INTRODUCTION TO POWER QUALITY

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SUMMARY

Power quality has become a major concern for a large number of industrial sites and buildings. This guide provides an easy-reference to the major power quality phenomena, the problems they are causing, and measures to avoid those problems. It is unlikely that a single solution will be effective. Careful design of a solutions mix, tailored to the PQ problems experienced, and based on a detailed understanding of the causes of the PQ problems, is needed.

INTRODUCTION TO POWER QUALITY

Electrical power is perhaps the most essential raw material used by commerce and industry today. It is an unusual commodity because it is required as a continuous flow – it cannot be conveniently stored in quantity – and it cannot be subject to quality assurance checks before it is used. It is, in fact, the epitome of the 'Just in Time' philosophy in which components are delivered to a production line at the point and time of use by a trusted and approved supplier with no requirement for 'goods in' inspection. For 'Just in Time' (JIT) to be successful it is necessary to have good control of the component specification, a high confidence that the supplier can produce and deliver to specification and on time, and a knowledge of the overall product behaviour with 'on limit' components.

The situation with electricity is similar; the reliability of the supply must be known and the resilience of the process to variations must be understood. In reality, of course, electricity is very different from any other product – it is generated far from the point of use, is fed to the grid together with the output of many other generators and arrives at the point of use via several transformers and many kilometres of overhead and possibly underground cabling. Where the industry has been privatized, these network assets will be owned, managed and maintained by a number of different organizations. Assuring the quality of delivered power at the point of use is no easy task – and there is no way that sub-standard electricity can be withdrawn from the supply chain or rejected by the customer.

From the consumers' point of view the problem is even more difficult. There are some limited statistics available on the quality of delivered power, but the acceptable quality level as perceived by the supplier (and the industry regulator) may be very different from that required, or perhaps desired, by the consumer. The most obvious power defects are complete interruption (which may last from a few seconds to several hours) and voltage dips or sags where the voltage drops to a lower value for a short duration.

Naturally, long power interruptions are a problem for all users, but many operations are very sensitive to even very short interruptions. Examples of sensitive operation are:

- Continuous process operations, where short interruptions can disrupt the synchronisation of the machinery and result in large volumes of semi-processed product. A typical example is the paper making industry where the clean-up operation is long and expensive.
- Multi-stage batch operations, where an interruption during one process can destroy the value of previous operations. An example of this type is the semiconductor industry, where the production of a wafer requires a few dozen processes over several days and the failure of a single process is catastrophic.
- Data processing, where the value of the transaction is high but the cost of processing is low, such as share and foreign exchange dealing. The inability to trade can result in large losses that far exceed the cost of the operation. In a recent example a claim for 15m compensation was made as a result of a 20 minute power interruption.

These are examples of the most sensitive industries, but it is surprising how many apparently mundane operations have quite critical power supply requirements. Examples include large retail units with computerized point of sale and stock control equipment and manufacturing plant with distributed control. So, what do we mean by 'power quality'? A perfect power supply would be one that is always available, always within voltage and frequency tolerances, and has a pure noise free sinusoidal wave shape. Just how much deviation from perfection can be tolerated depends on the user's application, the type of equipment installed and his view of his requirements.

Power quality defects – the deviations from perfection – fall into several categories: –

- Harmonic distortion

- Short interruptions (< 1 minute)
- Long interruptions (> 1 minute)
- Voltage dips (or sags) and surges (or swells)
- Transients
- Flicker
- Unbalance
- Voltage level tolerance
- Poor earthing and EMC

Each of these power quality problems has a different cause. Some problems are a result of the shared infrastructure. For example, a fault on the network may cause a dip that will affect some customers and the higher the level of the fault, the greater the number affected, or a problem on one customer's site may cause a transient that affects all other customers on the same subsystem. Other problems, such as harmonics, arise within the customer's own installation and may or may not propagate onto the network and so affect other customers. Harmonic problems can be dealt with by a combination of good design practice and well proven reduction equipment. Electricity suppliers argue that critical users must bear the costs of ensuring supply quality themselves rather than expect the supply industry to provide a very high reliability supply to every customer everywhere on the network. Such a guaranteed quality supply would require a very substantial investment in additional network assets for the benefit of relatively few customers (in numerical, not consumption, terms) and would be uneconomic. It is also doubtful whether it would be technically feasible within the current social and legal framework in which any customer is normally entitled to be connected to the supply and utility providers have the right to excavate roadways with the risk of cable damage. Weather conditions, such as high winds and freezing rain, frequently cause damage to overhead lines, which, in these conditions, are difficult and time consuming to repair. It is therefore the consumer's responsibility to take steps to ensure that the quality of power *delivered to his process* is good enough, with the clear implication that this quality level may well be higher than that *delivered to the plant* by the supplier. There are a variety of engineering solutions available to eliminate or reduce the effects of supply quality problems and it is a very active area of innovation and development. As such, customers need to be aware of the range of solutions available and the relative merits and costs.

Users are faced with the need to make design investment decisions about the type and quantity of additional plant required to achieve the quality of supply required. Unfortunately, some vital information is missing – the extent and severity of power quality problems likely to be experienced in any particular location is largely unknown. Because there are so few published statistics it is very difficult for consumers to quantify the cost of failure and justify the cost of preventative measures. In the UK, for example, the only data available gives the number and average duration of interruptions longer than one minute, broken down by supplier. On average, for 1998/9, each consumer was likely to have one interruption of about 100 minutes every 15 months representing an availability of 99.98 %.

Unfortunately, it is the 0.02 % that causes the problems. The reported performance of most suppliers was close to their historic best, with the best and worst performers at 50 % and 200 % of the average, so the current situation is probably close to the best that can be achieved economically. It has to be remembered that these figures relate only to interruptions of longer than one minute and there is an unknown, but large, number of interruptions in the 0.1 to 5 second range. The disruption caused by one of these interruptions can be just as costly as a one-hour interruption.

