Design Techniques for EMC
Part 6 - ESD, electromechanical devices, power factor correction, voltage fluctuations, supply dips and dropouts

By Eur Ing Keith Armstrong C.Eng MIEE MIEEE, Cherry Clough Consultants

This is the **sixth** and final article in this series on basic good-practice electromagnetic compatibility (EMC) techniques in electronic design, published during 2006-8. It is intended for designers of electronic modules, products and equipment, but to avoid having to write modules/products/equipment throughout – everything that is sold as the result of a design process will be called a 'product' here.

This series is an update of the series first published in the UK EMC Journal in 1999 [1], and includes basic good EMC practices relevant for electronic, printed-circuit-board (PCB) and mechanical designers in all applications areas (household, commercial, entertainment, industrial, medical and healthcare, automotive, railway, marine, aerospace, military, etc.). Safety risks caused by electromagnetic interference (EMI) are not covered here; see [2] for more on this issue.

These articles deal with the practical issues of what EMC techniques should generally be used and how they should generally be applied. Why they are needed or why they work is not covered (or, at least, not covered in any theoretical depth) – but they are well understood academically and well proven over decades of practice. A good understanding of the basics of EMC is a great benefit in helping to prevent under- or over-engineering, but goes beyond the scope of these articles.

The techniques covered in these six articles will be:
1) Circuit design (digital, analogue, switch-mode, communications), and choosing components
2) Cables and connectors
3) Filtering and suppressing transients
4) Shielding (screening)
5) PCB layout (including transmission lines)
6) **ESD, electromechanical devices, power factor correction, voltage fluctuations, immunity to power quality issues**

Many textbooks and articles have been written about all of the above topics, so this magazine article format can do no more than introduce the various issues and point to the most important of the basic good-practice EMC design techniques. References are provided for further study and more in-depth EMC design techniques.

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6.5.8 Undervoltages (sags, brownouts, dips, dropouts and interruptions)

Undervoltages are caused by load current fluctuations, and by faults (and fault clearance) in the electrical power distribution. The series impedance of the distribution network means that load currents flowing in it create voltage drops. At various points in AC networks there are automatic tap-changing transformers that maintain the mains voltage within certain limits at their location, so in such networks it is usually the impedance 'downstream' of such devices that cause the undervoltages in response to the load current.

During an insulation fault, only the supply impedance limits the mains current taken from an ordinary single-phase mains plug, since the phase voltage collapses to 0V at the fault. In an ordinary house the currents can reach or exceed 1000 Amps RMS, and commercial and industrial sites with lower-impedance supplies can source correspondingly higher fault currents. (In fact, a common measure of supply impedance in the electrical distribution industry is the 'short-circuit current'.) This current flows until the protective fuse or circuit-breaker opens, which is generally well under a second.

Another cause of undervoltage is when the generated power is inadequate for the load. In AC networks the generator will slow down and eventually stop, so the undervoltage will also be associated with a significant fall in frequency (see 6.5.4). In highly developed and integrated networks, such as the UK's mains distribution network, loads (e.g. whole towns) will be shed (have their mains power cut off) before the frequency drops dramatically, to protect the generators from stalling, but this is not necessarily the case for all mains networks worldwide or for local or portable generators.

I have a 2kW portable generator with a circuit breaker on its output, but find that if I overload it, sometimes it keeps running and the circuit breaker opens, but sometimes it stalls without the circuit breaker opening.

Other causes include when the electrical power is switched off, for example by the operation of a protective overcurrent device (e.g. fuse, circuit breaker, etc.) in an LV or MV network, or by 'arc quenching' devices in the HV network in response to a flash-over arc caused by lightning strikes, and of course by load-shedding by the electricity network to protect their generators from damage by overheating or stalling when the power demand exceeds the generated supply.

Dips are short-term reductions in supply voltage e.g. 30% down for 10ms, 60% down for 100ms, see Figure 6BE, and usually happen abruptly as a result of inrush currents and/or insulation breakdown in other equipment connected to the same network. If the equipment is located nearby on the same branch of the network, the dip depth increases and when it exceeds 95% it is called a dropout or 'short interruption', different words for the same thing.

Dips, dropouts and 'short interruptions', see Figure 6BE, generally last less than 1 second, because inrush currents do not last that long, and because safety standards require equipment to be designed so that faults that draw excessive mains current will blow fuses or open circuit-breakers within 1 second, to minimise fire risks.

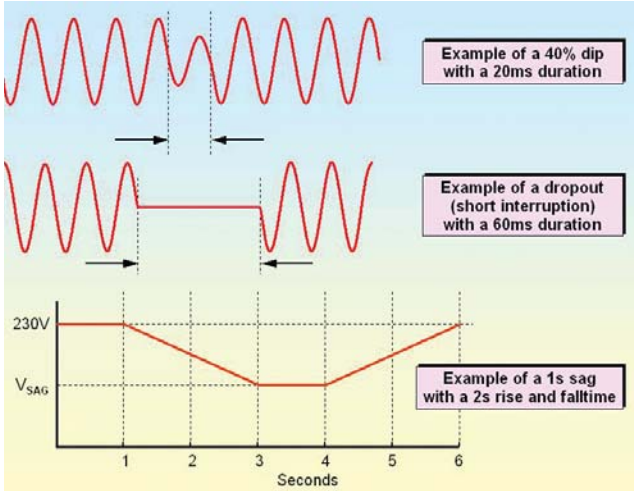

Figure 6BE Examples of types of undervoltage events

Note that the dips and dropouts in Figure 6BE started and stopped at the zero-crossings of the mains waveforms. This is the way they are tested by the EN/IEC 61000-4-11 test method – but not like real life, where the start and stop phase angles occur at random.

Sags (often called brownouts in the USA) are reductions in supply voltage that last longer than 1 second. They are generally caused by the accumulated loading on a network, and so are assumed by the tests in EN/IEC 61000-14-11 to build up and recover slowly, however in an industrial location where there is a very high-power load, real-life sags could occur instantaneously and recover abruptly too. A sag of 50% for 8 hours has occurred in the UK (see No. 21 in [12]), although this is unusual.

'Long interruptions' are caused by fault clearance can last for seconds, minutes, hours, days, etc., and are caused by removal of power to protect the network, or by damage to the network (e.g. trees falling across roadside power lines) in which case after an extreme weather event or earthquake they can last for weeks.

