EUROPEAN TRANSACTIONS ON ELECTRICAL POWER
Euro. Trans. Electr. Power (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/etep.370

Trends, challenges and opportunities in power quality research

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SUMMARY

This paper outlines a number of possible research directions in power quality. The introduction of new sources of generation will introduce the need for new research on voltage–magnitude variations, harmonic emission and harmonic resonance. Statistical performance indicators are expected to play an important role in addressing the hosting capacity of the power system for these new sources. The quickly growing amounts of power-quality data call for automatic analysis methods. Advanced signal-processing tools need to be developed and applied to address this challenge. Equipment with an active power-electronic interface generates waveform distortion at higher frequencies than existing equipment. The emission, spread, consequences and mitigation of this distortion require more research emphasis. The growing complexity of the power system calls for remote identification of system events and load transitions. Future DC networks, at different voltage levels, require the research on DC power quality next to AC power quality. Research on methods to describe and analyse time-varying harmonics has applications in a number of the above-mentioned issues. So does the use of hardware-in-the-loop (HIL) and real-time-digital simulation.

Existing power quality standards should not form a barrier against future research; instead research should result in improved standards as well as completely new concepts. Examples are: voltage dips in three-phase systems, flicker due to non-incandescent lamps, and voltage variations on the timescale between 1 second and 10 minutes.

All together, it is concluded in this paper that sufficient important and interesting research challenges and opportunities remain in the power quality area. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: power quality; harmonics; distributed generation; signal-processing applications

1. INTRODUCTION

The number of papers on power quality has been growing almost linearly since about 1990 (see Figure 1) with over 800 papers published on this subject in 2007. Many of the original research questions have been solved through the years and significant progress has been achieved on others, for instance [1,2]. That however does not mean that all is solved and that power quality research is no longer needed.

A number of interesting research subjects remain, others have appeared only recently due to the appearance of new types of equipment connected to the power system. This paper will introduce some of the research challenges within the power quality field at the moment. Examples of new equipment are new sources of generation (Section 3), equipment with active front end (Section 5), HVDC links (Section 10) and new types of lighting. The need for automatic analysis methods (Sections 4 and 7) is on the other hand a consequence of the success of power-quality measurements. Other developments are made possible by the availability of fast computing tools (Sections 6, 8 and 9). This paper gives some directions envisaged for future research on power quality, where each of the forthcoming sections addresses the different trends. The exception is Section 2 in which a number of subjects and directions are merged together with some general views on the future of power quality.

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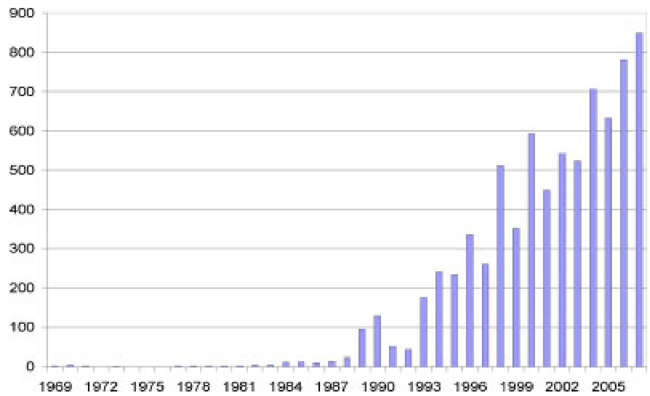

Figure 1. Number of papers per year in the INSPEC database using the term ‘power quality’ in the title, abstract or keywords.

2. DIFFERENT TYPES OF DISTURBANCES

There are different ways of defining a power quality disturbance or problem. A power quality disturbance can be defined as a deviation from the ideal (sinusoidal, constant magnitude) voltage or current [1]. There exist numerous alternative definitions. According to IEEE 1100 ‘power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of the equipment’. Within IEC standards the related term electromagnetic compatibility is used. According to IEC 61000-1-1 ‘Electromagnetic compatibility is the ability of an equipment or system to function satisfactory in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment’.

The term ‘interference’ is usually used when a device or a power-system component or equipment gets damaged, experiences a reduction in lifetime or functions outside of its specification due to insufficient power quality. These interferences are the principal reason for interest in power quality. However a large part of the studies in power quality concern disturbances. For example a ‘voltage dip’ is a disturbance that may or may not result in interference. A small deviation of the system frequency from its nominal value (like a drop to 49.7 Hz) is also an interference, but one that will almost certainly not result in any interference. Some studies have been performed that study the interference directly. In the case of a voltage dip this could imply keeping a record of the production stoppages of a large industrial installation. For voltage dips the interference mechanisms are rather well understood, but for other disturbances the mechanisms are still under investigation. An example of the latter is the failure of common low-voltage equipment due to high voltage magnitude.

Related to the impact are the economic consequences of power quality disturbances. A review of the knowledge on power quality economics is currently being made in CIGRE, CIRED joint working group C4.107. The final report of this group, expected to be available in 2010, will present a number of research challenges on power quality economics.

The study of the relation between disturbances and interference suffers from the compartization of power quality. The understanding of power quality disturbances has gained enormously from the distinction between different disturbances, for example voltage dips *versus* harmonics. This has in turn resulted in a set of useful power quality standards. Standardization, where very important to prevent interference, has often the tendency to slow down or even block further research. Researchers should not feel constrained by standards and they should dare to deviate from them when needed. Some random examples are

- Voltage dips are, according to standards, characterized by one magnitude and one duration. This should not stop researchers from looking into additional characteristics. Especially the three-phase character of voltage dips has been underexposed because of these standards. Recently a joined working group by CIGRE, CIRED and UIE looked among others into the characteristics of voltage dips. One of the conclusions from the work was that manufacturers should be aware of more characteristics than just magnitude and duration [3,4].
- Harmonic standards cover the frequency range up to 2 or 2.4 kHz. There is however plenty of scope for research at higher frequencies [5]. This will be further discussed in Section 5 of this paper.
- Waveform distortion is quantified by means of a spectrum obtained over a 200-ms window. This should not stop researchers from persuing alternative methods. Tracking individual interharmonics with high time resolution is a subject that requires more advanced methods [6].

DOI: 10.1002/etep

- The flickermeter standard has been one of the most successful power-quality documents, one that has been using the above mentioned 'impact-based description of power quality' for many years. The flickermeter is however based on continuous voltage fluctuations and incandescent lamps. Future concerns will more likely involve other types of lamps and continuous as well as occasional changes in voltage magnitude. The flickermeter concept either has to be adjusted or replaced by something completely different [7].
- Voltage–magnitude variations are quantified at one end of the timescale by means of the 10-minute rms voltage and at the other end by the flicker-severity indices (Pst and Plt). The time range between 1 second and 10 minutes is rarely covered [8].
- A new generation of standards and engineering recommendations which take into account the actual susceptibility of electronically controlled and/or electronically processed loads and equipment rather than the existing generic standards based on thermal or mechanic impact of voltage deviations. New standards will require both a micro (individual equipment) and macro (system wide) perspective regarding the technical specification as well as a time dependent nature and equipment impact correlation [9].