The issue of short interruptions and voltage dips highlights the difference in perspective between supplier and customer. They are by definition short term events so that unless there is a permanent monitor installed the very existence of the event is difficult to prove. It is even more difficult to attribute a business loss to a particular event. The electricity supply industry tends to value an interruption in terms of the cost of the electricity that was not supplied as a result, while the consumer values it in terms of the revenue lost as a consequence of the break in production. Electricity is relatively cheap and the supply interruption relatively short, while lost production can be very valuable (as in the case of semiconductors) and the downtime very long to allow for clean-up (as in the paper making industry). The two parties therefore have completely different views of the importance of voltage dips and on the level of investment in reduction equipment that is justified.

Longer interruptions – power cuts – are usually thought of as being caused by the supplier but can also be caused by the failure of on-site equipment, conductors and connections. Careful design using high resilience techniques can minimize the effects. The objective is to identify single points of failure and eliminate them by providing redundant equipment or alternative supply paths so that operation can continue despite a single failure. Systems designed in this way are easier to maintain and are better maintained as a result. It is important that maintenance procedures are developed at an early stage as part of the resilient design concept. Standby generation and UPS systems, required to cover short and longer term power cuts are essential elements of a resilient system.

While the majority of voltage dips and interruptions originate in the transmission and distribution system and are the responsibility of the supplier, harmonic problems are almost always the responsibility of the consumer. It is harmonic *currents* that cause problems in installations and when these currents flow back into the supply impedance at the point of common coupling, a harmonic voltage is developed. This voltage distortion, or at least some components of it, are distributed around the system and are combined with the background harmonic voltage distortion present in any transmission system (due to the non-linearity of transformers for example). By limiting the harmonic current consumers are permitted to draw the level of voltage distortion *on the supply* is kept within acceptable limits. Most national limits are based on the UK electrical supply industry standard, (currently G5/4) which originated as G5/1. This planning standard established arbitrary voltage distortion limits which, over the last 40 years, have been proven to be largely correct. Determining the source of harmonic distortion can be difficult and this often leads to consumers blaming the supplier for the problem. In fact, it is unusual for harmonic problems within an installation to arise from external causes – the cause is almost always due to the equipment on site and the installation practice used. Section 3 covers harmonic causes and solutions in detail.

Transient disturbances are high frequency events with durations much less than one cycle of the supply. Causes include switching or lightning strikes on the network and switching of reactive loads on the consumer's site or on sites on the same circuit. Transients can have magnitudes of several thousand volts and so can cause serious damage to both the installation and the equipment connected to it. Electricity suppliers and telecommunications companies go to some effort to ensure that their incoming connections do not allow damaging transients to propagate into the customers' premises. Nevertheless, non-damaging transients can still cause severe disruption due to data corruption. The generation and influence of transients is greatly reduced and the efficacy of suppression techniques greatly enhanced where a good high integrity earthing system has been provided. Such an earthing system will have multiple ground connections and multiple paths to earth from any point, so ensuring high integrity and low impedance over a wide frequency band.

Power quality problems present designers with many questions, perhaps the greatest of which is, 'How good is good enough?' This question is impossible to answer. While it is relatively simple to quantify the behaviour of a particular piece of equipment to voltage dips, determining the likely incidence of voltage dips at a particular location on the supply system is rather more difficult; it will change over time as new consumers are added and assets replaced. It is extremely difficult to collect any meaningful data on the sensitivity of equipment to harmonic voltage distortion, and even on the harmonic current distortion caused by equipment. The real question is one of compatibility between the equipment and the supply. There are some international standards available that set limits of voltage variation and harmonic voltage distortion below which equipment should function without error.

Similarly, there are standard limits for voltage deviation and harmonic voltage distortion of the supply. Ideally, there should be a guard band – a safety margin – between the two limits but because supply quality is difficult to measure on a continuous basis, the supply limits are set in statistical terms and not as hard limits.

Ensuring good power quality requires good initial design, effective correction equipment, co-operation with the supplier, frequent monitoring and good maintenance. In other words, it requires a holistic approach and a good understanding of the principles and practice of power quality improvement.

Power Quality Phenomena

Harmonics

Harmonic frequencies are integral multiples of the fundamental supply frequency, i.e. for a fundamental of 50 Hz, the third harmonic would be 150 Hz and the fifth harmonic would be 250 Hz. Harmonic distorted waveform is clearly not a sine wave and that means that normal measurement equipment, such as averaging reading rms-calibrated multi-meters, will give inaccurate readings. Note also that there could be also many zero crossing points per cycle instead of two, so any equipment that uses zero crossing as a reference will malfunction. The waveform contains non-fundamental frequencies and has to be treated accordingly.

When talking about harmonics in power installations it is the current harmonics that are of most concern because the harmonics originate as currents and most of the ill effects are due to these currents. No useful conclusions can be drawn without knowledge of the spectrum of the current harmonics but it is still common to find only the total harmonic distortion (THD) figures quoted. When harmonics propagate around a distribution system, that is, to branch circuits not concerned with carrying the harmonic current, they do so as voltages. It is very important that both voltage and current values are measured and that quoted values are explicitly specified as voltage and current values. Conventionally, current distortion measurements are suffixed with 'I', e.g. 35% THDI, and voltage distortion figures with 'V', e.g. 4% THDV.

Harmonic currents have been present in the electricity supply system for many years. Initially they were produced by the mercury arc rectifiers used to convert AC to DC current for railway electrification and for DC variable speed drives in industry. More recently the range of types and the number of units of equipment causing harmonics have risen sharply, and will continue to rise, so designers and specifiers must now consider harmonics and their side effects very carefully.

Long and Short interruptions

A short interruption is the temporary reduction of the supply voltage to near zero, in all phases according to some definitions or in one or more phases according to others.

In IEEE Standards, the voltage drop during an interruption is > 90% of nominal (i.e. the retained voltage is less that 10% of nominal). A short interruption has a duration of > 20 ms and < 3 minutes, while a long interruption of >= 3 minutes.

In EN Standards, the voltage drop during an interruption is > 99% of nominal (i.e. the retained voltage is less that 1% of nominal). A short interruption has a duration of > 20 ms and < 1 minute, while a long interruption of >= 1 minute.

