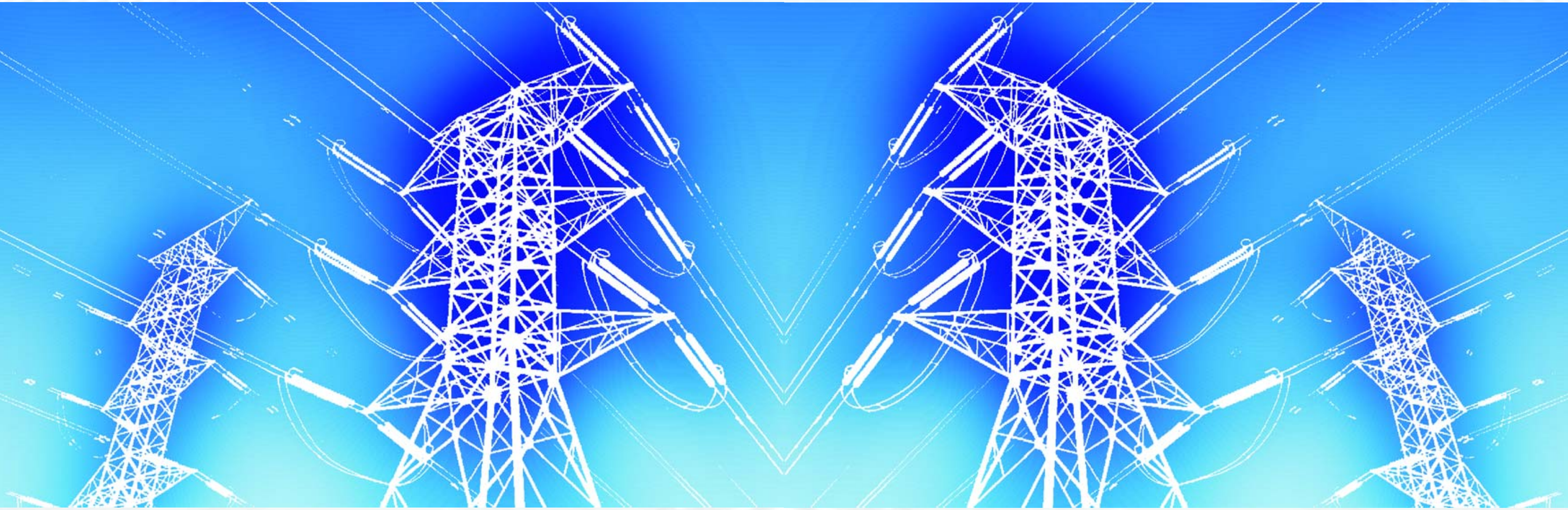
Mains Power Quality



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1. What is mains power quality, and why is it increasingly important?

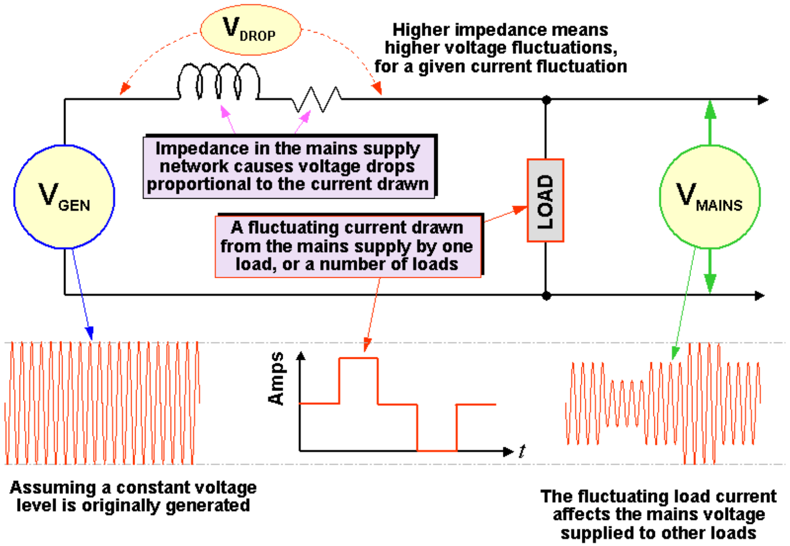
AC mains electricity is distributed in public networks from the electricity generators to the consumers. When it is generated it has a very pure sinewave voltage at 50 or 60Hz (the rest of this guide will assume 50Hz, but the 60Hz issues are identical) – but generators can run slow or fast, and so we have the Power Quality problem of frequency variations.

As the electricity travels along its journey to its consumers it suffers various degrading influences, such as surges due to lightning activity, and radio frequency (RF) interference from radio and TV transmitters. The generators have a source impedance, and the conductors and transformers that the electricity flows through along its route add series impedance, so fluctuations in the current consumption of one load current affect all the others.

Figure 1 shows how a fluctuating current in one load affects the mains voltage supplied to the other loads on the network, because of the impedance in the mains supply. The 'stiffer' the supply (i.e. the lower its impedance) the less is the effect of load fluctuations.

By the time the mains reaches the consumer, it is showing the strain, and wear and tear of its long journey, like a medieval pilgrim who starts off fresh and healthy in smart clothes, and arrives at his destination tired and weary, dirty and travel-stained, with a few injuries and infections picked up along the way.

Figure 1 How mains voltage fluctuations are caused by fluctuating load currents



A list of the ailments that afflict the consumer's mains power quality include…

- Frequency variations
- 3-phase unbalance
- DC in AC supplies
- Overvoltages (swells, surges, transients and electrostatic discharge (ESD)
- Undervoltages (sags, brownouts, dips, dropouts and interruptions)
- Voltage fluctuations and flicker
- Common-mode low-frequency voltages
- Voltage waveform distortion (harmonic and interharmonic)
- Mains signalling voltages
- High-frequency surges and transients, radio-frequency (RF) voltages and currents

1.1 Developments that are making the mains quality worse…

More and more electrical and electronic equipment is being used, increasing the loads on mains power distribution networks. This is a problem in itself, but electrical and electronic technologies are continually changing, especially due to the current trend towards higher efficiencies, which is replacing older technologies that were 'kinder' to the mains supply with technologies that are far less kind, in particular: phase-angle or 'burst fire' power control using thyristors or triacs; and electronic switch-mode power converters with rectifier-capacitor mains input circuits.

For example, almost all direct-on-line (DOL) motors, from tens of MW to a fraction of a kW, are being replaced with variable-speed motor drives driven by 'choppers' (electronic switch-mode power converters). Tungsten filament lamps are being replaced with 'energy-saving fluorescents' (which use electronic switch-mode power converters with rectifier-capacitor mains inputs).

In our working lives we now employ many more computers, printers, and other electronic 'machines' than we used to, and in our home lives we are all busy acquiring computers, wide-screen televisions and home theatre systems, DVD players, etc. All of these modern work and home appliances are connected to the mains via electronic switch-mode power converters.

Frequency-changing switch-mode power converters, such as variable-speed motor drives, also inject significant amounts of noise on the supply at interharmonic frequencies – their output frequency and its harmonics – and also at frequencies that are due to the intermodulation of the output frequency and its harmonics, with 50Hz and its harmonics.

Energy-saving trends are also leading to devices being switched more often, for example occupancy-controlled lighting, and PC monitors that blank if the mouse has not been moved for a while, etc. These are leading to increased levels of short-term fluctuations in load levels, hence increasing fluctuations in mains voltage.

All of these draw currents from the mains that are not at the generated frequency of 50Hz, ranging from switch-on surges (as the capacitors in rectifier-capacitor AC-DC converters charge up) to transients and other current waveshapes with frequency spectra from below 1Hz to over 1GHz.

This increased loading by more 'unfriendly' technologies is increasing the distortion of the mains voltage sinewaves, and also causing increased fluctuations in the voltage level. More devices connected to the mains means more possibilities for failure, so the number of dips and dropouts and imbalances caused by faults, as fuses blow and circuit-breakers open, is increasing.

1.2 Developments that are increasing the need for good power quality…

It is coincidental (but perhaps appropriate) that modern electrical and electronic technologies rely a great deal on the correct operation of software code running on microprocessors – but microprocessors require very high quality DC supplies to operate correctly. Such technologies require good quality AC supplies, if costs of manufacture are to be kept low. But since the increasing adoption of these technologies is causing the mains power quality to reduce, their designs need to continually improve their AC-DC power conversion circuits, increasing their costs of manufacture.

In the case of SCR power converters, the power devices are almost always triggered directly from the AC mains waveform itself. Distortion of the waveform can lead to misfiring, and in some cases possibly to destruction of the power devices. In the case of 'burst-fired' SCRs, distortion around the zero-voltage-crossing point of the AC waveform can cause harmonic current consumption to increase, making EMC compliance less likely, and incidentally increasing the distortion of the mains waveform that caused the problem in the first place.

To fully cover this subject would require a textbook, but this is only a guide. Where readers want to know more they should read [1] and also follow up the many other published documents that describe power quality problems, their causes, effects and solutions, such as [2], [3], [4], [5] [6] and [7]. The REO EMC Guides [8] – [19] are also useful sources of information on causes, effects and immunity test methods for equipment, but do not describe solutions.

According to [20], in 2001 the estimated cost to the US economy of power quality problems was between $119 billion and $188 billion, with about 85% of this cost due to power interruptions ('outages'). Corresponding figures will probably apply to all other industrialised nations, in proportion to the size of their economies.

Power quality is thus a very significant reliability, safety, and financial issue for *all* companies, especially as all companies now rely on computers and computer technology (e.g. the Internet and email) for their financial performance, and computers are notoriously susceptible to power quality problems, plus of course they do not work at all when their power is interrupted.

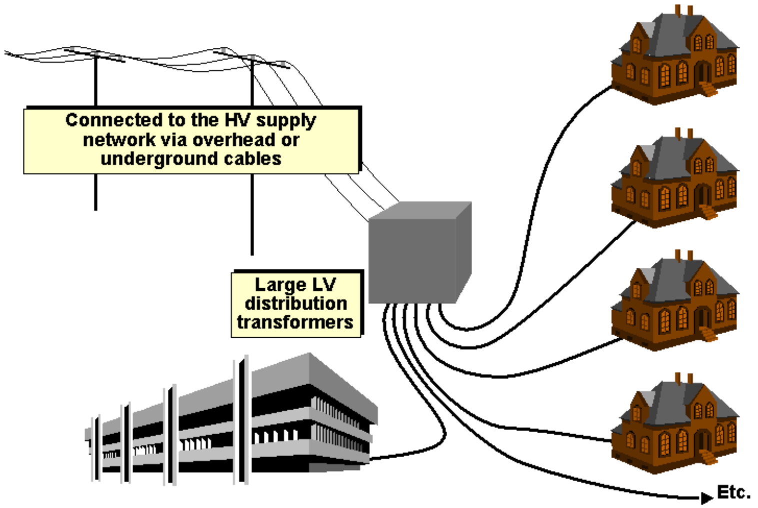
In general there are three kinds of mains power source, as shown by Figures 2 - 4, each with their own characteristics for impedance and frequency stability. In general, the higher the impedance of the mains supply, the worse the power quality problems. This is one of the reasons why the mains distribution systems on large ships, which of course are powered from their own generators, often suffer a lot more from power quality problems than similar networks of equipment powered from a national mains distribution network.

Figure 2 Three kinds of AC power supply – The public supply network

This example is typical of European mains distribution

Range of frequency variations: ±3%, +4% -6% for industrial sites (but maybe -15% or more before an interruption caused by severe overload of the whole network)

Source impedance typically 0.5Ω, less for commercial or industrial supplies



2.1 Frequency variations

Frequency variations are caused by significant load fluctuations on the speed of the generators. Automatic controls normally keep them within very small tolerances, but when a generator reaches its maximum power output any increased loading results in it slowing down. In national mains networks the generators must all stay in synchronism, and any generator that has a rotational speed that varies by more than a tiny fraction of a percent has to be disconnected, so the network frequency stays very stable unless it is overloaded as a whole.

But small distribution networks with limited generation capability are very prone to significant frequency variations. An extreme example occurred on a North Sea oil exploration platform where the 230V mains supply from its diesel generator had frequency variations of about ±90%, lasting for several seconds. The lowest frequency was about 5Hz, when the diesel almost stalled when the drill motor was switched on, and the highest was about 95Hz during the overspeed caused by switching the drill motor off. This would happen numerous times each day.

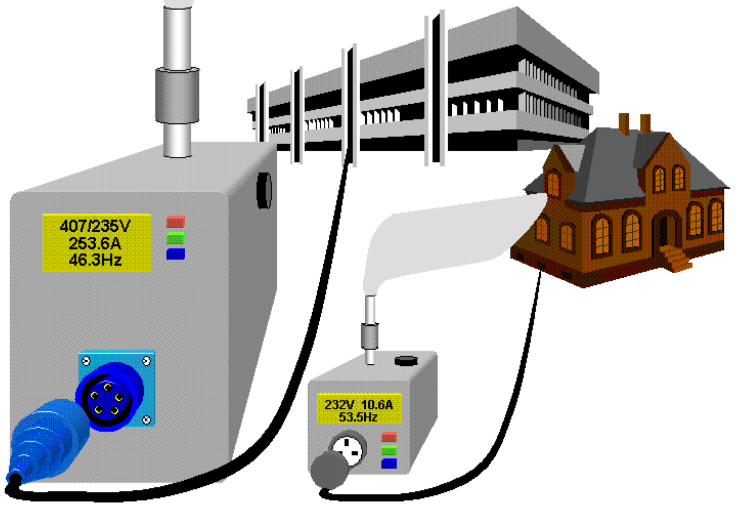
IEC 61000-4-28 is a standard for testing the immunity of equipment to this type of mains power quality problem, also harmonised for Europe as EN 61000-4-28. [13] describes this test standard and how to apply it. Its Clause 3 says that frequency variations can affect:

Figure 3 Three kinds of AC power supply – Local generation

Examples of local generation, driven by internal combustion engines

Range of frequency variations: up to ±15% (but maybe up to 50% or more when heavily overloaded and about to trip out, or when a heavy load has just been switched off)

Source impedance typically 3× that of a distribution transformer with the same VA rating



a) Control systems referring to time (measurement errors, loss of synchronisation, etc.).

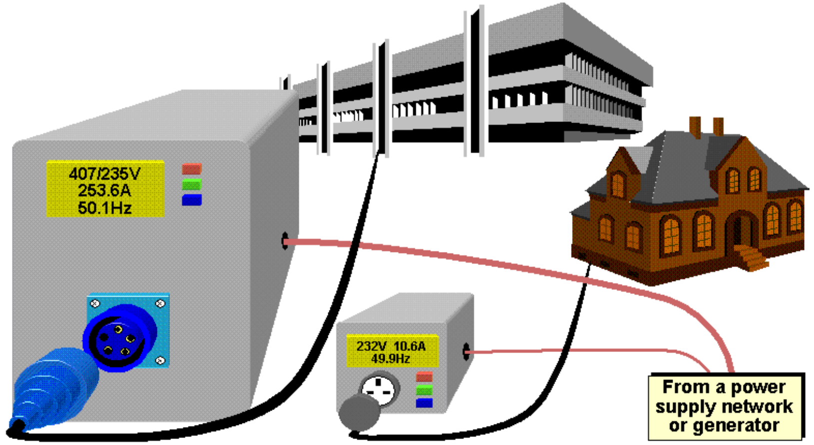
b) Equipment including passive mains filters, which can become detuned.

Examples of a) include real-time clocks operating from the supply frequency, and also processes in which the rates of production are related to supply frequency. For example an induction motor driven machine may get unacceptably out of step with a DC motor, or with anything else that is controlled from a different time reference.

Examples of b) include harmonic filters used to protect supply networks from the effects of severely non-linear loads. Such filters are carefully tuned to the 3rd, 5th, 7th (etc.) harmonics, and if the supply frequency varies significantly they may become less effective, allowing harmonic currents to flow in supply networks that are unable to deal with the resulting heating effects.