For equipment powered by DC, for example telecommunications equipment and blade servers at 48V, a test method for immunity to dips, dropouts and interruptions is EN/IEC 61000-4-29, which is described in a guide available from [7]. This guide also describes what causes these phenomena, what kinds of effects they have on equipment, and how to test to improve real-world reliability.

For AC supplies, a relevant immunity test standard is EN/IEC 61000-4-11, and a guide on it is also available from [7]. Some low-cost but non-compliant tests that can be done by anyone with sufficient competence are described in [6]. [7] includes more detailed descriptions of undervoltage phenomena, including what causes them, what they can affect and how. EN/IEC 61000-4-11 includes a large range of tests, only some of which are called up by the generic and product immunity standards listed under the EMC Directive.

Figure 6BF is a block diagram of a make-it-yourself tester that could even be designed to comply with the generator specification in EN/IEC 61000-4-11.

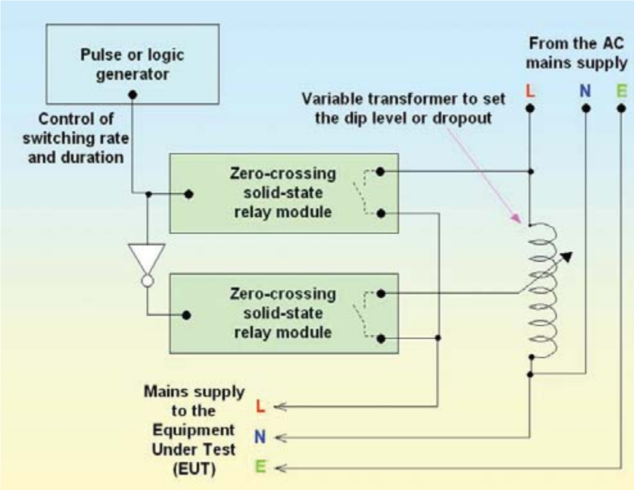

Figure 6BF Block diagram of a do-it-yourself dips and dropouts tester

The definitions of dip, dropout, short interruption, long interruption, sag and swell (see 6.5.3), are all derived from the IEC EMC standards, but it important to be aware that other industries might use the same terms to mean different phenomena, and this might also depend upon the country.

For example, in the USA it is common to use the term ‘sag’ to mean a dip, and the UK’s electricity supply authorities have decided that a ‘short interruption’ in the electricity they supply to consumers, is any interruption lasting less than two minutes. They do not regard short interruptions as being as serious as long ones, although for most electronic equipment a power interruption of greater than one second is as serious as one lasting a minute or more.

Figure 6BG shows how undervoltages can cause problems for electronic circuits, by causing the unregulated DC voltage rail to drop below the minimum input voltage of the voltage regulator, causing its regulated output voltage to fall below specification. ICs require a certain minimum DC supply voltage for their correct operation to be guaranteed, and when their DC supply falls below this value, for example due to a dip or dropout, they can behave in very strange ways. For example, a NAND gate might behave as a different kind of gate, microprocessors and other programmable devices might over-write their data or program memories with garbage, and software operation might be corrupted by ‘looping’, ‘hanging’ or ‘crashing’

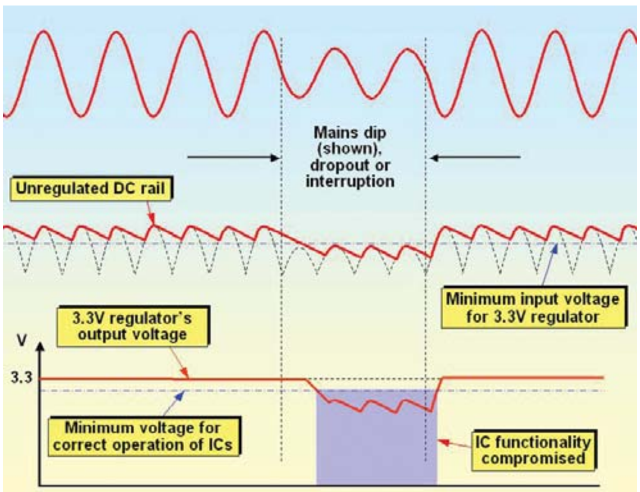

Figure 6BG How undervoltages can cause problems for electronic circuits

Undervoltages can also cause problems for electromechanical devices such as solenoids, relays, contactors, solenoids, AC and DC motors. Solenoids can lose control of their loads, relays and contactors can drop out. Motors might slow down or overspeed depending on their type and control method, but during a sag they can lose so much power that they stall, which causes their magnetising currents to increase significantly, in turn causing overheating that can lead to fire (if not interrupted in time by a protection device) – or at least damage their winding insulation so that reliability is significantly impaired and electric shock risks increased.

If a relay or contactor that is held-in by a normally-open contact will not recover to its original state afterwards. If a relay or contactor that is held-in at reduced voltage (to reduce power consumption and heating) is held-in by a normally-open contact, it might not pull back in again when the supply recovers – depending on the type of coil power supply.

Until recently, most safety systems in industry relied upon so-called ‘hard-wired’ devices such as solenoids, relays and contactors. But few designers of such systems ever bothered to consider the effects of undervoltage events, or the fact that the responses of solenoids, relays and contactors to them varies depending on their temperature, and on how old they are.

Since the publication of IEC 61508 in 2000, many industrial safety systems have started to use computer techniques and fieldbusses instead of hard-wiring, but in all the very many glossy advertisements for this new equipment I have yet to see anything that indicates that the designers have taken undervoltages or other power quality issues into consideration.

Perhaps it is a requirement of their manufacturers that these new computerised safety system controllers will be operated from continuous on-line double-conversion UPSs (see 6.5.3 and 6.5.11) with sufficient energy storage at least to maintain safety whilst shutting down the equipment under control? But if this is so – the advertisements do not state it – perhaps it is in the small print somewhere in the sales terms and conditions or user instructions.

