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EMC design of Switching Power Converters Parts 8 and 9 Suppressing emissions of voltage fluctuations

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EMC design of Switching Power Converters

Parts 8 and 9 —
Suppressing emissions of voltage fluctuations and flicker
plus: some miscellaneous issues

The last in this series of articles on the EMC design of all types of switching power converters, from mW to MW

First published in The EMC Journal, Issue 105, March 2013

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Contents

Issues 93-104 of The EMC Journal carried the preceding twelve parts of this "Stand Alone" series – my attempt to cover the entire field including DC/DC and AC/DC converters, DC/AC and AC/AC inverters, from milliwatts (mW) to tens of Megawatts (MW), covering the control of electromagnetic emissions from *all* power converter applications, including: consumer, household, commercial, computer, telecommunication, radiocommunication, aerospace, automotive, marine, medical, military, industrial, power generation and distribution, in products, systems or installations.

Hybrid & electric automobiles, electric propulsion/traction; "green power" (e.g. LED lighting); and power converters for solar (PV), wind, deep-ocean thermal, tidal, etc., are also covered.

Issues 93-95 used a different Figure numbering scheme from the rest, for which I apologise.

This is the final article in this 'stand-alone' series. Previous articles, and much else, is available from the archives at www.theemcjournal.com.

8 Suppressing emissions of voltage fluctuations and flicker

8.1 Causes of emissions of voltage fluctuations and flicker

There is always impedance in an AC or DC power distribution network, so fluctuating mains load currents cause fluctuating mains voltages. Figure 8.1-1 sketches this effect for an AC mains supply, but the effect of supply impedance is just the same (of course) for DC supplies.

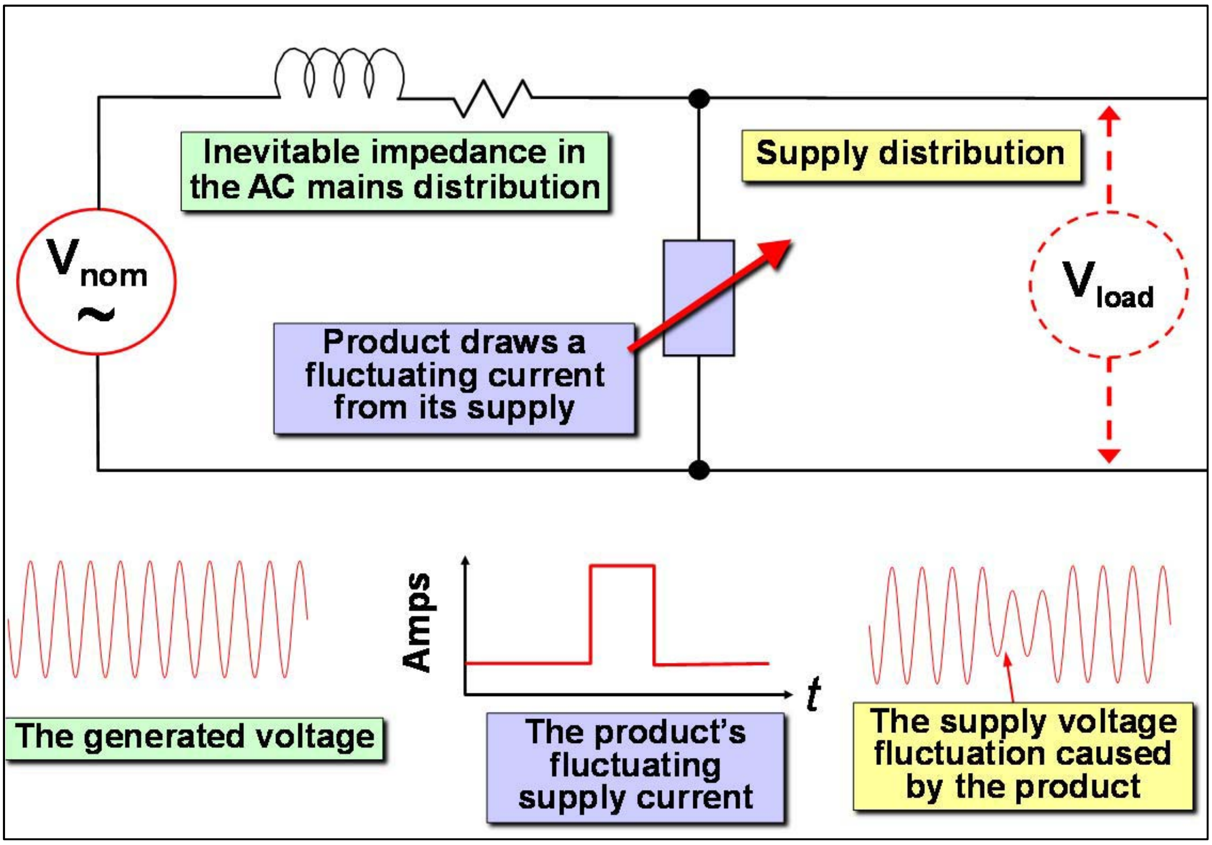

Figure 8.1-1 How supply voltage fluctuations occur

'Flicker' is the term used for rapid fluctuations in the mains voltage, which makes traditional filament lighting suffer from visible "flicker". Fluorescent and LED lighting can also cause visible flicker when its supply voltage fluctuates, but their interactions are more complex than those of filament lights.

Emissions standards for voltage fluctuations and flicker 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.

Some 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!