Passive harmonic filters are often 'off-tuned' slightly to help prevent the occurrence of resonances in the distribution network they are used on. If supply frequency variations result in peak tuning of the filters, supply resonance might occur in some circumstances, possibly resulting in severe waveform distortion, possibly leading to malfunction and damage to the equipment powered from the network, if not to the network equipment itself.

Figure 4 Three kinds of AC power supply – The UPS



Examples of inverters — solid-state DC-AC power converters — e.g. UPS

Range of frequency variations: maybe as much as ±2% due to initial tolerances, temperature coefficients and ageing (check manufacturer's data)

No drop in frequency even when overloaded to the point of tripping out

Source impedance controlled electronically and can be very low, but peak current ratings can be lower than equivalently rated motor-driven generators or distribution transformers

From a power supply network or generator

EN 61000-4-28 mentions that AC motors tend to draw less power when their supply frequency reduces. But it does not mention the corollary – that a higher supply frequency causes AC motors to spin faster, and since the power required by most loads are proportional to some power of motor speed (e.g. the square or cube), the increased loading could be significant even for quite a small increase in supply frequency. Increased loading generally means increased current drawn from the power supply, but AC motors that cannot supply the power required could increase their slip speed dramatically, maybe even causing them to be unable to supply sufficient power to their loads, causing them to stall, with consequences that depend upon the application.

EN 61000-4-28 also does not mention that reducing the frequency of the AC voltage supplied to a mains transformer increases the magnetic saturation of the core and hence increases the magnetising current. This can lead to overheating transformers, which has occurred when transformers designed for 60Hz mains were used on 50Hz. In normal circumstances this should not be a problem, but there is great pressure to keep costs low – and reducing the amount of copper and iron in transformers is one way to do that. This increases the saturation of the core and the magnetising current, and makes the transformer much more susceptible to reduced mains frequency. The range of the AC supply frequency should always be taken into account when designing cost-effective mains transformers.

Relays and contactors powered from the AC power supply (usually via an isolating transformer) and held-in at reduced voltage (to save energy) might drop-out if the supply frequency changes by a significant amount, and high ambient temperatures make this more likely. When the frequency variation returns to within a few % of nominal, they will not pull back in again because of the low value of the voltage applied to their coils.

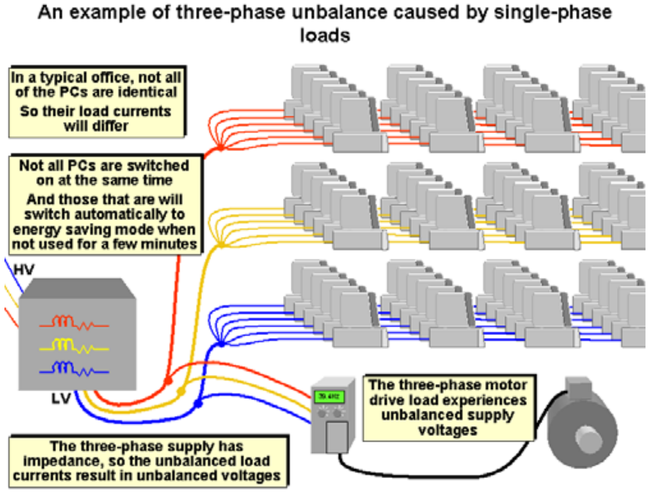
Most electronic equipment that is powered by the AC mains supply simply rectifies it and converts it to DC to power its circuits. These are usually unaffected by small variations in the frequency of their mains power supplies, but may be badly affected by large falls in frequency.

Both linear and switch-mode AC-DC converter types will suffer increased ripple amplitude in their unregulated rails at power supply frequencies less than nominal. When the frequency falls by more than 10% or so, the effect on the equipment could be that the unregulated rail drops below its minimum value up to 100 (or 120) times every second. This can have a similar effect on equipment as dips or dropouts in the supply, such as are tested by EN 61000-4-11 (see [8]). But whereas EN 61000-4-11 tests with dips or dropouts with 10 seconds between each – high values of ripple due to low supply frequency is like each dip or dropout occurring much more often.

2.2 3-phase unbalance

Three-phase voltage unbalances can be caused by unbalanced load currents, as sketched in Figure 5, unbalanced distribution network faults, etc. (most network faults are unbalanced). Both the voltage and the phase can become unbalanced either separately or at the same time, such as the example waveforms shown in Figure 6.

Figure 5 An example of three-phase unbalance caused by single-phase loads



An example of three-phase unbalance caused by single-phase loads

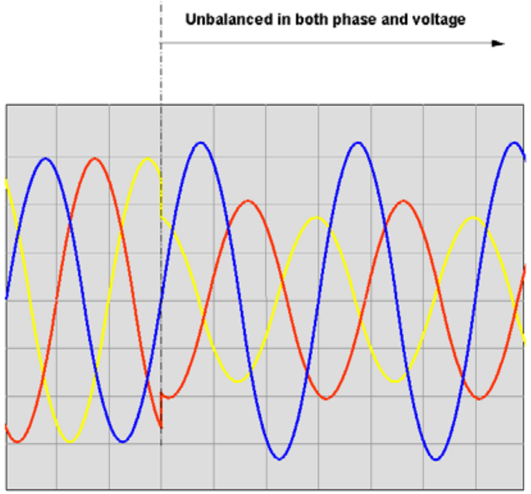
In a typical office, not all of the PCs are identical
So their load currents will differ

Not all PCs are switched on at the same time
And those that are will switch automatically to energy saving mode when not used for a few minutes

The three-phase motor drive load experiences unbalanced supply voltages

The three-phase supply has impedance, so the unbalanced load currents result in unbalanced voltages

Figure 6 An example of a three-phase unbalance in both voltage and phase



[12] describes IEC 61000-4-27, a standard for testing the immunity of equipment to this type of mains power quality problem, also harmonised for Europe as EN 61000-4-27. This test standard says that its aim is to investigate the influence of unbalance in a three-phase system on equipment that may be sensitive to this type of disturbance, which could cause…

a) Overcurrents in AC rotating machines;

b) Generation of non-characteristic harmonics in electronic power converters;

c) Synchronisation problems or control errors in the control part of electrical equipment.

When induction motors are supplied by unbalanced voltages, their current consumption on one or more phases can rise to levels similar to what they draw at start-up – much higher than their normal operating voltages. But start-up only lasts for a fraction of a second (or for a very large motor, a few seconds) whereas some unbalances can exist for minutes, hours, weeks, even years, so overheating – with consequent damage to the insulation of the windings and implications for future reliability – can be a real problem.

Motors are usually protected by overcurrent devices, but if one phase is opened the motor will soon destroy itself. This is why motor control contactors should always break all of the phases simultaneously, whichever phase(s) are suffering the overcurrent.

Most electronic equipment relies upon electronic power converters to turn mains AC power into DC power. Three-phase converters use 6-pulse, 12-pulse and even 24-pulse rectifiers to generate a DC voltage that consists of a constant voltage with a small amount of ripple on it – even though they may not be fitted with any storage capacitors. The higher the pulse rating of the rectifier – the smaller the ripple voltage and the higher its frequency.

But the ripple voltage and frequency on the DC rails of three-phase rectifiers without storage capacitors is very rapidly affected by any unbalance in their three-phase supply. If the circuits following the rectifier have not been designed to cope with the ripple that can result from likely unbalances – they may be affected by it.

Large telecommunication facilities generally power their equipment from a -48V DC bus from float-charged batteries located in a central room, and computer facilities based on modern 'blade servers' can do this too. Their battery chargers are very powerful three-phase units, and the quality of the DC power supplied is crucial to the operation of these facilities. IEC 61000-4-17 is a test standard used to test the response of such equipment to likely levels of ripple on their DC supplies.

In the case of AC-DC-AC converters, often called 'inverters', such as variable-speed drives for AC motors, the result of an unbalance in their three-phase supply is an increased level of interharmonic distortion in their output (waveform distortion that is not harmonically related to the output frequency). This output 'noise' can be harmful to the converter's load. They also intermodulate their mains frequency DC ripple and its harmonics with their output frequency and its harmonics, resulting in increased emissions of interharmonics back into the mains distribution network, worsening its power quality. It is not unusual for poor power quality to interact with electronic loads in a way that results in even worse power quality.

For reasons of cost, sensors (voltage, current, power, etc.) are usually placed on one phase of a three-phase supply, on the assumption that all of the phases behave in the same way. So when an unbalance occurs the sensors might not measure what is required to control the equipment correctly, and misoperation, overheating and even damage might be the result.

2.3 DC in AC supplies

Mains distribution networks are supposed to operate with symmetrical AC voltage and current waveforms, and most loads are supposed to be symmetrical too. Some very powerful loads, such as rectifiers for Chlor-Alkali industrial processes, are half-wave rectifiers, and some low-power loads are too (e.g. hair-dryers, electric blankets), and so cause DC currents to flow in the networks, giving rise to DC voltages due to the impedance in the networks. Many items of electronic equipment will continue to operate satisfactorily despite damage that converts its full-wave bridge rectifiers into half-wave rectifiers, another source of DC currents in power networks.

The rotation of the earth in the magnetic field caused by the sun induces DC voltages into long cables, especially a problem for very long east-west distribution cables, especially during a 'solar storm'. In the past this combination has caused large-scale blackouts in Canada, as the protection devices in their high-voltage networks tripped out transformers to prevent damage due to overheating.

DC in AC supplies is especially a problem for magnetic circuits, such as transformers and DOL AC motors, because the DC voltage results in a DC current that increases the saturation of their magnetic cores. This leads to excessive magnetising currents, increased self-heating, and in the case of transformers a reduced transformer ratio, which can cause problems for loads, particularly electronic devices that can be running on lower DC rail voltages than they were designed for (see 2.1).

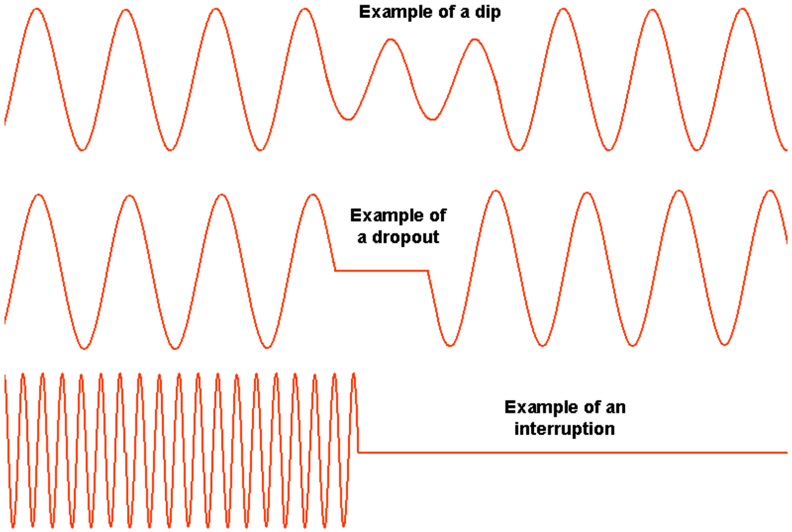
Increasing magnetic saturation means increasingly non-linearity of the load, which in turn causes increased harmonic distortion of the mains voltage waveform – an example of one EMC problem causing another.

2.4 Undervoltages: Dips, dropouts, interruptions and sags

Increases in load current cause the supply voltage to dip (sag) below nominal, until the automatic voltage regulators on the network can adjust (which typically takes a second or two). And decreases in load current cause the supply voltage to temporarily rise above nominal. Short-term load currents (e.g. less than 500ms) cause dips that can be finished before the automatic regulators can respond, a typical example being faults, which cause very high currents to flow for a fraction of a second until they are cleared by the operation of protective fuses or circuit breakers.

According to IEC standards, dips are transient reductions in the supply voltage, to as little as 5% of nominal, typically lasting for less than 1 second. In North America it is common to call these events 'sags', but the IEC reserves this term for longer-term reductions in voltage, lasting seconds or more, which are called 'brownouts' in North America.

Figure 7 **Dips, dropouts and interruptions**



Dropouts and interruptions are simply dips with a depth of more than 95% of the nominal mains voltage. The closer a fault is to the measuring point, the deeper the dip tends to be. 'Short interruptions' are another term for dropouts, and are generally considered to last less than one second. 'Long interruptions' are generally considered to last longer than one second, and are usually caused by faults.

Figure 7 shows some idealised examples of dips, dropouts and interruptions, where the voltage changes occurred at the zero-crossing of the waveform, as is done in the standard immunity tests. Of course, in real life the point on the waveform at which the voltage changes is just given by chance. Figures 8 and 9 show some real-life examples of dips in MV three-phase supplies.

The reader should beware that there is very little standardisation of terminology, from one country to another, and between different industries within one country. For example, electricity distribution companies in the UK use the term 'short interruption'; to mean an interruption that lasts for less than three minutes – whereas in IEC immunity test standards for equipment, a 'short interruption' is one that lasts less than one second.

If you are concerned with whether people can manage with torches and will not suffer hyperthermia or hypothermia due to lack of power for either air-conditioning or heating, three minutes is probably a reasonable maximum for a 'short' interruption. But if designing electrical or electronic equipment to 'ride-out' a dip or dropout, an interruption of more than one second generally marks the boundary between just adding a few more capacitors to the power converter board, and having to use serious energy storage like supercapacitors or batteries.

Figure 8 **Example of a three-phase voltage dip, from Figure 3 of [21]**

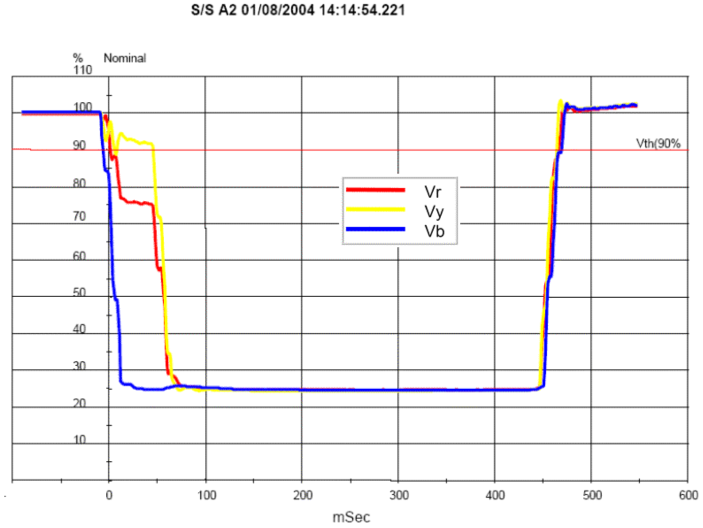
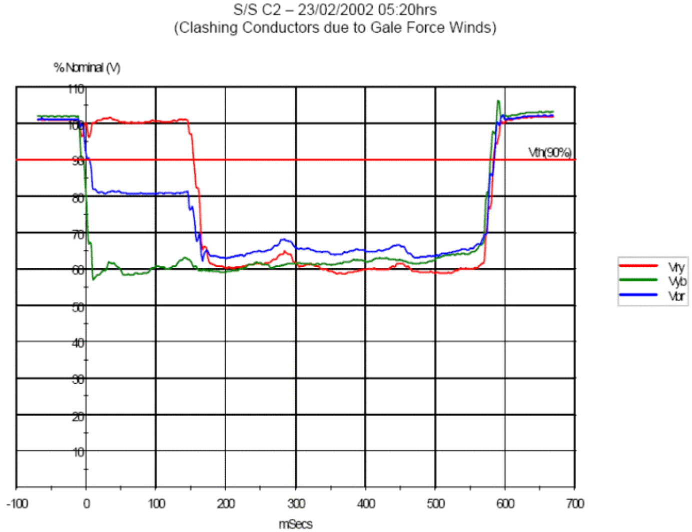


Figure 9 **Example of a voltage dip, from Figure 4 of [21]**



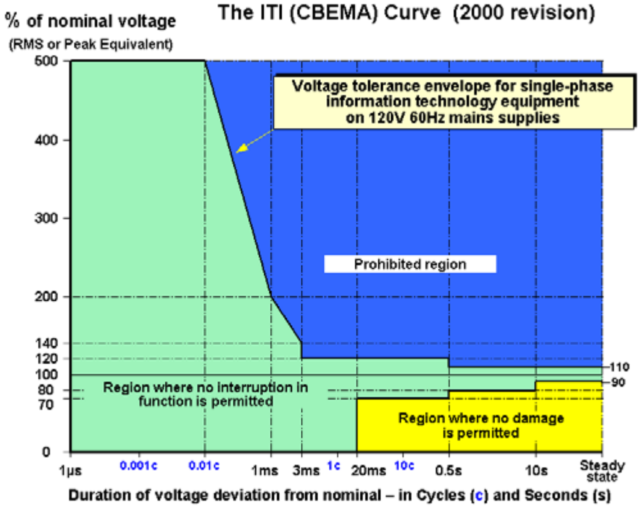
In the HV or MV parts of the mains distribution network, the faults are mostly caused by overvoltages due to lightning, which cause arcing on overhead power lines. The overcurrent protection devices are now mainly of the 'automatic recloser' type that reapply the power after a few seconds to see if the arc has ceased. If the fault is still there after a few retries, the protection device assumes a permanent fault and switches off until reset manually by a service engineer. As a result, many of the long interruptions in the mains supply last for just a few seconds, and 'outages' are much less frequent.