An interesting fundamental research challenge is to develop a power quality framework that is not based on any comparization. The consequences of such an approach cannot be overseen by the authors of this paper, but such research will certainly lead to interesting results.

Most standards, for obvious reasons beyond the scope of this paper, address disturbances independent from their impact. An impact-based approach would likely result in another classification of disturbances than the existing one. For example, the risk of overload of a distribution transformer is impacted by variations in active power, by reactive power, by current unbalance, by harmonic currents, by load-switching inrush and more. The challenge is to combine all these disturbances in such a way that it results in an index that predicts the loss of life or the overload risk of the transformer due to the load current.

3. NEW SOURCES OF GENERATION

The penetration of new sources of generation into distribution and transmission systems is taking place in many countries around the world. The advantages and disadvantages of this development have been discussed in detail at many places and the discussion is ongoing. Of importance for this paper are the power quality research challenges associated with this new development.

3.1. Performance indicators

A very important first observation should be that connection of generation at low- and medium-voltage levels has a lot of similarities with the connection of industrial installations. This implies immediately that a power-quality based approach may also be appropriate for the connection of distributed generation. The so-called 'hosting-capacity approach' developed within an integrated European research project (EU-DEEP, www.eu-deep.com), originated from recognizing this equivalence [10]. The hosting-capacity approach combines appropriate performance indicators with a limit (the 'hosting capacity approach') of what constitutes acceptable performance. The main challenge is to define a set of indicators and limits that cover all the tasks of the power system.

3.2. Voltage–magnitude variations

Voltage–magnitude variations in distribution networks will be impacted in a number of ways by the introduction of distributed generation. The injection of active power will result in overvoltages beyond what is normally considered as acceptable, as illustrated in Figure 2 where the introduction of generation in a distribution feeder may raise the voltage level. This will in turn require additional and complex voltage control at the distribution system.

A thorough study of the expected overvoltages and their impact on end-user equipment is needed. In addition to changes in voltage profiles, distributed generation will cause transients, increase in the short circuit level, congestion in system branches, power quality and reliability impact and will require protection adjustments. Any limits set on overvoltages or other performance parameters should be a fair balance between the need for more renewable energy and the risk of damage to end-user equipment. The before-mentioned 'impact-based approach' would form an important part of such a discussion.

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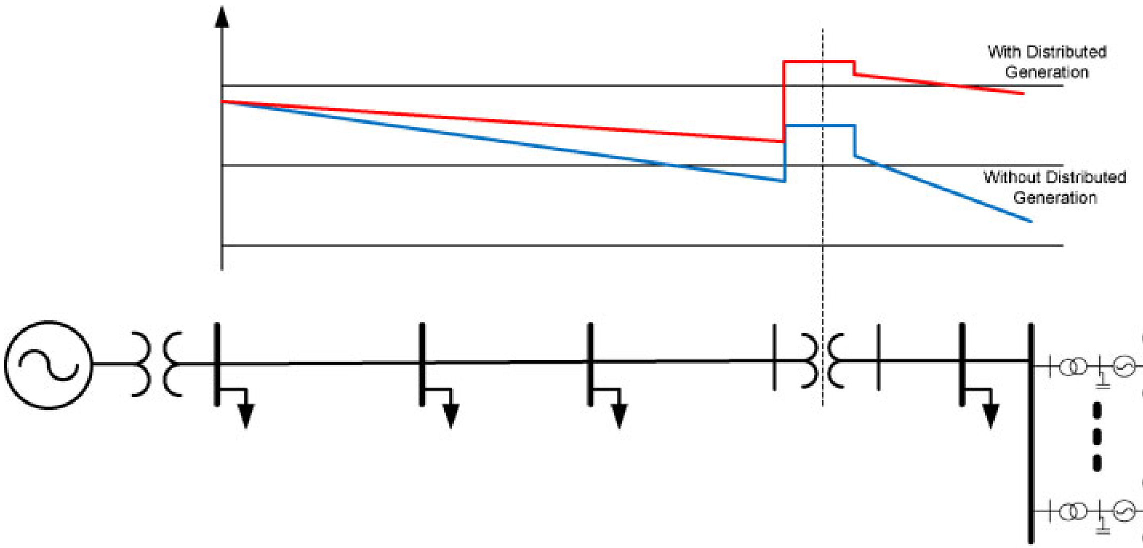

Figure 2. Voltage profile of a distribution system with DG.

Note also that this subject contains mainly normal low-voltage equipment with domestic and commercial customers, like televisions, computers, lamps and refrigerator motors. This kind of equipment has somewhat been underrepresented in power-quality investigations.

Distributed generation produces voltage–magnitude variations over a range of time scales from less than 1 second through 10 minutes and longer. This holds especially for weather-based sources like solar and wind power. The challenge is to develop stochastic models of the generated power including the correlation over different time scales and between generators at different locations.

An example of the hosting-capacity approach for voltage–magnitude variations is shown in the forthcoming figures. A measurement of the 1-second rms voltages was used as a starting point. Added to this was the voltage rise due to the injection of active power by a wind turbine connected to a 10 kV feeder. The probability distribution function of the wind power production was calculated from the wind speed using the power curve for a 600 kW turbine scaled to the size of the wind power (1, 2 or 3 MW in this case). For the wind speed aWeibull distribution with an average value of 7 m/second and shape factor of 2 has been used. A Monte–Carlo simulation has been used to obtain the probability distribution of the sum of the two stochastic variables (pre-wind voltage and voltage rise). The results are shown in Figure 3, with the amount of wind power increasing from left to right. The rise in voltage magnitude due to increasing amounts of wind power is clearly visible.

In this example, only one wind turbine has been assumed, so that the wind-speed distribution for this location can be used. With more units connected to the same feeder, the correlation between the wind speeds at the different locations should be considered. In this example it has also been assumed that the pre-wind voltage and the wind speed are statistically independent. This might not be the case in reality as both show daily and seasonal variations.

To determine how much wind power can be accepted at this location without the need for additional measures, a suitable performance indicator and an appropriate limit are needed. For this example the maximum voltage has been compared with the 99.99, 99.9 and 99-percentiles of the voltage magnitude. These four performance indicators have been calculated for different amounts of wind power and the results are shown in Figure 4. The dashed line at 100% voltage corresponds to the overvoltage limit: the maximum-acceptable value for the indicators. The maximum pre-wind voltage was equal to 99% of the overvoltage limit.

As mentioned before, the hosting capacity is the amount of wind power that can be connected to the grid without resulting in unacceptable performance. In Figure 4 the hosting capacity is found as the intersection between each of the curves and the 100% line (the overvoltage limit). As can be seen in the figure, the resulting hosting capacity depends strongly on the choice of the performance indicator, thus on what constitutes unacceptable behaviour.

