Special Report – Technical Theme 2

POWER QUALITY & EMC

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

- **Power Quality**, i.e. voltage continuity (often referred to as supply reliability) and voltage quality; Power Quality is related to outages and to LF disturbances (≤ 9 kHz) reaching equipment through the electricity supply;
- **EMC** (Electromagnetic Compatibility) in the usual narrow sense (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 (overvoltages, earthing systems...) are also considered.

The 2001 session will be divided in four sections of 90 minutes: I. EMC and Safety Problems, II. Voltage dips and Interruptions, III. Disturbing Loads and Phenomena (harmonics, interharmonics, flicker, unbalance), IV. PQ Monitoring and New Technologies.

Each section will be divided in two main parts : 1) a few presentations by keynote speakers or authors, 2) discussion (prepared contributions and free discussion).

The aim of this special report is : 1) to present a **synthesis of the present concerns** in each of the four sections, mainly based on the selected papers, 2) to **call for prepared contributions** on particular points which appear in the papers or which are not covered by them, 3) to **stimulate the free discussion**.

Call for prepared contributions. Prepared contributions will preferably aim at answering the questions of the Special Report. However, other kinds of contributions will be welcome :
- fresh information on particular points which appear in the papers or which are not covered by them ;
- case studies (outstanding disturbance experiences, causes, solutions...) ;
- comments on a particular paper ("I agree/disagree with that result/conclusion", "My own practical experience in the same field is...") ;
- just plain questions to the author of a paper.

According to the successful experiment of CIRED 1997 and 1999, all prepared contributions will be made available to attendees at the entrance of the conference room. Furthermore, some of the most relevant ones will be selected for a verbal presentation (second part of each section).

General guidelines for authors of prepared contributions :
- language: preferably English for the written document ;
- starting with: title, name of author(s), affiliation, country, number of the relevant question in the special report or number of the commented paper ;
- font: Arial or Times New Roman, minimum size: 10, margins: 2.5 cm top and bottom, 1.8 cm left and right, preferably two columns with 0.5 cm gap ;
- maximum length: 2 pages, including both text and illustrations (this allows for a lot of information if a 2-column presentation is chosen) ;
- deadline: preferably May 25 (possibly June 1 at the very latest) ;
- address: Alain ROBERT, CPTE, Rodestraat 125, B-1630 LINKEBEEK, Belgium, Fax: +32.2.382.2300, E-mail: alain.robert@cpte.be (the preferred way being to send your contribution by e-mail as an attached file).

I. ELECTROMAGNETIC COMPATIBILITY AND SAFETY PROBLEMS

As during the previous sessions very different topics will be addressed here, ranging from typical ***EMC*** subjects dealing with immunity and emission of installation or equipment, up to resistibility and safety problems due to ***GPR (Ground Potential Rise)*** under fault conditions, or questions related to ***lightning***.
EMF (Electromagnetic fields) issues are also included in this part of the report.

EMC

Pure EMC problems (i.e. interferences between equipment or systems) are not very often discussed in CIRED, either because they are considered as too specific and left to more specialised forums, or because they are no more considered as being a primary concern.
Two papers however deal directly with EMC. The first, paper 2.6 (IR), addresses the problem of HF conducted emission due to pulse width modulation in a switching power supply; the second, paper 2.2 (MK), relates to the modelling and calculation of the coupling between transient disturbances (lightning, switching…) and cabling in HV substations.
Both papers highlight the importance of using such calculation methods at the design level of an equipment or

installation either to keep the emission level under control or to improve the immunity.

Paper 2.2 gives also some answer to a question, which has divided the scientific community for a while: The respective importance of scalar (resistive) voltage drops versus induced voltages in earthing- and equipotential bonding networks (Figure 1 and Figure 2).

QUESTION 1

1.1 Are there known cases, in the distribution world, of equipment or systems which meet the HF emission requirements of the international standardisation (CISPR, Cenelec, ...) but which nevertheless have caused interference with other systems (e.g. because of a bad cabling) ?

1.2 What is the common practice for assessing the immunity of equipment to install in substation :
- **No systematic test**
- **Systematic test by a utility lab or an independent lab**
- **Case dependent ?**

1.3 In a substation with poor cabling / earthing conditions, what ought to bring the best improvement: to add parallel earth conductors (PEC) in the cable trench or to add extra earth electrodes ?

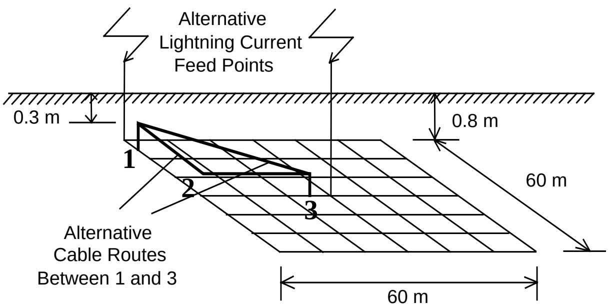

Figure 1: Cable following different paths above an earth grid

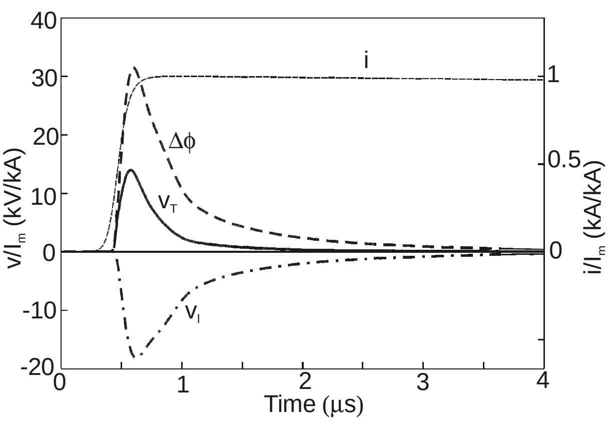

Figure 2: Induced and conducted voltage along path 123 of Figure 1

Lightning

Three papers deal with the lightning protection of networks.

Paper 2.11 (RO) stresses upon the advantages of using Metal Oxide Arrestors for protecting HV lines. Paper 2.13 (RA) presents an interesting stochastic method for estimating the amplitude of lightning currents in MV lines and hence, for dimensioning some protection elements like the earthing electrodes. Paper 2.10 (BR) makes also recourse to numerical simulations for dimensioning and evaluating the best location of Surge Protection Devices (SPDs) in LV networks.

QUESTION 2

2.1 Up to what extend is it the responsibility of the utility to protect LV networks against lightning overvoltages knowing that the customer has also the ability to install SPDs in his premises and knowing also that the efficiency of the protection is higher when it is located close to the sensitive equipment ?

2.2 Tall structures have a natural protection effect on other structures located in their vicinity but, on the other hand, they are likely to be struck more often. With that respect, wouldn't it be a good principle to recommend to customers connected on a LV cable feeding a tall building to install SPDs ?