Voltage dips and swells

A voltage dip is a short-term reduction in, or even complete loss of, supply voltage. It is specified in terms of duration and retained voltage, usually expressed as the percentage of nominal RMS voltage remaining at the lowest point during the dip. A voltage dip means that the required energy is not being delivered to the load and this can have serious consequences depending on the type of load involved.

Motor drives, including variable speed drives, are particularly susceptible because the load still requires energy that is no longer available except from the inertia of the drive. In processes where several drives are involved individual motor control units may sense the loss of voltage and shut down the drive at a different voltage level from its peers and at a different rate of deceleration resulting in complete loss of process control. Data processing and control equipment is also very sensitive to voltage dips and can suffer from data loss and extended downtime.

There are two main causes of voltage dips; starting of large loads either on the affected site or by a consumer on the same circuit and faults on other branches of the network.

A voltage swell is a temporary increase in the RMS value of the supply voltage with the magnitude of between 110% and 180% of the rated voltage.

Transients, surges (switching, lightning)

A transient is a very rapid changes in voltage. It may be in either direction (i.e, it may increase or decrease the magnitude of the instantaneous supply voltage) and will often take the form of a damped oscillatory wave.

Causes include switching or lightning strikes on the network and switching of reactive loads on the consumer's site or on sites on the same circuit. Transients can have magnitudes of several thousand volts and so can cause serious damage to both the installation and the equipment connected to it.

Electricity suppliers and telecommunications companies go to some effort to ensure that their incoming connections do not allow damaging transients to propagate into the customers' premises. Nevertheless, non-damaging transients can still cause severe disruption due to data corruption. Where a good high integrity earthing system has been provided, the generation and influence of transients is greatly reduced and the efficiency of suppression techniques greatly enhanced. Such an earthing system will have multiple ground connections and multiple paths to earth from any point so ensuring high integrity and low impedance over a wide frequency band.

Flicker

Flicker is the visual effect resulting from cyclic variations in the voltage supply to tungsten filament lamps. The visibility of flicker is complex because it depends on the perception of the human eye. The mechanism is well understood and a standard model has been defined to allow the effect to be inferred from voltage measurement. Noticeable flicker can cause loss of concentration and migraine leading to a loss of productivity. It is responsible for some instances of the so-called 'sick building syndrome'.

The cyclic variations that can cause flicker result from rapid switching and are often associated with welding operations and similar activities where large intermittent currents flow.

Unbalance

A three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitude and are phase shifted by 120° with respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical. It is implicitly assumed that the waveforms are sinusoidal and thus do not contain harmonics.

In most practical cases, the asymmetry of the loads is the main cause of unbalance. At high and medium voltage level, the loads are usually three-phase and balanced, although large single- or dual-phase loads can be connected, such as AC rail traction (e.g. high-speed railways) or induction furnaces (large metal melting systems employing highly irregular powerful arcs to generate heat).

Low voltage loads are usually single-phase, e.g. PCs or lighting systems, and the balance between phases is therefore difficult to guarantee. In the layout of an electrical wiring system feeding these loads, the load circuits are distributed amongst the three-phase systems, for instance one phase per floor of an apartment or office building or alternating connections in rows of houses. Still, the balance of the equivalent load at the central transformer fluctuates because of the statistical spread of the duty cycles of the different individual loads.

Abnormal system conditions also cause phase unbalance. Phase-to-ground, phase-to-phase and open-conductor faults are typical examples. These faults cause voltage dips in one or more of the phases involved and may even indirectly cause overvoltages on the other phases. The system behaviour is then unbalanced by definition, but such phenomena are usually classified under voltage disturbances since the electricity grid's protection system should cut off the fault.

Out-of-tolerance Voltage

The supply voltage is normally controlled to be within +/-10%. When the voltage is outside these limits it is said to be under- or over-voltage. They are caused by major switching events. Under-voltages are sometimes imposed intentionally in periods where the demand for energy is high and there are restraints on the availability of supply, such as non-availability of generating or transmission assets.

Out-of-tolerance voltages can influence voltage sensitive equipment e.g., under/overvoltage protected or voltage controlled equipment such as motors.

Earthing and EMC

Earthing of installations and equipment is an issue that crosses the boundaries of the various disciplines involved in the construction and equipping of a modern commercial or industrial building. In general any earthing system needs to satisfy three demands:

- Lightning and short circuit: the earthing system must protect the occupants, prevent direct damage such as fire, flashover or explosions due to a direct lightning strike and overheating due to a short-circuit current.
- Safety: the earthing system must conduct lightning and short-circuit currents without introducing intolerable step-voltage and touch-voltages.
- Equipment protection and functionality: the earthing system must protect electronics by providing a low impedance path to interconnect equipment. Proper cable routing, zoning and shielding are important aspects and serve the purpose of preventing sources of disturbance from interfering with the operation of electrical equipment.

Although requirements for these three aspects are often specified separately, the implementation of them requires an integrated systems approach.

Every piece of electrical and electronic equipment produces some electromagnetic radiation. Similarly, every piece of equipment is also sensitive, to a greater or lesser extent, to electromagnetic radiation. If everything is going to work, the cumulative level of radiation in an environment must be rather less than the level that will disrupt the operation of the equipment working in that environment. To achieve this goal, equipment is designed, built and tested to standards to reduce the amount of radiation that is emitted and increase the amount that can be tolerated.

EMC is defined in the IEC 61000 series as:

> "The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment."

Maintaining this compatibility in practice requires great care in the design and implementation of the installation and the earthing system.

In traditional electrical engineering separate earthing systems were used, for example, signal earth, computer earth, power earth, lightning earth etc. etc. In today's electrical engineering new insights have been gained on the aspect of earthing and grounding and its relation to instrument protection. The concept of separate earthing systems has been abandoned and the international standards now prescribe one overall earthing system. There is no such thing as ‘clean’ and ‘dirty’ earth.

This single earthing concept means in practice that protective earth (PE) conductors, parallel earthing conductors, cabinets and the shields and screens of data or power cables are all interconnected. Also steel construction parts and water are part of this system. Ideally all cables entering a zone must enter at one point at which all screens and other earth conductors are connected.

