Power Quality Application Guide

Education and Culture

Leonardo da Vinci

Introduction

Power Quality Self-assessment Guide

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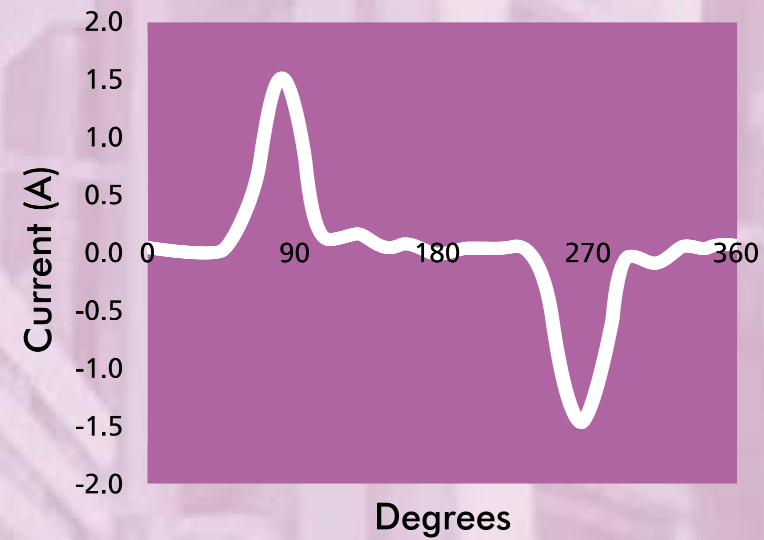

Copper Development Association

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Introduction

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Power Quality Self-assessment Guide

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European Copper Institute
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European Copper Institute (ECI)

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Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and the user industries and maintains close contact with the other copper development organisations throughout the world.

CDA is an IEE endorsed provider of seminar training and learning resources.

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Power Quality Self-assessment Guide

This guide allows a quick self-assessment to decide whether your organisation should adopt a Power Quality (PQ) improvement programme. The list of potential PQ problems is surprisingly long. PQ problems are complex, and often an expert team needs to be assembled for their diagnosis and solution. Similar symptoms, such as equipment overheating, can have different causes (harmonics, unbalance, overloading), and each needs a different solution.

Are you likely to suffer from PQ problems?

Whether or not you're likely to suffer from power quality problems depends on:

- the quality of the voltage supplied by your utility
- the types of loads in your installation
- the sensitivity of your 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. This guide does not address utility issues, amply covered elsewhere, but focuses on the aspects of power quality which are within the control of a site operations manager.

Typical problems

The following checklist gives an overview of the most frequently occurring power quality problems. According to a study performed by European Copper Institute in 2001, covering 1,400 sites in 8 countries, any given site in Europe has a 5-20 % probability that it will suffer from one or more of the problems listed. Typically, half of sites in energy-intensive industries or mission-critical office buildings will suffer from two or more problems. Very few sites are trouble free (see Figure 1).

