· 23 · Power Quality

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23.1 INTRODUCTION

Over the last thirty years or so, the amount of equipment containing electronics has increased dramatically. Such equipment can both cause and be affected by electromagnetic disturbances. A disturbance that affects a process control computer in a large industrial complex could easily result in shutdown of the process. The lost production and product loss/recycling during start-up represents a large cost to the business. Similarly, a protection relay affected by a disturbance through conduction or radiation from nearby conductors could trip a feeder or substation, causing loss of supply to a large number of consumers. At the other end of the scale, a domestic user of a PC has to re-boot the PC due to a transient voltage dip, causing annoyance to that and other similarly affected users. Therefore, transporters and users of electrical energy have become much more interested in the nature and frequency of disturbances in the power supply. The topic has become known by the title of Power Quality.

23.2 CLASSIFICATION OF POWER SYSTEM DISTURBANCES

To make the study of Power Quality problems useful, the various types of disturbances need to be classified by magnitude and duration. This is especially important for manufacturers and users of equipment that may be at risk. Manufacturers need to know what is expected of their equipment, and users, through monitoring, can determine if an equipment malfunction is due to a disturbance or problems within the equipment itself. Not surprisingly, standards have been introduced to cover this field. They define the types and sizes of disturbance, and the tolerance of various types of equipment to the possible disturbances that may be encountered.

The principal standards in this field are IEC 61000, EN 50160, and IEEE 1159. Standards are essential for manufacturers and users alike, to define what is reasonable in terms of disturbances that might occur and what equipment should withstand.

Table 23.1 provides a broad classification of the disturbances that may occur on a power system, some typical causes of them and the potential impact on equipment. From this Table, it will be evident that the electricity supply waveform, often thought of as composed of pure sinusoidal quantities, can suffer a wide variety of disturbances. The following sections of this Chapter describe the causes in more detail, along with methods of measurement and possible remedial measures.

Category	Causes	Impacts
Voltage dips	Local and remote faults Inductive loading Switch on of large loads	Tripping of sensitive equipment Resetting of control systems Motor stalling/tripping
Voltage surges	Capacitor switching Switch off of large loads Phase faults	Tripping of sensitive equipment Damage to insulation and windings Damage to power supplies for electronic equipment
Overvoltage	Load switching Capacitor switching System voltage regulation	Problems with equipment that requires constant steady-state voltage
Harmonics	Industrial furnaces Non-linear loads Transformers/generators Rectifier equipment	Mal-operation of sensitive equipment and relays Capacitor fuse or capacitor failures Telephone interference
Power frequency variation	Loss of generation Extreme loading conditions	Negligible most of time Motors run slower De-tuning of harmonic filters
Voltage fluctuation	AC motor drives Inter-harmonic current components Welding and arc furnaces	Flicker in: Fluorescent lamps Incandescent lamps
Rapid voltage change	Motor starting Transformer tap changing	Light flicker Tripping of equipment
Voltage imbalance	Unbalanced loads Unbalanced impedances	Overheating in motors/generators Interruption of 3-phase operation
Short and long voltage interruptions	Power system faults Equipment failures Control malfunctions CB tripping	Loss of supply to customer equipment Computer shutdowns Motor tripping
Undervoltage	Heavy network loading Loss of generation Poor power factor Lack of var support	All equipment without backup supply facilities
Transients	Lightning Capacitive switching Non –linear switching loads System voltage regulation	Control system resetting Damage to sensitive electronic components Damage to insulation

Table 23.1: Power Quality issues

Table 23.2 lists the limits given in Standard EN 50160 and notes where other standards have similar limits.

Type of disturbance	Voltage Level	Limits from EN50160	Measurement period	Typical duration	Other applicable standards
Voltage Variation	230V	+/- 10%	95% of 1 week	-	
Voltage Dips	230V		10-1000/year	10ms –1sec	IEEE 1159
Rapid voltage changes	230V	5% to 10%	Several per day	Short duration	
	1kV-35kV	<6%	Per day	Short duration	IEEE 1159
Short Interruptions	230V	>99%	20-200 per year	Up to 3 mins	EN61000-4-11
Long Interruptions	230V	>99%	10-50 per year	>3 mins	IEEE 1159
Transient Overvoltage	230V	Generally <6kV	Not specified	<1ms	IEEE 1159
Voltage unbalance	230V				
Undervoltage	230V	<-10%	Not specified	>1 min	IEEE 1159
Voltage surge	230V	<150% of nominal voltage	Not specified	>200ms	IEEE 1159
Voltage fluctuations	230V	3%	10 min	<200ms	IEC 60827
Frequency variation		+/- 1%	95% of 1 week	Not specified	Measured over 10s
		+4%, -6%	100% of 1 week	Not specified	Measured over 10s
Harmonics		THD<8% up to 40th	95% of 1 week	Not specified	

Table 23.2: Power system disturbance classification to EN 50160

For computer equipment, a common standard that manufacturers use is the ITI (Information Technology Industry) curve, illustrated in Figure 23.1. Voltage disturbances that lie in the area indicated as 'safe' should not cause a malfunction in any way.