Ground Potential Rise

Ground potential rises leading to Temporary Overvoltages (TOV), step and touch voltages remain an acute concern for utilities as it involves important "resistibility" (ability of equipment to withstand the TOV) and safety aspects.

Four papers discuss questions related to GPR and to the spreading of dangerous potentials by metallic conductors:

Paper 2.1 (MK) is focused on the spreading of potentials in the vicinity of HV substation and on the difference in behaviour between a highly urbanised area and a rural area.

Paper 2.3 (BE) exposes how the concept of Global Earthing System (GES) will be transposed from the international standardisation (Cenelec HD 637-S1) to the national regulation. Paper 2.12 (NL) presents with many details a case study related to a LV network feeding a GSM installation located on a HV pole. It is shown, in particular that the best way to avoid a transfer of potential from the HV tower to the LV network is to use an isolation transformer but also that insulation coordination has to be carefully fulfilled (*Figure 3*). The same kind of safety issue is deeply analysed in paper 2.14 (CA) related to the interconnection of HV and MV/LV grounding systems in North America.

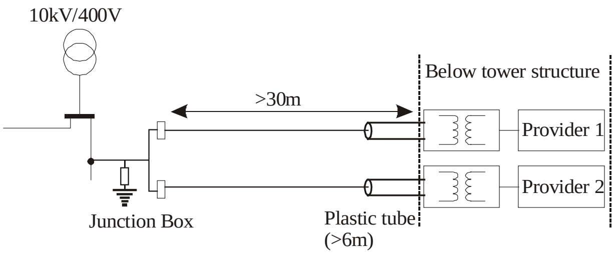

Figure 3: Feeding of a GSM installation located on a HV pole

QUESTION 3

3.1 In a completely liberalised electricity market without vertical integration, how will the responsibilities be shared between Transmission System Operators (TSO), Distribution System Operators (DSO) and customers when problems related to the transfer of unwanted potential arise at the border between each system (cf GSM case study) ?

3.2 Paper 2.1 recalls the fact that many telecommunication lines are protected (against lightning) by gas discharge tubes. Isn't it worthwhile to warn telecommunication people that making recourse to MOV is a better practice when there is a risk of power frequency overvoltage ?

3.3 A risk management approach where the acceptable level of overvoltage is combined with its duration is more and more accepted in the standardization world as the following table taken from prEN 50352 (influence of electric power supply and traction systems on telecommunication systems) shows it:

Duration (s)	Voltage (Vrms.)
t ≤ 0,1	2000
0,1 < t ≤ 0,2	1500
0,2 < t ≤ 0,35	1000
0,35 < t ≤ 0,5	650
0,5 < t ≤ 1	430

Safety of people
Limits for coupled r.m.s voltages

This approach has also been followed in ITU rec K.33 and K.53, IEC 364-4-442 and 61936-1 (CDV), CLC HD 637-S1 and IEEE 80 but each time with different values.
How are these limits incorporated in the different national regulations ? What are the criteria chosen for selecting an appropriate safety curve (cf. IEC 479-1) or additional resistances (shoes…) ?

3.4 Paper 2.14 shows that, even when HV and MV/LV installations are isolated from each other, there remains some risk in the vicinity of earth electrodes not connected to the HV installation.
Up to what extend can the shape of this earth electrode influence the voltage decay in its vicinity and hence the syep and touch voltages ?

Electromagnetic fields

The application of the precautionary principle or, in some cases, of regulations which are more severe than the international recommendations (ICNIRP, European Council...) induces the utilities and the manufactures to seek after the best possible mitigation measures for reducing EMF in the vicinity of electrical installations.
This is highlighted by the increasing number of papers dealing with the subject:
Paper 2.4 (SE) shows how, by introducing some appropriate shielding material round a "standard" LV switchgear, it can be modified into an "improved" design. Comparison is also made with "old" switchgears having larger distances between busbars.
Paper 2.7 (DE) describes another method applied to MV switchgears, and mainly based on calculation. The challenge here is to find a way to take into account at the design level all the possible configurations that the great modularity allows.
Paper 2.5 (SE) and 2.8 (SI) summarise the different methods that can be applied for reducing the field levels:
Shielding by ferromagnetic material, by conductive materials, by active or passive compensation (
Figure 4), at the source or around the victim etc. It is clearly shown that depending of the source configuration, the place where the field has to be reduced, the accessibility etc, different solutions can be put forward.
Aside from the mitigation methods it is of course very important to know how far existing installations do or don't meet the different requirements.
Paper 2.9 (SI) describes how the assessment of the MV overhead and underground network has been performed in Slovenia and how it is situated with respect to the local regulation concerning EMF.

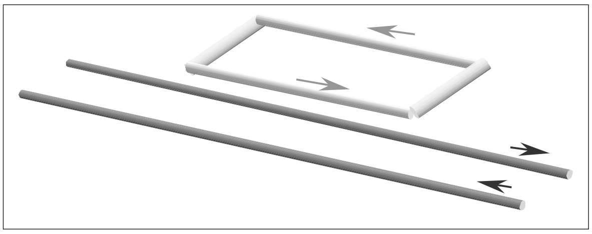

Figure 4: Passive compensation of magnetic field

QUESTION 4

4.1 The application of active and passive loops for the cancellation of magnetic fields has already been used for HV lines and for the protection of computer CRT's. Are there known cases where this mitigation method has been applied to MV or LV switchgears ?

4.2 Paper 2.5 states that ferromagnetic materials are usually less efficient than conductive materials, due to the coexistence in the same material of two mechanisms with opposite effects on the field. Isn't

this explanation in contradiction with the observation that shields formed by a sandwich made of both materials are precisely the most efficient ? Is the need for protection against corrosion not a greater drawback for ferromagnetic materials ?

4.3 Are there utilities that have performed a systematic assessment of their electrical installation and found some discrepancies with respect to the international recommendations or with their own national regulation ?
In such a case what were the consequences of this finding ?
Have the cost implications be evaluated in cases where the national regulation is, or would become, comparable to the Swiss or the (proposed) Italian regulation in which exposure levels not exceeding about 1 µT are mentioned.

II. VOLTAGE DIPS AND INTERRUPTIONS

Voltage continuity (supply reliability)

Among the constituting parameters of Power Quality, voltage continuity is obviously the first one being systematically taken into account in regulations, procedures or contractual applications. It is sometimes leading to possible financial consequences, such as penalties against system operators, in case of not fulfilment of the quality criteria.
In order to measure and characterise the voltage continuity (reliability of supply), indices are defined. They are commonly related to statistics concerning the number of interruptions, their duration and their non-delivered energy (NDE), at system level as well as at consumer level.

