Special Report - Session 2
POWER QUALITY AND ELECTROMAGNETIC COMPATIBILITY

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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 network disturbance phenomena, both from equipment and system perspective. This includes flicker, unbalance, slow voltage variations, distortion in the frequency range from DC up to 500 kHz as well as events like sags or swells. Furthermore, the session covers all aspects of electromagnetic compatibility (EMC) including emission, immunity, its coordination and the related standardization. Conducted and radiated electromagnetic interferences, electric and magnetic fields (EMF) as well as earthing issues are also 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 and advanced PQ data analysis.

The aim of this special report is to present a summary of the present challenges in PQ and EMC, based on all selected papers of Session 2 (117 papers). The session and consequently the report are divided in the following four blocks:

Block 1: EMC, earthing and safety

Block 2: Equipment related power quality aspects

Block 3: System related power quality aspects

Block 4: Standards, measurements, regulation and advanced data analysis

An unambiguous allocation of the contributions is not possible and topical overlapping may appear to some extent between the blocks.

Three Round Tables are organized within Session 2:

RT1: Safety and earthing facing modern technologies
Chair: Katrin Friedl & Herwig Renner

RT3: Power quality and other challenges in DC grids
Chair: Jan Desmet

RT5: Turning data into information – Future needs in Power Quality data analysis
Chair: Jan Meyer

Since the impact of e-mobility, especially fast charging, seems to attract particular attention the RIF (research & innovation forum) is dedicated to this topic.

Block 1: "EMC, Earthing and Safety"

Electromagnetic Fields

Following the trend of recent years, the number of papers dealing with electric and magnetic fields is decreasing. However, there are still some special problems existing, justifying scientific work and publications in that field.

In [11347(SE)], the magnetic field emission in the frequency range from 9 to 150 kHz is analyzed. The authors clearly describe the problems of reproducibility due to a variety of factors, influencing the measurement. The levels of an exemplary measurement close to a freight train are clearly below the (withdrawn) limits of IEC 62236 (2018). Onboard power electronics and pantograph arcing are identified as sources for some dominant frequencies.

An artificial-neural-network (ANN) method to estimate magnetic fields in the vicinity of single- and multi-circuit overhead lines is presented in [10368(BA)]. The geometrical position of the phase as well as the position of the evaluation are used as input. Multi-circuit systems are handled by superposition of results from single-circuits. For the training of the ANN, analytic calculations based on Biot-Savart's law are used. An almost perfect match between training data and output of the ANN is found. According to the authors, the advantage is that the use of the ANN model is straightforward and does not require special programming knowledge or specialized software. Balanced loading of the phases is assumed.

In contrast to that assumption, the zero-sequence currents of overhead lines are investigated in [10640(NL)]. Due to their homopolar characteristic, those currents can have a significant impact on the magnetic field of an overhead line or cable. In the paper, zero sequence currents were simulated, considering only radial lines. A linear

correlation between the positive sequence current (actual loading of the line) and the zero sequence current was found. Transposition of the line has a huge impact, since it effects the coupling between positive and negative sequence. In cable systems, zero sequence current was significantly lower due to their symmetrical configuration. For double circuit lines, increasing circuit length leads to increasing pass-through currents, while currents circulating between the two circuits are barely affected.

To evaluate the electromagnetic field exposure of workers, the authors of [10683(PT)] developed a methodology to assess the risk in substations. In a case study, the methodology was applied to a 60 kV/30 kV substation. A digital 3D-model of the substation was developed and validated by real measurements. Following that, the maximum exposure was estimated by simulations with maximum voltage and maximum current on the busbar and on feeders. With the results, an evaluation according to EU directive 2014/35/EU can be performed.

Low power voltage transformers (LPVT) based on R or RC-voltage divider technology are a modern alternative for voltage measurement in MV grids. However, due to the stray capacitances, external electric fields might have an influence on the transfer characteristics. The equivalent for a LPVT, considering relevant stray capacitances, is shown in fig. [11431(DE)]. For a more precise analysis of all the individual stray components, the finite element method calculation can be used as a tool to identify all the various required elements. Simulation and measurement of the frequency dependent transfer ratio of a R-divider type was performed for different geometric configurations (distance to wall, distance to other devices), achieving good accordance.

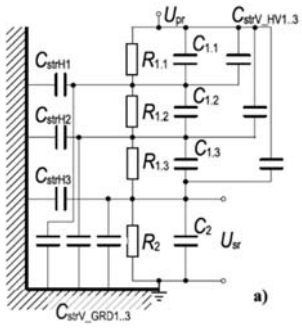

Fig. [11431(DE)]: RC-divider equivalent incl. various stray capacitances

Earthing Design and Management

Several papers deal with the design and management of earthing systems.

An important basic factor for the design of an earthing system is the assessment and modelling of earth resistivity. Paper [10443(AT)] and [11028(UK)] put their focus in that field. The authors of the first contribution use the results from multiple application of traditional Wenner's array method with different electrode distance as input data. By an inversion algorithm, this data is transformed in a 3-dimensional earth model, considering inhomogeneous situations. In the paper, a proof of concept of the method is presented with synthetically generated measurement data. Having a 3-dimensional picture of earth, the next step is to reduce that information to an equivalent uniform single for earthing design calculations with standard tools. The authors of [11028(UK)] provide a new method to reduce multi-layer earth resistivity models to a single layer. The method is applied to a huge number of combinations of different soil configurations and earthing arrangements and correction factors, representative for a typical configuration, were derived. Good results were achieved for horizontal as well as vertical rods.

In paper [10944(AT)], an optimal earthing system for a simple layout is designed, using horizontal and vertical rods. In the paper, basic characteristics of horizontal rods are discussed. It is concluded that vertical rods should not be used at the edge of the horizontal mesh to avoid high local partial fault voltages.

Special installations require special solutions regarding earthing systems. Exemplarily, the earthing design of a solar farm and the earthing design of EV charging stations at fuel stations are presented. Paper [10935(AU)] lists special requirements and issues to be considered for large scale solar farms. As for the two papers above, assessment and interpretation of soil resistivity is crucial. Segregation or bonding of earthing systems belonging to HV, MV and PV arrays must be investigated carefully. Bonded systems usually have a lower earth potential rise. Solar farm power systems have physical attributes and electrical configurations that preclude the use of traditional major substation earthing methods. However, it is important not to apply general design rules where they will not universally satisfy design requirements or will over-specify equipment with insufficient risk reduction.

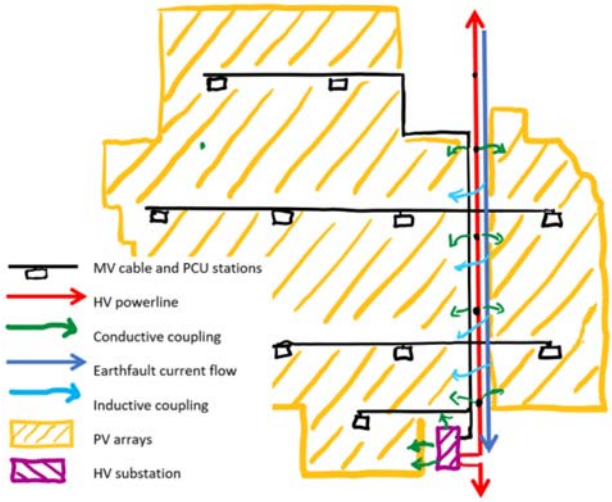

Fig. [10935(AU)] HV substation/line effect on MV/PV systems

The rapid increase in the use of electric vehicles (EV) has required the installation of fast charging stations, many co-located at existing fuel filling stations. To host those charging facilities, HV distribution substations are

required. Until now the preferred design was a separated LV and HV earthing system to prevent direct transfer of earth potential rise. However, as in the case of the solar farm above, inductive and conductive coupling has to be considered. Arising challenges and solutions, new UK requirements and a case study from a real project is described in [11021(UK)].

In (11024(UK)] the focus is put on inductive, capacitive and conductive coupling, leading to possible hazard during fault conditions. These couplings are known as impressed voltages (IV). The designer should aim to identify as many IV hazards at an early stage, as repositioning equipment, changing the sequence of construction activities, or requesting additional network outages could reduce the restrictions placed upon individuals during construction. However, assessment of possible IV is quite time consuming, requiring a huge amount of data and information. In this paper, the situations and construction activities that commonly require IV hazards to be considered are provided and mitigation options are presented. Applicable safety limits are identified and a real-world example is shown.

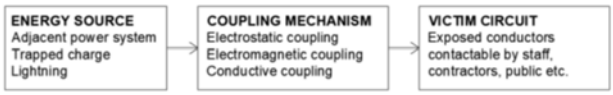

Fig. [11024(UK)] Accident chain

Earth Potential Rise and Touch Voltage Assessment

This sub block, dealing with earth potential rise (EPR) and safety (touch voltage, step voltage), is strongly connected to the previous one. In the event of an earth fault the permissible touch voltages for the entire electrical installations must comply with standards. The following papers deal with EPR as well as touch voltages.

Paper [10849(AT)] describes the evaluation of a connected earthing system. If it is possible to assess the earthing impedance correctly, the maximum EPR can be determined quite easy. For an EPR lower than the touch voltage limit, the installation is safe since the actual touch voltage is always lower than the EPR. For large earthing system the measurement of the earthing impedance can be costly and time consuming. In the paper it is shown that with a suitable choice of the positioning of the current electrode, it is possible to prove the safety of a connected grounding system with a relatively small effort.

In [10213(AT)], the authors describe the situation of a ski resort in mountain area with high earth resistivity, fed via a MV cable from a substation in the valley with good earthing conditions. Earth faults in the ski resort were simulated for the MV grid operated isolated and resonance grounded. In both cases the earthing via the cable sheath in the substation was sufficient to keep touch voltages below the limits.

In paper [10356(DE)] it is shown that for certain grid structures (MV line with grounded stations, forming a lattice network) the measured grid impedance does not reflect the real earth impedance. A modified measurement procedure is proposed to solve this problem. Comparison of different earth impedance measurement methods are given in [10536(AT)]. For earthing system measurements on transmission towers, it is often hard to get an infeed directly over the transmission lines. For this purpose, measurements with a test current injection over auxiliary electrodes are widely used. Six methods ("fall-of-potential", "63%", "slope", "two-point", "three-point", "star-delta") were tested with varying injection distance. At the two measured towers, the fall-of-potential method provided the most consistent results, as they are virtually constant for larger distances and different directions.

Earth resistivity is not constant but can change seasonally due to climatic changes. Laboratory tests and field measurements in [10288(BE)] demonstrate that earthing resistance of MV cabinets vary in time due to temperature and moisture content variations. Resistivity variations due to moisture content variations can be as significant as the ones due to seasonal temperature changes, but they can occur much quicker, from one day to the next for example in case of a heavy rain after a period of drought. As can be seen in the following figure, the range of measured values (normalized) is quite large. Such range should be kept in mind when measuring the earthing resistance of a cabinet, to account for the fact that the measured value could be a maximum or a minimum value, depending on the season or meteorological context of the measurement.

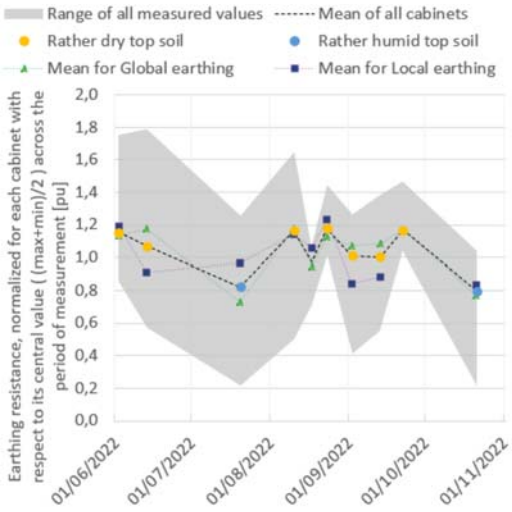

Fig [10288(BE)] MV cabinets' earthing resistance measurements in Wallonia for DSO RESA (26 cabinet measurements)

In resonant grounded systems, the earth fault current holds a rather high harmonic content since only the fundamental is compensated by the Petersen coil. The authors of [10680(DE)] performed simulations and measurements to investigate whether those harmonics have a significant impact on EPR. It could be shown that high levels of harmonics in the residual earth fault current do not necessarily lead to increased EPR and to thus impermissible touch voltages U_T.

Although the advantages of the TN-C – Protective

Multiple Earthing (PME) scheme are well known, with the PEN conductor being locally earthed at multiple locations along its path and the PEN voltage profile being consequently kept further close to zero, the quantification of those advantages are lacking in the literature. The authors of paper [10289(BE)] tried fill this gap in knowledge and present a study case. The impact of PME earthing points has been investigated via three main use-cases: single-phase short circuit, load unbalance (with or without neutral point rupture) and EM travelling waves. For all these use-cases, the conclusions are qualitatively the same: although the impact of PME earthing points can be significant in some worst-case scenarios, it remains marginal at best in most cases and is even negligible in typical cases.

The phenomenon of faults of cable joints on the MV underground network especially during the summer, triggered investigations from the authors of paper [10334(IT)]. It is shown that the sheath current consists of a constant capacitive component and an induced component, proportional to the phase current. Increased load during the summer time thus leads to increased thermal stress of sheath and joints

Unconventional distribution systems are tackled in the following three papers. The detection of broken neutrals in single-phase-three-wire LV systems (split phase system) is addressed by the authors of (10899[ES]). They investigate the possibility to use smart meters for detection, based on the voltage shift caused by unbalanced load of the phases. In case of a broken neutral, this voltage shift is significantly larger. With different meters connected along a longer line, the location of the interruption can be identified. Further investigations, considering the effect of decentralized generation (rooftop PV) will follow. Two-wire three-phase-systems use earth as third conductor. Despite the cost savings of that system, security issues need to be addressed before implementing this type of topology.

In [11448(BR)], simulations regarding the step voltage close to the grounding of the third conductor were performed, applying different electrode configurations. For normal operation, no dangerous step voltages have been detected. A validation of the simulation was done with a reduced scale model of the two-wire three-phase system. However, further studies on short-circuit operation are necessary.

South Korea's MV system is a three-phase four-wire system with a multiple grounded neutral. Due to unbalanced load and due to harmonic zero sequence currents, rather high currents are observed in the neutral. This current as well as neutral-to-earth voltage are used to assess the earthing impedance. In downtown areas, it's often difficult to access a measuring point for reference earth in an appropriate distance. That problem was overcome by the authors of paper [10978(KR)] deriving a correction factor, considering the actual distance from an accessible measuring point.

Transient Voltages and Currents and Equipment Immunity

Regarding equipment immunity, the main concern is often the risk of damage due to overvoltage. This is addressed for household appliances in the following three papers.

In [10197(BE)], transient overvoltage caused by switching of miniature circuit breakers (MCB) are investigated. Due to mechanical tolerances, exact synchronous switching of the three poles is not possible. An unfavorable pole switching sequence of a MCB occurs when two or more poles of the breaker are closed but the neutral pole is still open, leading to neutral point shifting.