In LV distribution networks, the main type of fault is damaged cable insulation, and automatic reclosing is not appropriate. Overcurrent protection devices are usually fuses or circuit-breakers that remove power from an entire branch of the distribution network, so faults usually cause very long interruptions or outages.

The “ITI (CBEMA) Curve” and its Application Note [22] describe an AC input voltage envelope for 120V 60Hz mains power networks, which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE) in the USA. It is shown by Figure 10. The ITI Curve and its Application Note make it very clear that it is not intended to be used as a specification of the mains power quality – or as a specification for designing products – but nevertheless it is often employed in these ways.

A dips survey was carried out by a SEMI Task Force in the late 1990s [7]. They were concerned with improving the reliability of semiconductor manufacturing equipment, and focussed on the problems caused by dips and dropouts and short interruptions. Figure 11 is copied from Figure 1 of Part 2 of [7], and shows the results of their survey plotted against the 1996 version of the ITI/CBEMA curve. This shows that a good many dips, dropouts and short interruptions occurred that were outside the ITI/CBEMA curve, which could therefore be expected to cause problems for PCs and other Information Technology equipment. The Task Force came up with a test method and standard (SEMI F47 “Specification for Semiconductor Processing Equipment Voltage Sag Immunity”) designed to cover a large proportion of the dips, dropouts and short interruptions revealed by their survey.

Figure 10 **The ITI (CBEMA) Curve**



In the UK, a government body (“ofgem”) regulates the electricity supply industry and produces annual reports on aspects of power quality. [23] is their report dated December 2006, and Figures 12 and 13 are taken from it. Figure 12 shows data on 'customer interruptions' lasting more than 3 minutes, from mid-2001 to mid-2006. Figure 13 shows data from mid-2005 to mid-2006 on 'short interruptions' lasting less than 3 minutes.

In the UK, the Energy Networks Association (ENA) is an industry body representing companies that are associated with the national mains distribution networks. They produce regular reports, such as [21], which concerned dips, dropouts and interruptions measured at electricity substations (where the HV or MV power is transformed to LV 230/400V power and distributed to houses and commercial/small industrial premises). Because these are measured at the substations, they generally do not take much account of load fluctuations and faults occurring in the customers premises, which as a result can be expected to be worse.

Figure 11 The results of the SEMI F47 Task Force dips/dropouts survey

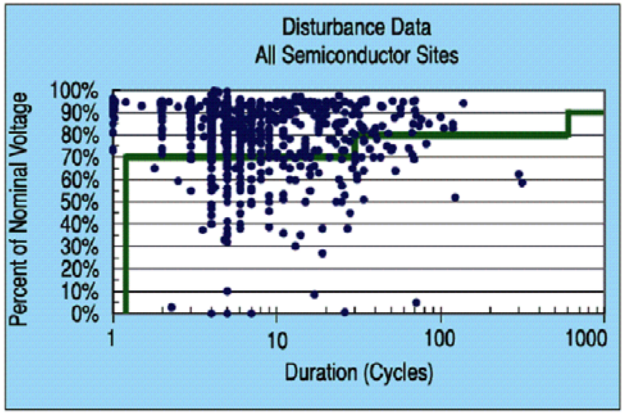
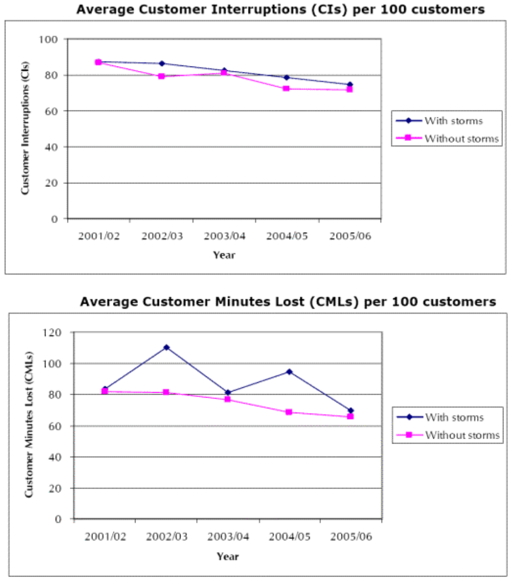


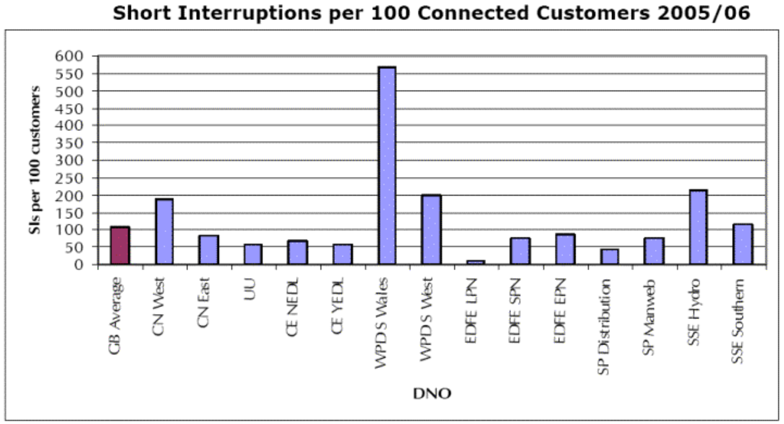
Figure 1. *Scatter plot of voltage sag event data considered by SEMI Task Force with CBEMA '96 curve overlaid.*

Figure 12 Customer interruptions lasting *more* than 3 minutes, from [23]



From…
"*2005/06 Electricity Distribution Quality of Service Report*"
***ofgem* report ref: 204/06,**
1 December 2006,
www.ofgem.gov.uk

Figure 13 Customer interruptions lasting *less* than 3 minutes, from [23]



Short interruptions are interruptions lasting less than 3 minutes, and are caused by operations of the network designed to reduce the length of interruptions

The majority of short interruptions are associated with automatic restoration schemes, such as: pole or ground-mounted auto reclosers; rural automation schemes; and load transfer schemes

From: "*2005/06 Electricity Distribution Quality of Service Report*"
***ofgem* report ref: 204/06, 1 December 2006, www.ofgem.gov.uk**

Slow variations in the supply voltage are caused by load current variations. Sags are when the voltage slowly declines, usually over a period of seconds or minutes, to a lower rms voltage. Swells are when the voltage slowly rises (see 2.5). Both are caused by variations in loading on the supply network. Figure 15 shows an example of a sag followed immediately by a swell. Mostly the automatic voltage regulators on the network prevent these from being more than a few percent of the nominal voltage, but if the regulators have run out of correction range, or have failed, sags and swells can have much larger values.

However, some applications can suffer from extreme sags and swells – an extreme example being the North Sea oil exploration platform mentioned in 3.1, where the 230V (nominal) mains supply from its diesel generator had sags and swells of 95% (12V to 450V rms), lasting several seconds each, caused by starting and stopping its huge drill motor. These enormous voltage variations would last for several seconds each, and much of the equipment on the platform was required to keep functioning normally at all times, and certainly not to be damaged. Another example is the mains distribution in an African country in 2005, which was a nominal 220Vrms, but in fact varied from 140Vrms to 300Vrms.

[8] describes IEC 61000-4-11, a standard for testing the immunity of equipment to dips, sags, dropouts and interruptions. It is harmonised in Europe as EN 61000-4-11.

Undervoltages can cause electromechanical devices such as relays, contactors and solenoids to drop-out, and their drop-out voltage varies with temperature, vibration, shock and the age of the device. Where they are 'held-in' at reduced voltage to minimise power dissipation, they might not pull back in again after the dip or dropout. Few 'relay logic' designers seem to consider the effect that random drop-outs of individual relays might cause for the functioning of their circuits, with possible safety consequences for 'hard-wired' safety systems. See 2.11 for more on the effects on electronic circuits.

Some electronic circuits rely on counting mains cycles, and these can be fooled by dips and dropouts, but the biggest problem is the hold-up time of products' mains power supplies. Figure 14 shows an example of a 3.3 volt supplied digital circuit. The mains supply dip causes the unregulated rail to discharge to a level lower than the minimum input voltage for the 3.3 volt regulator, so the regulated 3.3 volt DC rail can fall to below the level required for the ICs to function as specified. In this situation the ICs can do almost anything, and memory corruption is a real possibility along with 'illegal' functioning that could cause problems for whatever the circuit is controlling.

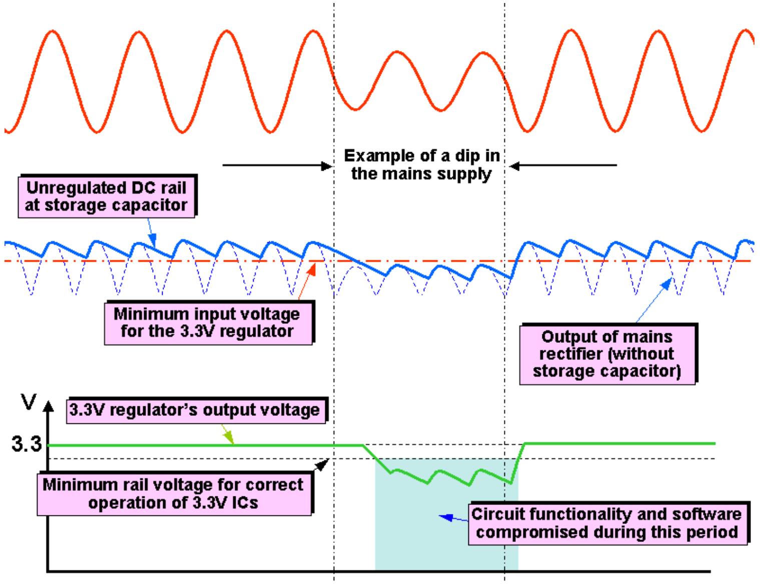
The above reason is why digital circuits employ power supply monitors. But there is usually so little margin between the minimum possible value of the regulated rail and the minimum specified IC operating voltage that very high-precision (hence costly) monitors can be required. Old-fashioned digital circuits would often be fitted with nothing more than a simple watchdog, on the assumption that if the regulated power was going to fall below specification, it would go all the way down to zero. Such designs will produce unreliable products that will not pass tests to EN/IEC 61000-4-11.

A momentary drop in the regulated rail for an analogue circuit can cause functional errors, but they are usually self-recovered after the dip or dropout is over. However, power amplifiers can suffer transient glitches or short 'squeals' of instability, either of which can sometimes damage the loads they drive (or in the case of loudspeakers or headphones cause objectionable sounds). See 2.11 for more on the effects on electronic circuits.

Discharge lamps often will not re-illuminate for several minutes after a short mains interruption. This can of course cause problems where the lighting is required for safety or security reasons.

The generic and product standards that are used by manufacturers to achieve a 'presumption of conformity' to the EMC Directive for mains-powered equipment, require testing with only a few of the wide range of tests in EN/IEC 61000-4-11 [8]. As a result, equipment that fully complies with all relevant harmonised EMC immunity standards under the EMC Directive can still have unreliability problems in real life. This is shown very clearly by Table 1 of [4], and [4] concludes that “*…whilst EMC standards are useful, equipment complying with them will not necessarily be immune enough to function correctly under many of the disturbances that can be considered normal, if infrequent, on their mains power supply. Voltage dips, dropouts, and interruptions are especially poorly covered by standards.*”

Figure 14 **How dips and dropouts cause problems for electronic circuits**



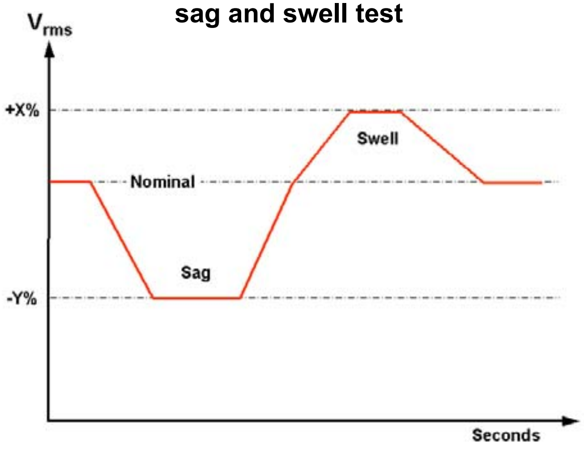
Telecommunications facilities and computer facilities using 'blade servers' are powered by -48VDC power distribution networks within their premises from batteries float-charged by powerful mains rectifiers. Dips, dropouts and interruptions in their DC supplies can cause them problems, and an appropriate immunity test is IEC 61000-4-29 [14], also adopted in Europe as EN 61000-4-29.

2.5 Overvoltages: Swells

Swells are when the supply voltage is higher than normal limits for a while (e.g. a few seconds), and are assumed by IEC equipment test standards to have slow rise and fall times (e.g. seconds). This usually occurs when there is excess power generation connected to a network, for example when a large amount of load has been lost and the automatic voltage stabilisers have not yet operated, or are at the end of their range.

Swells are normally expected to remain within ±10% of the nominal mains voltage, but in some circumstances they can be very much larger, as in the North Sea oil exploration rig example in 2.1 and 2.4, or the African mains supply example in 2.4.

Figure 15 **Example of a typical IEC 61000-4-11 sag and swell test**



[8] describes IEC 61000-4-11, a standard for testing the immunity of equipment to dips, dropouts, sags and swells, also harmonised for Europe as EN 61000-4-11.

Typical values of swells should not cause insulation breakdown or fire hazards where products meet their respective EN or IEC safety standards.

But surge overvoltage protection devices connected to the mains supply, such as Metal Oxide Varistors (MOVs), are often designed to start conducting as close to the maximum expected mains voltage as possible, to protect the equipment better. Consequently their leakage currents at voltages more than a little above nominal mains range can cause overheating and damage and possibly fire if the swell lasts for more than a fraction of a second. Alternatively the surge protection devices could be damaged and made inoperative, leaving the equipment exposed to interference and damage from mains surges.

2.6 Voltage fluctuations and flicker

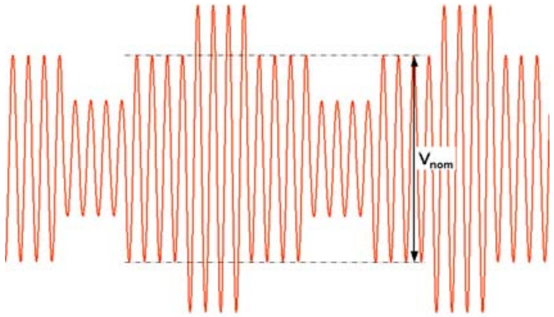
Rapidly fluctuating load currents cause rapidly fluctuating supply voltages both above and below the nominal, with the automatic voltage regulation operating on the average value of the supply voltage. 'Flicker' is a term often applied to repetitive dips, or other voltage fluctuations, that are less than one second apart, because of their effect on artificial lighting levels as perceived by the human eye. Figure 16 shows an example waveform for an extreme voltage fluctuation (flicker) event.