System operators use various tools either to assess the actual reliability or to try to predict its future evolution.
Reliability data collection is essential in the actual context, as stated in Paper 2.32 (NL). Cost reductions imposed by the free market, are in fact leading to an increasing surveillance of reliability. The results are crucial in the planning of supply systems, where cost/benefit analyses are made. For new network designs or new operational procedures the statistics provide the input data for reliability studies, predicting the damages for customers or penalties to be expected. Those results are suitable to be compared with the investments or savings involved. Their value and their importance is still increasing, not in the least due to the liberalisation. In the past, the data collection was mainly used to gain insight in the system and the components. Nowadays it can be used also for benchmarking and asset management in view to reduce costs. The data collection also shows its added value as a very useful tool to give the regulator information about the quality of supply. As an example, Figure 5 shows the benchmarking result of several Dutch utilities, regarding the availability of supply for one year (i.e. the product of interruption frequency and mean outage duration, in min/year).

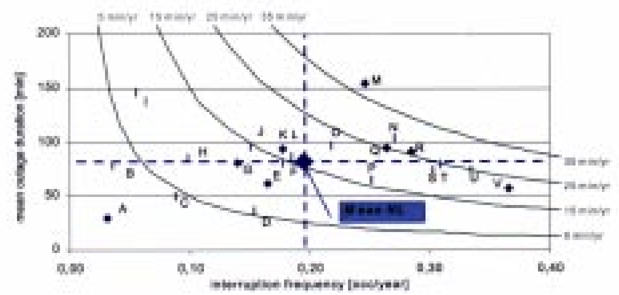

Figure 5 : Comparing utilities on the availability of supply

Paper 2.23 (BR) deals with a methodology for the assessment of reliability indices in electric power distribution companies based on Monte Carlo simulation models. Risk analysis regarding frequency and duration of interruptions for individual customers can be readily applied for actual distribution systems based on some few network attributes, on the company's general network protection practices and on current system average reliability indices. The paper also shows how existing models for investment planning can be extended to consider individual customer reliability indices, so that actions and future system reinforcements are evaluated to meet such established goals.
Also considering the financial aspects of reliability, Paper 2.27 (AR) investigates the relationship between distribution costs and tariffs, by use of simulations of some typical networks (high density urban, urban and rural). Results prove a great quality homogeneity for high-density urban cases and, on the other hand, a great dispersion in the case of rural networks, depending mainly on their characteristics and length. It may be observed that even though there is a similar tendency in cost curves and the quality of service predictable for each type of network, the latter shows a greater dispersion.
Further, the great dispersion in quality levels is not related to the unit capacity costs. In the case of rural networks, the absence of relationship between distribution costs (incorporated in tariffs) and the predicted quality of service (expected from an efficient network management) was verified. In most cases it was also verified that the necessary costs to increase quality of service are of a magnitude order comparable to the distribution cost itself, even if not making it possible to achieve the demanded levels.

In some countries, the regulation authorities impose penalties linked to the reliability of supply. Some resolutions - see Paper 2.29 (IT) - may even establish this more dynamically, by stating minimum improving trends for continuity of supply to LV customers and the relevant premiums / penalties for distribution operators in case respectively of compliance or non compliance with these trends, taking into account, as a weight, the yearly energy consumption of MV and LV customers. This kind of system supposes that control and/or calculation procedures are well established. In this context, it is very important, as pointed out in Paper 2.29 (IT), to establish uniform criteria and methodologies to record and process data on continuity of supply to customers in order to allow comparisons among statistical reports produced by different distribution operators. This report also discusses the concept of load concentration and consequently the possible subdivision of territory into different areas, acknowledging that accidental interruptions depend at large extent on external environment and network structure, which is optimised according to the density and nature of loads fed.

Paper 2.26 (AR) describes a calculation procedure of the corresponding penalties, including the record of network contingencies, type of customer-network connection and non-supplied energy estimation. The control method which is described, comprises the record of interruptions at supply points and the following calculation procedure. The present starting-up stage of the method provides deterministic information about long term interruptions, obtained from about three years of systematic recording. The used method is based on the direct control over points at customer supply level, selected on the basis of statistical sampling techniques. Further statistical processing is oriented towards obtaining indexes expressed as average values by monitored location per semester, for four mentioned interruption categories. The processing target is to obtain some Electrical Service Quality indicators about short interruptions and some indicative figures of the present situation that can be compared, for instance, with the levels published by UNIPEDE (application guide of the European Standard EN 50160) and with the values established in the Franchise Agreements.

At the consumer's side, the assessment of the value of the quality of service and the corresponding satisfaction is of great importance. These topics are investigated, respectively, in Papers 2.20 (GR) and 2.24 (BR). Both studies rely upon large scale inquiries.

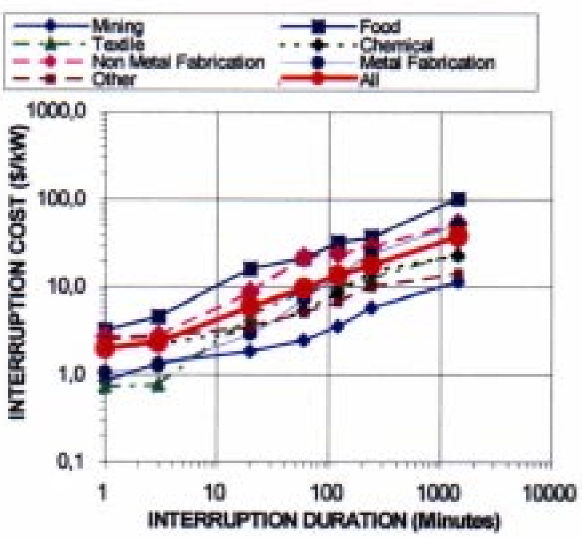

Figure 6 : Industrial consumers damage function

Paper 2.20 is based on the point of view that this assessment is a very difficult task to conduct directly but, alternatively, the costs and losses incurred by the customers as a result of an electric interruption can be easier quantified. These unreliability costs are not identical to the reliability worth but they can be considered as their representative and realistic measures since they constitute a lower bound. Figure 6 gives an example of the costs variations with interruption duration, for various types of industrial consumers (damage function).

Paper 2.24 reports a statistical study aiming at detecting the expectations of the population with regard to power services and deriving two main conclusions: understanding the population's acceptance and tolerance to the services offered and evaluating the practical possibility of fulfilling these expectations.

Finally, Paper 2.16 (ES) deals with more technical aspects of reliability, by studying the most efficient way to operate the MV busbar connection switch in a HV/MV substation with 2 transformers. The aim is to identify the most efficient operation, basing the study on the parameters affecting the problem and to provide a tool to solve each specific case. The main conclusions of the report are that remote control for the MV switch is justified in all cases and, in these circumstances, the substation should be operated with the transformers being disconnected. However, in the absence of remote control, it is better to keep the transformers connected.

QUESTION 5

5.1 There seems to be a great dispersion of the quality in some areas, depending on the geographical situation. Is it acceptable from the customer point of view ? How is this question actually dealt with, among others in contractual applications ?