8.2 Suppressing inrush currents

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 network that is heavily loaded – an insulation failure somewhere on the branch could 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, 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 8.2-1 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-rated 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.

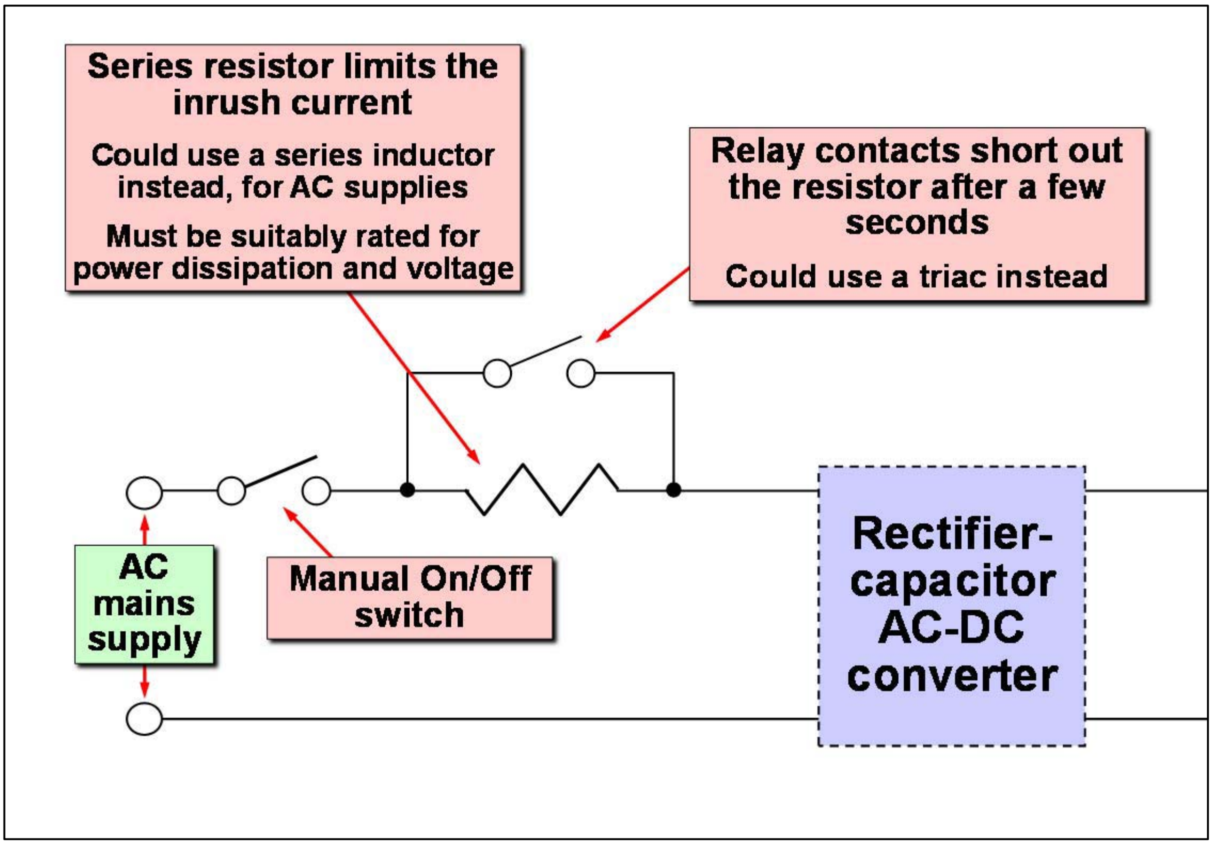

Figure 8.2-1 An example of a technique for reducing the inrush current

In many real products, the electromechanical relay contacts shown in Figure 8.2-1 are replaced by a triac. But triacs are not true short-circuits, and in some applications their heating and/or emissions of noise around the zero-crossings might have to be suppressed.

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 8.2-2 shows a similar scheme to Figure 8.2-1, but this time the relay contacts (or a thyristor 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.