However, some disturbances at LV levels that lie within the boundaries defined by EN50160 might cause a malfunction because they do not lie in the safe area of the ITI curve. It may be necessary to check carefully which standards are applicable when considering equipment susceptibility.

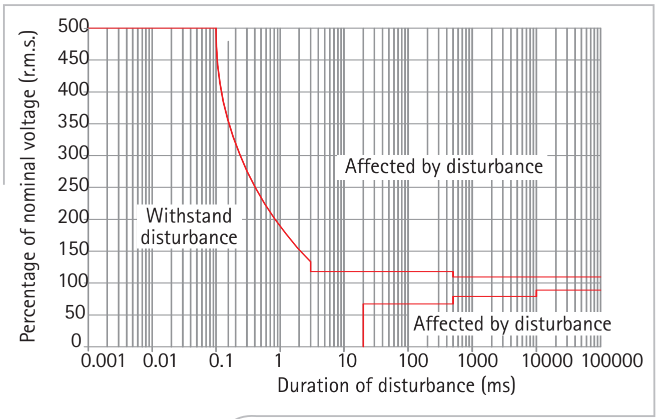


Figure 23.1: ITI curve for equipment susceptibility

23.3 CAUSES AND IMPACT OF POWER QUALITY PROBLEMS

Each of the Power Quality disturbance categories detailed in Table 23.1 is now examined in more detail as to the possible causes and the impact on consumers.

23.3.1 Voltage Dips

Figure 23.2 shows the profile of a voltage dip, together with the associated definitions. The major cause of voltage dips on a supply system is a fault on the system, that is sufficiently remote electrically that a voltage interruption does not occur. Other sources are the starting of large loads (especially common in industrial systems), and, occasionally, the supply of large inductive loads.

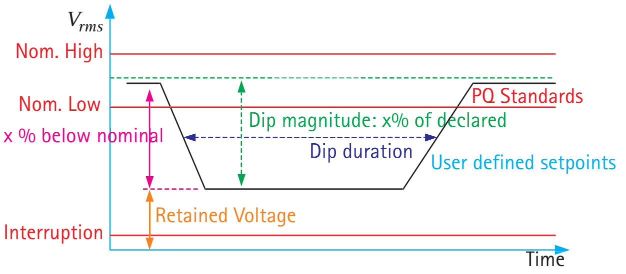


Figure 23.2: Voltage dip profile

Voltage dips due to the latter are usually due to poor design of the network feeding the consumer. A voltage dip is the most common supply disturbance causing interruption of production in an industrial plant. Faults on a supply network will always occur, and in industrial systems, it is often practice to specify equipment to ride-through voltage dips of up to 0.2s. The most common exception is contactors, which may well drop out if the voltage dips below 80% of rated voltage for more than 50-100ms. Motor protection relays that have an undervoltage element setting that is too sensitive is another cause. Since contactors are commonly used in circuits supplying motors, the impact of voltage dips on motor drives, and hence the process concerned, requires consideration.

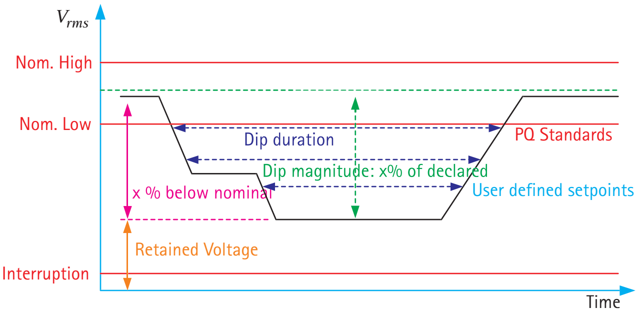


Figure 23.3: Multiple voltage dip

Other network-related fault causes are weather–related (such as snow, ice, wind, salt spray, dust) causing insulator flashover, collisions due to birds, and excavations damaging cables. Multiple voltage dips, as illustrated in Figure 23.3, cause more problems for equipment than a single isolated dip.

The impact on consumers may range from the annoying (non-periodic light flicker) to the serious (tripping of sensitive loads and stalling of motors). Where repeated dips occur over a period of several hours, the repeated shutdowns of equipment can give rise to serious production problems. Figure 23.4 shows an actual voltage dip, as captured by a Power Quality recorder.

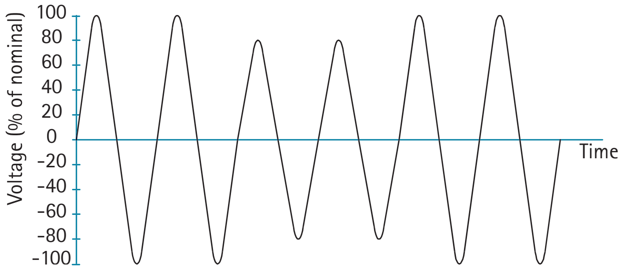


Figure 23.4: Recording of a voltage dip

Typical data for undervoltage disturbances on power systems during evolving faults are shown in Figure 23.5. Disturbances that lie in the front right-hand portion of the histogram are the ones that cause most problems, but fortunately these are quite rare.