5.2 Are there any large scale measurement campaigns going on, in order to assess the supply reliability at LV end-user level ? What kind of sensors or measuring devices are used for this purpose ? How are the result statistically processed ?

5.3 Are "premium power" contracts used for industrial consumers ? Are these contracts offered by electricity suppliers of by system operators ?

Voltage dips and short interruptions

The emergence of new electricity applications has increased the consumer sensitivity to voltage dips and short interruptions. Beside outages, these phenomena – being to a certain extent unavoidable in the normal exploitation of electrical networks - are by far perceived by today's industrial consumers as the most harmful disturbances and, consequently, the most important Voltage Quality aspect.
Utilities all over the world are aware of this and assign important means in dealing with the problematic. The different topics that are usually addressed are :

▪ Organising long duration measurement campaigns or installing permanent monitoring systems in order to get an as accurate as possible knowledge of the behaviour of the networks and the loads connected thereto.
▪ Using prediction methods, such as simulation tools.
▪ Studying the immunity of sensitive loads (measurement and/or simulation).
▪ Assessing the costs related to voltage dips, in industrial premises.
▪ Assessing the cost of mitigation techniques (these actions being considered at the consumer's side as well as in the network).

These general topics are illustrated in Paper 2.18 (SG).
An "analytical methods of voltage dip prediction" is presented in Paper 2.17 (GB). It can deal with the probabilistic occurrence of faults and with various meshed networks. This method has been developed to predict the number and severity of voltage dips at bus of interest. It can also be used to predict the characteristics of voltage dips by taking into consideration distributions of line faults and generation dispatches, both of which affect the propagation of dips through a transmission network. A full statistical description of voltage dip occurrence in the form of a probability density function is obtained by using closed form equations derived from the conventional fault calculation procedure. This method is particularly useful when a fast voltage dip assessment on large networks is required and can be easily applied to study the impact of various system conditions and future expansion plans.
Paper 2.17 also thoroughly investigates a modern mitigation technique, called the DVR (Dynamic Voltage Restorer), the principle of which being to inject a voltage in series with the supply voltage such as to mitigate any voltage deviation seen by a sensitive load. It is shown how the results of the dip prediction method can be used for efficiently dimensioning the device.

The estimation of frequency and cost of voltage dips for customers of five Finnish distribution companies, was made in a study reported in Paper 2.25 (FI). An important question to be presented in such a prediction study is what is the voltage dip magnitude that should be kept as a limit when estimating the damage caused to customers. The least severe dips do not cause any trouble to most of the customers. On the opposite a voltage dip of U < 50 % is assumed to cause tripping or malfunction for most of load types. Further, the voltage dip frequency is typically remarkably higher for the least severe dips. Thus the decision as to what is the critical dip magnitude to take into account in the studies has a strong effect on the assessed dip frequency and cost. For instance, the dip frequency of U < 90% is typically several times higher than the dip frequency of U < 50%.

Assessing the economic value of voltage dips for distribution company customers is not a simple or easy task. Due to the lack of exact initial data about dip frequencies and customers' dip oriented costs only rough estimates can be achieved. The relevant value should arise from the real direct and indirect economic consequences of a dip. For example, the dip price for an industrial process which trips should at least cover shutting down the process, cleaning the system, starting up the process, loss of production during the re-start procedure and the eventual cost of damaged equipment.
The reports concludes that further studies are still needed for determining more exact figures of customers' dip related inconvenience and actual economic losses. Also the more precise calculation of dip frequencies would obviously give more accuracy in cost evaluation.

The behaviour of different low voltage appliances during the occurrence of voltage dips is considered in Paper 2.31 (AT). The tested devices were mainly various types of lighting equipment, personal computers and video recorders. For the investigated devices the combinations of amplitude and duration of voltage depressions which result in a malfunction are evaluated. The test described in the paper were performed according to IEC standard 61000-4-11. Measurements have shown that the area of malfunction can be described in many cases by a single point, which represents the minimum voltage needed for continuous operation and the maximum permissible duration of a voltage dip. This is illustrated in Figure 7 for various devices. If the voltage falls below the minimum for steady state operation and exceeds the permissible duration of a voltage dip, a malfunction will occur.

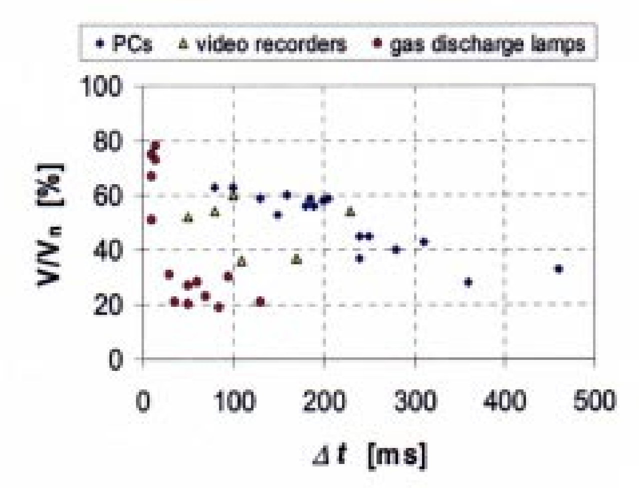

Figure 7 : Left upper points of the malfunction rectangular areas of different electrical devices

Voltage dips industrial case studies are reported in Papers 2.15 (UY), 2.18 (SG), 2.21(MY), 2.28 (EG)and 2.30 (IT).

In Paper 2.15 (UY), it is shown how Power Quality monitoring results can be used to perform on-site assessment of the immunity of sensitive industrial equipment (in this case-study, a rotary-hearth furnace in a cement plant). It is pointed out that even faults occurring at transmission (150 kV) level, and leading to dips not deeper than 30% at plant level, might already be damageable for very sensitive devices.

The electronic process equipment compatibility is addressed in Paper 2.21 (MY). The compatibility is investigated through identifying process equipment at factory facility that is most prone to voltage sag malfunction. Subsequently, evaluations in terms of the identified equipment ride-through capability against voltage dip are carried out, using programmable AC voltage sources. This process is categorised as load side analysis. In addition, the analysis of the reliability and quality of the supply system of TNB transmission is also carried out. This process is essentially a voltage dip stochastic analysis using full network data comprising of the transmission and the distribution systems.
The project is also aimed at developing guidelines on how to improve electronic process equipment compatibility performances and the associated economic considerations.

Paper 2.30 (IT) deals with some practical case studies towards the improvement of industrial processes immunity against voltage dips. In this context, the use of a voltage dip generator, in order to test the sensitivity of devices, is also pointed out. The described desensitising experiences on end-user equipment allows to come to the following conclusions :

- Notwithstanding the high variety of production cycles, sensitivity to disturbances mainly affects similar devices: DC and AC motor drives, asynchronous motors, logic controllers, automation logic.
- The most frequent and dangerous network disturbance types essentially depend on voltage dips whose depth accounts for more than 50% and lasting for more than 50 ms or on short interruptions lasting between 200 and 500 ms.