IEC 61000-4-14 [10] is a standard for testing the immunity of equipment to rapid voltage fluctuations and flicker, and is harmonised in Europe as EN 61000-4-14. This standard lists the following problems that can be caused by voltage fluctuations…

a) Degradation of performance in equipment using storage devices (e.g. capacitors)

b) Instability of internal voltage and currents in equipment

Figure 16 **An example of a voltage fluctuations test**



c) Increased ripple

d) Loss of function in control systems

A further possibility is…

e) Interference with low-frequency measurements and signal processing (below 50Hz)

The first three points above focus on the quality of the DC power that is converted from the mains supply and used in electronic products. Mains voltage fluctuations will cause a ripple on an unregulated DC power 'rail', that will couple directly into any circuits it powers and could interfere with their operation. Some circuits operate from regulated DC rails – but the problem here is that the changes in the unregulated voltage might be enough to effect the voltage of the regulated rail.

Some power supply circuits (whether linear or switch-mode) might be made to go unstable when their control loops are excited by the fluctuations in their unregulated DC rails. This could cause the error in the regulated DC voltage to be much larger than would be expected given the change in the mains voltage.

The power supply ripple, and the fluctuating magnetic and electric fields (for example, near cables and mains transformers) caused by the mains voltage fluctuations could couple into circuits and long measurement leads and disturb them directly. This is more likely to be a problem for circuits that measure or control small signals, especially if those signals lie in the DC to 50Hz range.

2.7 Common-mode low-frequency voltages

In most low-voltage mains supply networks in the UK, and in many other countries, the neutral is connected to earth at the high-voltage transformer. But the neutral-to-earth voltages at various locations around the area served by that network will not be zero, and will vary. Typically, they have a small, fluctuating voltage at the frequency of the mains power supply, often with significant harmonic distortion, from a few hundred millivolts up to a few tens of volts.

This is partly caused by the voltage drops in the neutral cables themselves, due to the currents they carry – especially due to three-phase unbalance and harmonic currents in the phases, and partly by potential differences between different parts of the earthing system due to earth currents from leakage currents (e.g. from mains filters) and stray capacitive and magnetic coupling.

But neutral-to earth voltages can be much higher, for short periods, during phase-to-earth faults. They can be as high as the nominal value of the mains voltage, depending on the proximity of the fault to the measuring point. These temporary neutral-earth faults can also be caused by the follow-on current caused by the operation of spark-gap types of surge arrestors. On high-voltage mains distribution networks, earth faults or follow-on currents can cause the neutral-to-earth voltage to rise by several kV.

Similar effects to those that cause neutral-to-earth voltage variations also cause differences in the earth (ground) potentials between equipment, as shown by Figure 17 and Figure 18. These appear as CM voltages on signal, data and control interconnections [24]. Figure 19 shows an example of a neutral-to-earth voltage at a point in a typical installation, a very distorted waveform. Such waveforms are also typical of inter-system earth voltages.

Some supply networks operate with a 'floating' neutral, in which case the neutral-to-earth voltages can be at the same level as the phase-neutral voltage, possibly for very long periods of time. Powerful loads that draw significant currents at frequencies other than 50Hz and its harmonics (e.g. high-power audio amplifiers) can cause neutral-to-earth voltages at those frequencies, these frequencies are called 'interharmonics' by the power quality industry, but they are simply frequencies that are not synchronised to the 50Hz supply frequency.

Figure 17 **CM LF noise voltages caused by earth/ground impedance and leakage currents**

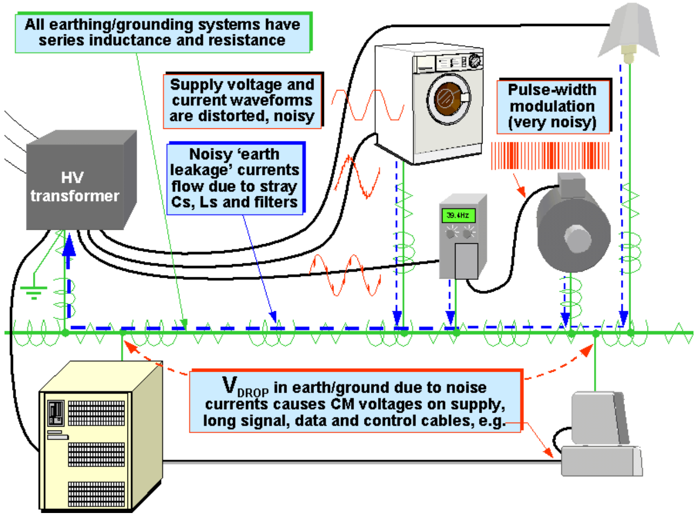


Figure 18 **CM LF noise voltages caused by 'stray' capacitance and inductance coupling**

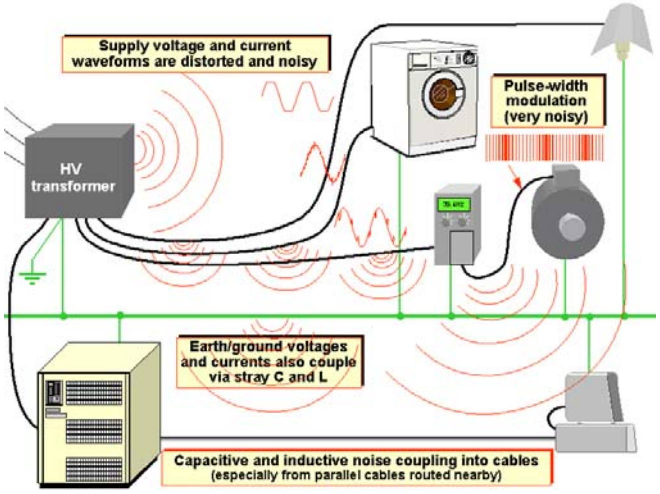
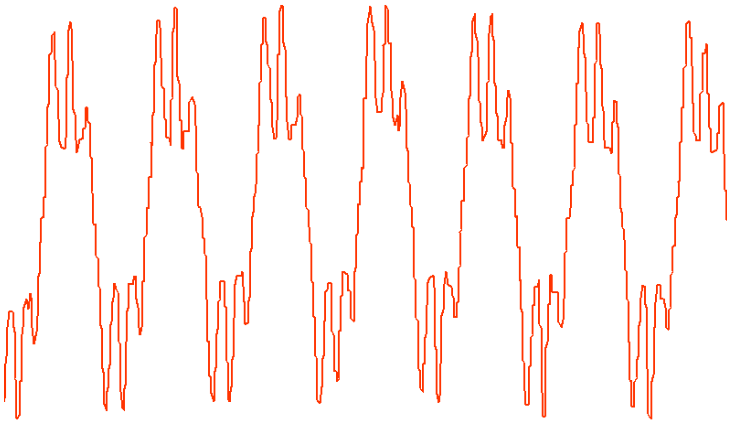


Figure 19 **Typical example of neutral-to-earth, and inter-system earth voltage(50Hz with high levels of harmonic distortion)**



IEC 61000-4-16 [11] is a standard for testing the immunity of equipment to low-frequency CM voltages, and it is harmonised in Europe as EN 61000-4-16. Neutral-to-earth voltages are tested by applying its tests to an equipment's mains inputs, and inter-system earth (ground) noise [24] is tested by applying them to its signal, data and control interconnections.

Clause 3 of EN 61000-4-16 says that CM disturbances from DC to 150kHz can "*…influence the reliable operation of equipment and systems installed in residential areas, industrial areas and electrical plants.*" The author does not know why commercial, entertainment, medical, healthcare or military areas were omitted from this list despite suffering from exactly the same problems with CM disturbances below 150kHz.

The DC and low-frequency CM disturbances covered by EN 61000-4-16 cause CM noise to appear in the circuits associated with the cable ports. Depending on the design of these circuits, a proportion of the CM noise is converted into DM noise in the wanted signal. Depending on the circuit design, this DM noise might cause the circuit to function outside of its specification, malfunction, or even suffer permanent damage.

Continuous CM disturbances are not expected to cause actual damage to the circuit (although damage to equipment controlled by the circuit might occur), but short-term CM disturbances can have much higher levels so could actually cause permanent damage to the circuit components.

It is impossible to be any more precise about the types of errors, malfunctions or damage that can occur due to CM disturbances below 150kHz. This is because they depend entirely on the design of the circuits, the signals they are processing, the functions they are providing, and the applications they are used in.

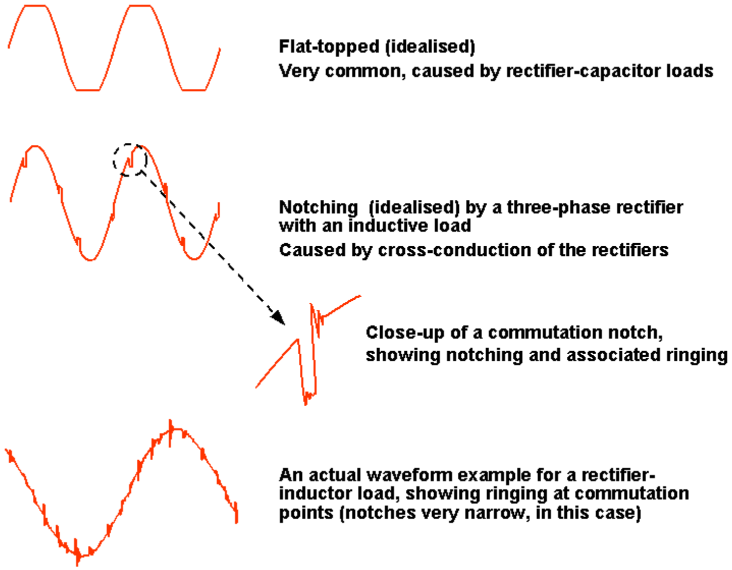
For example, at one extreme the only effect of CM interference might be an increase in the 'hum' level in an audio recording, or a slight wobble on a video display. But at the other extreme, control of a powerful industrial robot could be lost, causing damage to the workpiece and financial loss. (It is assumed that the designers of the robot, and similar equipment and systems, will have taken such possibilities into account in their safety design, so that safety risks are not increased.)

Faults in the LV power distribution network can cause CM voltages of a few hundred volts to occur, at the mains supply frequency, and faults in the MV power distribution network can cause disturbance voltages up to several thousand volts to occur for several seconds. EN 61000-4-16 does not cover such issues, which can cause actual damage to electronic equipment.

2.8 Voltage waveform distortion (harmonic and interharmonic)

Waveform distortion can be harmonic (mostly caused by the non-sinewave currents drawn by rectifiers and fluorescent lamps), and/or interharmonic (mostly caused by non-50Hz non-sinewave currents drawn by frequency-changing power converters and high-power audio amplifiers). Figure 20 shows some examples of typical types of harmonically distorted waveforms.

Figure 20 Some examples of harmonically distorted mains waveforms, from various figures in [25], [26] and [27]



Interharmonic distortion really means other frequencies that are not phase-locked to the mains waveform, and appears on a 'line-triggered' oscilloscope as non-synchronised frequencies that ripple through the display. On a spectrum analyser it is obvious that the interharmonic frequencies beat with the mains frequency to produce additional frequencies, and if they are close to 50Hz, these beats can easily be seen on an oscilloscope.

Signal frequencies from 110Hz to 3kHz are used in some mains networks (or parts of them) to transfer data from one part of the network to another, or to control equipment in parts of the network. The frequencies used are interharmonics, but are actually injected onto the mains as voltage signals, directly causing waveform distortion.

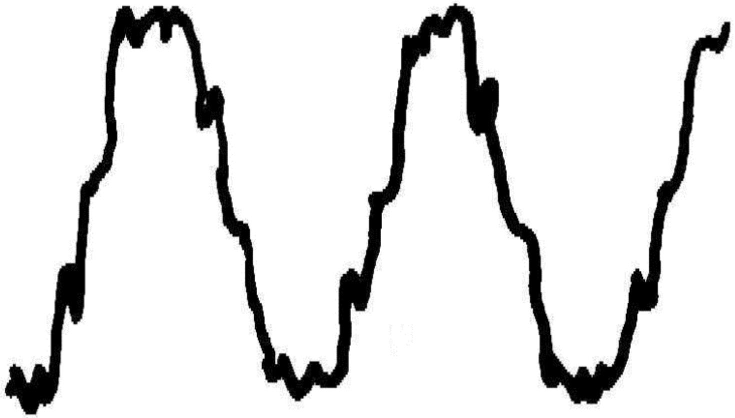
This signalling method is often called 'ripple control', because when seen on an oscilloscope it appears as a ripple in the peak level of the mains voltage. It is mostly used in national power systems, and sometimes in industrial power systems too, at LV, MV or HV. The level of the added signalling frequencies are between 2 and 5% of the nominal mains voltage. Resonances can increase the levels of this voltage distortion component to as much as 9%. More detail will be found in [28].

All the above mains-power-related phenomena can be much worse where the mains distribution system is of poor quality, or when mobile or portable generators are used (see Figures 2, 3 and 4) because they have higher source impedances.

Figure 21 Example of a real-life AC mains waveform, from No. 104 of [29]

This example of harmonic distortion is from a domestic house,

(traced from an oscilloscope screen with a felt-tip pen)



IEC 61000-4-13 [9] is a standard for testing the immunity of equipment to distortion of its mains supplies by harmonic or interharmonic frequencies, and is harmonised in Europe as EN 61000-4-13. But none of the tests in 61000-4-13 would predict the immunity of equipment to the real-life mains waveform shown in Figure 21.

A wide range of equipment can be affected by distorted mains waveforms, including:

- Capacitors: reduced life, increased likelihood of damage, fuse disconnection, damage to any switching contacts.
- Rotating machines (motors and generators): reduction in efficiency, increased temperatures, overheating, reduced life, increased acoustic noise emissions, pulsating or reduced torque, shaft fatigue, reduced bearing life, damaged products.
- Cables: increased temperatures, inability to provide full current rating without overheating, reduced life, increased likelihood of damage.
- Transformers: increased temperatures, overheating, reduced life, increased likelihood of damage, increased acoustic noise emissions.
- Fuses and circuit-breakers: reduced life, increased 'nuisance tripping' when the power consumed by the loads is still within the current trip rating.
- Surge suppressors: reduced life, increased likelihood of damage.
- Electricity meters: increased errors.
- Residential equipment: increased emissions of acoustic noise, incandescent lamp flicker.

- Electronic equipment: defective operation of circuits that rely on the zero-crossing of the mains waveform; noise coupling from mains cables and devices into analogue and digital circuits causing interference with radio and TV sets, digital clocks and timers, hi-fi and other audio systems; unreliable operation of computers.
- Telephones: increased levels of audible noise (even to the point of making conversations impossible, which can cause health and safety problem in some circumstances).
- Power distribution networks: excitation of system resonances leading to increased levels of voltage distortion – exacerbating many of the above

Harmonics and interharmonics, and their effects, is a very big subject, and is dealt with in some detail in [9] and [6]. To avoid simply repeating their many pages of detail and associated references in this guide, readers are requested to refer to those publications.

2.9 Mains signalling voltages

IEC 61000-4-13 [9] is a standard for testing the immunity of equipment to harmonic and interharmonic distortion of its mains voltage waveform, and its interharmonic tests also address immunity to mains signalling voltages. It is harmonised in Europe as EN 61000-4-13.

The problems caused by mains signalling voltages are the same as those caused by other interharmonics, see 3.8 and [28].