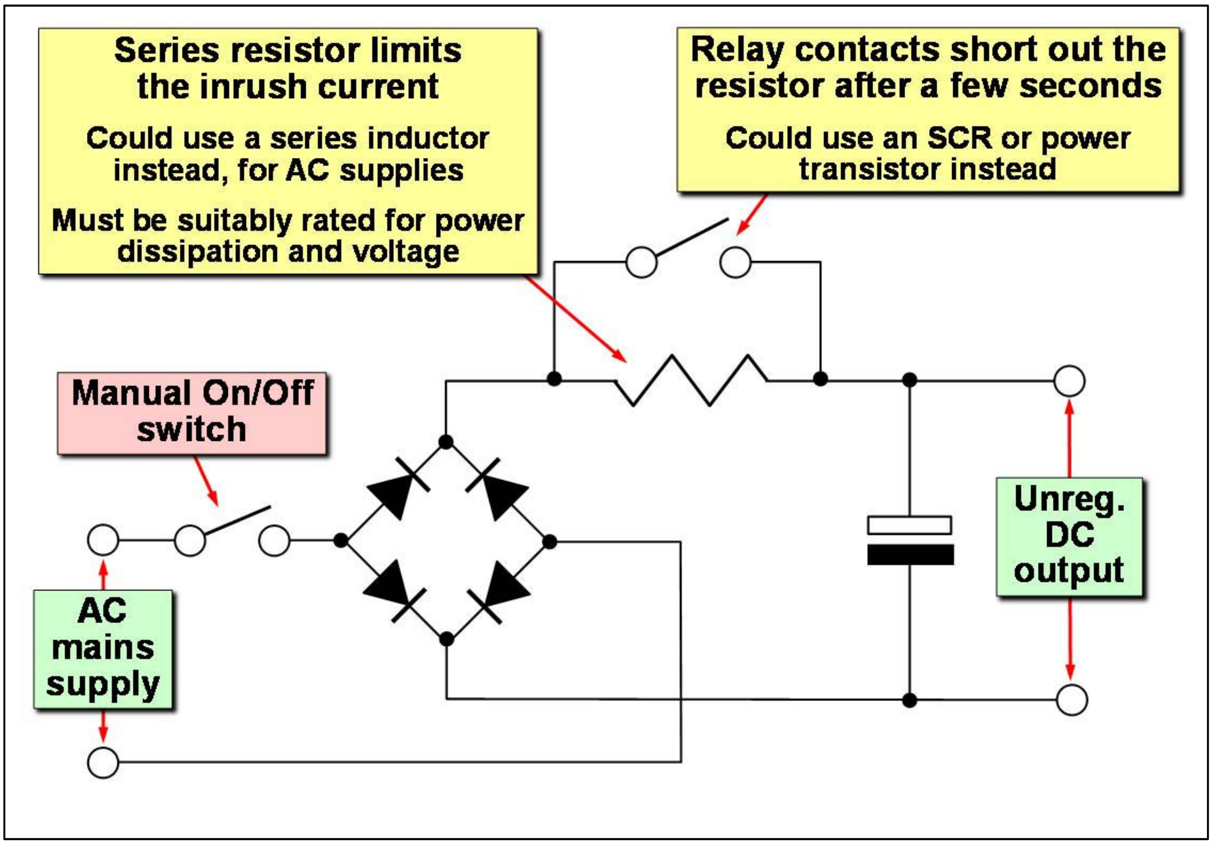

Figure 8.2-2 Another example of a technique for reducing the inrush current

Figure 8.2-3 shows 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'.

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 soften a plastic enclosure and cause safety hazards. 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.

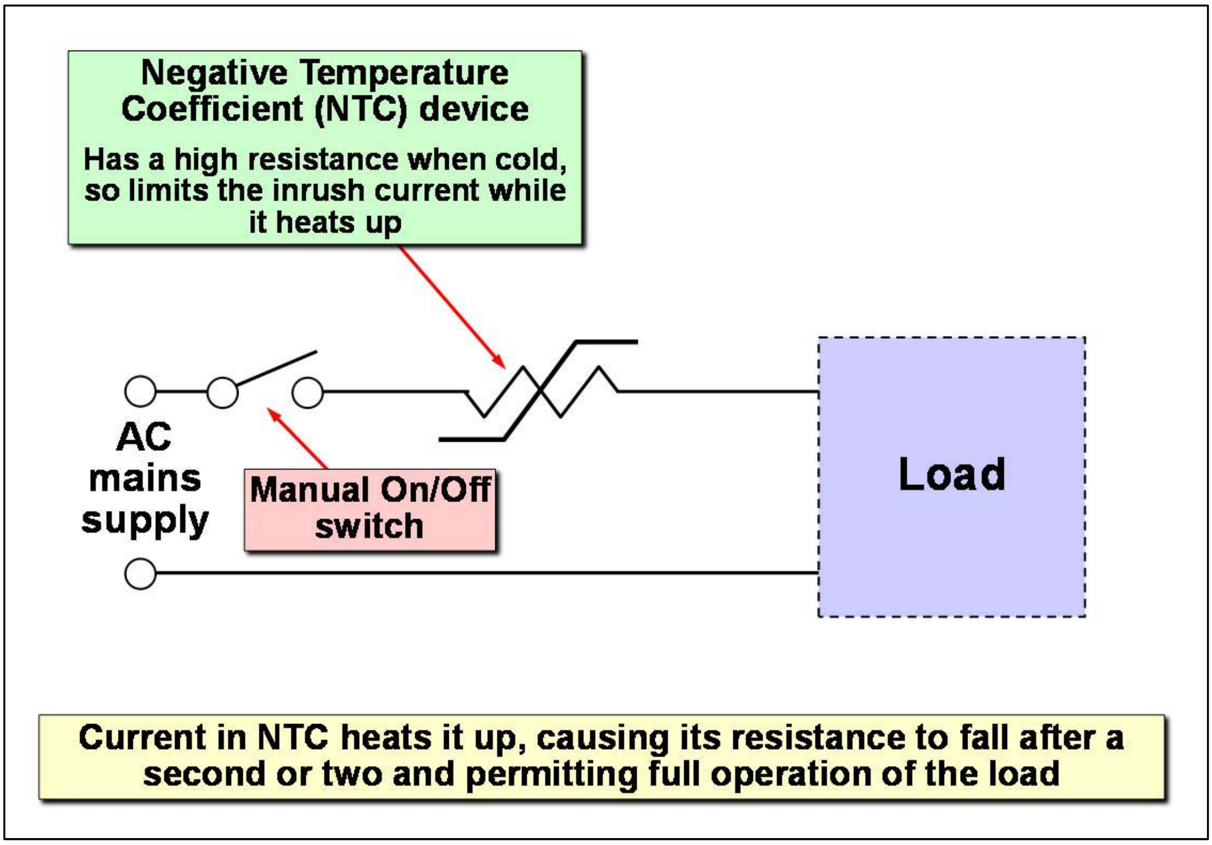

Figure 8.2-3 Reducing inrush current with an NTC

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 8.2-1 and 8.2-2, unless they are appropriately designed so they cannot be defeated by brief interruptions in mains power.