Such a conclusion allows in many cases to simplify the problem solution in the case of the power supply quality improvement, as it is possible to define a limited number of desensitising methods on different equipment which can be easily and rapidly set on site at convenient costs for the customer.

Applications requiring a constant terminal voltage may benefit from using a distribution transformer based on ferroresonance. This transformer guarantees an output voltage complying with all standards for large fluctuations in input voltage. This offers significant advantages over on-load tap changer control for certain applications, and can be an alternative for power electronic based systems. In Paper 2.19 (BE) the operation of a three-phase constant-voltage-transformer (CVT) is analysed, its behaviour is modelled, and the model is used in simulations. A low power prototype has been built up, in order to validate the design equations. Measurements are compared to simulation results to test the accuracy of the numerical model. An excellent agreement is found between experiments and calculated results, if component losses are taken into account properly.
This device may be considered too for mitigating “light” voltage dips, i.e. not deeper than 30%.

Paper 2.22 (IR) describes an algorithm to take harmonics, flicker and voltage dips into account, in developing tariff or contract between utilities and customers. It includes a classification of loads and an assessment of damages due to lack of Power Quality, allowing the design of contracts. The proposed procedure is used in Iran for industrial and commercial customers but it is applicable at residential level too.

QUESTION 6

6.1 Are simulation tools frequently used in order to predict the statistical occurrence of voltage dips ? Which tools are the most frequently used ? Are they commercially available ? What are the major advantages / drawbacks linked to this approach ?
6.2 What are the most frequently used indices to characterise Power Quality with respect to voltage dips ? What are the reporting techniques ?
6.3 Are there any economic sector-based studies of the effect of voltage dips ? What are the main results of such studies ?
6.4 Is it common practice to use a voltage dip generator for on-site testing the immunity of sensitive industrial processes ? Up to which rated power is it done ?
6.5 What is the methodology for assessing the cost of voltage dips effects in industrial installations ?
6.6 What is the methodology for choosing voltage dips mitigation technologies ?

III. DISTURBING LOADS AND PHENOMENA

Harmonics

Among LF disturbing phenomena, harmonics are still receiving much attention from electrical energy suppliers and grid operators. Harmonics are basically produced by distorting loads (non linear loads) that may be found everywhere, at all voltage levels, from LV distribution (household appliances using switching mode power supply such as TV sets, personal computers, compact fluorescent lamps etc) to MV or HV levels, where big industrial consumers are connected (power electronics, adjustable speed drives, welding machines, arc or induction furnaces and so forth).
Important standardisation works have been done during the last ten years within IEC, concerning the measurement methods and emission limits assessment so that the ongoing practical works today cover

- large scale measurement campaigns in distribution or transmission networks (to be aware of the existing situation and the time evolution),
- connection case studies of big distorting loads (respect of emission limits on public grids),
- industrial networks problems solutions.

Paper 2.37 (FR) presents a measurement campaign to assess the harmonic levels on the LV public networks. For the 5th harmonic voltage (the most important one), the first measurements taken over one week from a sample of 16 typical LV networks revealed:

- levels between 4 and 5% in about 40% of the monitored networks,
- an average increase of about 1% in 10 years (comparison with measurements done in 1991).

These initial results thus reinforce the need to limit harmonic emissions in order to control network disturbance levels. Moreover, if these results are confirmed after a full year of measurements, the situation on the French distribution networks will be critical 10 years hence. If such is the case, more severe emission limits will have to be applied to the equipment and installations.

On the other hand, a similar study performed in Italy (Paper 2.44, IT) rather seems to show that there are no significant problems of voltage distortion. The only exception is the increase of voltage distortion in LV distribution networks with a significant public lighting load. The distortion level, in certain cases, could be remarkably high. An analysis of the problem has been presented based on field measurements and on theoretical and experimental models. The proposed models and experimental tests show that the main cause of the voltage distortion can be traced back to the power factor correction capacitors of the lamps, while their current distortion plays a negligible role. Some possible remedies are the PL load reduction with respect to the rated power of the MV/LV transformer or the increase in the rated power of the transformer with fixed PL load, the partial elimination of the lamp capacitors, the addition of capacitors (with series reactor) with or without the corresponding elimination of lamp capacitors. The effectiveness of the proposed remedies has been verified by field tests or laboratory experiments.

At industrial level, large variable speed drives have become more and more attractive during the last ten years, especially for pumping and compressing applications. Paper 2.38 (DE) explains that, prior to the connection of such drives to the ac system, careful investigation of their effects on the feeding system is required. However in most cases, there are solutions to reduce these effects to such an extent that the limits set by the utility will be met. To obtain the most economical solution for the mitigating equipment, a close co-operation between utility, operator and manufacturer of the plant is required.

Controlling the harmonic level is important not only with respect to the emission limitations on the public distribution grids but also within the facilities themselves, in order to guarantee the compatibility with other sensitive equipment. A case study of harmonic mitigation is discussed in Paper 2.39 (DE), concerning an electrolysis process in a chemical plant. Influence of the internal network structure is analysed as well as filter solutions.

More fundamental works about harmonics still concern modelling techniques for computational purposes. These are very useful when trying to predict harmonics level that may be expected in power systems, i.e. at design stage. Such a matter is proposed in Paper 2.43 (AR) exploring the load models in harmonic flow computation. The CIGRE – or similar – model is presented as the most appropriate one.

Introducing a Steinmetz circuit in a network for voltage unbalance compensation can lead to unsymmetrical harmonic effects. These are thoroughly analysed in Paper 2.42 (RO) showing that, due to the presence of reactive components, they might amplify the currents generated by the existing supply voltage harmonics. As a result, tremendous line currents can occur in the industrial power systems, possibly damaging both the utility and consumer equipment. The results obtained by authors highlight that, if the ratio S_{sc}/S is great enough, the unpleasant consequences of the resonance phenomena can be practically neglected.

Possible harmful effects of harmonics are described in Paper 2.34 (TW), giving the most important results of a study concerning differential relays for transformers.

QUESTION 7

7.1 Is there a general trend towards the increase of harmonics levels in distribution networks ?

7.2 Besides harmonics, are there any recent experiences or interesting cases-studies with other distorting-type disturbances (e.g. interharmonics, transients) ?

Voltage fluctuations and Flicker

When fluctuating or intermittent electrical loads are large enough, they may impact the voltage supply by causing it to fluctuate. Even slight voltage fluctuations on the order of less than one percent cause changes in light output from most types of electric lighting. Most people can detect these slight changes in luminance, and might be irritated by the repeated fluctuations. The degree to which flicker is annoying is not as straightforward a measurement as for other Power Quality phenomena. Much research has been done to understand and quantify the phenomenon of flicker. The ongoing works regarding rapid voltage changes and flicker include individual emission level assessment (this particularly concerns big fluctuating loads, such as electrical arc furnaces) and also the characterisation of flicker generated by new possible sources, such as windmills.

