Special Report - Session 2

POWER QUALITY AND ELECTROMAGNETIC COMPATIBILITY

Emmanuel DE JAEGER
Chairman – Belgium
emmanuel.dejaeger@laborelec.com

Herwig RENNER
Special Rapporteur – Austria
herwig.renner@tugraz.at

Kurt STOCKMAN
Special Rapporteur – Belgium
kurt.stockman@howest.be

Introduction

The **scope of Session 2** has been defined as follows by the Session Advisory Group:

- **Power Quality (PQ)** : voltage continuity (often referred to as supply reliability - problem of outages) and voltage quality (LF disturbances, ≤ 9 kHz, reaching equipment through the electricity supply);
- **EMI, EMF and Safety:** HF disturbances on the electricity supply and all disturbances - HF or LF - reaching equipment other than through the electricity supply; some safety and resistibility concerns (Electromagnetic fields – overvoltages - step, touch and transferred voltages...) are also considered.

The **S2 papers** will be discussed in **three events**:

- Main Session (Wednesday 8 June),
- Poster Session (Thursday 9 June),
- Research & Innovation Forum (Tuesday 7 June).

Three **Round Tables** will be organised:

- Voltage quality monitoring, dips classification and responsibility sharing (RT.2a, Tuesday 7 June, am)
- Economic framework of power quality (RT.2b, Tuesday 7 June, am)
- EMF - Revision of magnetic fields limits (RT.2c, Tuesday 7 June, pm).

Several PQ&EMC-related papers will be discussed within other sessions (S1, S3, S4, S5, S6).

The **aim** of this **special report** is to present a synthesis of the present concerns in PQ&EMC, based on all selected papers (S2 and other sessions : 160 papers !).

Block 1: Electromagnetic interference, electric and magnetic fields and grounding systems

Electromagnetic interferences (EMI)

Three papers from Austria are devoted to specific EMI problems. [B1-0013(AT)] and [B1-0014(AT)] focus on induced voltages in pipelines. The first paper describes the correlation between specific soil resistivity, coating holiday diameter, induced voltage and current density at coating holidays. "Coating holiday" is the technical term for small defects in pipeline coating. Even for low induced voltages around 1V, high current densities might result in case of very low soil resistivity and coating holiday diameters up to 5 mm, thus being prone to risk of AC corrosion.

An optimal reduction of induced voltage can be achieved by combining mitigating measures. Proper design of earthing systems, isolating joints, compensation conductors as well as the phase arrangement and transposition of inducing overhead lines is necessary.

The influence of HV cables on isolated conductors bedded in the same trench (pipelines, communication lines) is investigated in [B1-0753AT]. The effect of passive shielding conductors is demonstrated and reduction factors for different arrangement derived.

Electromagnetic field measurement

Most papers dealing with electromagnetic fields focus on magnetic fields. Several papers present results from magnetic field measurement surveys in the vicinity of electric installations.

[B1-0118(EG)] gives examples of measured magnetic field distribution inside electrical substations. Measurements in the vicinity of HV, MV and LV installations are presented in [B1-0972(PT)]. The authors report that average exposure levels resulting from HV and MV equipment are usually below 1 µT. However, the LV cables of some distribution transformers located in buildings can generate tens of µT in the nearest rooms. In both papers measurement results are compared to results from simulation programs, based on Biot-Savart formulas.

Magnetic field measurement around a typical 10 kV substation shows highest values outside at the wall, directly behind the LV switchboard [B1-1141(NL)]. To correlate the measured magnetic field and current to a yearly magnetic field pattern, the current of the MV station was measured during a week.

The authors of [B1-0681(DZ)] present measurement results for electric and magnetic field in the vicinity of a 220 kV overhead line. Recorded values are significantly lower than ICNIRP limits

An innovative method to study the exposure of people to 50 Hz magnetic fields is presented in [B1-0818(FR)]. Two samples (children and adults) representative of this population were equipped with a magnetic field data logger recording the magnetic field to which the person was exposed during 24h. Additional information was gathered by a questionnaire. In total, 977 measurement series were validated for children and 1052 for adults. The arithmetic and geometric means observed were respectively 0.09 and 0.02 µT for children and 0.14 and 0.03 µT for adults. Electric installations on MV and LV level and especially domestic appliances were identified as factors influencing the mean exposure. In [B1-0823(FR)], written by the same authors, a more detailed breakdown of exposition to magnetic fields caused by power system installations is given. Corridors with a mean magnetic field value greater than 0.1 µT were defined around electric installations. All subjects from the above mentioned study were classified whether to live inside or outside of a corridor. Results are given in Table **1** and Table 2

Table 1: Distribution of subjects (out of 2029) exposed to magnetic field generated by ERDF networks [B1-0823(FR)]

	Number of subjects
Overhead line 20 kV	46
Overhead low voltage line	792
Underground line 20 kV	674
Underground low voltage line	1081
MV/LV substation	94
From which MV/LV substation in building	26

Table 2: Distribution of subjects (out of 2029) exposed to magnetic field generated by ERDF networks [B1-0823(FR)]

	Number of subjects	remarks
Overhead line 400 kV	9	8 subjects « exposed » to several power overhead lines (of the same type or not)
Overhead line 225 kV	13	
Overhead line 63 to 150 kV	27	
Underground line 225 kV	17	5 subjects « exposed » to several lines
Underground line 63 to 150 kV	20	

EMF mitigation

In a field study [B1-0119(EG)] different options of magnetic field management in a distribution station are demonstrated. The effects of reducing LV cable clearance and rearrangement of low voltage panel boards – resulting in a reduction of maximum field values below 50% - are shown by simulation. Additionally results for shielding with different materials are given. However, field reduction achieved is rather poor in the investigated case.

A so called aluminium-steel-sandwich construction was tested for shielding by the authors of [B1-1141(NL)]. After successful laboratory tests a first pilot project was realised in a distribution transformer station. In the vicinity of the sandwich construction shielding factors of ~15 were achieved (Figure 1).

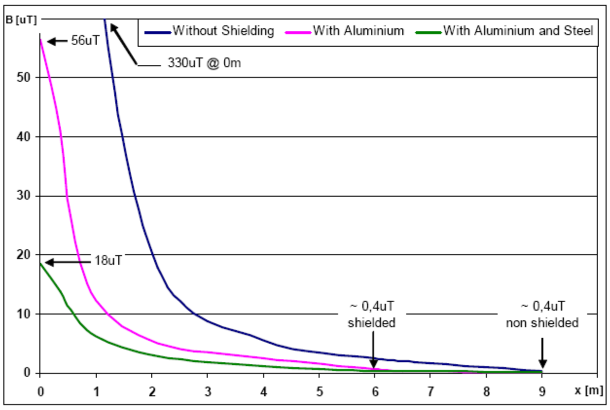

Figure 1 : Band attenuation of the magnetic field with use of shielding material [B1-1141(NL)]

For underground cables several phase arrangements (flat, triangle, stacked) are analysed in [B1-0815(EG)].

Non-power frequency magnetic field

An easy way to take into account the contribution of harmonics to the total exposure ratio (electric and magnetic field) is given in [B1-0355(AT)] by introduction of a harmonic factor. Harmonic voltages and currents can be represented in symmetrical components. It's quite evident that a zero sequence system results in a different field profile than positive and negative sequence systems, with the latter generating equal shaped field profiles. Taking this into account, the calculation of the total exposition ratio – including the effects of harmonics - can be simplified to the following principal formula.

$$ER = ER_1^0 \cdot k_H^0 + ER_1^1 \cdot k_H^{1+2}$$

ER ... total exposition ratio including harmonics

ER_1^0 ... exposition ratio for zero sequence fundamental

ER_1^1 ... exposition ratio for positive sequence fundamental

k_H^0 ... factor for zero sequence harmonics

k_H^{1+2} ... factor for positive and negative sequence harmonics

Indicative values for harmonic factors applicable to magnetic field are given in Table 3.

Table 3: Typical values of harmonic factors $k_{H,I}$ for magnetic field exposure ERB [B1-0355(AT)]

	ICNIRP 1998 [1]		ICNIRP 2010 [3]	
	$k_{H,I}^0$	$k_{H,I}^{1+2}$	$k_{H,I}^0$	$k_{H,I}^{1+2}$
LV	0.5	1.5	0.2	1.2
MV	0.15	1.3	0.1	1.15
HV	0.05	1.2	0.03	1.1

Electromagnetic forces on LV bus bars due to harmonic currents caused by rectifier load are presented in [B1-0136(EG)]. These forces in the presence of harmonics cause excess vibrational stress on the busbar leading to rupture of the insulating supports and permanent busbar bending.

On the basis of real measurements at a three panel switchgear installation, the authors of [B1-0388(DE)] compare HF emission of different switching devices like an air insulated disconnector, SF6 insulated disconnector and vacuum circuit breaker. In case of radiated disturbance, the vacuum circuit breaker plays the most decisive role due to the wide bandwidth of the generated disturbance. Regarding the conducted disturbance, the disconnectors are more severe due to the rather long duration of their switching operations.

Earthing systems

With the implementation of smart meters many new electric energy applications in supply areas and in buildings (single or multiple dwelling, office buildings, industry) will be initiated. The usage of smart meters in smart buildings and smart grids requires enhanced communication lines and the usage of modern electrical installations and sensitive measurement, data acquisition and control systems. This affects the area of customer installations and the grid under consideration and demands high reliability. Low induction grounding, equipotential bonding and lightning protection systems are a pre-condition starting from the transformer stations via the mains connection to the location of the electrical / electronic equipment in the buildings. Especially the refurbishment of old buildings to meet modern ICT demands is a complex challenge. The authors of [B1-0760(AT)] propose to realise a fish trap like structure of conductors with an appropriate profile to achieve a preferably low impedance equipotential system. As the grounding and equipotential bonding system changes to a predominate equipotential system the refurbished grounding system has now to meet only the demands of a proper lightning protection system and can be realised usually with vertical grounding rods.

Interval mathematics provides a powerful tool in the case of “unknown but bounded” parameter, avoiding the need of multiple simulation runs. Usually there are a lot of uncertain parameters (soil resistance, exact position/depth of components) when calculating the resistance of a grounding system. The author [B1-0141(EG)] uses interval mathematics in a new design method for substation grounding systems. Results for a 115/13kV substation grounding grid system are provided. Additionally a parameter sensitivity analysis is made.

The present calculation method in UK standards seems to significantly overestimate transfer potential between HV grounding system and multiple earthed LV systems. The authors of [B1-376(GB)] present a new method to calculate the overall potential on any number of interconnected LV electrodes. In a case study, a comparison between the existing method, a detailed simulation study and the new proposed method is given (Figure 2).

In [B1-0020EG] simplified approaches for the earth surface potentials and ground potential rise of substations are presented in the case of uniform or non-uniform soil resistance. The results of arrangements with different spacing of grounding conductors are presented. The arrangement with unequal spaces having denser conductors at the edges provides the most efficient design (Figure 3).

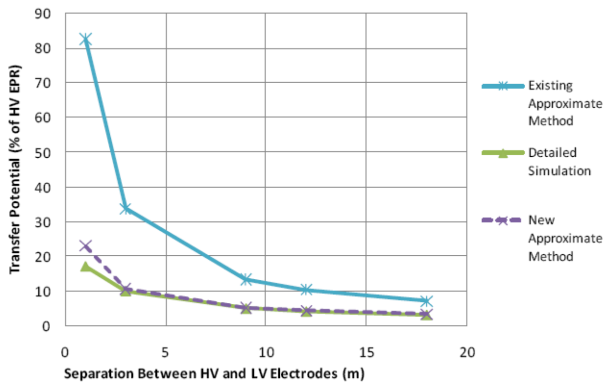

Figure **2** : Comparison of calculated transfer potential using different methods [B1-376(GB)]

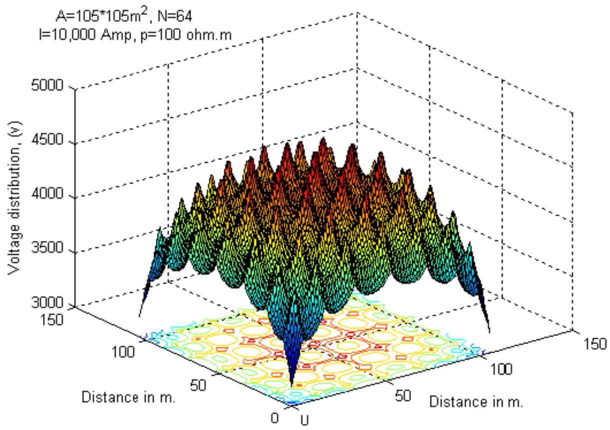

Figure **3** : Voltage profile along all grid conductors in case of unequally spaced grid having denser conductors at the edges [B1-0020(EG)]

In [B1-0522(AT)], parameters affecting the currents in the grounding system (ground wires, pylons) and the prospective touch voltages are analysed.

A spreadsheet based routine for the calculation of the splitting of earth fault current between available return paths (local earth, cable armour, sheath, pipes) is presented in [B1-0548(GB)].

In the concept of smart grids the autonomous islanded operation is a normal operational state for micro grids. A micro grid is a restricted and decentralised supplied grid which most of the time is connected to the public power supply. In the case of a fault in the public supply the micro grid is operated as an islanded grid. In this case decentralised generators or other sources have to provide a sufficient fault level to guarantee proper function of protection devices. In [B1-0759(AT)] different fault scenarios with different treatment of transformer and generator neutrals are investigated.

A new method for measurement of grounding impedance, ground potential rise and step voltage is presented in [B1-0085(AT)]. The method is based on the beat frequency method (slightly detuned source) and an evaluation with adaptive window length FFT. Inductive or ohmic-coupled disturbing signals with power frequency, including harmonics, can be eliminated effectively.

The concept of a ± 750 VDC bipolar distribution system with isolated neutral is analysed in [B1-1270(FI)] regarding safety issues. The results show that the double fault situation can introduce dangerous contact voltages and touch currents to human body. Fault currents highly depend on the earth resistance. High contact voltage and touch current values are introduced with low earth resistance value.

Wooden power line poles are assumed to be a good electric insulator. Live wires contacting the pole due to loosened phase conductor or broken insulators normally pose no danger. However, it has been noticed that under certain circumstances such poles can get conductive enough to result in hazardous or even lethal current for power line maintenance workers climbing the pole. A number of variables have been identified by the authors of [B1-0347(SE)] and tested in order to examine their influence on the pole-resistance. Measurements of pole resistance were taken over a 12 month period to get values for different temperatures and precipitation type and duration. The results clearly show that currents with amplitude to be potentially harmful to a human climbing the pole can occur (Figure 4).