Large transformers (or any other inductors, such as motors) 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, especially when magnetic saturation occurs, as shown by Figure 8.2-4.

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 8.2-4 shows some examples of inrush currents in 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 with high slip speeds they can draw more current than is allowed by the emissions standards or is desirable for the power distribution network. Variable speed motor drives driving such motors can use 'soft-start' techniques to slowly bring the motor’s drive frequency up to the desired operating speed.

By maintaining the slip speed at no more than a few percent as the motor speed is ramped up, sudden and/or large fluctuations in the mains supply current are avoided.

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. So as well as ramping motor speed up slowly, the variable frequency drive can ramp it down slowly too.

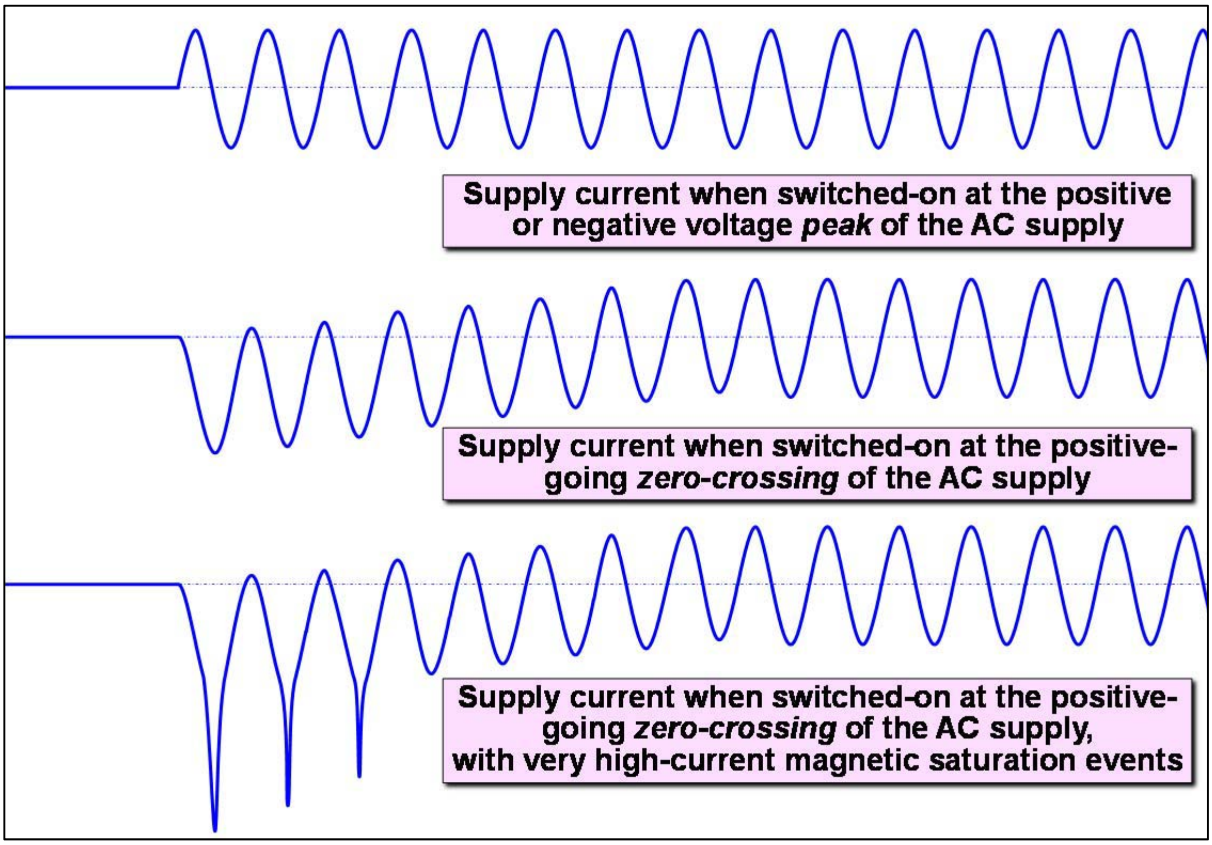

Figure 8.2-4 Inrush current for inductive loads

Similar “soft start” and “soft stop” techniques are appropriate for all types of variable-speed motor drives and other loads (unless their application cannot cope with it, which is rare).

In the case of AC-AC power converters used to link different AC supply systems operating at different frequencies, or used to connect wind, wave, tidal, etc. AC generators to a power supply network, inrush currents at switch-on could be enormous and cause damage to the supply systems if not managed correctly, never mind emissions standards. Such converters will match the frequency and voltage of the load power network whilst maintaining an exact phase match so no power is supplied at first. To supply power to the load network, the phase angle of the AC source is slowly increased with respect to the load waveform, slowly increasing the converted power supplied until the desired level is achieved.

As for the motor drive discussed earlier, a “soft stop” is also generally required for AC-AC power supply converters, so they should also ramp down their source phase angle before disconnection.

There are many other applications of AC-AC, AC-DC, DC-DC and DC-AC power converters, and they generally benefit greatly from the use of soft-start and soft-stop functions.

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 8.2-5.

