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

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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. Part 6 – ESD, electromechanical devices, power factor correction, voltage fluctuations, immunity to power quality issues

6.1 Electrostatic Discharge (ESD)

This was published in Issue 74

6.2 Electromechanical devices and spark ignition

6.3 Power factor correction (emissions of mains harmonic currents)

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6.4 Emissions of voltage fluctuations and flicker

6.4.1 Causes of emissions of voltage fluctuations and flicker

This section addresses equipment powered by the 230/400V AC mains, for which there are standards (EN 61000-3-3 and EN 61000-3-11) listed under the EMC Directive that limit emissions of voltage fluctuations and flicker for equipment up to 75A. The same principles apply to limiting the emissions of voltage fluctuations and flicker into AC and DC electrical power supplies at any voltage (see 6.4.2).

As Figure 6AU shows, there is always impedance in an electrical power distribution network; so any fluctuating currents in a network will cause the supplied voltage to fluctuate accordingly. 'Flicker' is the term used for rapid fluctuations in a supply voltage.

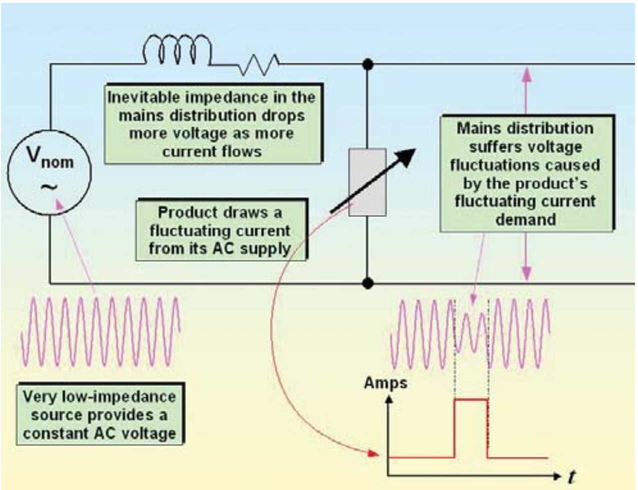

Figure 6AU How voltage fluctuations and flicker occur in the electrical supply

6.4.2 The standards and their limits

Historically, the main problem has been fluctuation in lighting levels, which can be very annoying to people and can even cause stress-related illnesses. Rapid fluctuations in lighting levels are known as flicker, and can quickly cause headaches, and even epileptic episodes in some people. The limits in the emissions standards are based on the human perception of the variations of luminous intensity from a mains-powered 60W filament light bulb – so they are not at all like the straight-line limits used by most other emissions tests.

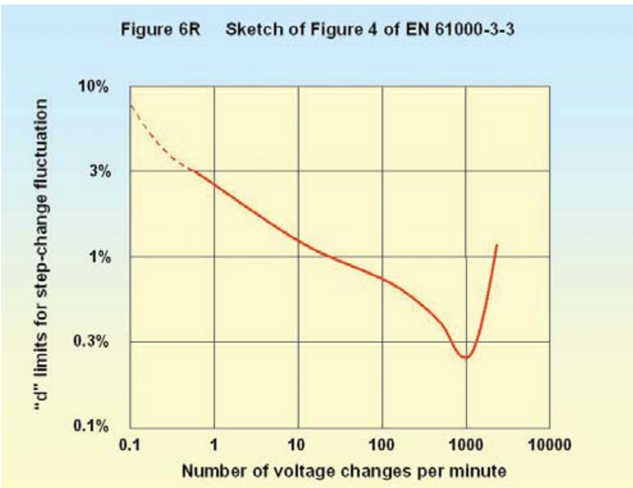

Figure 6AV An example of the emissions limits, from Figure 4 of EN 61000-3-3

Figure 6AV is an example for continuous 'square wave' load current variations; current fluctuations with different mark-space ratios will have different limits over the same range of frequencies. Irregular, transient and discontinuous current fluctuations will attract different limits still. Because of this complexity, all due to the psychometrics of human flicker perception combined with the time-constants of 60W filament bulbs, compliant measurements can only be made with a 'flickermeter' that uses digital processing techniques to determine pass or fail.

The standard for the processing involved in flickermeter measurements is IEC 61000-4-15. Low-cost test instruments are available for flicker measurements, for example the product shown in Figure 6AF combines the functions of measuring emissions of harmonics and voltage fluctuations and flicker. It is also possible to determine compliance in a rather rough and ready way by using calculations and/or simple test equipment. Those who are interested in DIY measurements of voltage fluctuations and flicker should read sections 7.5 and 7.6 in Part 7 of [6] – always taking the safety considerations in 6.2.1 fully into account.

Lighting flicker is mostly a problem for people reading or performing tasks illuminated by mains-powered filament lamps. Due to the 'smoothing' in AC-DC power converters, it hardly affects the illumination levels of mains-powered TV and computer screens.

In the modern world there are a great many things other than filament light bulbs that can be upset by voltage fluctuations and flicker on their mains electricity supplies. A particular problem is that dips in the mains voltage could cause a product's internal DC rails to drop below acceptable levels, causing errors, malfunctions or re-booting. Some discharge lamps will switch off due to dips, and not come back on again until they have cooled down sufficiently, which could take several minutes.

However, despite all this, and despite the fact that filament bulbs will soon not be legally available (for reasons connected with saving the planet from CO_2), the limits in the standards (EN 61000-3-3 and EN 61000-3-11) continue to be based on human perception of 60W filament bulb flicker.

Even where no legally mandatory or contractually-applied standards apply to products that connect to a DC or AC electrical power supply, there is still a good engineering practice requirement not to interfere with the operation of other devices, products, equipment, systems, etc., that share the same supply.

> Note: When talking to managers, always replace the phrase '*good engineering practice*' with '*practices that reduce warranty costs and financial risks*'. Of course in a properly managed company they mean the same thing, but the latter phrase expresses it in terms of the desirable financial outcome rather than the process by which it is achieved. Since it seems few managers care anymore about doing good engineering, but they all care passionately about saving money or making more of it, it is important for engineers to use language that will be understood.