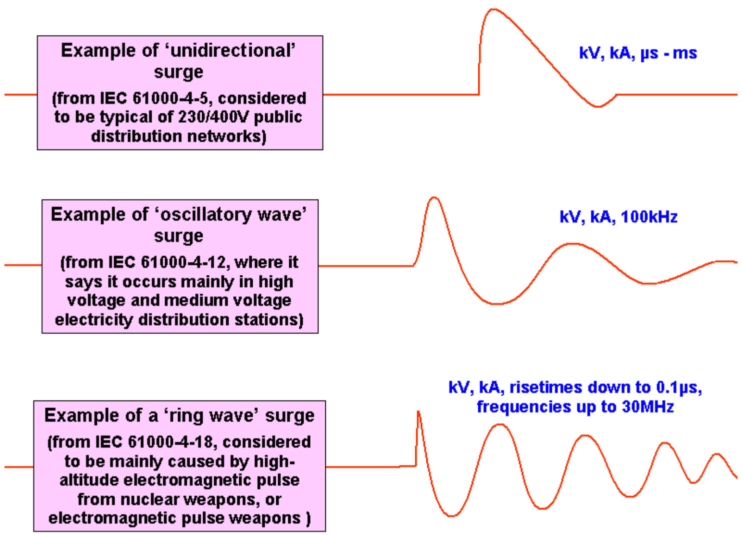
2.10 High-frequency power quality problems

All the above phenomena are specifically problems of mains generation and distribution networks. But all mains supply distribution networks use long cables, and so suffer from all of the electromagnetic (EM) disturbances that conductors can suffer. These include transient over-voltages, commonly called 'surges', typically caused by the various effects of lightning, and flyback voltages caused by the release of stored energy when large reactive loads such as large motors, large transformers or capacitor banks (e.g. power factor correction capacitors) are disconnected from their supply.

The supply distribution network itself also has significant inductance in its transformers and conductors, so an abrupt disconnection of a load also causes a flyback surge. The worst cases are generally caused by fault clearance. Even quite small power cables to equipment can carry 100s or even kA of current during a fault, so when the fault current is interrupted ('cleared') by a fuse, circuit-breaker or other protective device the flyback voltage can be much larger than when the equipment is switched-off normally.

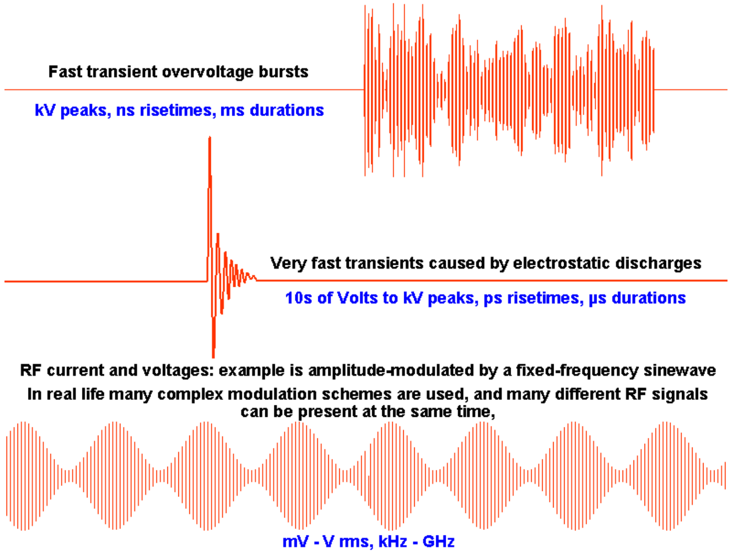
Surge waveforms are almost infinitely variable, depending on the source of the surge and the impedance and resonance characteristics of the supply network. Three types are used by IEC immunity standards: unidirectional surges, ring-wave surges, and oscillatory surges, as shown in Figure 22. See [18] for more information on surge overvoltages.

Figure 22 **Examples of three types of surge**



Sparking caused by flyback voltages during the opening of electro-mechanical contacts causes a radio-frequency disturbance called Fast Transient Bursts, discussed in more detail in [17]. Electrostatic discharge events also couple with cables, generating very brief high-frequency overvoltages, see [15] for more information on this phenomenon. Radio frequencies are present from 150kHz up to thousands of MHz, from broadcasters, radars, certain kinds of industrial and medical equipment, and portable wireless devices like walkie-talkies and cellphones, and cause RF currents and voltages in all conductors, including mains cables, typically at levels of a few tens or hundreds of mV, but up to tens of volts in some cases (possibly hundreds). RF current levels are typically about one-hundredth of the voltage levels – so could be up to hundreds of mA in some cases (possibly Amps). Figure 23 sketches some examples of these EM phenomena.

Figure 22 **Examples of fast transient burst, ESD, and conducted RF voltages**



These high-frequency power quality problems can cause significant problems, especially for electronics (see 3.11). As mentioned earlier, high-frequency power quality issues are not within the scope of this guide. But for further information on the following please refer to the indicated publications:

- Surge overvoltages: refer to [18]
- Fast transient burst overvoltages: refer to [17]
- Electrostatic discharge (ESD) overvoltages: refer to [15]
- Radio-frequency voltages and currents: refer to [19] for conducted phenomena and [16] for radiated.

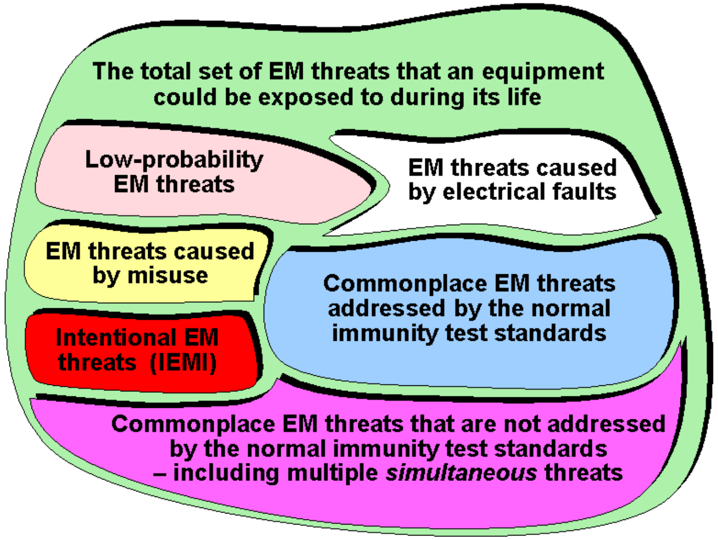
Figure 24 illustrates an overview of the kinds of EM phenomena that should be taken into account to help ensure adequate reliability (and/or safety) and reduce financial risks.

2.11 Problems with electronics and software

Electrical and electronic circuits are designed for the range of supply voltages supplied by the Electrical Utility, but poor mains power quality can make the range actually experienced by an item of equipment wider than what was expected. This is especially so because many types of equipment derive their unregulated DC rail from the peak of the mains waveform, whereas it is the rms value that is controlled by the Utility.

Supply voltages that are higher than a circuit was designed for can cause misoperation, as well as overheating and even permanent damage. Supply voltages that are lower than a circuit was designed for can cause them to misoperate, but overheating and damage are only a problem for some rare circuits. How a

Figure 24 **The totality of EM threats**



circuit can misoperate depends on the type of circuit and on the details of how it was designed.

Analogue signal processing circuits may simply find that their maximum signal amplitude is reduced, but it is not unusual for bias levels to shift the operating points of semiconductors in such a way that they do not behave as intended – the result can be any amount of error and any type or degree of malfunction. For example, audio power amplifiers might become unstable and 'whistle' at full power at high or ultrasonic frequencies, or they may 'thump' – either of which might destroy the speakers they are connected to.

Digital circuits might reset or reboot cleanly. If they don't reset cleanly, or at all, they might experience almost random errors ranging from a change in operational mode (e.g. from crawl speed forward with reduced torque, to full speed reverse with full torque); continuously repeating a section of code; or a 'crash' or 'lock up' where the circuit ceases to operate at all.

In competently designed digital equipment a crash will eventually lead to a reboot, whereupon the equipment might then find itself in an undesirable state, depending on its application. If a reboot leaves the equipment in 'power-up' mode – this could cause problems if what is required is that the function that was being performed before the reboot should be continued. For example, a flashing lamp that indicates a hazard should continue to flash after the disturbance, and not switch off.

But sometimes the time taken by the reboot means that whatever is being controlled should shut down in a controlled manner and then require an automatic or manual restart once the correct starting conditions have been met. For example, where a number of motor drives are controlling the processing of a web of material, their speeds must be synchronised. If any one of them gets 'out of step' it risks breaking the web, which can be very costly. So it may be necessary to bring the web safely to a halt, and restart the process when the disturbance that caused the problem is over.

An often-overlooked aspect of a crash or lock-up is that the outputs of the digital circuit can be left in any random combinations of states until the successful reboot. In the case of computerised systems running large operating systems, the reboot time can be measured in minutes. During this time the digital outputs may be sending erroneous control signals to powered actuators that could create undesirable situations. In some applications such random outputs might even cause damage to the equipment being controlled, or safety hazards to its users or third parties.

Some types of high-reliability equipment, such as life-support, cannot be allowed any deviation from full-specification operation. Such equipment is often powered from an uninterruptible power supply (UPS), in which case the UPS must be very reliable and withstand all the power quality problems present in its real-life application. Some types of UPS are not as 'robust' as they need to be usefully improve the reliability of mains-powered equipment.

Power control circuits (e.g. inverter drives, switch-mode power converters) might suffer actual damage due to cross-conduction in their power switching devices, when their controlling devices create timing errors due to malfunctions in their circuits. The damage might extend to exploding transistors, which can create safety hazards, and would certainly cause costly downtime and repairs.

3.1 Guidance on the EM environment

There are nine IEC standards containing guidance on the low-frequency power quality issues covered by this guide, which can exist in certain environments:

- 61000-2-1: Description of the environment. Electromagnetic environment for low frequency conducted disturbances and signalling in public power supply systems. (Low voltage power systems, i.e. up to 1kV rms)
- 61000-2-2: Compatibility levels for low frequency conducted disturbances and signalling in public power supply systems.
- 61000-2-3: Description of the environment. Radiated and non-network related conducted phenomena.
- 61000-2-4: Compatibility levels in industrial plants for low frequency conducted disturbances.
- 61000-2-5: Classification of electromagnetic environments.
- 61000-2-6: Guide to the assessment of the emissions levels in the power supply of industrial plants as regards low-frequency conducted disturbances.
- 61000-2-7: Low frequency magnetic fields in various environments.
- 61000-2-8: Voltage dips, short interruptions and statistical measurements.
- 61000-2-12: Compatibility levels for low frequency conducted disturbances and signalling in public medium voltage power supply systems.

There are also some IEC standards containing guidance on high-frequency EM environment issues that are not covered by this guide, that can exist in certain environments, including:

- 61000-2-14: Overvoltages on public electricity distribution networks

3.2 For testing equipment emissions and immunity

There are four IEC (and EN) basic standards relevant for testing the emissions of equipment that could affect low-frequency power quality issues covered by this guide:

- 61000-3-2 for harmonic emissions from equipment consuming up to 16A per phase [30]
- 61000-3-12 for harmonic emissions from equipment consuming between 16A and 75A per phase [31]
- 61000-3-3 for emissions of voltage fluctuations and flicker from equipment consuming up to 16A per phase [32]
- 61000-3-11 for emissions of voltage fluctuations and flicker from equipment consuming between 16A and 75A per phase [32]

Considering harmonics, there are three possible criteria for connecting equipment to the public mains network:

a) The equipment meets the limits in EN 61000-3-2 – in which case no notification or further assessment is required, the equipment can be connected freely.

b) The equipment meets a relaxed set of limits or rules given by IEC 61000-3-12. In this case the Network Operator must be notified of the connection and relevant details. They may subsequently choose to perform an assessment to G5/4 -1 but they cannot prohibit the initial connection.

c) The equipment does not meet even the relaxed limits or rules in IEC 61000-3-12. In this case the Network Operator must be notified and must give their permission before connection is undertaken.

A similar set of three connection criteria exist in the case of EN 61000-3-3 and EN 61000-3-11, see [32].

Product standards can also contain power quality requirements, for example the new EMC standard for lifts and elevators EN 12105 [33]. This sets limits regarding total harmonic distortion (THD) and partial weighted harmonic distortion (PWHD) and sets out specific values for permanent and short duration harmonic emissions for specific orders of harmonics (5th, 7th, 11th and 13th).

There are numerous IEC/CISPR standards relevant for testing the emissions of equipment that could affect the high-frequency power quality issues not covered by this guide, including the ones most often used as basic test methods:

- CISPR 22 (EN 55022) emissions of conducted and radiated RF above 150kHz
- CISPR11 (EN 55011) emissions of conducted and radiated RF above 150kHz

There are eight IEC (also adopted as EN) standards relevant for testing the immunity of equipment to the low-frequency power quality phenomena covered by this guide:

- 61000-4-11: AC supply dips, dropouts, interruptions, sags and swells, [8]
- 61000-4-13: Mains harmonics and interharmonics, [9]
- 61000-4-14: Mains voltage fluctuations (flicker), [10]
- 61000-4-16: Common-mode disturbances, 0 - 150kHz, [11]
- 61000-4-17: Ripple on DC input port
- 61000-4-27: Three-phase unbalance, [12]
- 61000-4-28: Power frequency variations, [13]
- 61000-4-29: DC dips, short interruptions and variations, [14]

There are also five IEC (also adopted as EN) standards relevant for testing the immunity of equipment to high-frequency power quality phenomena not covered by this guide:

- 61000-4-2: Electrostatic discharge (ESD), [15]
- 61000-4-3: Radiated RF fields, [16]
- 61000-4-4: Fast transient bursts, [17]
- 61000-4-5: Surges, [18]
- 61000-4-6: Conducted RF currents and voltages, [19]

3.3 For designing equipment and systems and installations

There is just one IEC standard containing guidance on the design of systems and installations with respect to the low-frequency power quality issues covered by this guide, and it only covers earthing impedance and reduction of stray coupling between cables:

- 61000-5-2: "*EMC Installation and Mitigation Guidelines Earthing and Cabling*"

Various organisations, trade associations and professional institutions have their own codes of practice and other internal documents covering design, especially military (see [34] and [35]), and they can include issues relating to power quality. Customers (especially large organisations such as telecommunications or railway networks) will often have power quality requirements, which they should have included in the technical specifications sections of their 'request for quotation' or tender documents, and/or in purchasing contracts.

However, if a customer has not included such technical information, this does not mean that they do not have such requirements, or at least some guidance. Although it is always tempting to breath a sigh or relief and design the equipment, system or installation in the usual way, hoping that if any problems arise the customer will pay to have them solved, in practice customers generally expect new purchases to work as advertised, and will often hold back part of the agreed price until their expected performance quality and reliability is achieved. So the supplier ends up paying the costs of modifications necessary to deal with power quality on a given site anyway.

Since it is generally very much easier and less costly to obtain data on the power quality of an environment (see [36]) and design accordingly, than to modify a finished an installed design, I always recommend that where comprehensive power quality requirements or guidance are not specified by a customer, they should be asked specifically, in writing if they have any, or if they can suggest any that might be relevant.

In the case of volume-manufactured equipment with a wide variety of customers, it is best to rely on public information on power quality obtained from 3.4 and [36]. Where appropriate information does not exist, and the customer cannot obtain or recommend any proprietary information from their industry or trade/professional organisations, for best cost-effectiveness and lower financial risks it is generally recommended to perform a sufficient number of power quality surveys in relevant locations. These should last for *at least* a week (preferably for a full year), so whether they are required or not should be considered early in any new project planning.

3.4 For installations and power distribution networks

The author is only aware of one published standard governing the quality of the supplied mains voltage:

- EN 50160, "Voltage characteristics of electricity supplied by public distribution systems", [37].