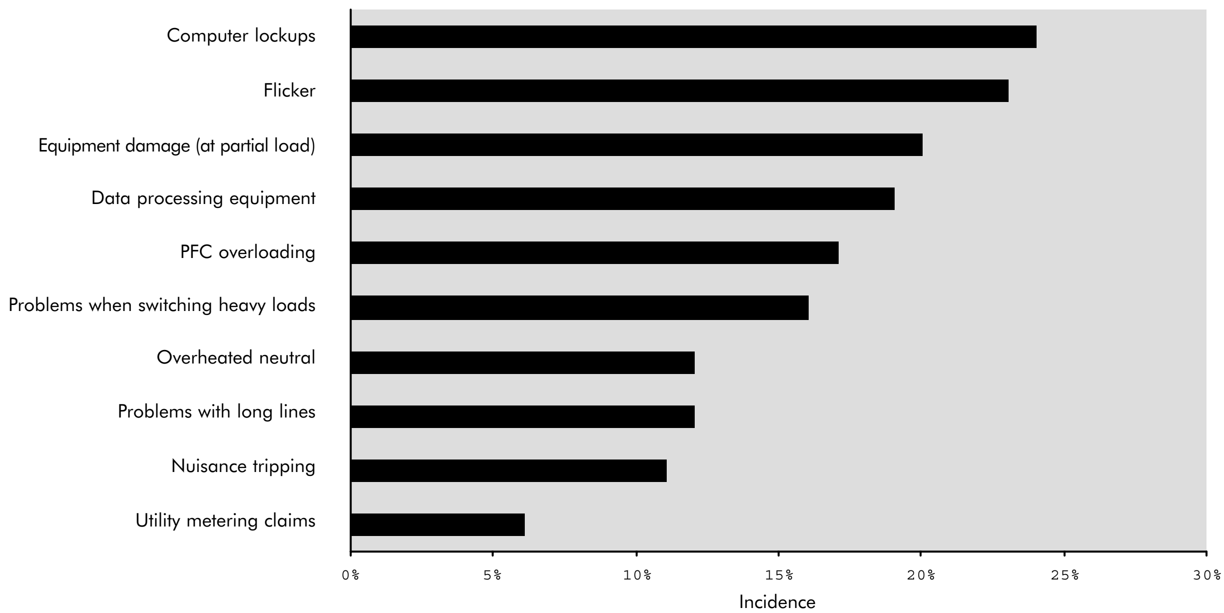

Figure 1 - Most prevalent PQ problems, measured at 1,400 sites in 8 countries

Of course, poor power quality is not the cause of every occurrence of the problems listed. For example, computer lockups can be software related. In addition, attribution of the origin of the problem to causes either before the meter (i.e. on the supplier's side of the point of common coupling (PCC)) or after the meter (i.e. on the customer's installation side of the PCC) is often difficult without detailed measurement and analysis.

Computer lockups

Earth current originating in the equipment results in a voltage drop between the equipment and true earth. Although small, this noise voltage may be significant compared with the signal voltages (of a few volts) on which IT equipment operates. PC hardware is designed to minimise sensitivity to this kind of disturbance but it cannot be eliminated entirely, especially as the noise frequency rises. Modern communications protocols have error detection and correction algorithms built in, requiring retransmission of erroneously received data - and consequently reducing the data throughput. As a result, PCs will often slow down or lock-up, a frequent phenomenon in today's office environments.

In a TN-C network, the combined neutral-earth conductor actively carries current, creating voltage drops. The earth reference plane of different computers on different floors is no longer at the same potential. Currents will flow, for example along the shields of data cables, connected to earth at both ends for EMC compliance.

Flickering screens

Triple-n harmonic currents sum in the neutral conductor. In a TN-C configuration the neutral and protective conductor are combined and connected in many places to the structure of the building. As a result, neutral return currents can flow anywhere in the metal structure of the building and create uncontrolled and uncontrollable magnetic fields. In extreme cases, these fields can result in flicker of computer screens. Neutral current always needs to be returned to the point of common coupling using a separate conductor as in the TN-S and TN-C-S systems. In fact, the discipline of having one and only one neutral-earth connection point in the installation improves safety and EMC.

Flickering lights

Short duration voltage changes, resulting from switching, short-circuits and load changing can result in light flicker. The permissible magnitude of light flicker is regulated by International Standards, based on perception criteria. Excessive flicker can cause migraine and is responsible for some instances of the so-called 'sick building syndrome'.

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.

Induction motors

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 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. Optimum sizing of motors should take into account:

- that the motor has been designed to run at maximum efficiency at about 70 % load
- frequency of voltage dips, and time one can afford to wait to resume motor operation.

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.

