Voltage disturbance monitoring

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1 Introduction

The aim of this application note is to introduce the readers to the monitoring concepts and provide them information on voltage disturbance monitoring that will help them select the most suitable type of monitor required for the intended application. This report is focused on power quality instruments as opposed to measurement methods, which are described in alternative application notes of the LPQI Guide.
There are different types of monitoring instruments, such as general purpose instruments, data loggers, disturbance capturing, flicker meters, harmonic analyzers etc. In general, we can divide instruments in two classes: general purpose instruments and instruments for a specific disturbance analysis, such as instruments for voltage transient analysis. In order to choose the right monitoring instrument, a general overview on the most common features will be given in this application note.

In order to manage a monitoring project, five significant questions will arise:

- Why measure? (What kind of objectives we have?)
- What kind of power quality parameter do we want to measure?
- Where should the measurement equipment be located?
- How should the measurement be carried out?
- What kind of equipment should be used for the measurement?

One important part of this application note treats the functions and features that are offered by modern power quality monitors which should help the user in the understanding and awareness of the functions and terms that are common to power quality monitors.
Mainly, we want to help the reader to choose the right measurement equipment and method for the intended application. Nevertheless, it is very important to understand the nature of the power quality problems to be able to analyze and solve the power quality problem.
Finally, a short introduction to the interpretation of monitoring results and the integration of the monitor in monitoring systems will be given.

2 Power Quality Monitoring

2.1 Monitoring Objectives (Why measure?)

The broadly used term Power Quality, includes all aspects of power supply that impact individual customers, whereas the term voltage quality refers to any variation of voltage waveform resulting in misoperation or failure of customer equipment.
In general, power quality monitoring is used to identify electromagnetic phenomena at a particular location on an electric power circuit or installation. There are several reasons to

monitor power quality. The most important reason is the economic damage, produced by electromagnetic phenomena in critical process loads. Effects on equipment and process operations can include misoperation, damage, process disruption and other anomalies [1]. The costs incurred by poor power quality can be distinguished according to the following factors:

- costs of product damage due to the process interruption of continuous or batched production;
- costs of equipment damage and equipment lifetime reduction
- costs of downtime production losses;
- costs of process restarting, including start up costs;
- and costs of lost opportunity in time-critical and just-in-time production.

Monitoring can help to identify power quality problems, minimise losses in the production process and increase plant productivity and efficiency. Monitoring is an essential component of the customer care process for this business.

The objectives of monitoring determine the choice of measurement equipment, the triggering thresholds, the methods for collecting data, the data storage and analysis requirements, and the overall level of effort required [2]. We have identified several general classifications for monitoring objectives, which we are classifying in two groups: The utility objectives and engineering or consulting objectives. The former is used by the utilities for planning, legal or contractual questions. The latter is used to identify power quality problems on plant site to mitigate those problems. Some classifications are listed below [2], [3], [4]:

Utility objectives:

- Monitoring to characterise system performance. This is the most general requirement. A utility may find this objective important if it has the need to understand its system performance and then be able to match that system performance with the needs of customers.
- Priorities for system improvements. Utilities traditionally prioritise capital expenditures and system maintenance based on solving system problems and handling system growth. These expenditures are also related to maintaining an acceptable level of reliability. Understanding the impacts of power quality variations on the customer's reliability requires monitoring.
- Monitoring as part of an enhanced power quality service. Many utilities are currently considering additional services to offer customers.
- Legal obligations. In the new context of open electricity markets it is necessary to report to external parties (regulators, etc.) about the power quality performance of the system. Utilities use also monitoring in their customer relationship in order to respond to domestic and industrial customer complaints about PQ related incidents.
- Determine effectiveness of system maintenance activities and power conditioning technologies. For utilities, monitoring can help determine the effectiveness of measures such as tree trimming and expansion of the distribution system.

Engineering objectives:

- Monitoring to characterise specific problems. Many power quality service departments or plant managers solve problems by performing short-term monitoring of specific customers or of difficult loads [4].
- Identification of problem conditions. Monitoring can identify problems with customer power systems before they cause equipment misoperation or failures and customer complaints.