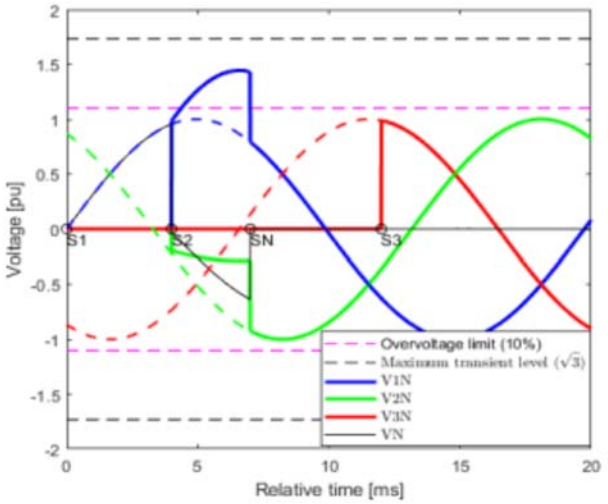

Fig. *[10197(BE)] Transient overvoltage due to MCB switching sequence, loads unbalanced - R1=10 Ω, R2=2 Ω, R3=4 Ω*

A large number of switching actions were performed in laboratory. The results yield that transient overvoltage has a significant probability of occurring. Their duration can range from a few milliseconds to up to tens of milliseconds. The amplitudes of the invoked transients range from 110 % up to the theoretical limit of 173 %. In [10199(BE)], the same authors analyze the effect of this transient overvoltage on household devices. A literature review reveals that phenomenon of overvoltage caused by neutral point shifting is known and addressed in EMC standards. In order to attempt a quantification of the risk for damage to household appliances, a statistical and probability analysis was performed. As reference for evaluation of the results, the ITIC curve was used. The ultimate result of this approach is a very low total risk of 1 % for damage to a household appliance during an MCB switching action. Laboratory tests, where no damage was observed, confirmed this result.

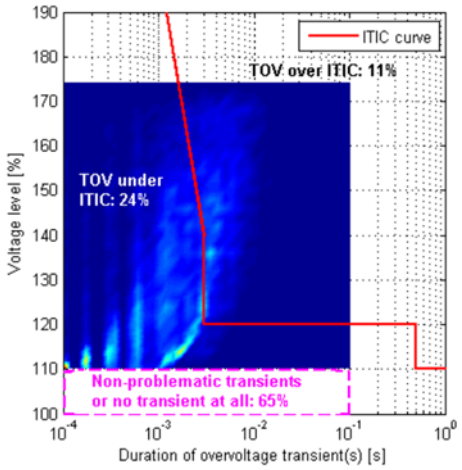

Fig. [10199(BE)] Results of Monte-Carlo simulations regarding the occurrence of MCB transient overvoltage (TOV)

For the rating of the impulse voltage at different locations in the network, standard IEC 60664 suggests a cascading approach when moving downstream in the network. For validation of that approach, propagation of transients in LV systems is analyzed in paper [10302[BE]) analytically and by experiment. It was confirmed that on short lines (30 m) no significant attenuation nor voltage buildup is observed, hence adopting different insulation levels between equipment located close from one another is irrational. Therefore, it is worth considering reassessing the degressive cascading approach of IEC 60664 and the therein defined overvoltage categories. For non-loaded feeders, an increasing maximum voltage towards the end of the feeder is observed. However, even a small load already reduces the overvoltage sufficiently.

In [10503(FR)] the focus is again on household appliances, but this time looking at slow RMS variation of the supply voltage. 18 devices had been tested in the laboratory, steady state under- and over voltage in the range of 0.7 to 1.3 pu were applied to the devices. In some cases, temporary loss of function was observed. However, the functionality was self-recoverable or could be restored by the operation of the controls. No damage occurred during the tests. Risks associated to undervoltage and overvoltage are not symmetrical, but case-dependent. On the limited sample tested, appliances seem to be slightly more prone to malfunction under overvoltage conditions than undervoltage ones. Generally, the tests showed that recent devices can operate over a wider voltage range than those imposed by IEC or EU.

In future grid with inverter-based generation dominating, the stiffness of the grid will likely be significantly reduced. In that case, motor starting currents or transformer inrush currents can cause severe voltage dips, impairing normal operation of customer devices. The authors of [10947(DE)] had a closer look on the effect of transformer inrush in a grid, fed by a grid forming converter. Tests were performed in a 10-kV-laboratory system. Different transformers with rated power between 250 kVA and 1250 kVA were energized. Inrush currents as well as phase voltages were recorded. To get representative results, 40 repetitions of inrush transient measurements were performed for each configuration, thus covering different switching moments and different transformer remanence. As soon as the inrush current exceeds the inverter current, the current limitation leads to significant voltage dips. Although the analyzed scenario is rather extreme, transformer inrush currents have to be considered for stable operation in islanded or weakly connected grids, fed by inverter-based generation.

Transients originating from shunt reactor switching have been analyzed in paper [10942(AT)]. When breaking rather small reactive currents, two effects must be explicitly considered: Current chopping and re-ignition, both leading to possible harmful transient voltages. Controlled switching with a point-of-wave-device, surge arrestors and RC-snubber are potential measures to manage this problem. In a case study with a shunt reactor installed on the tertiary winding (24 kV) of a power transformer, it is clearly shown, that an optimized RC-snubber can reduce the transient recovery voltage significantly.

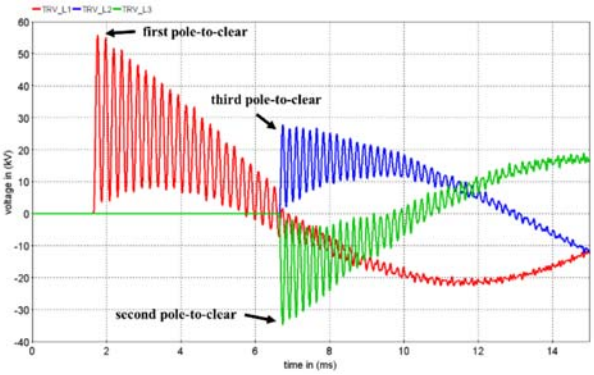

Fig. [10942(AT)] Transient recovery voltage on 24 kV tertiary bus bar

Besides voltage deviations, also short interruptions originating from autoreclosing, can cause malfunction of devices. Autoreclosing is an important functionality of feeder protection designed to automatically clear intermittent faults on overhead lines and reduce both the number of permanent faults and the interruption time experienced by the customers. The authors of [11067(FI)] made a closer look on the impact on variable frequency drives (VFD). Based on a questionnaire, the typical settings of autoreclosure used by Finnish DSOs and operating experiences were gathered. Following that, a laboratory test system with adjustable autoreclosure delay time and point of wave switching device was set up. The equipment under test was a 5.5 kW VFD. The results clearly show that delays of 0.3…0.7 s are too short, especially, for VFDs operating in scalar control mode. Longer delays above 2 s avoid high inrush currents and allow a controlled automatic restart of the device.

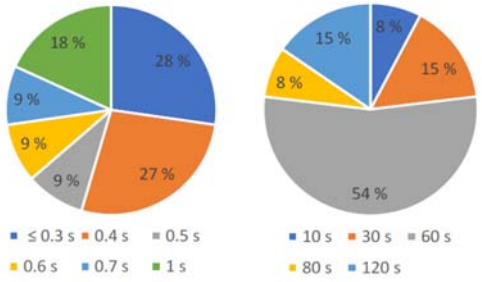

Fig. [11067(FI)] High-speed and delayed autoreclosing delays used by the DSOs answering the questionnaire

Managing lightning strokes

The high amount of lightning strikes in a 20-kV-grid in Indonesia had a significant impact on supply reliability. Due to high earth resistivity, grounded lightning arrester as lightning protection failed to work. For field tests, 13 feeders of the affected MV grid were equipped with ungrounded externally gapped line arresters (EGLA), mounted parallel to the insulator. The procedure and the results are presented as study case in paper [10444(ID)]. Statistical evaluations after a year of operation indicate a reduction of disturbances by 72 %. The same problem is addressed in paper [10463(TR)]. Besides other measures like installation of ground wires, increasing BIL or improving tower earthing resistance, the installation of EGLA proved to be the optimal solution. The aim is to reduce the number of disturbances by 75 %. For unshielded overhead lines, it is expected to have the majority of EGLA at the top phases.

Conductive and inductive coupling of harmful transient voltages due to lightning strokes is addressed by the authors of [10283(IR)]. A study based on EMTP simulations is presented. Considering different values for earth resistivity and electrode shapes, the effect of the distance between the earthing system hit by a lightning strike and an influenced earthing system is analyzed. From the point of view of lightning protection, earthing systems should be placed at a suitable distance from each other so that there are no significant effects on the sensitive earthing system.

Potential scope for discussion

Advantages and disadvantages of separated and bonded earthing systems with regards to safety, maintenance and inspection should be discussed, especially considering new types of electric infrastructure (high power EV charging stations, large solar farms, …).

Improved methods, easy to apply but reliable, for the evaluation of EPR and touch voltage in extensive earthing systems should be developed.

Table 1: Papers of Block 1 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
10197	Transient overvoltages caused by four pole Miniature Circuit Breakers (MCB) in three-phase circuits			X
10199	Impact of MCB Transient Overvoltages on Household Appliances			X
10213	Medium Voltage Cable Network in the Mountains – Verification of the Earth Potential Rise Voltage by Calculation			X
10283	Assessing the Bonding Distance of the HV Grounding System and Instrumentation to Reduce Electromagnetic Interferences Due to Lightning Strikes in the EMTP-RV Environment			X
10288	Evolution Of Earthing Impedance	X		
10289	Impact of Protective Multiple Earthing (PME) in TN-C Earthing Schemes in Public Low Voltage Networks			X
10302	The Propagation Behaviour of Surge Voltages on Public Low-Voltage Networks and the Consequences for Insulation Coordination			X
10334	Influence of Current Flowing on the Sheaths During the Standard Conditions and Preconditioning of Hot Spots of Joints			X
10356	The Benign Earthing System: A New Method to Classify the Earthing of Substations			X
10368	Application of Artificial Neural Networks for Overhead Distribution Lines Magnetic Flux Density Estimation			X
10443	Earth Resistivity Tomography Simulations Over An Earthing System			X
10444	The First Outlook on The Implementation of Groundless Lightning Arrester in Indonesia, Case Study: East Nusa Tenggara Province, Indonesia			X

10463	Effective Lightning Mitigation Method on Unshielded Distribution Line by Using High Charge Ratings Externally Gapped Line Arresters (EGLA)			X
10503	Sensitivity Of Household Appliances To Supply Voltage			X
10536	Practical Comparison Of Earth Impedance Testing Methods	X		
10640	Steady-State Zero-Sequence Currents in a Transmission System: a Parameter Analysis			X
10680	Evaluation of High Harmonic Components in the Residual Earth Fault Current with Regards to the Earth Potential Rise and Personal Protection	X		
10683	Methodology for the Evaluation by Simulation of Electromagnetic Fields in Live Working Areas in Substations			X
10849	Realistic Maximum Touch Voltages in Global Earthing Systems			X
10899	Floating Neutral Detection Using a 2S Form Meter: Large Distribution Lines with Multiple Houses And Rooftop PV Effect			X
10935	Solar Farm Earthing – Not Just an Extra-large Substation - Special Requirements Met by Risk-based Design and Focused Testing	X		
10942	Switching Overvoltages Caused by Shunt Reactor Switching and Mitigation Methods	X		
10944	Investigations Of 3D Meshed Earthing Systems			X
10947	Does Transformer Inrush Challenge Future Grids? – Laboratory Insights			X
10978	Development of Measuring a Combined Impedance of Ladder Networks Using Unbalanced Current on Neutral Line in 4-wire Distribution System			X
11021	Earthing Design of EV Charging Substations in Fuel Stations - UK Requirements and Experience		X	
11024	Managing Impressed Voltages Near High Voltage Installations - UK Requirements, Common Problems and Solutions			X
11028	A New Algorithm to Estimate Uniform Soil Resistivity for Earthing Design Calculations			X
11067	Effect of Time Delay of High-speed Autoreclosing on Variable Frequency Drives and Other Loads	X		
11347	Radiated Emissions from an Electric Railway: Review of Methods and Measurements mainly from 9 kHz to 150 kHz			X
11431	Investigating the Impact Of External Fields On The Accuracy Of LPVTs			X
11448	Evaluation on Safety Of People On Ground Generated Voltages In Unconventional Networks.			X

Block 2: "Equipment related power quality aspects"

Improvement/optimization/reduction techniques for devices

The performance of a wind energy conversion system consisting of a permanent magnet synchronous generator coupled to a wind turbine and used to feed a microgrid with variable AC loads is investigated in [10176(EG)]. In this presented study, different types of inverters and different two control strategies are examined with the aim to analyze the effect of mitigation of harmonics injected to the grid. Therefor an alternative method to mitigate the harmonic content injected into the grid via the PMSG converters is to use power electronics converter that actively cancel harmonic currents and providing a sinusoidal waveform. Space vector modulation techniques have been used since they allow reducing commutation losses and/or the harmonic content of output voltage, and to obtain higher amplitude modulation indexes when compared with conventional techniques. In conclusion, it can be stated that the effect of control strategies on the harmonics injected into a microgrid due to interfacing inverters resulting from PWM controlled three phase inverters are higher than those resulting from SVM controlled 3-phase inverters. The effect of adding a filter between the inverter and the grid is investigated, showing lower grid-injected harmonics for both types of inverters.

Since microgrids aggregate distributed renewable energy sources and local loads most of the time single-phase

connected, mitigation of phase imbalance is an important issue in order to guarantee PQ limits at PCC. A control scheme for the converter of a battery storage system to achieve symmetrical currents at the point of connection of a microgrid is presented in [10742(FR)]. The voltage source controller and the control scheme are implemented as a real time model for subsequent integration into a Power Hardware-in-the-loop simulation. The converter is implemented as an average model with a control scheme realized in the synchronous rotating reference frame. A real time simulation demonstrates that the inverter is capable of effectively reducing unbalances by controlling the negative and zero sequence of the currents to zero. In a practical power hardware-in-the-loop laboratory experiment, it is shown that the load flow to the utility grid is balanced at the presence of unbalanced loads as well as a single-phase connected storage system.

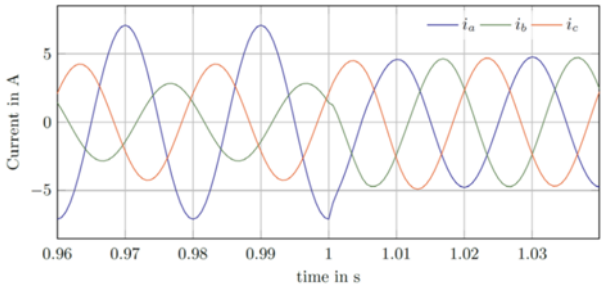

Fig. [10742(FR)] View of the activation of the imbalance control

Paper [11333(IT)] deals with the planning and operation of an intelligent voltage regulator capable of solving voltage regulation problems in LV-networks with a high penetration of local PV. Operation problems associated with the connection of PV systems on weak electricity distribution grids will lead to the occurrence of excessive overvoltages in case of injection or undervoltage (without PV injection) causing unsatisfactory operating conditions for RES installations due to system disconnections if the grid's operating limits are exceeded. It is shown that the adoption of an innovative LV regulator. A real-life case study is presented and discussed to show the effectiveness of the dynamic variation obtained with an intelligent regulator. It is concluded that the introduction of an intelligent voltage regulator can significantly contribute to solving voltage regulation problems in networks with a high penetration of renewable energy sources.