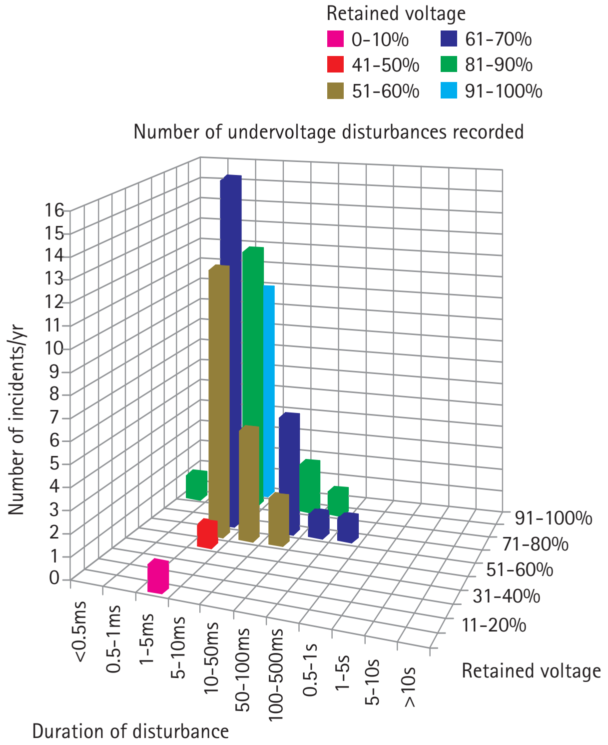


Figure 23.5: Undervoltage disturbance histogram

23.3.2 Voltage Surges/Spikes

Voltage surges/spikes are the opposite of dips – a rise that may be nearly instantaneous (spike) or takes place over a longer duration (surge). These are most often caused by lightning strikes and arcing during switching operations on circuit breakers/contactors (fault clearance, circuit switching, especially switch-off of inductive loads). Figure 23.6 shows the profile of a voltage surge.

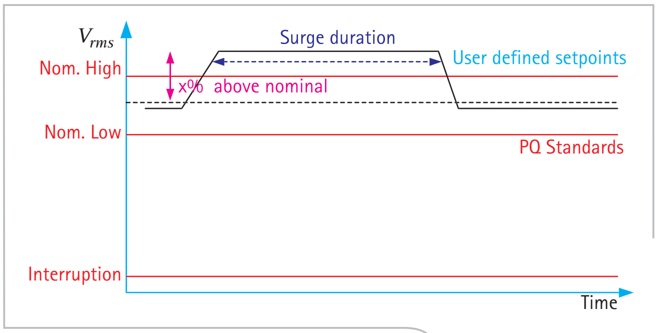


Figure 23.6: Voltage surge profile

Equipment may suffer serious damage from these causes, ranging from insulation damage to destruction of sensitive electronic devices. The damage may be immediate and obvious by the fact that equipment stops working, through to failure at a much later date from deterioration initiated from a surge or spike of voltage. These latter failures are very difficult to distinguish from random failures due to age, minor manufacturing defects, etc.

23.3.3 Overvoltages

Sustained overvoltages are not common. The most likely causes are maladjusted voltage regulators on generators or on-load tap changers, or incorrectly set taps on fixed-tap transformers. Equipment failures may immediately result in the case of severe overvoltages, but more likely is accelerated degradation leading to premature failure without obvious cause. Some equipment that is particularly sensitive to overvoltages may have to be shut down by protective devices.

23.3.4 Harmonics

This is a very common problem in the field of Power Quality. The main causes are Power Electronic Devices, such as rectifiers, inverters, UPS systems, static var compensators, etc. Other sources are electric discharge lamps, arc furnaces and arc welders. In fact, any non-linear load will be a source of harmonics. Figure 23.7 illustrates a supply waveform that is distorted due to the presence of harmonics. Harmonics usually lead to heating in rotating equipment (generators and motors), and transformers, leading to possible shutdown. Capacitors may be similarly affected. If harmonic levels are sufficiently high enough, protective devices may shut the equipment down to avoid damage. Some equipment, such as certain protection devices, may maloperate and cause unnecessary shutdowns.

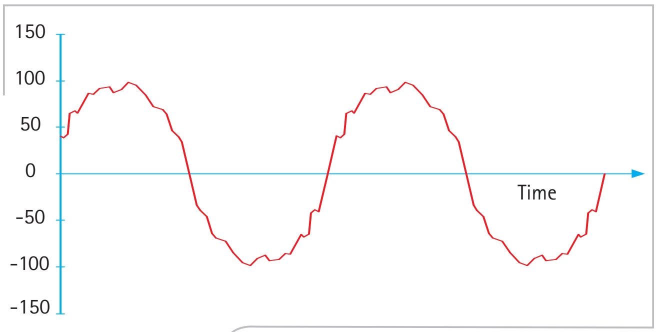


Figure 23.7: Supply waveform distorted due to the presence of harmonics

Special provision may have to be made to filter harmonics from the measured signals in these circumstances. Interference may be caused to communication systems. Overloading of neutral conductors in LV systems has also occurred (the harmonics in each phase summing in the neutral conductor, not cancelling) leading to failure due to overheating. This is a particular risk in buildings that have a large number of PC's, etc., and in such cases a neutral conductor rated at up to 150% of the phase conductors has been known to be required. Busbar risers in buildings are also at risk, due to harmonic-induced vibration causing joint securing bolts, etc. to work loose.