- The maximum voltage exceeds the limit for 1 MW wind power.
- The 99.99% voltage exceeds the limit for 1.4 MW wind power.

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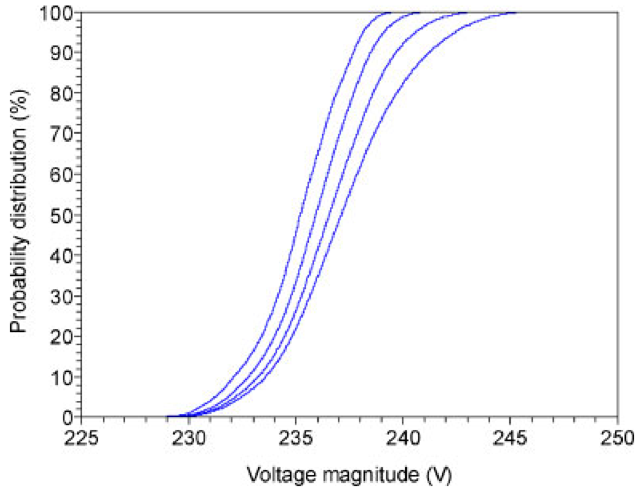

Figure 3. Probability distribution function of the voltage magnitude; left to right: no wind power; 1 MW wind power; 2 MW wind power; 3 MW wind power.

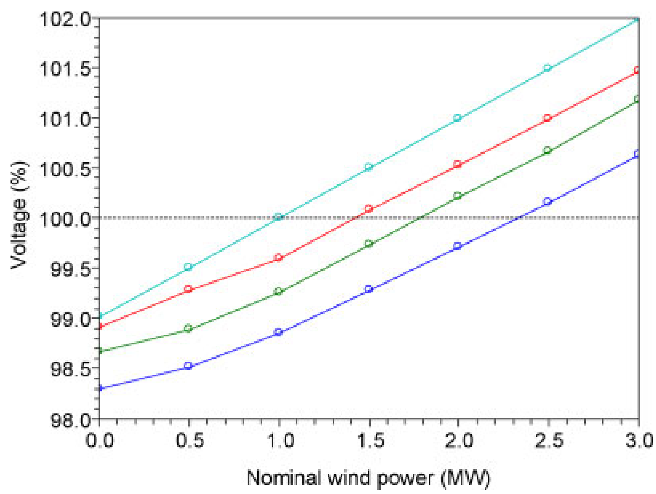

Figure 4. Statistical overvoltage indicators as a function of the amount of wind power; top-to-bottom: 100, 99.99, 99.9 and 99%.

- The 99.9% voltage exceeds the limit for 1.8 MW wind power.
- The 99% voltage exceeds the limit for 2.3 MW wind power.

The calculations have been repeated for voltage variations measured at 20 different locations in several different countries. The resulting hosting capacities are presented in Figure 5. To make the comparison meaningful, the measured voltage magnitudes have been scaled in such a way that the maximum pre-wind voltage magnitude equals 99% of the overvoltage limit. The source resistance at the point-of-common coupling between the customer and the wind turbines has been scaled such that 1 MW of injected power results in a 1% rise in voltage.

The figure shows that the probability distribution function of the pre-wind voltage has a significant influence on the hosting capacity when a statistical indicator is used. When a deterministic criterion is used (the maximum voltage) the hosting capacity is the same at all locations, as a direct consequence of the scaling used.

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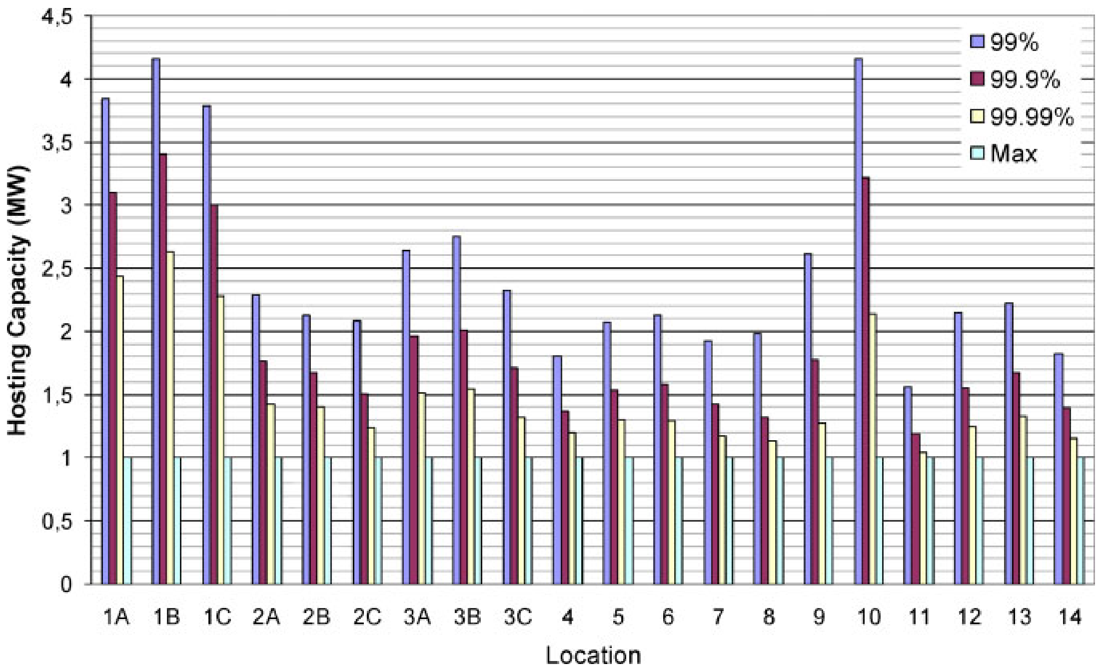

Figure 5. Hosting capacity at 20 different locations; left-to-right (for each location): 99, 99.9, 99.99% and maximum voltage.

3.3. Harmonic emission and resonances

The emission of harmonics due to renewable energy depends on the interface with the grid. When rotating machines (induction or synchronous machines) are used the harmonic emission is generally small. For power electronics interfaces the situation is different. Some cheap converters used for the connection of solar panels inject high levels of low-order harmonics. This is however not the case with the majority of converters and for most converters the emission is significantly less than for equipment like televisions and compact fluorescent lamps.