To reduce interference on equipment the earthing loops between cable-screens and other earthing structures must be kept small. Bonding cables against metal structures makes these structures act as parallel earthing conductors (PEC). Parallel earthing structures are used both for data and power cables. Examples are, in ascending order of effectiveness: earthing wires, cable ladders, flat metal surfaces, cable trays or ultimately metal pipes. The PEC reduces the impedance of the loop formed by the cable and the earthing network. The earthing resistance to mother earth is mostly not important for the protection of equipment. A very effective form of a PEC is a densely woven or completely closed cable screen with a large metal cross-section, connected all around at both ends of the cable.

To keep the impedance of bonding connections in the earthing network small for high frequencies, litz wire (stranded, individually insulated) or metal strips with a length to width ratio smaller than 5 must be used. For frequencies higher than 10 MHz round wires should not be used.

A raised floor can serve as a good equipotential plane. The copper grid underneath it must have a maximum spacing of 1.2 metres and be connected to the common bonding network via many equipotential bonding conductors. The grid should be connected to a 50 mm^2 copper ring placed around the raised floor area, within the boundaries of the floor, at 6 metre intervals. Power and signal cables should be at least 200 mm apart and, where they cross, they should do so at right angles.

Power Quality problems

The list of potential problems caused by PQ phenomena is surprisingly long. Many problems are complex, and often an expert team needs to be assembled for their accurate diagnosis and solution. Problems with similar symptoms, such as equipment overheating, can have different causes (e,g, harmonics, unbalance, overloading), each requiring a different solution.

Whether a site is likely to suffer from power quality problems or not depends on several factors:

- the quality of the voltage supplied by the utility
- the types of loads in the installation
- the sensitivity of the equipment to various kinds of disturbances

There is no single, generic solution. An optimum techno-economic solution needs to be designed for each site, taking into account the above three interacting factors.

Nuisance tripping of Circuit breakers and RCDs

Nuisance-tripping of circuit breakers has several possible causes.

Inrush currents, especially of electronic equipment with switched mode power supplies, can reach several hundred times normal current for a period of several milliseconds. Depending on the class of circuit breaker, it may trip.

Where harmonic currents are present, the circuit breaker may not respond correctly to the higher frequency harmonics and either trip erroneously or fail to trip. It should be noted that some older measuring instruments do not respond correctly to harmonic currents leading to under measurement. The apparent ‘nuisance tripping’ is actually a genuine and correct response to overcurrent.

RCDs operate by detecting imbalance between phase and neutral currents, indicating that a portion of current is returning via the earth connection instead of the neutral. This condition would normally indicate a fault, but a lot of electronic equipment is fitted with supply filters which deliberately pass current to the protective earth conductor. Where several items of this type of equipment are connected to a circuit it is possible for the leakage current to trip the RCD. Note that there are special regulations covering circuits with high leakage currents.

Whatever the reason for nuisance tripping, simply oversizing the breaker is never the correct solution.

Computers lock up

Currents in the protective earth – which originate from noise and leakage currents – cause voltage drops between the earth reference points of equipment and true earth. Although these voltages are small, they may be significant compared with the noise margin of IT equipment. IT hardware is designed to minimise sensitivity to this kind of common mode disturbance but it cannot be eliminated entirely, especially as the noise frequency rises. Modern communications protocols have built-in error detection and correction algorithms, requiring retransmission of erroneously received data - and consequently reducing the data throughput. As a result, PCs will often slow down or even lock-up, a frequent phenomenon in today's office environments.

The situation is worse in a TN-C network, where the combined neutral-earth conductor actively carries current, creating voltage drops. The earth reference plane of different computers on different floors or circuits is no longer at the same potential, increasing common mode noise. Where equipment is connected by data cables, currents will flow along the cable shields.

Flickering screens

In TN-C configurations the neutral currents can flow by myriad routes throughout the building. As a result, the net magnetic field is stronger and larger than would be the case in a TN-S system where the 'go and return' currents are confined to the same cable. Triple-N currents generate fields at higher frequencies. These fields can cause distortion of CRT screen images.

Only TN-S and TN-C-S systems should be used in modern installations. The discipline of having one and only one neutral-earth connection point in the installation improves safety and EMC.

Computers or other electronics are damaged

Lightning and large switching strikes occurring electrically close to computers and other electronic equipment may, if the surge protection is insufficient, cause damage to the equipment.

Lights dim or flicker

Voltage dips cause instantaneous dimming of lamps. Some discharge lamps may not automatically restart following deep or long dips.

Loss of synchronization of processing equipment

Severe harmonic voltage distortion can create additional zero-crossings within a cycle of the sine wave; this can affect sensitive measurement equipment. Synchronisation of process control equipment in continuous manufacturing may be disturbed and PLC devices may lock up.

Motors or other process equipment malfunctions

Voltage harmonics cause extra losses in direct line-connected induction motors. The 5th harmonic creates a counter-rotating field, whereas the 7th harmonic creates a rotating field beyond the motor's synchronous speed. The resulting torque pulsing causes wear and tear on couplings and bearings. Since the speed is fixed, the energy contained in these harmonics is dissipated as extra heat, resulting in premature ageing. Harmonic currents are also induced into the rotor causing further excess heating. The additional heat reduces the rotor/stator air gap, reducing efficiency even further.

Variable speed devices cause their own range of problems. They tend to be sensitive to dips, causing disruption of synchronised manufacturing lines. They are often installed some distance from the motor, and cause different electromagnetic interference and voltage spikes due to the sharp voltage rise times.

Special care has to be taken at start-up of motors after a voltage dip when the motor is normally operating at close to full load. The extra heat from the inrush current at start-up may cause the motor to fail. This phenomenon can be mitigated by optimum sizing of motors, taking into account:

- that the motor has been designed to run at maximum efficiency at about 70 % load
- the incidence of voltage dips, and the permissible rest time that can be tolerated before the motor must be restarted.

NOISE INTERFERENCE TO TELECOMMUNICATION LINES

If the electrical noise cannot be reduced to a low enough level it will produce interference signals, which exceed telecommunication immunity level increasing transmission error rates.