The behaviour of the loads in the presence of voltage fluctuations is studied in Paper 2.33 (GB). A voltage step is generally used as the “initiating” disturbance in tests and simulations related to load model development. The common practice is also to assume the voltage change as an ideal step, and then apply a model identification and parameter estimation algorithm. The voltage step however will not be an ideal one in real life, nor will the voltage of load bus be constant following the step. This paper addresses the influence of voltage variations on the estimation of the load model parameters. Three different load models are compared. Sensitivities of load model parameters for different load models to voltage variation are observed.

When connecting big fluctuating loads to the power grid, individual emission limits are usually specified. It is not an obvious task to measure the emission levels and field experiences have demonstrated that the existing flicker emission assessment approaches do not always lead to good results. The existing approaches (“the simplified approach” and the “voltage drop approach”) suppose that the active power variations and the resistive component of the power system impedance can be neglected. Paper 2.36 (BE) demonstrates that this hypothesis may lead in some cases to important errors and proposes a new assessment method “the load current approach”, which takes the network resistance and the active power fluctuations into account, to overcome this problem. Practical examples are given, involving two different technologies of big electrical arc furnaces (EAF), in the steel industry.
Another report (Paper 2.35, ES) also deals with flicker produced by EAF. Field measurement results are presented together with the application of emission limits assessment, according to IEC technical report 61000-3-7. The practical conclusion of the report is that the current limits for the two characteristic indices may be too strict, as, in a specific margin above the established limits, no visual effect might be perceived.

In the past two decades, wind power has emerged as one of the most economically competitive and promising renewable energy and there is in fact actually a growing interest in the integration of wind power generators in distribution networks. However, such generators may be at the origin of voltage quality problems, among others flicker.
Paper 2.40 (DK) gives the main results of a study aiming at predicting the flicker level that would be caused by windmills in the 50 kV –132 kV –400 kV power system of the Eastern Denmark. Actual recorded power signatures (see Figure 8) and network models are introduced in a dynamic stability analysis software.

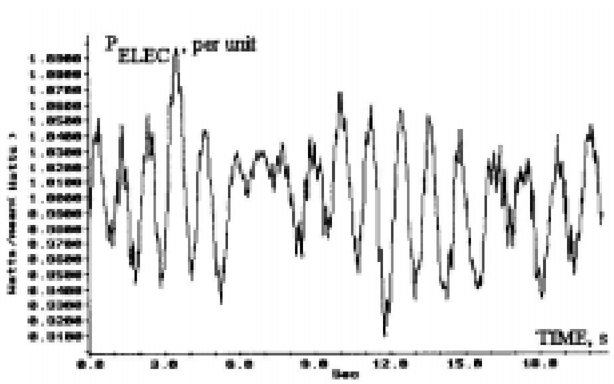

Figure 8 : Measured active power (p.u.) from a windmill generator

The implemented model incorporates the load consumption and the power generation in thermal power plants (the northern part of the power system), a large number of decentralised combined heat-power units, and a large amount of land-based wind power. The windmill settings are scattered throughout the power system. In the model of the power system they are represented by more than 60 on-land windmill equivalents where the largest equivalent is of 30 MW of installed power capacity and the smallest one is less than 1 MW. Each equivalent has a size equal to the sum of all the windmills being connected to the given point of the 50 kV network.
The simulated voltage fluctuations are then processed through a flickermeter model. Flicker levels obtained in MV do not exceed P_{st} = 0,25.

QUESTION 8

8.1 Beside the flicker caused by very large fluctuating loads such as arc furnaces, are there any experiences of flicker caused by other sources in distribution networks ? How problematic is it ?
8.2 What are the usually defined planning levels for flicker in HV and MV networks ?

Unbalance

The distribution of single-phase and double-phase loads along the network and their random instant demand values can be considered as the main causes to voltage unbalance in three-phase distribution systems. Voltage unbalance in three-phase distribution systems is defined as the asymmetry in phase angles and/or in magnitude of voltage phasors.

Paper 2.41 (BR) presents a methodology for measuring, monitoring and controlling voltage unbalance in electrical power distribution networks. A computational model was developed to evaluate voltage unbalance indices. The model considers a three-phase representation of the network, taking into account medium and low voltage network branches as well as distribution transformers (three-phase transformers or bank of single-phase transformers), capacitor banks, etc. A load flow calculation is carried out as many times as necessary following a Monte Carlo method that randomly generates scenarios in a given instant along the load daily curve.
Simulation results were validated mainly when considering that 95% of the time the voltage unbalance index is inferior to 3%.

QUESTION 9

In MV or HV networks, voltage unbalance has to be measured at the secondary side of voltage transformers with an accuracy of about 0.1 %. Field measurements proved that these measurements are highly unreliable. We know that several devices were developed to overcome the problem in the case of harmonics. Do simple solutions also exist for measuring voltage unbalance ?

IV. PQ MONITORING AND NEW TECHNOLOGIES

Power Quality Monitoring

Paper 2.53 (CZ) describes systematic Power Quality measurement campaigns performed in distribution networks. For harmonics, it is concluded that in nearly all cases the measured values, in some cases even with some margin, comply with the requirements according to European standard EN 50160.
No particular problems were reported, regarding flicker and unbalance.
The paper also investigates some particular network problems, related to Power Quality: effect of harmonics on generators and motors, effect of capacitor banks on ripple control signals.

Based on state of the art Power Quality measurement systems for online monitoring Paper 2.51 (DE) suggests several methods for an enhanced assessment. Starting from the assessment algorithms provided by actual standards these methods are extended to be more detailed and reliable. Several new quality parameters like planning reserve or quality index are introduced. Introducing these new Power Quality parameters and indices enhances the simple qualitative rating algorithm of the standard and helps the utilities to provide different customer-dependent grades of power quality at optimum costs. Thanks to the new easy-to-understand quality parameters, quality monitoring is no longer a matter for power quality experts only.

As widely discussed in Papers 2.45 (BE), 2.46 (FR) and 2.47 (FR), Power Quality monitoring is today required for technical reasons (technical management of the system, technical problem detection or troubleshooting, investment and planning purposes), marketing reasons (care policy towards the customer) and liability reasons (reporting towards Regulation Authorities).
Thanks to the competition amongst PQ monitoring equipment manufacturers, solutions are proposed today that allow wide scale and powerful PQ monitoring at a cost effective price.
Among the advantages of permanent PQ monitoring, one is surely the fact that, when an instruments has been installed, it automatically provides all kind of information the system operator and users might need. Long term trends for harmonics, dip statistics or standard compliance analysis are performed automatically and data coming from the whole network are centralised at one location. No more need for long trips to install a portable equipment, all operations (configuration change, data upload,…) being performed remotely. A second advantage is that when an event (outage, voltage dip) occurs in the network, PQ monitoring equipment are already installed and comparison of the event at different places shows relevant information about the cause and the effect. The presence of PQ monitoring instruments installed at the feeding point of the major customers has been considered by many of them as a real care policy from the supplier. Although this is hardly transposable into clear profit analysis, it is obvious that improving the relationship with the customer is, in the deregulated market, a key issue.