Equipment can be designed with increased protection against undervoltages, for example by operating DC equipment from AC-DC (or DC-DC) power converters that have a very large input voltage range. For example, the typical ‘universal input’ power converters used for charging the batteries of laptops and cellphones are rated for 100-240Vrms inputs, so that their manufacturers can sell the same product all around the world, only having to ensure that each shipment is packed with the correct type of mains cord. Using such converters on nominally 230V mains supplies provides total protection against dips and sags down to 43% of nominal (a dip or sag of 57%).

AC-DC power converters that automatically select either 115 or 230V nominal inputs are not suitable, and not recommended. For example, if the mains voltage was 180Vrms and the AC-DC power converter device selected a 115V input, the DC output would be damagingly high, and the converter might be damaged too. But if is selected 230V the DC output would be too low and the equipment would be powered at too low a voltage for correct operation. Power converters with a continuous range of input voltage are strongly recommended.

To protect against dips and sags that go below the input range of the power converter, or of course against dropouts and short interruptions, requires the power converter have an adequate 'hold-up' time, for the load it is powering. This requires sufficient energy to be stored in electrolytic capacitors, supercapacitors, batteries, fuel cells, flywheels, etc., and the energy storage is generally provided at the unregulated DC rail. Figure 6BH shows some examples of energy storage devices.

Figure 6BH Some examples of energy storage devices

It helps make best use of the stored energy in the unregulated DC rails' capacitors, if the DC regulators and/or equipment being powered from it are designed to cope with very large fluctuations in the unregulated DC voltage.

If using capacitive energy storage, operating the unregulated DC storage capacitors at higher voltages requires less physical volume (size) for a given stored energy, because capacitive energy storage is proportional to the capacitor voltage squared (stored energy in Joules = $\frac{1}{2}CV^2$). Figure 6BJ shows a block diagram of a power converter that uses this effect.

The step-up (boost) stage could be an active power factor correction circuit (see 6.3.6 and 6.4.6 in [36]). If aiming to double the unregulated voltage, for operation from nominally 115V mains supplies, the switching devices and storage capacitors need only be rated the same as for a normal power converter running on nominal 230V mains (at least 600V and 350Vdc respectively). But for operation from nominal 230V mains the switchers would probably need to be rated for 1200V and the capacitors for 800V – which might limit the availability of low-cost components, so maybe a smaller boost percentage might be more cost-effective.

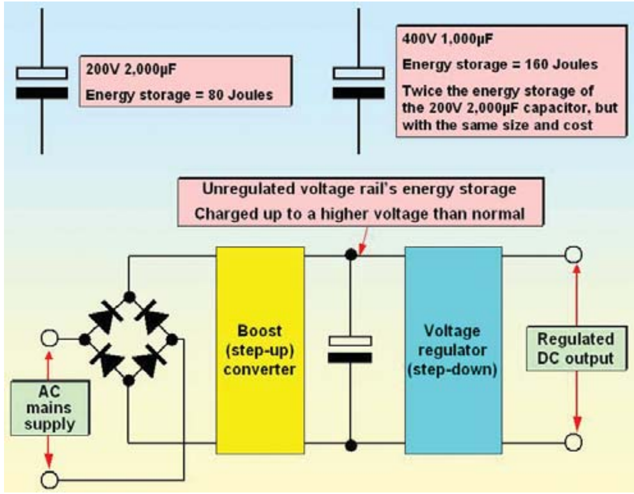

Figure 6BJ Storing more energy in unregulated storage capacitors by using a higher voltage

Where very large energy storage is required, large battery systems or fuel cells may be required, perhaps just while back-up generators get up to speed, and Figure 6BK shows the example of a 'battery room' used for such a purpose, and such rooms are typical of large UPS installations.

To reduce the size and cost of the energy storage, it is sometimes possible to identify certain parts of the product that must keep operating at full specification during the undervoltage event, whilst others can be operated at lower power or even switched off completely. For example, the brightness of a backlight or other illumination could be allowed to reduce, microprocessor clock speed reduced, etc.

Before the energy storage runs out completely and the product must cease to operate, it is important to initiate a 'controlled shutdown' to prevent loss of data, damage or safety incidents. However, in some critical applications (such as life-support) shutdown can never be permitted, and such products will need to have a guaranteed source of electrical power (e.g. generators, and sufficient fuel for them).

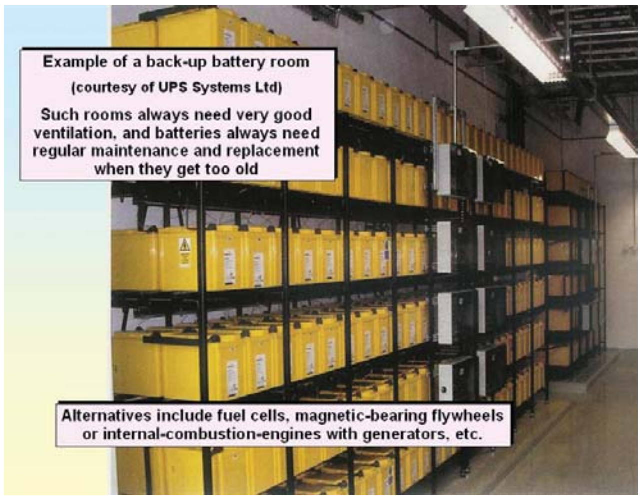

Figure 6BK Example of a large battery room

All digital devices, including microprocessors, microcontrollers, etc., should be protected by voltage monitor devices, often called 'brownout detectors' or 'brownout monitors'. These detect an out-of-specification DC voltage (ideally, one that is *about* to become out-of-specification) and freeze RAM and programmable ROM, terminate disc writes, etc, so that malfunctioning ICs can't destroy data or alter programs. They are available with a range of accuracy specifications, and of course the more accurate ones are generally the better ones to use, and they cost more.

Non-volatile RAM can be used to store the operating state so that operation as before can resume after the undervoltage event is over – but only in appropriate applications where such self-recovery is acceptable, for example does not increase safety risks.

Some circuits sample the mains voltage (usually to control heat or other parameters), and they can often use a large value capacitor, or rely on a digitally-stored value, to cope with short-term variations in mains voltage.

Relays, contactors and solenoids can often use DC coils (instead of AC coils) and be powered by a AC-DC power converter which has a very large input voltage range and/or sufficient hold-up time (energy storage) as discussed earlier. An advantage of DC power is that it is relatively easy to operate the devices from batteries that are 'float-charged' from the regular mains supply, the way that a normal laptop PC is operated.