Electric vehicles

The contribution [10131(ES)] presents a statistical analysis of a measurement campaign of harmonic currents injected by several plug-in electric vehicles (EVs) connected to the LV distribution network. The used methodology is based on harmonic measurements in both magnitude and phase and including retracted power of 15 different EVs on a parking facility during one month @1min resolution. The correlation between the different harmonic magnitudes has been investigated. As can be seen in the figure below, 7th harmonic has the strongest correlation with the rest, showing a Pearson correlation of 0.78 with the 9th harmonic, while the 3rd harmonic is only weakly correlated with the rest. As a conclusion, it can be stated that typical time patterns for different EVs are found and when the battery reaches the final stage of charging, the control mode of the power converter increases significantly leading to particular increased 3rd order harmonic.

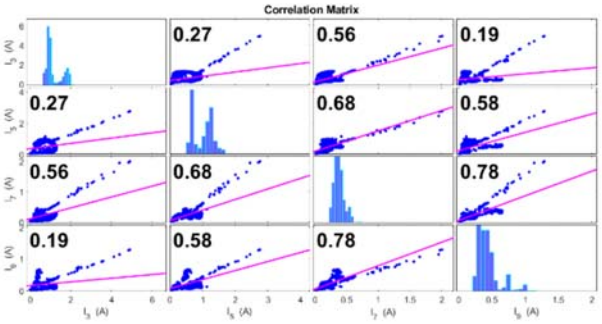

Fig. [10131(ES)] Correlation matrix between different harmonic current magnitudes

With a continuously increasing number of charging infrastructure, electrified mobility becomes more usable. [10157(DE)] analysis the HF behavior of fast charging, especially in concentrated areas. Since each fast charging infrastructure emits a HF-spectrum of harmonics, it may challenge both communication and electric equipment by showing the resulting emissions for voltage odd harmonics up to the 39th order and supraharmonics from 2 kHz to 9 kHz within 200 Hz bands as 10 min rms values. It is concluded that total, fast charging with higher power shows higher supraharmonic emissions. However, this is highly depending on the types of observed EV chargers. Ultimately, the voltage harmonics during charging comply with given voltage harmonic limits by the IEC 61000-3-2 (or EN 50160). However, they still propose a higher stress on other electronic equipment within the same LV grid.

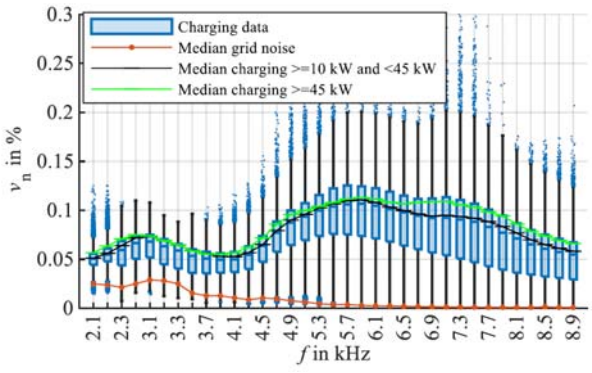

Fig. [10157(DE)] Voltage supraharmonics in L1 for fast charging station "Type 4"

In paper [10538(CA)] EV charging stations and their impact on PQ issues is analyzed. The evaluation of the charging stations impact on PQ has been analyzed in a two-phase process who was scheduled over several years. In the first stage both environmental and PQ laboratory

tests were performed on DC fast chargers while in a second stage PQ field monitoring was performed. The performed tests are part of the project to set up "The Electric Circuit" a public network of charging stations for electric vehicles in Quebec. The tests included the monitoring of the power supply during idle periods and charging periods during start-up, full charge, and end of charging process. The analysis of the results from the PQ survey related to EV charging superstations concluded that the behavior of DC fast charging stations connected to the distribution network were not violating both EN 50160 and IEC 61000-3-12 standard. They also complied with the compatibility levels to the IEC 61000-2-2 standard.

LED

The long-term ageing process of LED lamps is considered in [10196(SE)] starting from the light intensity of LED lamps. The minimum value of the luminance is stated to be 70 % over the rated life in IEC 62612 standard. A method to study the sensitivity of the LED lamps to voltage variations is here proposed and applied. The aim of the paper is to study the light intensity of LED lamps when they are new and after different long-term ageing process, and the flicker sensitivity to voltage variations of new and aged LED lamps of the same model. The approach is made by analyzing the variation of the light intensity and the rms voltage. In an ideal non-sensitive LED lamp, for any voltage variation, intensity variation should be zero. The subtraction of both variations should be equal to the voltage variation. Deviations of this subtraction gives a measure for the sensitive or non-sensitive to voltage variations of LEDs. It is also shown that different LED lamp models have different light intensity response to ageing.

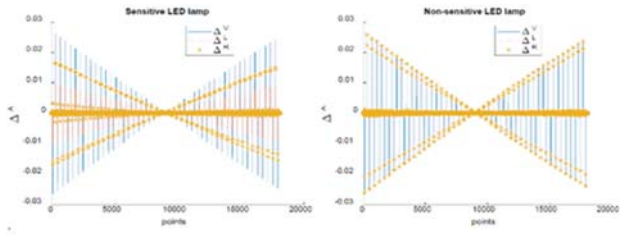

Fig. [10196(SE)]Aspect of a sensitive LED lamp (left) and a non-sensitive LED lamp (right) using the visual method

Power electronic based equipment

It is well known that waveform distortion initiates several phenomena decreasing the supply quality of the power system, such as harmonics, interharmonics and disturbances between 2 to 150 kHz. The challenging task regarding waveform distortion in railway electrification is to address the proper and available assessment or solution. In this paper [10659(DE)] the investigation of noise interference caused by waveform distortion in lineside railway systems has been performed based on measurement. This work assesses pantograph measurements from different rolling stocks using "psophometric" indices covering the range of 16 2/3 Hz to 25 kHz. The main goal is trying to calculate the psophometric current variation using different ITU-T K.68 and C-message curves that qualify the human ear sensitivity.

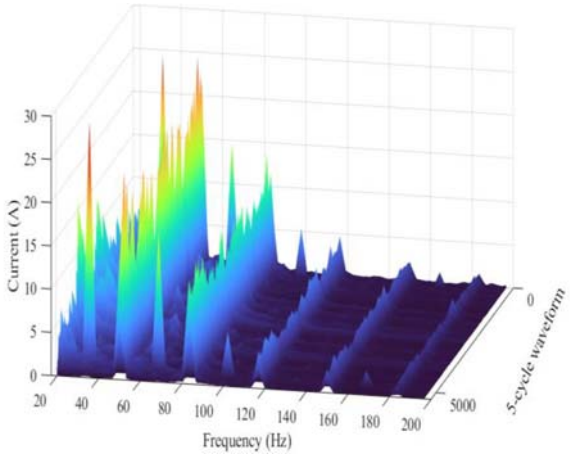

Fig. [10659(DE)] Spectra variations for psophometric currents

The contribution of separated waveform distortion is estimated through the weighted spectra. It is concluded that waveform distortion generated by a rolling stock can disturb systems in the vicinity of traction grids. The results show different ways to explore the psophometric indices. Finally, one can state that this work can be considered as a reference in this domain.

For an inverter-based microgrid operating in grid-tied mode, consequently the low voltage ride-through capability is a challenge in its inverter controller design to support the grid voltage. The paper [10665(IT)] proposes a practical method for improving LV-ride through capability of an inverter-based AC microgrid during grid faults. High penetration of renewables such as PV inverters in the power system results in weakening the grid during grid faults. Next to that, the intermittence and uncertainty of the solar irradiance and wind speed lead to the inverter DC voltage fluctuating and thus it is not suitable for controlling such inverters as a voltage source. Consequently, the inverter may disconnect from the grid causing reduced reliability. Using a DG grid-following inverter limitation of its output current magnitude can be done directly. The control strategy of the inverter with LCL filter and the improved quasi-proportional resonant controller for the inverter output current regulation are used. Simulations are performed using Matlab/Simulink and implemented in a real-time simulator with a hardware setup to validate the usefulness of the proposed method.

The aim of paper [11088(BE)] is, to bring some insights regarding the behavior at the switching frequency of a specific converter, namely the Inter-Leaved Boost Converter that uses pulse width modulation. The behavior at switching frequency can be classified as either a voltage harmonic or current harmonic source. In order to distinguish between the two classifications, three possible approaches are considered, starting from experimental

research over simulation models up to an analytical approach. In this contribution, the simulation approach has been investigated. The different steps in the modulation are analyzed and discussed in order to bring an answer to the question if high frequency components, due to the switching frequency of the converter, do behave as a current or voltage harmonic source and to what extend a converter can be referred as being a voltage or a current source without using filters that would induce an equivalence between the two representation. It is concluded that the difference of behavior can only be caused by the difference in controller's parameters and control structure as the converter is the same and the passive element have the same values.

Drives

In paper [10200(EG)] the effect of an unsymmetrical grid voltage sag on the performance of a slip power recovery drive (SPRD) is studied and two strategies to mitigate its effects are investigated. The first strategy consists of a three-phase parallel RL impedance connected to the rotor circuit. The second strategy consists of three-phase LCL filter connected to the rotor circuit. A PI controller is tuned to test the drive at constant speed. Since the speed for such a kind of machines is also highly depending on of grid frequency, the effect of a sudden frequency variation on the drive performance is also investigated. Therefor two protection strategies are proposed and modelled with Matlab/ Simulink. It is shown out of the simulation results that an extra RL impedance added to the rotor will decrease drastically the transients during unsymmetrical voltage drops while those affected by a frequency drop, have a moderate decrease when connecting the rotor with an LCL filter.

The requirements for a grid supporting inverter in relation with both voltage and frequency support is elaborated in contribution [10229(AT)]. This paper investigates the behavior of an MV grid with a grid supporting inverter and ZIP load during frequency as well as grid voltage fluctuations. Previously, large PV parks and wind farms were obliged to disconnect from the grid in in case of faults. Since nowadays the due to high share of RES they need to be connected to the grid in order to support the grid in case of faults. With the goal of the research, this paper will focus on grid-supporting inverters. After building up the model, test cases are carried out with the aim to analyze the stability of the droop parameters, in case of short circuit capacity, load parameters, and cable lengths in order to seek for the selection of a stable working points in case of grid supporting functions of the inverter. It can be concluded that in general, the inverter is able to provide support for the grid in the event of frequency and/or voltage change with a correctly adjusted droop control. This is observed during the stable mode as well as instable mode of the inverter. In addition, the capacitance value of the grid can change the stable area significantly.

Generating units (solar, wind)

Large solar installations can occasionally experience higher residual current or short duration current surges, particularly when connected to systems with variable speed drives, heat pumps, EVs and other disturbing loads. This can cause unintended operation of protection Next to that seasonal effects also can affect "normal" operation. In paper [10181(UK)] contributory factors can be identified which may constitute a 'fault' event or create a malfunction of protection devices, control boards and invertor failure.

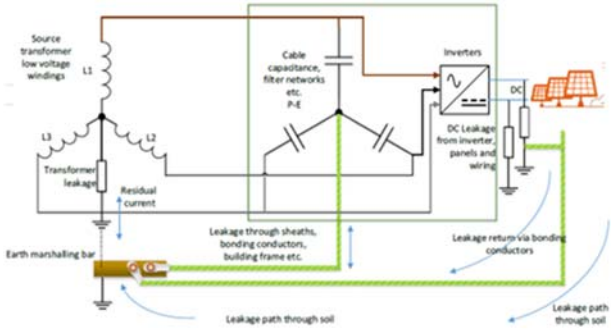

Fig. [10181(UK)] Typical PV system current flow paths

Even transformer and cable overheating can occur. All these aspects are explored in this contribution where a number of techniques which have been used to good effect to identify the sources of problems on solar and other generation sites. The use of a PQ logger is suggested as the most useful tool to identify trends or to capture short-term events.

Due to decreasing rotational inertia, frequency control is becoming more challenging. A potential approach could be to modify grid codes in order to allow larger dynamic and transient grid frequency deviations. In this contribution [11225(GE)] the potential impact of such changes on grid-connected PV and battery inverters is investigated. Future RoCoF (rate of change of frequency) values during severe disturbances may become so high that frequency stability will be endangered. The approach in this paper is rather pragmatic by suggesting to modify frequency standards in order to allow for larger deviations from 50 Hz since loads can be assumed to be able to withstand deviations of at least ±5 Hz. Experiments were conducted on lab scale using a linear three-phase four-quadrant voltage amplifier which allows exposing the installed devices to specific grid conditions, such as frequency fluctuations. It is shown by experimental research with inverters installed in the German that adjusting the inverter behavior to stay connected to the grid during frequency variations of ±5 Hz can be achieved through minor parameter modifications via Modbus.

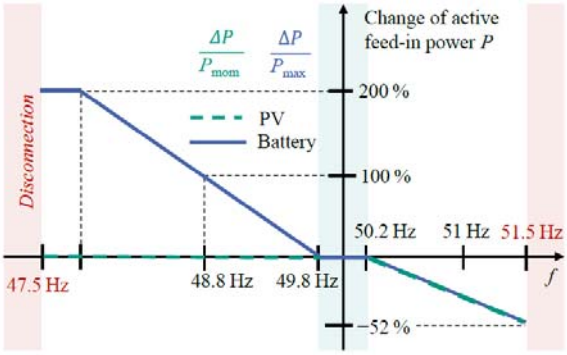

Fig. [11225(GE)] Droop requirements defined in AR-N 4105

The contribution [11233(SE)] discusses the transient stability of grid forming invertors during large signal disturbances by using phase portrait analysis. Since the stable operation of wind power plants is becoming more and more critical for the stability of power system due to relatively weak grid connections, grid-forming control structures have been proposed as a promising solution for connecting voltage source converters. Next to that, several mechanisms for realizing grid forming inverters, such as droop control, power synchronization control and virtual inertia are possible solutions. A simple and effective fault-ride-through stabilizing control scheme is proposed to improve the synchronization stability of converter. In the proposed scheme, the active power reference for the active power control loop is proportionally adjusted with respect to the grid voltage, whereas an additional reactive power is injected to the grid with respect to the absolute value of active power unbalance. To verify the merits of the proposed fault-ride-through stabilizing scheme, simulations are performed in SimPowerSystem environment.

Frequency converters, inverters

Microgrids based on pure RES are upcoming and consequently the development of new types of power inverters. Challenges are arising since fewer synchronous generators (rotating inertia) and more inverter-based resources will have a major impact on power system's reliability and stability. Grid forming inverter structures are presented in paper [10518(FR)] in order to deliver more supporting services to the grid and improve the participation of inverter-based sources in the reliability of power systems. In addition, the dynamic behavior and stability problem in microgrids are different compared to conventional power system, since especially rotating inertia is missing. The main objective of this contribution is to analyze how to maintain stable voltage and frequency in a microgrid. Different methods to assess stability of microgrids all based on modelling the system components and their controls are discussed.

Modelling of individual network elements

Power Line Communication (PLC) allows data transmission through the power system. Recently, these systems have been planning to move upwards in the frequency spectrum, aiming to get higher throughput. The contribution [10893(ES)] addresses a methodology for obtaining a model for power cables in the MHz band, based on standard transmission line theory. In many cases, the measurements taken in the grid to characterize the impedance, attenuation or emissions, require the placement of an extension cable to connect the measurement equipment to the connection point. When taking measurements, the extension cables used to influence the measurement.