A future possibility is to define Power Quality monitoring functions as a part of integrated distribution automation, as pictured in Figure 9. Such a project is described in Paper 2.54 (FI). Distribution automation opens in fact new possibilities for continuous Power Quality monitoring. For example, modern protection relays and monitoring units or intelligent kWh-meters include new functions to monitor Power Quality both at primary substation and secondary substation levels. The advanced computer systems of the control centre with open architecture make it possible to integrate Power Quality data in the normal network operation and planning processes.

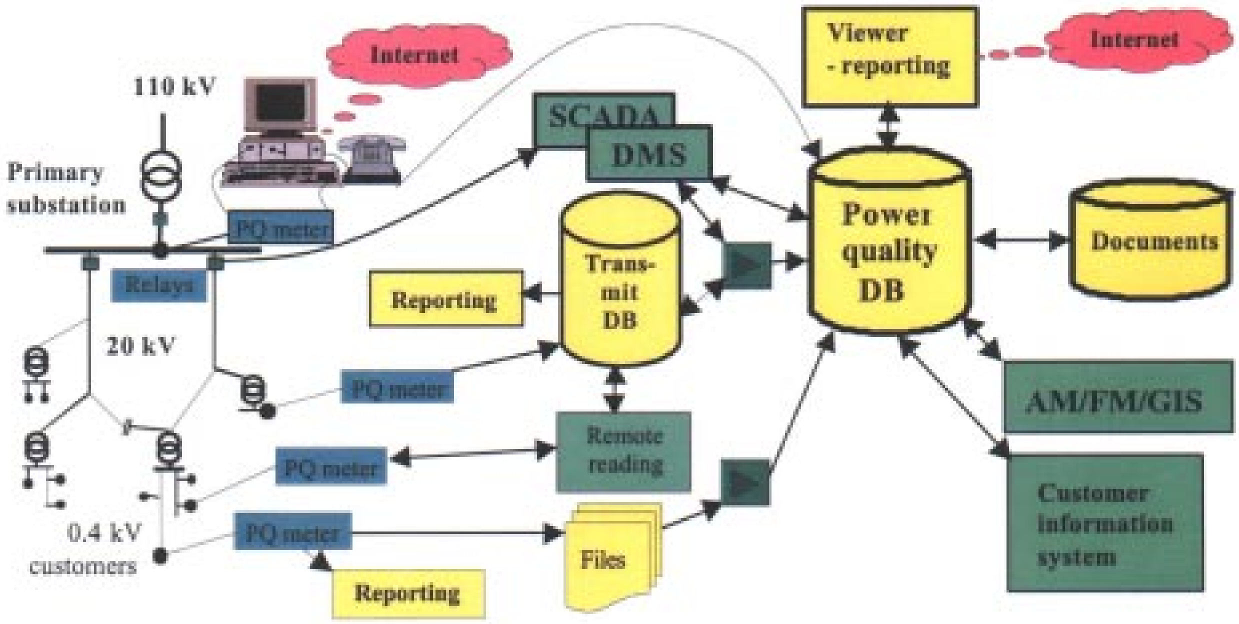

Figure 9 : The Power Quality data management system as a part of the integrated distribution automation concept.

When some abnormal parameters are identified by continuous on-line monitoring, more detailed measurements with advanced measurement equipment can be done at specific network points or at customers location. Automated assessment of disturbances may then facilitate the overall PQ assessment. More specifically on this matter, Paper 2.52 (US) is focusing on :

- developing better tools for automated detection, classification and characterization of PQ disturbances,
- carrying out system and equipment modeling studies to better understand the PQ disturbances,
- finding the fault location if the disturbance is identified as a dip caused by a fault. Intelligent techniques like fuzzy logic, expert system and genetic algorithm, as well as signal processing techniques like Fourier transform and wavelet analysis have been utilized for developing the tools.

QUESTION 10

10.1 What are the most commonly monitored PQ-parameters ? Which methods are the most suitable for the measurement of these parameters and the assessment of PQ-indices ? Are the actually available meters satisfactory ?

10.2 Is there an interest of combining functions in a single device, such as distribution automation or metering and PQ-measurement ? What are the future trends ?

10.3 Who has the responsibility for Power Quality monitoring ? What is the situation today and what could be the trend in the future ?

10.4 What kind of periodic quality reporting is currently done – or will be in the near future – by the system operators ?

Mitigation techniques & Emerging technologies

Mitigation techniques available today for solving Power Quality problems, range from rather very low cost solutions with respect to the involved process (see Paper 2.30), to high technological products, which are obviously more expensive. This quite broad range of techniques should continue to exist in the future although the evolution of the technology, together with other influencing factors such as the expected growth in dispersed generation, might drastically change the way Power Quality is dealt with.

New series of medium-voltage circuit-breakers with a magnetic drive instead of a spring-based operating mechanism are presented in Paper 2.55 (CH). The magnetic actuator, based on limited number of parts, very simple cinematic chain and compact design, allows a higher number of mechanical operations. A power electronic controller supervises and operates the magnetic drive from one to the other of the two stable positions by injecting a current pulse in the actuating coil.

This new generation of intelligent switching device with high performances allows improved functionality towards Power Quality improvement:

- High Speed Transfer System (HSTS), based on a fast circuit breaker, to drastically reduce the operating time, enables to transfer the load to an undisturbed power supply (Figure 10).
- Synchronous Circuit Breaker (SCB), with independent single phase real-time controlled operation, to reduce network switching transients (capacitor banks, transformers).
- Power Factor Controller (PFC), integrating the Power Factor improvement function in MV switchgear, with state of the art and resonant protection.

This technology is presented as a good compromise, in some cases, with respect to more expensive sophisticated ones.

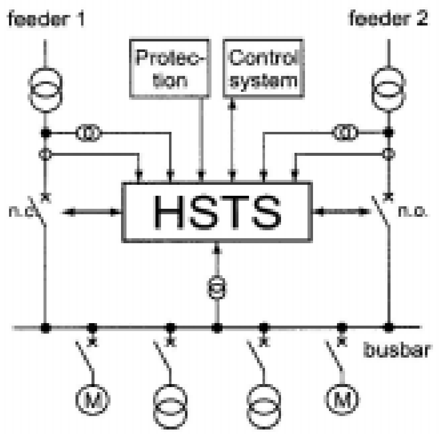

Figure 10 : Example of HSTS application (2 circuit breakers configuration)

In order to solve emission as well as immunity problems, innovative power electronics devices are emerging for a few years. The availability of these technologies – generally known as “active conditioners” - allows for customised solutions and a greater flexibility for the satisfaction of the technical as well as economical needs of the consumers.

