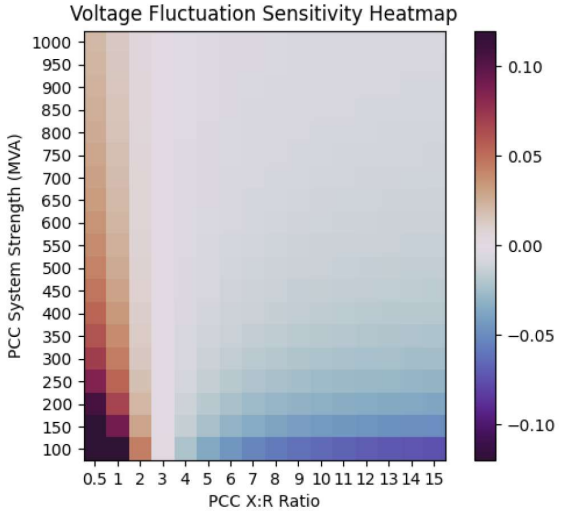

Fig. [496(IE)] Voltage change due to a 30 MW generating customer at power factor of 0.95 lagging

Paper [847(HR)] analyses the impact of an increasing penetration of PV installations in Croatian LV networks on the voltage rise and possible violations of the limit for the upper voltage band according to EN 50160. End of 2024 about 26,000 PV plants with a total capacity of about 800 MW had been installed. This is about twice as much as at the end of 2023. In one of the costal supply regions with about 2000 PV plants, in about 30 % of the cases the voltage for at least one 15-minute interval exceeds 253 V. Extreme cases with up to a maximum voltage of 283.5 V have been observed. To mitigate this issue, several measures have been considered with reactive power compensation being identified as the most effective one.

Paper [921(BA)] determines the optimal placement of PQ monitors in a real MV network in Sarajevo. The authors apply their method to flicker, which has been identified as one of the critical PQ parameters in MV networks. The method is based on a simulation model of the MV network including the dominant flicker sources. The selection of the measurement sites is based on multiple linear regression, which puts one representative PQ monitor in each area with similar expected flicker levels. For the considered network, which supplies about 118 LV networks with about 20,000 customers, the method determined five measurement sites, where one site covers already the flicker levels at 113 out of 118 substations.

The authors of paper [570(CN)] address the challenge of harmonic modelling of EV charging installations consisting of multiple EV chargers and PV inverters in LV networks. As the detailed (time-domain) modelling increases in complexity and computational burden with the number of considered devices, an equivalent harmonic Norton aggregated model (EHNAM) in frequency-domain is proposed. In a first step, the individual models of a single PV inverter and EV charger are determined, which are

aggregated in the second step to a single, but time-dependent model of the whole EV charging station. Time-dependency is included by considering variating irradiance for PV inverter and EV usage patterns. The methodology is validated in a case study, which connects one EV charging station in the IEEE 33-node network. Results show a reasonably good match between the accurate and the simplified model for the 5th harmonic. The simplified model tends to provide slightly lower values than the accurate model (cf. Fig. [570(CN)].

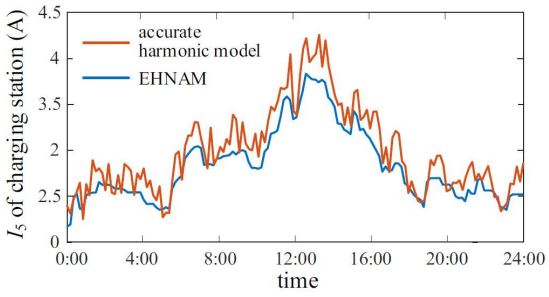

Fig. [570(CN)] Comparison of 5th harmonic current of the EV charging station between accurate and simplified model

Frequency-dependent impedance of the network is a crucial parameter to understand the level of distortion and its propagation. Paper [365(ES)] studies the impact of grid topology on the impedance in the frequency range 20 – 500 kHz in a testbed of an LV network reproducing characteristic Austrian LV grid conditions. The considered frequency range is relevant for PLC the in CENELEC Band A and the Federal Communications Commission band (FCC band). The testbed has the advantage of controlled conditions without the impact of unwanted external influences.