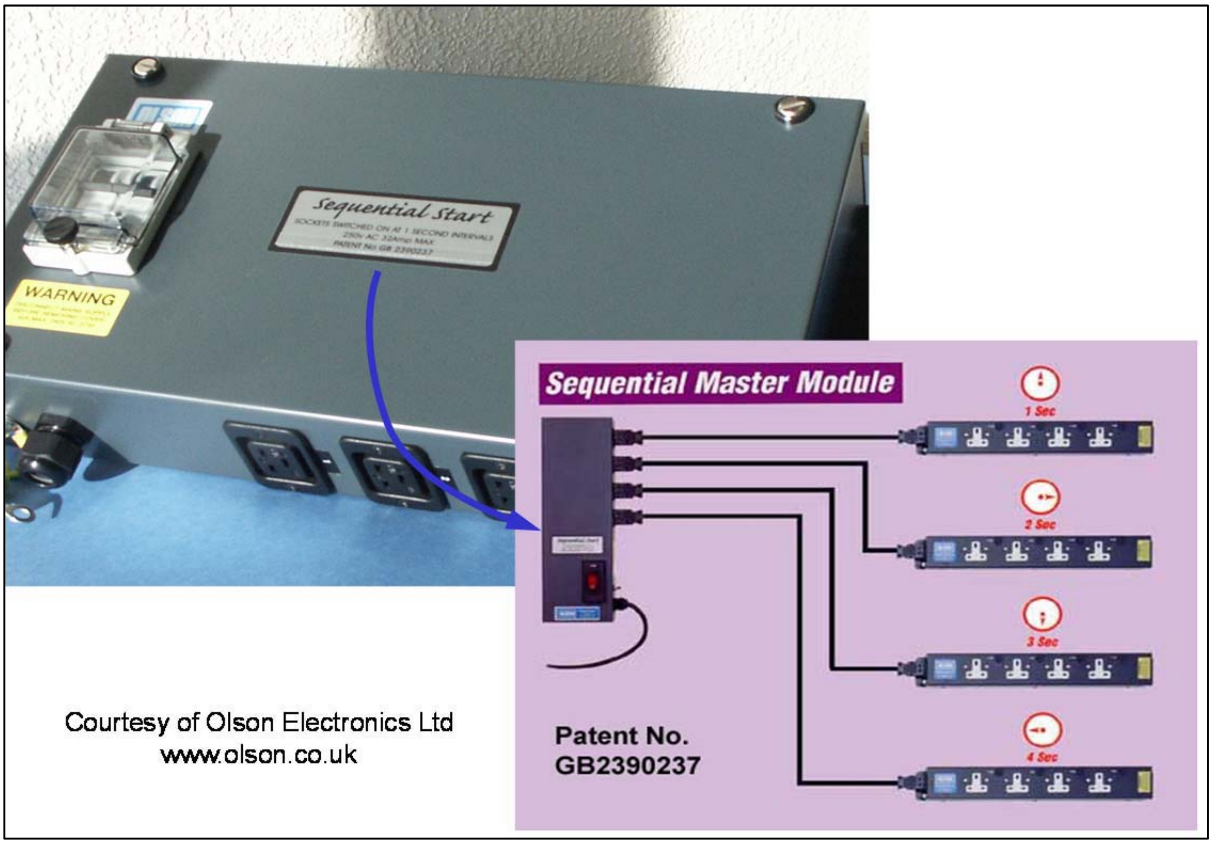

Figure 8.2-5 Examples of a sequentially-switched mains socket-strip

8.3 Reducing the voltage fluctuations caused by load current fluctuations

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 8.2.

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.

(Because filament lightbulbs are being phased out, the limits in the voltage fluctuation and flicker standards need to be changed to achieve similar results for the types of lighting that are replacing them. But at the moment we are stuck with limits based on coiled-coil 60W filaments.)

The 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 and RF conducted and radiated noises, as discussed in the earlier parts of this series, and they also have EMC immunity issues not discussed in this series (see [5] [47] and [48] for immunity design of electronics).

But – providing their maximum rate of change of power is set low enough – they will not cause significant emissions of voltage fluctuations or flicker.

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

8.4 Filtering, and active filtering

We often need to filter the emissions caused by load fluctuations, especially to increase transient rise-times to 10µs or more to reduce the amplitude of spike emissions. This is usually easy enough to do with adequate decoupling capacitance, plus (perhaps) a small series inductor, but to low-pass filter with a corner frequency of less than 1Hz, to reduce emissions of voltage fluctuations and flicker, would require large, heavy and costly components, especially if carrying large currents.

However, '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. They are much more reliable than batteries, have much lower ESR, and can handle very much larger short-term currents, but cannot store as much energy.

Figure 8.4-1 Example of a supercapacitor suitable for large fluctuations in power

With an AC mains supply source impedance of, say, 1Ω and a load impedance of 0.1 Ω, a passive low-pass filter with a corner frequency of, say, 0.5Hz would require the unregulated DC storage capacitor following a bridge rectifier to have a value of about 3F, which is not unreasonable.

For example, a stack of 27 series-connected capacitors of the 450F 13.8V types shown in Figure 8.4-1 would have a voltage rating of 372V and a capacitance of just under 17F – giving (with the example impedances above) a -3dB point of around 0.1Hz.

So, supercapacitor-based passive filters are feasible, and don't require series inductors, and may well be the easiest way to deal with excessive emissions of voltage fluctuations and flicker from legacy equipment. However, when designing new products we would generally prefer something smaller, lighter, and less costly, and active filtering can provide this.