23.3.5 Frequency Variations

Frequency variations that are large enough to cause problems are most often encountered in small isolated networks, due to faulty or maladjusted governors. Other causes are serious overloads on a network, or governor failures, though on an interconnected network, a single governor failure will not cause widespread disturbances of this nature. Network overloads are most common in areas with a developing electrical infrastructure, where a reduction in frequency may be a deliberate policy to alleviate overloading. Serious network faults leading to islanding of part of an interconnected network can also lead to frequency problems.

Few problems are normally caused by this problem. Processes where product quality depends on motor speed control may be at risk but such processes will normally have closed-loop speed controllers. Motor drives will suffer output changes, but process control mechanisms will normally take care of this.

Extreme under- or overfrequency may require the tripping of generators, leading to the possibility of progressive network collapse through network overloading/underfrequency causes.

23.3.6 Voltage Fluctuations

These are mainly caused by load variations, especially large rapid ones such as are likely to occur in arc and induction heating furnaces, rolling mills, mine winders, and resistance welders.

Flicker in incandescent lamps is the most usual effect of voltage fluctuations. It is a serious problem, with the human eye being particularly sensitive to light flicker in the frequency range of 5-15Hz. Because of the wide use of such lamps, the effects are widespread and inevitably give rise to a large number of complaints. Fluorescent lamps are also affected, though to a lesser extent.

23.3.7 Voltage Unbalance

Unbalanced loading of the network normally causes voltage unbalance. However, parts of the supply network with unbalanced impedances (such as untransposed overhead transmission lines) will also cause voltage unbalance, though the effect of this is normally small.

Overheating of rotating equipment results from voltage unbalance. In serious cases, tripping of the equipment occurs to protect it from damage, leading to generation/load imbalance or loss of production.

23.3.8 Supply Interruptions

Faults on the power system are the most common cause, irrespective of duration. Other causes are failures in equipment, and control and protection malfunctions.

Electrical equipment ceases to function under such conditions, with undervoltage protection devices leading to tripping of some loads.

Short interruptions may be no more than an inconvenience to some consumers (e.g. domestic consumers), but for commercial and industrial consumers (e.g. semiconductor manufacture) may lead to lengthy serious production losses with large financial impact. Longer interruptions will cause production loss in most industries, as induction and synchronous motors cannot tolerate more than 1-2 seconds interruption without having to be tripped, if only to prevent excessive current surges and resulting large voltage dips on supply restoration.

On the other hand, vital computer systems are often fed via a UPS supply that may be capable of supplying power from batteries for several hours in the event of a mains supply failure. More modern devices such as Dynamic Voltage Restorers can also be used to provide continuity of supply due to a supply interruption. For interruptions lasting some time, a standby generator can be provide a limited supply to essential loads, but cannot be started in time to prevent an interruption occurring.

23.3.9 Undervoltage

Excessive network loading, loss of generation, incorrectly set transformer taps and voltage regulator malfunctions, cause undervoltage. Loads with a poor power factor (see Chapter 18 for Power Factor Correction) or a general lack of reactive power support on a network also contribute. The location of power factor correction devices is often important, incorrect location resulting in little or no improvement.

The symptoms of undervoltage problems are tripping of equipment through undervoltage trips. Lighting will run at reduced output. Undervoltage can also indirectly lead to overloading problems as equipment takes an increased current to maintain power output (e.g. motor loads). Such loads may then trip on overcurrent or thermal protection.

23.3.10 Transients

Transients on the supply network are due to faults, control and protection malfunctions, lightning strikes, etc.

Voltage-sensitive devices and insulation of electrical equipment may be damaged, as noted above for voltage surges/spikes. Control systems may reset. Semiconductor manufacture can be seriously affected unless the supplies to critical process plant are suitably protected.

23.4 POWER QUALITY MONITORING

If an installation or network is thought to be suffering from problems related to Power Quality, suitable measurements should to be taken to confirm the initial diagnosis. These measurements will also help quantify the extent of the problem(s) and provide assistance in determining the most suitable solutions. Finally, follow-up measurements after installation will confirm the effectiveness of the remedial measures taken.

23.4.1 Type of Installation

Monitoring equipment for Power Quality may be suitable for either temporary or permanent installation on a supply network. Permanent installation is most likely to be used by Utilities for routine monitoring of parts of their networks to ensure that regulatory limits are being complied with and to monitor general trends in respect of power quality issues. Consumers with sensitive loads may also install permanent monitoring devices in order to monitor Power Quality and provide supporting evidence in the event of a claim for compensation being made against the supplier if loss occurs due to a power quality problem whose source is in the Utility network.