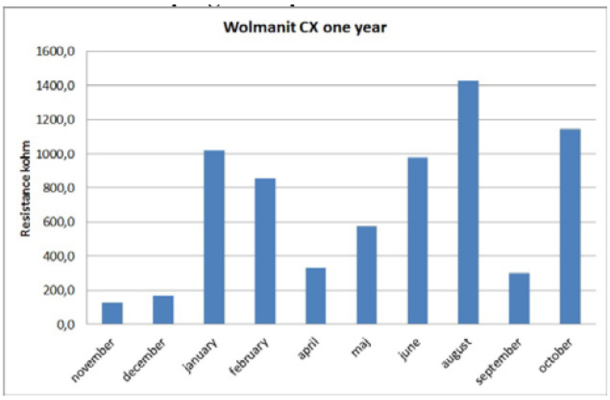

Figure 4 : Yearly variation of the resistance in a one year old wolmanit CX impregnated pole [B1-0347(SE)]

[B1-0511(IT)] investigates temporary overvoltages (TOV) affecting the healthy phases of a radial MV distribution networks operated with non-effectively grounded neutral, originated by a single phase-to-ground fault. Theoretical analysis carried out for several network configurations and fault parameters proved that worst-case TOVs can reach 3.5 p.u. phase-to-ground with ungrounded neutral and 1.8 p.u. with compensated neutral (pure reactance or Petersen coil in parallel with an earthing resistance). These theoretical results have been fully confirmed by full-size experimental real field tests, both with insulated neutral, stand-alone Petersen coil and Petersen coil with permanent parallel resistance. The study confirms that extended radial MV networks with insulated neutral may experience “abnormal” TOVs for certain ground faults, and that neutral compensation has a remarkable effectiveness in suppressing the phenomenon, similar to low earthing resistors, in addition to a drastic reduction of fault currents in earthing plants.

A novel active earthing system for MV networks is presented in [B1-0560(ES)]. This system performs zero-sequence impedance measurement by injection of fundamental and other frequencies currents; it is also able to produce and inject a controlled neutral voltage. During single phase-to-ground faults, the system performs fault location, fault extinction and reduction of the faulty phase-to-ground voltage in weak insulation points.

[B1-0853(PT)] highlights the fact that changing the neutral earthing from isolated to reactor earthing improved the quality of service by reducing the interruption time and the number of network incidents. Following these improvements, EDP (Portuguese distribution grid operator) is currently changing its entire substation neutral earthing to earthing reactors.

The importance of neutral conductor

[B1-0240(TN)] discusses the role of neutral conductors in MV distribution networks. The effects on temporary overvoltages, protection behaviour and safety aspects are investigated. It claims that multi-grounded MV neutral is not strictly necessary.

Similar topics are also dealt with in [B1-0525(BR)]. However, this paper aims specifically at analysing the impact of the neutral conductor absence at specific sections over the performance of the power distribution lines, and proposing alternative solutions to mitigate the problems caused by neutral conductor theft. Simulations show that the absence of neutral conductor at specific sections of power distribution lines may increase the neutral-to-ground voltages, which seriously compromises the system's safety. Solutions are developed in order to keep the technical performance of the power distribution system at satisfactory levels – regarding the voltage profile – or, at least, close to the level before the neutral conductor's theft.

Further research topics

Increasing energy demand in densely populated areas raises more and more problems with magnetic fields of electric installations. What are the achievable improvements in field reduction by optimised station design, passive shielding and active compensation related to the costs?

Papers of Block 1 (B1)

Paper No.	Title	MS a.m.	RIF	PS	Other Sess.
0013	Impacts of Inductive and Conductive Interference due to High-Voltage Lines on Coating Holidays of Isolated Metallic Pipelines	X			
0014	Simulation and Optimized Reduction of Induced Pipe Voltages caused by High-Voltage Lines on Inductively Interfered Pipelines			X	
0020	Earth Surface Potentials and GPR of Substation Grounding			X	
0085	New Optimized Analysis Method for Measuring Extended Grounding Systems		X		
0118	Extremely Low Frequency Magnetic Field Measurements Survey in Distribution Substation			X	
0119	Power Frequency Magnetic Field Management In Power Distribution Substation	X			
0136	Electromagnetic Forces Densities for 3 Phase Busbar Parallel Connected to Rectifier Load			X	
0141	Designing Substation Earthing Grid System Using Interval Mathematics			X	
0240	Effect of Missing 30 kV Neutral Wire on Network Behavior				S1
0347	Currents in Power Line Wood Poles	X			
0355	Harmonic Factor Evaluation for Electric and Magnetic Fields Using Symmetrical Components			X	
0376	New Design Methods to Achieve Greater Safety in Low Voltage Systems During a High Voltage Earth Fault	X			
0388	Investigation of Electromagnetic Disturbance Sources in Medium Voltage Switchgear			X	
0511	Abnormal Ground Fault Overvoltages in MV Networks: Analyses and Experimental Tests				S3
0522	Influence Parameters of Step and Touch Voltages in the Vicinity of HV Power Line Towers under Normal and Fault Operating Conditions			X	
0525	Alternative Solutions to Mitigate Problems Due to Neutral Conductor Theft in MV Power Distribution Systems				S3

0548	Impact of Cable Sheath Sizing, Material and Connections upon the Safety of Electrical Power Installations			X	
0560	Experimental Validation Results of the Active Grounding System for MV Networks				S3
0681	Characterization of the Electromagnetic Environment at the Vicinity of Power Lines			X	
0753	Induced Disturbance Voltages in Isolated Conductors Situated in Close Vicinity of a Inducing High Voltage Cable Line			X	
0759	Operational Behavior of Electrical Equipment in Islanded Low Voltage Grids Concerning Safety Issues			X	
0760	Integrated Grounding, Equipotential Bonding and Lightning Protection in Smart Grids and Smart Buildings - a Multi-faced Approach	X			
0815	Magnetic Fields Management for Underground Cables Structures			X	
0818	Exposure of the French Population to 50 Hz Magnetic Fields: General Results and Impact of Electric Networks	X			
0823	Analysis of Distribution, High Voltage and Train Networks in the EXPERS Study			X	
0853	Effects on the Quality of Service of Changing the Neutral Grounding of MV Networks				S3
0972	A Survey of Magnetic Field Emissions for Typical HV and MV Equipments of a Distribution Network			X	
1141	EM Measurements and Mitigation Techniques on MV Installations			X	
1270	Electrical Safety in LVDC Distribution System		X		

Block 2 : Steady-state disturbances

This block gives a summary of the papers dealing with steady state disturbances, to which belong questions of voltage level, voltage flicker, harmonics and unbalance. In this year’s conference this block is definitely dominated by papers concerning harmonics. A few papers address flicker whereas unbalance isn’t in any paper’s scope.

Poor power quality is often coupled with low short circuit capacity. Several hundred weeks of power quality measurements at locations with known fault level were analysed by the authors of [B2-0031(CZ)]. The results indicate, that reference impedance as given in IEC 725 (corresponding to 570 kVA and 760 kVA fault level) does not guarantee compliance with EN50160 limits.

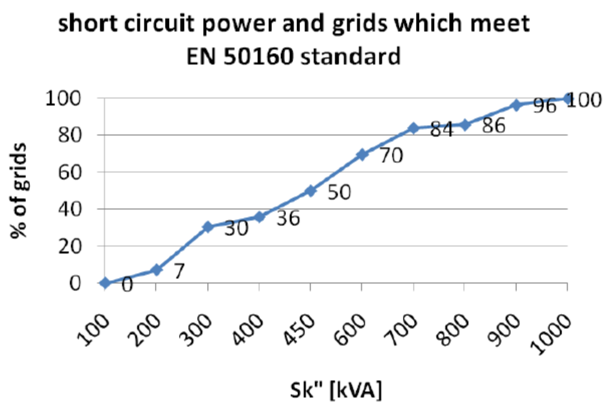

Figure 5: Number of LV networks with unsatisfactory voltage quality as function of fault level, cumulative probability function [B2-0031(CZ)]

Voltage level general

Conservation Voltage Reduction (CVR) may be one of the most cost-effective energy conservation measures that can be implemented. In [B2-1312(US)] the CVR factor as percentage reduction in load consumption divided by the corresponding percent reduction in voltage is introduced. For prediction of CVR effectiveness, accurate system models are necessary. A model structure was developed that can be applied across the different classes of customers to characterise the response to voltage variations. The models include consideration of the load vs. time impacts of the voltage variations as well as the demand impact so that the impacts on overall energy savings can be properly represented.

Paper [B2-0851(JP)] describes the use of step voltage regulators (auto transformer with on load tap changer) in medium voltage systems to cope with slow voltage variations due to photovoltaic infeed. Reverse power flow is taken into account. By simulation a compromise between smooth control using a small tap voltages and avoidance of too many switching operations was found.

[B2-0059(EG)] studies the impact of reactive power control at load level on the technical performances of MV feeders. The impact on the voltage drop, the losses and the feeder capacity are investigated.

[B2-0496(IT)] proposes a new probabilistic method to solve the capacitors and voltage series regulators allocation problem. The proposed method is based on the use of a Micro-Genetic Algorithm. Two different techniques based on the linearised form of the constraints of the probabilistic optimization model and on the Point Estimate Method were tested and compared to reduce the computational efforts.

[B2-0518(US)] presents an integrated (centralised) volt/var control (IVVC) solution that continuously analyses and controls capacitor banks, step-voltage regulators, load-tap changers, and reclosers in order to optimise the system voltage and power factor. The provided benefits are reduced generation requirements, reduced carbon footprint, continual (real-time) maintenance of unity power factor for all weather and load conditions, flat feeder voltage profile, conservation voltage reduction (CVR) to reduce demand during peak hours, immediate notification of a capacitor malfunction, remote switching/regulation of voltage regulators and capacitor banks, and real-time alarms for voltage threshold violations.

[B2-0747(CN)] analyses the impact of energy storage systems (battery based) on the distribution grid of a big city (such as Shanghai).

Impact of distributed generation (DG) on voltage level

The increasing amount of electricity generation from renewable sources, usually coupled to the public grid by inverters, raises some concern regarding power quality. Again, harmonic emission appears as one possible problem. The majority of papers deal with reactive power control respectively voltage control. Most authors agree that intelligent reactive power control significantly improves voltage levels.

[B2-0108(US)] and [B2-1130(BE)] deal with testing of inverters used for photovoltaic systems. The American paper discusses the test method according to IEC draft 61000-3-15 (Electromagnetic immunity and emission requirements for dispersed generation in LV networks) and some of the result, mainly concentrating on the effects that grid-tied inverters may have on power quality (emissions), and how inverters respond to less than ideal power quality of the grid itself (immunity). The behaviour of an inverter in response to dips, interruptions, voltage and frequency variations and harmonics is demonstrated exemplarily. The latter is investigated in particular by the authors of [B2-1130(BE)]. It is observed that the harmonic current response (magnitude and phase angle) of the converters depends strongly on the phase angle of the voltage harmonic that was added to the ideal grid voltage.

Continued improvement in the cost and efficiency of photovoltaic (PV) technology hints at a future in which utilities will need to accommodate high levels of randomly varying generation in distribution systems. High-penetration solar PV on a distribution system can result in objectionable fluctuations in feeder voltage. The voltage rise problem is indeed one of the challenges that could limit the integration of DG in the distribution grids. Many papers deal with this very topic and propose some solutions to increase the hosting capacity of the distribution grids. Most of these solutions rely on the possibility for DG to exchange reactive power with the grid, by adapting and configuring adequately their voltage control system. Other proposals discuss control possibilities implemented at the substation transformer level. Combinations of both are also investigated in the context of central voltage control systems. Finally, on-load tap changers (OLTC) are also suggested for MV/LV substations transformers.

A common solution is explained in [B2-0879(FR)] consisting in using reactive power capacities of generators, especially those with power electronics (e.g. PV), in order to minimise connection costs.

The aim of [B2-0806(DE)] is to evaluate the acceptable penetration limit of photovoltaic systems and also their possible interaction with EVs in urban residential areas. By generating reactive power through the inverters of the PV-generators (cos φ=0.95), the permissible PV-capacity can be increased by (40-50) %. Unfortunately in reality the already installed PV-capacity cannot be limited anymore and only pure active power generated by PV-systems is permissible, consequently, network extension is inevitable. Furthermore, in the future, the uncontrolled charge of the electric cars will lead to a much higher peak load. This can be avoided by shifting the charging time or using batteries, which could store the solar energy in the daytime and charge electric cars during the peak load time. Hence, not only the stress caused by the electric cars for the network can be decreased, but the acceptable PV-capacity rises as well.

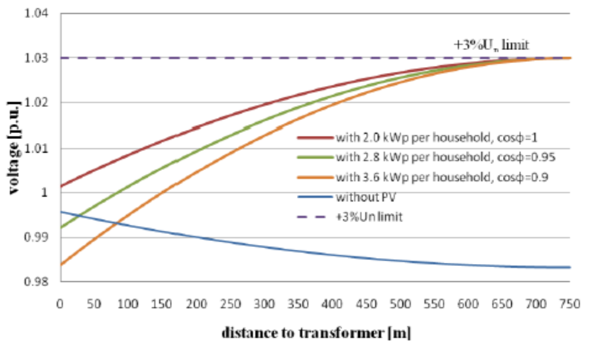

Figure 6 : Voltage rise along a LV feeder for various power factor at the PV inverter [B2-0806(DE)]

In [B2-0934(IT)], the proposed approach is also based on a modulation of reactive power injected/absorbed by the DG power plants; in particular the proposed control law is based only on local measures. The analysis indicates that the proposed local voltage control may increase the hosting capacity of existing networks regarding distributed generation. Moreover the proposed control strategy could minimise the reactive power flows on the distribution network limiting the consequent impact on active power losses.

The results show that, unlike what is usually expected, feeders with small voltage drop in passive condition do not always have high capacity for DG penetration. In case of overvoltage the reactive power absorption by generators allows significantly increased DG penetration itself. However, in some circumstances low power factor doesn't introduce benefits in term of HC because of thermal constraints. For this reason it is necessary to use a voltage control scheme that guarantees operation at variable power factor and absorbs reactive power according to the network response.

To mitigate the negative aspects usually associated with high penetration level of PV, highly distributed PV generation with Smart Grid features are described and implemented in [B2-1058(US)]. The advanced control of the PV micro-inverters is included where reactive power, ride-through capabilities and voltage regulation is available at the micro-inverter level. Therefore the concept of Generator Emulation Controls (GEC) is proposed. GEC is a control scheme under which grid-tied inverter-based is controlled to mimic the behaviour and inertial dynamics of synchronous machine-based generation.