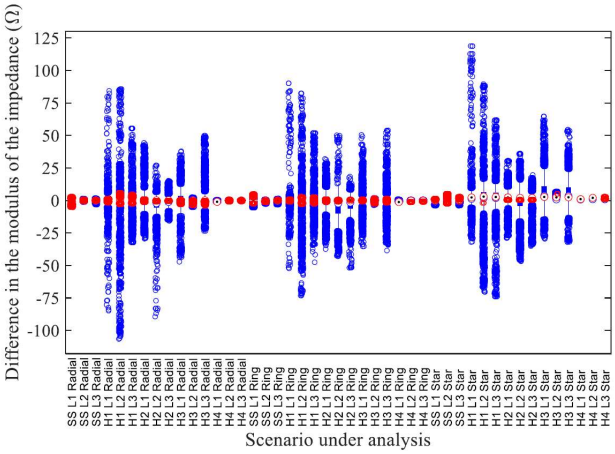

Fig. [365(ES)] Variation of magnitude of impedance between different topologies for busbar (SS) and aPCC(H1 .. H4) with the fork topology used as reference

Impedance measurements have been carried out at the busbar and one PCC under different grid topologies, namely radial, star, ring and fork. The results show that the measured impedances significantly differ from the reference Line Impedance Stabilization Network (LISN impedance) according to CISPR 16-1-2. While the impedance characteristics in terms of resonances remains similar, differences in magnitude and phase are observed between the topologies. Moreover the variations between the different topologies are significantly higher in the frequency range 20-150 kHz compared to 150-500 kHz (FCC band) as exemplarily shown in Figure [365(ES)] for the magnitude.

Potential scope of discussion

Related to measurement methods in the frequency range 9 - 150 kHz it should be further discussed, if the presently required CISPR 16 Quasi Peak algorithm is suitable to capture the relevant interference phenomena in this frequency range that should be protected by EMC coordination (especially malfunction of equipment and disturbance of PLC). It is strongly recommended to jointly discuss this topic also in the relevant IEC SC77A working groups to avoid unnecessary costs especially on the part of instrument manufacturers.

Another important topic requiring more discussion and research are efficient and suitable approaches to manage EMC in AC-networks with dominating or 100 % share of power electronic based supply (i.e. by grid-forming converters). In terms of network disturbances and PQ, the simple requirement that such converters should behave similar to the “traditional” grid based on synchronous generators might not be straightforward and especially the derivation of emission limits based on short-circuit power seems not reasonable anymore. Similar considerations apply also to DC-networks, which are always supplied by power electronics. Their characteristics in terms of impedances and disturbances levels significantly deviate from traditional AC-networks. E.g., impedances are usually much lower, and harmonics related to a fundamental frequency as for AC-networks do not exist.

The increasing application of power electronics in distribution networks require reliable simulations of harmonic emission, propagation and resulting levels in the network. There is a need for improved harmonic models that can not only equivalently aggregate the harmonic emission of multiple devices, but also reflect their dependency on usage behaviour or varying operating points. In this context, the accurate representation of modern power electronic devices that includes next to the circuit also advanced controls as well as their possible impact on the stable operation of the grid are still open challenges.

Table 3: Papers of Block 3 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
31	Is CISPR quasi-peak an appropriate metric for evaluating power line communications?	X		X
50	Efficient Computation Alternatives for IEC 61000-4-30 Supraharmonic Quasi-Peak Detector		X	X
126	High-Frequency Characteristics of Low Power Voltage Transformers (LPVTs)	X		X
183	Estimating system inertia in sparsely measured dynamic power systems using graph neural networks	X		X
216	Understanding Small-Signal Stability of DC Microgrid	X		X
242	Optimal Sizing and Allocation of Shunt Capacitors for QV Control in MV Distribution Networks			X
249	A Study on Signal Processing Methods for Implementing IEC 61000-4-30 Class A Measurements in Low-End Power Quality Meters			X
365	Influence of the grid topology on the grid access impedance in the 20-500 kHz frequency range		X	X
368	Strategic Integration of High-Pass Filters and Detuned Reactors for Effective Harmonic Mitigation and Resonance Shifting: A Case Study			X
496	Short Circuit Level and Power Quality Variations			X
516	Development of Effective Impedance Measurement Techniques for Low-voltage Distribution Lines - Validation of Measurement Method using Harmonics on a Full-Scale Experimental Distribution Line -		X	X
570	A method for aggregation of harmonic emission characteristics of power electronics and model order reduction	X		
789	Challenges and solutions of harmonic monitoring application as per IEEE 519 and IEC 61000-4-30 standards			X
847	Analysis of the Impact of Small Solar Power Plants on Voltage Conditions in a Distribution Network with Pronounced Seasonal Load			X
921	Power Quality Monitor Locations in Real Medium Voltage Distribution Network			X
1059	Network balancing to improve PV hosting capacity and reduce voltage excursions – Belgium experiment	X		X
1142	Coordinated Integration of Solar PV Systems and Electric Vehicles Charging Stations: An Optimization Framework for Enhanced Distribution System Power Quality			X
1176	Should the Impulse Train and White Noise with the Same Power Spectrum be Considered Equal in the Estimation of Supra-Harmonics?			X