RELAYS AND CONTACTORS NUISANCE TRIPPING

Relays and contactors are sensitive to voltage dips and can often be the weakest link in the system. It has been established that a device may drop out during a dip even when the retained voltage is higher than the minimum steady state hold-in voltage.

The resilience of a contactor to dips depends not only on the retained voltage and duration but also on the point on the waveform where the dip occurs, the effect being less at the peak.

TRANSFORMERS AND CABLES OVERHEATING

Harmonics produce extra eddy current losses. These losses lead to transformers and cables overheating. Additionally triple n harmonics add up and flow in neutral conductors and delta windings of transformers creating additional extra heat.

OVERHEATING OF CONDUCTORS DUE TO SKIN EFFECT

All harmonics cause additional losses in the phase conductors. The skin effect, which is negligible at 50 Hz, starts to play a role from 350 Hz (7_{th} harmonic) and upwards. For example, a conductor with 20 mm diameter has 60 % more apparent resistance at 350 Hz than its dc-resistance. The increased resistance, and even more, the increased reactance (due to higher frequency), will result in an increased voltage drop and an increased voltage distortion.

OVERHEATING OF TRANSFORMERS AT MODERATE LOAD

Harmonics cause additional losses in the transformer. When the transformer is close to maximum load, these losses can lead to early failure due to overheating and hot spots in the winding. With the current trend to push equipment harder to its limits, and the increasing harmonic pollution in low-voltage networks, this problem is occurring ever more frequently.

Losses in transformers are due to stray magnetic losses in the core, and eddy current and resistive losses in the windings. Of these, eddy current losses are of most concern when harmonics are present, because they increase approximately with the square of the frequency. In a typical mixed load building the transformer eddy current losses will be about 9 times higher than would be expected, approximately doubling the total load losses. Before the excess losses can be determined, the harmonic spectrum of the load current must be known.

PROBLEMS WITH POWER FACTOR CORRECTION EQUIPMENT

Harmonic frequencies may coincide with resonant frequencies of the combined stray inductance and power factor correction (PFC) equipment, creating excessive voltage or current and leading to premature failure. Moreover, as a general problem, measurement devices may not correctly measure the loading of the PFC, as they incorrectly measure the harmonic content in the current.

Problems with specific (long) lines or when switching heavy loads

Long lines mean higher impedance, resulting in higher voltage disturbances from inrush currents, for example when a heavy motor starts up, or when switching on computers. Harmonic currents generated by variable speed drives, or switch-mode power supplies, located at the end of long lines, result in higher harmonic voltage distortion. It is important to dimension power line conductors to reduce impedance and voltage drop. As a side benefit, upsized power lines will have lower losses. When loaded more than 3,000 hours, the economic payback will be very short.

Overloaded neutrals

In a 3-phase circuit, there are 3 active conductors, and a return conductor, which carries the unbalance between the 3 phases. However, with the triple-n harmonics adding up, significant currents flow in the neutral conductor. As many neutral conductors have been, in the past, half-sized, this situation can become critical, even when the phase conductors are operating well below full load.

Power Quality Solutions

Measures to improve energy availability

Voltage stabilisers

Most voltage dips on the supply system have a significant retained voltage, so that energy is still available, but at too low a voltage to be useful to the load. Voltage stabilisers have no energy storage mechanism and use the retained voltage to generate a voltage to boost the supply back to the nominal voltage. Since the energy required by the load does not change, the stabiliser draws a proportionately higher current during the dip, which, depending on the cause of the dip, may make it more severe.

The minimum retained voltage for which the stabiliser can compensate depends on the detailed design of the device but is also limited by the characteristics of the installation; the conductor sizing and protection system must be designed for the input current at the minimum required retained voltage.

The main types of automatic voltage stabilisers are as follows:

- Electro-mechanical
- Ferro-resonant or constant voltage transformer (CVT)
- Electronic step regulators
- Saturable reactors (Transductor)
- Electronic voltage stabiliser (EVS).

An important point to note in the selection of an automatic voltage stabiliser is that the chosen solution must solve the particular problem without creating additional problems. One example of this would be the use of a ferro-resonant stabiliser on the output of an inferior generator to reduce voltage variations. The performance of this arrangement would be compromised because the frequency variations due to the generator would result in an output voltage change of 1.5 % for each 1 % change of frequency.

Uninterruptible power supply (UPS) devices

UPS systems are now commonly used as standby power supplies for critical loads, where the transfer time must be very short or zero. Static UPS systems are easily available in ratings from 200 VA to 50 kVA (single-phase) and from 10 kVA up to about 4000 kVA (three-phase). As well as providing a standby supply in the event of an outage, UPSs are also used to locally improve power quality. The efficiency of UPS devices is very high, with energy losses ranging from 3% to 10%, depending on the number of converters used and the type of secondary storage battery.

For small loads, the UPS is often sized so that it is capable of supporting the load for an extended time – perhaps up to an hour or more. For larger loads the cost of batteries makes this impractical so it is usual to size the system so that it will support the load for long enough to ensure that a backup generator can be started.

The basic classification of UPS systems is given in the standard IEC 62040-3 published in 1999 and adopted by CENELEC as standard EN-50091-3 [1]. The standard distinguishes three classes of UPS, indicating the dependence of the output voltage and output frequency from the input parameters:

- VFD (output Voltage and Frequency Dependent from mains supply),
- VI (output Voltage Independent from mains supply),
- VFI (output Voltage and Frequency Independent from mains supply).

However, in practice this classification closely corresponds to classification by internal structure:

- Passive standby
- Line interactive
- Double conversion.