The concept presented in [B2-1067(DE)] again uses reactive power which is generated by the solar power inverters to increase power capability and quality of the grid. Voltage fluctuations due to varying power input, e.g. caused by passing clouds, can also be reduced. Distributed data collection and central control is required for control of a distributed system of multiple solar inverters installed in a grid segment. The concept can be applied not only to PV systems; it is a rather basic technology which can be used in future grids with distributed generation and storage.

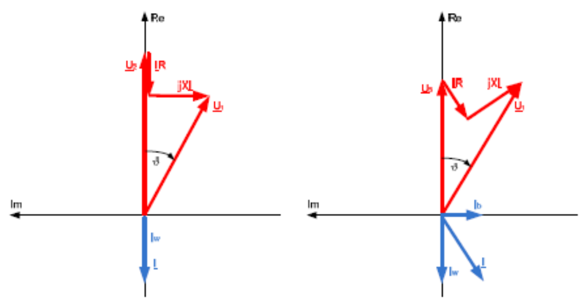

Figure 7 : Voltage drop at a line when feeding in active (left) as well as active and reactive power (right) [B2-1067(DE)]

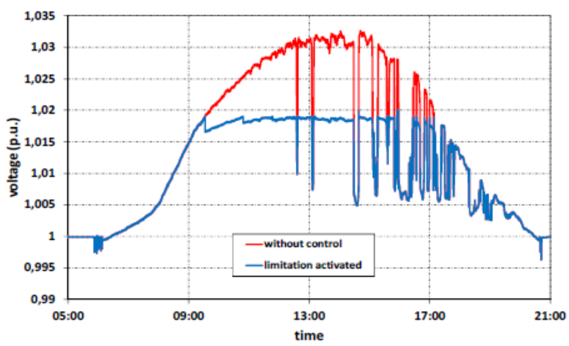

Figure 8 : Effect of reactive power control on the voltage profile over one day [B2-1067(DE)]

Similarly, it is shown in [B2-1203(US)] that if the PV inverters utilise so-called advanced volt-var control, the voltage variations caused by the solar PV ramping can be reduced. In some cases, an advanced control actually achieves improved overall voltage regulation at the customer and feeder level. It is possible to increase the hosting capacity of distribution systems without excessive voltage fluctuations if the appropriate control were to be built into PV inverters.

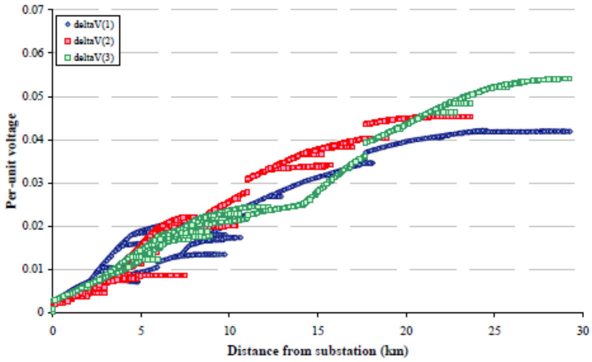

Figure 9 : Maximum Change (Rise) in Circuit MV Due to PV with Volt/Var Control [B2-1203(US)]

[B2-0933(CZ)] also deals with possibilities of reactive power regulation of PV power sources. This paper stresses pros and cons of some solutions. Moreover, the paper displays results of the simulation of transient phenomena when switching on of long cable lines which output power of PV fields into distribution network.

A control strategy for PV generators is developed in [B2-0953(CN)]. It takes the active current output from inverter and reactive current of the grid to compose the voltage set point in a PI regulation, achieving not only the maximum active power output but also the stability of system voltage in the situation of fluctuating reactive load. The scheme has obvious advantages compared to the traditional unity power factor control for grid-connected PV system.

In [B2-1243(DE)], general diagrams are shown concerning the maximum permissible connection power from distributed generators into low voltage radial distribution networks. Network short circuit power and network impedance angle at the end of the feeder turn out to be appropriate parameters for the diagrams. By using reactive power voltage control the maximum permissible PV power may be increased by a factor 1.5 up to more than 2. For higher penetration levels however other limits, like thermal limits of transformers and cables become applicable. While voltage control by reactive power is quite limited in long feeders, a controllable MV/LV transformer allows to connect 2.7 times more PV power to the network compared to the normal case. This would however require allowing a voltage change caused by PV power of more than 3%.

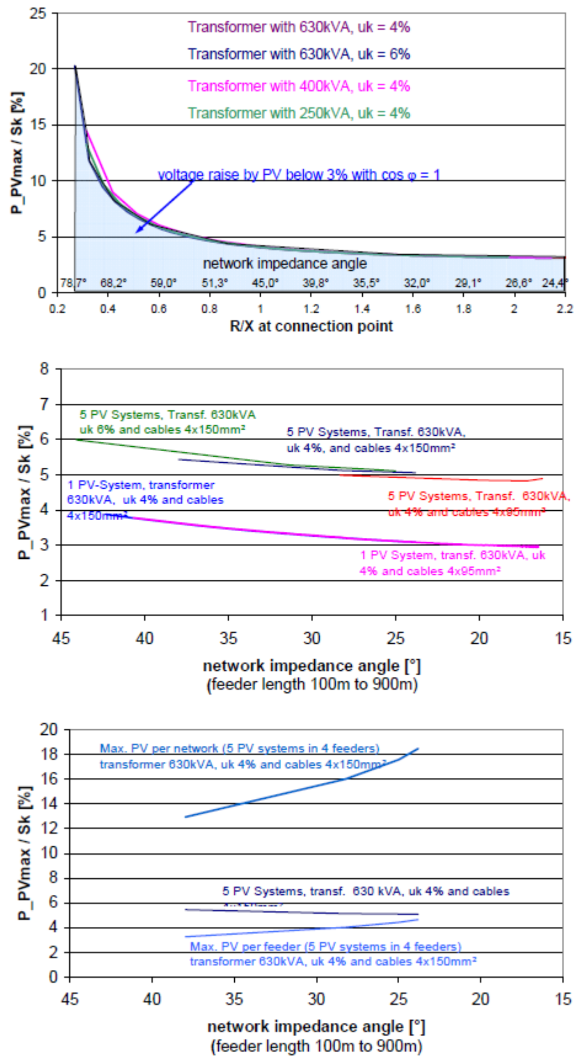

Figure 10 : Maximum permissible connection power as percentage of the short circuit power at the end of the feeder and as function of the network impedance angle [B2-1243(DE)]

[B2-0989(HR)] analyses the impact of a given wind park on the surrounding network. The analysis is made using load flow simulations and available measurements. It is concluded that the impact on the voltage profile in distribution network mainly depends on the reactive power control strategy. Constant power factor regime considerably increases voltage variations, while voltage control regime with PCC voltage regulation, significantly reduces voltage variations.

[B2-0171(FI)] discusses implementation of coordinated voltage control (CVC) as a part of distribution management system. Practical issues regarding the implementation are covered and the benefits compared to a separate CVC system are represented. Also an example case is presented which shows benefits of CVC compared to passive network management. The operation of the studied CVC method has also been demonstrated in a real distribution network.

[B2-0510(PT)] describes a centralised voltage control scheme to control the Automatic Voltage Control (AVC) relays set point. These relays control the On-Load Tap Changing Transformers. The controller, based on on-line state-estimation and constraint optimization, has been simulated in Matlab. The paper confirms that using AVC relays is possible, in some circumstances, to minimise the impact of the connected generation. Results also show that the use of the voltage controller can increase the DG that may be connected to a feeder as the voltage across the distribution network may be maintain within their technical limits.

Finally, [B2-0969(DE)] considers a new voltage regulation approach for LV feeders. The effects of changing the tap position of the MV/LV transformer are presented as well as the reactive power control by photovoltaic systems. By using an OLTC transformer in the MV/LV substation, the voltage of each subordinated LV feeder is influenced in the same way. This causes problems, if the load flow situation is unsymmetrical in the LV network. Also the required frequently change of the tap position, which results from the time dependency of the voltage, is problematical. In contrast to the MV/LV OLTC transformer the reactive power control by PV systems enables the autonomous variation of the voltage in LV feeders. The power factor can be set depending on the load flow situation of each feeder. In the worst case the considered voltage regulation methods are insufficient. Because of this other methods to regulate the voltage are necessary. In this context series controllers and other methods which are applied in the MV network have to be considered. Also the possibility to regulate the voltage by active power control has to be mentioned.

[B2-0693(CN)] introduces a power-electronic based component for distribution networks. The device serves as a universal interface between the distribution system and any user which may contain DG units and electric vehicles. The power electronic interface utilises the batteries inside the electric vehicles for energy storage as well as an energy buffer layer. Therefore, it can balance out the output power variation of the DG units. The control strategy and some simulation results are discussed in detail, together with some design considerations of a 50kVA prototype.

Harmonics in public grids

Several papers deal with harmonics in public networks. A review of harmonics and related problems is given in [B2-0061(EG)]. The authors address especially nonlinear single phase loads. Measurements of different household and office devices with distorted current are presented in [B2-0745(IR)] and [B2-1194(BA)]. Those devices are usually of low power. However, due to their large number they have a significant effect on voltage distortion.

A harmonic coupled Norton equivalent is introduced in [B2-1217(BR)]. Instead of constant harmonic current sources for modelling nonlinear loads the authors propose a complex approach taking into account the interaction between voltage distortion and current distortion of the load. A methodology for obtaining the parameters for this model by measurement is presented.

The effect of harmonic currents on transformer losses is described in [B2-0150(EG)]. In particular the influence on eddy current losses is presented. A theoretical case study for a 500 kVA transformer, supplying electronic loads (PCs), results in an inevitable derating down to 60% of nominal power.

The results of a harmonic disturbance survey on distribution level are given in [B2-0576(AR)]. Almost all harmonics did not exceed the limits except 15th and 21st harmonic. Due to the daily profile of these harmonics, the authors suspect energy saving lamps as possible reason. Nevertheless it should be discussed whether the violation of extreme low limits (0.3% respectively 0.2%) is to cause concern.

[B2-0069(GB)] recommends a closer look on existing levels of harmonics during network planning process. Utilization of installed capacity increases slower than harmonic levels, thus leaving not enough THD headroom between existing levels and limits.

The general ambition of the European Union to reduce primary energy consumption should be supported by the 'Eco-Design-Directive'. Amongst others, this directive enforces the stepwise replacement of incandescent lamps by promoted alternative energy saving lamps. The following papers investigate the influence of increasing number of new lighting devices in the grid. In [B2-0172(SE)] measurement results of the harmonic emission performed at a medium-sized hotel before and after the replacement of all incandescent lamps with compact fluorescent lamps (CFL) and LED lamps are given. It is shown that the increase of emission due to the replacement of incandescent lamps by energy saving lamps is not as large as would be expected from the heavy-distorted waveform of individual lamps. It is also important to quantify the load using parameters that have a direct relation with the impact on the power system. Power factor and total harmonic distortion in percent are not seen as suitable indicators for this.

70 different CFLs of different type and additionally 30 CFLs of the same type were analysed with regard to the current harmonics by the authors of [B2-0275(AT)]

under sinusoidal and distorted supply voltage. In Figure 11 the amplitude and phase angle range of harmonic currents is shown. The results are used to validate a simple time domain model for CFLs. In a case study a LV grid was simulated and the impact of CFLs on voltage distortion analysed. Taking into account the pre-existing distortion, an increase of 3rd, 7th, 9th and 11th harmonics and a decrease of 5th harmonic voltage is expected.

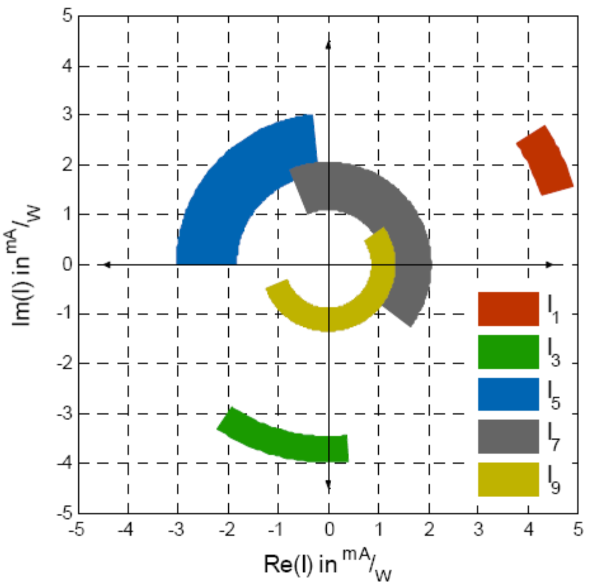

Figure 11 : Band width of harmonic currents of 70 CFLs expressed in real and imaginary part – sinusoidal supply [B2-0275(AT)]

The results of simulations and measurements in [B2-0755(DE)] show that impact of modern lamp technologies to the voltage distortion is a complex issue and no really consistent conclusion can be drawn up to now. Harmonic current cancellation effects play a decisive role for voltage distortion cannot be neglected for realistic simulations. A decrease of 5th harmonic voltage in a studied case is demonstrated. Since this effect depends on the pre distortion in voltage this decrease can not be generalised.

Measurements at wind parks connected via full power converter, performed by the authors of [B2-0251(SE)], show that the harmonic emission from those devices is small but the interharmonic emission is rather high. The harmonic groups and interharmonic groups were recorded each 10 minutes according to IEC 61000-4-7. The interharmonic content determines requirements for minimum fault level to keep the voltage distortion below given limits. 95 % values of current harmonics for a 2 MW / 32 kV wind power installation with converter are given in Figure 12.

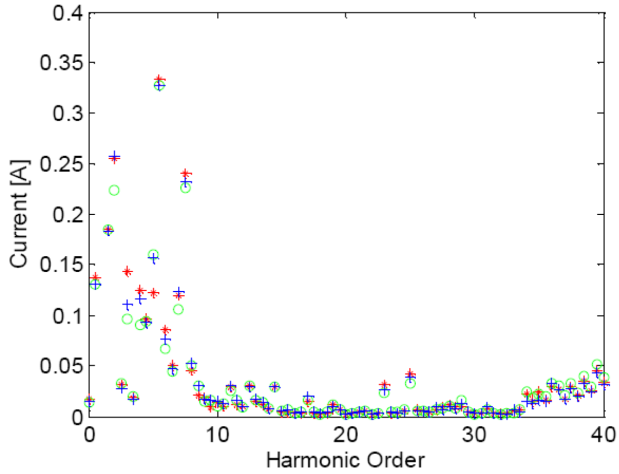

Figure 12 : Spectrum of current for 2 MW wind power installation; 95% values of the harmonic and interharmonic groups (10 min values) [B2-0251(SE)]

The authors of [B20582(CN)] analysed the emission of harmonics arising from wind parks. For a practical case study they conclude that a large share of emitted harmonic currents is absorbed by local capacity banks and cable capacity.