6.4.3 Background to the suppression techniques

The standards measure the actual fluctuations in voltage in an electrical supply that has a specified impedance. In fact, what is really being measured (although indirectly) by their tests are the variations in the product's current demands from its electrical power supply – the variations in its load current.

So the design techniques for controlling emissions of voltage fluctuations and flicker centre on controlling the range and rate of variation in a product's supply current.

Note that some of the emissions standards permit greater fluctuations in a product's supply current, where the supply has lower impedance than usual. So sometimes it is possible to comply simply by specifying the characteristics of the electrical power supply that should be provided by the user. Of course, this must be reasonable – it would not be acceptable for the manufacturer of a coffee maker intended for domestic use, to specify that it must be connected to an industrial-strength 100A supply.

6.4.4 Reducing inrush current at switch-on

The inrush current at switch-on is a major cause of emissions of voltage fluctuations. The standards generally allow slightly higher values at switch-on (whether manual or automatic), and they generally do not apply any limits at all for the inrush currents during an uncontrolled power-up due to the resumption of mains power after an unanticipated interruption or failure of the mains supply.

Although the standards may not set limits for inrush following mains interruptions or failures, in practice it can be very important to limit them too. Consider the example of a branch of a mains distribution that is heavily loaded – an insulation failure somewhere on the branch will cause the overcurrent protection to trip, removing power to all the equipment.

But if the power is restored when all the loads on the network are switched on, their combined inrush currents can cause the overcurrent to trip again. It may be impossible to restart the mains power to that branch without going around and manually switching off many items of equipment, restoring the power and then going around switching them back on again one at a time. So unless automatic sequential mains switching is used (see later) on that branch, there could be significant benefits in limiting the inrush currents during uncommanded power-up events, even where not required by standards.

Most electronic equipment has a huge 'spike' of inrush current into their smoothing capacitors following their bridge rectifiers (see Figure 6AB), at the instant of switch-on. Even on power supplies rated at just a few watts, with normal current consumptions measured in tens of milliamps, the peak inrush current at switch-on can be tens of Amps, causing very high levels of voltage fluctuations at that instant.

However, flickermeters integrate voltage fluctuations over 10 millisecond periods, whilst charging the smoothing capacitors of low-power equipment might only takes a few tens of microseconds, so the very high but very brief voltage fluctuations caused by capacitor charging get averaged over 10ms and are generally measured as having much lower values.

Where the initial charging of capacitors would cause emissions to exceed the limits, Figure 6AW shows one technique for limiting the inrush current. At switch-on the relay contacts are open and the capacitors charge up more slowly, their peak charging currents limited by a suitable power and voltage-rated series resistor. After a short time (usually under two seconds) the capacitor should be substantially charged and the relay contacts (or triac) switched on to 'short out' the series resistor.

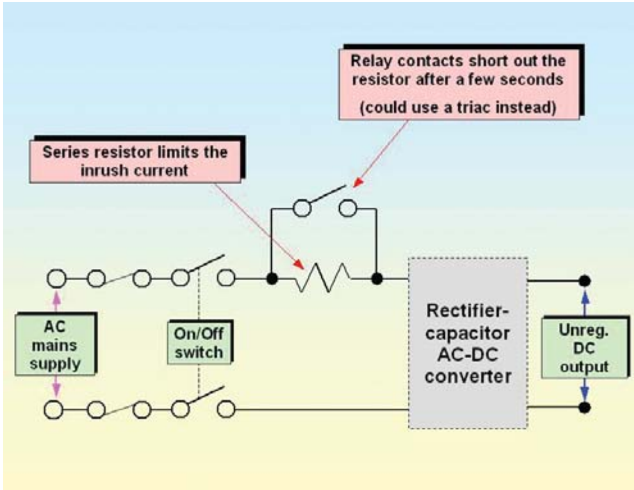

Figure 6AW An example of a technique for reducing the inrush current

In many real products, the electromechanical relay contacts shown in Figure 6AW are replaced by a triac. But triacs are not short-circuits, and in some applications their heating and/or emissions of noise around the zero-crossings might have to be dealt with.

For electronic loads it is usually very important to ensure that the load is not permitted to begin to operate until the unregulated voltage on the smoothing capacitor has ramped up to within specifications for correct operation of the load. In microprocessor circuits this is usually done with a combination of 'power-on reset' and 'voltage monitor' devices that hold all the devices in reset mode until they are both satisfied that the power supply conditions are acceptable. Many switch-mode controller ICs have soft-start functions, which also help reduce inrush currents at switch-on and so reduce emissions of voltage fluctuations.

Analogue circuits might need to actually monitor the DC power characteristics and switch DC power to the circuits using relay contacts, SCRs or power transistors. For example, power amplifiers that are connected to their voltage rails as they slowly ramp up to limit inrush currents, can often suffer instability and output false signals that might even damage their output transducers. In the case of audio systems, the false output signals can cause very loud and unpleasant noises.

Figure 6AX shows a similar scheme to Figure 6AW, but this time the relay contacts (or an SCR or power transistor) are installed after the bridge rectifier and before the capacitor, in the raw unregulated and unsmoothed DC supply. The operational principles are just the same.

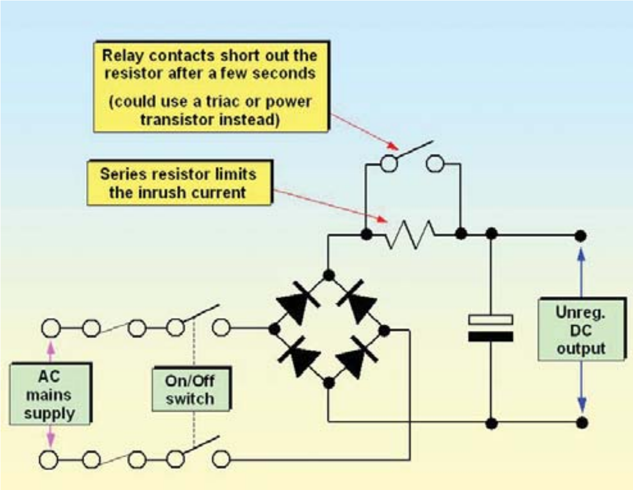

Figure 6AX Another example of a technique for reducing the inrush current

Figure 6AY shows the scheme of Figure 6AW with a negative temperature coefficient thermistor (or 'NTC') replacing the series resistor. NTCs are temperature-dependent resistors with a non-linear relationship between temperature and resistance. When they are at ambient temperature they have quite a high resistance, allowing the smoothing capacitors to charge up slowly and limiting inrush current. As charging current flows in their high resistance they heat up, and when they are hot enough their resistance very rapidly changes to a low resistance value. The NTC should be carefully chosen so that the flow of the normal load current through it is sufficient to keep it hot enough for it to remain 'switched on'.