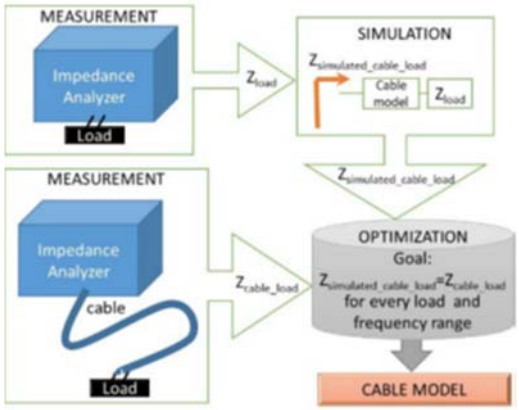

Fig. [10893(ES)] Diagram of the experimental approach obtaining values out of measurements

The presented methodology for characterizing the cables, based on both measurements and an optimization process allows extracting a model based on elementary cells placed in cascade. It is shown that the model is valid for accurately evaluating the access impedance independently for a wide frequency range. It is stated that the cable models obtained by applying the proposed methodology will serve both to calibrate measurement systems and to simulate PLC systems.

In Paper [11464(BE), the Bergeron model of a non-lossless transmission line is studied and analyzed using the MATLAB/Simscape toolbox for high frequency behavior in the supraharmonics range (2-150 kHz). It is shown that the Bergeron approach is preferable among other models for software since it can describe the lossless transmission lines in the time domain without no frequency range restrictions except close to the resonance regions. This contribution limits the usage of the simulation software for studying super harmonics. It is shown that the model under its current form has intrinsic errors in line impedance calculations for frequency ranges where resonances occurs. The reason can be found in the length of the downstream part of the line. In order to solve that problem, the line can be divided into a number of cascaded lossless lines in such way that, the second resonance of the downstream part must be shifted out of the under-study frequency range.

Mitigation

A secondary substation is being reviewed to build a high reliability distribution system. This contribution

[10591(KR)] deals with the issues to manage PQ in a distribution system where various loads are connected. However, unlike the transmission system, distribution system has low utilization of power electronics technology for PQ. Consequently, here a concept is applied to an underground distribution system to operate the system more stable by proposing a method to improve PQ by applying a device using power electronics technology to a secondary substation. Different improving methods are discussed starting from a BESS connection method over the integration of PV up to converting single-phase into three-phase line structures. In this analysis, causes of sag, swell, overvoltage and undervoltage in LV distribution systems and methods to solve them are presented, and future tasks are discussed.

The paper [11518(SE)] describes how the deployment of dynamic reactive power compensation in mining facilities can make use of existing electrical infrastructure with the aim to improve both process efficiency and increased production capacity. Since commonly mining facilities are facing low short circuit power due to remote locations while large loads are connected, it creates major voltage fluctuations caused by plant operating conditions. Especially during the starting process of large loads, the absorption of inductive power is causing major voltage fluctuations for several seconds that might lead to undervoltage trips and production losses. It is shown that PQ of the mining facility electrical grid is improved by installing dynamic reactive power compensation technologies such as STATCOM who will support the system's voltage by improved stability and robustness, ensuring safe operation and continuous production of mining loads. Next to that, the introduction of a grid forming converter capabilities will results in enhanced power import capability and enhanced PQ.

Stability (OVRT, grid forming inverters, frequency, inertia, RoCoF)

The analysis and modelling of temporary overvoltage events compared with over-voltage ride-through requirements presented in [10483(DE)] discusses the temporary overvoltages. Due to the massive ongoing of integration of RES in the course of the energy transition, changes at the generator side significantly will change the relevance of overvoltages. Here, a comprehensive analysis of relevant overvoltage incidents leading to widespread generator tripping are compared with over-voltage ride-through requirements , including historical events that led to the introduction of those regulations, as well as more recent events. In order to have a better insight, simulations are carried out in the context of grid stability studies and the introduction of the overvoltage ride-through requirements regulations. Since grid faults (i.e. short-circuits), resulting in voltage dips will lead to overvoltages due to reduced active and increased reactive power feed-in after fault clearance. Since the stiffness of the grid has a significant influence on the level of overvoltages this will be further elaborated in this contribution. Different methods of simulating overvoltage events in distribution grid studies are compared. It can be concluded that the developed simulation models indicate only minor differences between a network-reduction representation and the full test grid.

The contribution of paper [10556(MY)] discusses how to manage the distribution network stability with a high integration of distributed renewable energy sources including PV and small-scale wind turbines. Next to the provision of a variety of benefits, including improved resilience to power outages they can also lead to technical and operational challenges, such as voltage fluctuations and overloading of distribution circuits. The paper addresses these challenges using various approaches to ensure the stability and reliability of the distribution network. Since the electromagnetic compatibility is an important aspect when integrating renewable energy sources, the ability to function in its intended environment without being affected by or affecting other equipment from the perspectives emissions and susceptibility. Both intermittency, PQ, protection issues and grid congestion problems are discussed.

A case study on the implementation of power convertors for the stabilization of the power system is presented in [10617(KR)] Therefore a low-voltage three-phase converter is proposed to integrate distributed renewable energy sources into the distribution power system. Different examples of power conversion solutions, such as FACTS, STATCOM and SST, applied in the power system, were evaluated, including the applicability through the simulation of a three-phase converter for the distribution power systems. Finally, the consideration for developing a low-voltage three-phase converter is discussed.

In paper [10969(GE)] a classification of grid-forming converter control and its application to improve power system stability is presented. Due to the drastic changes to renewable energy sources and its decentralization with an increasing number of smaller, inverter-based generation units, grid stability will be affected. Consequently, the concept of grid-forming control systems becomes more and more important from the point of view of voltage source behavior and load sharing. Next to that, also inertia has to be considered as well. It is shown that in terms of frequency and voltage stability, the grid forming convertors' reaction to grid disturbances has to be analyzed. Therefore, appropriate models were developed and simulations performed. In addition, the contribution to system resiliency and island operation are analyzed. It is shown that grid forming convertors may contribute to system stability and resilience by counteracting grid disturbances, such as phase jumps, frequency ramps and undervoltage events as well as by keeping a small, islanded grid section in operation.

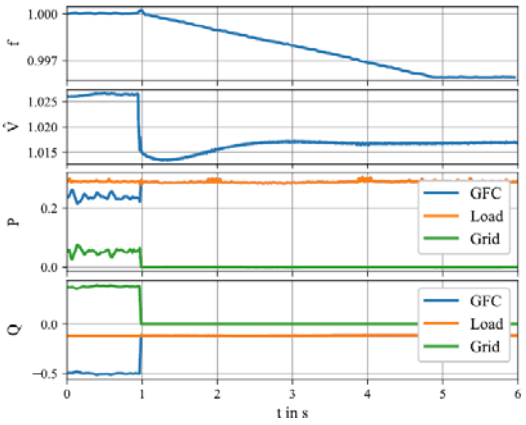

Fig. [10969(GE)] Measured voltage, frequency, active and active power during islanding (in pu)

Potential scope of discussion

In contrast to other blocks, the submitted papers for Block 2 of Session 2 is 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 PQ and this for all kinds of equipment, most of all related to grid stability.

The upcoming integration of grid forming inverters due to renewable energy sources and/or storage systems is a topic who wins more and more interest during the two latest CIRED conferences, especially from the point of view of both frequency variations and security of supply in case of faults. However, due to the upcoming need of more grid flexibility with the aim to increase local hosting capacity, challenges to mitigate PQ issues such as unbalance, frequency disturbances, short voltage interruptions in the grid may and will increase and win in importance.

Together with the emerging integration of EVs, both in "slow" and "fast" charging structures the distribution networks will be massively affected, in both load imbalance, current congestion and high frequency related issues due to the switching frequency cross talk. As is mentioned in a number of papers, it is recommended to analyze and monitor grid forming inverter systems, what the origin of application may be in order to obtain sufficient information for a reliable assessment of their impact on both hosting capacity, PQ and HF related issues.

Table 2: Papers of Block 2 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
10131	Measurement based Identification of harmonic currents Injected by Electric Vehicles			X
10157	Harmonic and Supraharmonic Emissions of Fast Charging Infrastructure – Field Measurements in LV Grids		X	
10176	Minimization Strategies Of Harmonics in Microgrid Connected Wind-Driven PMSG			X
10181	Advanced Techniques For Troubleshooting Solar Arrays And Generator Connections	X		
10196	Power Quality Impact on Light Intensity and Flicker Sensitivity of LED Lamps			X
10200	Comparing Methods to Mitigate The Effect of Grid Voltage Sag And Frequency Variation on The Operation of Variable Speed Drives			X
10229	Requirements For Grid Supporting Inverter In Relation With Frequency And Voltage Restoration And Standardisation	X		
10483	Analysis and Modelling of Temporary Overvoltage Events and Comparison with OVRT Requirements	X		
10518	Comparative Analysis of Grid Forming Inverters Based Power Systems in Phasor Domain and Electromagnetic Transient Domain			X
10538	Electric Vehicle Charging Stations and their Impact on PQ		X	
10556	Managing Distribution Network Stability with Penetration of Distributed Energy Resources			X
10591	A Study on the Application of Power Electronics Technology in Secondary Substation to Improve PQ			X
10617	A Case Study on the Introduction of Power Electronic Technology for Stabilization of Power System and Development of Phase Converter of Power Distribution System			X

10659	Psophometric Indices Analysis for Waveform Distortion from Rolling Stocks in Electrified Traction Systems	X		
10665	A Practical Method for Improving Low Voltage Ride-Through Capability of Inverter-based AC Microgrid			X
10742	A Four-Leg Inverter Control Scheme for Current Imbalance Compensation in Microgrids			X
10893	Modeling of Power Cables for Measurement Calibration and PLC Simulation up to 20 MHz	X		
10969	A Classification Of Grid Forming Converter Control And Its Application To Improve Power System Stability And Resilience			X
11188	Supraharmonic In Low-Voltage Distribution Grids. Analysis Of the Specific Case Of The Interleaved Boost Converter			X
11225	Impact of Changing Frequency Standards on Grid-connected PV and Battery Inverters in the German Low Voltage System	X		
11233	Accurate Power Control of Grid forming Power Converters for Improving Large-Signal Stability			X
11333	Planning and Operation of an Intelligent Voltage Regulator for PQ Improvement in PV-rich Power Distribution Systems			X
11464	Analysis of Transmission Line Modelling in the MATLAB/Simscape Software Package.			X
11518	Dynamic Reactive Power Compensation For Improved Mining Production			X

Block 3: "System-related power quality aspects"

This block is dedicated to papers studying PQ in the context of system behavior. Like at the CIRED in 2021, the majority of papers (60 %) deals with harmonics (frequencies below 2 kHz) and supraharmonics (frequencies above 2 kHz) from different perspectives, like measurement, simulation, or limit allocation. The dominating share of these papers again relates to frequency-dependent impedance and resonances, which underlines the continuously high importance of this topic. About 20% of papers deal with established phenomena like unbalance, voltage variations (voltage band), flicker and voltage dips, but considering new perspectives.

Two emerging topics of this CIRED are PQ aspects related to LVDC grids and the impact of active customers (prosumers) on PQ in LV networks. AC microgrids and the effect of electric vehicle charging, with particular focus on fast charging, remain important topics at this CIRED.

Low voltage DC grids

Paper [10179(BE)] discusses the advantages and disadvantages of unipolar vs. bipolar DC microgrids in a simulation with eight loads in terms of losses, voltage at load terminals and loading of the lines. While bipolar networks require a careful balancing between poles, they have in general fewer losses and better voltage management. On the other hand, unipolar networks with increased nominal voltage (1 kV vs. ±700 V) can achieve similar performance. Finally, no general recommendation can be given and the decision should be based on a case-by-case evaluation including both technical and economic aspects.

Paper [11146(KR)] studies some PQ aspects in a DC microgrid connected via an AC/DC converter to a typical AC distribution network based on RTDS simulations. The analysis focuses on the impact of different operating conditions of a connected DC customer, especially the impact of load changes. While the DC ripple is maintained in the range of ±1 %, especially an overload of 110 % causes the converter to reach its current threshold with a remaining voltage deviation of about 25 %. The paper identifies voltage changes due to load changes as one of the major PQ issues in DC grids.

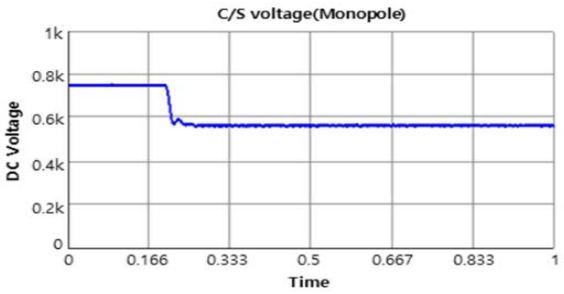

Fig. [11146(KR)] Voltage drop of converter station output at DC load of 1.1 pu.

The authors of paper [11166(KR)] identify the need to establish grid connection codes for the operation of LVDC networks, which also include requirements for PQ. It is

proposed to set limits for slow and fast voltage variations, short-circuit current, and voltage unbalance, while ripple is not yet considered. Simulation studies based on a MATLAB/Simulink implementation of an existing demonstration site are used for initial studies of feasible value ranges.

Paper [10787(FR)] develops a frequency-dependent impedance model of the source-side of a DC network based on Thevenin equivalent, which can be used for DC network distortion studies. The impedance on the DC-side of an AC/DC power converter is measured based on multi- and single-frequency injection and a respective frequency-dependent impedance is identified with the single-frequency sweep method providing results that are more accurate.

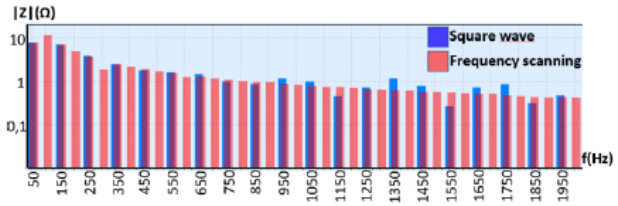

Fig. [10787(FR)] Impedance equivalent model determined by two different excitation methods

Active customers (prosumers)

Optimization of self-consumption is one important aspect for residential customers in order to reduce energy costs. However, especially the impact on flicker must be studied due to the unavoidable delay in the reaction time of storage to compensate for load changes.

Paper [10831(DE)] investigates the aggregated impact of prosumers on flicker and voltage unbalance based on the simulation of single-fed radial village and suburban networks with 68 and 115 households, respectively. The results show that especially due to the price incentives a significant impact on voltage profile and voltage unbalance has to be expected, while the impact on flicker and rapid voltage changes is visible but not significant.

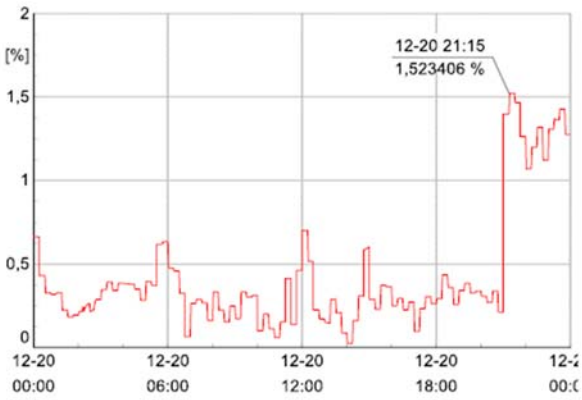

Fig. [10831(DE)] Voltage unbalance at the end of a feeder

Another reason for controlling the energy flow of households is a connection requirement of zero infeed in presence of renewable sources. Paper [10431(CZ)] studies the impact of this requirement based on measurements in 70 different LV grids with PV installations. While in about 80 % of the grids the EN 50160 requirements for voltage quality are met, 14 % of the grids exceeded the flicker limit and 6 % of the grids the harmonic limit. However, the root cause for exceeding the limits must not necessarily be the customer with PV installation. Complementary laboratory measurements have shown that the requirement of zero energy generation seems not feasible and should be revised.