Harmonics in industrial environment

Due to the variety of devices with high power and non ideal characteristics (non linear, fluctuating, unbalanced), power quality in industrial environment usually means a challenge for power system engineers.

The authors of [B2-0403(CN)] present in their paper power quality measurement in steel plants. Voltage and current harmonics emerged as the critical parameter. Harmonic current limits are adjusted according the ratio of the actual short circuit capacity to the reference short circuit capacity. The installation of filters reduced the harmonic voltages significantly below limits.

Determination of harmonic emission according to IEC 61000-3-6 can be challenging. In [B2-0556(SI/AT)] a method which determines harmonic emissions based on current and voltage phasor measurements is compared with the "conventional" way, by simply multiplying magnitudes of harmonic current with reference network harmonic impedance. Both methods are applied to recorded voltage and current waveforms of steel plants. In general both methods provide feasible results, correlating with plant's operating cycles and reflecting the daily harmonic variation from the utility side.

However, particular the results diverge with the cause still under investigation.

Voltage notches due to commutation in rectifiers can have a significant effect on input current of non linear devices. Measurements in [B2-0580(NL)] demonstrate the interaction between a DC drive producing voltage notches and discharge lamps with electromagnetic ballasts and parallel compensation. An increase of higher order harmonic currents by a factor of 10 has been observed for certain operational modes of the DC drive (Figure 13).This phenomenon was also reproduced in laboratory experiments.

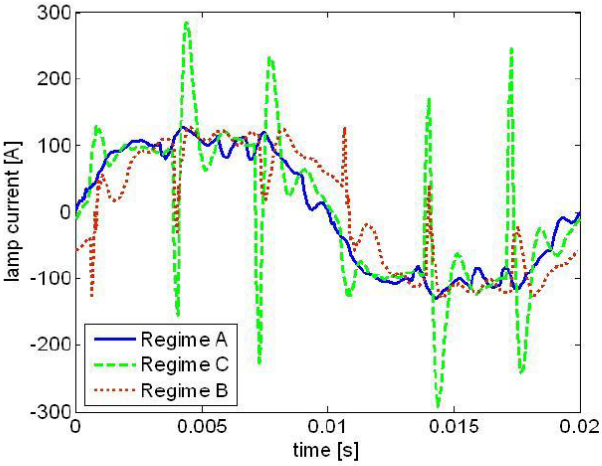

Figure 13 : Current of lamps in phase 1 with different regimes of the DC drive [B2-0580(NL)]

High frequency emission

Harmonic studies in almost all cases are limited to the frequency range up to 2 or 2.5 kHz. In the frequency range above 2 kHz, almost no standards exist and measurements are rare. In [B2-0173(SE)] the authors present measurement results from a full-scale electrical laboratory model of a domestic installation and from field measurements in a hotel. For different scenarios of used lighting equipment the emission between 2 and 150 kHz is analysed. Modern energy saving lighting can emit high frequency currents which seem to flow rather between equipment than towards the grid. High frequency currents shunted by small end-user equipment are rather a threat to the function of equipment within the own installation than to other installations.

A simple model for interaction at high frequencies of some tens of kHz between equipment with active power-factor-correction is provided by the authors of [B2-0206(SE/FR)]. The emitting device is modelled as a high frequency current source and a shunt capacitor. Since impedance in LV grids is dominated by the ohmic part, a simple resistance is chosen as grid equivalent. The current of the emitting device consists of two components: the part of the current driven by the device itself ("primary emission") and the part of the current driven by other devices ("secondary emission"). The emission of a total installation is inversely proportional to the square-root of the number of devices for higher frequencies and proportional to the square-root of the number of devices for low frequency.

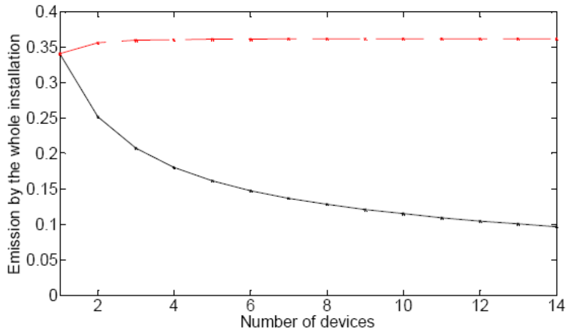

Figure 14 : Emission by a complete installation as a function of the number of devices in the installation; highest amplitude in time domain (top); value in frequency domain (bottom) [B2-0206(SE/FR)]

Measurements shown in [B2-250(SE)] indicate two types of emission by fluorescent lamps with electronic ballast, in frequency range between 2 and 150 kHz: recurrent oscillations (a few kHz) and high frequency components generated by the active PFC (some tens of kHz). The recurrent oscillations increase in amplitude with the number of lamps turned on since the oscillations from each lamp are synchronised with the fundamental. The high frequency part generated by the active PFC does not add in the same way as the recurrent oscillation and decreases fast with increasing number of lamps.

Harmonic filters

Application of different filter designs, using passive, active and hybrid filter, to eliminate harmonics and avoid unwanted resonance are presented in [B2-0090(EG)]. The use of detuned filter banks (combined ant resonant filters) is demonstrated in [B2-0911(RS)] as efficient measure to reduce harmonics and improve power factor.

In harmonic simulation studies the use of simplified grid equivalents is often necessary. To solve the problem of determining the rational approximation of a (measured) harmonic grid impedance, an evolutionary algorithm based technique is proposed in [B2-1208(BR)]

Impact of electric vehicles (EV) on voltage quality

Advances in the development of EVs, along with policy incentives, will see a wider uptake of this technology in the transport sector in future years. However, large penetrations of EVs could lead to adverse effects on power systems, especially at the residential distribution network level. The major possible issues related to the connection of EVs to LV distribution grids are the voltage drop, the injected harmonics and the possible unbalance. Thermal loading of some network components could also be an issue.

A stochastic method is developed in [B2-1158(IE/US)] to take account of the uncertainties associated with EV charging. Although the results indicate that the network limits are rarely exceeded in the considered examples, this may not be the case for other LV networks. If the typical connection time for EVs coincided more with the existing residential load peaks, occurrences of under-voltage and high cable loading could increase significantly. It would also be beneficial to monitor the allocation of EVs across the 3 phases of the network for each simulation. Due to the unbalanced characteristics of LV networks, an uneven allocation of EVs on one of the 3 phases may increase the voltage drop on that phase.

[B2-0126(DE)] also investigates to what extent the current grid can cope with area-wide deployment of electrical vehicles and renewable energies. It is also investigated at what point additional measures, such as grid reinforcement or load management systems (LMS) are necessary for stable operation. To show the effectiveness of the developed methodology a German low voltage grid was investigated. The analysis showed that this grid has significant excess capacity and therefore is capable to provide the necessary infrastructure needed for an area-wide outlay of renewable energies and electric vehicles. In other grids problems might be more severe. However, local accumulations may lead to under-voltage situations already by 2020. Hence, two load management concepts were introduced. They balance the grid load and reduce over- and under-voltage situations even with local accumulations of electric vehicles.

The impact on harmonics is analysed in details in [B2-0583(CN)]. In that perspective, when an EV charging station is constructed, the effect on the power quality should be fully considered for equipment selection, planning design and maintenance. Under the same working condition, the harmonic current injected into the grid by uncontrollable rectifiers is obviously higher than the one produced by rectifiers with PWM control principle.

The authors of [B2-0167(GB)] took measurements while a battery charger was used to charge a battery pack. It was observed that total harmonic distortion in current (THD_i) for a single charger increased from 44% to 55.3%. Based on these measurements, a simulation model was build, reflecting different degrees of penetration levels of electro vehicles in households. It seems that the authors assumed worst case conditions and did not take into account phase angle variations.

Load patterns for a car pool of 15 EVs are analysed in [B2-0785(NO)]. In the case of a rather strong urban distribution network, the values of voltage THD were less than 2% which is well below the PQ code limits. The values for current THD were higher, at most 6.8%. A problem that can arise is unbalance as the chargers use single phase circuits. At times there was a significant unbalance in the supply voltage. This unbalance was within the limits of the PQ code, but unbalance can cause problems if electric vehicles get more common. The DSOs should consider voltage unbalance as a consequence of a large influx of EVs and do measures to reduce the impact of charging on the grid. It should be emphasised that the charging stations that were investigated are located in the city centre of Trondheim where the grid connection is strong. In rural areas with weak grids, installation of many charging stations may cause quality problems. With the expected increase of EVs over the next decades, fast charging stations will be established. Several market participants are looking into fast charging as a business concept. This development will give much higher charging powers with more severe consequences than reported in this study.

Measurement of power quality parameters

The use of wavelet transforms as alternative method in power quality measurement is proposed in papers. In [B2-0143(EG)] the authors apply wavelet transform to flicker analysis. In [B2-0695(EG)] wavelet transform is used for transient harmonic analysis during dips. However, wavelet analysis turns out to be well suited for transients and single events but not for long term monitoring of continuous power quality parameters. In neither of the papers new parameters describing the harmonics or flicker characteristics are proposed.

A method for determination of optimal placement of power quality monitoring devices for ideal harmonic estimation is presented in [B2-1220(BR)]. Simulation studies applied to IEEE 14 bus system show good results of the method

HV and MV potential transformers (PT) usually have a limited frequency range in which the transfer function is ideal. In [B2-0917(DE)] an automated measurement of transfer characteristic of HV-PT up to 5 kHz is presented. Tests showed that testing with harmonic signals only, without fundamental introduces no significant error. Generally, the critical frequency up to which accurate measurements are possible decreases with voltage level. Even for PTs with same primary voltage the critical frequency can vary in wide range due to different design. Typical values for MV-PTs are between 600Hz and 3500Hz whereas results for 110kV PTs are between 400Hz-1000Hz.

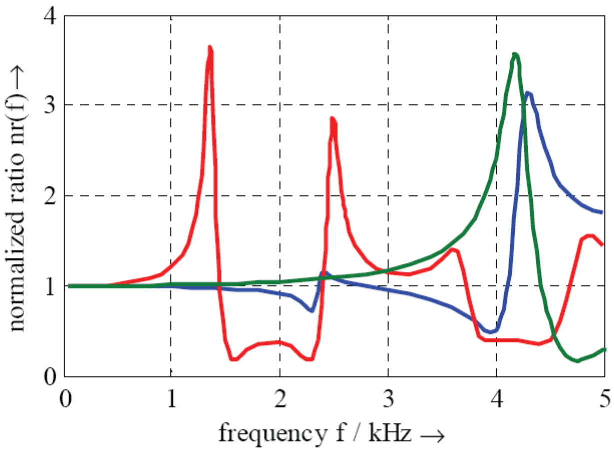

Figure 15 : Normalised transformer ratio for 66 kV PT (green), 110 kV PT (blue) and 220 kV PT (red) [B2-0917(DE)]

[B2-0822(CH)] focuses on the applications of low power current and voltage sensors, such as the optimization of switchgear in dimensions, weight and costs, power measurement in a compressor test field and new possible applications such as DC measurement or Power Quality Measurement. One of the requirements to low power ITs is that the behaviour over a certain frequency range is comparable with the behaviour of the conventional inductive CTs and VTs. Measurements on LPVTs and LPCTs confirmed that they are basically suitable to detect the parameters up to the required 50th harmonic. It can be seen from Figure 16 and Figure 17 that good frequency behaviour can be expected up to several tens of Kilohertz for LPCTs and several thousand of Hertz for the LPVTs.

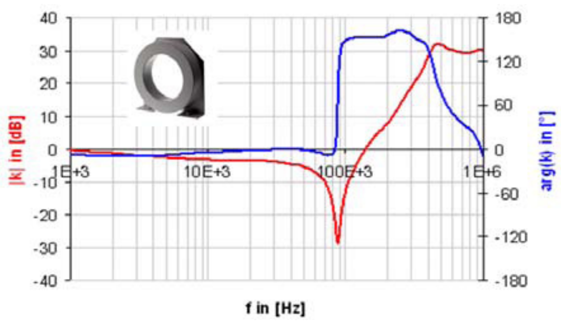

Figure 16 : Typical frequency response behaviour of a low power current transformer [B2-0822(CH)]

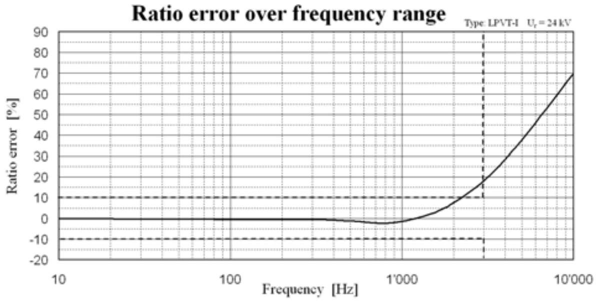

Figure 17 : Typical frequency response behaviour of a low power voltage transformer [B2-0822(CH)]

In [B2-0513(AR)] indirect measurement of voltage flicker and harmonics via the electric field are presented. This technique can be used at locations not equipped with PTs. Good results were achieved in laboratory tests with single phase arrangements. First field tests are so far promising. However problems are expected by the authors in case of zero sequence system harmonics.

12 different power quality meters were tested for accuracy in flicker measurement by the authors of [B2-0682(CZ)]. Tests were performed using recorded real flicker signals and synthetic signals including signalling voltage and harmonics. One instrument failed clearly, for the others the difference between maximum and minimum reading was between 9...63% for real signals. Since the deviation in case of IEC test signals was within 5%, the relevance of those test signals is questionable.

In [B2-0964(DE)] the determination of the grid harmonic impedances in LV four-wire systems is examined. In order to determine first the open circuit, grid voltage is measured. Then a resistive load is switched with a random-pulse-width-modulation (RPWM) while measuring the voltage and the current in the load (Figure 18). Finally all measured voltages and currents are transformed into the frequency domain using FFT-algorithms. The frequency dependent grid impedance is calculated as quotients of the complex voltages and currents of the same frequency.

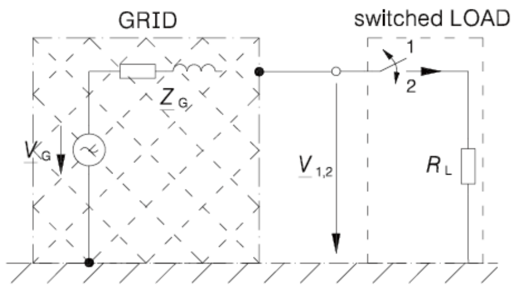

Figure 18 : General measurement setup for harmonic impedance measurement [B2-0964(DE)]

Measurements in a laboratory setup using an ideal voltage source and a standard impedance are presented. Not only the line impedances are identified but also the impedance of the neutral line is explicitly determined.