Correct functioning of process control equipment

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

Data network congestion

Earth leakage currents cause small voltage drops along the earthing conductor. In a TN-C network, the combined earth-neutral conductor will constantly carry significant current, dominated by triple-n harmonics. Due to the increasing use of low-voltage signals in IT equipment, bit error rate increases, up to the point that the entire network locks up. How many large and small, privately owned networks enjoy this phenomenon almost on a weekly basis? For an unexplained reason, the network locks up, e-mail services fail, it is no longer possible to print …

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 (see Section 3.2.2 of this Guide).

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. Therefore, upsize long power lines for low 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.

Nuisance tripping of protective devices

Inrush currents may trip circuit breakers. Circuit breakers may not correctly sum the current contained in the fundamental and various harmonics and so trip erroneously, or not at all, when they should. Leakage currents may reach thresholds that cause residual current devices to trip.

The remedies against erroneous tripping must not compromise safety of personnel on-site. The general solution is to reduce the inrush currents and earth leakage currents by splitting equipment over more circuits, each feeding fewer loads. Specially designed circuit breakers, that can cope with harmonics, should be used. Oversizing is never the correct solution.

Utility claims resulting from harmonics affecting supply

Not many utilities charge (yet) for harmonic pollution, as they currently do for reactive power. However, they may start to do so in the future, as harmonics also lead to sub-optimal exploitation of the electricity distribution system.

Solutions

The list of possible solutions for power quality problems is again long and non-complete. Figure 2 lists the power quality solutions adopted according to a survey of 1,400 sites in 8 countries.

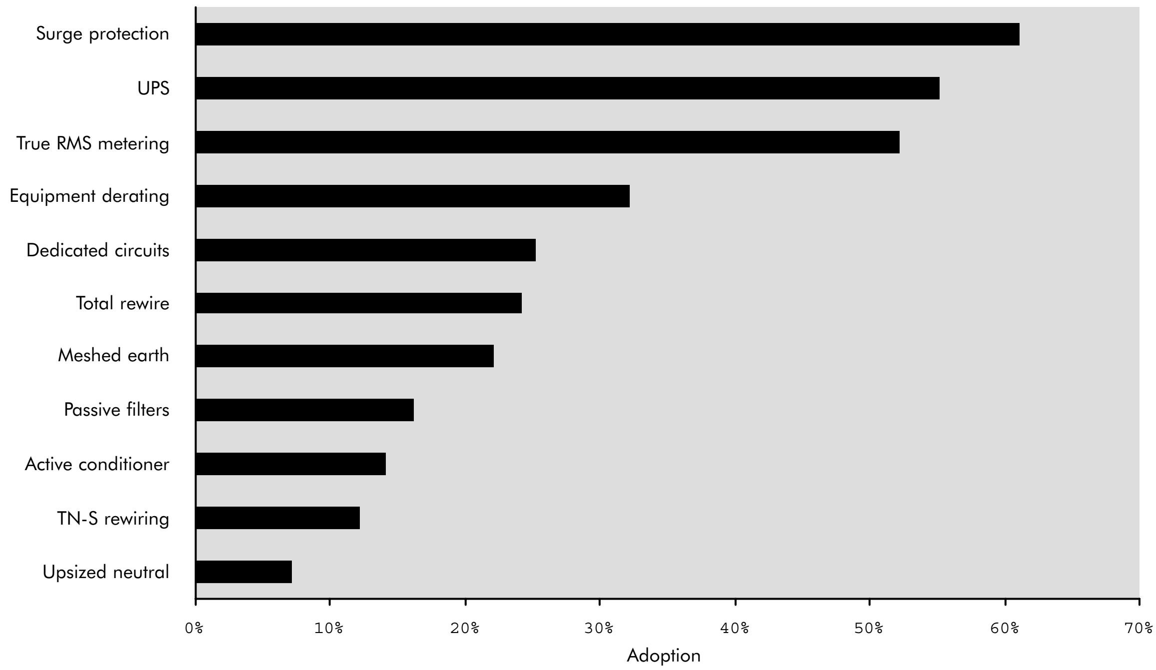

Figure 2 - Most prevalent PQ solutions, in terms of % adoption rate at 1,400 sites in 8 countries