The introduction of new sources of generation is associated with the introduction of additional amounts of capacitance to the grid. Examples are the electromagnetic interference (EMI) filters of solar panels, power-factor correction capacitors for induction generators, and long cables to connect wind parks to the transmission grid. This additional capacitance will both add new resonance frequencies and shift the dominant resonances to lower frequencies. In low voltage networks, resonance frequencies below the 10th harmonic are not likely, but further investigations will be required. In transmission networks much lower resonance frequencies may occur in the future. A resonance frequency of 140 Hz has been found for the cable connecting a sea-based wind park to the 150 kV grid [11]. Two frequencies of interest are the second and third harmonic (100 and 150 Hz on a 50 Hz system). At 150 Hz the main source of emission at transmission levels is the magnetizing current from power transformers. This emission will be further increased by the higher voltage magnitude because of the presence of the cable. This plus the harmonic resonance could result in high third-harmonic voltages. At 100 Hz, the positive feedback from HVDC converters could result in high levels of DC current and second-harmonic voltage.

The main emission due to new sources of generation will take place at frequencies above those that normally are considered. Power electronic converters used for wind turbines, solar panels and microturbines are based on switching elements (like transistors, IGBT's and GTO's). The main emission of these convertors takes place around the switching frequency and around multiples of the switching frequency. The switching frequency ranges from somewhat above 1 kHz through some tens of kHz. This frequency range will be discussed further in Section 5 of this paper.

4. AUTOMATIC ANALYSIS OF DISTURBANCE RECORDINGS

The availability of growing amounts of measurement data makes it impossible to analyse all recordings manually. Methods to automatically extract all important information from the available data are needed.

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A first level of information extraction is already available and implemented in almost every power quality monitor. This concerns the classification of an event (transient, voltage dip, interruption, etc.) and the calculation of standard characteristics for events (magnitude, duration, etc.) and variations (THD, Pst, rms voltage,etc.).

Instead, the available research resources should be directed to the next steps in automatic information extraction.

- The definition and automatic extraction of additional characteristics that provide information on the origin of events. The segmentation method introduced in Reference [12] has proven to be a suitable base for an automatic analysis of voltage dips and interruptions. Although it is certainly possible that the method can be further improved, a bigger research challenge is to develop similar methods for voltage and current transients. An example of segmentation is shown below.
- Additional characteristics linking waveform distortion, frequency variations, and voltage–magnitude variations with their origin. This could be not only characteristics recognizing certain spectra but also pattern recognition methods to correlate time variations of power-quality disturbances with the variation of certain loads or consumption patterns with time.

An example of a segmented waveform is shown in Figure 6. In this example, the segmentation results in detected time interval [4.8, 25] cycles, consisting of four 'transition segments' (marked by the yellow colour), three 'event segments' in between each of the two nearest transition segments. Further, the segment before the first transition segment ('pre-event segment'), and the segment after the last transition segment ('post-event segment') are segments related to the normal states.

The segmentation method has also shown to be very useful as a tool to describe voltage dips [13]. The method has therefore been adopted recently by an international working group to allow communication between power quality experts and developers of new equipment that might be sensitive to voltage dips.

Detecting the segments from visual inspection of the waveform is in many cases obvious, as for example has been observed in Figure 6. The development of accurate and reliable automatic analysis methods is the research challenge that requires cooperation between signal processing and power-system experts.

Triggering and segmentation both involve the detection of a deviation from the quasi-stationary character of a voltage or current signal. Therefore the same kind of signal-processing tools are used for segmentation and for triggering. The segmentation of an event is equivalent to finding transition segments. Three basic types of methods for detecting transition segments can be distinguished.

- The first type, containing the simplest methods, is to calculate a number of time-dependent waveform features, typically the time-dependent RMS voltage/current magnitudes. The transition segments are then detected by comparing the change in magnitude with a pre-determined threshold. Although this method only requires simple signal processing, it turns out to be remarkably efficient for most measurement recordings. The triggering method used for voltage dips, swells and interruptions, in the vast majority of existing instruments, uses the RMS voltage.

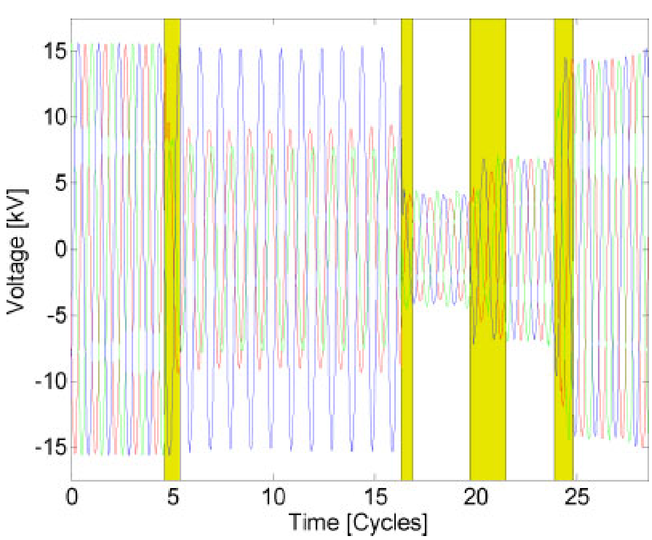

Figure 6. Example of event segmentation from a voltage waveform recording. The shaded blocks indicate the transition segments.

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- The second type is to use high pass or band pass filters followed by detecting step changes or oscillations. An event in the power system often results in a fast step change in voltage (or current), and also results in high-frequency oscillations. A high pass filter can thus be used to detect such a step change or oscillations. Many studies have been conducted, especially using wavelets, and are common in the literature. Wavelet filters are known to be effective in detecting multi-scale singular points, and triggering points are usually related to significant sudden changes or singularities in the signal waveform. Since wavelet filtered signals show all multi-scale singular points of a signal waveform, some post processing is required to identify the triggering points (i.e. the start and end points). An advantage of using wavelet filters is their ability to automatically find the best resolution scale for detecting the triggering points. However, there is no reason to restrict the use of wavelet filters, as other high pass filters may perform equally well for detection or segmentation. An analogue or digital high-pass filter is typically used in existing instruments to detect transients.
- The third type is parametric methods, where a signal model (e.g. damped sinusoids model, autoregressive model) is used. Depending on the algorithms used, a recorded data sequence may be divided into blocks, and the model parameters in each block are estimated (e.g. using ESPRIT (Estimation of Signal Parameters *via* Rotational Invariance Techniques), MUSIC (MUltiple SIgnal Classification) or AR (Auto Regressive) models). Alternatively, iterative algorithms may be used without dividing data into blocks (e.g. using Kalman filters). The 'residuals' (or model errors), which indicate the deviation between the original waveform and the waveform generated by the estimated model, are then calculated. As long as the signal is quasi-stationary the residual is small; however, for a sudden change in the signal, e.g. a transition, the residual values become large. Hence, residuals of a model can be used to detect the transition segment.

Each of these methods has their own advantages and disadvantages. An important requirement for further study is to evaluate and compare the performance of different methods for real disturbance recordings. It is important to realize that the final aim is to detect the instant at which a change in the power system takes place. The different methods should therefore be evaluated for their ability to correctly detect and localize these changes: in terms of time resolution, the detection rate, and the false alarm rate of the detected points. The classic tradeoff between the detection rate, false alarm, and time resolution may play an important role here.