DC-DC switch-mode power converters, whether step-up or step-down are generally followed by DC storage capacitors, and act as active filters for frequencies above the converter's bandwidth (the frequency above which the response of its feedback loop to changes in output voltage is reduced by 3dB).

There is a trend to reduce decoupling capacitance and use fast-reacting converters instead, but the opposite is needed to reduce emissions of fluctuating current from the load back through the DC-DC converter and the AC-DC bridge rectifier and unregulated storage capacitor to the AC mains supply – a great deal of capacitance to support the load voltage, and a slow-responding converter.

For example, a DC-DC converter with a response time of 0.5 seconds would act as a low-pass filter having a -3dB frequency of about 0.3Hz, and would need a sufficiently large output capacitor to supply the load current without creating excessive voltage ripple on the DC supply, see Figure 8.4-2.

For example, with a 0.5s DC-DC converter response time, a load current that fluctuated regularly by 10A for periods of 0.5s or more would create a DC voltage ripple of 1V or less – if the regulated DC storage device was a supercapacitor of 5 Farads or more.

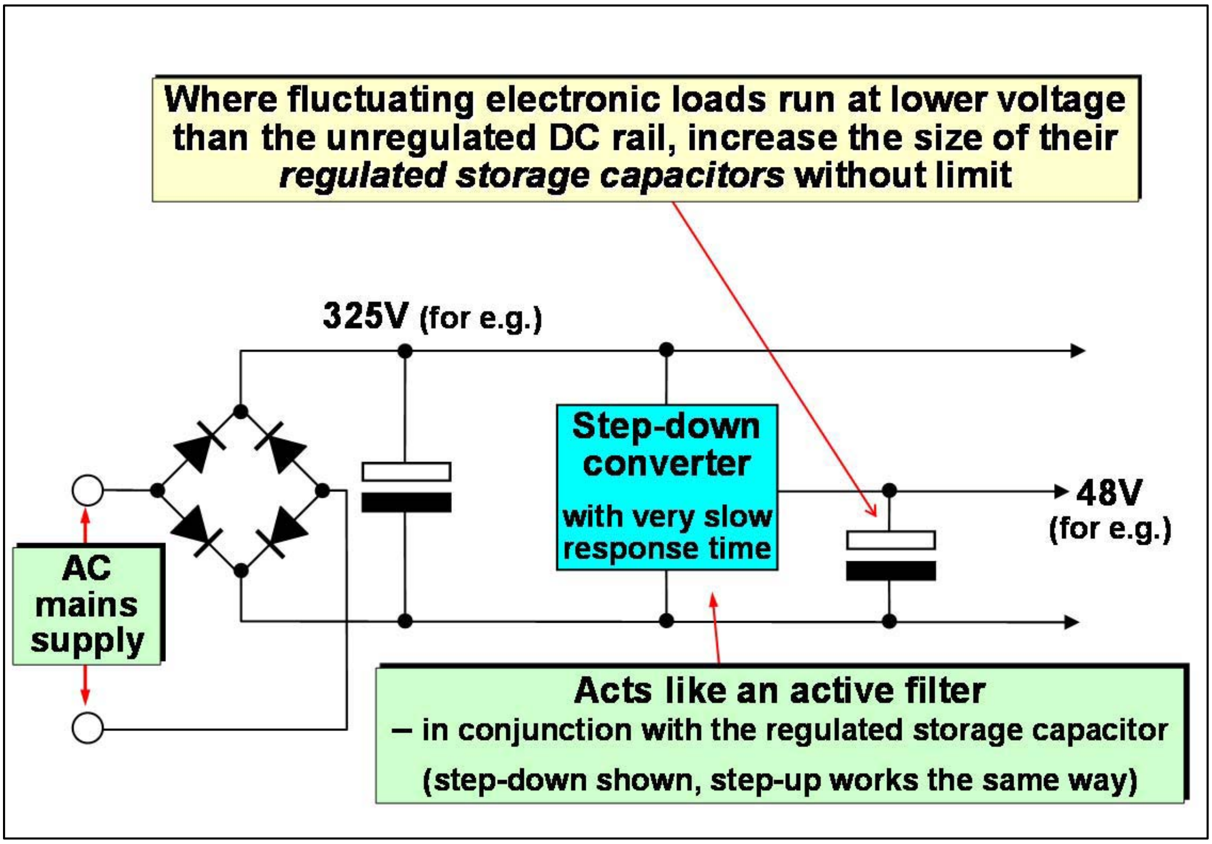

Figure 8.4-2 Suppressing mains voltage fluctuations from a fluctuating low-voltage load

It may also be possible to design the load so that is can stand greater variation of its regulated voltage supply, to be able to use less decoupling capacitance with a slower-responding power converter.

The slow response time of the DC-DC converter can cause new problems to arise. If the fluctuating load current suddenly drops by a large amount, for example if the load is removed (e.g. switched off) the converter will keep supplying much the same current for a significant fraction of its response time-constant until it starts to reduce its current output. During this period, the DC voltage on the storage capacitor could rise by so much that it (or the load) could be damaged by overvoltage.

To prevent this from happening, we could sense the DC output voltage and abruptly switch off the converter before the voltage rises by too much – but this would cause a significant emission of voltage fluctuation in the AC supply, and if it happened repetitively could cause excessive flicker.

This is obviously undesirable so – although we should keep the over-voltage shut-down protection circuit – we should choose converter response times and storage capacitor values to make sure it is only triggered in exceptional circumstances, and not during even extreme values of what might be considered normal operation.