It is important to appreciate that there is no single solution to power quality problems. For each type of problem, there is a range of possible mitigation approaches, several of which could be equally successfully applied. In the real world, it is likely that several problems will co-exist, and the solutions adopted must be compatible with each other and with the loads that make up the installation. One must beware of the so-called 'black-box' wonder solutions that are sometimes heavily marketed as curing a particular problem in all circumstances - in general practice, they do not exist! Designers must always seek the optimum mix of solutions for the problems being experienced and expected to arise in the future in the context of the installation. These solutions should be robust.

It is important to realise that the electrical load is not static. Differences in duty cycles of equipment and variations in working patterns contribute to a constantly changing load pattern. A large office building, for example, may have hundreds of mutations per year so that the 'harmonic culture' - the spectrum of aggregate harmonic currents - in the installation changes constantly. The harmonic profiles from IT equipment do not average out but, especially for the important third and fifth harmonics, add up. Operation of short duty cycle equipment, such as lifts and metal working equipment (whether on site or at neighbouring sites) causes local voltage variations to add to those that originate in the distribution system. The result is that power quality problems are often statistical in nature and require careful monitoring to define fully.

The cost of power quality problems, in terms of lost output and disruption varies widely depending on the type of industry. However, the cost of mitigation measures frequently falls within the typical investment criteria for business and industry of 2-3 years payback. Of course, the cost of prevention - by avoiding problems at the initial design stage - is 10-20% of the cost of retrofitting mitigation measures into a working installation (see Section 2 of this Guide). Unfortunately, for a building in design stage, the nature and size of the final load is generally unknown so potential power quality problems and their costs are difficult to quantify. Building a business case for investment in PQ solutions can represent quite a challenge. In the future, engineers will be able to confidently predict the likely scale of problems and have practical experience of solving them. At the same time, perhaps building owners and operators will have realised that prevention is always cheaper than cure.

Surge protection

The number one solution in terms of adoption rate. It is discussed in detail in Section 6 of this Guide (Earthing and EMC).

UPS (un-interruptible power supply)

Very few sites incoporating significant amounts of IT or process control equipment do not have some kind of UPS. This can range from one or more simple low power units protecting individual server computers to a large central unit rated at up to 1 MVA or so. UPS strategy must be carefully thought out because UPS energy is stored energy and so has incurred substantial extra losses in its production. It is expensive and should be used selectively. The most frugal approach is to use UPS power only to maintain the server computers, process control equipment and safety equipment long enough to allow an orderly shutdown and/or evacuation - this leaves all the client computers and auxiliary plant without power. At the other end of the spectrum, the UPS may be dimensioned to support virtually the whole operation for the time required to bring an auxiliary supply on-line. For most situations, the optimum will lie somewhere between these two extremes. Section 4 of this Guide discusses these issues in more detail.

Back-up generator

Because of the start-up delay, the generator is the second line of defence against power blackouts. This device is able to provide power to a large portion of loads over a longer period of time.

True RMS measurement

Measuring is knowing. True RMS measured values can be significantly higher than the incorrect values measured by average reading meters. Fortunately, most of the sites surveyed have a true RMS meter on site. However, to be completely sure, all measurement instruments must be true RMS instruments.

Transformer derating

The practice of derating transformers for harmonic loads is well documented, though not yet widely understood, in standard IEC 61378-1 'Transformers for industrial applications'. It should be noted that the additional heat generated by harmonic pollution can lead to a spectacular decrease in lifetime. Use of a K-rated transformer, specially designed to cope with harmonic loads, should be preferred over transformer derating because the K-rated transformer is designed to have lower eddy current losses. A derated transformer has larger losses - it is simply oversized so that the resultant heat can dissipate. On a practical level, it is difficult to maintain the derating of a transformer over its lifetime - as the load grows, the derating tends to be overlooked and the transformer becomes seriously overloaded.