EN 50160 is intended to control the quality of the public mains power distributed within the European Union (EU). A guidance document [38] is available, although it takes some searching to obtain via the internet. There are probably many other standards, or codes or practice, used within power generating and distribution organisations in other countries, but they might not be published as public documents. Another guide is Part 5.2.4 of [1].

Because harmonics have become a significant problem for power networks, all Electrical Utilities have codes of practice for dealing with them. Two that are published are:

- G5/4-1, ER G5/4-1 Issue 1, 2005: "*Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom*", [39] and its various guidance documents [40] [41] and [42]

- IEEE 519 1992 "*Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*", [43], which is more likely to be referenced in North America.

G5/4-1 is used for managing harmonic distortion in the UK's public mains power distribution systems. It applies to all consumers at their point of common connection to the public supply network (the point at which the consumer is connected to other consumer's on the network) and effectively it forms part of the consumers agreement to connect with the Network Operating Company.

For installation of equipment above 75A per phase, if the pre-existing total harmonic voltage waveform distortion is close to 5%, then the Electrical Utility (often called the Network Operator, in the UK) must be notified first. He could call for an assessment of the total harmonic currents generated by all equipment connected to a point of common coupling, which is usually fairly easy to produce using manufacturer's data. Another set of rules applies for equipment that draws its power from a dedicated transformer connected to the MV or HV distribution networks. In these cases more complex procedures are called for. [44] is an interesting magazine article about the 'hidden costs' of G5/4-1 compliance.

Mains power quality can be measured in a variety of ways, but proper tests use instruments that comply with IEC 61000-4-30 [45]. Annex A to this standard contains a great deal of useful information about measuring power quality in practice, including:

- Installation precautions for power quality measuring instruments
- Characteristics of various types of measurement transducer
- Guidelines for contractual applications of power quality measurements
- Trouble-shooting power quality problems

The IEEE have the standard: IEEE 1159-1995 – "*Recommended Practice for Monitoring Electric Power Quality*", June 1995, [46], which is more likely to be referenced in North America.

Power quality measurements are all based upon measuring voltages and currents. Voltages are measured by connecting test instruments to voltage probes, and currents by connecting them to current probes. Current probes are essentially transformers with a core that is split and hinged so that it can be clipped around the cable in which the current is to be measured. Each probe is supplied with a transducer factor by which the reading of the test instrument is converted into the quantity being measured. For example a current transformer might output 0.1V/A, so that for instance when it is used with a voltmeter or oscilloscope a reading of 3.04V represents a current of 30.4A.

As discussed at length in [31] and Part 3.2.2 of [1], all voltage and current meters should use true-RMS measurement technology. To save cost, typical electrician's meters are average-responding but calibrated as RMS – but the calibration is only correct for pure sinewave voltages or currents. All such meters should be immediately scrapped, and replaced by true-RMS types that are accurate up to at least 2kHz (preferably 5kHz), because they will not be providing accurate readings of modern mains voltages or currents, increasing the risks of downtime and safety hazards like smoke and fire.

Ignoring power quality problems with RF content, the highest frequency power quality tests are those for harmonic voltages and currents, which are measured up to the 50th harmonic. For 60Hz mains this is just 3kHz, so there are no particular requirements for the test site or test set-up, as there are for EMC tests at frequencies above 150kHz.

It is not the purpose of this guide to describe how to do power quality measurements. Readers who wish to do this should purchase a copy of IEC 61000-4-30 from the IEC webstore (http://webstore.iec.ch) and read and understand it. For more information on measuring harmonics, see [6].

The Copper Development Association (see Part 5.2.1 of [1]) and others recommend monitoring power quality as a preventative maintenance activity, to detect and deal with issues before they become significant enough to cause problems such as downtime (with consequent financial loss).

A number of manufacturers offer a range of power quality measurement equipment. Correctly setting-up the equipment to make meaningful measurements is very important. In the case of an equipment problem, deciding which power quality characteristics to measure to try to solve the problem can require considerable expertise. So it might be more cost-effective, or give better results more quickly, to engage one of the several companies who specialise in such work. They can be found by searching the Internet using terms such as 'power quality surveys service' or 'power quality consultancy'. [47] has an example of a typical power quality survey.

5.1 What power quality specifications to aim for?

The figures in EN 50160 [37] are quite surprising when compared with the requirements of the equipment standards listed under the EU's EMC and Safety Directives, [48] and [49] respectively. For example, EN 50160 states that for 95% of each year, the level of surges on single-phase public mains supplies can be 6kV "or more". Quite what levels of surges are possible during the remaining 5% of the year is not specified (although the 6kV limit is usually set by the flash-over voltages between the terminals of single-phase wall sockets, so it might not be much higher).

However, obtaining a 'presumption of conformity' by fully applying all relevant standards listed under the EMC Directive, requires surge testing to only 2kV. And safety standards listed under the Low Voltage Directive [49] generally base their 'voltage withstand' requirements on IEC 60664, which specifies surges of up to 2.5kV.

So it seems that equipment that fully complies with all relevant EU standards for compliance with EMC and Safety Directives can still suffer interference and/or become unsafe as a result of 6kV (or more) surges on the mains supply. This has implications for warranty costs, customer perception, brand image, and financial risks under the Product Liability Directive [50]. This disparity was sufficient for the EICTA to lobby the European Commission about it (to no avail, so far as I know), as described by the warning in [53].

Where equipment is powered from three-phase mains distribution networks that are not connected to single-phase sockets, the terminal spacings of the IEC 6309 mains sockets are larger and so the surge levels could be higher. There are companies whose three-phase supplied products are used in such environments who have had to design their equipment for 12kV surges before they were reliable enough in certain industrial plant.

There are many other examples of the disparity between the requirements of EMC Directive immunity standards and EN 50160 [37], and these are discussed in detail in [4].

The power quality specifications to be used in the design of a new equipment, system or installation depend upon the financial risks. Considering two extremes: a data centre (sometimes called an 'internet hotel') might require 99.99% (or higher) reliability – and the design of its costly mains power supply will be very thorough, and able to cope with a wide range of power quality problems – for good financial reasons. On the other hand, a mains charger for a fashionable consumer electronics item made by a company with no brand reputation to protect (and not seeking a reputation) might apply the narrowest range of power quality to keep component costs lowest, at the expense of reliability.

Don't forget that [37] specifies the power quality expected for 95% of the time over most of Europe. There are places in Europe where its specifications are not met, such as parts of rural Spain that, a few years ago, experienced mains voltages as low as 170Vrms during a typical working day. And, as mentioned before, it says nothing about the power quality that could obtain for the remaining 5% of the year. Part of the UK experienced a voltage sag to 120Vrms for 8 hours in 1998 (see No.21 of [29]), but that only represents 0.09% of a year, so is within the European mains power quality specification [37].

5.2 Equipment design or modification

Where equipment is purchased, modifying it would invalidate its warranty, so improving the quality of the mains supply by adding other equipment (see 5.3) is usually the only option.

This section is intended for equipment designers, not for people modifying equipment designed by other people. If equipment is to be modified, it is best done in conjunction with its manufacturer, otherwise its operation or safety could be degraded. Large items of equipment may be able to incorporate methods for improving the mains power quality (see 5.3) within themselves.

5.2.1 Setting the range of mains voltages expected

Undervoltages or overvoltages generally cause greater problems for equipment when the real-life average mains voltage differs from the nominal supply voltage expected by the equipment. So it helps to determine the real-life range of the mains voltage in the intended application, over a period of at least one year, then, depending on the type of equipment and its characteristics, set its nominal voltage to one of the following:

- The average RMS voltage of the mains supply (usually for passive loads like heaters, AC motors, etc.)
- The average peak voltage of the mains supply (usually for equipment powered by rectifier-capacitor AC-DC converters, because they operate on the peak not RMS values)
- A voltage that prevents damage due to the expected overvoltages and/or undervoltages

In urban environments in developed countries the range of mains voltages experienced can be quite small, usually within the range specified by the power providers, which may be within ±6% of the declared nominal. But in those same countries the mains supply in some rural or remote areas can be very much worse, due to the high impedances in the very long mains distribution cables required to reach them. In parts of rural Spain, during the late 1990s, the nominally 230V mains supply would fall to as low as 180Vrms during the afternoon. Some remote parts of Australia were still, in the early 2000s, supplied by a single wire, with the earth (meaning the soil, in this case) used for the power return – resulting in very high impedances and very poor power quality, along with huge magnetic fields. In rural and remote parts of the UK, it is not unusual for the typical mains supply voltage to be 245Vrms, or even higher.

In undeveloped countries the range of the mains voltages can be more extreme, such as the African country in 2005, mentioned earlier, in which the nominal 220Vrms mains varied from 140Vrms to 300Vrms.

5.2.2 Frequency variations

Timers and real-time clocks should rely upon stable reference oscillators (e.g. as used in wristwatches) instead of the frequency of the mains supply. For the highest precision: use existing on-air frequency references from terrestrial or satellite transmitters (e.g. GPS).

The core size of transformers or AC motors should be increased, and/or more turns used in their windings, so that they normally operate with less saturation and lower magnetising currents. For relays, contactors and solenoids: choose types that have lower drop-out voltages.

Replace 50/60Hz mains transformers with switch-mode power converters (AC-AC or AC-DC as appropriate). Power AC motors from switch-mode AC-AC inverter drives (instead of direct-on-line, DOL). Replace AC motors with DC motors powered from rectified mains.

5.2.3 Three-phase unbalance

Direct-on-line (DOL) three-phase AC motors can be powered instead from switch-mode inverter motor drives set to a fixed frequency, or replaced with DC motors powered from rectified three-phase mains. Similar techniques can be used for other types of inductive loads.

5.2.4 DC in AC supplies

Replace AC-DC power converters based on 50/60Hz transformers (so-called 'linear' power converters) with switch-mode converters. As for three-phase unbalance, DOL three-phase AC motors can be powered instead from switch-mode inverter motor drives set to a fixed frequency, or replaced with DC motors powered from rectified three-phase mains
.

5.2.5 Undervoltages: Dips, sags, dropouts and interruptions

Operate DC equipment from AC-DC power converters that have a very large mains voltage range, e.g. 'universal input' power converters rated for 85-264Vrms mains inputs. Such converters are ubiquitous for laptop PCs and cellphone chargers, so that they can be used anywhere in the world. Converters that are 'auto-ranging' and automatically select either 115V or 230V are not appropriate,

Figure 25 **Examples of energy storage devices suitable for use in equipment**

and can even result in damage when the mains voltage is between the two ranges, for example 180V.

Also ensure the converters have adequate 'hold-up' (or 'ride-through') time, for the load being powered. This requires sufficient energy to be stored in electrolytic capacitors, supercapacitors, batteries, etc. for example as shown in Figure 25.

Simply adding more capacitance to the output of a bridge rectifier increases its harmonic emissions, and designing circuits so that they can withstand large fluctuations in its unregulated DC rail voltage is a way to increase its hold-up time without causing problems with meeting harmonic emissions standards [30]. But where increasing the size of the unregulated energy storage is unavoidable, fitting an inductor between the bridge and the energy storage can create a filter that avoids increases in harmonic emissions, and also helps reduce emissions of voltage fluctuations and flicker [32]. But the filter can increase the ripple of the unregulated voltage so the following circuit needs to be able to cope with this.

Active power factor correction (PFC) circuits, fitted between the bridge rectifier and the energy storage capacitors, are often used for reducing emissions of main harmonics. They generally behave as constant current sources over timescales of a few hundred milliseconds, and in combination with the storage capacitance will act as an active filter. Like passive filtering with an inductor, this helps reduce emissions of voltage fluctuations and flicker. Also like filtering with an inductor, the unregulated ripple voltage can increase.

Active PFC is often designed in such a way as to increase the range of mains input voltages, so combining an active PFC with a large amount of energy storage can result in equipment that has low levels of mains emissions, and high levels of immunity to power quality issues.

Some circuits sample the mains voltage, usually to control heat or other parameters, these can often use a large value capacitor or non-volatile RAM to ride-through short-term variations in mains voltage.

Electromechanical devices such as relays, contactors and solenoids should be chosen to have low 'drop-out' or 'hold-in' voltages. Typical low-cost relays can drop-out at 78% of nominal supply, whereas higher-quality types will stay held-in down to 50% or less.

AC coils can be protected by 'coil hold-in' devices, (which powers them individually from a very small AC-AC converter with capacitor energy storage) e.g. 'KnowTrip' or 'Coil-Lock', which both claim to keep coils energised when supply is as low as 25%, or they can be powered from an 'uninterruptible power supply' (UPS, see later).

Relays, contactors and solenoids can also use DC coils (instead of AC) powered by an AC-DC power converter that have a very large input voltage range and sufficient hold-up time (energy storage) as discussed above for powering electronic devices.

Where energy storage is used as described above to improve the ride-through performance of electromechanical devices, care should be taken to ensure that the operation of any safety functions are not delayed by too much.

Costs can be reduced by identifying especially susceptible devices, circuits, equipment, etc., and applying appropriate measures to them alone. During a long interruption, less essential functions could be shut down, or have their intensity or rate of operation reduced. For example, the backlight on a typical laptop PC's display automatically dims when the mains charger is disconnected, to extend the time of operation on battery power.

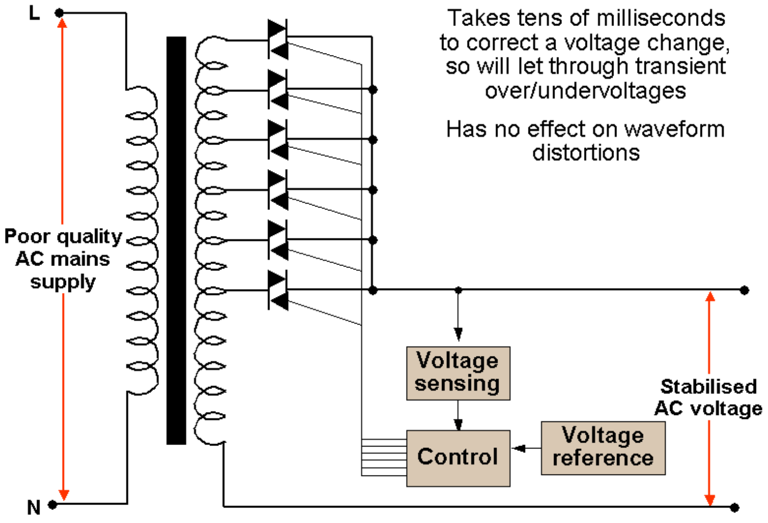
Microprocessors, microcontrollers, and any other devices running software programs, should employ voltage monitor devices, often called 'brownout detectors' or 'brownout monitors'. These detect an out-of-specification DC voltage and freeze RAM and programmable ROM, terminate disc writes, etc, so that if an IC starts to malfunction it will not destroy data or alter programs.

If a software reboot is necessary following the intervention of the voltage monitor, non-volatile RAM can be used to store the previous operating state, so that – in appropriate applications – after the reboot, operation can resume as before. This is sometimes called a 'warm restart', and whether to use it or not depends heavily on any foreseeable safety implications.

The mains power can also return at unpredictable times, so it is also vital to ensure that *any* reboot or power-up always causes a complete ('clean') reset of all registers and programmable devices. Depending on the application, a 'warm start' (continuing operation as before the interruption) may or may not be preferable to a 'cold start' (a default state, waiting for operator input before operating).

Power amplifiers must not output instability, pops, clicks, or thumps during any unanticipated power-down or power-up, as these can damage transducers and peoples ear's. Motor drives and other

Figure 26 Multi-tapped transformer with triac switching



Takes tens of milliseconds to correct a voltage change, so will let through transient over/undervoltages

Has no effect on waveform distortions

machinery or process control might need to ramp up quickly, slowly, or even not restart at all until manually commanded. It all depends on the application, and especially on any foreseeable financial or safety implications.

In some critical applications (such as life-support) even a temporary shutdown cannot be permitted. These will need sufficient energy storage to last until the interruption is over, or until alternative energy supplies can be established (e.g. from a back-up generator).