For future smart grid applications the communication via power line carrier (PLC) has increasing relevance.

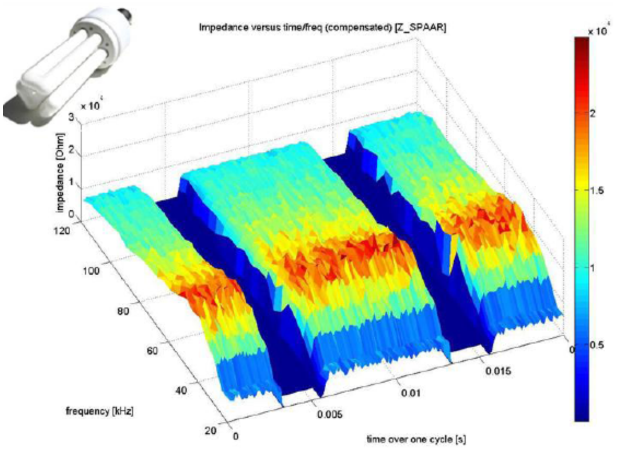

Figure 19: Periodic Impedance of an Energy saving light bulb [B2-1172(BE)]

[B2-0878(FI)] and [B2-1172(BE)] present measurement instruments to monitor and analyse PLC signals and disturbing noise in the range of 3 kHz to 95 kHz.

Typical applications of these measurement instruments are signal analysis in time and frequency domain, measurement of impedance behaviour (periodic variations) and analysing signal propagation in different grid topologies.

Further research topics

A change regarding electric lighting systems is in progress. Several papers reported about the influence on harmonics. What will be the consequence for flicker? Is it possible to define a generic behaviour for LED-lamps and CFL to define a new flickermeter design or new flicker limits?

How should wide area power quality surveys be conducted? Which methods are used for determining the trade-off between minimum number of instruments and achieved accuracy? Is a statistical approach reasonable?

Papers of Block 2 (B2)

Paper No.	Title	MS a.m.	RIF	PS	Other Sess.
0031	Minimum Short Circuit Power in the LV Distribution Network to Meet EN 50160 Standard Requirements	X			
0059	Experimental Simulation to Evaluate the Impact of Reactive Power Control on Distribution Networks Voltage and Energy				S4
0061	Effect of Single-Phase, Non-Linear Loads, as Sources of Harmonic Currents in Low Voltage Electrical Distribution Systems			X	
0069	Allocation of Harmonic Distortion Margins at Point of Common Coupling			X	
0090	Damping Techniques of Harmonic Resonances in Power Distribution Systems			X	
0108	Solar Inverter Testing per IEC TR 61000-3-15			X	
0126	Impacts of Electric Mobility on Distribution Grids and Possible Solution through Load Management				S5
0143	Application of Continuous & Discrete Wavelet Transform for Study of Voltage Flicker-Generated Signal			X	
0150	Effect of Types of Loads in Rating of Transformer Supplying Harmonic-Rich Loads			X	

0167	Power Quality Analysis of Distribution Systems Incorporating High Penetration Level of EV Battery Chargers			X	
0171	Coordinated Voltage Control as a Part of Distribution Management System				S4
0172	Laboratory and Field Measurements of Harmonic Emission from Energy-Efficient Lamps			X	
0173	Total Conducted Emission from a Customer in the Frequency Range 2 to 150 kHz with Different Types of Lighting	X			
0206	A Simple Model for Interaction between Equipment at a Frequency of some Tens of kHz.		X		
0250	Emission (2 to 150 kHz) from a Light Installation			X	
0251	Characteristic and Non-Characteristic Harmonics from Windparks			X	
0275	Characteristics of the Input Current of Energy Saving Lamps and their Impact on Power Quality	X			
0403	The Effect of Sensitive Consumers on Power Quality in 35KV Power System and Countermeasures			X	
0496	A Probabilistic Approach for Voltage Regulators and Capacitor Placement in Three-Phase Unbalanced Distribution Systems				S5
0510	The Application of Distribution State Estimation to Support a Real-Time Voltage Control Algorithm: A path to Increase the Integration of Distributed Generation				S4
0513	Perturbation Measurements on Overhead Networks Using Electric Field Sensors		X		
0518	Volt/Var Control for Smart Grid Solutions				S4
0556	Determination of Harmonic Emission of an Industrial Installation			X	
0576	Harmonic Disturbances Survey in Distribution Networks			X	
0580	Analysis of Harmonic Current Interaction in an Industrial Plant	X			
0582	Evaluation on the Effect of the Integration of Offshore Wind Farms on Power Quality			X	
0583	Analysis of the Effect of Shanghai EXPO Electric Vehicle Charging Station on Urban Grid Power Quality				S4
0682	Results of Several Flickermeters Comparison			X	
0693	A Universal Power Electronic Interface for Distributed Generation and Electric Vehicles				S1
0695	Harmonic Analysis of Actual Power Quality Problems: Wavelet Transform Vs. Fourier Transform			X	
0745	Analysis of Harmonic Distortion in Distribution Networks Injected by Nonlinear Loads			X	
0747	Research on the Application of Multiple Energy Storage System in Shangai Power Grid				S4
0755	Harmonic Summation Effects of Modern Lamp Technologies and Small Electronic Household Equipment	X			
0785	Integration of Electric Vehicles to the Distribution Grid				S5

0806	Impact of an Increasing Penetration of Urban Photovoltaic Systems and Electric Cars on the Low Voltage Networks				S4
0822	Applications of Low Power Current and Voltage Sensors				S1
0851	Problems of SVR Operation in Large Penetration of Photovoltaic Power Generation and Proposal of Improved Operation			X	
0878	Development of DSP Based Instrument for Monitoring PLC and Other High Frequency Signals in Distribution Networks			X	
0879	PV development in France : Impact on Distribution Network and Potential of Innovative Solutions				S4
0911	Power Factor and Harmonic Distortion Correction of Consumers by Combination of Detuned Filters			X	
0917	Accuracy of Harmonic Voltage Measurements in the Frequency Range up to 5kHz Using Conventional Instrument Transformers			X	
0933	Integration of Large Photovoltaic Power Plants to Distribution Networks				S4
0934	MV Networks with Dispersed Generation: Voltage Regulation Based on Local Controllers				S4
0953	A Grid-Connection Control Scheme of PV System with Fluctuant Reactive Load				S3
0964	Grid Impedance Determination - Identification of Neutral Line Impedance				S4
0969	Analysis of Various Voltage Control Methods for Low Voltage Networks with Distributed Generators				S4
0989	Voltage Profile Analysis in 30 kV Network after Connection of Wind Power Plant				S4
1058	Distribution Network Impacts of High Penetration of Distributed Photovoltaic Systems				S4
1067	Increasing Grid Transmission Capacity and Power Quality by a new Solar Inverter Concept in Low Voltage Grids with a high Proportion of Distributed Power Plants				S4
1130	Harmonic Behavior of two Commercial PV Converters under Distorted Voltages			X	
1158	Stochastic Analysis of the Impact of Electric Vehicles on Distribution Networks				S5
1172	A Power Line Communication measuring toolbox for the distribution grid	X			
1194	Power Quality Degradation Due to Low Power Electronic Loads			X	
1203	Simulation of Solar Generation with Advanced Volt-Var Control				S4
1208	An Evolutionary Algorithm Based Technique to Determine Rational Approximation of Frequency Domain Responses			X	
1217	A Novel Technique for Modeling Aggregated Harmonic-Producing Loads			X	
1220	Harmonic State Estimation through Optimal Power Quality Monitoring			X	
1243	Increasing the Photovoltaic-System Hosting Capacity of Low Voltage Distribution Networks				S4
1312	Load Models for Voltage Optimization			X	

Block 3: Disturbing events

Power Quality Monitoring

Power quality indices and permanent power quality monitoring are essential to benchmark distribution networks and to verify the supply quality with respect to standards. The integration, the management and the results of a power quality monitoring program are discussed in 9 papers. In [B3-0868(HR)] the integration process of a constant online monitoring system starting in 2009 in Croatia with the focus of the maximal use of the existing infrastructure to reduce the costs is discussed. The evolution of the Shanghai online PQ monitoring and management system since 2006 is described in [B3-0421(CN)]. Currently 305 monitoring points are effective. Current monitoring programs require large data storage capacity. In [B3-0882(CZ)], new data modelling algorithms are compared with plain data compression. Storage space savings between 5% and 15% are reported. The PQ monitoring in a German municipal power grid based on 60 monitors is described in [B3-0417(DE)]. The approach of a Romanian TSO is presented in [B3-1294(RO)]. Interesting here is the educational program for their personnel to support the correct use and interpretation of the monitoring system results. The state-of-the-art of the monitoring within Portugal is found in [B3-1021(PT)] (Figure 20). Due to the rural nature of the country, 80% of the network is overhead type. From the measurement results, improvement actions are reported with respect to voltage variations (transformer tap changes), flicker (busbar topology changes) and harmonics. Also, sensitive customers are invited to report PQ disturbances. Typically the customers report production disturbances due to voltage dips.

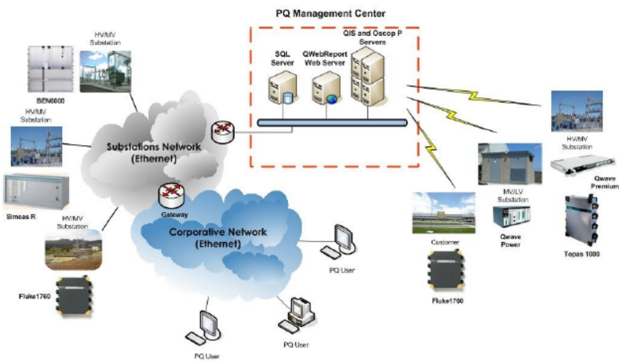

Figure 20: Power Quality monitoring platform [B3-1021(PT)].

Experiences on power quality monitoring in Norway related to smart grids are reported in [B3-0942(NO)]. Interesting is the use of a second harmonic in the phase to phase voltages to eliminate false voltage dip readings due to voltage measurement transformer saturation,

Disturbing events

Power quality characterization of disturbing events is discussed in two papers. [B3-1314(BR)] starts with an overview of the state of the art in characterization and classification of PQ disturbances. Afterwards, software tools for recognition of similar disturbances in a waveform database based on wavelet techniques are presented. The waveforms are captured with 128 samples/cycle and a total of 30 cycles per event. In [B3-1151(ES)] voltage disturbances resulting from animal/tree contacts, cable failure and broken insulators (external causes) in the northeast of Spain are dealt with (Figure 21). From the recorded voltage/current waveforms useful patterns to distinguish between the different external causes are extracted. The analysis is based on several features such as voltage dip magnitude, maximum neutral current and fault impedance. Finally the results are compared with data from the USA. The USA data is collected in the Northeast at overhead and underground cable distribution networks.

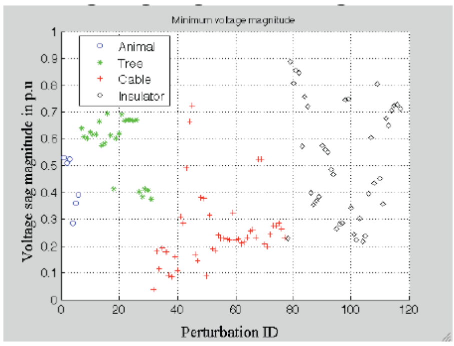

Figure 21: Voltage dip magnitude due to animal/tree contacts, cable failure and broken insulators [B3-1151(ES)]

The reliability indices for a power system in Egypt are analysed in [B3-0191(EG)]. To improve reliability to customers, two main plans are presented: minimise the effect of faults by using more protective devices, faster reclosing and improved coordination and minimise faults by using better equipment replacement programs, better maintenance and better arrester applications. In [B3-0748(CZ)] measurements over a period of three years in the Czech Republic are reported. For voltage unbalance and harmonics only marginal changes over the years are detected. For flicker however a clear increase is noticed

Voltage dips

Voltage dip monitoring is essential for characterizing and predicting of the performance of the distribution network. An acceptable trade-off between the number of monitors installed and the accuracy of the monitoring results is crucial. In [B3-0529(GB)] a method for cost-effective voltage dip monitoring is presented. The aim is both to minimise the number of monitors installed and to minimise the dip estimation error at non-monitored buses for pre-specified dip characteristics (for example dip characteristics relevant to a certain customer). The results show that the method is highly immune to the fault resistance and fault location changes and is shown to be more robust than other methods.

In [B3-1216(BR)] another methodology for the optimal allocation of PQ monitors for voltage dips and also voltage swells is presented. The minimum number of monitors is reached by installing them in the strategic buses. Identification of the strategic buses is based on the construction of an observability matrix and the use of a genetic algorithm. This allows the complete observation of the system with a minimum of monitors.

[B3-0587(CN)] addresses voltage dip frequency assessment starting from the customer satisfaction degree (CSD). The authors define CSD as the percentage between equipment normal operation time and total operation time (Figure 22, Table 4). Starting from this CSD the fault area resulting in customer dissatisfaction and customer uncertainty region is determined in an analytical way. The proposed analytical approach results in a reduced number of iterations to obtain critical fault points

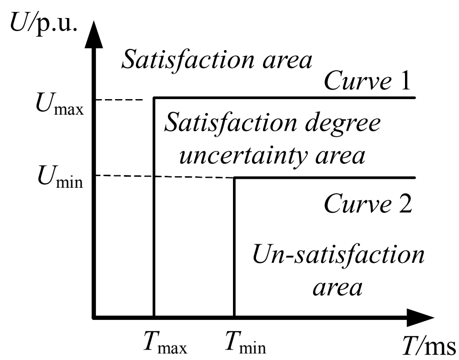

Figure 22: Uncertainty region of load satisfaction [B3-0587(CN)]

Table 4: The uncertain ranges of sensitive equipment [B3-0587(CN)]

Equipment types	U_{min}(%)	U_{max}(%)	T_{min}(ms)	T_{max}(ms)
PLC	30	90	20	400
ASD	59	71	15	175
PC	46	63	40	205

In [B3-0500(CO)] voltage dip information of the city of Bogota is analysed by means of contour charts (method suggested by the C4.110 CIGRE – CIRED working group in 2010). The actual measurement data is decomposed and reconstructed by means of wavelet functions. A software application is presented to implement the methodology and to produce the contour charts.

In [B3-0553(NG)] the occurrence of outages in four Nigerian cities based on ten years of data is studied. A model was constructed to predict outages two years ahead. According to the authors, the prediction accuracy is 95%.