AC microgrids

Paper [10513(SE)] analyses the harmonics measurements of a small single-house AC microgrid based on applying machine learning algorithms. In grid-connected operation the background distortion, especially 5th and 7th harmonics are clearly visible, but within the values of EN 50160. In islanded operation, some of the harmonics, particular the 9th harmonic, exceed the limits given in EN 50160 for a considerable amount of time. This happens more likely during the night hours in low load situations. The paper shows that neural network based algorithms are able to identify differences in harmonic levels during grid-connected and islanded mode.

Paper [11450(US)] studies a considerably larger microgrid with a size of about 10 MVA at MV level. During islanded operation, significant supraharmonic voltage levels have been observed reaching up to about 12 % at 4 kHz. In order to identify the cause of these high levels, an EMTP simulation has been performed. The simulation qualitatively proves that the change in impedance between grid-connected and islanded mode can cause elevated supraharmonic levels. The authors expect supraharmonics to become more important in the future also in MV networks. Furthermore, the suitability of sensors used for the supraharmonic measurements should be carefully evaluated.

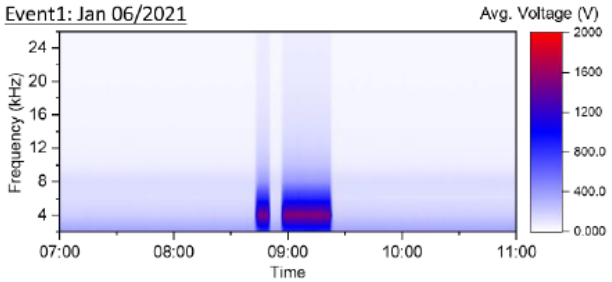

Fig. [11450(US)] Supraharmonic voltage during an islanding event

Both studies confirm that impedance configuration plays an important role in propagation of both harmonics and supraharmonics.

E-mobility

Paper [11079(DE)] studies a fast charging infrastructure with three charging stations and a storage system for peak

shaving purposes in a real LV grid. Based on decoupled Norton models, which have been derived from in-situ measurements, a simulation model is developed to estimate the harmonic emissions under different utilization scenarios. The 7th harmonic has the highest sensitivity to the utilization of the fast charging infrastructure and is the harmonic order with highest emission levels. Results show that emission limits for the 7th harmonic are expected to be considerably exceeded, especially at higher utilization levels. This issue gets even worse as the peak shaving effect of the storage system only affects the fundamental, but not the harmonic current levels. Therefore, in the context of energy efficiency and grid-friendliness a more holistic approach is required in the future.

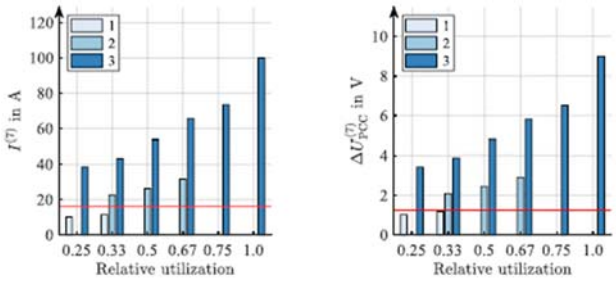

Fig. [11079(DE)] 7th harmonic current and voltage emission of different utilization scenarios compared to the respective limits

Based on a large set of measurements of charging profiles and charging behavior, paper [10703(FI)] implements a simulation to predict the impact of large-scale EV charging on the harmonic currents in distribution networks. The measurements of charging for different cars confirm considerable differences in their harmonic emission spectra. Assuming the worst-case of harmonic phase angles of all EVs being equal, the simulation results in TDI values of up to 110 A at a fundamental current of about 2000 A with 5th and 7th harmonic currents having the highest values.

Using the measurements of a single EV capable to charge both single- and three-phase, paper [10691(SE)] studies the impact of combined single-phase and three-phase charging on the harmonic and supraharmonic hosting capacity. A comparison with emission limits provided in IEC 61000-3-2 shows several violations, while the phase angles of 5th and 7th harmonic present a good diversity. As expected, the hosting capacity is higher for combined single- and three-phase charging compared to only single-phase or only three-phase charging. Moreover, the estimated hosting capacity is higher applying exact phasor addition compared to the use of the general summation law. The authors conclude further that filter circuits of modern power electronics can introduce resonances and have to be carefully considered.

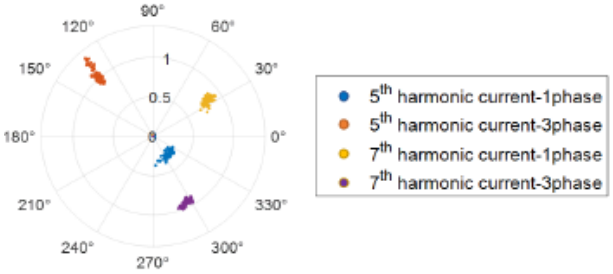

Fig [10691(SE)] Harmonic current phase angles of 5th and 7th harmonic for single- and three-phase charging

Paper [10202(AT)] discusses the impact of bidirectional charging stations to the frequency-dependent network impedance in the frequency range from 2 Hz to 500 kHz. The charger model is implemented in MATLAB and contains a LCL filter. Based on different grid impedances from real measurements as well as from standards the impact of different parameter values of the charger implementation is studied. The results show that the charge causes significant parallel and series resonances, which depend not only on the circuit parameters, but also on the operating conditions of the charger. Furthermore, the charger can act as sink for supraharmonics.

Harmonics and supraharmonics

This subsection summarizes the papers dealing with both, distortion below 2 kHz (harmonics) and distortion above 2 kHz (supraharmonics). Papers on harmonics clearly dominate, while papers on supraharmonics mostly consider only frequencies up to 150 kHz. Only one paper looks also in the frequency range 150 kHz-500 kHz, which recently gained more importance due to PLC communication (FCC band).

Frequency-dependent impedance and resonances

Paper [10428(DE)] reports on a European survey about the impedance characteristics at socket outlets in the frequency range 2-150 kHz with the main intention to verify the suitability of CISPR 16 LISN impedance for equipment emission measurements in the frequency range 9-150 kHz. The measurements have been carried out in different residential and commercial buildings in the United Kingdom, Spain and Germany. The variation of measured impedance magnitudes increases with rising frequency, while the 95th percentile of the magnitude is considerably lower than the CISPR16 LISN impedance. Especially above 10 kHz, the phase angle of impedances often shows a clearly capacitive behavior, which is also not reflected in the CISPR 16 LISN. Measurements at different sockets in the same room as well as at a single socket over time show considerable diversity and variation.

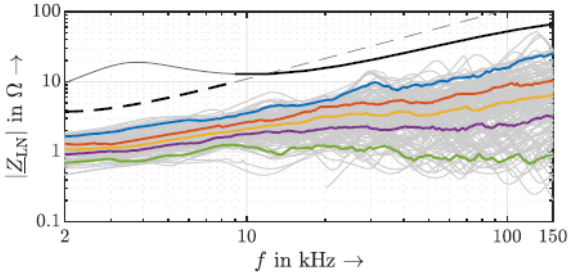

Fig. [10428(DE)] Magnitude of measured impedances with respective percentile values (5th, 25th, 50th, 75th, 95th) and reference impedances according to IEC 61000-4-7 (dashed black) and CISPR 16-1-2 (solid black)

Paper [11191(SI)] compares two established methods for resonance analysis in network models, namely the nodal impedance method (frequency scan at each node) and the modal analysis. Based on the example of a small HV/MV/LV network with multiple capacitor banks, the authors confirm that modal analysis is more efficient. Analyzing participation factors and sensitivity, modal analysis is more suitable to understand the resonance behavior (e.g. which are critical nodes in the system and from which nodes a resonance can be considerably excited).

Paper [10270(DE)] deals with testing a three-stage method for non-invasive resonance detection in residential LV networks. The method is based on measuring voltage and current harmonics at the LV busbar and can continuously monitor the resonance situation in the network, which is likely to be time-dependent. The method is applied to measurements carried out in two different LV networks for a duration of about two days. As reference for validation invasive impedance measurements have been carried out at the same location at the same time. The success rate of the non-invasive method is in the range of 75 % to 80 %. The results confirm a considerable variation of frequency and amplification factor of the first parallel resonance in residential LV networks, which can also differ between the phases.

Paper [11239(DE)] studies the frequency-dependent impedance of 110-kV-networks based on a simplified equivalent scheme as well as the impact of changes in its parameters (e.g. due to addition of cables or change in connected loads) on the resonance characteristics. The objective behind the study is the concern of the involved network operator that the increasing share of underground cables in MV and HV grids in combination with the significant increase in power electronics devices might increase the risk of grid operation difficulties in the future. At first, the expansion of a real existing 110-kV-network by an 18 km double line cable is analyzed. It results in a more significant reduction of the frequency of the first resonance in the zero-sequence than in the positive sequence. Secondly, the impact of cable switching is studied. The transient results in highly distorted voltages, but in this case no critical overvoltages. To avoid overvoltages due to the excitation of local resonances, the use of controlled switching is recommended.

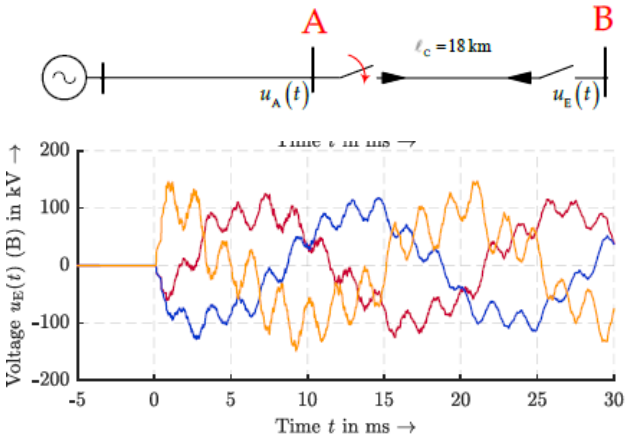

Fig. [11239(DE)] Voltage at substation B during cable energization

Simulation-based studies

Paper [11084(IT)] discusses the challenges of system simulations in the 2-150 kHz range. The commonly used iterative harmonic analysis is applied combining a frequency domain representation of the system and a time domain simulation of the connected devices. In case the load impedance becomes smaller than the grid impedance, which is a typical case in the considered frequency range, the traditional approach of representing the load as a voltage controlled current source results in divergence of the simulation. Introducing suitable shunt impedances at the grid side and the load-side, which finally cancel out in the simulation result, can resolve the problem of divergence. By applying this compensation method, results of iterative harmonic analysis using hybrid frequency-domain and time-domain models perfectly match the results obtained by a reference simulation completely performed in time-domain.

Paper [10674(GB)] studies the optimal location of PQ monitors in order to determine the harmonic disturbance levels in meshed distribution networks. Based on the calculation of an electrical distance index, highly correlated nodes are grouped together with only one monitor required for the group. The method is tested in a simplified 48-bus-network, which is based on a more complex generic distribution network with 295 busses.

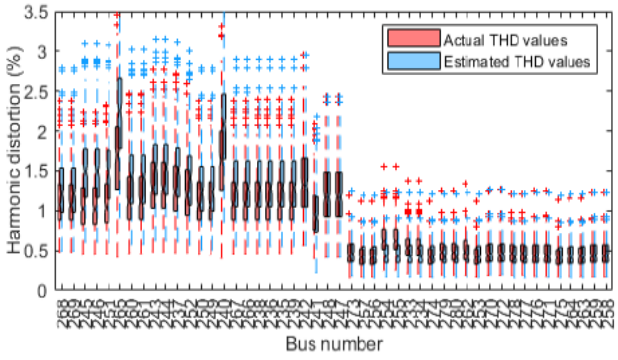

Fig. [10674(GB)] Estimated vs. actual THD values (monitored busses are 242, 247 and 258)

Reference harmonic disturbance levels are determined by injecting load-type specific harmonic spectra and performing a harmonic power flow. Utilizing the electrical distance values, disturbance levels at unmonitored busses are estimated. Results show a sufficient match with the reference disturbance levels at 46 out of the 48 busses.

The authors of paper [10130(ES)] have developed a methodology to estimate THD levels in residential networks based on PQ monitors at about 10-20% of all busses plus the information about active and reactive power from conventional meters installed at the customers. This paper applies the methodology to five simulated real LV networks with sizes differing from 42 to 471 customers. With an average relative error between 2 % and 3 % for the 95th weekly percentile, the method provides a reliable estimation of harmonic voltages in LV residential networks.

Measurement-based studies

Paper [10142(NL)] studies the transfer of supraharmonics from LV network LV1 to the upstream MV and a neighboring LV network LV2. The supraharmonic source is a fast charger connected to LV1. Supraharmonic currents are transferred from LV1 to MV with a transfer coefficient of about 1.0. The transfer coefficient for supraharmonic voltages from LV1 to MV largely varies between 0.1 and 1.0. Amplification of voltages in the downstream transfer from MV to LV2 up to a transfer coefficient of 3.0 confirm that downstream amplifications have to be expected also in the supraharmonic range. Moreover, the results show that even the common opinion of efficient damping of supraharmonic voltages in upstream direction might need to be revised.

Paper [10658(SE)] presents a survey of voltage harmonics measured at the outlets in 14 different trains in Europe. Measurements are performed with an aggregation interval of 1 s and are compared with different standards including IEC 61000-2-2 and EN 50160. The 95th percentile of THD is with values between 1.37 % and 4.89 % well below the limit of 8 % for LV networks. In some cases single values, in particular of even harmonics do exceed the limits, in only one measurement an exceedance of IEC 61000-2-2 limits (which are based on 10 minute aggregation) is observed for some even harmonics over the whole measurement time.

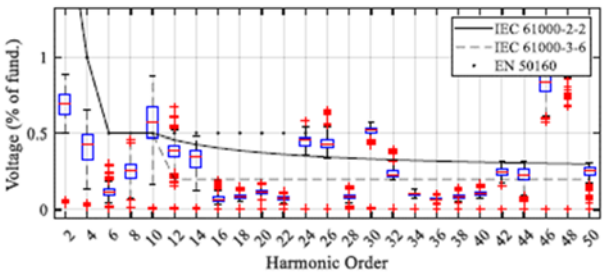

Fig. [10674(SE)] Even harmonics measured on a train Madrid-Cordoba

Paper [10121(SE)] investigates the harmonic levels in LV, MV and EHV networks in Sweden during a high geomagnetic storm activity. The results show that this activity (change in magnetic field) is highly correlated to an increase of even harmonics not only in the EHV, but also in the MV and LV system. Less correlation is observed for triplen harmonics, as their propagation majorly depends on the zero-sequence propagation path, which is, amongst others, determined by the switching group of transformers between EHV and LV networks.

Harmonic limit allocation

Although the emission allocation is based on voltages, it is usually more straightforward to provide harmonic current emission limits. Paper [10587(NO)] addresses the challenge that translating voltage into current limits requires knowledge about network harmonic impedance. The developed tool estimates the network harmonic impedance based on a simplified grid model and is consequently expected to provide better results than approaches solely based on extrapolated short-circuit impedance. Based on six real cases the harmonic impedance calculated by the tool is compared to the harmonic impedance obtained from a simulation. The results do sufficiently match in terms of resonance frequencies, but show deviations in the amplification factor. The authors did also try to identify the harmonic impedance based on measurements performed with and without the customer connected. However, uncertainties in the phase angle measurement as well as the lack of knowledge about the true summation exponent makes the measurement-based determination of harmonic impedance virtually impossible.