The performance of any devices installed to improve Power Quality can also be monitored.

Such devices may have a data link to a DCS or data logger in order to provide historical data recording and data processing/presentation facilities. They are quite small and are fitted in a suitable cubicle forming part of a switchboard line-up. The data link may be hard-wired, use a modem connection to a telephone line, or in the case of a utility with many geographically-dispersed substations, radio links for data transmission may be used. Internal data storage will be provided to ensure effective use of the data link. The units may be self- or auxiliary supply powered, and in the case of important Utility substations may have battery-backed supplies to ensure capture of voltage interruptions. Time synchronisation may be required to ensure accurate identification of events.

For investigation of particular problems, a portable instrument is more suitable. The same range of Power Quality measurement capabilities is provided as for permanent instrumentation. The instrument may have built-in analysis/data storage capabilities, but external storage in the form of floppy discs or a data link to a laptop or desktop PC is commonplace. Analysis/report writing software running on a PC is often available, which may be more comprehensive than that provide in the instrument itself.

23.4.2 Connection to the Supply

Connection to the supply being monitored may present problems. For LV supplies, the voltage inputs are usually taken directly to the instrument in single-phase or three-phase form as required. Monitoring of currents may be through a current shunt or suitable CT, depending on circuit rating. At higher voltages, VT's and CT's already fitted for instrumentation/protection purposes are used. In general, the conventional electromagnetic voltage or current transformer is suitable for use without special considerations being required, but capacitor voltage transformers often have a low-pass filter on the output that has the potential to seriously affect readings of harmonics and transient phenomena. In such cases, the input to the monitoring device must be taken prior to filtering, or the filter characteristics must be determined and the measured signals processed to take account of the filtering prior to analysis being undertaken. In addition, the CVT itself may have a non-linear transfer function with respect to frequency, though the variety of types of CVT and difficulties of testing make confirmation of this point virtually impossible at present.

Where harmonics or high-frequency phenomena are being measured, suitable connecting leads between the transducers and the measuring instrument are required to avoid signal distortion. This is especially important if long cable runs are used; this may be the case if the measuring instruments are centralised but measurements are being made at a number of switchboards.

23.4.3 Types of Power Quality Measurements

Instruments for power quality monitoring may not offer the full range of measurements for all Power Quality issues. Care is therefore required that the instrument chosen is suited for the purpose. Most instruments will provide provide measurements of current and voltage harmonics, and capture of voltage dips and frequency excursions (Figure 23.9).

Measurements to the commonly encountered standards may be built-in. For capture of surges, spikes and interruptions, more specialised instrumentation may be required as transient high-speed waveform capture is required. This requires a high sampling rate and large memory storage.

Most instruments designed for Power Quality use A/D conversion of the input waveforms. The raw waveform is stored and either transferred to a computer for analysis, or the instrument contains built-in software to carry out analysis of power quality in line with accepted standards. Often the software will have a choice of standards for user selection. Figure 23.10 shows the capture of data and analysis for a period of one week to determine compliance with EN 50160.More detailed analysis using the same instrument can show directly how the results compare with this standard, as shown in Figure 23.11.

To facilitate the interchange of data between locations and/or users, the public-domain PQDIF data interchange format for Power Quality may be used and facilities provided for in the software.