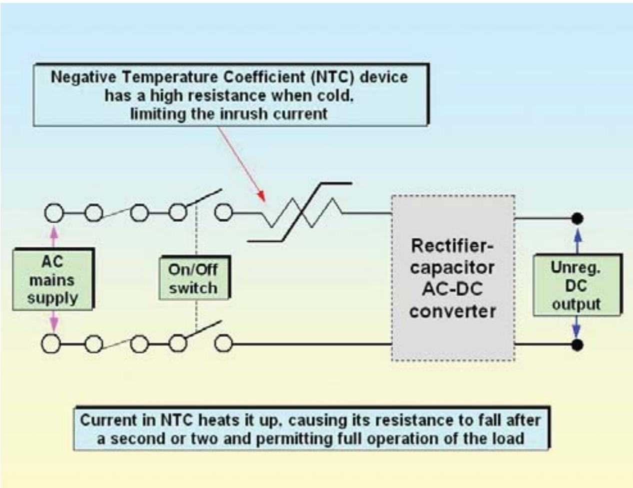

Figure 6AY Reducing inrush current with an NTC

NTCs run hot all the time when in normal operation – so it is necessary to design appropriate precautions to make sure they don't damage PCBs or nearby components, or melt a hole in a plastic enclosure. It is also important that they are protected from accidental contact so as not to burn service engineers who might have the covers removed.

It takes a number of seconds for an NTC to cool down by enough for its high-resistance state to be re-established, so if the power goes off and returns quickly they will not limit the inrush current.

Some designers have been known to take advantage of the use of inrush current limiting techniques to specify bridge rectifiers with lower surge current ratings to save space and reduce costs.

When inrush is limited by NTCs, they can be caught out because short interruptions in the mains power – or users who switch off and then on again – can defeat the NTC, permanently damaging the bridge rectifier due to the peak inrush currents being much higher than it can handle.

Similar problems can occur for the inrush limiting schemes shown in Figures 6AW and 6AX, unless they are appropriately designed so they cannot be defeated by brief interruptions in mains power.

Large AC motors, transformers and other inductive loads can draw larger than normal inrush currents for many cycles after switch-on – when switched on at some point in the mains cycle that is not close to the voltage peaks. Switching on at zero-crossing causes the largest inrush currents.

The issue is the establishment of the load's steady-state AC magnetising current, which if allowed to overshoot by too much could saturate the magnetic circuit. Magnetic saturation reduces the impedance of the load to that of the resistance of the winding, effectively short-circuiting the mains supply and causing huge inrush currents. Figure 6AZ shows some examples of inrush currents in inductive loads.

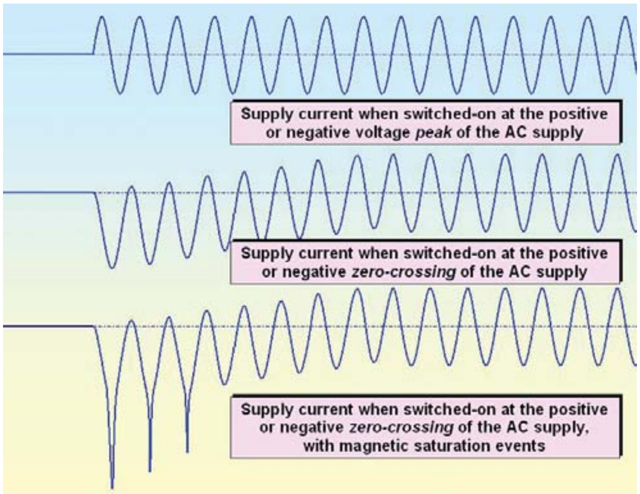

Figure 6AZ Examples of inrush currents into inductive loads

One obvious technique for reducing switch-on surge in inductive loads is to ensure that power is only applied at the instant when the AC supply is near a positive or negative voltage peak, and some manufacturers make triacs with the appropriate controls.

AC motors draw more current the greater their 'slip speed', so while they are spinning up their loads they can draw more current than is allowed by the emissions standards or is desirable for the power distribution network. Such motors and similar loads can use 'soft-start' techniques, which use phase-angle-controlled triacs with automatic ramping of their phase angle. Over several seconds, their conductive phase angle increases, increasing the average RMS voltage while the load slowly builds up to speed, until the full working voltage is reached.

It can also help meet emissions limits if the load current is reduced slowly instead of abruptly stopping at the instant of being switched off. Soft-start phase-angle controllers can easily be designed to also function as a 'soft-stop', slowly ramping the phase angle down to zero when the motor (or other load) is switched off.

There are many suppliers of soft-start/soft-stop SCR modules that can be added to industrial motors and other products, replacing their ordinary on/off switches. But few/none of them seem to be fitted with filters to attenuate the harmonics and RF emissions from the SCRs during ramping. The assumption seems to be that any interference will only be for a second or two once in a while, but whilst this might be permitted by emissions standards, it might not be acceptable in all applications for functional reasons.

Where products have their power or speed controlled by phase-angle SCRs, or similar methods using IGBTs, soft-start and soft-stop functions can easily be designing in. A very simple way to do this is to control the power with a rotary potentiometer that has the on/off switch mounted on the same shaft, so the potentiometer has to be turned down before it can be switched off, and when switched on it is always at low power.