Classification according to the standard	**VFD**	**VI**	**VFI**
UPS solution	Passive standby	Line interactive	Double conversion
Cost	lowest	medium	highest
Voltage regulation	none	limited	Yes
Frequency regulation	none	none	Yes
Transfer time	short	zero	Zero

Table 1 Classification and characteristics of standard classes of UPS

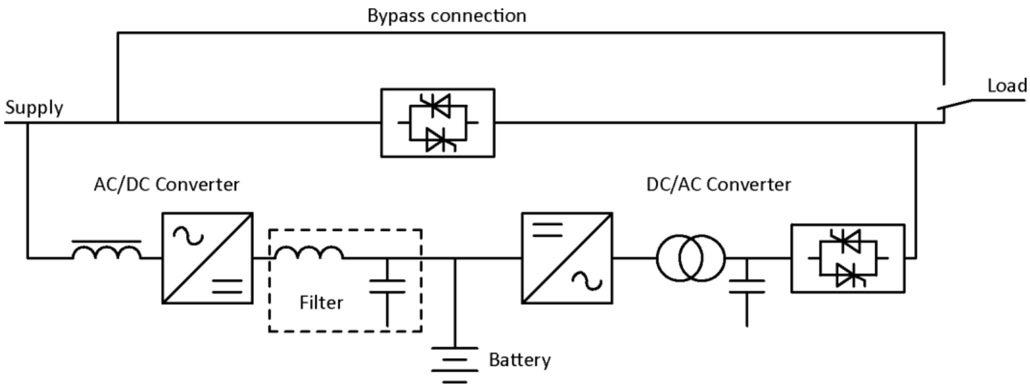

Figure 1 – Double Conversion UPS

BACK-UP GENERATORS

Engine generating sets (EGS) usually consist of one or more diesel internal combustion engines as the source of mechanical energy, a generator to convert mechanical to electric energy, accelerators, control and regulation systems and switchgear. This type of equipment may be designed for relatively long-term operation, say up to several hours or days, or may be designed for continuous operation. EGSs are available in a wide range of power ratings, usually from a few tens of kW up to few MW. Instead of a diesel engine, a gas turbine is sometimes used to drive generators of few MW or more. Generator sets driven by gas turbines are often designed as sources of power for peak lopping or as co-generation plants. The EGSs are also used for special applications where no power network is available, such as marine applications, or where a short-term, high demand requirement exists, such as major televised sports events.

Dynamic voltage restorers

Dynamic Voltage Restorer (DVR) may be used to support large loads during deep supply dips. The device is series coupled to the load and generates the missing part of the supply; if the voltage dips to 70%, the DVR generates the missing 30%. DVRs are normally expected to support the load for a short period and may use heavy-duty batteries, super capacitors or other forms of energy storage such as high-speed flywheels. DVRs cannot be used to correct long term under and over voltage. This is a relatively expensive solution.

Multiple independent feeder

Where there is a need for very high availability of energy in continuous process industries (e.g. paper or steel making), two independent connections to the distribution grid may be provided. This approach is only effective if the two connections are electrically independent, i.e. a predictable single failure in the grid will not cause both network connections to fail at the same time. It depends on the network structure, and often, this requirement cannot be met without the use of very long (and expensive) lines.

The use of two independent connections from the distribution network does not mean that other measures are unnecessary because the number or severity of voltage disturbances will not be reduced. The networked nature of the distribution system allows dips – the result of faults - to propagate over very long distances.

Static transfer switches

Static transfer switches (STS) are fast-acting solid-state AC power devices which can be used to transfer a load between energy sources. They can be used, for example, to switch between multiple feeders, to standby generators or between redundant UPS units.

An example is shown in *Figure 2*. The outputs of two UPS units are coupled to two output lines, 1L and 2L via four STS. Either output line may be connected to either UPS at will, so that the load can be protected in the event of the failure of one UPS unit.

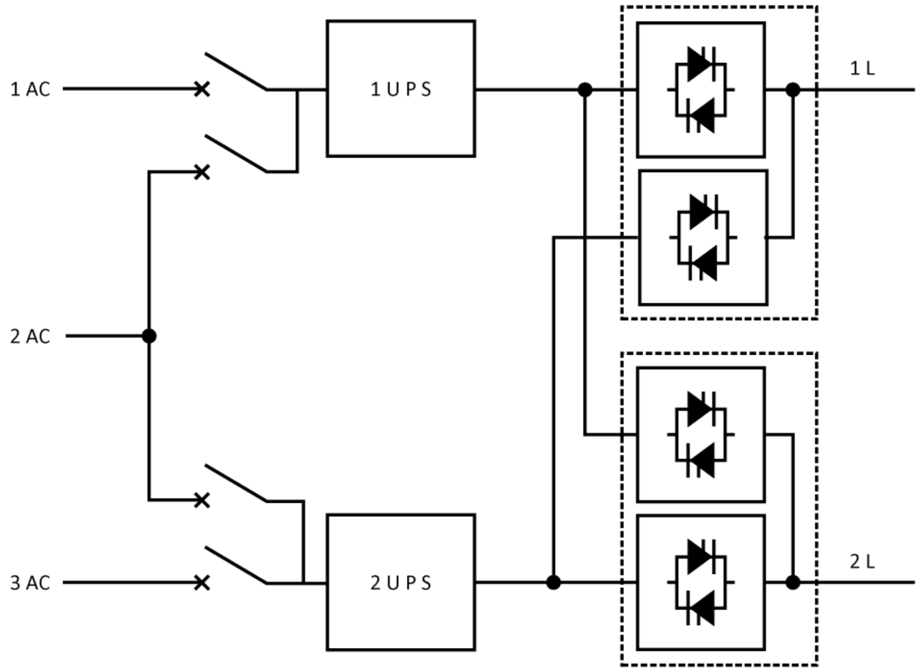

Figure 2 – Improving power supply reliability by means of the static-switches.

Measures to control Harmonic Currents and Voltages

Harmonic filter (passive)

Passive shunt filters are used to provide a low impedance path for harmonic currents so that they flow in the filter and not the supply. The filter may be designed for a single harmonic or for a broad band depending on requirements. Sometimes it is necessary to design a more complex filter to increase the series impedance at harmonic frequencies and so reduce the proportion of current that flows back onto the supply.

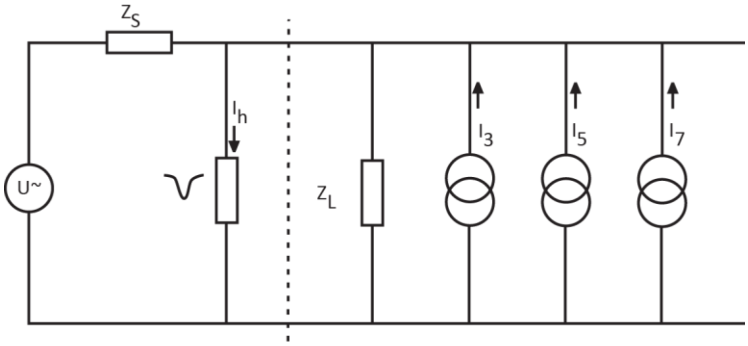

Figure 3 – Passive Harmonic Shunt Filter.