The segmentation method, resulting in a number of characteristics (a power quality term) or features (a signal processing term), is just the first step in the automatic analysis of voltage dips and interruptions. These characteristics are next fed into an automatic classification method, which might be an expert system, a neural network, or an advanced signal processing method like a support-vector machine. The development of an expert system builds completely on existing human knowledge, whereas statistical methods like neutral networks or support-vector machines deduct their own rules based on the analysis of large amounts of data.

A detailed overview of these and other research challenges in signal processing applications to power quality is presented in Reference [14].

5. HIGH-FREQUENCY DISTURBANCES

The introduction of equipment with a so-called active front end results in new frequency components being injected into the power system. As an example, the upper trace in Figure 7 shows the current measured at the terminals of a modern fluorescent lamp with high-frequency ballast. The current waveform is close to sinusoidal and the harmonic distortion is clearly less than what used to be common for such types of lighting. The absence of low-order harmonics (like 3, 5 and 7) comes at the expense of high-frequency distortion at frequencies of several kHz and higher. The bottom trace in Figure 7 shows the high-frequency contents in the current: after a high-pass filter with a cut-off frequency around 2 kHz. This high-frequency content varies during the course of one cycle of the power-system frequency (20 milliseconds). A number of short-duration spikes are visible as well as a high-frequency oscillation of varying amplitude. Study of a large number of devices has shown that this is a common pattern of behaviour for equipment with an active front end [15].

To describe the emission due to such equipment, and to study the spread of the disturbance through the power system, new tools are needed. The spectrogram, once developed to describe speech signals, has shown to be a very useful tool for this [16,17]. An example of such a spectrogram is shown in Figure 8. The figure was created by averaging the spectrogram of the high-pass-filtered current in Figure 7 over nine 20-ms windows. A simple discrete Fourier transform (DFT) has been used to obtain the spectrogram, but more advanced signal-processing methods might be able to extract more information. A sliding-window ESPRIT method is successfully applied to this signal in Reference [18]. Another interesting challenge is to find the best way of presenting the spectrogram, in colour as well as in black and white.

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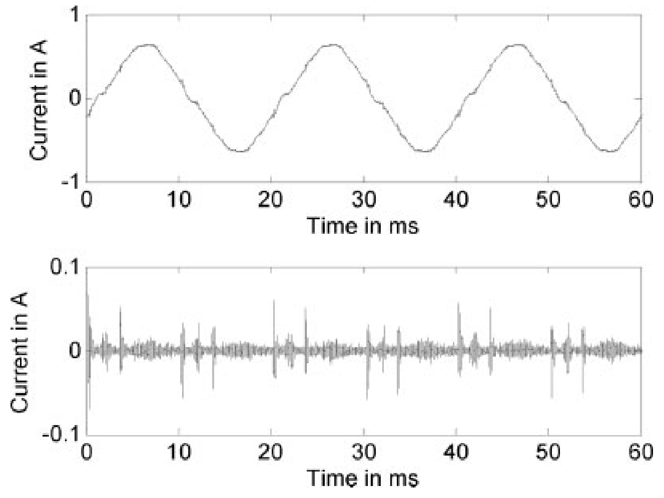

Figure 7. Measured current taken by a fluorescent lamp (top) and high-pass filtered version of the current.

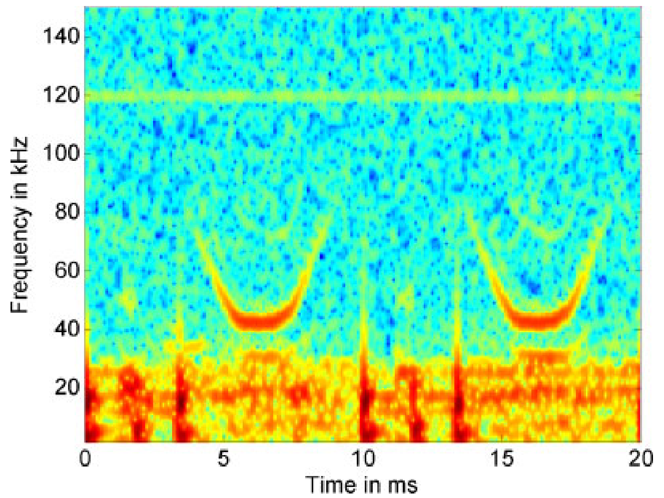

Figure 8. Spectrogram of the current taken by a fluorescent lamp.

Other equipment, beyond common consumer equipment, that emits in this frequency range includes certain types of wind turbines, solar panels, microturbines, voltage-source converter based HVDC and other FACTS devices. The growing penetration of this kind of equipment will require further knowledge on the emission and spread of waveform distortion at frequencies above 2 kHz.

6. AGGREGATION AT THE POINT OF COMMON COUPLING (PCC) OF MULTIPLE TIME-VARYING NONLINEAR SOURCES

The aggregation of time-varying signals produced by multiple nonlinear sources at the PCC seems to be one of the topics which will require some significant effort in the near future. The methods for aggregating distributed generation such as wind power farms (i.e. IEC 61400-21) require better validation and generalization as a function of the different types of sources and system topologies. Figure 9 illustrates the nature of the problem.

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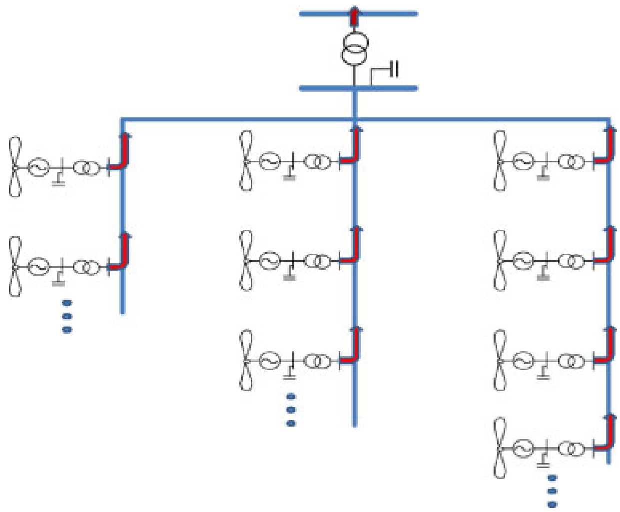

Figure 9. Example of generation aggregation.

As an example of the aggregation of harmonics at the PCC the IEC 61400-21 proposes the following expression:

$$I_{h\Sigma} = \sqrt[\beta]{\Sigma_{i=1}^{N_{\mathrm{wt}}}\left(\frac{I_{h,i}}{n_i}\right)^{\beta}}$$

where N_{wt} is the number of generators connected; $I_{h\Sigma}$ is the hth term of the harmonic component at the PCC; n_i is the transformation ratio of the ith generator;$I_{h,i}$ is the hth term of the harmonic distortion of the ith generator;β is a constant which depends on the harmonic order.