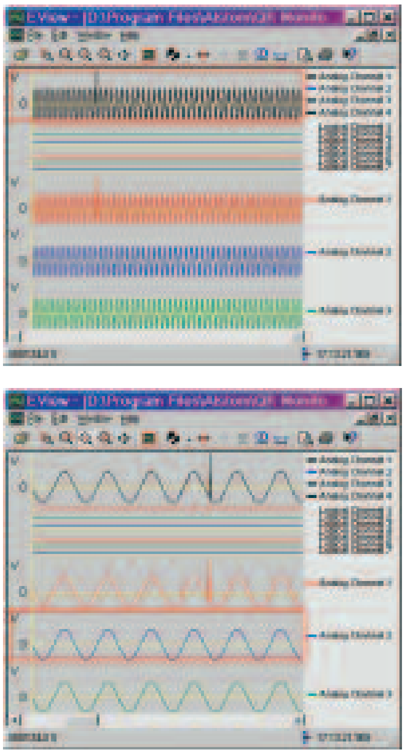


Figure 23.9: Transient voltage disturbance capture

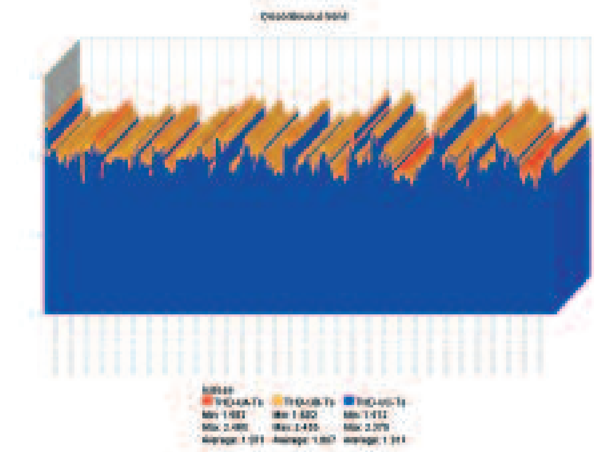


Figure 23.10: Data capture for analysis of data to EN50160

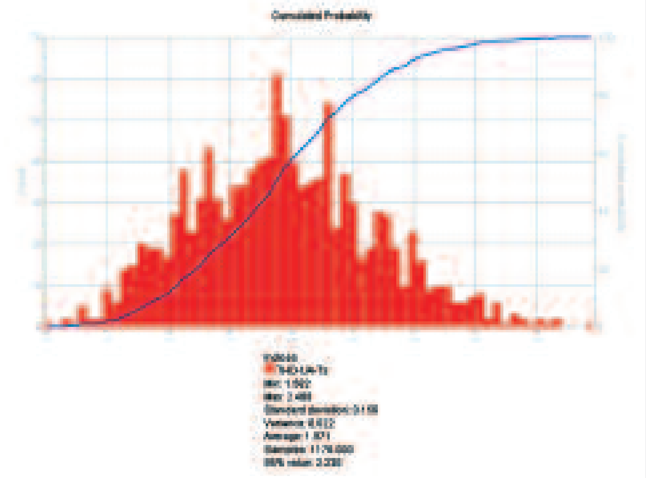


Figure 23.11: THD analysis to EN50160

23.4.4 Instrument Location

The location of the measuring instrument also requires consideration. By careful placement and observing the relative polarities, it is possible to deduce if the source of the disturbance is on the source or load side of the monitoring device.

23.5 REMEDIAL MEASURES

There are many methods available for correcting Power Quality problems. The most common are given in Table 23.3. Brief details of each method are given below, but it is emphasised that the solution adopted will be tailored specifically to the problem and site.

Equipment	Application
UPS	Voltage variations Supply interruptions Frequency variations
Earthing practices	Harmonics
Filters (Active/Passive)	Harmonics
Energy Storage Devices	Voltage variations Supply interruptions

Table 23.3: Power system disturbance classification to EN 50160

23.5.1 UPS Systems

A UPS system consists of the following:

a. an energy storage device – normally a battery

b. a rectifier and inverter

c. transfer switches

The UPS may be on-line (continuously in operation) or offline (switched in when a disturbance occurs). The former eliminates all problems due to voltage surges/spikes/dips and interruptions (within the capacity of the storage device) while the latter passes some of the disturbance through, until the supply is transferred from the normal source to the UPS. Harmonics originating in the source may be reduced, but not eliminated in the load, because the UPS itself is a source of harmonics, as it contains Power Electronic Devices. Thus it may increase harmonic distortion on the source side.The main disadvantages of UPS systems are cost and efficiency. An on-line UPS incurs continuous losses, while both types require energy storage devices that can be expensive. Fast-acting switches to transfer load to the energy storage device are required for offline devices, while transfer switches to bypass the rectifier/inverter when these are undergoing maintenance may also be required. Figure 23.12 illustrates conceptually both types of UPS.

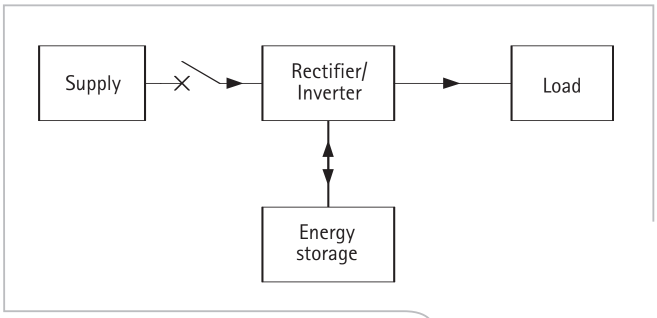


Figure 23.12: UPS system

23.5.2 Dynamic Voltage Restorer (DVR)

This is a voltage source converter and energy store, connected in series (either directly or via an injection transformer) that controls the voltage downstream directly by injection of suitable voltage in series with the source. Ratings of up to several MW are possible at voltages up to 11kV. Figure 23.13 illustrates the concept.

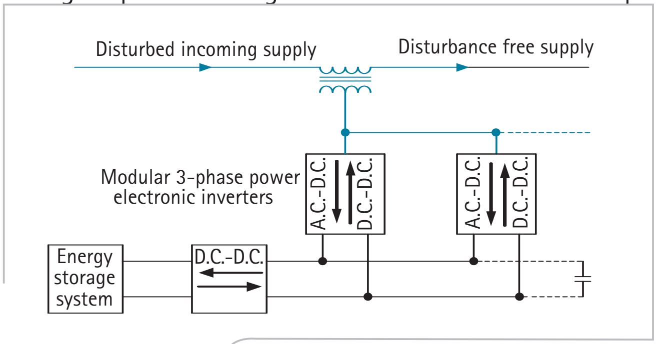


Figure 23.13: Dynamic Voltage Restorer concept

23.5.3 Earthing Practices

A site that suffers from problems with harmonics may need to investigate the earthing of equipment. The high neutral currents that result can give rise to overheating/failure of neutral/earth connections, while high neutral-earth impedances can give rise to common-mode voltage problems. All neutral and earth connections need to be checked to ensure they are adequately sized and have sound joints.