Where several items of equipment are assembled in one unit, cabinet or system with a single master on/off power switch, their inrush currents will all occur simultaneously. The result can be emissions of voltage fluctuations that exceed the limits in the relevant standard, and/or practical problems of interference with other equipment. Sometimes, as mentioned earlier, the combined inrush currents will cause the overcurrent protection (fuse or circuit breaker) to open, although in such cases it is often possible to fit time-delay fuses or inrush-resistant circuit breakers.

One way to deal with the problem of simultaneous inrush currents is to power each item of equipment via a time-delay relay or contactor, a common industrial component, with the time delays all set to different values. Some manufacturers also offer mains distribution products (‘socket strips’) with built-in sequential switching, such as the units shown in Figure 6BA.

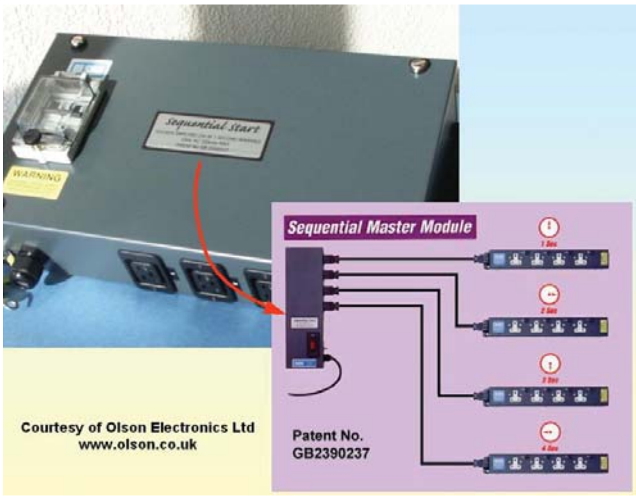

Figure 6BA Examples of sequentially-switched mains socket-strip

6.4.5 Reducing emissions of voltage fluctuations caused by varying AC loads

Time-proportioning on/off control is often used to provide power control of resistive loads such as heaters by varying the mark/space (on-time/off-time) ratio. It is sometimes called ‘bang-bang control’ because the load is switched on and off repetitively, and is a rather crude technique that is very unkind to the voltage that the distribution network supplies to other loads.

One way of reducing emissions of voltage fluctuations and flicker from bang-bang controlled loads is to split the load into two or more smaller loads, and switch them at different times, so there is a faster rate of smaller voltage fluctuations. Figure 5 of EN 61000-3-3 and its associated text gives some guidance on this technique. Another method is to use the soft-start/stop techniques described in 6.4.4.

It is very important to avoid using bang-bang control (or any other kind of power control) that results in voltage flicker in the range 100 to 2000 voltage changes per minute (1.7 - 33Hz) because this is where the human eye is most sensitive to lighting flicker from a mains-powered 60W filament bulb, so the flicker limits are much more severe, as can be seen in Figure 6AV.

However, the very best suppression of emissions of voltage fluctuations is achieved by replacing bang-bang control with some type of continuous power control, such as variable transformers or phase-angle-controlled triacs (or similar IGBT circuits). Variable transformers are a traditional remedy for controlling the AC power delivered to heating and similar loads, and although they are large, heavy and expensive they are also reliable, rugged, have no emissions, have very high levels of immunity, and when fitted with motors can be electronically controlled by analogue signals, or data from a computer.

All electronic circuits have other EMC problems, such as emissions of harmonics (see 6.3) and RF conducted and radiated noises, and also have EMC immunity issues. But – providing their maximum rate of change of power is set low enough – they will not cause significant emissions of voltage fluctuations or flicker.

6.4.6 Reducing emissions of voltage fluctuations caused by varying electronic loads

In a rectifier-capacitor AC-DC converter, increasing the size of the smoothing capacitor (unregulated storage capacitor) will reduce the ripple voltage caused by load fluctuations on the DC rails, and hence reduce emissions of voltage fluctuations and flicker. ‘Supercapacitors’ are now available with values measured in Farads, and peak current ratings measured in kA, which can provide huge energy storage and ‘smooth out’ the load’s current demands very considerably.

Unfortunately, as discussed in 6.3, increasing the size of the smoothing capacitor increases the emissions of harmonics currents into the AC supply, making it more likely that ‘power factor correction’ will be required.

Adding series inductors to reduce harmonic emissions, as shown in Figure 6AK, will help ‘round off’ the edges of any very sudden fluctuations in load current, but the effect will probably be too small to have a significant effect on flickermeter measurements because they are integrated over 10ms periods.

Sometimes it is possible to design electronic loads so that their fluctuating current demands are not as severe, for example using Class A or AB analogue power amplifiers instead of Class B.

An excellent method of reducing emissions of voltage fluctuations and flicker due to variations in electronic loading, is to use an ‘active PFC’ boost circuit, such as described in 6.3.6 and Figure 6AN.

Active PFC controllers have a typical response time-constant to variations in load current of about 500 milliseconds, so for periods of time shorter than this they act like constant-current sources. Ripple voltages on the smoothing capacitor, due to variations in the current drawn by the electronic load, do not feed directly into mains current – they are smoothed out by the active PFC's time constant.

This helps reduce emissions of voltage fluctuations and flicker, but it is important to realise that the same slow response will cause ripple voltages on the unregulated DC rail to increase, and it may be necessary to either increase the value of the smoothing (storage) capacitor (C1 in Figure 6AN), or else design the electronic load to cope with the increased ripple.

The slow response time of the active PFC controllers can have another downside that needs to be guarded against. If the electronic load on the unregulated DC rail suddenly reduces by a large amount, for longer than 1 second, the active PFC will keep supplying the same current for at least 500ms and only then start to reduce it – so the voltage on the smoothing capacitor could rise so much that it would be damaged by overvoltage.

To prevent this from happening, active PFC controllers sense their output voltage and abruptly switch off their current before the capacitor's voltage rating is exceeded. Obviously, suddenly switching off the mains current causes a significant emission of voltage fluctuations and flicker – so with some types of loads and values of smoothing capacitance, active PFC circuits can *increase* emissions of mains voltage fluctuations and flicker. The solution is to design the circuits and dimension the components (especially the value and voltage of the smoothing capacitor) to make sure this protection mechanism doesn't happen, at least during normal operation with the worst-case load variations.