Better aggregation expressions and procedures to determine the overall characteristics at the PCC and the impact of the system characteristics and conditions on the nonlinear sources and also the interaction among sources are necessary. The multitude of sources connected electrically very close to each other presents also some challenge to the analyst, both analytically and computationally.

7. REMOTE IDENTIFICATION OF EVENTS AND LOAD TRANSITIONS AND NONLINEAR CHARACTERISTICS

As the system topology, generation and load characteristics become more diverse and complex the more urgent the need for the identification of system and power quality events, load transitions and nonlinear characteristics. The identification from a remote location is important because intelligent monitors will be connected only on a limited number of locations. The identification of these events and loads characteristics will be of significant importance to assist utilities to take action and more efficiently operate the transmission and distribution system.

The challenges toward this subject include the accuracy of the analysis/diagnostic (positive identification of load transition and operation) as a function of many conditions such as distance from the point of connection, *signal to noise* ratio (SNR), topology of the network, composition and aggregation of loads at the load measuring point, and existence of loads with similar signature located between the load point and remote observation point. These issues demand investigations in: (a) load signature or load characterization, (b) load disaggregation and (c) load classification or identification.

Load signature or load characterization is concerned with the set of information used to identify the load. Some methods found in the literature are the harmonic content of the load [19], the *discrete wavelet transform* (DWT), [20] and Fractal Information [21].

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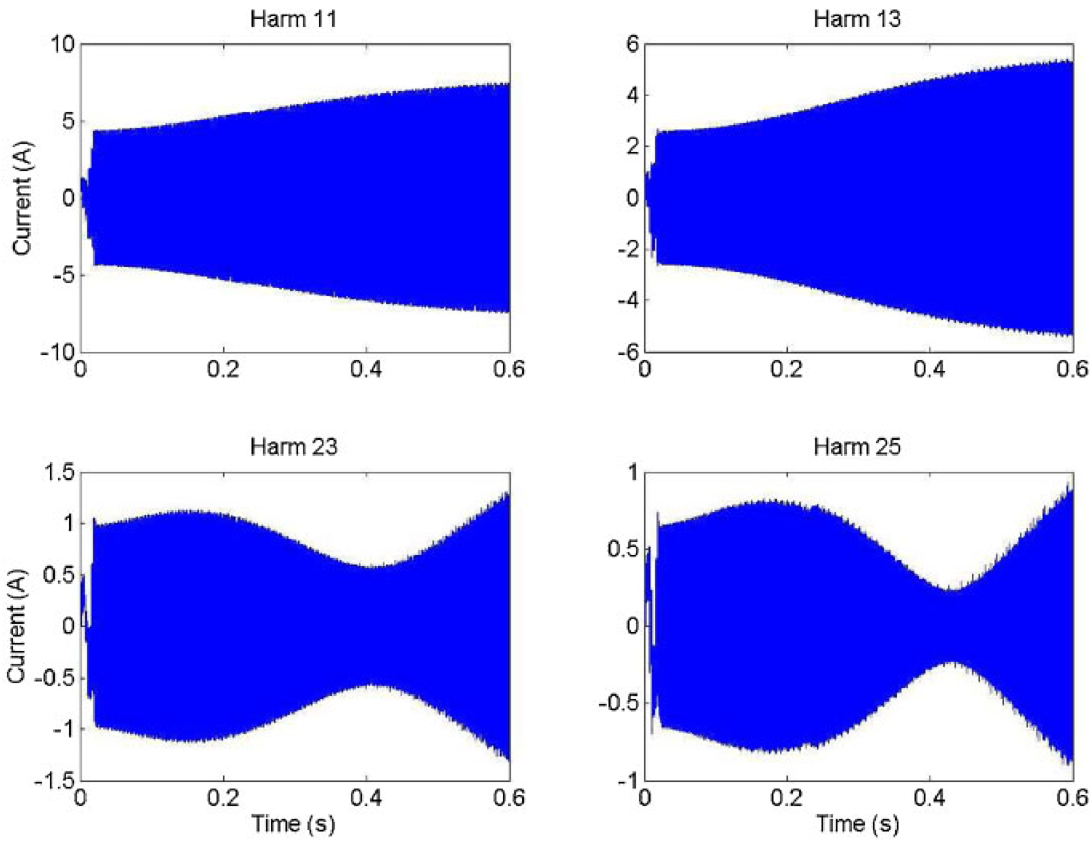

Figure 10. Harmonic decomposition for six pulse converter (firing angle variation).

Figure 10 shows an example of load signature using harmonic content. This figure shows only the 11th, 13th, 23rd, 25th harmonics for a six pulse converter when the firing angle varies.

Any of the previous methods, regarding load signature, work appropriately if the loads are isolated and the measurements are taken near the load, which is not a desirable situation, as the existence of several loads mix their signature. The challenge is then to find a way to disaggregate the information or use an expert system able to accomplish the classification in a mixed data. One approach to accomplish the signature separation is the time-varying harmonic transition principle. This principle is based on the assumption that *'the probability of two or more nonlinear loads turning on or off at the same time is relatively small!'* The method needs to identify the transition points, when loads turn on or turn off, and then analyse the harmonic content of the transition. Figure 11 shows how such a method could work; the grey line represents the harmonic current contribution, after the fundamental component is extracted. In this example there are three nonlinear loads, each one connected at a different bus: A1(1) means that a load of type A1 is connected at bus 1, B1(2) means that a load of type B1 is connected at bus 2 and C1(3) means that load of C1 type is connected at bus 3. Each load is characterized by its harmonic content. The small circle represents where the load turns on or turns off. For example, load A1(1) turns on at point 1 and turns off at point 7, it turns on again at point 8 and turns off at point 10, and so on. The content of the harmonic transition is estimated and analysed by an expert system and then the load identification takes place. For example, 150 random experiments were simulated. In each experiment, the types of loads, the position at the bus, the time of the load transition and the harmonic composition for each equivalent source were sorted. The attained results, obtained using the new approach are summarized in Table I. Note that correct classification reaches 94.7% and the highest misclassification happened when B1 load was classified as A1.

As this topic is in its youth a large amount of new research needs to be carried out regarding load signature, signature disaggregation and load identification.