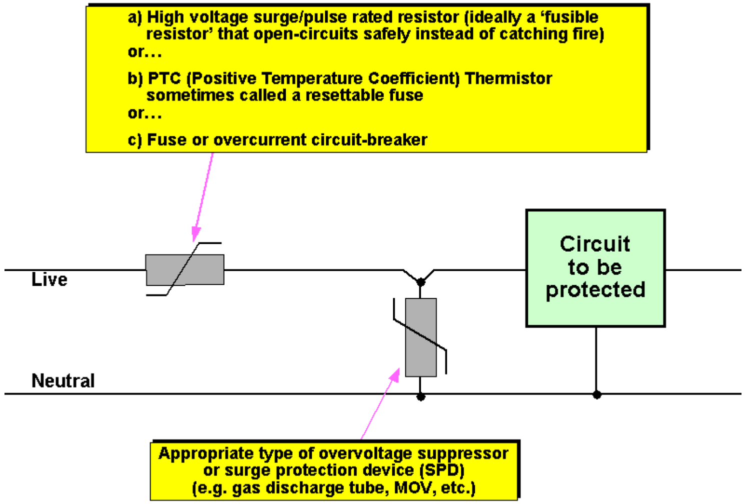
5.2.6 Overvoltages: Swells

The best way to deal with these is to design the AC-DC power converter input circuits with higher-voltage devices and circuits, or specify/choose proprietary power converters with higher voltage ratings. Linear converters can use a multi-tapped mains transformer with automatic tap selection, as shown in Figure 26.

Swells can cause problems for surge protection devices. They are only rated for transient currents lasting a few tens of microseconds, and if the mains voltage rises sufficiently to cause them to draw current they soon overheat and fail. When failing, they can cause fire or shock hazards, so where this is a possibility they need to be protected by a series resistance, positive temperature coefficient (PTC) thermistor, fuse or circuit-breaker, as shown in Figure 27.

If using a PTC, fuse or circuit-breaker the mains power could be removed from the equipment during a swell – so this is not a suitable method where equipment uptime is important. But using a resistor limits the maximum mains current to very low values, so is only appropriate for a very few types of equipment (series resistors are more appropriate for protecting signal, data or control inputs, for instance from 'power cross' tests). So where equipment uptime is important and currents are *not* very low, the surge protection devices must be protected by PTCs, fuses or circuit-breakers and dimensioned so that for any likely swell they do not start to conduct significantly.

Figure 27 An example of swell protection for an SPD



a) High voltage surge/pulse rated resistor (ideally a 'fusible resistor' that open-circuits safely instead of catching fire)
or…
b) PTC (Positive Temperature Coefficient) Thermistor sometimes called a resettable fuse
or…
c) Fuse or overcurrent circuit-breaker

Appropriate type of overvoltage suppressor or surge protection device (SPD) (e.g. gas discharge tube, MOV, etc.)

An alternative is to operate the critical equipment from a battery, or UPS, so that the operation of the PTC, fuse or circuit-breaker can be reset whilst the equipment is powered from the energy stored in batteries and the like, or from a standby generator.

The same technique as is shown in Figure 27 for protecting an SPD from swells, can used to protect circuits from excessively high mains voltages. In this case the SPD is called an overvoltage protector.

5.2.7 Voltage fluctuations and flicker

Protect equipment by designing it to withstand the expected undervoltages and overvoltages, and interharmonic waveform distortion (see below).

5.2.8 Common-mode (CM) low-frequency voltages

Mains AC-DC power converters should be designed to protect against CM low-frequency voltages by complying fully with the relevant electrical safety standard e.g. IEC 60950, 60335-1, 60601-1, 61010-1, etc. This means either using a protectively-earthed chassis; or double insulation and a safety-isolating mains transformer. In either case the primary circuits must have adequate insulation from the frame/chassis and all secondary circuits, including mains windings in AC motors and transformers. Higher values of 'voltage withstand' (dielectric strength) than those specified by the normal safety standards will be required for applications in which the levels of CM voltage can exceed those assumed by the standards.

The above approach helps ensure safety, but the CM signal can still pass through the interwinding capacitance in the mains transformer and interfere with signals in secondary circuits. Solutions include:

- Increasing the CM attenuation of the transformer by adding an earthed interwinding shield, and/or…
- Increasing the CM attenuation of the transformer by reducing the primary-secondary capacitance (e.g. by winding them on different limbs of the core), and/or…
- Using CM filtering on the mains supply at the appropriate frequencies (such filters can be large and costly due to the high mains currents and voltages)

Signal inputs and outputs can be designed to protect them against CM low-frequency voltages in the mains supply and the protective earthing system. Galvanic isolation is the best technique, using signal transformers with good CM attenuation, or opto-isolators/couplers. These should all have sufficient 'voltage withstand' (dielectric strength) – ideally the same as required by relevant IEC safety standards for primary-secondary circuits. As for mains power converters above, some applications may need to withstand higher voltages than those specified in the safety standards.

The very best galvanic isolation, useful up to the highest voltages, is achieved by passing signals over fibre-optic, infra-red, wireless (e.g. Bluetooth), microwave or free-space laser links.

Where signal corruption is to be minimised, but damage an/or safety issues due to high levels of CM voltages are not considered relevant, signals should use balanced/floating input and output amplifiers, and/or CM filtering.

5.2.9 Voltage waveform distortion (harmonic and interharmonic)

Appropriate design techniques include those already described for frequency variations, undervoltages, overvoltages and CM voltages.

Thyristor/triac power control circuits with switching signals derived directly from the mains waveform should be designed to cope with all foreseeable timing errors due to distorted mains waveforms.

Passive loads such as AC motors, transformers, and the like can be protected from overheating due to distorted voltages by converting them into electronic loads, e.g. an AC motor can be powered from a variable-speed inverter motor drive, or replaced with a DC motor supplied by a rectifier.

5.2.10 Mains signalling voltages

Appropriate design techniques include those already discussed for interharmonic waveform distortion and CM voltages.

Example of REO Surge Suppressor

5.3 Improving the quality of the mains power supply itself

5.3.1 Power single-phase equipment phase-to-phase

It generally helps to power single-phase equipment from phase-to-phase mains voltage, instead of phase-neutral, by employing a suitable step-down isolating transformer. Many power quality problems are caused by faults or loads that affect a single phase, so powering phase-to-phase reduces their effect (although it cannot eliminate them).

5.3.2 Connecting to a higher-quality point in the mains distribution network

If fluctuating loads are the cause of the power quality problem, connect the sensitive equipment to a different branch of the mains supply distribution from the one powering those loads, or else to an 'upstream' point in the mains supply distribution that has better quality and/or lower impedance. This latter approach might require a high-voltage transformer to connect to 11kV, 33kV, even 132kV.

5.3.3 On-site generation, and motor-flywheel-generator sets

These can cure all problems due to the poor quality of the public mains power distribution.

But electricity generators have significantly higher impedances than mains distribution transformers, so fluctuating or distorted load currents cause significantly larger effects than when powered from the normal mains supply. So this technique is most appropriate when the equipment to be powered do not include high-power non-linear loads.

Some electricity generators use automatic voltage regulators (AVRs) that cause noise spikes and waveform distortion.

On-site generation is often used in 'stand-by' mode, but changing over equipments' mains supplies from mains to generator (and back again) can give rise to very significant undervoltages, overvoltages, fast transients, and surges. So, careful design is needed to ensure that on-site generation does not simply exchange one set of power quality problems for another. One solution is to operate all sensitive/critical equipment from high-reliability continuous-on-line double-conversion UPSs (see later).

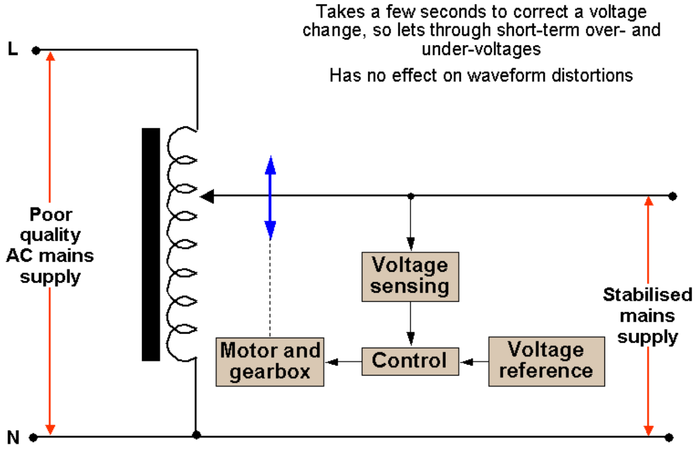
Motor-flywheel-generator sets can use speed control and automatic voltage regulation, plus energy storage in the flywheel, to totally isolate the protected supply from the mains supply and solve all power quality problems except long interruptions. But the motor must be designed and rated to withstand the poor power quality expected from its mains supply without overheating or other damage, and without significant variations in speed.

5.3.4 CVTs (constant voltage transformers)

These ferro-resonant regulators operate their secondary winding in saturation, as part of a 50/60Hz resonant circuit, so they are inefficient, run hot, and their output waveform is often not a very good sinewave. As well as performing their primary task of stabilising the mains voltage, suppressing sags brownouts and swells, they also help remove mains waveform distortions (replacing them with their own).

Their resonant circuits have significant stored energy, and can help equipment ride-through short dips and dropouts,

Figure 28 **The principle of the servo-motor controlled variable transformer**



especially when oversized. To take advantage of this, CVTs rated at least 2.5 times the load power are generally recommended.

5.3.5 Saturable reactors (Transductors)

For a description of this method, please refer to Part 5.3.2 of [1].

5.3.6 Multi-tapped transformer with automatic tap-changing

This technique was sketched in Figure 26. It takes tens of milliseconds to correct a voltage change, so will let through transient over/undervoltages, and has no effect on waveform distortions. It is just a method for helping stabilise the RMS or peak mains voltage – whichever its control circuit is set to monitor.

Where the load is mainly electronic equipment supplied by rectifier-capacitors AC-DC converters, it may be more important for the correct operation of the equipment to control the peak voltage.

Figure 26 shows the tap-changing being done by triacs, but of course relays or contactors could be used instead.

Example of a REO type MEK7711 voltage stabiliser designed for use in airport baggage x-ray machines.

5.3.7 Servo-motor controlled variable transformers

The general principle is shown in Figure 28. They take a few seconds to correct a voltage change, so will let through short-term over- and under-voltages, and have no effect on waveform distortions.

Just as for the multi-tapped transformer with triac switching described earlier – where the load is mainly electronic equipment supplied by rectifier-capacitors AC-DC converters, it may be more important for the correct operation of the equipment for the variable transformer to be used to control the peak voltage, rather than the RMS.

Figure 29 shows an example of a three-phase voltage stabiliser, using a servo-motor variable transformer from REO (UK) Ltd. These are available from a few hundred watts to tens of MW rating.

A variation on the method shown in Figures 28 and 29 is to use a buck/boost transformer in series with the mains supply, as shown in Figure 30. This has the advantage that the whole power does not have to be passed through a variable transformer, reducing size, weight and cost.

5.3.8 Uninterruptible power supplies (UPSs)

A UPS is an AC-DC-AC switch-mode power converter (inverter), with its output set to the required mains frequency. It can be used to convert from one mains frequency to another. Unlike inverters intended for driving AC motors with variable speeds, its switch-mode output is filtered to produce a reasonable sinewave voltage.

'Continuous-on-line double-conversion' types' of UPS can cure all power quality problems. These always power the protected equipment from their inverter powered from their energy storage (e.g. battery, fuel cell, etc.). While mains power is available they charge their energy storage. Figure 31 shows the general principles of such UPSs.

Figure 29

Example of a servo-motor controlled variable transformer

Some lower-cost types of UPS can cause more power quality problems than they solve. For example, some types power the load from the mains and only switch the load to their inverter's output when a certain power quality aspect has dropped below its preset threshold. These cannot protect against *all* power quality problems, and can cause dips/dropouts and transients at switch-over. So when purchasing a UPS, take great care to make sure that it *really will* provide the power quality improvements required.

Figure 30 The principle of the servo-motor controlled buck/boost transformer

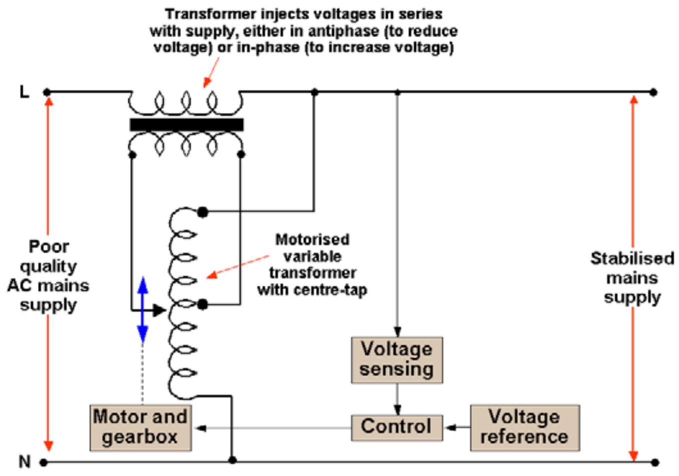
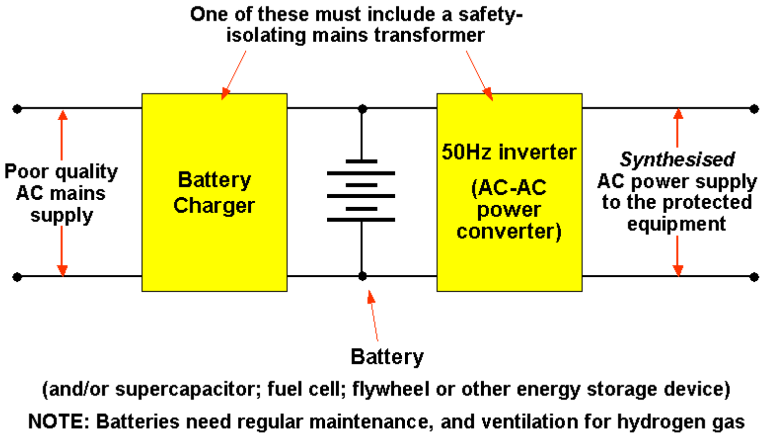
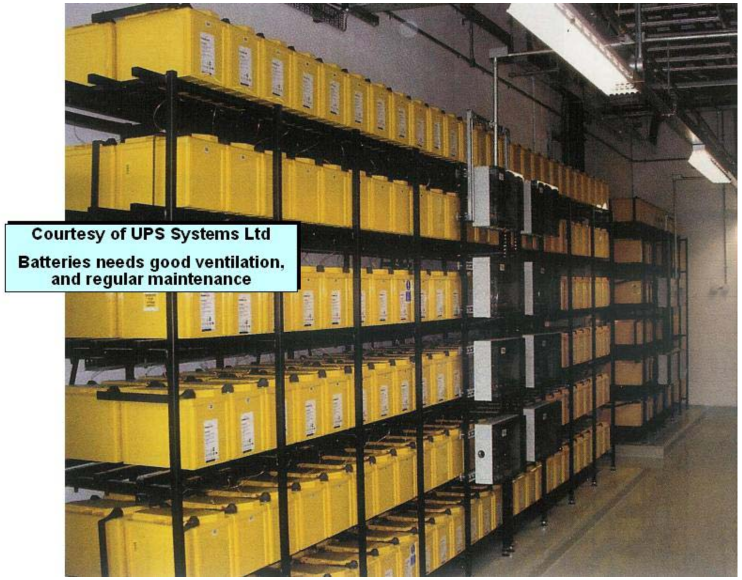


Figure 31 Overview of a 'continuous-on-line double-conversion' type of UPS



NOTE: Where a UPS is powering critical equipment
– or any equipment for a long time
– it is important to use a type that has been
independently proven to be reliable enough

Figure 32 Example of a back-up battery room


Courtesy of UPS Systems Ltd
Batteries needs good ventilation, and regular maintenance

Just as for the motor-flywheel-generator method discussed earlier, the UPS's mains-powered charging circuit must be able to withstand the expected poor mains power quality.