Where an 'Active PFC' boost circuit, such as described in Section 10.6 of [5] is used to reduce emissions of mains harmonics, we can also use them as active filters because they generally already have a slow response time to variations in load current, typically about 0.5 seconds. See Figure 8.4-3.

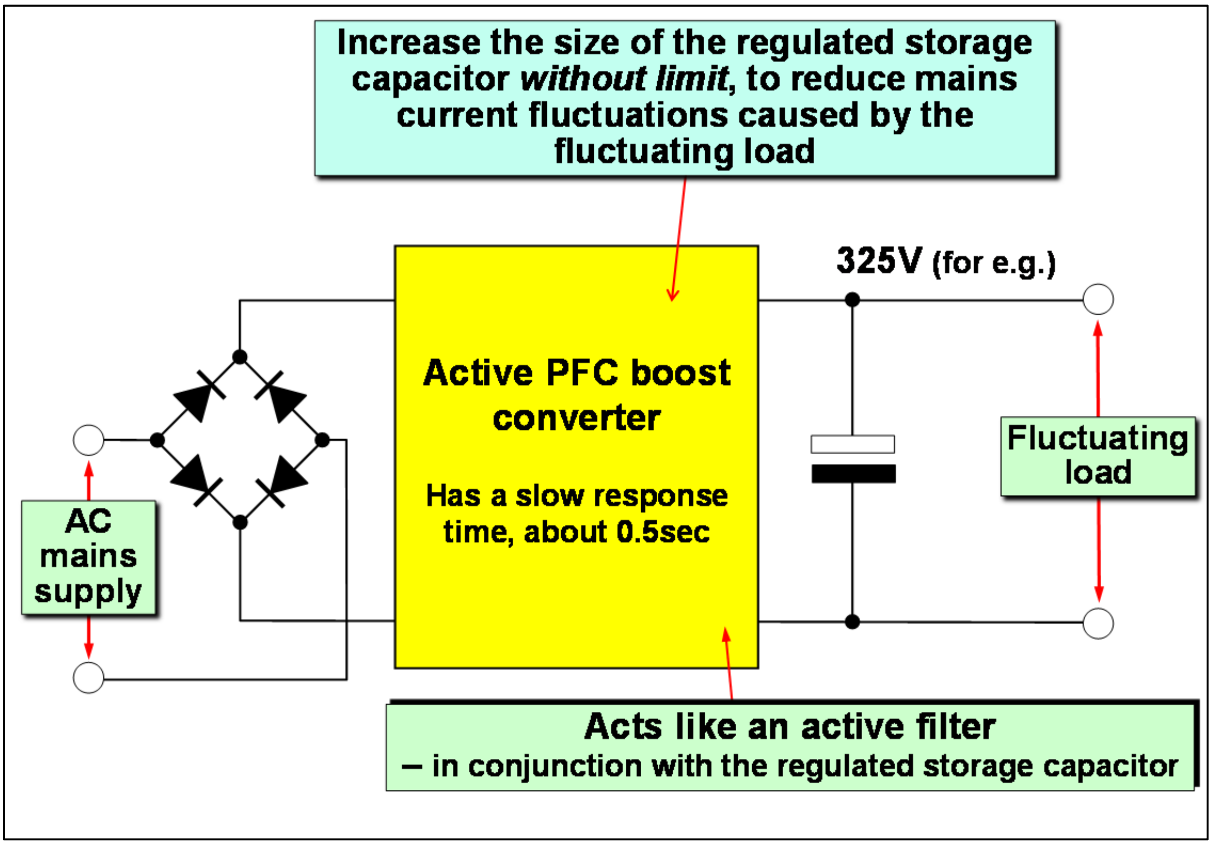

Figure 8.4-3 Suppressing mains voltage fluctuations with an active PFC

All of the same issues for active filters of the type shown in Figure 8.4-2 apply when using Active PFC circuits as low-pass filters to reduce emissions of mains voltage fluctuations and flicker.

So we can see that appropriate design of Active PFC boost circuits can provide a wide range of benefits…

- Comply with harmonic emissions standards (see Section 10.6 of [5])
- Achieve 'universal' operation from 84 to 260V AC rms, and DC to 400Hz, helping to sell the same product world-wide (only need to ship it with appropriate mains lead)
- Reduce emissions of voltage fluctuations and flicker by acting as an active filter
- Improve immunity to voltage variations, fluctuations and dips in the electricity supply

8.5 System and Installation-level fixes

Motor-flywheel-generator sets and continuous on-line double-conversion UPSs will "smooth out" the current demands to the mains distribution. In the case of the M-G set, the degree of smoothing depends on the mass of the flywheel. See [7] [8] [60] [68] [69] [70] and [114] for more on these and other installation-level approaches.

9 Some final miscellaneous switcher/chopper EMC issues

9.1 Ferrite-loaded PCBs?

Even though we design PCBs very carefully, via holes and traces are all "accidental antennas" and so cause emissions and worsen immunity. Ferrite-loaded PCB material might be a solution for some circuits, but such materials are not yet available, as far as I know.

However, in 2010 Murata announced a DC/DC converter (the LXDC2HL series) that uses a ferrite substrate instead of normal PCB material. It has much lower radiated emissions, plus it uses planar coils buried in its "PCB". Solid ferrite is a ceramic, so I imagine that this converter is made like a hybrid circuit on an insulating ceramic such as alumina. Murata already make RF chokes out of through-hole plated "PCBs" made on slices of unfired ferrite instead of PCB material, stacked together to create a larger coil and then co-fired, so I suppose it is a short step to assembling other components onto these hybrid ferrite circuits and creating a DC/DC converter with coils embedded in its substrate.