23.5.4 Filters

These are shunt-connected devices used to eliminate harmonics. Either passive (LC or RLC) networks or active (voltage source converter) technologies are possible. Passive filters may take up significant space, depending on the harmonics being filtered and the connection voltage. A voltage source converter may be used instead to provide a reduced footprint. It can filter several frequencies simultaneously and track changes in the frequencies of the harmonics as the fundamental frequency changes. It can be expensive when used solely as an active filter, but be viable where space is at a premium. Figure 23.14 shows the concept of an active harmonic filter. A danger with filters is the possibility of resonance with part of the power system at some frequency, giving rise to problems that would not otherwise occur.

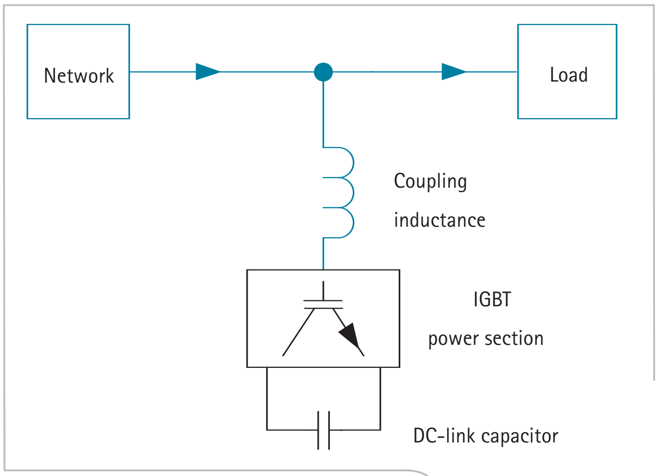


Figure 23.14: Active harmonic filter concept

23.5.5 Static Var Compensator (SVC)

This is a shunt-connected assembly of capacitors, and possibly reactors, which provides reactive power to a network during disturbances to minimise them. It is normally applied to transmission networks to counter voltage dips/surges during faults and enhance power transmission capacity on long transmission circuits. The devices are switched either in discrete steps or made continuously variable through the use of PED's. It works by providing reactive power (leading/lagging as required) to assist in keeping the voltage at the point of connection constant. Voltage variations at that point are reflected in var variations, so provision of reactive power of appropriate sign can reduce the voltage fluctuations. The STATCOM is a SVC comprised of a self commutated static converter and capacitor energy storage. The switching of the converter is controlled to supply reactive power of appropriate sign to the network.

23.5.6 Ferro-resonant Transformer

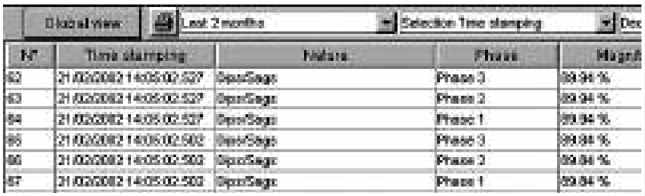
This is a transformer that is designed to run highly saturated. Thus, input voltage dips and surges have little effect on the output voltage. Voltage interruptions of very short duration result in the magnetic stored energy being used up in maintaining output voltage and current. The transformer is normally of 1:1 ratio, although taps may be provided for fine adjustment of output voltage. Appropriate shielding of the windings enables the impact of voltage spikes to be reduced. It is used in LV systems, with a power output of up to a few tens of kVA.

23.6 EXAMPLES

The following sections show some examples of the measurement of Power Quality problems, using an AREVA M720 Power Quality meter.

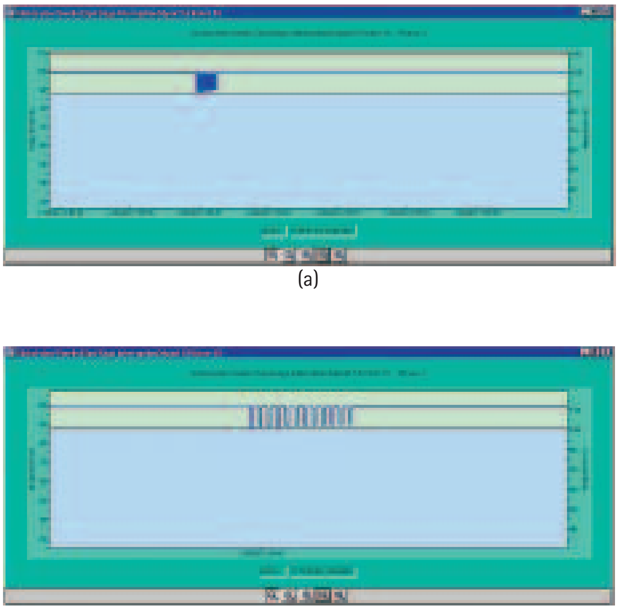
23.6.1 Flicker Detection on a LV network, using Power Quality Monitoring Instruments