This may be done at customer level, as detailed in Paper 2.48 (FR) as well as at system level, as explained in Paper 2.56 (CH).

Harmonics mitigation in LV industrial networks is more and more achieved by use of active filters. These devices are discussed in Paper 2.50 (SE) while some experimental case studies are presented. Some of the most currently given advantages of the active filter are :

- The filter does not affect the impedance of the network, i.e. does not create any resonance.
- The performance of the filter is not affected by changes of load or of network impedance.
- The filter enables selective choice of filtering with respect to harmonic frequencies and extension of filtering.
- Filtering of harmonics can be obtained independently from reactive power generation.
- There is no risk of overloading.

- Compact design.

The design of active filters being based on PWM with IGBT technology, they generate disturbances at frequencies which are multiples of the switching frequency of the IGBT. Generation of high frequency disturbances, up to 100 kHz, might thus be feared.
Active filters may possibly be used in combination with classical passive filters (hybrid filter). This solution, combining the advantages of both technologies, is discussed in Paper 2.47 (FR).

With recent development in the power electronics and semiconductor fields, Voltage Source Converters (VSC) far into the tens of MVA range have become feasible. Applied in MV to power systems, VSCs will bring about dynamic as well as steady-state voltage control in subtransmission and distribution, as well as power quality improvement. Thus, VSCs equipped with high power Insulated Gate Bipolar Transistors (IGBT) and utilizing Pulse Width Modulation (PWM) as part of the concept are a reality today. These enable power grid conditioning with high efficiency and high dynamic response, achieving power quality improvement as well as an increase of system stability without any need for grid reinforcing in the more traditional sense. These devices are described in Paper 2.49 (SE), in particular the “SVC light” application for flicker mitigation and the DC-link, for the asynchronous connection of two systems.

Paper 2.56 (CH) explains how power electronics devices will probably deeply modify the structure and operation of distribution grids, in the coming years. In fact, besides the classical PQ-problems which can be mitigated as described above, the growing share of distributed resources (like distributed generators, storage etc., uncontrollable and controllable one’s) and new network control strategies with wide area communication requirements have to be considered.
It is pointed out that all controlled distributed resources can contribute to Power Quality improvements, in particular storage equipment for bridging short term dips or outages which are the most frequent problems. Hence, in the future, classical PQ-problems cannot be considered alone any longer and the integration of different functions for different applications will lead to economically attractive solutions.

New system configurations will probably appear, such as the one shown in Figure 11..
Important breakthroughs in DC-cable technology and in technologies derived from modern HVDC-systems will likely play an important role in the future, because new high power semiconductors with fast switching capability allow extremely compact installations with extended functionality integration.
Within the next years the economical range of a power electronics-based MV power distribution system is expected to go down to typical power and voltage levels of the MV-distribution grid.

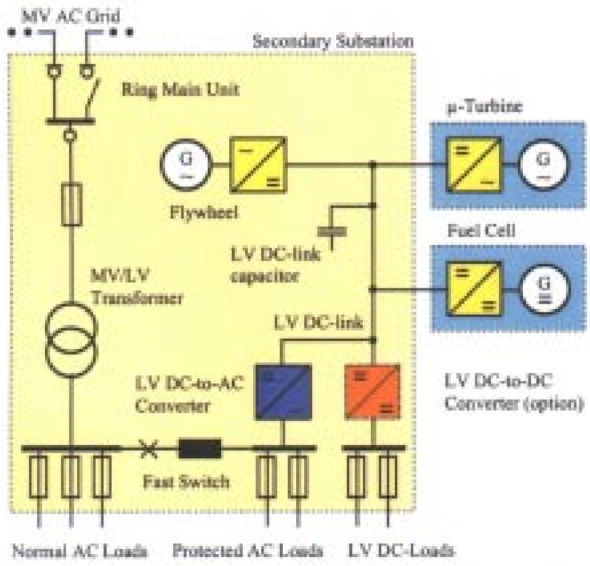

Figure 11 : Future Power Quality oriented sub-system

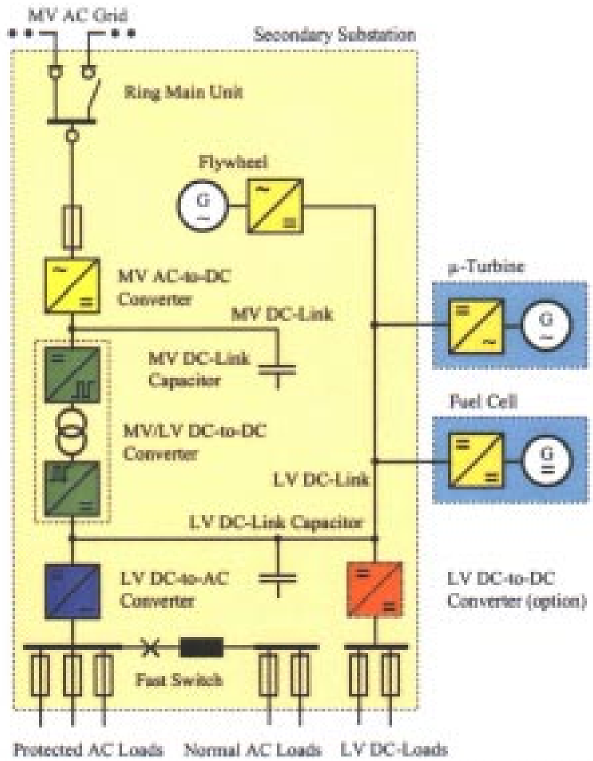

Figure 12: Future oriented fully integrated PQ-system with high frequency switched “electronic transformer”

Driven by these technical innovations also the economical replacement of a MV/LV distribution transformer with a high frequency switched “electronic transformer” seems to be feasible. The power electronics based transformer can operate either on an MV AC input (3 phases or 1 phase) or a MV DC input. The electronic transformer can be considered as a fully integrated PQ-system which enables load balancing, mitigates flicker and guarantees low harmonic current distortion. Voltage dips or outages on the MV-side can be bridged.

Figure 12 shows such a future oriented PQ-system. The system consists of a high frequency switched “electronic transformer” with MV and LV DC-bus, an integrated short term bridging device (e.g. a flywheel connected directly to the common LV DC-bus) and an interface for local power generation units to bridge long-term outages and to serve for co-generation.

QUESTION 11

11.1 Are there recent experiences with active conditioners ?

11.2 Are there any problems with the HF components generated by PWM converters ?

11.3 Do we think that the evolution of distribution networks will be such as described inFigure 11 and Figure 12 ? Are there any other technological breakthrough to be expected within the next decade ?