Block 4: "Standards, regulation, monitoring and advanced data analysis"

This block covers new approaches for standards and regulations, measurement campaigns and monitoring systems as well as advanced data analysis.

Standards and regulations

Timely amendments in grid regulation and standards for PQ are highly important for setting an appropriate framework for a reliable and resilient grid. This sub-block summarizes nine papers.

Five papers are dedicated to standards. The topics discussed include frequency-dependent network impedance, harmonic emission allocation and the phenomenon of harmonic resonance in calculating harmonic emission limits. Furthermore, a possible framework for EMC coordination of interharmonics in low voltage distribution networks is discussed. Three papers describe changes in regulation in Sweden and Croatia related to energy transition, specific end users and extreme weather events. One paper addresses the challenge for DSOs to find a balance between improving service quality and optimizing cost.

[330(SE)] outlines the voltage characteristics that the Swedish Energy Markets Inspectorate (Ei) monitors to ensure good quality of electricity supply according to new Swedish regulations. The revised regulation refines limits on voltage characteristics and introduces three voltage categories instead of two in order to be more consistent with the categorization in EN 50160. Additionally, requirements for flicker are introduced and minor changes on the regulation of voltage dips and swells applied. One difference to EN 50160 is that for harmonics and unbalance limits apply in 100% of the time instead of 95%. Ei concludes that it becomes increasingly important to monitor the voltage quality in the grid due to the energy transition and its entailment.

[811(SE)] presents the recent changes of the Swedish regulatory framework for Continuity of Supply (CoS), which entered into force in 2024. The revised regulation includes increased flexibility by introducing the possibility for DSOs to be exempt from CoS requirements for certain end-users. The paper aims to explain the reasoning behind these changes and outlines the necessary requirements for exemptions to be granted by The Swedish Energy Markets Inspectorate (Ei). Furthermore, it discusses cases handled by Ei so far and the impacts of exemptions, both for both end-users and DSOs.

[479(HR)] explores the impact of extreme weather events on the distribution network resilience in Croatia. The Croatian Energy Regulatory Agency stresses the necessity for regulatory programs that can mitigate the effects of extreme weather events, to ensure the safety and reliability of the energy supply. The paper discusses the resulting consequences for customers and economic consequences of previous extreme weather events in Croatia, as well as the recovery efforts and investment programs used to improve the grid reliability and CoS.

[588(BR)] presents a simulation tool to support Brazilian DSOs to find a balance between improving service quality and optimizing financial costs. Simulating different investment scenarios, the software allows DSOs to identify the most profitable interventions maximizing return on investment and ensuring business effectiveness. The paper shows the results of simulations of interventions in the distribution power grid, presenting the variation in the collective indicators System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) as well as the estimated cost-benefit. The main goal is to select the locations and types of interventions that will bring the greatest benefits, rather than precisely predicting the future results of the indicators.

[1056(DE)] evaluates the validity of the assumptions used to approximate the frequency-dependent network impedance (FdNI) below 9 kHz, as applied by VDE AR-N 4100 (German low-voltage grid connection rules) and D-A-CH-CZ rules for assessment of network disturbances. The article compares the approximations with recently collected data from measurements conducted in LV networks in Austria, Czech Republic, Germany and Switzerland. It also introduces a novel approach for approximating the FdNI in the 9-150 kHz frequency range. The paper recommends a reconsideration of the approximation based on linear extrapolation for frequencies above the 20th harmonic up to the 40th harmonic. In the 9-150 kHz frequency range, it recommends the incorporation of the novel approach into the next revisions of VDE AR-N 4100 and the D-A-CH-CZ rules.