Simple series band stop filters are sometimes proposed, either in the phase or in the neutral, but are not recommended. A series filter is intended to block harmonic currents rather than provide a controlled path for them so there is a large harmonic voltage drop across it. This harmonic voltage appears across the supply on the load side. Since the supply voltage is heavily distorted it is no longer within the standards for which the equipment was designed and warranted. Some equipment is relatively insensitive to this distortion, but some is very sensitive. Series filters can be useful in certain circumstances, but should be carefully applied; they cannot be recommended as a general purpose solution.

Isolation transformers

As mentioned previously, triple-N currents circulate in the delta windings of transformers. Although this is a problem for transformer manufacturers and specifiers - the extra load has to be taken into account – it is beneficial to systems designers because it isolates triple-N harmonics from the supply.

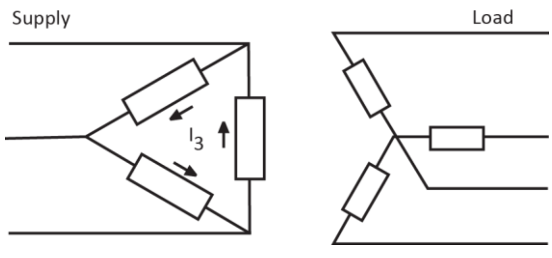

Figure 4 – Delta star isolation transformer.

The same effect can be obtained by using a 'zig-zag' wound transformer. Zig-zag transformers are star configuration auto transformers with a particular phase relationship between the windings that are connected in shunt with the supply.

Line conditioners or active filters

The idea of the active harmonic conditioner is relatively old, however the lack of an effective technique at a competitive price slowed its development for a number of years. Today, the widespread availability of insulated gate bipolar transistors (IGBT) and digital signal processors (DSP) have made the AHC a practical solution. The concept of the AHC is simple; power electronics is used to generate the harmonic currents required by the non-linear loads so that the normal supply is required to provide only the fundamental current. The load current is measured by a current transformer, the output of which is analysed by a DSP to determine the harmonic profile. This information is used by the current generator to produce exactly the harmonic current required by the load on the next cycle of the fundamental waveform. In practice, the harmonic current required from the supply is reduced by about 90%.

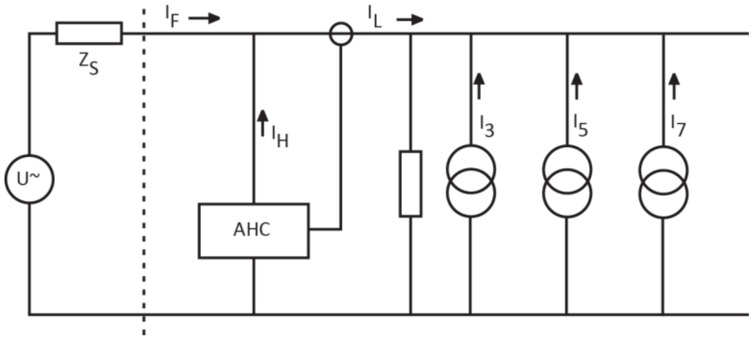

Figure 5 – Principle of Active Harmonic Conditioner Operation.

Because the AHC relies on the measurement from the current transformer, it adapts rapidly to changes in the load harmonics. Since the analysis and generation processes are controlled by software it is a simple matter to programme the device to remove only certain harmonics in order to provide maximum benefit within the rating of the device.

Sizing of Transformers and motors

Transformers are affected in two ways by harmonics. Firstly, the eddy current losses, normally about 5 to 10% of the loss at full load, increase with the square of the harmonic number. In practice, for a fully loaded transformer supplying a load comprising IT equipment the total transformer losses would be twice as high as for an equivalent linear load. This results in a much higher operating temperature and a shorter life. In fact, under these circumstances the lifetime would reduce from around 40 years to more like 40 days! Fortunately, few transformers are so fully loaded in practice, but the effect must be taken into account when selecting plant.

The second effect concerns the triple-N harmonics. When reflected back to a delta winding they are all in phase, so the triple-N harmonic currents circulate in the winding. The triple-N harmonics are effectively absorbed in the winding and do not propagate onto the supply, so delta wound transformers are useful as isolating transformers. Note that all other, non-triple-N, harmonics pass through. The circulating current has to be taken into account when rating the transformer.

Harmonic voltage distortion causes increased eddy current losses in motors in the same way as in transformers. However, additional losses arise due to the generation of harmonic fields in the stator, each of which is trying to rotate the motor at a different speed either forwards or backwards. High frequency currents induced in the rotor further increase losses. Where harmonic voltage distortion is present motors should be de-rated to take account of the additional losses.

Sizing of Line and Neutral Conductors

Alternating current tends to flow on the outer surface of a conductor. This is known as skin effect and is more pronounced at high frequencies. Skin effect is normally ignored because it has very little effect at power supply frequencies but above about 350 Hz, i.e. the seventh harmonic and above, skin effect will become significant, causing additional loss and heating. Where large high-order harmonic currents are present, designers should take skin effect into account and de-rate cables accordingly. Multiple cable cores or laminated busbars can be used to help overcome this problem. Note also that the mounting systems of busbars must be designed to avoid mechanical resonance at harmonic frequencies.

Triple-n currents add in the neutral leading to excessive heating in the neutral conductors of three phase circuits feeding single phase non-linear loads. In such a case, the cable size should be suitably oversized to carry the additional current.

DESIGN STRATEGIES TO IMPROVE PQ

Good design of the installation can considerably improve the PQ experienced at the point of use. Some 'good practices' are described in the following paragraphs.