- Determine effectiveness of system maintenance activities and power conditioning technologies. For customers, monitoring can verify the performance of ride through measures such as UPS systems and backup generation or power conditioning technologies such as harmonic filters.
- Development of preventive maintenance systems. We can find a new application for power quality monitoring in those systems that measure real-time conditions in order to identify problems before they occur. These systems can save time and money and provide improved reliability for the overall system. Preventive maintenance systems can be used to
    - Identify source and frequency of events
    - Establish precise location and timing of events
    - Develop maintenance schedules based on power quality trends
    - Identify power quality problems by the operational history

Benefits of a power quality monitoring:
Monitoring requires an investment in equipment, time and education. In many cases management, production and plant engineers must be sufficiently convinced of the benefits of monitoring. Monitoring is an essential analysing tool in order to improve the availability of power. The investment in monitoring can be justified by the increased availability due to the following action:

- Preventive and predictive maintenance
- Determining the need for mitigation equipment
- Ensuring equipment performance
- Sensitivity assessment of process equipment to disturbances

2.2 Power Quality Parameters (What to measure?)

Power quality includes a wide variety of conditions on the power system. The important disturbances can vary in duration from very high frequency impulses (lightning strokes), to long-term overvoltages and interruptions. The IEC 61000-4-30 is part of the standard IEC 61000 concerning electromagnetic compatibility and defines the power quality parameters for measurement in 50 Hz systems. The power quality parameters used in the IEC 61000-4-30 are [5]:

- Magnitude of the supply voltage
- Supply voltage dips and swells, voltage interruptions
- Rapid voltage changes
- Supply voltage unbalance
- Transient voltages
- Mains signalling on the supply voltage[1]
- Power frequency
- Voltage and current harmonics and interharmonics
- Flicker

The European standard EN 50160 also presents set parameters that define the quality of the power supply customers and establish limits of variations of these parameters.

[1] The aim of the measurement of mains signalling is to verify the level of signal voltage on the supply voltage. Mains signalling frequencies are signal frequencies between harmonics for control and communication purpose.

What kind of parameter you need to monitor depends on the monitoring objectives. Clear and well defined objectives will help to select the specific resources (monitors, personnel, etc.) and the level of analysis for the parameter that must be obtained to perform the survey. Once specific parameters have been defined, the monitoring characteristics should be defined:

- *Number of input channels to monitor.* In this step it should be decided how many channel are needed. In some case, were we only voltage disturbances are recorded, it is recommended to measure also the current in order to identify if the disturbance is cause by the external grid or by the load itself.
- *Monitoring period.* The period of the measurement should be defined, depending on the type of the expected disturbance and the number of their occurrence.
- *Measuring method.* Depending on the parameter to measure, the measuring method changes between RMS measurements, waveform display, transients measurement, etc.
- *Threshold setting.* The amount and details of the captured power quality information is depending on the thresholds. If the limits are to low, the instrument collects too much data and runs out of the memory. If the limit is set to high, the monitor may not record any significant events. Therefore, the threshold should be chosen very carefully.
- *Kind of analysis.* In some cases, a specific analysis is required, e.g. harmonic analysis, voltage dip plot, etc.
- *Mode of analysis*: Some instruments permit a analysis by using build in features, others perform the analysis a software via PC.

For example in the case of dips the recording of rms and wave shape enables the user to make diagnostics of the kind of failure and solution for the problem. In this case, 3 or 4 input channels are needed for the voltage measurement, the current measurement is required, when the location of the disturbance should be determined, the monitor period should be longer than a month or permanent, there is no harmonic analysis necessary, thresholds are typically in the range 85 % to 90 % of the fixed voltage reference and the recording of transient voltage (high frequency voltages should be recorded with high sampling rates) is not needed.

2.3 Monitor placement (Where to measure?)

Power quality monitoring can be very expensive when a high number of monitors in required. It is very important, therefore, to select carefully the monitoring locations based on the monitoring objectives to minimize the involved costs. For example, for trouble shooting applications, the monitor should be placed as near as possible to the sensitive load. On the other hand, for an overall power quality monitoring, the monitor is located at the power entrance. Often, the monitor placement is limited by the access to the power lead, especially for current metering.