Voltage dip performance assessment of the Italian MV network, based on 5 years of monitoring, is reported in [B3-0886(IT)]. Voltage dip indices are used to analyse trends at national level, macro area level and regional level. Remarkable consistent territorial differences especially were revealed. It is also reported that the dip values assumed by an index depend on whether the calculation is referred to immunity class 2 or class 3 equipment curves. The use of a normalization procedure is suggested to overcome the dependence of the voltage dip index on the class 2 or 3 curves.

A Voltage dip source detection method based on S-Transform time-frequency representation in presented in [B3-0109(MY)]. The proposed method is benchmarked against existing methods for dip source detection. For the 237 samples taken into consideration, the new method scored 100% in identifying the source being located either upstream or downstream of the monitoring point. Especially for upstream source locations, this method seems to be more reliable compared with existing methods.

Transformer inrush currents and the associated voltage dips have been well addressed in the past. [B3-0657(GB)] contributes by analysing the voltage dips that appeared during the simultaneous energization of two transformers and the sympathic interaction between transformers (Figure 23). The analysed system (simulation and field measurement) has a low short-circuit fault level which contributed to the sympathic interaction.

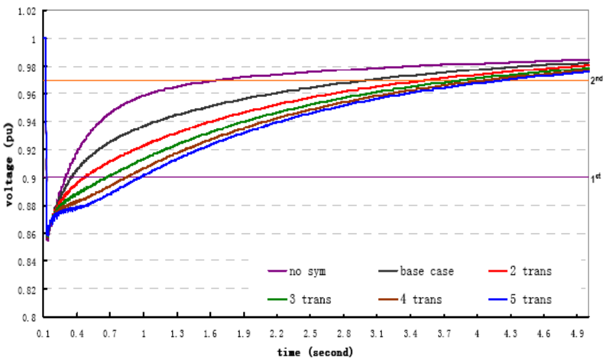

Figure 23: Impact of the number of already energised transformers on the magnitude and recovery of voltage dips [B3-0657(GB)]

Voltage Swells

[B3-0946(NO/DE)] is the only paper reporting on the impact of voltage swells. Laboratory test of 60 commercial appliances are described. Similar measurements were reported in the CIRED 2009 conference. For the new test the maximum overvoltage duration is increased for 100 seconds to 30 minutes and the maximum voltage from 320V to 400V. The results show that electrical appliances in general have a high level of rms overvoltage immunity. As the tested equipment is typically moderate cost to low cost equipment, it is concluded that assuring overvoltage immunity of all electronic equipment might not be very costly and should be considered.

Improving PQ through control

The impact of extended switching reclosing time on the interruptions in distribution networks is addressed in [B3-0700(IT)].Through simulations it is shown that the number of self-extinguishing faults is increased by increasing the reclosing time especially in transient double phase faults (Table 5). For DSO's this can result in a reduction of interruptions due to transient faults. It is stated that the impact of the increased reclosing time on the severity of voltage dips is minimal since the equipment is already susceptible for shorter voltage dips.

Table 5: Reduction of transient faults with enlargement of reclosing time delay [B3-0700(IT)]

	% of reignitions Single Phase fault		% of reignitions Double Phase Fault
Reclosing Time delay	Fault in free air Isolated Neutral	Fault inside of MV cell	Fault inside of MV cell
0.4s Ref. case	0.03%	33.5%	83.75%
0.5 s	0.01%	9.56%	63.76%
0.6 s	-	1.40%	56.71%
0.7 s	-	0.12%	43.60%
0.8 s	-	0.08%	42.45%

Power electronics solution for Power Quality enhancement

Three papers deal with flicker control. The flicker originates from welding applications, electric arc furnaces or from intermittent distributed generation sources such as fixed-speed wind turbines.

In [B3-0213(AU)] a case study presents a hybrid VAR compensator for the flicker control of a welding plant. The welding process and the compensation are modelled in ATP software. The level of P_{st} calculated at the 22kV bus before compensation was 1.1. After activation of the compensation, calculations predict this value to be reduced to 0.35.

In [B3-0337(SE/CA)] a static compensator (STATCOM) is installed at a steel plant in Thailand for reducing the flicker. The compensator comprises a voltage source converter (VSC) and two harmonic filters (Figure 24). A flicker reduction > 5 is reported and the flicker demands at the 115 kV point of common coupling are met. Furthermore, the installation of the STATCOM also resulted in a lower harmonic distortion and a high and constant power factor of the system.

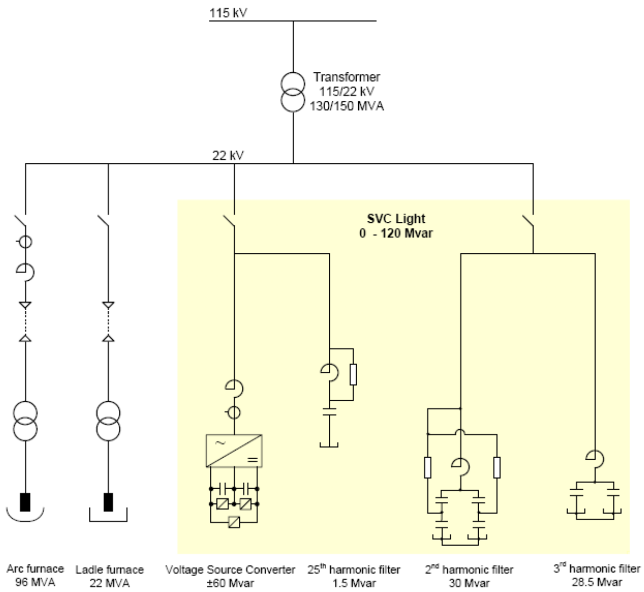

Figure 24: Single-line diagram of SVC Light Statcom and arc furnaces [B3-0337(SE/CA)]

The use of the grid-side voltage source converter of a distributed generation to improve power quality is discussed in [B3-1139(GB)] and [B3-0676(ES)]. In [B3-1139(GB)] flicker mitigation is addressed. The proposed controller is based on the concept of "Local Controllable Zones" (LCZ, Figure 25). The network is split in LCZs. The V/Q sensitivity between buses in the network is calculated to identify the LCZ. Each zone consists of DG and other autonomous controllable devices that can provide voltage control to all buses located within that zone.

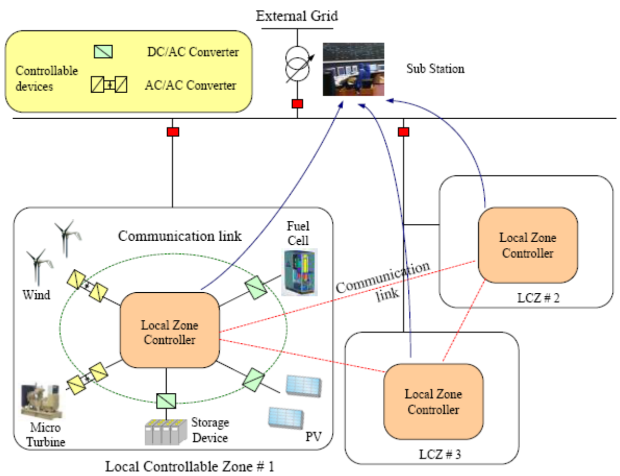

Figure 25: Decentralised control structure in a distributed generation network with Local Zone Controller [B3-1139(GB)]

Simulation results show that the use of a DG unit to control the flicker at a remote bus within the LCZ is effective and additional local compensation equipment may not be required.

In [B3-552(SE)] a dynamic VAR compensator of a mine hoist is presented. The design procedure was presented at CIRED 2009. Now the results of 1 year operation are discussed. The summary of the results of measurements at the 6.3 kV bus are presented in Table 6 below. It is concluded that the contractual requirements regarding the performance of the compensator are met and that the hoisting capacity has been increased by 30%.

Table 6: Result summary for a 6,3 kV busbar for a mine hoist application [B3-552(SE)]

Parameter	Limit	Result
Flicker	1,0	0,9
Max. voltage variations	3%	3%
Power factor	0,98	0,998
Voltage distortion UTHD	4,8%	3,2%
Individual voltage distortion, odd harmonics	<60% of compatibility limits acc. to EN 50160	< Limit
Individual voltage distortion, even harmonics	<60% of compatibility limits acc. to EN 50160	< Limit
Total current distortion ITHD	5%	2%
Individual current distortion	3%	≤ 1,6 %

[B3-0676(ES)] illustrates the reduction of voltage unbalance and harmonic distortion by means of distributed generators based on voltage source converters. Two compensation criteria are considered: load current compensation and PCC voltage compensation. When the harmonic distortion or voltage unbalance is high, VSC oversizing is required.

The performance of a microgrid connected to the utility grid by means of a back-to-back converter is simulated in [B3-0200(IR)]. This way of connection reduces the impact of voltage disturbances in the microgrid. Also the control of the inverters in the back-to-back converter influences the power quality within the microgrid. When both the utility side inverter and the microgrid side inverter use active and reactive power control, voltage disturbances can be optimally mitigated.

A new control method for the shunt active power filter based on neural networks for the reference current prediction is presented in [B3-0264(IR)]. The simulation results show an increase in the speed of compensation of the filter.

In [B3-0288(CN)] distributed generation units are used to compensate for voltage dips. Shunt DG, such as electrical vehicle charging stations are proposed to support typical series compensators (Figure 26). As a result the energy storage demands for the series compensators can be reduced. A combined compensation strategy is proposed and simulation results are presented.

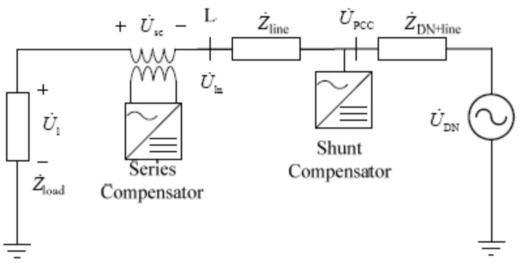

Figure 26: Combined compensation strategy with distributed generation shunt units [B3-0288(CN)]

In [B3-097(IR)] an inverse unified power quality (I-UPQC) conditioner for compensation of voltage and current quality problems is proposed. The series active power filter is located at the load side instead of the network side. In doing so, the total rating of the conditioner can be reduced especially if the load draws a large amount of reactive power. Furthermore, an new control algorithm is presented to avoid phase jumps during voltage injection.

In [B3-0055(IR)], the application of voltage source converters (VSC) to manage power flow of a feeder in a microgrid is presented. Transmission capacity is increased by decreasing the effective impedance of the feeder and therefore allowing to using an optimum size for the main feeder of the microgrid. Fault current limiting can also be achieved by increasing the impedance of the feeder using VSC. Back-to-back converters as a connecting interface between the utility grid and the microgrid is another application that is presented in this paper. By using back-to-back VSCs for interconnection, the impacts of fast transients of the utility grid side on the power quality of the sensitive industrial loads in the microgrid are mitigated.

This application enhances the performance of the microgrid, especially in case of grid disturbances.

[B3-0278(GB/DK)] explores the steady-state and transient performance of the H-bridge modular multilevel converter (M2C) in high-voltage DC transmission systems (HVDC). Steady-state performance investigation focuses on the converters ability to manipulate its active and reactive output power so as to control the ac voltage at the point of common coupling. To examine the H-bridge M2C resilience to large disturbances, the converter station is subjected to AC and DC side faults. It is concluded that despite the H-bridge M2C increased semiconductor losses, the feature of DC fault reverse blocking capability is valuable and may facilitate the expansion of voltage source converter HVDC systems to multi-terminal configurations as the recovery from DC side fault is no longer an obstacle or is greatly simplified.

Due to its compactness and fast response, the STATCOM presented in [B3-1212(DE/NZ)] could be preferred in several projects with classical SVC applications, like network voltage support, and for grid access in connection to large wind parks. Due to its short reaction time, it promises to offer improvements for the reduction the flicker effect caused for instance by arc furnaces, for which it has been already preferred as well. But the Modular Multilevel Converter (MMC) output voltage is not limited to a sinus and presents high resolution due to the achieved switching frequency. This makes possible to extend the benefits of the MMC to the mitigation of harmonics in the network. The paper extends the discussion on characteristics and applications of the MMC technology for FACTS.

[B3-1259(BR)] describes the development of a Portable Voltage Regulator for Low Voltage Networks (PVRLVN) that aims at maintaining consumers feeding voltage within the limits set by Brazilian regulations. PVRLVN allows adjusting the input voltage by means of the addition or subtraction of the adequate amount of voltage so that output voltage is within an adequate level. Power control is carried out based on static switches and repairers, all controlled by a microprocessor. The developed regulator was installed in an actual network of the AES-Eletropaulo, a local Brazilian Distribution System Operator.

Capacitor bank switching is required when providing compensating reactive power for power systems. However, high inrush currents and voltage transients from capacitor bank switching not only affect the performance of the capacitor banks themselves and their switching devices, they can also cause nuisance tripping of nearby electrical equipment such as drives and other sensitive loads. [B3-0839(SE/DE/US)] describes how a novel solution using diodes for capacitor switching reduces these negative effects and enables a more optimised power factor correction of the electrical distribution system (Figure 27).

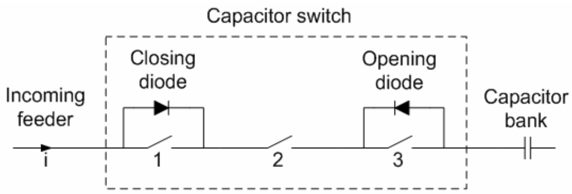

Figure 27 : Medium voltage diode capacitor switch [B3-0839(SE/DE/US)]

The inrush currents are so much reduced that they are only about 50% higher than the nominal load current and the voltage distortion is almost not detectable. The high mechanical and electrical endurance (arc free switching) can also enable more frequent operations of capacitor banks to allow a timely reactive power compensation and thus optimise the power factor correction and thereby reduce system losses and increase distribution capacity.

DG fault ride-through capability

Electrical networks are facing changes with regards to the uptake of a greater number of integrated distributed generators (DG). With an increasing number of DG units many network operators have defined mandatory "fault ride through" requirements, resulting in generators maintaining connection during system disturbances. This means that the generation must withstand a "low voltage ride through profile". [B3-0030(GB)] presents a simple and effective method in the laboratory of varying the fault / voltage dip profile to determine if the generator under test conforms to the appropriate ride through requirement profile.

A control strategy of photovoltaic power generation systems under unbalanced voltage dip conditions is presented in [B3-0615(IR)]. In order to control the DC link power and to regulate the DC link voltage, a self tuning fuzzy controller is used to determine the necessary power according to the amount of energy in the DC link. Moreover, robust current control strategy has been developed to control the positive and negative sequence of dq-components. Simulation and experimental results show that the proposed control strategy is able to tolerate various voltage dips and keeps the system performances such as active power control and stability of DC-link.