If using AC coils, choose AC relays, contactors and solenoids with lower 'drop-out' or 'hold-in' voltages. As mentioned earlier, typical low-cost relays can drop-out at 78% of the nominal supply, whilst better types are available with hold-in voltages down to 50% (or less) of nominal. So-called 'coil hold-in' devices (such as 'KnowTrip' or 'Coil-Lock') are available, some of which claim to keep coils energised when the AC supply is as low as 25% of nominal.

Whilst a lower hold-in voltage will increase protection from dips and sags, it will not protect against dropouts and interruptions in the AC power, for which AC coils will need a source of AC power from a UPS (see 6.5.11) that has sufficient energy storage.

6.5.9 Voltage fluctuations

Voltage fluctuations – according to the IEC 61000-4 series of standards – are rapid sequences of voltage dips and/or voltage increases or alternating dips and increases, and an example is shown in Figure 6BL. For AC supplies, a relevant immunity test standard is EN/IEC 61000-4-14, and a guide on it is available from [7]. This guide includes more detailed descriptions of voltage fluctuation phenomena, including what causes them, what they can affect and how, and how to test to help improve real-world reliability. Some low-cost but non-compliant tests that can be done by anyone with sufficient competence are described in [6].

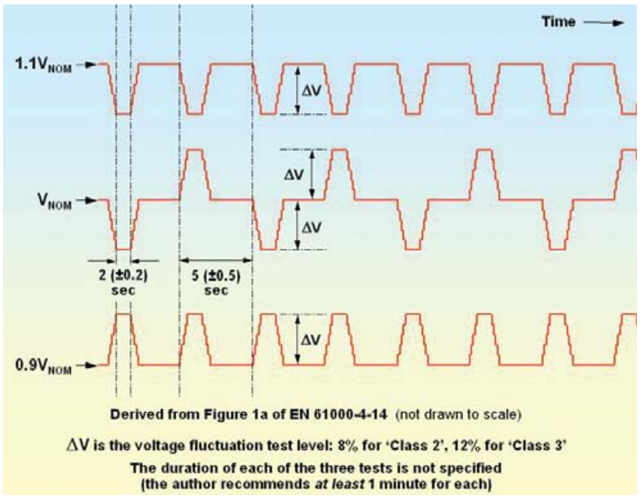

Figure 6BL The three types of voltage fluctuation test in EN/IEC 61000-4-14

Tests appropriate for *individual* mains voltage dips, sags, swells, etc. are covered by EN/IEC 61000-4-11, see 6.5.3 and 6.5.8 and the relevant guides from [7]. However, these tests do not cover individual abrupt voltage increases (the opposite of dips), even though they can occur.

For DC supply networks, a relevant immunity test standard for voltage fluctuations is EN/IEC 61000-4-29, which it calls "variations" instead of fluctuations, and a guide on this standard is available from [7]. This guide also goes into what causes the phenomena, what they can affect and how, and how to test to help improve real-world reliability.

Voltage fluctuations are dealt with by designing equipment to protect against both undervoltages (see 6.5.8) and overvoltages (see 6.5.3). Note that the frequency of the fluctuation will appear as a ripple on the unregulated DC rail, and circuits that are not powered via a DC regulator operated within its correct input range, will experience this ripple directly, and it might appear as noise in the passband of the circuit.

6.5.10 Waveform distortion (harmonic and/or interharmonic)

Harmonic distortion is when a spectrum analysis shows that the AC electricity supply contains frequencies that are integer multiples of the fundamental mains frequency (e.g. for 50Hz: 100Hz, 150Hz, 200Hz, 250Hz, etc., known as the 2nd, 3rd, 4th, 5th, etc., harmonics respectively). When viewed on a 'line-triggered' oscilloscope, the supposedly sine-wave mains waveform will be seen to be distorted, with the distortions 'phase locked' to the mains waveform.

Harmonic distortion is caused by non-linear loads, such as the rectifier-capacitor AC-DC converters typical of almost all AC mains-powered electronic products. Products using thyristor/triac power control are also non-linear loads. As more and more direct-on-line motor and heating loads are replaced by electronic controlled loads (e.g. variable-speed AC motor drives) the waveform distortion is generally worsening. Typical values are under 4% total harmonic distortion (THD) and the electricity supply authorities in Europe have agreed that they must keep it below 8% because it is commonly observed that typical electronic equipment often malfunctions with THD above this level.

As was discussed earlier, many offshore vessels now use electronically-controlled 'thrusters' that represent such a large proportion of their generator capacity that it is not unusual for their on-board mains waveforms to suffer THDs of up to 30%. Figure 6BM shows an example of a mains waveform recorded in a domestic house in Israel in 2000.

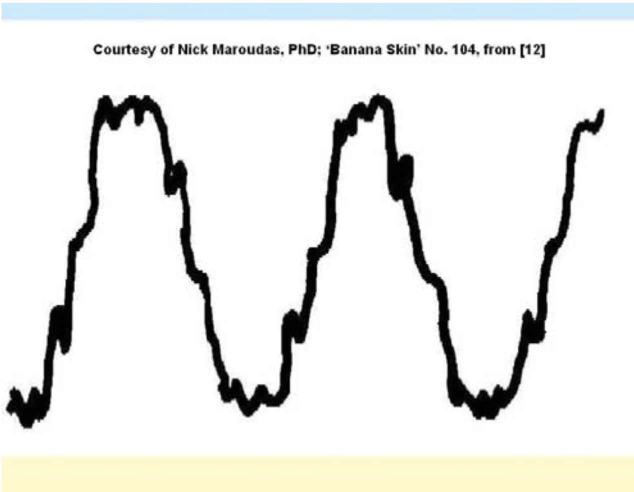

Figure 6BM An example of a mains waveform in a house in Israel in 2000

Interharmonic distortion is when a spectrum analysis shows that the AC electricity supply contains frequencies that are not integer multiples of the fundamental mains frequency (e.g. 39Hz, 105Hz, etc.). When viewed on a 'line-triggered' oscilloscope, the shape and amplitude of the supposedly sine-wave mains waveform will be seen to wobble, or even be blurred, because the distortions are not phase-locked to the mains waveform.