2.4 Organisation of Measurements (How to measure?)

2.4.1 Input Channels

The voltage sensing leads and current transformers are connected to the main analogue inputs called channels. Therefore, the number of channels on the power quality monitor determines how many voltages and currents can be monitored. A voltage input channel has two terminals which are normally insulated from earth. This allows the user to configure the instrument for phase or line voltage sensing. In some instruments the configuration of star or delta voltage sensing in a 3-phase measurement can be changed by software.

2.4.2 Measurement Chain

The measurement chain stated by the IEC [5] is shown in Figure 1. We can find three elements of power quality measurement, namely the measurement transducer, the measurement unit and the evaluation unit.
The first is used to adapt the electrical input signal for the measurement unit, for example: to step down the voltage, to isolate the input circuits or to transmit the signals over a distance. Two important considerations when using transducers are the signal level in relation to the full scale of the monitor and the frequency and phase response.
The measuring unit realises the measurement of the input signal and provides the measurement results to the evaluation unit, which processes them to obtain the measurement evaluation. A measurement evaluation can be, for example, the FFT for the harmonic or interharmonic analysis.

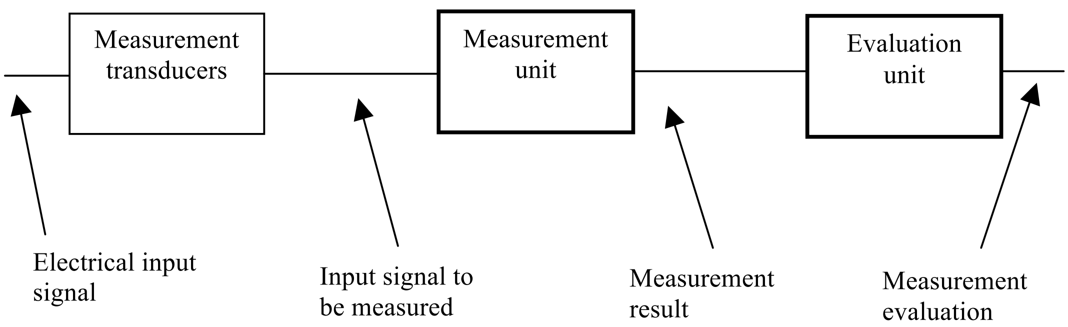

Figure 1: Measurement chain [5]

2.4.3 Measurement Method

The first step of voltage disturbance monitoring is to obtain samples of voltage waveforms, typically for three phases. It is necessary that the sampling rate and the resolution of the signal are adequate to record the disturbance. Due to the fact that the monitor also is used to obtain the harmonic spectrum, typical samples per cycle[2] are 128 or 256 [6], [7].

RMS Measurement
In order to calculate the magnitude of the supply voltage the rms value is calculated based on the sampled values over a specified period. For the measurement of a voltage dip and swell the $U_{rms(1/2)}$ shall be used on each measurement channel, where $U_{rms(1/2)}$ is defined as “the value of the rms voltage measured over one cycle and refreshed each half cycle”[5].

Transients Measurement
Voltage transients are by nature fast varying signals and a wide range of waveforms, amplitudes and durations. Transients can be classified into two categories, namely impulsive transients and oscillatory transients. These terms reflect the wave shape of a current or voltage transient. Obtaining their signatures allows classifying them into a few typical waveforms. The requirements for the data acquisition of transients are higher than for the RMS measurement. Common sources of transients include:

- Lightning
- Capacitor bank switching
- Large variable speed drives

[2] A cycle is the fundamental frequency of the measured waveform

- Electrostatic discharges
- Faulty wiring

The frequency spectrum of transients, for example, a.c. main transients can have frequencies up to 10 MHz (100 ns rising time) and up to 1 MHz for large amplitude. The sampling rate must be at least twice the maximum frequency of the measured signal to record the original waveform. For example, a sampling rate of 8 kHz (160 samples per cycles) captures transients and impulses down to 130 µs.