Superconducting fault limiters

Superconducting current limiters, often identified with SFCL (Superconducting Fault Current Limiter), are innovative devices that, when properly designed and placed in an electrical grid, are able to limit the short-circuit current to values compatible with safety and reliability of the installed network components. The impact on the voltage dips characteristics is also obvious as their depth is reduced.

A SFCL device usually combines unique features such as transparency in the network under normal conditions, together with quick response and recovery without external intervention. [B3-0339(IT)] reports on the development of SFCL devices for MV applications (Figure 28). The main results are related to the comparison of network simulation studies with laboratory short-circuit testing on a single-phase SFCL unit.

A consortium comprising three UK Distribution Network Operators is deploying three superconducting fault current limiters (SFCLs) in the UK distribution system. [B3-0456(GB/DE/US)] reports progress to date with the work which is being undertaken

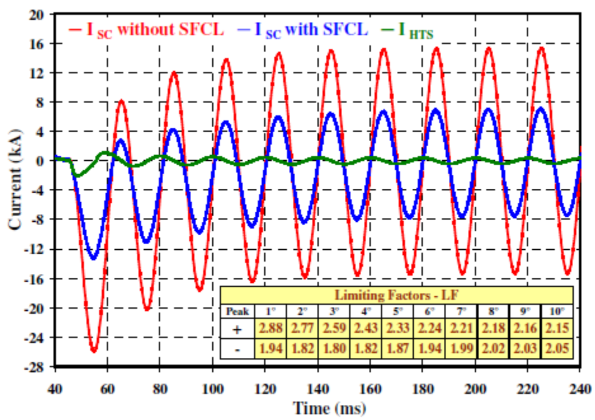

Figure 28 : Short-circuit tests on 1-phase SFCL at Vnom= 5.4 kV: Current with and without SFCL and ILim carried by the HTS [B3-0339(IT)]

Further research topics

How to deal with the minimum number of PQ monitors required for voltage dip monitoring within the future grid with continuous changes in topology?

Papers of Block 3 (B3)

Paper No.	Title	MS p.m.	RIF	PS	Other Sess.
0030	Electrical Network Testing and Simulation : An Effective Method of Testing the Fault Ride Through Capabilities of Proto-Type Embedded Generation				S4
0055	Application of Voltage Source Converters to Manage Power Flow and Enhance Operational Performance of a Microgrid				S1
0097	Inverse Unified Power Quality Conditioner			X	
0109	An Effective Time Frequency Method for Voltage Sag-Source Detection			X	
0191	Elementary Evaluation of Reliability Indices for Power System in Egypt			X	
0200	Power Quality Aspects of Different Control Schemes of Back-to-Back Converters Interfacing Utility-Grid to Microgrid			X	
0213	Application of Hybrid Var Compensator for Flicker Control in Mesh Welding Applications			X	
0264	A Fast Detection of Harmonic Compensation Current for Active Power Filters using Adaptive RBF Neural Network and Hysteresis Current Controller			X	
0278	H-Bridge Modular Multilevel Converter for High-Voltage Applications				S1
0288	Combined Compensation Strategy of Voltage Sags for Distribution Network with Distributed Generation		X		
0337	STATCOM for Mitigation of Flicker Emanating from a Large EAF			X	
0339	Development and Testing of Innovative Fault Current Limiters for Distribution System Applications				S1
0417	Systematic Power Quality Monitoring in Municipal Power Grid	X			
0421	A Practical Method of Power Quality Monitoring and Management			X	
0456	Fault Limiting Technologies in Distribution Networks				S1
0500	Development and Implementation of a Methodology for the Study of Voltage Dips in Bogota D.C.			X	
0529	Methodology for Flexible, Cost-Effective Monitoring of Voltage Sags	X			
0552	Dynamic Var Compensation of Mine Hoists for Improvement of Power Quality and Increase of Productivity at LKAB Sweden	X			
0553	Time Series Analysis of Outages in Four Nigerian Cities			X	
0587	A New Assessment Method of Voltage Sag Frequency Considering Customer Satisfaction Degree		X		
0615	Control of Photovoltaic Power Generation System During Unbalanced Grid Voltage Sag Conditions				S4
0657	Evaluation of Transformer Inrush-Induced Voltage Dips			X	
0676	Improving Power Quality Using VSC-based Distributed Generation Units			X	
0700	Extending Switching Reclosing Time to Reduce Interruptions in Distribution Networks	X			

0748	EN 50160 Ed.3 and Voltage Quality in the Czech Republic			X	
0839	A Diode Based Capacitor Switch - a Novel Solution for Power Quality Improvement				S1
0868	Integration of Power Quality Monitoring System in Croatian Distribution System			X	
0882	Data Modelling for Reduction of Volume in Large Archives of Power Quality Data			X	
0886	The Voltage Dip Performance Assessment of the Italian MV Network through Global Indices			X	
0942	Advanced Power Quality Measurement Campaign - Interesting Measurement Results	X			
0946	Overvoltage Immunity of Electrical Appliances - Laboratory Test Results From 60 Appliances	X			
1021	Power Quality in the Portuguese Distribution Network			X	
1139	Decentralised Controller for Flicker Mitigation in Converter-connected DG Networks		X		
1151	Feature Analysis for Voltage Disturbances Resulting from External Causes			X	
1212	Innovative VSC Technology for Integration of "Green Energy" - Without Impact on System Protection and Power Quality				S3
1216	Optimal Voltage Sag and Swell Monitoring through Genetic Algorithms, Fuzzy Mathematical Programming and Stochastic Simulation of Short-Circuits			X	
1259	Portable Voltage Regulator for Low Voltage Networks				S1
1294	Power Quality Monitoring System Smart Grids Component			X	
1314	Transient Disturbance Recognition for Power Quality Analysis			X	

Block 4: Power Quality in a competitive market

Economics of Power Quality

The knowledge of the costs and economic losses due to disturbing events (interruptions, voltage disturbances, harmonics, dips, …) is important for DSOs. The costs are required to estimate an optimal level of continuity of supply from the point of view of the DSO or the customer. 9 papers dealing with the costs and economics of power quality have been selected for inclusion in session 2, pointing out the importance of this topic.

In [B4-1242(NO/IT/SE/PT/AT)] the recommendations of CEER (Council of European Energy Regulators) on the estimation of costs due to interruptions and voltage disturbances are published. The paper is based on the Guidelines of Good Practice on Estimation of Costs as published by CEER in 2010. Reliable cost estimation of customers is essential to implement proper financial incentives regarding continuity of supply by the national regulatory authorities. The conclusions can be summarised as in Figure 29.

C-1: Results from cost-estimation studies on customer costs due to electricity interruptions are of key importance in order to be able to set proper incentives for continuity of supply.

C-2: Results from cost-estimation studies on customer costs due to voltage disturbances are important input on the consequences of various voltage disturbances when deciding where to focus regulation.

C-3: Society costs should be considered in addition to customer costs when doing a cost-estimation study, as these can differ significantly.

C-4: National Regulatory Authorities should perform nationwide cost-estimation studies regarding electricity interruptions and voltage disturbances.

C-5: A pre-study should be performed in advance of a main study in order to define the objectives and to clarify country-specific characteristics, budget and consultancy needs, possible funding partners, timeline and possibilities in general for the main study.

C-6: These GGP [1] – including the SINTEF consultancy report [2] – should be used as a reference when performing a nationwide cost-estimation study, always taking into account country-specific issues and needs.

Figure 29: Conclusions from CEER on estimation of costs due to interruptions and voltage disturbances [B4-1242(NO/IT/SE/PT/AT)]

The relation between the costs and the duration of interruptions for industrial customers is further analysed in [B4-0253(SE)]. Based on interviews, it is shown that the cost/duration is unique for every customer, even after normalization of the results (Table 7). It is concluded that the use of a mean value for cost/duration has no meaning in the design and operation of a network for a specific customer.

Table 7: Cost due to an interruption of different duration, normalised by annual electric energy consumption [B4-0253(SE)]

Duration time [h]	Cost [SEK/kWh]			
	Min.	Median	Mean	Max.
Initial	0	0.004	0.036	0.4
2	0.003	0.028	0.144	2.025
4	0.004	0.056	0.170	2.075
8	0.007	0.106	0.227	2.250

A survey of cost/duration for industrial and commercial customers made in 2009 in Brazil is reported in [B4-1305(BR)]. The results are based on a questionnaire and internal data of the customers. For a large customer in the steel sector, the results are validated by means of measurements and customer declared costs. 82% of the customers judged that utility initiatives would improve their quality of supply. However 68% is not willing to pay for the resulting benefits.

In [B4-0116(EG)] a similar cost/duration evaluation is made. First customer damage functions are generated. They provide the interruption cost versus interruption duration for a specific group of customers. This input is elaborated to generate the Expected Customer Damage Cost (ECOST) for a part of the Alexandria electrical system. It is shown that the ECOST decreases rapidly when the load level decreases from 260 to 208 MW and does not vary significantly when the load level decreases further (Figure 30).

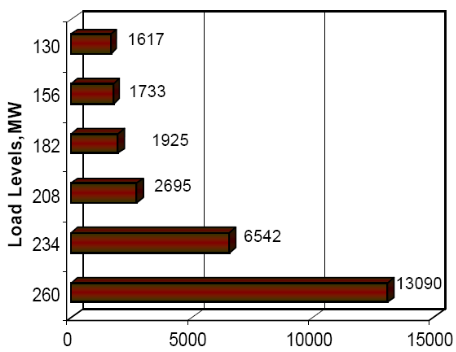

Figure 30: Expected customer damage cost at various load levels in kLE/year [B4-0116(EG)]

In [B4-0115(EG)] the same author presents a guide for the assessment of power quality related costs (both interruptions and harmonics) and contributed to the definition of worst served customer. This definition should cover not only supply continuity but also minimal voltage requirements.

In the Czech Republic, LV customers are granted a discount on the electricity price in case of a justified complaint concerning voltage quality. [B4-0045(CZ)] describes a survey based on the customer complaints. The number of complaints is increasing year by year and the majority of complaints are due to voltage fluctuation resulting in flicker (Table 8). The increasing amount of photovoltaic power plants installed is a main reason. It is shown that the voltage quality is closely related to the short circuit power at the customer side.

Table 8: Causes of complaints in the Czech Republic between 2007-2010 [B4-0045(CZ)]

cause of complaint	% of complaints
voltage fluctuation	33
overvoltage	15
voltage sags	13
supply interruption	13
voltage quality	11
low voltage	10
other	6
total	100

Reliability

[B4-0233(SE)] presents the results of the annual evaluation of the reliability in local electricity networks in Sweden. A distinction is made in SAIFI and SAIDI for rural, suburban and urban networks. The values are significantly higher for rural than for urban networks; also the spread between network operators is higher for rural networks. Data is also presented on the number of very-long interruptions and on the investment and running costs by the network operators.

[B4-0444(PT)] proposes a framework to understand and manage reliability in distribution networks, based on the analytical breakdown of popular indexes, such as SAIDI. The aim is to isolate and quantify the key determinants of reliability, providing a tool that decision makers can use to understand the past and make decisions for the future. The proposed framework may be used to support the definition of reliability improvement strategies (e.g. feeder refurbishment vs. investment in automation vs. additional outage handling crews vs. new maintenance rules) and enables a systematic evaluation of the merit of past decisions. Additionally, it may be used to quantify the individual contribution of different functional areas (e.g. planning, operation, maintenance) to overall network reliability, much like the individual impact of each area is quantified in CAPEX and OPEX expenditure. This knowledge can support budgeting decisions and even be incorporated in scorecards, to provide targeted incentives to reliability.

The beginning of unplanned interruptions obviously occurs stochastically. Also, reliability has dynamic (fluctuating) nature depending on the time. For observing this phenomenon, additional indicators like three-hourly (3-h) SAIFI and SAIDI are proposed in [B4-0714(HR)]. After analysing a three years data set it became obvious that probability of interruption with more difficult consequences is higher within heavily loaded network than during low load regimes. Also, the interruptions that happen during off-peak hours usually have longer duration, particularly during the nights. Activities with respect to load balancing and better maintenance organization especially out of working hours time could significantly improve reliability indices and consequently power quality and customer service. The knowledge on daily dynamic of electric distribution reliability can clearly have positive impact on maintenance strategy, distribution network development and power system control.

Utilities can expect to see an increase in the amount of DG connected to their distribution systems. Although these sources of power can create many complications, they also have the ability to improve system reliability. Based on the theory of Bayesian network, [B4-0404(CN)] discusses backup generation to radial model and the use of DG for improving the supply reliability in distribution systems. The DG impacts on reliability indices and interruption cost are calculated with different DG sizes. The results show that the larger the DG size, the better the reliability and the lower interruption cost of the system.

[B4-0551(NG)] describes a real-time outage reporting system based on the Short Message Service (SMS) feature of the GSM, developed and implemented in Nigeria. The given solution is a GSM modem interfaced to a computer which would receive customer originated messages, process them and update a database and finally alert essential units in the organization for action in real time while providing the means of relatively accurate collection of data useful for planning and other functions. The software was developed with Microsoft C# and MapWindows which provided a means of overlaying the faults reported on a digital map of the coverage area. The system proved to provide a shorter mean time to repair of faults on a given distribution test area.

Improved reliability using distributed generation

In [B4-0083(RS)], the impact of synchronous distributed generators on the reliability of the supply in a 20 kV/0,4 kV underground network in Serbia is investigated by means of simulation. It is found that the proper choice of the DG can significantly improve the reliability indices in the network. Small power DG with high failure rate are shown to have a deteriorating effect. Due to the use of DGs, the voltage quality under normal operation was improved, the rms current in the LV cables decreased but the total harmonic current distortion increased.

In [B4-0935(SE)], the power quality losses in distribution transformers originating from electronic loads such as lamps based on LED, electric vehicle chargers and electronic transformers is discussed. The focus is on the impact of the harmonics on the losses. The paper gives a nice review of the research conducted on this topic.

Regulatory aspects

In [B4-0168(SE)], the voltage quality requirements set by the Swedish energy regulator are presented. This paper also discusses recommended measurement methods for verification of compliance with the requirements. For harmonics, unbalance and slow voltage variations, the limits in EN 50160 always need to be fulfilled. There are no limits for interharmonics and harmonics above order 25. For flicker, new developments in standardization are waited for. Regarding voltage dips and swells, requirements on a maximum number of events and a maximum permissible event severity in terms of voltage and duration are defined. Very severe dips (group C in Figure 31 for voltage levels up to 45 kV) are considered to be of insufficient quality. For rapid voltage changes, again standardization is waited for. The use of power quality measurement data is limited to internal use within the network operator. There is no reporting to the customers and no such reporting is planned in future. At the occurrence of a customer complaint, the Swedish Energy Markets Inspectorate becomes involved to help to solve the problem between the customer and the network operator.