[459(DE)] compares the efficacy of the joint and separate allocation of harmonic emission limits for high-voltage (HV) and extra-high-voltage (EHV) networks following the procedures provided in IEC/TR 61000-3-6 and the German application rules for connecting customers to HV/EHV networks (VDE AR-N 4120/4130). The methods are applied to a test network with 380 kV, 220 kV and 110 kV voltage levels. A Monte Carlo Simulation is applied to consider the probabilistic aspect of concurrency and phase angle diversity. After testing various network scenarios, the calculated harmonic voltages are compared with the planning levels, to analyse the efficiency of the methods with respect to the different voltage levels. It is shown that due to resonance condition the separate coordination of voltage levels can lead to an exceedance of planning levels at certain nodes.

[758(NO)] describes user experiences with a tool for emission allocation according to the technical reports IEC/TR 61000-3-6, -3-7 and -3-13, and the changes made to accommodate them. The article concludes that the adoption rate and positive feedback have shown that it is possible to improve and streamline the connection process of disturbing installations.

[1287(US)] compares the different approaches used in IEEE standards, such as IEEE 519, and IEC documents, such as IEC/TR 61000-3-6, to tackle the phenomenon of harmonic resonance in calculating harmonic emission limits. IEEE provides tables of emission limits. However, it is not clear if resonance scenarios were considered while deriving these tables. In contrast, regulatory frameworks derived from IEC principle provide specific guidelines to account for harmonic resonance while allocating harmonic limits. An actual system example is used to emphasize pros and cons of each approach, for both radial and meshed networks. The results show that the IEEE procedure provides higher voltage limits for installations than the IEC procedure. The study observes that it is likely that the IEC limits may be too restrictive, while IEEE limits may be too relaxed.

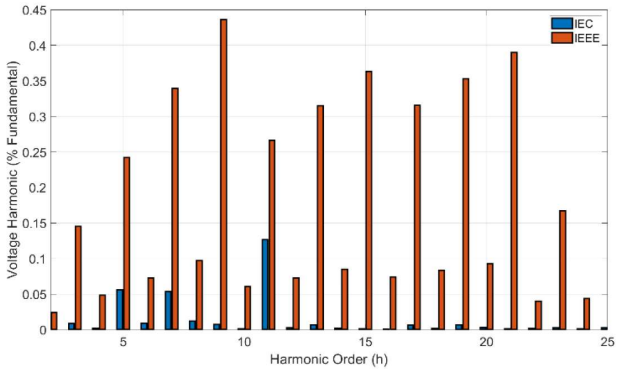

Fig. [1287(US)] Comparison of limits calculated by following the IEEE and IEC procedures.

[1282(DE)] highlights that flicker caused in LED lamps due to interharmonic distortion is an interference mechanism that is not yet adequately covered by EMC standardization. In this paper, a possible framework for EMC coordination of interharmonics in low voltage distribution networks is proposed. To ensure a consistent and credible framework, appropriate indices describing the interference are required. Furthermore, non-intentional and intentional emissions have to be considered equally, because several countries apply mains signalling at interharmonic frequencies below 2 kHz. The main intention of the paper is to propose ideas and directions for a possible extension of EMC standardization considering the interest of all stakeholders.

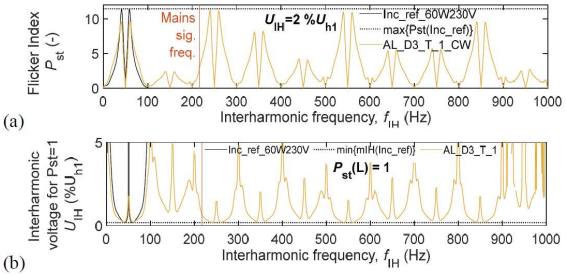

Fig. [1282(DE)] Interharmonic-flicker performance of a ceiling LED luminaire: (a) Pst(L) sensitivity to IHs and(b) immunity to IHs, Pst(L) = 1 curve.

Measurement campaigns and monitoring systems

This section summarises eight papers dedicated to measurement campaigns and monitoring systems. Two papers present insights into observed trends in different countries. Another paper highlights challenges with the evaluation of rapid voltage changes in comparison to standards. Two papers address the use of smart meters for PQ monitoring. Another paper presents the idea of an overall PQ online map. Finally, two papers deal with determining the minimum number and optimal placement of PQ monitors.