Where very large energy storage is required, large battery systems or fuel cells may be required, maybe just while back-up generators get up to speed. Figure 32 shows an example of a battery room used for such a purpose.

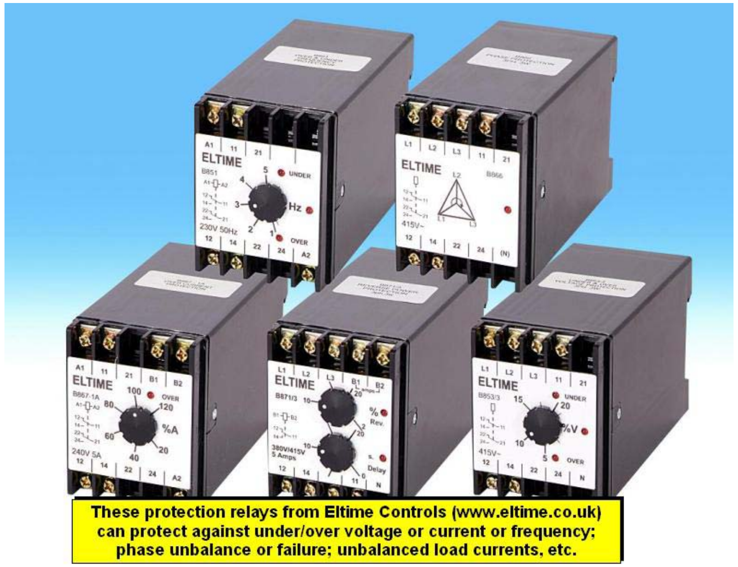
5.3.9 Dynamic voltage restorers (DVRs)

These are sometimes called dynamic sag restorers, or electronic voltage stabilisers (see Part 5.3.2 of [1]). They employ essentially the same principle as the buck/boost stabiliser shown in Figure 30 – adding or subtracting a voltage in series with the mains supply, to increase or decrease (respectively) the voltage of the mains supply provided to the equipment. But instead of using a motorised variable transformer to energise the series transformer, they use an electronic converter based on switch-mode technology.

They are usually used to maintain the mains voltage during a dip or short sag, and need adequate energy storage (supercapacitors, batteries, etc.) – depending on the load power and the dip/sag depths and durations that are to be protected from.

The power switching devices operate at a high frequency, for example 20kHz, so DVRs can respond very quickly indeed to voltage waveform fluctuations. Conceivably they could be used to correct for waveform distortion, but the author has never seen them described for that purpose

Figure 33 **Some examples of Protection Relays**



These protection relays from Eltime Controls (www.eltime.co.uk) can protect against under/over voltage or current or frequency; phase unbalance or failure; unbalanced load currents, etc.

5.3.10 Solutions for harmonics

These are described in [6]. There are some other methods that are used on ships and similar installations where harmonic distortions of the mains waveform can be very severe, that are described in [51].

5.4 Tripping out

Protection devices are available that can detect a wide variety of power quality problems, and remove the power completely from the protected equipment by operating a circuit-breaker. These devices are often called 'protection relays' when purchased as separate items of equipment for use in systems and installations. (Of course, the circuit techniques they use could also be incorporated directly into equipment.)

'Protection Relays' are available commercially that can protect against under/over voltage or current or frequency; phase unbalance or failure; unbalanced load currents, etc., as shown in Figure 33.

Trips can occur at unpredictable times, so it is vital to ensure that they do not cause unacceptable damage, financial loss, or safety incidents. For example, it might be necessary to combine tripping techniques with UPSs or other techniques to provide a controlled power-down.

6. Power Quality mitigation products from REO

An example of a 380kVA Voltage Stabiliser from REO

[1] “*The Power Quality and Application Guide*”, The Power Quality Partnership, http://www.cda. org.uk/PQP/pqag.htm. Its contents include:

1. Introduction

1.1 Introduction to Power Quality
1.2 Power Quality Self-assessment Guide
1.5 PQ in Continuous Manufacturing Download

2. Costs

2.1 The Cost of Poor Power Quality
2.5 Investment Analysis for PQ Solutions

3. Harmonics

3.1 Causes and Effects
3.1.1 Interharmonics
3.1.2 Capacitors in Harmonic-Rich Environments
3.2.2 True RMS - The Only True Measurement
3.3.1 Passive Filters
3.3.3 Active Harmonic Conditioners
3.4.1 Understanding Compatibility Levels
3.5.1 Neutral Sizing in Harmonic Rich Installations
3.5.2 Selection and Rating of Transformers

4. Resilience

4.1 Resilience, Reliability and Redundancy
4.3.1 Improving Reliability with Standby Power Supplies
4.5.1 Resilient and Reliable Power Supply in a Modern Office Building

5. Voltage Disturbances

5.1 Introduction
5.1.3 Introduction to Unbalance
5.1.4 Flicker
5.2.1 Predictive Maintenance - The Key to Power Quality
5.2.3 Flicker Measurement
5.3.2 Voltage Dip Mitigation
5.3.4 Considerations for choosing the appropriate voltage sag mitigation device
5.4.2 Standard EN 50160
5.5.1 Voltage Sags in Continuous Processes

[2] “*The Seven Types of Power Problems*”, Joseph Seymour and Terry Horsley, White Paper #18, American Power Corporation, 2005, www.apc.com

[3] Power Quality Magazine, www.powerquality.com

[4] “*The Impact of International and European Standards Upon Power Quality*”, ERA Report 99-0009, Proceedings of the Quality and Security of Supply in Electrical Networks Conference, 16th - 17th February 1999, London, UK, ISBN 0 7008 0693 8, ERA Technology Ltd, www.era.co.uk This is also available as 'Industrial Annexe B1' in [52]

[5] “*Optimising Building Services: Making Business Sense, Selected Papers*”, ERA Report 99-0560 September 1999, ISBN 0 7008 0699 7, ERA Technology Ltd, www.era.co.uk. This is also available as Industrial Annexe B2 in [52]

[6] REO Guide on “*Harmonics*”, available from the 'Members' area at www.reo.co.uk to people who have registered

[7] a) “*Semiconductor Tools – Part 1: History of Effort and Equipment Sensitivity Findings*”
b)”*Power Quality Solutions for Semiconductor Tools – Part 2: Voltage Sag Immunity Standard and Testing Methodology*”
c) “*Power Quality Solutions for Semiconductor Tools – Part 3: (Conclusion): Equipment Design Solutions*“
All three parts published in Power Quality Magazine www.powerquality.com during 2000, written by Mark Stephens, John Soward, Dennis Johnson and Jim Ammenheuser, available from
a)http://www.f47testing.com/semi_documents/Semi_part_1_PQ_Magazine_Article.pdf
b) http://www.f47testing.com/semi_documents/Semi_part_2_PQ_Magazine_Article.pdf
c) http://www.f47testing.com/semi_documents/Semi_part_3_PQ_Magazine_Article.pdf

[8] REO Guide to EN 61000-4-11 (AC dips, short interruptions, variations), from www.reo.co.uk/guides

[9] REO Guide to EN 61000-4-13 (Mains harmonics and interharmonics), from www.reo.co.uk/guides

[10] REO Guide to EN 61000-4-14 (Mains voltage fluctuations), from www.reo.co.uk/guides

[11] REO Guide to EN 61000-4-16 (Common-mode disturbances, 0-150kHz), from www.reo.co.uk/guides

[12] REO Guide to EN 61000-4-27 (Three-phase unbalance), from www.reo.co.uk/guides

[13] REO Guide to EN 61000-4-28 (Power frequency variations), from www.reo.co.uk/guides

[14] REO Guide to EN 61000-4-29 (DC dips, short interruptions and variations), from www.reo.co.uk/guides

[15] REO Guide to EN 61000-4-2 (Electrostatic discharge, ESD), from www.reo.co.uk/guides

[16] REO Guide to EN 61000-4-3 (Immunity to radiated RF fields), from www.reo.co.uk/guides

[17] REO Guide to EN 61000-4-4 (Immunity to fast transient bursts), from www.reo.co.uk/guides

[18] REO Guide to EN 61000-4-5 (Immunity to surges), from www.reo.co.uk/guides

[19] REO Guide to EN 61000-4-6 (Immunity to conducted RF), from www.reo.co.uk/guides

[20] “*The Cost of Power Disturbances to Industrial & Digital Economy Companies*”, Report reference 1006274, Electric Power Research Institute, from orders@epri.com or download from http://www.epri-intelligrid.com/intelligrid/docs/Cost_of_Power_Disturbances_to_Industrial_and_Digital_Technology_Companies.pdf

[21] “*Voltage Dip survey on UK distribution networks: January 2000 to December 2004*”, Energy Networks Association, Engineering Technical Report 125 September 2005, http://www.energynetworks.org

[22] ITI (CBEMA) Curve and Application Note: http://www.itic.org/technical/iticurv.pdf

[23] “*2005/06 Electricity Distribution Quality of Service Report*”, ofgem report ref: 204/06, 1 December 2006, www.ofgem.gov.uk

[24] “*Inter-system Ground Noise: Causes and Effects*”, White Paper #8, American Power Corporation, 2003, www.apc.com

[25] “*Power System Harmonics, Part 1: Harmonic Sources*”, R. Yacamini, IEE Power Engineering Journal, August 1994, pp 193 – 198, available from the IEE library: http://www.iee.org.uk/Library, libdesk@iee.org.uk

[26] “*Power System Harmonics, Part 2: Measurements and Calculations*”, R. Yacamini, IEE Power Engineering Journal, February 1995, pp 51 – 56, available from the IEE library: http://www.iee.org.uk/ Library, libdesk@iee.org.uk

[27] “*Power System Harmonics, Part 3: Problems Caused by Distorted Supplies*”, R. Yacamini, IEE Power Engineering Journal, October 1995, pp 233 – 238, available from the IEE library: http://www.iee.org.uk/ Library, libdesk@iee.org.uk

[28] “*Power Quality Application Guide – Section 3.1.1 – Interharmonics*”, Copper Development Association, select it from the list at: http://www.cda.org.uk/PQP/PQAG.htm or go direct to: http://www.cda.org.uk/megab2/elecapps/pub504/3_1_1_Low.pdf

[29] *“The Banana Skins Compendium”*, a large number of published reports and anecdotes on interference events, from the “Publications & Downloads” page at www.cherryclough.com

[30] REO Guide on EN 61000-3-2 (Emissions of mains harmonics), from www.reo.co.uk/guides

[31]IEC 61000-3-12:2005 “*Electromagnetic compatibility (EMC). Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16A and < 75A per phase*”

[32] REO Guide on EN 61000-3-3 and 3-11 (Emissions of voltage fluctuations and flicker), from www.reo.co.uk/guides

[33] EN 12015:2004, “*Electromagnetic compatibility. Product family standard for lifts, escalators and moving walks. Emission*”

[34] Def Stan 59-411 “*Electromagnetic Compatibility*”, from: http://www.dstan.mod.uk/ (you will need to register first)
Part No: 1: “*Management & Planning*”
Part No: 2: “*The Electric, Magnetic and Electromagnetic Environment*”
Part No: 3: “*Test Methods and Limits for Equipment and Sub Systems*”
Part No: 4: “*Platform and System Tests and Trials*”
Part No: 5: “*Code of Practice for Tri-Service Design and Installation*”

[35] MIL-STD-461E, “*Department of Defense, Interface Standard, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*” This includes the EMC test methods used by US Military. To find a downloadable copy it is often easiest to google the number of the standard. At the time of writing MIL-STD-461F is nearing completion.

[36] “*Assessing an EM Environment*”, Keith Armstrong, from the 'Publications & Downloads' page at www.cherryclough.com

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[42] “*Differences between EA G5/4 2001 and ENA G5/4-1 2005*”, Power Quality Management Ltd., http://www.pqmanagement.co.uk/picts/G5-4%20changes.pdf

[43] IEEE 519 – 1992 “*Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*”, www.ieee.org

[44] “*The Hidden Cost*”, Steve Barker, IET Computing and Control Engineering, February/March 2007, pp10-11. Other very similar articles by Steve Barker on the same subject (compliance with G5/4-1) include: *"The Hidden Cost of Power Quality Problems*”, Electrical Engineering, February 2007, pp 36-37 ”*Industry Vulnerable to Hidden Power Costs*”, Electrical Review, Vol. 240 No. 3, pp 10-12, www.electricalreview.co.uk

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[46] IEEE Std 1159-1995 “*Recommended Practice for Monitoring Electric Power Quality*”, June 1995.

[47] Power Quality Survey at Wimbledon, PEML Ltd., http://www.peml.co.uk/pdf/typicalsurvey.pdf

[48] European Union Directive 204/108/EC on Electromagnetic Compatibility (2nd Edition): http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/oj/2004/ l_390/l_39020041231 en00240037.pdf.
A table of all the EN standards listed under the Directive is at: http://europa.eu.int/comm/enterprise/electr_equipment/emc/ index.htm

[49] The consolidated version of the Low Voltage Directive, 2006/95/EC, replaces 73/23/EEC and its amendment by 93/68/EEC, http://europa.eu.int/comm/enterprise/electr_equipment/lv/index.htm

[50] The Product Liability Directive, 85/374/EEC amended by 99/34/EC, implemented in the UK as the Consumer Protection Act 1987, http://europa.eu/scadplus/leg/en/lvb/l32012.htm, http://www.dti.gov.uk/files/file22866.pdf

[51] “*Guidance Notes on Control of Harmonics in Electrical Power Systems*”, American Bureau of Shipping, May 2006, from:http://www.eagle.org/absdownloads/listdetails.cfm?id=346 or via:http://www.eagle.org/news/PRESS/ jun07-2006.html

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[53] “*Quality of Electricity Problems in the European Union Cause Concern for Industry*”, STAT-USA,http://strategis.ic.gc.ca/epic/site/imr-ri.nsf/en/gr127068e.html

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Keith Armstrong graduated in electrical engineering with a B.Sc (Hons.) from Imperial College London in 1972, majoring in analogue circuit design and electromagnetic field theory, with a Upper Second Class Honours (Cum Laude). Much of his life since then has involved controlling real-life interference problems in high-technology products, systems, and installations, for a variety of companies and organisations in a range of industries.

Keith has been a Chartered Electrical Engineer (UK) since 1978, a Group 1 European Engineer since 1988, and has written and presented a great many papers on EMC. He is a past chairman of the IEE's Professional Group (E2) on Electromagnetic Compatibility, is a member of the IEEE's EMC Society, and chairs the IEE's Working Group on 'EMC and Functional Safety'.

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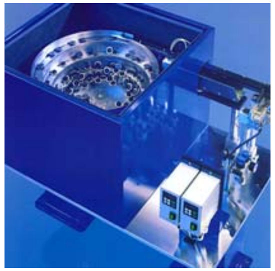
REO - Market Sectors

Train Systems

Chokes and high frequency transformers

Inductive Components

Chokes, resistors and transformers

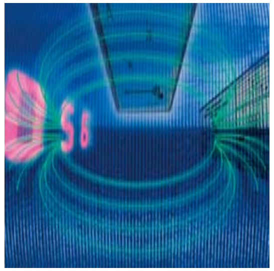


Automation Systems

Controllers for vibratory feeders

Communication Systems

Field bus and gsm

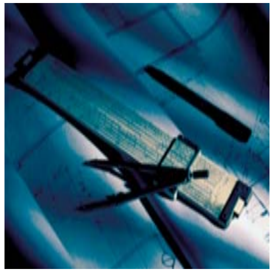


Test Systems

Power supplies and load banks

Power Electronics

Phase-angle and frequency controllers



Classics

Rheostats and variacs

Renewable Systems

Solar transformers

Drive Systems

Filters and braking resistors

Medical Systems

Medical Transformers

Motor Control Systems

Soft-starts