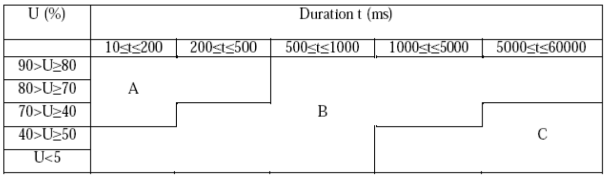

Figure 31: The three groups of voltage dips for voltage levels up to 45 kV as defined in Sweden [B4-0168(SE)]

Smart grids and power quality monitoring

The use of distributed generation units and the associated control requirements have a profound impact on the system performance. The challenges for voltage regulation, power quality monitoring and metering are huge. In this section several PQ papers contribute to the understanding of these problems.

In [B4-0406(DE)] the impact of conducted power quality phenomena up to 9 kHz on the accuracy of smart meters is investigated. The impact of currents with high harmonic content on the measurement accuracy and the reliability of the power line communication (PLC) is shown. A test signal has been developed and applied on a test set-up for several commercial smart meters. The measurement results do not show unacceptable impact on the measurement accuracy nor on the PLC. Only a coincidence of factors lead to incorrect measurements: a low-resistance grid impedance in combination with a power electronic inverter with output circuit filter is given as an example.

[B4-1240(NO)] reports on the current requirements on monitoring of voltage disturbances in Norway to achieve reliable statistics based on both continuous measurements and measurements due to customer complaints. Measurement location should be decided on related to the different characteristic networks present in the system as the occurrence of stochastic parameters are most likely to be similar in each characteristic network. It is believed that this approach results in a cost effective measurement strategy. The challenge to set up an effective reporting system to deal with the information from measurement data from units from 7 different vendors is discussed. The PQDIF format (Power Quality Data Interchange Format) is most suited for this purpose. PQDIF is based on an international standard and aggregation of data is limited offering the opportunity to perform detailed analysis of the data.

[B4-0425(FI)] deals with the evolution of PQ phenomena monitoring such as flicker and harmonics in the future distribution network. The authors suggest accurate PQ measurements in addition of current measurements via Advanced Metering Infrastructure (AMI). Also the need for an effective PQ management process is addressed in order to have business benefits resulting from better PQ monitoring.

[B4-0509(CA)] discusses the use of a condition based maintenance system for a distribution system. The methodology using a fault location technique based on voltage dip measurements (VDFL) was presented at CIRED 2007. Now the technique is deployed on seven distribution feeders. Temporary fault location is used to repair and prevent failures before they result in outages. The results on one specific feeder (HTD 236) are presented in the paper. The reduction of outages is remarkable (Table 9).

Table 9: Outage statistics for the HTD 236 feeder in Canada [B4-0509(CA)]

Description	2006-2007	2009	2010
# of outages	180	60	54
SAIDI (hrs)	16.6	7.2	5.28
Number of undetermined outage causes per 100 km	2.2	1.94	0.38

The functionalities of the web-based Enel Distribution Power Quality Data Warehouse in Italy and the opportunities with respect to smart grids are presented in [B4-1285(IT)]. The analysis tools can be used to support the DSO but are also useful for the customers to optimally design the equipment for their installation's power quality improvement.

Future grids

In [B4-0665(NL)], experiences with an intelligent distribution substation to increase the power quality in a low voltage grid with distributed generation units are reported. The substation contains a smart transformer, a storage system and a dedicated measurement system (Figure 32). The electronic tap changer of the smart transformer is used for the voltage control, flicker control and voltage dip mitigation. The storage system with bidirectional inverter is active for harmonic distortion reduction, flicker compensation and voltage dip mitigation. The paper presents the first field tests and demonstrates significant improvement of the power quality.

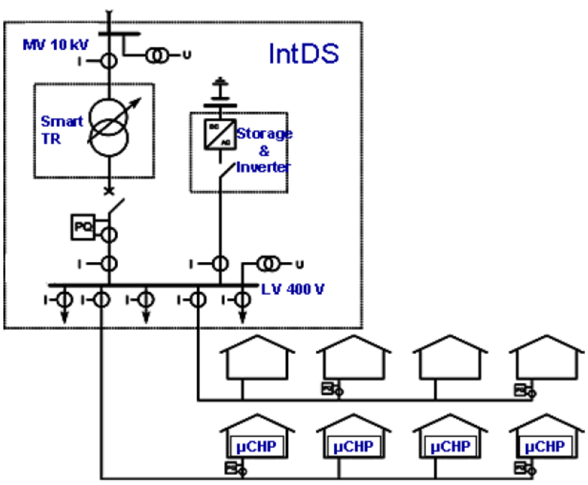

Figure 32: Overview of the Intelligent Distribution Substation and the connected LV feeders, including measuring devices [B4-0665(NL)]

Power quality aspects of the integration of photovoltaic installations (PV) connected to the LV grid is discussed in [B4-0273(DE)]. A method is presented to define the optimal locations for PQ measurements to analyse harmonic emissions. The method includes the evaluation of the network, consumer and generation topology. Analysis of the network shows that the short circuit power for the studied networks is often lower than the reference value given in IEC 60725. First results show emissions above 10 kHz which may cause interference with other equipment (Figure 33).

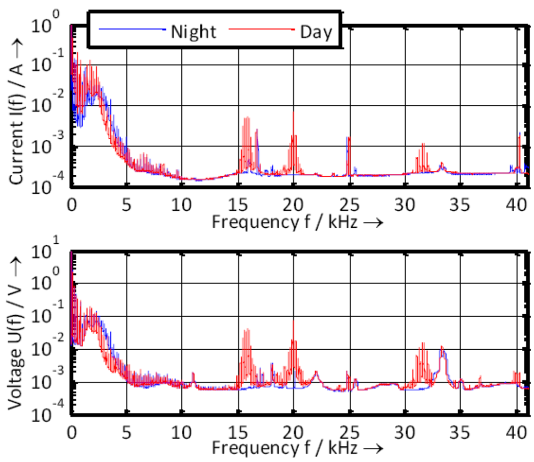

Figure 33: Harmonic spectrum measured up to 40 kHz in a grid with photovoltaic installations (PV) connected to the LV grid [B4-0273(DE)]

Optimization of voltage control is addressed in [B4-0993(BR)]. To maintain the secondary transformer voltage within appropriate limits, transformer tap zones (TAP) are defined. Also the integration of the voltage control in a smart grid context is briefly described. [B4-1209(IR)] presents a new method for the placement of fixed and switched capacitors as reactive power sources in microgrids in both grid connected and islanding mode. The method is based on a genetic algorithm and simulation results are presented. [B4-0301(CN)] analyses the optimal size and location of distributed generation units with respect to their harmonic impact. A multi-objective particle swarm optimization algorithm is presented for this purpose.

[B4-1160(IR)] addresses the selection of appropriate power definitions to be employed in smart grids. An overview of existing power definitions is given. The authors also set requirements that should be met by the power definitions and come to the conclusion that there is a need for a generalised power theory to deal with all aspects of smart grids.

Under the concept of smart grid, a novel planning method is proposed in [B4-0267(CN)] for customer friendly distribution system taking power quality evaluation into account. The assessment of potential costs caused by customer's equipment failures under possible disturbances is proposed for different planning schemes. The programming method is correlated with both the disturbance and immunity levels of customer equipment or installation. Based on maximum entropy principle and fuzzy analysis method, the compatibility between system disturbance and equipment is also studied.

[B4-0135(IR)] presents the impact of different load types on the performance of the control system of the power sources of a microgrid. It is shown that composite loads comprising of constant power and asynchronous motor loads have approximately the same effect on the system frequency compared with the case of only constant power loads. However, when the composite load is composed of motor loads, the frequency excursions are different, especially after isolation of the microgrid from the utility grid. It is also demonstrated that if the grid is connected to the microgrid by using back-to-back converters, then the impacts of grid isolation on the frequency is mitigated. It can be concluded that the performance of different control schemes of VSCs within a microgrid should be evaluated for different combinations of composite loads.

Energy storage is essential for maintaining the energy balance of a microgrid in islanded operation. [B4-0381(KR)] deals with voltage and frequency stability issues of islanded microgrids. In this context, the potentially positive role and impact of the energy storage and its coordinated control system on the stability and voltage quality of the islanded microgrid are highlighted, in experimental situations.

Increasing penetration of distributed generation such as wind power and photovoltaic systems as well as expected fast development of electrical vehicles faces existing distribution systems with new challenges such as: power fluctuations, changes of power flow directions, steady state voltage fluctuations etc. These problems can effectively be counteracted by the application of smart power electronic and storage devices. Thanks to their active and independent role the grid itself becomes also smarter. In [B4-0795(DE)] one solution of a combined power electronic and battery storage system for improvement of grid performance and solving above mentioned raising challenges will be presented, i.e. the SVC Light® with energy storage.

[B4-0830(JP)] introduces the concept of Autonomous Demand Area Power System (ADAPS) in order to cope with the increasing penetration of DG in distribution networks and its effect on voltage regulation, among others. A method using Static Var Compensator (SVC) and Step Voltage Regulator (SVR) in power distribution systems in transition period from conventional system to ADAPS is studied (Figure 34).

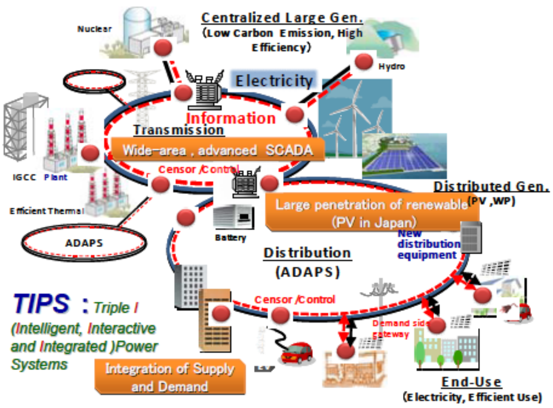

Figure 34 : Expected future power system (Triple I) [B4-0830(JP)]

Quality regulation sometimes contains incentives for electrical networks including monetary evaluation of reliability indices. Due to the stochastic character of these indices and the resulting financial risk for the network operators the assessment of the distribution of these reliability indices is necessary. In [B4-0837(DE)], a method to determine the distribution of the widely spread reliability indices for electrical networks is presented. In contrast to the established methods of probabilistic reliability calculations this method is based on the underlying statistical data of the reliability indices and other corresponding statistics and can therefore be applied to any network operator based on a basic description of the supplied region and aggregated network data.

Low voltage DC network

In [B4-1099(FI)] the dimensioning of capacitors for a low voltage DC network and the impact on the power losses is reported (Figure 35). For the studied system with a DC voltage of 750V the minimum capacitor values at the front-end rectifier of 30µF/kW and of 44 µF/kW at the customer end are required to keep the voltage ripple within 10%. The impact of capacitor size on network resonances and power losses are also described. Increasing the capacitors results in a reduction of losses. The additional investment costs should of course be balanced with the reduction of the cost of the losses.

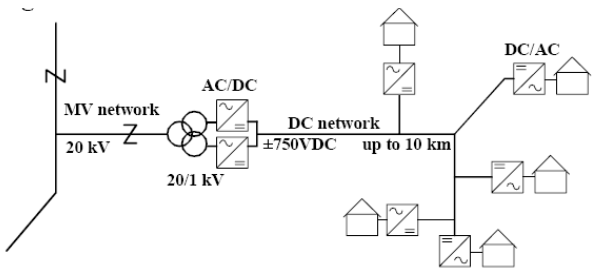

Figure 35: Basic concept of the LVDC distribution network as presented in [B4-1099(FI)]

Further research topics

What is the economic and technical sense of using distributed generation to compensate for Power Quality and what control is required to decide which DG needs to take action?

Papers of Block 4 (B4)

Paper No.	Title	MS p.m.	RIF	PS	Other Sess.
0045	How the Customers Perceive the Problem of Voltage Quality	X			
0083	Investigation into the Power Quality and Reliability of Supply in the Industrial Networks with Distributed Generation			X	
0115	A Guide For The Management of The Economics of Power Quality			X	
0116	Assessment of Cost Related Reliability of Power Systems			X	
0135	Load Type Impacts on Frequency Control of Microgrids in Transition from Grid-Connection to Islanding				S3
0168	Voltage Quality Regulation in Sweden	X			
0233	The Swedish Benchmarking Report on Continuity of Supply				S6
0253	Individual Interruption Costs of Industrial Customers as Basis for a Classification.			X	
0267	The Programming Method of Customer Friendly Distribution Systems Considering the Uncertainty of Short Time Power Quality Disturbances				S5
0273	Power Quality Aspects of Rural Grids with High Penetration of Microgeneration, Mainly PV-Installations	X			
0301	Harmonic Impact of DG Configuration in Distribution System			X	
0381	Voltage and Frequency Stability Enhancement of the Islanded Microgrid using Battery Energy Storage				S4
0404	An Approach for Reliability Assessment of Distribution Networks with DG				S5
0406	The Influence of Conducted PQ Phenomena on the Measurement Accuracy of Smart Meters			X	
0425	Vision of Power Quality Monitoring and Management in Future Distribution Networks			X	
0444	An Analytical Framework to Understand and Manage Reliability in Distribution Networks				S5
0509	PQ Monitoring with Smart Meters for Condition Based Maintenance on Distribution Systems.	X			

0551	Development of an SMS-Based Outage Reporting System				S6
0596	Study on the Economic Loss and its Evaluation Methods of Short Interruption			X	
0665	Intelligent Distribution Substation Improves Power Quality	X			
0714	Daily Fluctuations of Electric Reliability Indices				S5
0795	SVC Light with Energy Storage for Smart Grids				S4
0830	Development of Voltage Regulation Method including Power Factor Control by Customers in Autonomous Demand Area Power System				S3
0837	Distribution of Reliability Indices in Electrical Networks				S5
0935	Power Quality Losses in Distribution Transformers originated from Electronic Loads - A Review			X	
0993	Optimization of Voltage Regulators Settings and Transformer Tap Zones in Distribution Systems with Great Load Variation Using the Smart Grids Initiatives	X			
1099	On Dimensioning LVDC Distribution Network Capacitances and Impacts on Power Losses		X		
1160	Criterions to Select Appropriate Power Definitions Employed in Active Power Distribution Networks			X	
1209	Reactive Power Control in a Microgrid in Both Grid-Connected and Islanding Modes			X	
1240	Monitoring and Reporting of Voltage Disturbances - Regulatory and Technical Challenges and Solutions			X	
1242	CEER Recommendations on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances			X	
1285	Present and Future Functionalities of the Enel Distribuzione Power Quality Data Warehouse			X	
1305	Interruption Costs in Large Customers: Survey and Applications			X	