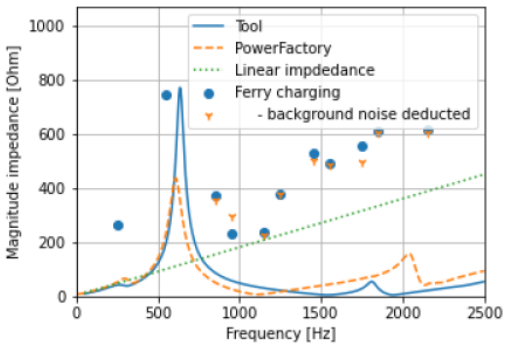

Fig. [10587(NO)] Results for a ferry charger connected to a weak grid

The allocation of harmonic limits is based on assumptions for the phase angle diversity, which is represented by the summation exponent α in many reports and standards, like IEC 61000-3-6. Paper [11081(DE)] provides a method to determine the actual diversity of the harmonic emission of a customer installation related to the background harmonics. The method is applied to six different LV customer installations with a contracted power between 400 kVA and 1400 kVA. Results show that actual diversity can significantly vary over time with periods of actual diversity being higher as well as lower than target

diversity with a large spread between the customers. Only for two customer installations, actual diversity is always higher than target diversity for the 5th and 7th harmonics

Paper [11117(DE)] deals with the downstream transfer of harmonic voltages from transmission to distribution systems, which is, next to diversity represented by α, another parameter that impacts the share of compatibility levels between voltage levels and consequently the allocation of emission limits. The highly distorted inrush current of an EHV/EV transformer is used as excitation to determine the frequency-dependent transfer coefficient based on measurements at two different locations in Germany. Results show a good confidence of results up to the 18th harmonic. The positive and negative sequence of the harmonic transfer coefficient behave similarly and are both in the range between 0.3 and 0.8. The zero sequence component behaves significantly different with pronounced resonances in one location.

Other phenomena

Unbalance

Paper [10638(AT)] proposes a method for the simulation of voltage unbalance in public MV networks. The models of the connected customers LV networks (customers) in terms of current unbalance are developed based on a comprehensive set of field measurements distinguishing different customer types. Upstream background unbalance is also modelled based on field measurements. The voltage unbalance at each node is determined by summing up the unbalance contribution of the customer connected to this node and the contribution of all other nodes considering the respective unbalance transfer factors between the nodes and a summation exponent as suggested in IEC 61000-3-13. The simulation for a real MV network shows a good match between simulation and respective field measurements.

Paper [11353(BR)] implements the simulation of a three-phase two-wire LV network, as it is commonly used in Brazil, in order to study voltage unbalance levels. The ground serves in this case as the third wire and consequently has a different impedance than the other two wires, which can inherently cause unbalance. For the simulations, the length of the network/feeder as well as the location of eight balanced three-phase loads with different apparent power have been varied. The results show that for a supply capacity of 300 kVA the voltage unbalance limit of 2 % is met as long as the feeder length is below 30 km.

Voltage band

Paper [10662(SI) addresses the challenge of higher volatility in consumption and generation in LV networks, which can result in a violation of the voltage band of ±10 %. Based on smart meter measurements for one year, locations where the voltage band has been violated for at least 30 minutes are identified. Based on network simulations the effectiveness of implementing battery storage units introducing demand-side and/or generation-side flexibility as alternative to network reinforcement to resolve the under-/overvoltage issues are evaluated. Results for the studied grid and period suggest that for a considerable share of locations no reinforcement would be needed to solve voltage band issues.

Paper [11141(SE)] studies the impact of EV charging on the hosting capacity for PV installations in a LV network with 83 customers based on probabilistic simulations. Hosting capacity is defined as the maximum amount of PV installations without violating the voltage band. The simulations consider single- and three-phase chargers of different size combined with single-phase and three-phase PV installations of different size. Uncertainties in the phase allocation, the time of charging as well as the background voltage are considered. The simulation results for this case study show that EV charging can significantly increase the hosting capacity for PV installations in LV networks with both three-phase PV installations and EV charging being the most effective.

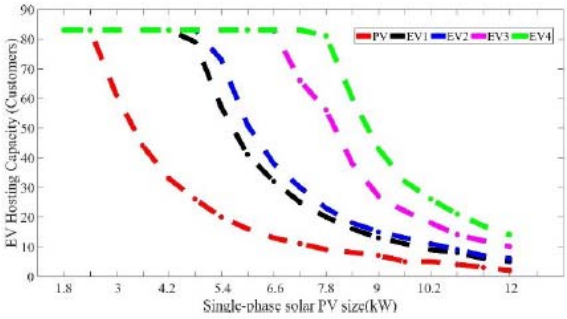

Fig. [11141(SE)] PV hosting capacity in case of single-phase charging of 1.9 kW (black) to 4.6 kW (green); no EV charging is indicated in red

Paper [11186(SE)] studies the impact of battery energy storage systems (BESS) on the hosting capacity for PV installations in an 83 customer network. The authors are the same as for paper [11141(SE)] and consequently similar methods and analyses are applied. Assuming a 15 kW_p PV installation and a generation pattern typical for Northern Sweden, only 33 customers can have a PV installation without the upper limit of the voltage band being violated. Installing BESS in this network can increase the hosting capacity by 40 % up to 71 %. The latter increase is achieved, if the BESS size is not chosen arbitrary, but in relation to the installed PV power and consumption pattern.

Flicker

Paper [10633(JP)] investigates the possibility of beat phenomena caused by the switching frequency emission of grid-connected inverters, which can lead to flicker. At first, the authors implement a simulation of two inverters connected to a distribution system, which has a considerable series resonance minimum at 6 kHz. If the switching frequency of both inverters is set to 6 kHz, resonance amplifications generate high levels of distortion at this frequency. No beating is observed, if the switching

frequencies are the same. If the switching frequencies differ by about 10 Hz the resulting voltage ripple can cause flicker. A laboratory measurement with incandescent light bulbs confirms that flicker resulting from the beat phenomenon is observed, if the ΔV_{10}-value, which is an alternative index to represent flicker-severity, exceeds the limit.

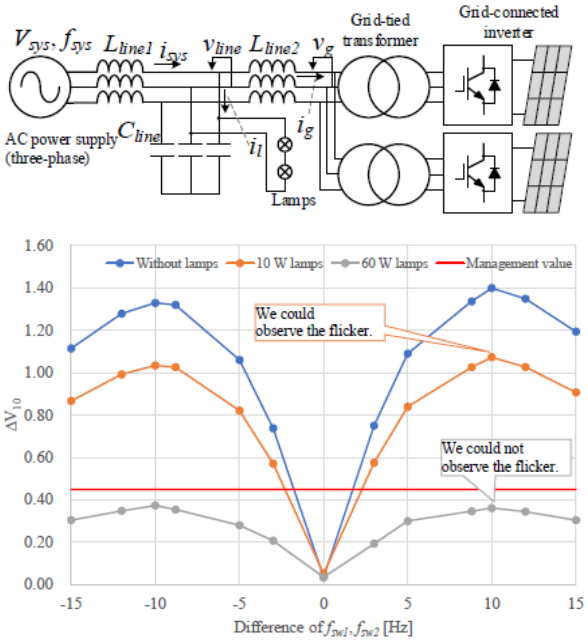

Fig. [11141(SE)] Equivalent scheme and ΔV_{10} depending on the difference in switching frequency between two inverters

Voltage dips

In order to face the challenges of energy transition, network operators have to adapt to changes in generation capacity and load demand. This requires significant adaptions in the network topology on the long-term perspective, which together with the introduction of load pockets and decrease of synchronous units have a significant impact on the short-circuit power and consequently on the severity and propagation of network disturbances, like voltage dips or rapid voltage changes. Paper [10531(NL)] studies this impact and its possible consequences in order to meet existing requirements on voltage dips in the future based on an real (E)HV network. Different future scenarios are simulated and compared to a reference case. The results show that the changes in terms of short-circuit power can be both, positive and negative and do significantly depend on the considered node.

Potential scope of discussion

The papers on system-related PQ aspects reveal several important topics that need further discussion and research in the future.

The high number of papers related to LVDC networks proves the importance of this topic. Further work is needed to improve the understanding of PQ aspects related to LVDC networks. This will provide a solid basis for the introduction of an appropriate EMC standardization framework in terms of compatibility levels, emission limits and immunity levels.

Any kind of system modelling in order to predict the impact of future developments related to the grid as well as to the connected equipment on network disturbances has also high relevance. Current topics include especially studies of the propagation and interaction in the frequency range above 2 kHz in AC networks, but also simulations of distortion phenomena in LVDC networks. A major challenge is the development of realistic models of all components and their implementation in the respective simulation environment, especially of connected equipment. Therefore, the complementary application of simulation-based and measurement-based approaches for model creation and validation can provide high benefits. In terms of distortion studies, only the equal consideration of both, emission and impedance enables the understanding of the usually complex interactions.

The changes related to energy transition in terms of equipment and networks require a critical revision of the present EMC framework. This relates in particular to the interference mechanisms and the procedures of allocating/defining emission limits, which have been introduced several decades ago based on assumptions that may not apply anymore today.

Finally, some of the papers indicate that network disturbances and PQ at system level have to become an integral part of distribution system planning. Particular in terms of "efficiency", only a holistic system-level view not being limited to power frequency is important to ensure the disturbance-free operation of future networks.

Table 3: Papers of Block 3 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
10121	Harmonics in the Transmission and Distribution Grid and their Relation to Geomagnetically Induced Currents			X
10130	Case Studies of Estimation of Harmonics in partly monitored Residential Networks			X
10142	Transfer of Supraharmonics through a MV/LV Transformer			X
10179	Comparative Study of Unipolar and Bipolar Industrial DC Microgrids Through Linear Power Flow			X

10202	The Impact of a Bi-directional V2G Electric Vehicle Charging Station to the Frequency Dependent Grid Impedance (10 – 150 kHz)		X	
10270	Continuous Non-invasive Resonance Detection in Residential Low-Voltage Networks			X
10428	Impedance Characteristics at Socket Outlets in Residential and Commercial Buildings in the Frequency Range 2-150 kHz			X
10431	Operation of Micro Sources and Impact of High Penetration on Low Voltage Distribution Grid			X
10513	Harmonic Distortion in Microgrids in Islanded Operation			X
10531	A Case Study on the Changes in Short Circuit Power to Analyze the Impact on Voltage Dips			X
10587	Verification of Tool for Allocation of Harmonic Current Emissions Considering Frequency-Dependent Impedance	X		
10633	The Beat Phenomenon and Flicker Caused by the Difference in Switching Frequency between Two Grid-connected Inverters			X
10638	Modelling of Voltage Unbalance in Large Real Medium Voltage Distribution Networks	X		
10658	Survey of Harmonic Distortion Measurements from Customer Grid Supply in Trains			X
10662	Large Scale Flexibility Requirements for Voltage Control in Low Voltage Distribution Network Analysis			X
10674	Probabilistic Estimation of Harmonic Distortion in Non-Radial Distribution Network	X		
10691	Combining Single Phase and Three Phase EV Charging: A way for increasing Harmonic Hosting Capacity			X
10703	Analysing Electric Vehicle Charging Power Quality in Large-Scale Charging Sites – A Data-Driven Approach		X	
10787	Dynamic Impedance Identification For Lvdc Power Quality Analysis			X
10831	Analysing The Impact Of Operating Strategies Of Active Customers On Flicker And Voltage Unbalance			X
11079	Modeling and Simulation of the Impact of a Fast Charging Infrastructure on Harmonic Disturbance Levels		X	
11081	Assessment of Harmonic Emission Level of Customer Installations Considering Actual Level of Cancellation	X		
11084	Analysis of the Propagation of Distortion in the Frequency Range 2-150 kHz using Iterative Harmonic Analysis			X
11117	Evaluation of Harmonic Transfer Between Transmission and Distribution Network Based on Measurements			X
11141	Opportunistic Impact Of Simultaneous EV Charging On Stochastic Hosting Capacity			X
11146	Power Quality Analysis of LVDC Distribution System using Real-time Simulator	X		
11166	A Study on VRE Grid Connection Code for LVDC System			X
11186	Solar PV Battery Storage Estimation For Overvoltage Mitigation Using Measurement Data			X
11191	Harmonic Resonances Analysis Methods in Power Distribution Networks			X
11239	Determination of Frequency-dependent Impedances of Large 110kV grids			X
11353	Analysis of the Voltage Unbalance Phenomenon in a Three-phase Two-wire Distribution System			X
11450	Investigation of Supraharmonic Emission from a Microgrid	X		

Block 4: "Standards, measurements, regulations and advanced data analysis"

This block covers new approaches for standards, regulations and reliability assessment, design and results of measurement campaigns, measurement methods as well as advanced data analysis for PQ data. This CIRED an increasing number of papers have been submitted regarding advanced data analysis, i.e. machine learning and artificial intelligence, which reflects the rise of the topic in PQ similar to other domains in society and industry.

Standards and regulations

Six papers are dedicated to standards and regulations. As to novel ideas in standardization, a new definition of interharmonic subgroups and the possibility of adapting the methodology for voltage unbalance limits according to D-A-CH-CZ rules for assessment of network disturbances to the US power system are discussed. Furthermore, the setup of a metrological framework for instrument transformers for PQ phenomena under different operation conditions is presented. In the context of regulation, the difficulties of benchmarking PQ across different countries are discussed and an overview of the results of a voltage quality survey in Sweden is presented. The impact of frequency reserve participation by flexible resources on PQ (FCR-N, Frequency Containment Reserve for Normal operation) is highlighted in a case study.

[11206(IT)] reports on the latest developments associated with the issues and challenges behind the choice of feasible interharmonic limits in distribution networks to be included in future international standards as discussed within the IEEE Interharmonic Distortion Task Force (IHD-TF). Due to the fact, that the sensitivity of modern lamps to interharmonics is higher around odd harmonics than around even harmonics, a new definition of interharmonic subgroups was introduced. For these subgroups a set of experiments have been carried out to show and support the robustness under more realistic conditions.

[11286(US)] presents a comprehensive analysis of the application of IEC derived voltage unbalance limits in the United States power system. The study focuses on the unbalance limit calculation method defined in the D-A-CH-CZ rules for assessment of network disturbances, which is IEC derived and simple in application. The application is illustrated by calculating the unbalance limits based on the D-A-CH-CZ rules for two MV connected installations in the United States. The calculated values were then compared to the actual unbalance current drawn by the installations. The authors conclude that the D-A-CH-CZ rules can serve as a suitable starting point for the derivation of the limits in an upcoming IEEE standard.

[11360(IT)] provides an overview of the progress achieved within the EU project 19NRM05 IT4PQ. The project develops a metrological framework for the assessment of instrument transformer (IT) error contributions in PQ disturbance measurements in the presence of realistic PQ phenomena and under different operating conditions. The results serve as input for the development of the respective IEC standards. Examples of the quantification of performance indices for the measurement of stationary phenomena have been provided with experimental tests on IVTs (instrument voltage transformer) and ICTs (instrument current transformer). Giving the complexity of the approach used in the performance evaluation of commercial ITs, simplified measurement procedures (E-SINDICOMP and S-LV) and setups have been developed to ensure traceable characterization of ITs vs frequency in industrial environments. Regarding influence factors, the temperature effect is significant as it affects both, low order harmonics as well as values around the first resonance frequency.