[32(CH)] presents a trend analysis of PQ in the LV grid of Zurich, utilizing data measured in compliance with EN 50160 from 62 PQ instruments. The analysis revealed that over half of the devices showed increasing trends in the 3rd, 5th, 10th and 14th harmonics, as well as in Total Harmonic Distortion of Voltage (THDU) and voltage unbalance, usually across multiple phases. On the other hand, flicker and the 15th, 21st, 22nd and 25th harmonics have negative trends. Seasonal decomposition was used to isolate trends, and the Seasonal Mann-Kendall test was applied to determine statistical significance. These findings suggest that harmonic distortion is increasing, which could impact overall PQ in the grid.

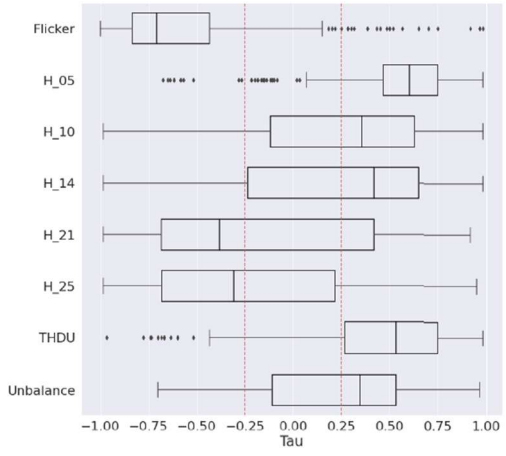

Fig. [32(CH)] Tau (trend indicator) for measurement categories with significant trends.

[98(NL)] analyses PQ trends in the Dutch HV and EHV grid between 2019 and 2023 using data from approx. 130 PQ meters. It can be concluded that overall, compared to 2019, steady state voltages and voltage unbalance have increased, while measured total harmonic distortion (THD) has decreased for most nodes and no major changes are noticed with respect to voltage dips. Compared to 2019, about 75% of the measurement locations have increased voltage magnitude. Compared to 2019, about 35% of the measurement locations have increased THD, while the remaining 65% have decreased.

[1285(CZ)] studies an assessment of rapid voltage change (RVC) measurements performed in the Czech public distribution networks. The results show that IEC/TR 61000-3-7 limits are very often exceeded, despite customer complaints do practically not occur. In this context, the paper discusses the suitability of settings for RVCs in IEC/TR 61000-3-7 and the need to adopt updated procedures based on experience of other countries. The evaluation of the effect of chosen threshold voltages and hysteresis showed a significant impact on the evaluated number of RVCs. This demonstrates the need for their unification, similar to the other voltage characteristics.

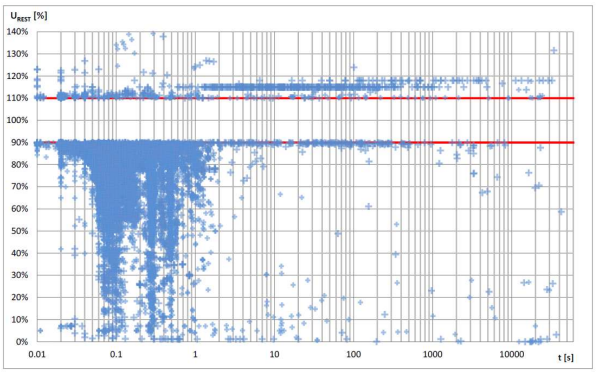

Fig. [1285(CZ)] The number and duration of voltage events on the MV side of 387 110 kV/MV transformers in 2022.

Based on these findings, the authors recommend not to evaluate RVCs according to IEC/TR 61000-3-7. Based on a review of international limits for rapid voltage changes in public distribution networks, it seems more suitable to use the approach published in the DACHCZ rules. Furthermore, the paper presents an extensive survey of voltage dips and swells (events) in the MV network.