Interharmonic distortion is created quite differently from harmonic distortion – it is simply the voltage fluctuations caused by rapidly fluctuating loads like those discussed in 6.5.9. The chief source is powerful switch-mode frequency-converters, such as variable speed AC motor drives, the use of which is rapidly increasing to save power consumption and hence help reduce the rate of warming of our planet. Another source of interharmonic distortion can be high-power frequency converters used in the AC power distribution networks themselves.

A switch-mode frequency converter operating at, say, 39Hz has AC mains current demands at 39Hz *and* at its harmonics, and these non-mains frequency currents flowing in the impedances of the mains supply network result in voltage fluctuations at those frequencies – known as interharmonic waveform distortion. The situation is actually much more complicated than this, because switch-mode power converters act as 'frequency mixers' that cause the mains frequency and its harmonics to intermodulate with the inverter frequency and its harmonics.

Figure 6BN shows a measurement of the spectrum of the current into a 700kW variable-speed AC motor drive running at an output frequency of 39.375 Hz. The X-axis markings are probably too small to read in this Figure, but include (for example) frequencies such as 131.25Hz created by the intermodulation of the 6th harmonic of the 50Hz mains and the 11th harmonic of the motor frequency. When this complex current waveform flows in the impedance of the mains distribution network, it will give rise to voltage waveform distortion at all of the frequencies shown in Figure 6BN.

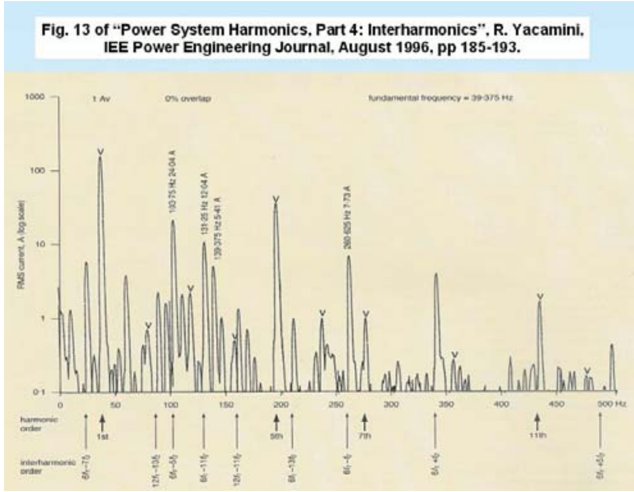

Figure 6BN Example of harmonic and interharmonic currents from an inverter-fed AC motor

Neither of the above waveform distortions apply to DC electrical power, of course, but DC power can (and usually does) carry frequencies other than DC, caused by the same rapidly fluctuating load currents that would create interharmonics in an AC supply.

A relevant immunity test standard is EN/IEC 61000-4-13, and a substantial guide on it is available from [7]. This guide includes more detailed descriptions of waveform distortion phenomena, including what causes them, what they can affect and how, and how to test for them to help improve real-world reliability. Other useful guides, more appropriate for systems and installations engineering, are [31] and [33].

Harmonic distortion can result in mains waveform peaks that are lower than the √2 Vrms expected from a pure sine wave, and an extreme example is a 230Vrms square wave supplied by single-phase mains sockets, which has occurred in China. Since the typical bridge rectifier-capacitor AC-DC converter used in almost all electronic equipment (other than thyristor power control) charges up to the peak of the supply waveform, a THD of X% means that the peak can be up to X% lower than expected.

A power converter for use on mains supplies of 230V ±10%, if supplied from a supply with 4% THD, could be running at -4% of its unregulated DC voltage even when the supply is at its nominal RMS value. So the unregulated rail could become too low for correct operation of the product when the mains voltage falls below 230Vrms -6%. If the THD was 8% (unlikely when powered by a national grid network except in some industrial sites, more likely when running on local generation) then the product might malfunction below 230Vrms -2%.

The same levels of THD, but with the harmonic components in different phases, can instead result in peaks higher than the expected Ö2 of the nominal RMS voltage, which could cause overvoltage damage. For example, a power converter for use on mains supplies of 230V ±10%, if supplied from a supply with 4% THD, could be running at +4% of its unregulated DC voltage even when the supply is nominal as measured on a true-

RMS meter. In the UK, the nominal mains voltage is in fact 240V (230Vrms +4.3%), so with a supply of 240V +4% THD, the product could be damaged by operating above its maximum unregulated DC voltage when the mains rose above 240V + 1.7%, which it often does.

Figure 6BP shows the example of adding 8% third harmonic to a pure sinewave. When added in-phase it causes the peak voltage to be 8% higher than √2 Vrms, and when added in antiphase it causes the peak voltage to be 8% lower than √2 Vrms.

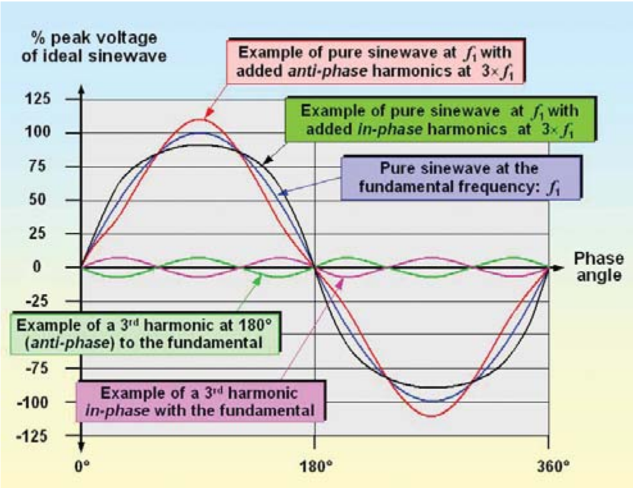

Figure 6BP An example of effect on peak voltage of the phase of a harmonic

Interharmonic distortion causes the same overvoltage and undervoltage problems, but they beat with the fundamental frequency so although they can cause instantaneous overvoltage damage they are only likely to cause undervoltage problems when the beat frequency is low, say less than 10Hz.

Both kinds of distortion can cause errors in the zero-crossing point, causing problems (such as double-zero-crossings) for circuits that use the zero-crossings of the mains supply to control power switching, timing or other functions. Thyristor/triac power control circuits that use simple gate drive circuits to derive their firing signals from the mains waveform can misfire causing malfunctions, even catastrophic damage.