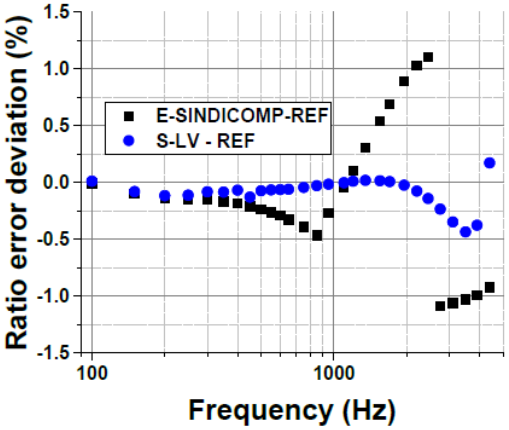

Fig. [11360(IT)] Comparison between E-SINDICOMP and S-LV procedures. Ratio error deviations are evaluated against "reference" errors measured under FH1 applied waveform

[10367(HR)] addresses the challenges of PQ benchmarking across different countries. According to the last report from the Council of European Energy Regulators (CEER), 27 countries have participated in the voltage quality survey. Most of these countries have adopted the EN 50160 standard for the transmission voltage level. Of the 27 listed countries, 18 have installed devices for measuring voltage quality levels, 18 measure voltage dips, 17 voltage surges, 15 voltage unbalance and 7 transient overvoltage. To make the concept of PQ level approachable to customers without technical knowledge, the Dutch DSO created a simple classification method by normalizing PQ parameters. By normalizing each individual parameter using the limit value according to the selected norm, it is easy to create an overview of voltage quality parameters and divide them into quality categories. The authors state that in this way, it may be possible to compare voltage quality parameters of different countries.

[10493(SE)] provides an overview of the results that the Swedish Energy Market Inspectorate (Ei) has obtained from the voltage quality (VQ) monitoring during the period 2016-2021. A selection of 30 DSOs, accounting for 51 % of all customers in Sweden submitted information on complaints they have received regarding VQ during 2016-2021. The analysis shows, that with 76 % most of the

complaints were received from households. In 41.3 % of the complaints, VQ measurements by the DSO met the standards set in EIFS 2013:1. In total, almost a third of all complaints reported were regarding flicker or voltage fluctuations, making it the most common reason for end-users to complain. Fig. [10493(SE)] shows the exact distribution on why customers complained about VQ in each year (2016-2021). In total, for 41.5 % of all the complaints, the DSOs took measures to improve their VQ. These measures include investments to strengthen the grid or to replace various components.

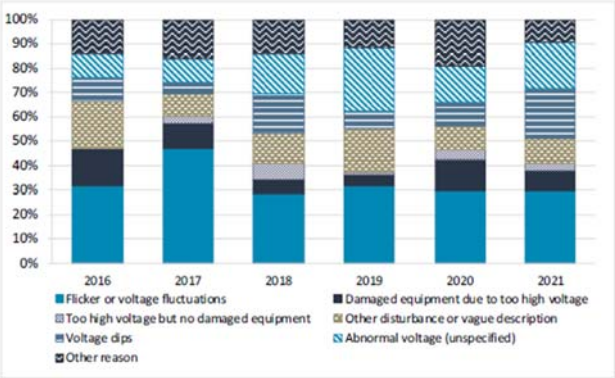

Fig [10493(SE)] Distribution of phenomena causing customers to complain about VQ per year 2016-2021

[10618(FI)] studies the effect of frequency reserve participation of different types of flexibility resources on different PQ phenomena. The authors state that reserve market resources can have similar characteristics to renewable power generation including intermittent operation based on fundamental frequency, driven by power electronic converters and located in a LV network. A case study measuring the PQ at two sites (office building, micro grid) was carried out, to find the impact of FCR-N (Frequency Containment Reserve for Normal operation) reserve participation. It was evident that the FCR-N control can drastically change the active power profile of a resource, which consequently can affect the PQ. However, for the cases studied in this paper the trends of fundamental frequency reactive power, total distortion of current and voltage, and voltage magnitude indicated little changes, which may be an encouragement for the aggregation of reserve resources. The authors conclude that in order to complement the picture an additional analysis on voltage and current harmonics and flicker index data is required to determine consequences of the drastically changed active power profiles of the resources.

Measurement campaigns and monitoring systems

Six papers have been submitted regarding design and results of measurement campaigns and monitoring systems. This CIRED, many papers have been submitted, which refer to new analysis methods for large amounts of PQ data. Therefore, a separate sub block “Advanced data analysis” is dedicated to these papers

[10433(EG)] presents the results of measurements of electrical parameters of an industrial feeder in Alexandria and the summary of indices for continuous and discrete PQ disturbances. The measured parameters include voltage, current, active and reactive power, total harmonic distortion (THD) for the period of one week. Results show no exceedance of applied limits.

[10733(JP)] examines the characteristics of harmonics in Japanese urban areas during the heavy load period of summer and the light load period of autumn in 2020. The findings are compared with a previous study from 2005. The harmonics were measured at 53 (summer) and 49 (autumn) measuring points in distribution substations. The 5th and 7th harmonic were found to be the major harmonic components for both seasons. Considering the 95th percentile values, in average a decrease in the 5th harmonic and an increase in the 7th harmonic compared to the 2005 study is observed. The representative harmonic level of voltage THD (95th percentile of the 95th percentile) in urban areas of Japan was found to remain below but close to the target value of 5 % for the harmonic environment level (HEL) in MV networks. In summer 2020, the representative harmonic level exceeded the HEL. The study also notes a shift from weekends to weekdays and a shift from nighttime to daytime of higher voltage THD levels in 2020 compared to the 2005 study.

In [10993(GB)] a long-term measurement campaign of grid voltage distortion in the 9 kHz to 150 kHz frequency range, performed in the United Kingdom, is presented. The location chosen for the measurements is a newly build residential estate equipped with low carbon technologies. In this work, the results obtained in the field have been compared to the corresponding compatibility levels defined in the IEC 61000-2-2 standard in terms of CISPR 16 quasi-peak values. The raw data were saved and a post-processing method based on a digital implementation of the CISPR 16-1-1 was applied. The maximum value of the quasi-peak for each day was taken and the maximum value for the whole period was calculated. It could be observed that voltage disturbance levels are well below the compatibility levels. Next, a quasi-peak spectrogram, showing the frequency on the y-axis and the 30-s-spectra aligned on the x-axis was created (Fig. [10993(GB)]).

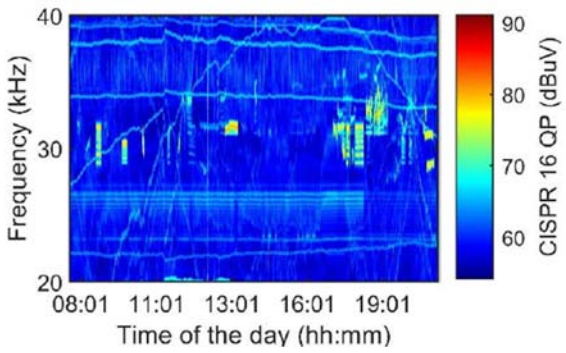

Fig. [10993(GB)] Detail of the spectrogram in the 20 kHz-40 kHz region

Besides some disturbances indicated by horizontal straight lines which are constant over time, short-term disturbances

at approximately 30 kHz have been measured. These disturbances are occurring during meal times, which could result from induction cookers' switching frequencies in the supraharmonic range.

[11328(GB)] proposes a unique method for online monitoring of multimode synchronous resonance (SR) frequencies in inverter based resources (IBR) interfaced weak grids connected through series compensated lines. The fidelity of synchronized phasors in such incidents is discussed by formulating the problem mathematically and a synchro-waveforms-based online approach is proposed that leverages sliding discrete Fourier transform (SDFT) to extract modes from high sampled time domain signal. The effectiveness of the proposed method is validated by synthetic signals, while online monitoring is realized using Matlab/Simulink simulation.

[10525(GB)] proposes a system strength monitoring system based on the application of Thevenin Equivalents (TE) and signal processing techniques. TE are derived from the Thevenin theorem, which is based on the conversion of a circuit into an open circuit voltage in series with an impedance allowing for the calculation of the current through the load impedance. The TE concept is utilized to estimate the impedance of the grid for near-nominal voltage events. An Electromagnetic Transient (EMT) model has been set up and tuned to match real grid data. These data have been recorded during the switching of a transmission connected 80 MVAr shunt reactor. Short circuit simulations have then been conducted using the EMT model to validate the accuracy of the TE measured values. The results show a good match. The values measured with the monitoring system can in general serve as basis for any simulation model validation.

[10374(HR)] investigates the characteristics of recorded voltage and current waveforms of events provided by a PQ monitoring systems installed in a MV network in the distribution area of Zagreb. The characterization can help to determine root causes of events and give helpful information for finding the faulty site faster.

Measurement methods

Seven papers related to new and improved measurement methods for PQ have been submitted. The topics cover techniques to measure harmonic network impedances, the evaluation of a simplified implementation of CISPR 16 Quasi-Peak (QP) receiver and methods to generate complex synthetic test signals for testing measurement methods in the frequency range 9 to 150 kHz.

Harmonic network impedance

[10269(DE)] assesses the technical feasibility of fluctuation-based- and covariance methods for non-invasive measurement of grid-side harmonic impedance in low-voltage (LV) networks. For the covariance-based method, a simulation model was used to model harmonic characteristics at various locations within the LV Network. The analysis showed that the actual and estimated harmonic impedances match very well at the busbar, while they do not match properly at other locations in the network. In a field measurement, the fluctuation-based- and the covariance methods were tested in three different networks. The results show that the fluctuation based method leads to more accurate results than the covariance method. However, both methods have limitations, which considerably impede their application in LV grids.

[10566(DE)] discusses various methods for measuring the frequency-dependent impedance in low-voltage networks. A reference model is presented, which can be used to develop and test methods to identify the frequency-dependent network impedance. The impedance model is representative for a typical LV grid (S_{Tr} = 400 kV, U_{LV} = 400 V/50 Hz) combined with a worst-case MV-grid (U_{MV} = 20 kV, S_{kV} = 20 MVA). This setup allows testing different perturbations. As visible in Fig. [10566(DE)], the resulting impedance of a broadband perturbation ($Z_{mes,\,puls}$) fits the basic shape of the original frequency dependent impedance (Z_{red}) quite well, but larger errors in reading the effective impedance values can be observed. This model was further utilized in a power hardware in the loop (PHiL) test bench to provide an environment to develop and test different methods and parameters.

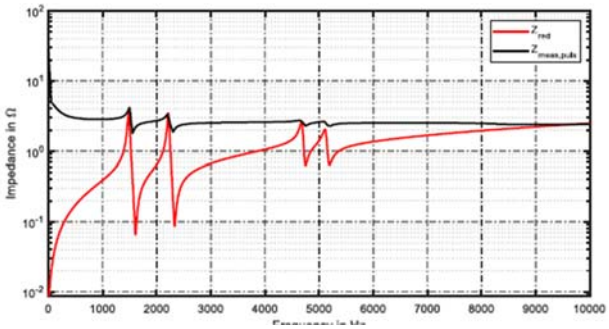

Fig. [10566(DE)] Single Pulse Ohmic Load, one period, 5 Ohm

[10622(BE)] presents a transient invasive method to assess the harmonic network impedance. The method presented is based on the first-order derivative of the positive sequence voltage and current found using the Taylor-Fourier transform and Fortescue transform. A case study shows the effectiveness of the method beyond the threshold where the relative amplitude of the positive sequence harmonic current phasor is lower than 1 % of the fundamental. The authors conclude that the method enables accurate assessment of the harmonic network impedance up to the 30th harmonic order.

Voltage and current distortion from DC to 500 kHz

[10581(ES)] presents and evaluates the extension of the Light-QP method for the 10 minute aggregation interval defined in IEC 61000-4-30. The aim of the Light-QP method is to provide quasi peak (QP) values in the CISPR Band A (9-150 kHz) with considerably lower computational complexity and memory requirements than the standard method defined in the CISPR 16 standard. To assess the feasibility of Light-QP in 10 min measurement

intervals, both methods have been evaluated with recordings in the LV grid. The analysis shows that the Light-QP requires only 11 % of memory resources and 5 % of the CPU processing time compared to the CISPR 16. Furthermore, the QP outputs of both methods have been analyzed statistically. The results in Fig [10581(SE)] show for the used test signals that the Light-QP method provides results similar to those obtained with the CISPR 16 method, as the differences are below the uncertainty limits defined for PQ measurement instruments.

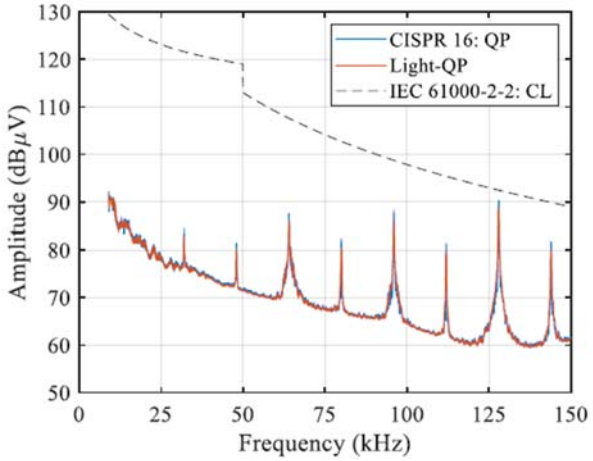

Fig. [10581(SE)] Results for the Light-QP and CISPR 16 methods for a 10-min measurement interval in the measurement point EVCS-1

[10879(CA)] compares two proposed digital implementations of the legacy analogue CISPR 16 EMI meter with field signals recorded from a harsh environment. The first implementation, Digital CISPR, aims to comply with the original analogue CISPR 16 EMI meter, while the second implementation, Light-QP, aims to reduce the computation burden by relaxing some requirements, but still providing results with acceptable accuracy. In a case study, these two methods were compared to a trivial heterodyne method that imitates the original analogue meter with high accuracy on the percentile analyses of each band. In Fig. [10879(CA)] the three-second aggregated values over 10 minutes at the output of the QP detector are visualized for each method, showing that Digital CISPR and heterodyne perfectly match, while Light-QP only matches the reference in a limited time interval.

[10866(DE)] discusses the possible applications of a novel PQ measurement approach, which can output one complex spectrum from DC to 500 kHz for every power cycle. The authors performed a case study in order to demonstrate the PQ measurement system (PQMS) prototype. The case study includes four EV charging stations connected to a MV/LV transformer. PQ measurements have been carried out directly at the EV charger as well as in the main distribution cabinet. It was observed, that with increasing distance to the EV, the magnitude of the emissions at 10 kHz is reduced. In addition, there were no disturbances at all in that frequency range when no EV was connected, indicating, that the EVs were the definite cause of the emission. Harmonic phasor measurements are used to calculate complex harmonic power flow for 5th and 7th harmonics. The positive active harmonic power indicates that the EVs draw the harmonic power from the network.