[492(SE)] focuses on leveraging smart meters to monitor harmonic voltage and current levels within LV and MV grids. Requirements, relevant to monitor PQ, involve the registration of events triggered by Total Harmonic Distortion (THD) of voltage exceeding the 8% threshold. At the same time, the authors emphasize that measuring THD of current is not straightforward, because low RMS currents result in high THD values that are not meaningful. The utilization of THD data from smart meters has surpassed initial expectations. Smart meters can assist DSOs in monitoring harmonic levels within the grid and provide data that facilitates the identification of sources.

[629(GB)] reports on Northern Powergrid's trial use of smart meter voltage data for early fault detection, in particular to pinpoint the place where a cable repair is required and to remotely check customer voltage queries. The Smart Metering team can visualize the data using Microsoft Power BI dashboards to display and analyse the voltage data. The benefits identified during the trial include saved time and resources due to quicker response times to complaints, reduced restoration times and reduced customer interruptions. A major benefit from these dashboards is that the teams have been able to identify developing faults before they occur and to arrange a repair before the customers are impacted.

[163(TH)] shows the process of the Provincial Electricity Authority (PEA) in Thailand to represent the overall PQ in an online map. For the analysis, available measurement data are used together with a model of the distribution grid. In a second step, the parts, which have not been measured are simulated in the model. Afterwards, the results are visualized in a PQ online map. This shall help relevant parties to see an overall picture of the grid and to be able to improve, develop, or maintain the system more efficiently.

[962(DE)] analyses suitable approaches for reducing the number of measurement sites in MV grids based on the statistical evaluation of real measurement data from Austria. It focuses on determining the number of sites needed to assess the voltage quality of the grid according to EN 50160 with reasonable confidence. The analysis confirms that even a reduction of the present number of measurement sites by 50% will not significantly reduce the confidence. However, a combined evaluation of multiple grid operators on national level should be carefully questioned for the range R_{90} of voltage RMS. In contrast to all other PQ parameters, the utilization of the voltage band is actively influenced by grid planning and grid operation.

[636(DE)] presents a novel PQ monitor placement method that balances observability and minimal amount of measurement devices. By aggregating voltage and current data under varying threshold settings, a scree-plot analysis using Singular Value Decomposition (SVD) identifies the optimal number of monitors. Experimental results confirm improved performance of Harmonic State Estimation (HSE) when voltage monitors are placed at nodes far from strong voltage sources and on less directly supported feeders. However, for current monitors the opposite applies. Validation through HSE based on neural networks applied to multiple test networks confirmed that the selected monitor locations yield improved accuracy compared to suboptimal placements.

Advanced Data Analysis

Five papers have been submitted that address the application of advanced data analysis for PQ. Data analysis using machine learning is becoming increasingly indispensable to cope with large sets of data and to generate applicable results. One of the papers presents a method for reduction of data storage. Three papers deal with machine learning to classify PQ data and one paper applies statistical methods for fault-cause identification.

[112(CA)] proposes a histogram-based method to reduce data storage for measurements of supraharmonics in the frequency range 9 to 150 kHz by a factor of 533 while preserving statistical integrity for comparison with compatibility levels. Based on IEC/IEEE standards, the method enables accurate 99th and 95th percentile assessment with controlled uncertainty. Field measurements at a metalworking site confirm that the compressed data closely matches full-resolution analysis within ±2.5 dBµV. The approach significantly lowers memory requirements, making long-term supraharmonic monitoring feasible for PQ instruments with limited storage.

[300(CN)] explores PQ analysis running Spark on a Hadoop cluster. It uses Fourier Transform, data normalization, and machine learning algorithms like logistic regression, decision tree, and multilayer perceptron to classify PQ data. Comparative experiments show that Spark significantly outperforms MapReduce in processing time. The multilayer perceptron model performs best in precision and recall, while decision tree shows the highest processing speed. The study confirms that big data storage and processing techniques provide strong support for analysing large-scale PQ data.

[301(CN)] aims to address the challenge of extracting insufficient useful information from the vast amount of PQ data. It explores innovative data mining and analysis methods using machine learning algorithms, such as Isolation Forest, Principal Component Analysis, and k-means clustering, to achieve accurate classification and pattern recognition. The results show that the proposed method can effectively extract potential correlations and anomalies in complex PQ data. These methods provide more accurate PQ assessment and help optimize grid operation and planning.