Distortion frequency components can exceed 2kHz, and because the impedance of a capacitor reduces as frequency increases, such high frequencies can cause very significant increases in the current flowing in capacitors in EMI filters, and in the displacement power-factor correction capacitors in luminaires and electricity distribution networks. These high currents can cause overheating damage, and such damage to capacitors is not uncommon, for example see No. 7 in [12].

Mains waveform distortions and their associated currents can also cause motors, transformers and cables to overheat, and can cause severe interference with wired telephones. They also produce ripple on the rectified DC voltages of AC-DC power converters, at the frequencies of the interharmonic noises, which could interfere with circuits powered from those DC rails.

To design products to protect against waveform distortions, appropriate overvoltage and undervoltage design techniques described previously should both be applied. Thyristor/triac power control circuits should be designed to cope with all foreseeable timing errors due to distorted mains waveforms. Timers and real-time clocks should use stable reference oscillators (e.g. as used in wristwatches) or off-air frequency references from terrestrial or satellite transmitters (see 6.5.4). Filters or voltage regulators may be needed in some applications, to remove in-band noise from unregulated DC power rails.

6.5.11 Improving the quality of the mains supply itself

There are numerous ways of obtaining a better quality of mains supply for a product, including the following:

- Obtaining a better quality mains supply
- On-site generation of an AC supply
- Passive or ‘active’ mains filtering
- Constant voltage transformer (CVT)
- Motor flywheel - generator sets
- Multi-tapped triac-switched transformers
- Servo-motor variable transformers
- Uninterruptible Power Supplies (UPSs)
- Dynamic voltage restorers (DVRs)

All the above techniques can be applied at system or installation level, which is covered by [33] but is not the subject area of this series of articles. However, the word ‘product’ encompasses a huge range of possible equipment, and some types of products may be able to incorporate some of these techniques within themselves.

Obtaining a better quality mains supply

Powering a single-phase mains-powered product from phase-to-phase mains voltage, instead of phase-neutral, reduces the amplitude of any phase-to-neutral or phase-to-earth dips, dropouts, interruptions, sags, swells and voltage fluctuations. The rate of occurrence of such problems is reduced (but not eliminated) and *average* power quality is improved. This technique will generally also reduce the effect of any DC in AC networks, but will usually have little or no effect on distortion, frequency errors, and CM voltages.

If it is the load currents consumed by other equipment connected to the same mains distribution network that is causing the power quality problem, the product could be connected to a different branch of the network from that used by those loads. It might even be necessary to connect it directly to the 230/400V distribution transformer feeding that mains network.

Going further, the product could be connected to a ‘point of common connection’ (PCC) that is upstream of that distribution transformer, and therefore operates at a higher voltage, with a lower impedance that is less disturbed by the load currents of the other equipment, and therefore provides a better power quality. This will generally require a high-voltage transformer to connect to the PCC (for example 3.3kV, 11kV, 33kV, etc.).

Generating a ‘clean’ AC supply on-site

Generating your own electricity supply, for example using an internal combustion engine driving a generator, can cure all of the problems caused by the poor quality of the normal mains power distribution.

But it is important to understand that electricity generators have significantly higher impedances (approximately 3 times) than a mains distribution transformer of the same kVA or kW rating

– so fluctuating or distorted load currents could cause significantly larger effects in a locally generated supply, than when powered from the normal mains supply network.

So it could happen that where a national electricity supply is plagued with (say) dips and dropouts, and a local generator is used instead, the non-linear nature (say) of one of more of the loads causes the local generator output distortion to rise to unacceptable levels – exchanging one set of power quality problems for another.

One solution is to ensure that the generator is rated for a much higher output than the load will consume, ideally three times higher, so for example a 100kW load would use a generator of 300kW or more. Greater cost-effectiveness can be achieved whilst also improving power quality if the likely effect of the loads on the generator is analysed in sufficient detail, taking the generator's output impedance from DC to at least 5kHz into account.

Some generators use automatic voltage regulators (AVRs) that cause voltage transients and/or waveform distortion, so it can be important to check the power quality provided by the generator.

Often, local generation is used in 'stand-by' mode, to pick up the load when the normal mains supply fails. But changing over the supply from mains to generator (and back again) can give rise to very significant undervoltages, overvoltages, fast transients, and surges, that can cause problems for some types of loads (see No. 55 of [12] for a hospital example).

One solution to the above problems inherent with local electricity generation is to operate all sensitive or critical equipment from high-reliability continuous on-line double-conversion UPSs (see later).

Passive or 'active' filtering to reduce distortion
Passive filtering at/above the 7th harmonic often uses low-pass (LP) filter techniques, but for the 6th harmonic and below LP filters often have excessive thermal losses at 50/60Hz so 'resonant trap' filters are mostly used, each one tuned to a specific problem harmonic frequency. The design of such mains filters for use in an installation is not trivial, and unless you are an expert in doing just this, I strongly recommend that you employ experts.

So-called 'active' filtering does not actually use filter technology, it is just a marketing term invented to try to make people who are used to traditional passive mains filtering feel more comfortable with this new electronic technology.

'Active mains filtering' uses 'anti-harmonic injection' techniques that employ switch-mode AC-AC power inverter technologies, and Figure 6BQ shows its basic operating principles.

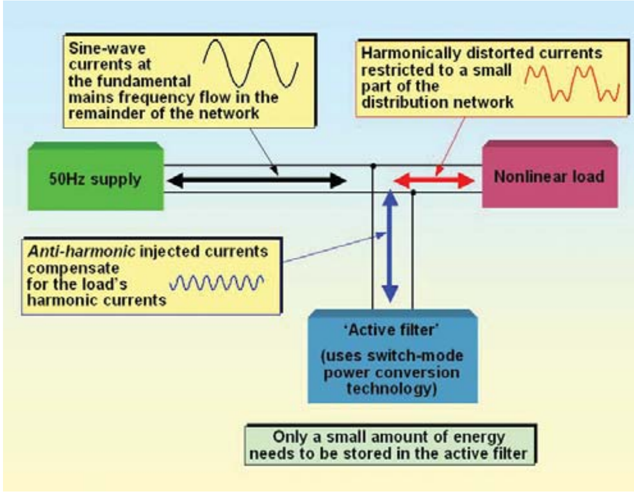

Figure 6BQ 'Active' mains filters – operating principles

Active filters monitor the non-linear currents consumed by the load, and inject antiphase harmonic currents into the mains distribution network so that, upstream of the injection point, the network is only required to provide sinewave current at the fundamental frequency and so its intrinsic impedance does not give rise to waveform distortion.