In a network known to have a high incidence of disturbances, some local industries were identified as the source of pollution of the electrical network, reducing the level of Power Quality at LV voltages. Measurements using a Power Quality meter show many voltage dips to about 88% of the nominal voltage, as illustrated in Figure 23.15. The voltage dips were found to occur at frequencies of up to 8 dips/second.The dips can also be seen using the graphical viewing facilities of the instrument. Figure 23.16(a) shows the display of the envelope of the r.m.s. voltage, and Figure 23.16(b), the same data magnified. The number, magnitude and frequency of the dips can be clearly seen.



N°	Time stamping	Nature	Phase	Magn
62	21/02/2002 14:05:02.527	Dips/Sags	Phase 3	89.94 %
63	21/02/2002 14:05:02.527	Dips/Sags	Phase 2	89.94 %
64	21/02/2002 14:05:02.527	Dips/Sags	Phase 1	89.94 %
65	21/02/2002 14:05:02.502	Dips/Sags	Phase 3	89.94 %
66	21/02/2002 14:05:02.502	Dips/Sags	Phase 2	89.94 %
67	21/02/2002 14:05:02.502	Dips/Sags	Phase 1	89.94 %

Figure 23.15: Voltage dip recording


(a)

(b)

Figure 23.16: Graphical view of voltage dip data

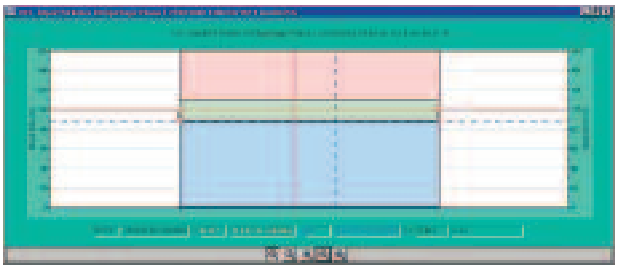


Figure 23.17: Detailed analysis on a single voltage dip

A detailed view of one dip shows clearly that the dips are only just outside the normal supply voltage limits (Figure 23.17).

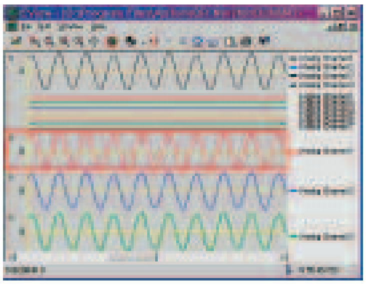


Figure 23.18: Detailed view of voltage dip waveform

Using the waveform capture facility, the problem can be viewed in great detail, as shown in Figure 23.18.

Using this information, and knowledge of the operating cycle of the industries causing the dip, the particular equipment responsible for causing the voltage dip can be identified and remedial measures implemented.

23.6.2 Investigation of Harmonic Pollution Problems on an Industrial Plant

An industrial plant was suffering Power Quality problems, and harmonic pollution was suspected as the cause. A Power Quality meter was installed at various parts of the network to determine the extent of the problem and the equipment causing the problem. Confirmation of the pollution as being due to harmonics was readily obtained. This can be seen in Figure 23.19, for the equipment identified as the source of the disturbance. The graphics enable rapid and clear identification of the frequency and amount by which the generated harmonics exceed the permitted limit. A Power System Analysis of the network was then conducted to replicate the measured results, and then used for testing the effectiveness of harmonic filter designs. The most cost-effective filter design and location can then be selected for implementation.

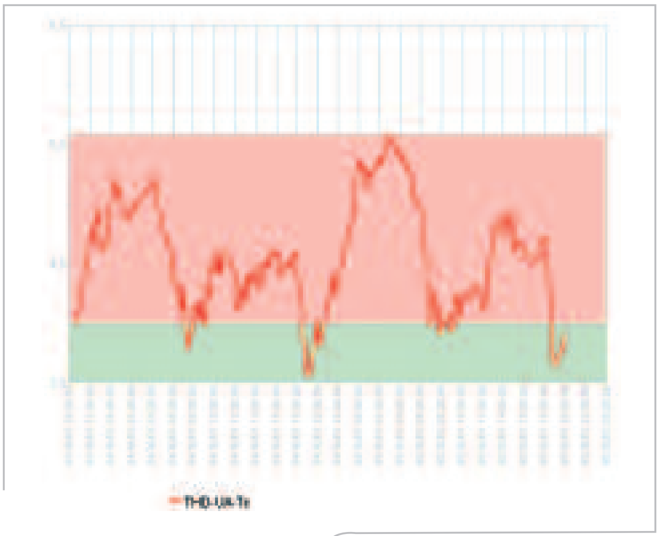


Figure 23.19: Harmonic pollution measurement