Active PFC boost circuits can be designed to provide many benefits…

- Comply with harmonic emissions standards (see 6.3.6)
- Achieve 'universal' operation from 84 to 260V AC rms, and DC to 400Hz, helping to sell the same product world-wide (only need ship it with appropriate mains lead)
- Reduce emissions of voltage fluctuations and flicker by acting as a constant current source
- Improve immunity to voltage variations, fluctuations and dips in the electricity supply (see 6.5)

6.5 Immunity to Power Quality issues

6.5.1 Introduction to power quality

Electrical power supplies, whether AC mains or DC (e.g. 48V for telephone exchange ('central office') equipment, blade servers, etc.), suffer from many types of high-frequency EM disturbances:

- Surges, spikes and other transients
- Bursts of transients
- Electrostatic discharge
- Common-mode (CM) and differential-mode (DM) RF voltages and currents

– all of which occur in all conductors (cables, wires, chassis, enclosures, PCB traces, etc.) and are dealt with by the earlier parts of this series [13] – [17].

This section covers 'non-RF' electrical power quality issues, at frequencies from DC to about 150kHz. It will generally refer to AC mains supply issues, but DC supplies suffer from many of the same power quality phenomena, so it is relevant for them too.

[33] is a guide to Power Quality issues from the point of view of systems and installations engineers. This article is aimed at product designers, but the descriptions of the various power quality phenomena in [33] will be just as useful for them too.

The quality of the delivered mains power can be measured in a variety of ways, but proper tests use instruments that comply with IEC 61000-4-30. The use of standardised and repeatable measurements can be an important issue when dealing with customer specifications or complaints – if both parties are measuring power quality in a different way there is endless scope for misunderstanding, wasted resources, and loss of customer goodwill.

In general, poor mains power quality generally causes more problems for electronic products when the real-life RMS mains voltage differs from the nominal supply voltage the product is expecting. So it is best to ensure that a product's mains input is set for the correct nominal voltage for the real-life mains supply. For example, products designed to run on 220V rms mains supplies have been known to overheat when run on 240V supplies in the UK. The official pretence that all of Europe has a common mains power rail at a nominal 230V rms does not help overcome this sort of problem.

The IET will sell you a wallchart listing the mains supply voltages (and many other details) for most of the countries in the world, and I have one of these. Unfortunately, it is pretty much useless because it only states the *official* specifications for nominal voltage and frequency and their tolerances, and they often differ from the real ones.

It is still quite easy to find rural areas of developed countries like the USA, Australia and Spain (to name just a few) where the normal range of mains voltages is much wider than the usual ±6% or ±10% specifications. In parts of rural Spain, during the late 1990s, the nominally 230V mains supply would fall to as low as 180Vrms during the afternoon. Parts of Australia are still supplied by single-wire mains, with the neutral current being returned through the soil, giving very poor power quality indeed.

The situation is often worse, or at least worse over wider areas, in less developed countries. For example, in 2005 in Nigeria the effective RMS value of the mains commonly varied from 140 to 300V. In India many people have their own standby electricity generators, so that when power fails they can keep operating. But when the mains power returns there is very little load on the distribution network and the nominal 230V mains voltage supply can rise to well over 300V for several seconds.

Small distribution networks with limited generation capability are very prone to significant power quality problems. An extreme example occurred on a North Sea oil exploration platform in the 1970s where the 230V mains supply from its 10MW diesel generator had frequency variations of about ±90%, lasting for several seconds. When the 10MW drilling motor was switched on, the diesel generator almost stalled and the mains voltage dropped to about 50V at about 5Hz. When the drill motor was switched off, the diesel generator would overspeed, and the mains voltage would rise to about 430V with a frequency of about 95Hz. This would happen several times each day.

A big problem for offshore and marine vessels these days is the use of electric thrusters, which are variable-speed AC motor drives often rated at 100kW or more, which cause their mains supplies to suffer severe distortion, often as much as 30%. For many more details on power quality phenomena see [31] and [33].

6.5.2 Important Safety Considerations for Mains Circuits
All components and wiring used in mains circuits must be rated for safe use on the highest anticipated mains voltage, including overvoltages and surges.

There are appropriate safety standards that should have been applied by component and cable manufacturers, who should make third-party Safety Approvals certificates available to their customers. Customers should check that the certificates are valid, by contacting the issuing authorities, and not use components that have anything suspicious about any details.

Stringent measures should be taken to avoid using counterfeit components, like the counterfeit circuit breaker shown in Figure 6BB alongside a genuine one, a photograph used to help promote the new "Electrical Industry Installation Charter" scheme launched by BEAMA, EDA, ECA and SELECT. People have died and premises burnt down because these safety precautions were not taken – make sure it is not your product that is the cause.

Figure 6BB Comparing a counterfeit circuit-breaker with the one it was imitating

6.5.3 Overvoltages (swells)
Swells are when the supply voltage is higher than normal limits, for a while (e.g. a few seconds), and are generally assumed to have very slow rise and fall times, such as a few seconds. They can exceed the normal tolerance of the mains supply voltage and cause overvoltage or overheating damage, and/or can cause surge protection devices (SPDs) to overheat and be damaged.

A relevant immunity test standard is EN/IEC 61000-4-11, and a guide on its application is included in [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 'swell' phenomena, including what causes them, what they can affect and how.

To protect products from swells, it is best to simply design (or choose) AC-DC power converters that have mains input circuits that use higher-voltage devices and circuits, so that they operate within their rated limits during anticipated swells, without damage for as long as the swells last. Their bridge-rectifiers and off-line switching power FETs might need to be rated up to 1200V or more, and their unregulated storage capacitors up to 600Vdc or more.

Before the days of switch-mode power converters, a range of electronic products were sold worldwide and proved to be very reliable despite the very wide range of voltages and waveforms that they were powered from. They used linear power supplies in which the mains transformers had multiple tappings with automatic tap selection, as shown in Figure 6BC. It is still a viable technique these days, especially for larger products, systems or installations.