Active filters can be sized just to deal with one load, and can even be incorporated into products to act as power factor correctors, see 6.3 in [36]. They can also be sized to cope with multiple loads, for example using one active filter per floor of a tall office building, so that the main risers providing power to the floors do not carry harmonic currents and any voltage distortion just arises within each floor.

Constant Voltage Transformers (CVTs)
This venerable technology operates the secondary winding of an isolating transformer in saturation, as part of a 50/60Hz resonant circuit, so it is inefficient and runs hot. Its output waveform is generally not a very good sinewave but it effectively suppresses other mains waveform distortions, sags, brownouts and swells.

There is stored energy in the resonant circuit, so if sufficiently oversized it can continue to provide power even during dips and dropouts, often called 'hold up' or 'ride-through' – and if this is required the general recommendation is to rate the CVT at 2.5 times the power of the load, or more.

CVTs are large, inefficient, and run hot, when compared with modern solid-state technologies. But because they contain no semiconductors they are very robust and reliable, and what little maintenance and repair they might ever need is easily provided using standard electrical knowledge and tools. In some applications, they may well be more cost-effective than their modern alternatives.

Motor-flywheel-generator sets
The motor is powered from the poor quality electricity supply (which could be AC or DC) and drives a generator to provide a 'clean' supply to the protected equipment. The motor has automatic speed control to set the output frequency, and the generator has automatic voltage regulation to set the voltage, and the flywheel provides some energy storage. If correctly dimensioned and competently designed and constructed, they

can solve all power quality problems other than long interruptions, and provide CM and DM isolation from DC to many GHz. They can also convert from one frequency to another.

The ‘hold-up’ or ‘ride-through’ time for longer interruptions depends on the size and rotational speed of the flywheel, which can be designed to store a great deal of energy. Modern types use lightweight non-metallic flywheels rotating at huge speeds to safely store very large amounts of energy in quite small volumes.

It is important that the motor is rated to withstand the poor quality of the mains power supplied, which generally means increasing its size and power rating to prevent overheating due to waveform distortions, low frequencies, DC in AC supplies, undervoltages, etc., and it should have insulation that will cope with the anticipated overvoltages (swells, see 6.5.3).

As described earlier for engine-driven generators, the generator will have an impedance that is approximately three times that of an HV distribution transformer of the same VA rating powered from a national mains supply network, so it is important to ensure that the fluctuating and/or non-linear loading on it does not result in worse power quality overall, than the original poor-quality electricity supply that it is supposed to be protecting against.

Multi-tapped transformer with triac switching

This technology was discussed in 6.5.3, and its block diagram was shown in Figure 6BD. It generally takes a few tens of milliseconds to correct a voltage change in the supply, and will not compensate for dips or voltage fluctuations that occur on shorter timescales. Having no energy storage it cannot compensate for dropouts and interruptions of any duration. It does not suppress the distortion of the waveform passing through it, but (as mentioned earlier) if its voltage sensing circuit is designed to respond to the peak of the mains waveform rather than its RMS or Average, it will operate so as to maintain the peak of its output voltage at a constant level, which is just what most rectifier-capacitor AC-DC converters require, and so for such loads it could be considered to be compensating for waveform distortion.

Servo-motor controlled variable transformers

This technology is very similar to the multi-tapped transformer with automatic tap-selection using triacs, discussed above, but instead of a multi-tapped winding it uses a continuously variable tapping via the sliding wiper of an autotransformer. Because the tapping point is infinitely variable, the output voltage can be ‘stabilised’ almost exactly at the desired voltage, but the mechanical movement required means that it can take a few seconds to correct for a voltage change, so it will not correct for short-term swells and undervoltages.

Figure 6BR shows the basic principles in block diagram form, and includes a photograph of a commercially available three-phase unit that shows that even very large powers can be controlled by just a small motor, driving the wiping contacts through a reduction gearbox.

As for the multi-tapped method, it has no energy storage so cannot compensate for dropouts and interruptions, and it has no effect on the distortion of the mains waveform, but if the voltage sensing works on the peak rather than on the RMS or Average value, it will maintain the peak voltage output at a constant level and thus compensate for waveform distortion as far as rectifier-capacitor AC-DC converters are concerned.

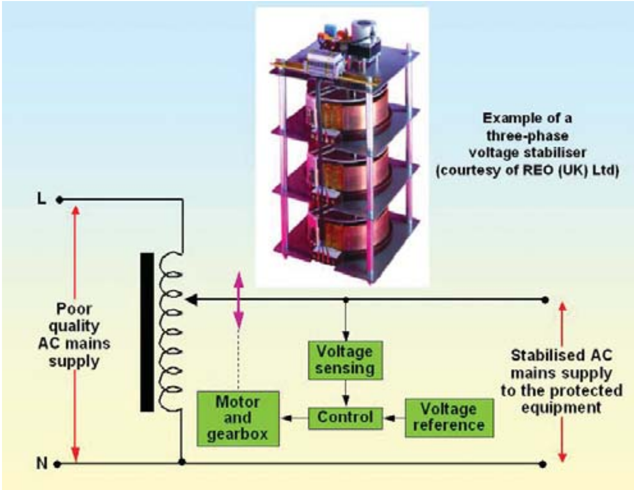

Figure 6BR Servo-motor controlled ‘voltage stabiliser’ principles

Uninterruptible power supplies (UPSs)

These are AC-AC (actually AC-DC then DC-AC) switch-mode power converters, often called ‘inverters’ with their output set to the required mains frequency. They can convert from one mains frequency to another, or can be used as DC-AC converters to generate an AC supply from a source of DC electrical power.

‘Continuous-on-line double-conversion’ types can cure all power quality problems, and are conceptually similar to a motor-generator set with flywheel storage. The poor quality power supply is used to charge their energy storage (e.g. battery, fuel cell, etc.), and their energy storage is used to supply power to the protected load circuit, as shown in Figure 6BS.