DOI: 10.1002/etep

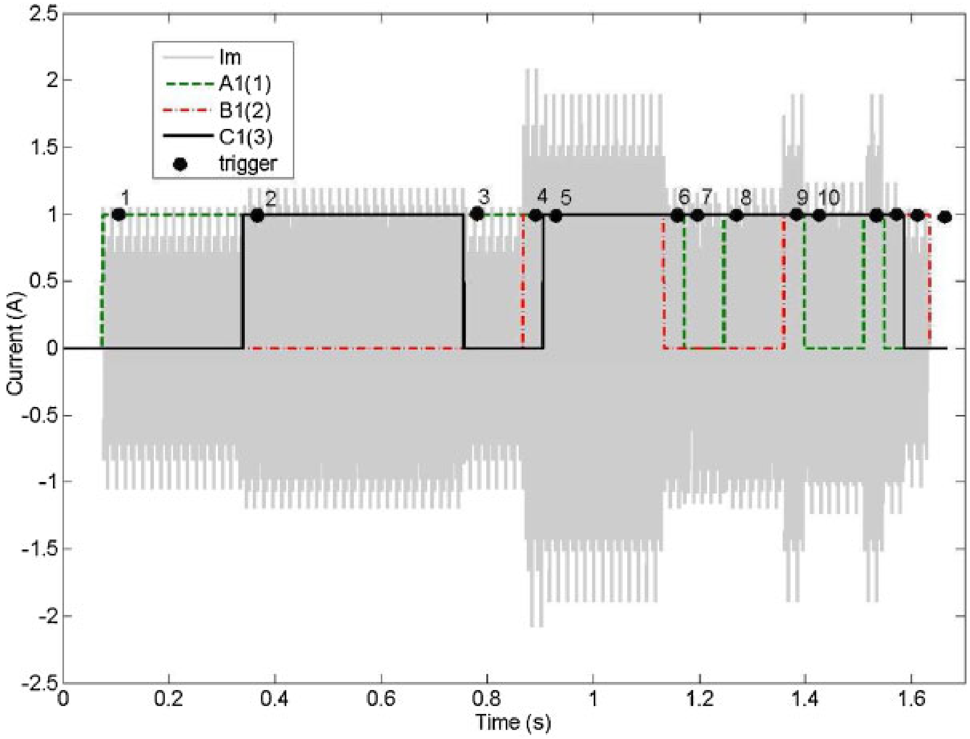

Figure 11. Example of load transition.

Table I. Results of load identification.

Classification	%
Correct	94.7
B1 → A1	3.3
C1 → A1	1.3
C1 → B1	0.7

8. TIME-VARYING HARMONIC ANALYSIS

Harmonics are a steady state concept where the waveform to be analysed is assumed to be periodic. The most common techniques used in harmonic calculations are based on the Fast Fourier Transform (FFT)—a computationally efficient implementation of the DFT. This algorithm gives accurate results under the following conditions: (i) the signal is stationary, (ii) the sampling frequency is greater than two times the highest frequency within the signal, (iii) the number of periods sampled is an integer, and (iv) the waveform does not contain frequencies that are non-integer multiples (i.e. inter-harmonics) of the fundamental frequency.

If the above conditions are satisfied, The FFT algorithm provides accurate results. In such a case, only a single measurement or 'snap-shot' is needed. On the other hand, if inter-harmonics are present in the signal, multiple periods need to be sampled in order to obtain accurate harmonic magnitudes.

In practical situations, however, the voltage and current distortion levels as well as their fundamental components are constantly changing in time. Time-variation of individual harmonics are analysed by windowed Fourier transformations (or short-time Fourier transform), and each harmonic spectrum corresponds to each window section of the continuous signal. But because deviations often exist within the smallest selected window length, different windows sizes (i.e. number of cycles included in the fourier transform) give different harmonic spectra and the selection of the most adequate window size is a complex issue that is still being debated.

DOI: 10.1002/etep

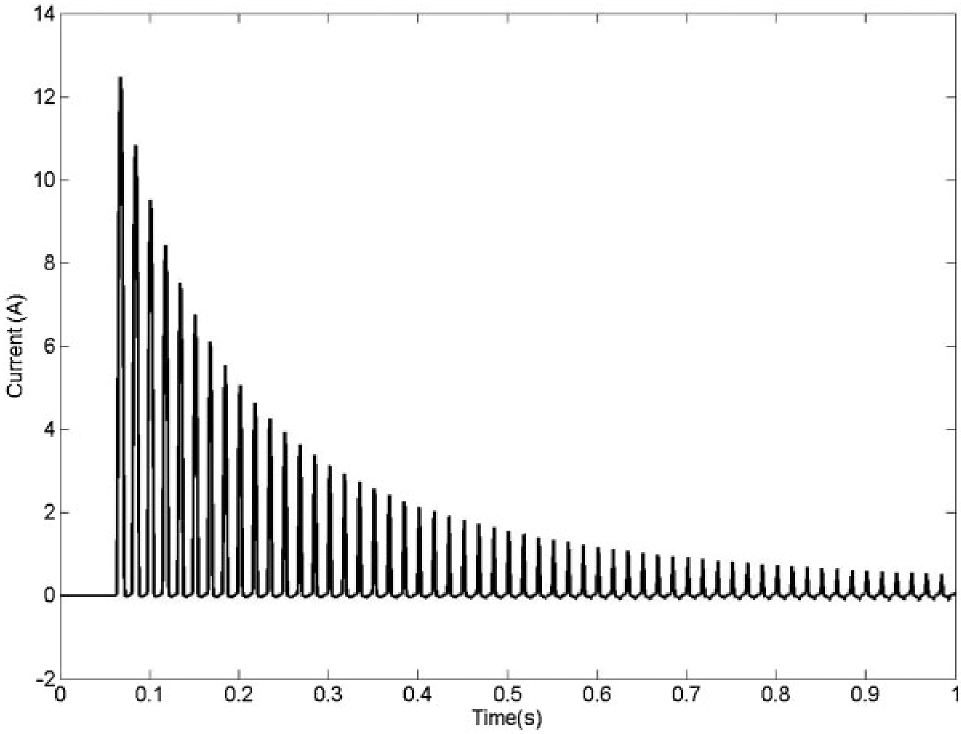

Figure 12. Inrush current in phase A.

Several approaches have been proposed in recent years to improve the accuracy of harmonic magnitudes in time-varying conditions. These include the Kalman filter based analyser [22], adaptive notch filter and the phase-locked loop (PLL) [23], a Fourier linear combiner using adaptive neural networks [24] and filter banks decomposition approach [25]. Each one of these methods has advantages and disadvantages, and the search for better methods continues to be an active research area in signal processing. As an illustrative example consider the inrush current due to the energization of a transformer. Figure 12 shows a typical current waveform and Figure 13 shows the time varying harmonic decomposition of some harmonics using a filter bank decomposition method. Using this new method of analysis can lead to a new philosophy for control and protection.