2.5 Monitor equipment (What kind of equipment?)

The evolution in the last years of power measurement instrumentation has given rise to lower cost multifunction instruments capable of simultaneously measuring power quality, harmonics, and energy consumption. A significant trend is to integrate the advantages of personal computers with instrumentation leading to increased automation in the collection of data. The latest generation of power monitors, may for example, store recorded data on an internal disk drive, or in a database format for downloading to a PC. Software operating in the Windows environment allows users to manipulate and use the recorded data more efficiently. An overview of the common instrument features of modern monitors will be given in the next chapter.

The instrument can be separated into two main types: power quality monitor and power quality analyzer. Power quality monitors are instruments equipped with memory and the ability to record power quality parameters over some period of time by triggers. Modern monitors can self adjust thresholds to capture the most relevant events and also ignore non-relevant events. On the other hand, power quality analyzers are instruments that measure and analyze real time data, sometimes only harmonics. The analyzing results will not be stored.

Another very important aspect in choosing the right instrument is the nature of the power quality parameter being metered. For example, the measurement of transient needs a high sampling rate whereas the rms measuring is sufficient with 128 samples per cycle.

Special attention should be given to the difference of sampling rate, resolution and accuracy of the instrument. The sampling rate defines the rate at which the input channels will be sampled and it is stated in samples per cycle or samples per second. In many cases the sampling rate is given over all channels. Consequently bandwidth per channel will be reduced (i.e. a 4 channel instrument will have the maximum sampling rate of ¼ of the total sampling rate when all 4 channels are used). Furthermore exists the aliasing problem which is the distortion caused by sampling a signal at an inappropriate rate. It can be avoided by applying an anti-aliasing filter limiting the bandwidth of the signal to half the sample frequency. Measurement of harmonics also require a high sampling rate, which is achieved by using 10 cycles in order to do FFT calculation. To remove possible errors due to power system frequency variations, PLL (Phase Locked Loop) is used to keep the sampling frequency locked at the fundamental signal frequency.

The resolution of an instrument is the number of binary bits used in the analogue digital conversion process and it measures the detail with which the sampled data is processed. The larger the number of bits the finer the resolution with which the sampled data is captured.

Finally, the accuracy is defined by the error of the measurement of the power quality instrument. Obviously, the better the accuracy the more accurate are the measurement results.

2.6 Installation Safety

Because power quality monitoring is connected to the electrical installation, the safety of site personal has the utmost importance. In order to connect the monitor, the manufacturer's instructions have to be followed and the integrity of the monitored circuit must be respected.

It is very important that the monitor is installed according to the local electrical code and that grounding, correct monitor placement, guarding live parts and overcorrect protection should be considered.

3 Measurement Instruments Features

In the last years a huge number of power quality monitoring instruments have appeared on the market with specialised features for disturbance and power quality monitoring. These instruments' features can vary from one instrument to another, so we will give in the following chapter an overview over the features and functions of power quality monitors.

3.1 General Features

The following list describes the general features of power quality monitoring instruments [8].

- *Enclosure options: handheld, portable and fixed*. The choice of the enclosure option depends on the user's requirement. The handheld and portable options are more dedicated for engineering and trouble shooting applications. The fixed install option is more used by utilities, industrial plants and equipments that are integrated in a power quality monitoring system.
- *Enclosure protections*. The environmental limits for the power quality monitors are usually specified by the manufacturers. The IP (Ingress Protection) rating also must be specified by the manufactures, instruments could have the similar NEMA rating too.
- Power supply. The power supply of a power quality monitor is also an important consideration. Supply voltage and frequency, battery back up during power failure or separately supply should be checked.
- *Memory.* The memory options for the recorded events can be hard disks, floppy disks, internal RAM and PCMCIA memory cards. In case of equipment malfunction, the stored data should not be damaged.
- *User interface.* The instrument – user communication is usually realised by built in displays, external viewing devices or personal computers. The user – instrument communication is done by keypads, keyboards or by a personal computer. The personal computer options require a connection interface from the instrument to the personal computer. Many instruments allow remote monitor operation and real-time displaying of the signals.
- *Software and data analysis tools.* The software and data analysis tools supplied with most power monitors have a variety of functions and data manipulating abilities.
- *Printer.* The printer can be installed internal, directly connectable or connectable by a personal computer.
- *Accessories*. Leads, probes, sensors, current clamps, frames, handles and carrying cases are typical accessories supplied by the manufacturer.
- *Warranty*. Manufacturer or supplier may provide a warranty for a year or more.
- *Update ability*. The update ability of software and hardware (optional modules or cards) can be important for the purchase of the monitor.
- *Maintenance and calibration*. Power quality monitor requires periodic maintenance and calibration. This is an important factor for the life time costs of monitoring and should be considered.
- *Accuracy*. The accuracy of a power quality monitor is specified by the manufacturer