Motor derating

Voltage unbalance and harmonic voltages result in additional losses in electric motors, so that the motor cannot be fully loaded up to its rated power. NEMA provides some guidance on how to derate the motor in the presence of harmonic voltages.

High efficiency motors (Eff1-class) not only save energy and hence money, but they are also more robust against some of the problems mentioned earlier. Using more and better materials, they run cooler and are hence better suited to handle the extra heat generated due to harmonics or inrush currents at start-up after a voltage dip.

Dedicated circuit

Loads that are sensitive to harmonic pollution should be served by dedicated circuits. Heavy loads should also have their own circuits, in order not to affect other loads during start-up. According to the survey, 25 % of sites adopt a policy of using dedicated circuits.

Multiple cables for harmonic loads

Apart from the additional heat generated by neutral currents, the effective cross-section of the cable is reduced because of skin effect, playing a role from the 7th harmonic. Using larger diameter cables is hardly a solution, since the current will continue to be displaced towards the periphery of the conductor. Hence, one should use multiple cables, appropriately disposed to maintain balance.

Complete rewiring of the installation

A rather drastic measure (except as part of a major refurbishment), but frequently adopted, as the old installation has not been designed for coping with modern loads. According to the survey of 1,400 buildings, this solution has been adopted in 24 % of cases.

Zoning of electrical loads

Different types of load have different requirements in terms of EMC, continuity of power supply and safety. Hence a classification of loads in various categories, each with its own approach for wiring, earthing or backup, is needed (see Sections 4 & 6).

Meshed earth

Required to provide a low impedance path to earth over a wide range of frequencies (see Section 6), a meshed earthing system needs to be adopted for each floor, with multiple vertical connections.

Passive filters

A popular solution, that may be applied to individual loads or centrally. When filtering as closely as possible to the point of generation of the harmonics, one can be sure that filtering remains effective during the many mutations that typically occur in office buildings. The disadvantage is that more filter capacity is provided than is actually required (i.e. it makes no allowance for load diversity) and the individual small filters are more expensive than a centralised one. One benefit is that harmonic currents are limited to a smaller area of the installation.

On the other hand, a centralised approach allows the combination of passive filters with power factor correction equipment. Designing these functions together allows steps to be taken to avoid resonance at harmonic frequencies. Usually, combined power factor correction and filtering equipment is centralised, allowing economy of scale due to diversity, reduction in the amount of control required and the ability to correct to a higher level without the risk of self-exciting motors. However, as the harmonic culture of the load changes steps must be taken to ensure that the filter remains functional.

This issue is further developed in Section 3.3.1 of this Guide.

Active conditioners

A best practice solution, but one that comes at a price. However, they are extremely flexible and adaptable and especially useful when dealing with a changing harmonic culture. To be used selectively.

TN-S rewiring

TN-C systems, with the so-called PEN-conductor, have become the exception, where, in some countries, they used to be the rule. In the standards committees, the PEN-conductor is now considered as a special case. For IT-intensive buildings, TN-C is no longer allowed. From an EMC viewpoint, TN-S systems are superior.

Neutral upsizing

Full sized neutrals are now required in most wiring codes except where it can be shown that a smaller conductor will suffice. Where harmonics are present a fully rated neutral - capable of carrying the actual neutral current - is required and, in some wiring codes, must be properly protected against overcurrent (see Section 3.5.1 of this Guide).

Conclusion

Power quality is a complex domain, covering over a dozen problem areas, for which an even larger number of solutions exist. At present, most energy-intensive sites suffer to a certain degree from poor power quality, while most sites have already adopted some solutions. This is typically the purchase of a UPS, back-up generator, adoption of true-RMS measurement and complemented with 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. The subsequent sections of the Guide aim to provide such knowledge for contractors, design engineers and maintenance managers.

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