9. HARDWARE-IN-LOOP/REAL-TIME DIGITAL SIMULATION

Electromagnetic transient simulations or laboratory experiments are often used for power quality studies. The results of different simulation programs could be different because of the usage of different mathematic models. Also, the simulation results largely depend on the accuracy and complexity of those models. On the other hand, the disadvantages of the laboratory experiments are the high cost and the large amount of developing time. Also, the power quality impact on power systems is hardly achieved due to the difficulties of connecting a tested device to real power systems. To achieve better accuracy on the power quality studies of large and complex power systems in an economic way, a real time (RT) hardware-in-the-loop (HIL) simulator can be utilized. Hardware-in-the-loop is an idea of simultaneous use of simulation and real equipment [26]. Generally, a HIL simulator is composed of a digital simulator, one or more hardware pieces under test, and their analog and digital signal interfaces (e.g. high performance A/D and D/A cards). It is very likely that this approach will be more utilized as the availability of RT digital simulation computers become more affordable. An illustration of the arrangement is shown in Figure 14.

DOI: 10.1002/etep

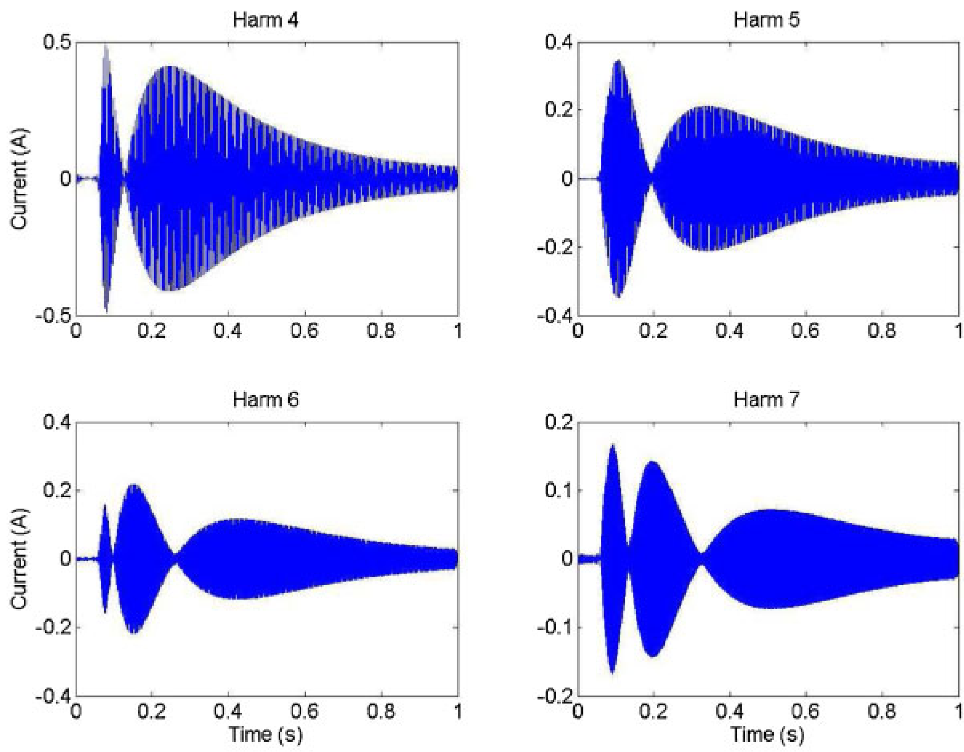

Figure 13. Decomposition of transformer inrush current.

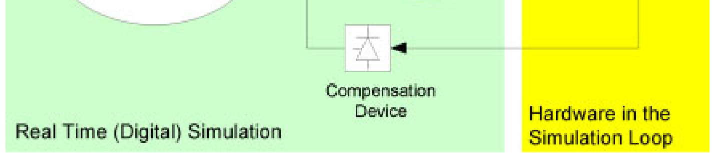

Figure 14. An illustration of the concept of the real time simulation plus hardware in the loop of the simulation.

10. DC POWER QUALITY

Although power quality deviations and standards have concentrated on AC systems, DC systems are also vulnerable to voltage deviations such as voltage spikes, transients and ripples. These deviations can impact parts or the entire system producing severe consequences [27]. Although DC systems are more stable and reported to be less susceptible to voltage deviations and distortions more research is required for this area as the utilization of DC distribution may develop in the near future. This is particularly important for data centres type of loads [28].

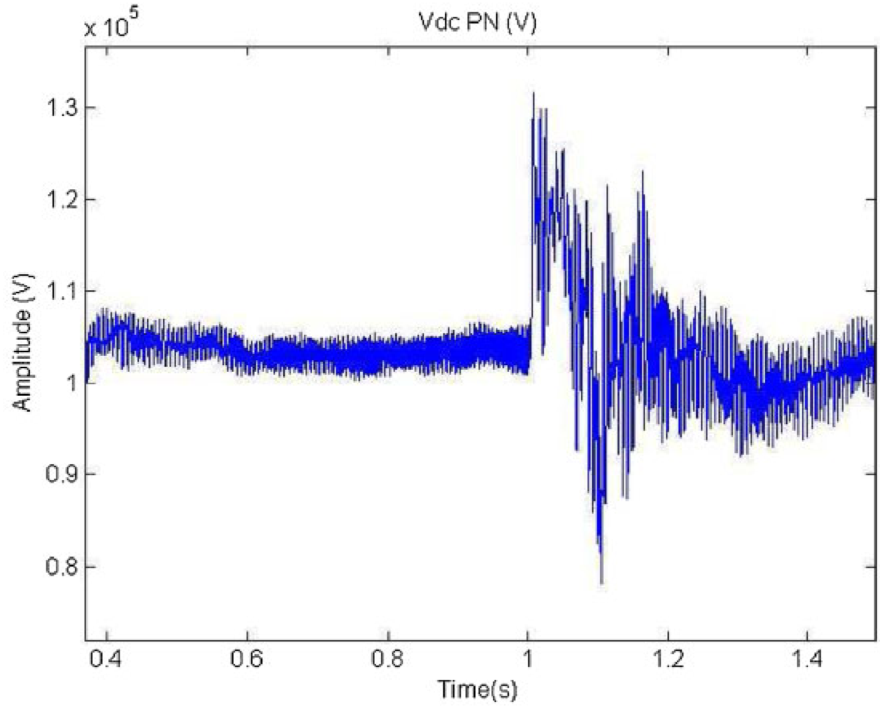

Figure 15. Voltage at DC terminal in a HVDC transmission system.

Figure 15 shows the voltage of the positive terminal, with reference to the neutral, for the DC line as part of an HVDC system, during an AC three-phase fault (of 0.1 second) 70 km away from the DC terminal. Note how the fault on AC system affects the quality of the DC voltage.

11. CONCLUSIONS

This paper attempts to highlight some new areas of interest and possible trends for the future regarding power quality issues and concerns.

Power quality interest and research will continue to grow, but under new contexts and perspectives. Proliferation of distributed generation, emphasis on energy efficiency, green power, and the intensification of the use of power electronics with new technologies, including high frequency switching, etc., will demand creative efforts to cope with the current and future developments. Adding to this, the inevitable increase in the complexity of the transmission and distribution system will produce challenges and exciting opportunities for research.

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DOI: 10.1002/etep