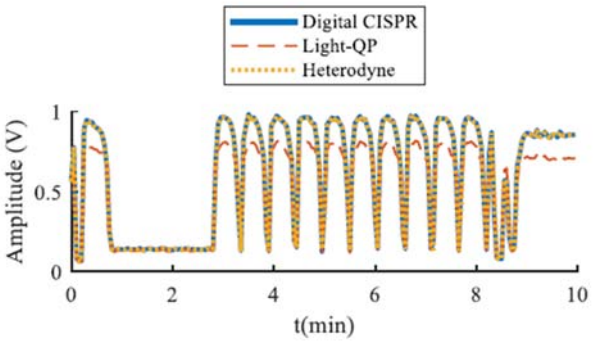

Fig. [10879(CA)] Result of a three-second aggregation over a sample of 10 minutes on the band 54 kHz

[10578(ES)] proposes a methodology using two complementary techniques to generate complex synthetic test signals in the frequency range 9 – 150 kHz, representative for the disturbances present in the LV grid. The power spectral density (PSD) of the signals is exactly known as reference. The first method is based on the intrinsic random amplitude variability in time and frequency of the Additive White Gaussian Noise (AWGN), in which the power is homogeneously distributed across the entire spectrum. The second method takes advantage of the characteristics of polar coding to create PLC transmissions. These two single-source synthetic test waveforms can also be combined to represent a complex recording from the LV grid. This allows the development of a wide range of complex test signals with different spectral content and variation over time. As all waveforms provide theoretical PSD levels over the entire frequency range, the authors conclude that this is a useful tool to compare the accuracy of measurement methods against specific patterns of grid disturbances.

Advanced data analysis

In this sub block, nine papers discuss advanced methods to analyze data and improve PQ. Seven of them apply concepts of machine learning, including deep learning and unsupervised learning to train models. Some of these models are designed to map actual PQ values, other papers model component failures or present a method to artificially increase the amount of training data. Another paper analyzes, if reliable trend estimations are possible based on discontinuous voltage quality measurements. The last paper presents a method to find fault locations faster based on the wave shapes of captured currents and voltages.

[10318(KR)] aims to analyze the influence of distributed energy resources connected to the distribution system on power losses. For the study an explainable artificial

intelligence (XAI) forecast model was used, which was trained based on real load profiles generated from Korea's 12'103 power distribution lines in 2021. To train the forecast model with the generated candidate features of load loss, the machine-learning model, LightGBM, which is based on a gradient boosting decision tree, is employed. For their forecast model, a composition of train data to test data of 7:3 was used. A comparison of the predicted loss factors and the measured loss factors highlights the learning performance of the loss factor forecast model. The authors propose that it will be possible to prevent increase of power losses caused by the connection of distributed energy resources in advance by using the XAI-based PQ impact evaluation analysis model.

[10324(SE)] presents a tool, based on an unsupervised method to aggregate the analysis of large amounts of long-term PQ data at multiple locations graphically. The method has been applied to PQ data sets from a Northern Swedish distribution system over the year 2017. The measurements consist of 10-min values according to IEC 61000-4-30 for the second to 50th harmonics. The deep learning method consists of an autoencoder (AE) followed by a clustering algorithm to obtain the principal features and main patterns of variations in PQ data. The reconstructed patterns are obtained by applying the cluster centers of the principal features on the trained decoder. By the distribution of the patterns, inferences concerning the propagation of the harmonics in the locations can be recognized visually.

[10417(SE)] provides an overview of deep learning (DL) applications to PQ. In order to obtain an overview of the applications of DL to PQ, this work analyzed 46 publications. The two machine learning (ML) methods linear principal components (PCA) and kernel principal components (KPCA) were employed and compared with deep autoencoder (DAE). The comparison among the methods for sub-10 min PQ data was carried out with the measurements of the 1-s RMS voltage at a residential outlet. Fig. [10417(SE)] shows the reconstruction error (RMSE) for the sub-10 min measurements.

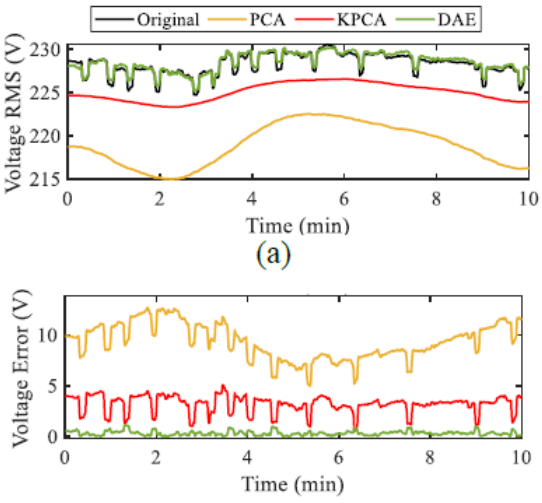

Fig. [10417(SE)] Example of reconstruction of a sub-10 min window: (a) reconstruction of 10-min window. (b) error

The maximum error for the PCA is close to 80 %, while for KPCA it is close to 30 %. The inclusion of the non-linearity from KPCA aggregates leads to some benefits in the reconstruction compared to the PCA. However, DAE presented a RMSE close to zero for the whole dataset. Due to the high RMSE, applications for events such as voltage dips and swells can result in higher false alarms when PCA or KPCA are employed.

[10747(GB)] presents the application of machine learning, using a dynamic library of template electric failure signatures (built up from PQ waveforms), to detect component failures in HV distribution networks. The classification algorithm was set up based on using a convolutional neural network (CNN) pre-trained on a large quantity of verified time-series data that show a wide range of common fault signatures. Outputs of the CNN give the user the closest match between the input fault signature data and a known fault signature type, along with a certainty score. By early identification of such pre-fault PQ signal disturbances and understanding the probability of components to fail, unplanned customer outages could be avoided and the reliability performance of the HV distribution network could be maintained or improved.

[11023(AT)] analyses, if reliable trend estimations are possible based on discontinuous voltage quality measurements. As reference continuous measurements at 23 sites in Austrian MV networks over five to six years are used. Annual trend gains based on simulating dis-continuous measurements have been compared with reference trend gains determined from the respective continuous measurements. The analysis shows that yearly repeated measurements over fixed three weeks can in general provide a sufficiently reliable trend assessment as is illustrated in Fig. [11023(AT)].

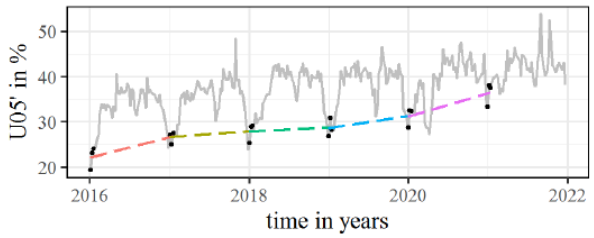

Fig. [11023(AT)] Time series of the 5th voltage harmonic (grey line) estimated yearly trends (colored dashed lines) based on annually repeated measurements of 3 weeks (black points) starting in 1st calendar week

The robustness of results tends to increase with number of years. The trend assessment based on discontinuous measurements is sensitive to single weeks with abnormal high/low 95th percentile values (e.g., due to routine maintenance).

In [11087(FI)] a load control detection of an FCR-N (Frequency Containment Reserve for Normal operation) resource was performed using machine learning models trained on the electrical measurement data. Two scenarios were implemented – supervised and unsupervised learning, which were preceded with the common feature

engineering step. Ensemble-based models were selected for the load control detection and neural networks (NNs) for the feature engineering as these models have demonstrated the highest performance in many different applications. In the proposed approach, the load control detection was performed as post-analysis at a daily level, which could be considered as the main limitation. Nevertheless, using this approach, DSOs may monitor if their customers begin to have flexibility resources, when the flexibility is in operation, or if there is a problem with the flexibility control.

[11269(DE)] investigates a possible approach for artificially expanding training data in order to enhance future research on machine learning applied to PQ monitoring data analysis. An approach based on TimeGAN, a special version of Generative Adversarial Networks was used. The TimeGAN implementation was enhanced using several methods from GAN research in order to improve convergence and diversity of the algorithm. As a proof-of concept, the algorithm was applied to a set of randomly generated PQ disturbances (PQD) data samples. For voltage sag and interruption data, several promising results could be presented as visualized in Fig. [11269(DE)], showing a principal component analysis (PCA) of the original and synthetic sag and interruption data respectively. However, mode collapse and non-convergence turned out to be major challenges during GAN training.

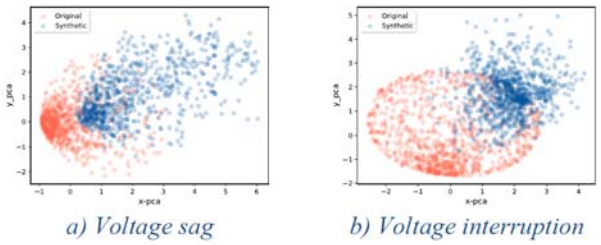

Fig. [11269(DE)]PCA plots of successfully generated synthetic data

[11515(KR)] suggests a PQ monitoring method for distribution systems with minimal data using machine learning. This method estimates the nth harmonic's voltage using the XGBoost technique (an ensemble model technique). Boosting generates a model with superior performance by influencing the next generation's prediction result using the previous one. Data of distribution transformers operated by the Korea District Heating Corporation were collected. Three transformer units have been monitored and afterwards three models were trained and optimized through hyper-parameter tuning. Fig. [11515(KR)] shows the 5th harmonic's estimation result of transformer unit 1 / phase L1 for a specific day. The authors state that the proposed methodology can also be used to estimate the total harmonics distortion (THD).

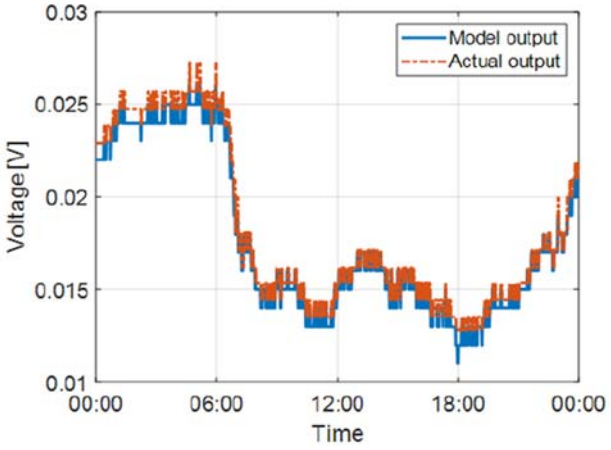

Fig. [11515(KR)] Comparison of model output and actual output for 5th harmonic voltage

Reliability and Customer Costs

From the three papers included in this sub block, one investigates the potential advantages of unmanned aerial vehicles for field observations. The second paper examines the impact of severe weather conditions to the quality of service in Portugal. Finally, a method to assess the long-term consequences of recovering from a voltage dip is presented.

[D5-10246(IR)] evaluates potential advantages of unmanned aerial vehicles (UAVs) to increase the supply reliability in distribution networks. Therefore, field observations with UAVs have been performed for a sample of seventeen 20 kV feeders in mostly urban areas using high resolution and thermal cameras in 2021, which have been traditionally inspected without UAV in 2020. A comparison of the impact on SAIDI and SAIFI indices for unplanned interruptions shows a decrease in 2021 compared to 2020.

[D5-11362(PT)] aims to identify the impact of severe weather conditions on the quality of service key performance indicators (KPIs) and the impact on the electrical infrastructure. The study includes an analysis of the life cycle of assets exposed to these weather events when compared to regular aging. The analysis includes three severe weather events in Portugal and analyses the 10 next days following the events. From the results obtained, it appears that there is a correlation between such an event and an increased number of faults in the grid in the following days. Depending on the intensity of the event, the following period of 10 days may account for an elevated portion of the overall KPIs. For example, the 10 days after one event contributed about 5 % of the yearly SAIDI.

[D5-11334(US)] provides an approach to measure the impact of a voltage dip event on a facility by assessing the change in the load, coincident with the event. This approach leads to parameters such as the recovery time, the recovery energy and the recovery energy cost. These parameters can be very helpful for customers to quickly

assess the long-term consequences of recovering from a voltage dip.

Potential scope of discussion

The on-going energy transition has been accelerated by the energy crisis in Europe resulting in faster and partly disruptive changes in the power grid. These changes are taking place on all voltage levels and not only require the integration of new loads for the electrification of heating and mobility and renewable generation systems, but also new complex instruments and platforms to keep the power system in balance and manage grid capacities and voltage. Today 24/7 availability of power in very good quality is taken for guaranteed in many countries of the world. However, when power is unavailable due to extreme events one recognizes that electricity is the backbone of today's infrastructure.

In this context, it is important to think forward and to implement monitoring of PQ to achieve a reasonable observability of the networks. Making use of innovative data analysis techniques enables the efficient extraction of information and easy interpretation, which should become an integral part of planning and operation of distribution networks in the future. PQ not only describes reliability but also the deviations of the actual PQ parameters to specified limits until which a smooth operation of all components in the grid can be expected. Identifying critical PQ trends and is important in order to take early measures and prevent malfunction and outages for both system operators and customers. New normative measurement methods should always critically question, if the covered interference mechanism is still relevant and properly reflected. Only this way, meaningful actions can be derived.

Table 4: Papers of Block 4 assigned to the Session

No.	*Title*	*MS*	*RIF*	*PS*
10246	Unmanned Aerial Inspection of Distribution Power Lines in MEEDC; Challenges and Lessons Learned			X
10269	Assessment of Technical Feasibility of Non-Invasive Measurement of Grid-Side Harmonic Impedance on Low-Voltage Networks			X
10318	Explainable AI-based Intelligent Approaches for PQ Prediction in Distribution Networks Considering the Uncertainty of Renewable Energy			X
10324	Deep Learning Graphical Tool Inspired on Correlation Matrix for Reporting Long-term PQ Data at Multiple Locations	X		
10367	Power Quality Benchmarking			X
10374	Determining Faults Cause Based On Disturbance Records From PQ Monitors			X
10417	Deep Learning for Power Quality with Special Reference to Unsupervised Learning			X
10433	Power Quality Survey in Industrial Zones in Alexandria			X
10493	Monitoring Voltage Quality in Sweden	X		
10525	System Strength Measurement, Testing and Validation			X
10566	Innovative High-Power Exiting Inverter for Frequency Dependent Grid Impedance Measurements			X
10578	Techniques to Generate Test Waveforms for Power Grid Measurement Methods up to 150 kHz			X
10581	Evaluation of the Light-QP Measurement Method for Extended Measurements			X
10618	Impact of Reserve Market Participation on PQ of Flexibility Resources and Local Electricity Networks	X		
10622	Assessment of Harmonic Network Impedance through Transient Harmonic Signals measured at an Industrial Power System			X
10733	Harmonics Analysis for Distribution Systems of Urban Areas in Japan			X
10747	Applying Machine Learning To PQ Signals To Detect Component Failure Signatures And Prevent Unplanned HV Outages			X

10866	Harmonic Phasor Measurement Technology from DC to 500 kHz with Time Resolution of a Single Line Cycle			X
10879	Supraharmonics Assessment: Methods Comparison Based on a Used Case in a Metalworking Shop			X
10993	UK Grid Disturbances Measurements From 9 kHz To 150 kHz On A Low Carbon LV Network			X
11023	Impact of Discontinuous Measurements on the Trend Analysis of PQ Parameters	X		
11087	Automated Load Control Detection Using PQ Data And Machine Learning	X		
11206	New Interharmonic Subgroup Concept for Quantifying and Limiting Distortion in Distribution Networks: Further Developments and Experimental Validation	X		
11269	Artificial Expansion of PQ Datasets using Generative Adversarial Networks			X
11286	Applicability of IEC derived Voltage Unbalance limits in the US Power System: A case study			X
11328	Multimode Synchronous Resonance Detection in Converters Dominated Power System using Synchro-waveforms			X
11334	New Approaches for Quantifying Impact of PQ Disturbances			X
11360	Performance Evaluation of Instrument Transformers in PQ Measurements: Activities and Results from 19NRM05 IT4PQ Project			X
11362	Impact Analysis Of Severe Weather Events In The Rest Of The Year KPI			X
11515	Power Quality Monitoring-Based Distribution Network Characteristic Analysis Using Machine Learning			X