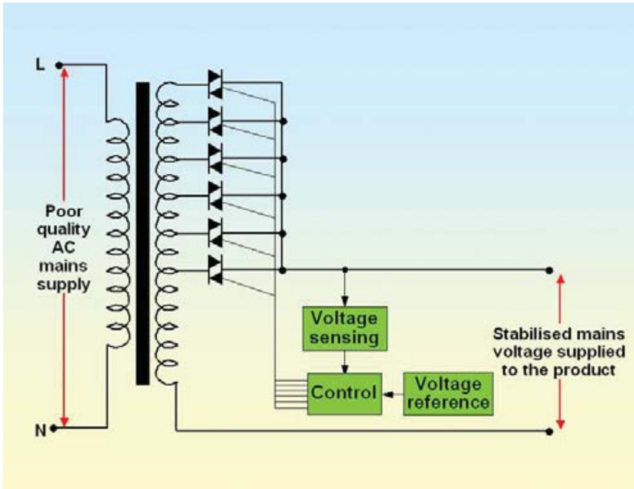

Figure 6BC Multi-tapped mains transformer with automatic tap selection

The primary winding of the transformer in Figure 6BD has to cope with all of the power quality problems discussed in this section, so will need insulation suitable for the swells and distortions; enough turns to ensure that swells, low frequencies, and any DC components do not saturate the core, causing excessive magnetising currents and overheating; and a core size large enough to prevent overheating due to harmonic distortion of the mains waveform.

Where it is not feasible to design (or choose) mains power converters with a swell capability that will cope with the worst-cases that can occur in some countries and/or situations, the mains input circuit should be protected from damage during such events.

<u>How</u> it is protected depends upon the application – whether the product must keep functioning; whether it is acceptable for it to stop during the swell but restart automatically later on, or whether it is acceptable for a fuse or circuit-breaker to open, requiring manual intervention to restore correct operation.

All of these options could use an overvoltage protection device

(OVPD) such as a metal oxide varistor (MOV) or gas discharge tube (GDT), described in section 3.5 of [15], to protect the product's mains input devices from damage. A series element is employed between the mains supply and the OVPD, as shown in Figure 6BD, to limit the power dissipated in the OVPD. Alternatives to using OVPD devices such as MOVs or GDTs are shown in figures 3AG and 3AJ of [15], and might be useful.

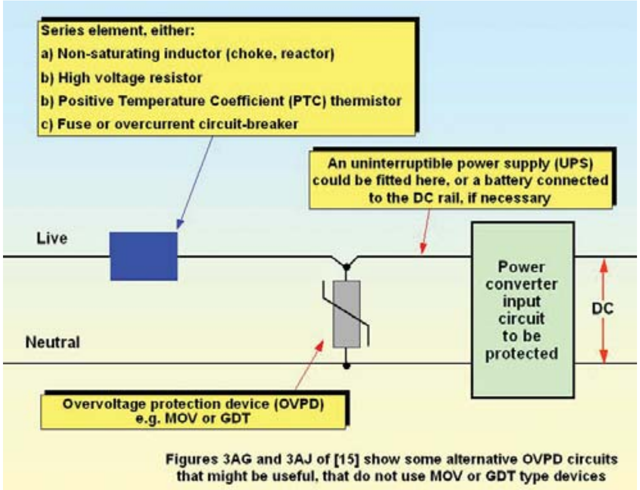

Figure 6BD An example of 'swell' protection

There are several choices of component, each with different design compromises:

- An inductor (choke) that does not saturate
- A resistor
- A PTC (positive temperature coefficient) thermistor
- A fuse or circuit-breaker

The inductor and resistor, when used with an MOV type of OVPD, ensure that the mains supply peaks are clamped (clipped) below the maximum level that the power converter input circuit will withstand, so the product keeps on functioning during the swell.

Inductors provide an impedance that limits the current, and those used for this purpose in industrial applications are often called 'reactors'. Resistors must be high voltage surge/pulse rated types, and may need to be 'fusible' types that open-circuit safely if overloaded beyond their ratings.

Power dissipation in the series elements and OVPDs are serious concerns, and have safety implications. Inadequate ratings will result in short product life, dissatisfied customers and increased warranty costs – even if they do not result in smoke and fire hazards. Section 3.5 of [15] discusses surge protection, and even quite small SPDs can handle very large pulses of transient power lasting a few microseconds. However, here we are talking about overvoltages that can last for several seconds, probably comparable with the thermal time-constant of the device itself, so the OVPDs must be rated for continuous power dissipation at the levels expected during the swells.

Where capacitive energy storage is used instead of OVPDs (see Figures 3AG and 3AJ of [15]) the capacitor value must be large enough for it not to suffer overvoltage damage due to absorbing the energy of the swell. Supercapacitors with values measured in Farads, might be suitable, but batteries are generally unsuitable because they cannot handle the very large charging currents.

A big advantage of using capacitive energy storage instead of OVPDs, is that there is less thermal cycling and so it can be easier to design for a longer, more reliable lifetime (taking account of the propensity of electrolytic capacitors to dry out and lose capacitance over time, especially if they are operated at high ambient temperatures).

Safety Note: Protection must be provided for if/when the OVPD fails low-resistance, so there should always be a co-ordinated overcurrent protection using a fuse, OPTC thermistor or circuit-breaker as well as the inductor or resistor. This safety feature is not shown on Figure 6BD.

The PTC thermistor, fuse or circuit-breaker, used with MOV or GDT types of OVPDs, will remove the power from the equipment during a swell that would otherwise exceed the ratings of the power converter.

PTC thermistors are often called 'resettable fuses' – their resistance increases suddenly when they heat up beyond a certain temperature, removing the mains power from the OVPD and from the power converter. When they cool down, below the critical temperature their resistance suddenly falls so they allow the full mains current to flow once more.

When PTC thermistors, fuses or circuit breakers are used and the product does not have a UPS or battery with sufficient energy storage, it must be acceptable (e.g. safe) for the product to stop in an uncontrolled manner. For some applications it will be acceptable for the product to start up again immediately upon the replacement of the fuse or resetting of the circuit breaker, whereas some others will require that a manual restart is also employed (see 6.5.12).