- *Resolution*. The resolution of an instrument is a measure of the detail of the digital sampled data after the analogue digital converting process and it is represented in bits. The larger the number of bits the finer the resolution with which the sampled data is captured.
- *Sampling rate*. It defines the rate at which the input channels are sampled and should state in samples per cycle. For detecting transients, high sampling rates in the MHz are necessary.
- *Voltage withstand*. Manufacturers may specify the voltage withstand of the monitor and the complied standards.

3.2 Signal Input/Output

The following list describes the signal input and output interface of power quality monitoring instruments [8].

- *Input channels.* The input channels are the main analogue inputs to which the voltage current transducers are connected.
- *Analogue inputs/outputs.* Analogue inputs can, for example, monitor additional parameters and analogue outputs are used, for example, for signals to other monitors.
- *Digital inputs/outputs.* This type of inputs and outputs is mainly used to trigger other monitors.
- *Communication and networks.* Internal and external modems via RS232, Ethernet and direct PC connection (USB, RS232, RS485, and Infrared) are provided with the monitor instrument. Many instrument manufacturers allow the user to download information or operate the monitor via internet.

3.3 Functions

The following list describes the functions of power quality monitoring instruments [8].

- *Data capture by present thresholds.* Parameters to be measured are usually captured when the disturbance exceeds a present threshold (event logging) or at repeated set time intervals. The thresholds and time intervals are set up by the user. By event logging, the captured waveform is usually logged one or more cycles before and after the event to provide a full picture of the event.
- *Data capture by self adjusting thresholds.* The monitor can set its own thresholds by an established steady state norm. This method allows the detection of small derivations and trends.
- *External triggered data capture.* Many monitors provide the feature to be triggered externally.
- *Manual data capture.* For a snapshot of the present situation many monitors provide a manual trigger function.
- *Data logging and time interval recording.* With data logging the parameters are continuously monitored and can be captured at set time intervals, established by the user.
- *Waveform capture.* Some power quality monitors have the ability to capture waveforms (mainly voltage and current). These captured waveforms can de viewed by built in displays or can be downloaded to the PC. Often the instruments are providing functions such as harmonic analysis and wave form analysis.
- *Time synchronisation.* Some power quality monitors have the option of time synchronisation by an external time signal or a radio signal.

3.4 Firmware

Some meter manufacturers periodically provide new releases of monitor firmware. Firmware releases, typically provided free of charge by manufacturers, are sometimes used to correct errors in the metering algorithms or to enhance the existing feature set of your meter without purchasing new hardware.

4 Postprocessing Monitoring Results

4.1 Interpreting Monitoring Results

Analyzing power quality data is a complex process and maybe the most critical part of the process of power monitoring. The investigator should have enough knowledge and skills to produce a solution from the available data. Through there is no standard solution for interpreting monitoring results, the following guide should be a brief example of a methodology for interpreting monitoring results.
Interpreting power quality reports starts with the interpreting of data summaries, which provide the information of what data needs to be examined more closely. We should be able to identify the critical events, which can contain more than one disturbance, for example during a short interruption the monitor can also report transients, dips or swells. Once the critical data events have been determined, the events should be checked on their reality. During a dip, swell or interruption, the measurement algorithm for other parameters can produce an inaccurate value. Therefore flagging should be used to indicate to the user that an aggregated value might be unreliable. This concept is only used for dips, swells and interruption measurement, and therefore, it depends on the thresholds set up by the user.
Subsequently, the interpreting of the critical events can be started. The possible causes can be deduced by the analysis of signature and waveshape, high frequency analysis, harmonic analysis and dip/swell analysis. There is plentiful literature on this topic that provides solutions for the most common power quality problems [1], [9], [10].