DEDICATED CIRCUITS

Dedicated circuits are used to reduce coupling between loads. For example, heavy loads that draw a high starting current should have a dedicated circuit connected as close as possible to the PCC so that it cannot cause voltage drops that might affect sensitive equipment. Similarly, circuits feeding loads that produce significant harmonic current should be separated that from those that feed sensitive loads.

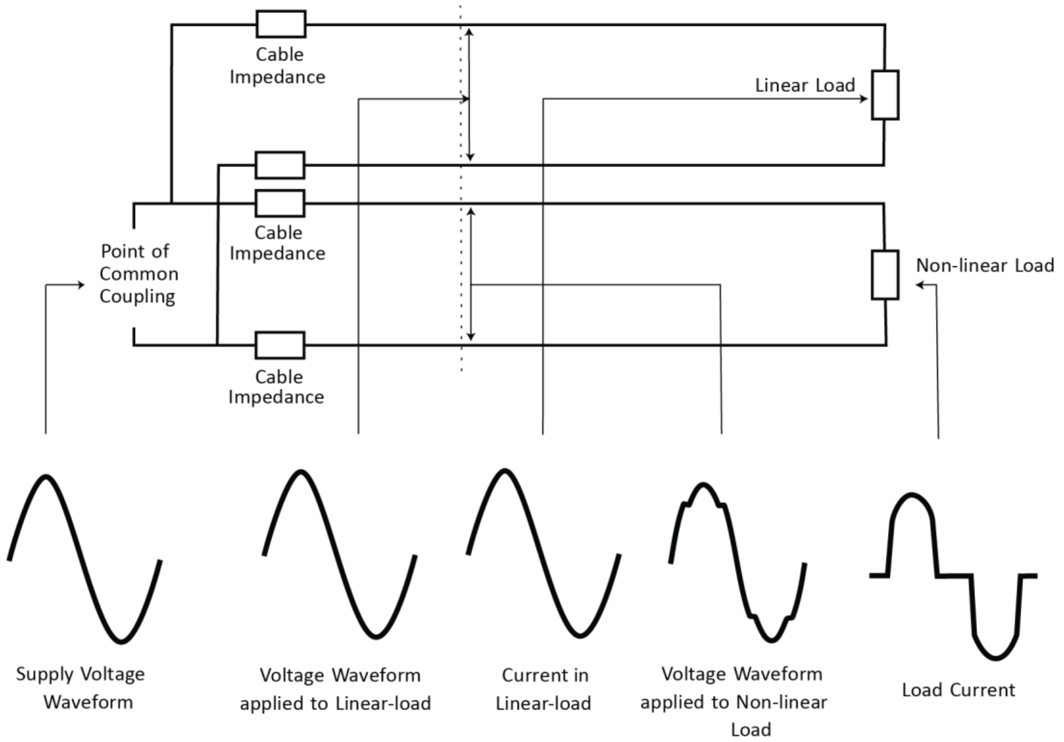

Figure 6 –Separation of Linear and Non-linear Loads.

ZONING OF ELECTRICAL LOADS

Classification of different types of loads by their requirements in terms of EMC, continuity of power supply, safety, etc. allows zoning in various categories, each with its own approach for wiring, earthing or backup.

AVOID TN-C WIRING

TN-C wiring, in which the neutral and protective earth are combined as the PEN conductor, are now either banned or deprecated in most standards because TN-S and TN-C-S systems provide better EMC performance. However, they remain very common in existing buildings. When these buildings are adapted for new uses where PQ may be important, complete re-wiring is necessary.

SHIELDING AND GROUNDING

Earthing of installations and equipment is an issue that crosses the boundaries of the various disciplines involved in the construction and equipping of a modern commercial or industrial building.

In general any earthing system needs to satisfy three demands:

- Lightning and short circuit: the earthing system must protect the occupants, prevent direct damage such as fire, flashover or explosions due to a direct lightning strike and overheating due to a short-circuit current.
- Safety: the earthing system must conduct lightning and short-circuit currents without introducing intolerable step-voltage and touch-voltages.
- Equipment protection and functionality: the earthing system must protect electronics by providing a low impedance path to interconnect equipment. Proper cable routing, zoning and shielding are important aspects and serve the purpose of preventing sources of disturbance from interfering with the operation of electrical equipment.

Although requirements for these three aspects are often specified separately, the implementation of them requires an integrated systems approach.

Shielding is the use of a conducting and/or ferromagnetic barrier between a potentially disturbing noise source and sensitive circuitry. Shields are used to protect cables (data and power) and electronic circuits. They may be in the form of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

OVERVIEW OF PQ PHENOMENA AND DESIGN ISSUES

PQ phenomena, problems and solutions approached by LPQI have been processed to define a PQ - design issue table which has been used for interview design and installation model design.

Design Issue #	Design Issue name	Design Issue Type	Interruptions	Frequency variation	Voltage changes	Voltage fluctuation/flicker	Voltage dips and swells	Harmonics and interharmonics	Unbalance	Overvoltages and transients	EMC and High frequency disturbances
DI-01	Power supply	PS	X	X	X	X	X	X	X	X	X
DI-02	Scheme	SY	X			X		X		X	X
DI-03	Transformers and reactors	EQ	X					X		X	
DI-04	Motors	EQ	X	X	X		X	X	X	X	
DI-05	PFC units	EQ						X		X	
DI-06	Cables	EQ						X	X	X	
DI-07	Protection devices	EQ						X		X	
DI-08	Ground systems	EQ						X		X	X
DI-09	Lighting	EQ	X		X	X				X	
DI-10	Plugs	FC	--	--	--	--	--	--	--	--	--

CONCLUSION

Power quality is complex, covering over a dozen problem areas, for which an even larger number of solutions exist. At present, most energy-intensive sites suffer to some extent from one or more aspects of poor power quality, even though most sites have already adopted some solutions. This is typically the purchase of a UPS, back-up generator and the adoption of true-RMS measurement, complemented by some of the other solutions, such as meshed earthing, TN-S rewiring, active conditioners, etc.

It is unlikely that a single solution will be effective. Careful design of a solutions mix, tailored to the PQ problems experienced, and based on a detailed understanding of the causes of the PQ problems, is needed.