6.5.4 Frequency variations

A relevant immunity test standard is EN/IEC 61000-4-28, and a guide to its application is included in [7]. This guide also describes the 'frequency variations' phenomenon, including what causes it and what it affects and how. Obviously, DC supplies do not suffer from variations in frequency.

Mains frequency variations can cause problems for circuits that rely upon the mains frequency for timing, and large frequency drops can cause problems for mains transformers, direct-on-line (DOL) AC motors, relays, solenoids and contactors. The problems caused include magnetic saturation, excessive mains currents and overheating. Saturation also has the effect of reducing the transformer ratio, causing electronic loads to run on a lower DC voltage than would be expected from the RMS value of the mains voltage, possibly malfunctioning as a result (also see 6.5.8). Some of these problems have occurred when equipment designed for 60Hz mains (e.g. USA) was operated on 50Hz (e.g. Europe).

Design solutions for timing accuracy include using stable reference oscillators, such as the 32kHz oscillators that are standard for digital wristwatches. For the highest precision, products can use off-air atomic clock time signals, from GPS (satellite), MSF (terrestrial, Rugby, UK) or DCF (terrestrial, Frankfurt, Germany) for example. I have an inexpensive wristwatch that corrects its own time using off-air terrestrial broadcasts, so these solutions are clearly low-cost and small.

For inductive components such as transformers or AC motors, it is best not to design them to run close to saturation on their nominal supply. Use larger cores and/or more turns on their windings to reduce the core flux density so that they still operate out of saturation, and their magnetising currents are not excessive, during anticipated frequency variations.

For relays, contactors and solenoids with AC coils: choose types that have lower 'drop-out' or 'hold-in' voltages. Typical low-cost relays can drop-out at 78% of nominal supply, whilst better types will remain held-in down to 50% or less. 'Coil hold-in' devices (e.g. 'KnowTrip', 'Coil-Lock', etc.) can also be used, some of which claim to keep coils energised when the supply is as low as 25% of nominal. They appear to power each coil individually from a small AC-AC converter with capacitor energy storage, essentially a small UPS (see 6.5.11).

If we are prepared to make greater changes, we notice that the typical rectifier-capacitor AC-DC rectifier used as the front-end of switch-mode power converters is insensitive to mains frequency (as long as the storage capacitor is large enough) – so we can replace all off-line mains transformers with switch-mode power converters, AC-AC or AC-DC as appropriate. We can also power all AC motors and AC coils from switch-mode AC-AC inverters, such as UPSs (see 6.5.11) instead of direct-on-line (DOL), or replace them all with DC motors and DC coils powered from rectified mains.

All solutions that involve 'adding electronics' can increase the harmonic emissions into the mains so might need power factor correction (see 6.3 in [36]), and they can increase other emissions and suffer immunity problems that the originals did not suffer from.

6.5.5 3-phase unbalance

A relevant immunity test standard is EN/IEC 61000-4-27, and a guide to its application is included in [7]. This guide includes descriptions of the '3-phase unbalance' phenomena, including what causes it and what it affects. 3-phase unbalance can be due to voltage and/or phase differences between the three mains phases, and unbalanced loading or faults in the mains distribution network cause them. Obviously, DC supplies do not suffer from such problems.

Unbalance causes big problems for larger three-phase motors, which can destroy themselves quickly (and expensively) when they lose a phase even momentarily due to a fault in the mains distribution network. Industrial control manufacturers guard against this by using special 'motor control contactors' (MCCs) (see 6.5.12) that detect excessive phase unbalance (and other potential problems, such as undervoltages, see 6.5.8) and remove power from the motors to protect them.

As for frequency variations above, it is also possible to overcome phase unbalance problems by powering three-phase AC motors from switch-mode inverter drives (instead of DOL), or replace them with DC motors powered from rectified mains.

6.5.6 DC in AC supplies

This is not often a problem for modern LV supplies, because the adoption of harmonic emissions standards that prohibit half-wave rectification (in most cases) have reduced the amount of even-order harmonics (hence DC) in the mains networks. But some process plants use high-powered half-wave rectifiers, maybe rated up to 0.5 MW or more, which distort the local distribution by adding a DC component (actually, even-order harmonic distortion, see 6.5.10) to it.

This problem has exactly the same deleterious effects as the low frequency mains discussed in 6.5.4, and the solutions are the same too.

6.5.7 Common-mode (CM) low-frequency voltages

A relevant immunity test standard is EN/IEC 61000-4-16, and a guide to its application is included in [7]. This guide includes descriptions of the phenomena, including what causes it and what it affects, in very much greater detail than this article does.

Currents flow out of equipment and their interconnecting conductors and into their safety earth/ground via a number of routes, including capacitive and inductive stray coupling, and also due to any 'Y' capacitors in their mains filters that are connected between phase or neutral and earth.

Equipment operation produces currents from DC to several tens of kHz, depending on the equipment, but the dominant frequencies are usually at the mains frequency (50 or 60Hz) and its harmonics. Insulation breakdown and similar earth-faults in equipment and mains distribution cabling also inject mains (and its harmonics) currents into the earth (ground). Surge protection devices (SPDs) connected to earth (see [15]) also inject currents into earth during their operation, and in the case of 'crowbar' devices, such as gas discharge tubes, they continue to inject a 'follow-on' current for some time after the surge is over, at least for the remaining part of the mains cycle before the next zero-crossing.

Because of the impedance in the earth (ground), all these currents create voltage differences between the earths (grounds) of items of equipment that are connected to different points in the earth structure of a site. These voltages appear as CM 'earth/ground noise' voltages on their interconnecting conductors (mains, signals, data, control, etc.), with continuous voltages generally in the mV-Volts range.

Earth-faults and SPD operation (and its follow-on) in the LV mains distribution can create up to the full mains voltage, for up to a few seconds, and similar events in the MV or HV distribution networks can create kV of earth/ground noise, for up to a few seconds. The designers of the MV and HV networks are keenly aware that most equipment intended to be powered from the LV mains supply will not survive CM voltages of much more than a couple of kV – and that their failure would result in severe safety problems such as fire and electrocution – so they design their networks to provide the necessary protection. However, I do not know how reasonable it is to assume that such protection is provided in every country in the world, or in every offshore or marine installation.