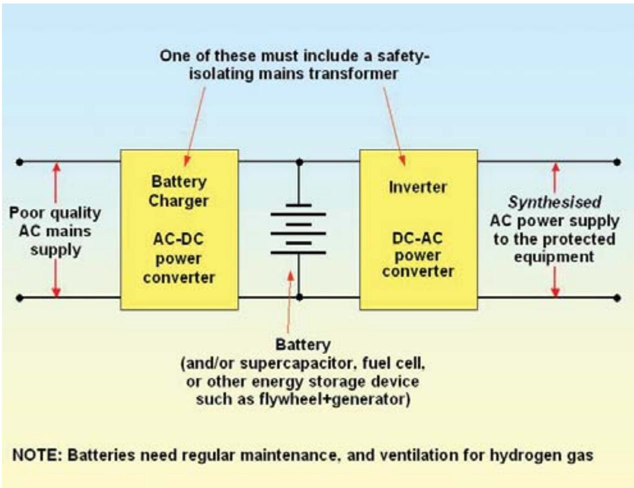

Figure 6BS Principles of continuous-on-line double-conversion UPS

Their mains-powered charging circuits must, of course, be able to withstand the expected voltage swells, sags, distortion, etc.

I have seen examples of UPSs specified by their manufacturers as providing at least 80dB of attenuation for all mains-borne disturbances from DC to 1GHz, from their input to their output. (Motor-generator sets can also be designed and manufactured to achieve such excellent EMC specifications.)

Many types of lower-cost UPSs are available, but can cause more power quality problems than they solve for their protected loads. For example, a common type powers the load from the mains supply, and only switches over to UPS mode when it detects that some aspect of the input supply's power quality (e.g. RMS voltage) has dropped below a preset threshold. These types do not protect against all power quality problems, and can cause dips/dropouts and transients when they switch-over, or when they switch the load back again to the normal mains power.

Reliability is another cost-related issue, and some models of UPS (even continuous double-conversion types) have been known to expose their loads to more supply interruptions (due to failure of the UPS) than the mains supply they were supposed to be protected from.

So take great care, when purchasing a UPS, to make sure that it really *will* provide the power quality improvements that that are required.

Dynamic voltage restorers (DVRs) (sometimes called dynamic sag restorers)
These use similar switch-mode power conversion technology to the 'active' filters described earlier, but instead of injecting currents in parallel with the mains supply, they inject voltages in series with it, usually with the aim of maintaining an adequate mains voltage during a dip, sag, dropout or short interruption. They need significant amounts of energy storage (supercapacitors, batteries, etc.) depending on the load power, and on the dip/sag depths and durations that are to be protected from.

Number 53 of [12] describes one successful application, called a 'voltage dip protector'.

6.5.12 Tripping-out techniques
Special protection devices, often called 'protection relays', are available to detect a wide variety of mains power quality problems and remove the power completely from the protected equipment by operating a circuit-breaker or triac.

'Protection Relays' can protect against under/over voltage, current or frequency; phase unbalance or failure; unbalanced load currents, and Figure 6BT shows some commercially available units.

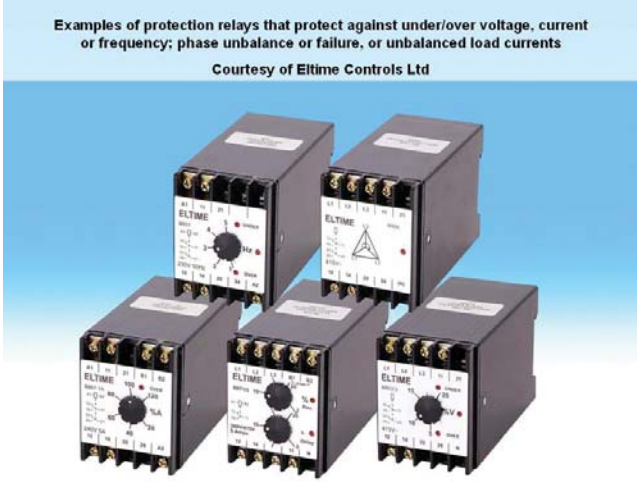

Figure 6BT Some examples of protection relays providing a variety of trip functions

Loss of power and/or trips can occur at unpredictable times, so it is important to ensure that they do not cause unacceptable damage, financial loss, or safety incidents depending on the application. For example, the industrial processing of webs of material (paper, plastic, tyre rubber, etc.) generally employs numerous motors that all need to keep rotating in step so as not to tear the web, which can require hours to repair at the cost of a great deal of lost production.

So, if the electrical power supply ceases either due to an interruption or trip, UPSs or other energy storage techniques are generally required to provide sufficient operating time for a controlled power-down of the motors that does not tear the web (although a length of it may be spoilt).

The electrical power supply will also be restored at unpredictable times, and it is important to consider all of the possible consequences. For example, it might be restored during the controlled power-down of an industrial process, in which case the process might be required to continue ramping down to a stop and await manual restart, or ramp back up again and continue production, but in either case the process must be controlled at all times.

Where a product is controlled by digital processing, it is important to ensure that all the register contents are set appropriately on restart. If a 'cold start' is required, they should all be reset to zero. If a 'warm start' (continuing as before the interruption) is required instead, they should all be loaded with the appropriate data.

Power amplifiers can misbehave during power down or power up, so to protect them and their transducer loads from damage their control circuits should protect them against all power down/up situations. Testing with the full range of dropouts and interruptions in EN/IEC 61000-4-11, or more, is recommended. How the product should be designed, to respond to power interruptions and/or restorations, depends on its application, especially if there are any possible safety implications.

6.6 Conclusion to the series

This series is now concluded, and I hope you have found it interesting and useful. It has spanned over a dozen issues and over more than two years, and it is all available from the EMC Journal's website at www.theemcjournal.com.

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Eur Ing Keith Armstrong CEng MIEE MIEEE
Partner, Cherry Clough Consultants,
www.cherryclough.com, Member EMCIA
Phone: +44 (0)1785 660 247, Fax: +44 (0)1785 660 247,
keith.armstrong@cherryclough.com;
www.cherryclough.com

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