[1147(IR)] presents a novel approach to PQ disturbance classification using Domain-Adversarial Neural Networks (DANN). The proposed method learns domain-invariant features through adversarial training, enabling generalization from synthetic to real-world data. It achieves 82.6% accuracy on real-world disturbances, compared to 48% for conventional convolutional neural networks (CNNs), while maintaining 99.4% accuracy on synthetic data. The DANN model can leverage unlabelled real-world data and address challenges such as domain shift, signal complexity, and noise mismatch. This work demonstrates a practical and robust solution for deploying deep learning in real-world PQ monitoring.

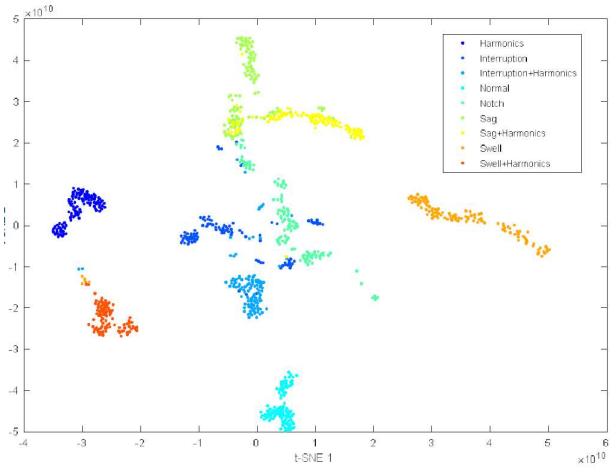

Fig. [1147(IR)] 4 t-Distributed Stochastic Neighbor Embedding (t-SNE) visualisation of proposed model perfomance in PQD classification.

[401(JP)] launched a fault cause identification as a new function of the advanced distribution automation system (ADAS). To identify fault cause categories, they analysed fault data accumulated over the past 15 years and extracted seven common fault categories. The estimation process combined statistical analysis using associated information such as the time and weather when the fault occurred, and waveform analysis based on measured zero-sequence current and voltage. They evaluated the identification accuracy using data from 89 ground faults collected on their distribution network and found that the above two measures improved the accuracy rate from 49% to 71%.

Potential scope of discussion

The power grid is in a phase of rapid development. Monitoring of PQ trends gives important insights that enable the different players in distribution systems to take the right measures in due time. To this end a meaningful collection, analysis and interpretation of data is essential. Here, academia has an important role to make sense of trends and phenomena reported and to propose efficient mitigation measures. It is of high importance that regulators and standardization bodies constantly adapt the framework to implement these findings.

Table 4: Papers of Block 4 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
32	Detecting Power Quality Trends and Thresholds: An Annual Analysis Using the Mann-Kendall Method			X
98	Observations and clarifications of measured trends in PQ disturbance levels in the Dutch HV and EHV grid			X
112	Reducing the data size of supraharmonic measurements to verify EMC compliance		X	X
163	Power Quality Modeling of PEA			X
300	Power quality analysis based on Hadoop cluster and Spark			X
301	Power quality analysis based on data mining			X
330	Recent updates in the Swedish regulation on voltage quality			X
401	The improved fault cause estimation for overhead distribution grid and field data evaluation			X
459	Influence of the coordination between transmission and distribution networks on the allocation of harmonic emission limits	X		X
479	Extreme climate events, network resilience and quality of supply as a regulatory issue			X
492	Monitoring harmonic voltage and current levels using smart meters	X		X
588	Monitoring and Simulation Tool for Enhancing Reliability in the Power Distribution System			X
629	Early fault detection using smart meter voltage readings			X
636	Optimal placement of power quality monitors for enhanced observability with fewer devices			X
758	User experiences with user-friendly emission limit allocation tool	X		X
811	Changes made to the Swedish regulation on continuity of supply			X
962	Determining the minimum number of measurement sites for voltage quality evaluation in medium voltage networks	X		X
1056	Approximation of Network Impedance for Defining Current Emission limits in the Frequency Range up to 150 kHz based on field measurements		X	X
1147	Robust Classification of Power Quality Disturbances in Electric Power Distribution Networks Using Domain-Adversarial Neural Networks			X
1282	Proposal of a framework for EMC coordination of interharmonics in low voltage distribution networks			X
1285	Rapid voltage changes and their evaluation in comparison to IEC TR 61000-3-7 and EN 50160	X		X
1287	A comparative assessment of the treatment of harmonic resonance for calculating harmonic emission limits in US and Europe	X		X