Off-line mains power converters, whether linear or switch-mode, are protected against CM low-frequency voltages by complying fully with the relevant electrical safety standard, for example EN/IEC 60950 (information technology, IT, and telecommunications), EN/IEC 60335-1 (household appliances and portable tools), EN/IEC 60601-1 (medical equipment), EN/IEC 61010-1 (equipment for measurement, control and laboratory use), etc.

All of these have very similar requirements for dealing with the problem of short-term kilovolt CM disturbances, either:

a) Use a safety-earthed metal chassis with mains wiring and components insulated to safely withstand CM voltages of around 1500Vrms continuously, or…
b) Use double or reinforced insulation and a safety-isolating mains transformer all rated to safely withstand CM voltages on the mains of around 3kV continuously.
c) Use overvoltage protection similar to that described in 6.5.3.

The actual values of voltages vary from one standard to another, but it is important to realise that they are all based on certain assumptions, and one of them is that the equipment is used in a building in a city or other built-up area.

I had recently to deal with some agricultural electronic equipment that was situated in fields far from any building, and subject to whatever the local farmers thought was good electrical installation practices. The very visible damage to the mains input stages indicated that the mains power converters (purchased from a Chinese manufacturer whose data sheet claimed that safety compliance to domestic safety standards was 'pending' (but hey, they were cheap!)) were being subjected to much higher mains voltages than they could safely handle.

Even when the CM voltages on the mains input are dealt with safely, the CM noise can pass through the interwinding capacitance in the mains transformer, putting noise on the DC rails and possibly interfering with signals. This is not so much a problem for 50 or 60Hz, as it is a problem for higher-order harmonics or non-mains-related CM frequencies, and it can be dealt with by using a mains isolating transformer with increased CM attenuation. This can be achieved by adding an earthed interwinding shield, and/or by reducing primary-secondary capacitance by winding them on different limbs of the core.

Another technique is to use CM filtering on the mains supply, at the troublesome noise frequencies, but such filters can be large and costly due to the high mains currents and voltages.

Signal inputs and outputs can be designed to protect against CM low-frequency voltages, and for example, in professional audio it has been normal for many decades to use galvanic isolation transformers for inputs and/or outputs, often replaced these days by electronically balanced-and-floating input and output amplifiers. Electronic technologies that started out being used on the small scale, such as video, often suffer from CM earth/ground noise when connected to longer cables to form larger systems. The electronic designers never designed the input or output amplifiers to be able to cope with such disturbances, because they were not significant for small-scale systems.

Another approach is to use CM filtering to remove the troublesome earth/ground noises, for example in video systems it not unusual to use large and heavy CM hum chokes, usually purchased as 'ground loop eliminators'. (The general assumption is that it is the earth/ground current flowing in the shield of the signal cable that cause the problem, hence the term 'ground loop' or 'hum loop' – but in fact it is easy to show with simple tests that it is almost always the CM voltage difference between the chassis of the two items of equipment that causes the noise, not the equalising current that flows in the shields of the signal, data or control cables. See [34] and [35] for more on this topic.)

But the above approaches will not cope with the high voltages that can occur from time-to-time, due to earth/ground-faults for example. The galvanically-isolating transformers used in professional audio in previous decades were not usually rated to safely withstand at least 1500Vrms continuously, although they could have been, and of course electronically balanced-and-floating amplifiers cannot withstand such voltages.

Ethernet transformers were traditionally rated to withstand 500Vrms, but to comply with EN/IEC 60950 for 'safety-earthed' equipment they should withstand 1500Vrms, and several manufacturers now offer such components.

Galvanic isolation rated at least at 1500Vrms continuously for use with 'safety-earthed chassis' equipment, or rated 3kVrms continuously for use with 'double insulated' equipment, is (in my view) the best way to protect against high levels of CM earth/ground voltage differences. (As was mentioned earlier, in some applications higher voltages than these may be necessary.)

Appropriately-rated signal or pulse transformers have already been mentioned as a possible solution, but there are many others including opto-isolators/couplers, fibre-optics, wireless (e.g. Wi-Fi, Bluetooth, ZigBee, etc.), infra-red, guided microwaves, free-space laser, etc. Fibre-optics are preferred for high-bandwidth signals/data, for reasons discussed in [14] although some of the newer wireless communication methods (e.g. 60GHz radio systems, UWB) might one day be able to handle several hundreds of MB/s using low-cost modules.

As an alternative to galvanic isolation, electronically-balanced amplifiers can be protected from overvoltages lasting a few seconds – providing loss of signal for that period is acceptable – by overvoltage protection similar to that described in 6.5.3. The typical method of protecting semiconductors connected to telephone cables that extend outside of a building uses high-voltage fusible resistors or PTC thermistors as the series elements, and SCR-based OVPDs. Many similar protection circuits exist to suit most common types of signal/data input and output circuits, and manufacturers such as Harris, Raychem (from Tyco), Texas Instruments, STMicroelectronics (used to be SGS-Thomson) and Bourns make a wide variety of special protection devices for use in them, often with special names. Chokes and fuses are also possibilities as series elements, but not commonly used.

The capacitive energy storage technique shown in Figure 3AG of [15] may also be suitable, and should be easy to design to be more reliable (although physically larger) than using OVPDs as shown in Figure 6BD.

Another alternative is shown in Figure 6R in section 6.2 of [36] – using reverse-biased transient-rated diodes or rectifiers to dump the excess energy into the 0V and/or power rails. Design issues that are not important for ESD, but *are* important for effectively handling high levels of CM earth/ground noise

– are that the series impedance must be high enough to limit the current to what the PCB traces will handle, and there must be enough decoupling capacitance to prevent the DC power rail voltage from rising so high that the semiconductors relying on it for power suffer overvoltage damage.

6.5.8 to 6.6 will appear in the next issue.

6.7 References

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