A significant problem with using ferrite-loaded fibreglass PCB materials must be that through-hole plated types are either drilled or punched, and adding ferrite would surely cause these tools to wear out very quickly indeed. But micro-via PCBs are drilled using lasers or plasma beams, which have no parts in contact with the substrate, to wear out. So perhaps future PCBs will be able to use ferrite-loaded substrates that dampen down their RF emissions.

I recently met a university researcher whose project was to design a 100W power converter operating at a switching speed of 30MHz. No doubt the RF emissions of such a converter would benefit greatly from the use of UHF and Microwave absorbing ferrite particles in its PCB substrates.

9.2 Good EMC emissions and immunity practices for systems and installations

Cabling techniques are very important, because switcher noise will couple (crosstalk) from one cable to another in a system or installation, possibly causing interference with other equipment.

"Earthing/grounding" techniques are also very important, and it is important to understand that single-point (or "star") systems are nothing more than resonant antennas at the frequencies emitted by power converters.

Both of the above issues are covered by IEC 61000-5-2 [115], on which standard the guides [68] [69] and [70] are based.

Good EMC practices for cabinets, systems and installations are described for "Industrial Cabinets" in [68] (equally relevant for anything that is a metal box with two or more items of interconnected electronics inside, e.g. a vehicle) and for "Systems and Installations" in [3] [7] [8] [60] [69] [70] and [114].

Additional references associated with for proprietary solutions for suppressing mains harmonics include [1], www.mirusinternational.com/pages/lineator.htm and www.harmonicsolutions.co.uk/solutions/solutions1.html.

9.3 QA in series manufacture

It is necessary to control serial manufacture to maintain compliance with the EMC Directive.

Simple EMC checks should be designed and easy-to-use test gear made with enough sensitivity to detect significant problems to maintain EM performance in serial manufacture.

Close-field probes and clamp-on current monitoring clamps can be used to great effect in serial manufacture, to check the EM emissions of every product that is made while it is undergoing its final functional testing. If these EMC checking systems are designed well, they will not add any time to the manufacturing process.

It is not merely a question of shipping legally compliant products – a power converter with excessive emissions is likely to cause claims under warranty, or visits by field service personnel, and quickly eat-up any profit that was made by selling it. In fact, it is possible for a warranty claim on one product to eat up the profits from several other products – making EMC compliance a significant financial risk factor that must be controlled.

9.4 Controlling suppliers

When we purchase parts with which to construct power converters, or purchase complete power converters to use with our own products, we should never rely on our suppliers own certificates and/or "buying in good faith". UK "Trading Standards Law" – the case laws that the Trading Standards Officers use to guide their enforcement of EU Directives – recognises that some suppliers lie about their products. This is the reason why suppliers' certificates, such as Declarations of EU Conformity, cannot be relied on for legal compliance, and also the reason why buying in good faith is not a defence against prosecution under UK Law (and possibly the laws in other countries too).

The law assumes that we are "professional integrators" who know enough to ensure that the parts and products we purchase to either make, or supply with, our products are appropriate. If our products are found to be non-compliant, we cannot pass the blame onto our suppliers.

An increasingly important issue in this context is counterfeiting, which is run by organised crime and has been increasing for years to the point where it has become such a problem that the US Military is now starting to require its suppliers to prove they are not using counterfeit components [115].

I have recently read of a large electronics sub-contract manufacturing company that has had to start X-raying every single one of the components it takes in, comparing the image with a known good image, and rejecting any that don't match. Even this is not enough on its own, but it helps!

Although this article is about EMC issues, it is worth digressing a little to say that the issue of counterfeiting is a very important one for power converters for safety compliance, for example to EU safety directives such as the Low Voltage Directive, Machinery Directive, Medical Devices Directive, etc.

The IET's magazine "Wiring Matters" contained an article about counterfeiting in its Spring 2013 issue [116] which mentioned the sad case of the young boy who, in 2007, was fatally electrocuted by a fake Nintendo Gameboy charger.

The article went on to say: "The tragic accident prompted a UK Trading Standards investigation that led to a Europe-wide recall of dangerous charger and adapters, but six years on sub-standard and counterfeit chargers are still on sale. According to UK-based Plugsafe, a voluntary group of electrical engineers, a number of major retailers are currently selling chargers that are illegal in the UK."

I have also worked with customers who were buying cheap mains battery chargers or power converters to bundle with their products, who suffered very expensive problems when customers reported that they had exploded or caught fire. The manufacturers had thought they could trust their suppliers to provide safe products, and had been caught out.

I always recommend everyone to treat all their suppliers, no matter how glossy their brochures, sales offices, or salespersons, as if they were dodgy back-street second-hand car dealers. Always check their claims for EMC and Safety, always do sample tests for EMC and Safety on what they supply, and always record what you do to help make a robust defence if you have to deal with future lawsuits.

9.5 Additional references that I did not use in this series

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- 'EMC Awareness' by the Radiocommunications Agency, at: http://www.ofcom.org.uk/static/archive/ra/topics/research/RAwebPages/Radiocomms/index.htm%20
- The Texas Instruments website includes many very useful application notes on designing PFC circuits (originally written by Unitrode)
- "Variable Speed Drives – A Guide to Supply Harmonics and Other Low-Frequency Disturbances", Emerson Industrial Automation: www.controltechniques.com/guides
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