4.2 Data Collection and Monitoring Systems

Instruments used for permanent monitoring are able to communicate through network cards or modems with a centralized monitoring system, which controls the monitor and downloads the recorded data from the monitor [11]. These systems are normally used for fixed installed monitors from utilities in order to process the vast amount of data proceeding from monitoring.
The core of any centralized monitoring system is a database, which stores the acquired power quality data. A communication process collects the data from the monitors and stores them into the database. The user interface is carried out by a reporting system, which can automatically generate disturbance reports, inform the user (customer or utility) by means of Web-based Internet applications or transfer data to other information systems (SCADA,ERP, etc.).

4.3 Software and data analysis tools

Most power quality monitor manufactures provide a software and data analysis tool, usually Windows based. The following list gives an overview of these functions.

- Download of captured data. It is one of the most important features. Due to the limited memory of the monitors the data should be downloaded periodically to a personal computer to conserve data this over a long period.
- Setting up the instrument for monitoring
- Display of data and waveforms (some instruments display real-time values)

- Correlating and categorising (for example event type, magnitude and duration are automatically classified according to EN 50160 or IEEE 1159 standards)
- Detection of trends for predictive maintenance
- Plotting the captured data against ANSI/CBEMA/ITIC plots (ITIC replaced CBEMA plots, older monitors can have the CBEMA plot option)
- Providing customised alarms and triggers
- Producing automatic reports
- Printing the data/waveforms
- Post processing the captured data
- Analysing threshold levels

4.4 Power quality data interchange format (PQDIF)

In many cases new monitoring instruments are placed alongside legacy equipment, there is a strong interest in data formats that enable different types of instruments to work together. Currently, most software programs for downloading and analyzing data are incompatible with other instruments, hence making comprehensive analysis difficult or impossible. In response to this, EPRI developed the PQDIF, which allows engineers to incorporate a wider range of instruments into their overall systems. Nowadays, several manufacturers have adopted the PQDIF.

5 Summary

After answering the five significant questions put forth in this paper the reader should be able to select the most suitable type of disturbance monitor required for the intended application. However, it is recommended that the reader contact the suppliers or manufactures to obtain detailed information on products they are interested in before making a decision on a specific monitor. Moreover, it is also recommended to study the related standards and more detailed literature on this subject.

6 References

[1] IEEE 1159:1995 – Recommended practice for monitoring electric power quality

[2] D. Sabin, M. McGranaghan, A. Sundaram, *A Systems Approach to Power Quality Monitoring for Performance Assessment*; Electrotek Concepts, Knoxville Tennessee; - Electric Power Research Institute, URL www.dranetz-bmi.com/pdf/systemsApproach.pdf

[3] M. McGranaghan; *Monitoring morphs into customer service quid pro quo*, Electric Light & Power, Jun2001, Vol. 79 Issue 6, p15, 2p

[4] J. Rull et al; *Voltage dips in industrial plants: identification methodology, effects and solutions. Immunization cases.* CIRED 2003, Barcelona, 2003

[5] IEC 61000-4-30 Electromagnetic compatibility (EMC) –Part 4-30: Testing and measurement techniques - Power quality measurement methods

[6] M.H.J. Bollen, 2002 *Ongoing standard work on statistical presentation of voltage dips*, Probabilistic Methods Applied to Power Systems, Naples, Italy, September 2002.

[7] IEEE P1564, 2001, *Voltage sag indices draft 2*, working document for IEEE project group 1564.

[8] D. Lam; *A Review of Power Quality Monitoring Instruments*, ERA Report 2002-0213, ERA Technology Ltd, ISBN: 0 7008 0761 6

[9] A. McEachern, Handbook of Power Signatures, BMI, Foster City, 1989

[10] The Dranetz Field Handbook for Power Quality Analysis, Dranetz Technologies, New Jersey,1991

[11] J. Bergas, A. Sudriá, J. Rull et al; Centralised Supervision of Energy Quality Using Analogical Cellular Telephony, *PQA '97 Europe*, Stockholm, 1997,

Other application notes recommended to read:

1-8 Power Quality Survey Methodology
1-10 EN61000 Standards Roadmap
3-2-1 Harmonic Measurement
5-2-1 Predictive Maintenance
5-2-3 Flicker Measurement