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EMC design of Switching Power Converters Part 5 - Design techniques for LF (mains) rectifiers

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EMC design of Switching Power Converters

Part 5 — Design techniques for LF (mains) rectifiers

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Contents

Issues 93 – 95 of The EMC Journal carried earlier parts this “Stand Alone” series, which is 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 *all* power converter applications, including: consumer, household, commercial, computer, telecommunication, radiocommunication, aerospace, automotive, marine, medical, military, industrial, power generation and distribution, whether they are used in modules, products, systems or installations.

I also aim to cover hybrid & electric automobiles, electric propulsion/traction; “green power” (e.g. LED lighting); and power converters for solar (PV), wind, deep-ocean thermal, tidal, etc.

I will generally not repeat stuff I have already published, instead providing appropriate references to material published in the EMC Journal [14] and my recently-published books based on those articles [15]. The reasons for this are three-fold:

- So that you don’t get bored by repetition
- To help save a few trees from an early death
- To help avoid building extra server centres for the Internet

The latter two bullet points you will of course recognise as being vital for reducing the human emissions of CO_2 that are acidifying the ocean and will most likely lead to the total collapse of several major global food chains, mass starvation, etc., etc. within the lifetimes of anyone under 50. We must all do our bit!

You will of course have noticed that the numbering of the sections does not correspond to the number of the published part of the series (this is the fourth Part), and I hope you can forgive me for this. At least from this Part on I will be numbering my figures in a more sensible way!

5 EMC design of LF (mains) rectifiers

The first possibility, is to use the type of converter described by Slobodan Ćuk in [42] that does not require an input rectifier at all.

But if we *are* going to increase the cost of the Bill of Materials (BOM) by using a mains rectifier, we will often have to further increase the BOM cost to deal with the switching noises and harmonic/interharmonic currents it emits.

5.1 Suppressing LF rectifier Radio Frequency (RF) noise

When a rectifier is forward-biased and carrying a current, its silicon body contains minority carriers (often called “holes”). It is the presence of minority carries that makes the silicon conduct, and when the rectifier’s voltage is reversed these minority carriers take a short time to decay to the point where the silicon becomes insulating again. So, for a short time, the rectifiers carry current even though they are reverse-biased, causing unwanted emissions at harmonics of the switching frequency that extend all the way from 150Hz up to (and into) the RF bands.

The faster the switching speed of the rectifiers, the more the emitted noise extends to higher frequencies, so this type of noise is a big problem for HF rectifiers and it is discussed in more detail in 6.2.

Low Frequency (LF) rectifiers are used on mains supply frequencies between 16.67Hz and 400Hz (most of them at 50 or 60Hz) and switch relatively slowly, so this type of noise is probably not the main cause of their RF noise emissions. If it is a significant cause, using silicon carbide Schottky rectifiers will stop it (Schottkies don’t have minority carriers). These are now becoming available with ratings to 1kV and more, and of course they cost more but as I keep telling people the BOM cost alone does not determine the profitable selling price, see [12].

But most likely the largest source of noise in an LF rectifier comes from the fact that silicon (PN junction) rectifiers are non-linear devices and the voltage needed to turn them on (make them conduct) is around 0.7V, depending on the forward current. So a bridge rectifier (whether PN Junction or Schottky) has a “deadband” of around 1.4V (for a PN junction type) where it is not conducting either one way or the other.

For the LF rectifiers being discussed, both noise sources can be dealt with by adding capacitors in parallel with the rectifiers themselves, as shown by Figure 5.1.

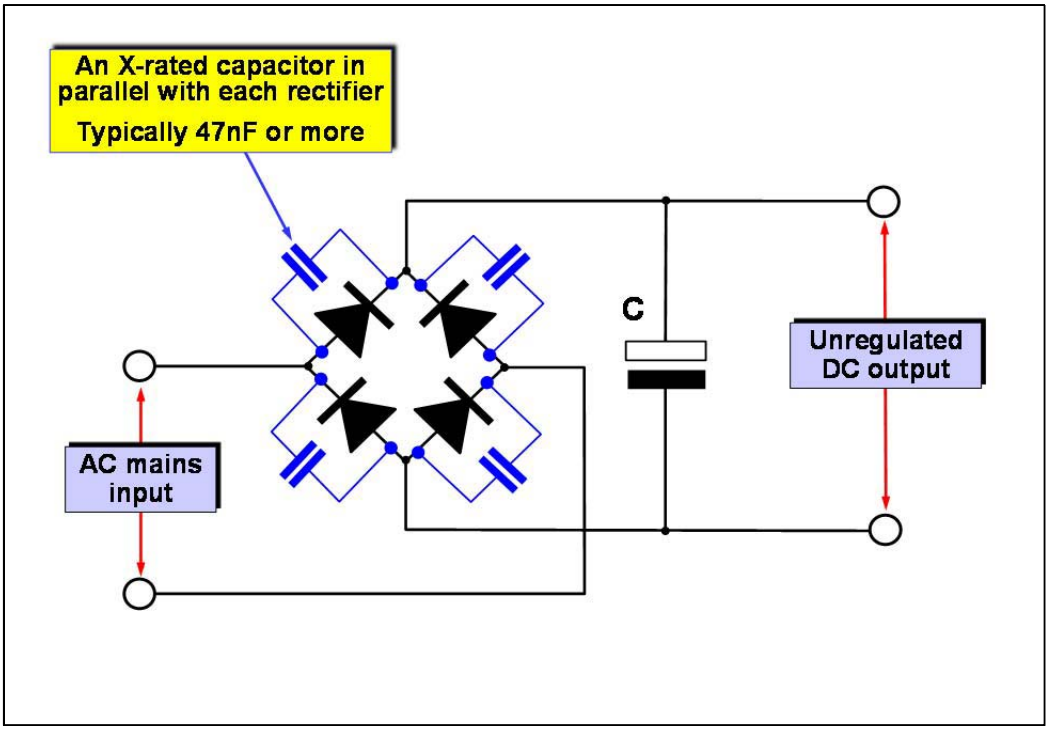


Figure 5.1 Suppressing the RF switching noise emitted by a mains bridge rectifier

Where the bridge rectifier is in the primary of the mains circuit, these capacitors must be safety-rated types. See section 5.2.12 of [5] for why it is necessary to ensure that all safety-rated capacitors really are what they claim to be, if your company is not to be held liable for accidents caused by the mistakes or frauds of your component suppliers.

But if the bridge is in the secondary of a safety-isolating mains transformer, it is only necessary for these capacitors to meet their appropriate maximum ratings, and for the design not to cause a fire or electric shock hazard if one or more of these capacitors fails.

To pass the conducted emissions limits in EN 55022 (CISPR22) or EN 55011 (CISPR11) class B, I have so far only found it necessary to suppress 50/60Hz mains rectifiers rated at more than 1kW, and then using (*very* approximately) 100nF per kW.

But I cannot claim that the above is a proven good EMC practice, so it is probably a good idea to provide prototypes with converters rated at more than 100W with pads suitable for a range of sizes of appropriate X-rated capacitors. If they are not required, they can be omitted from the production versions, but at least there will be room on the board for them if they are found to be required by EMC testing late in a project, when modifications that were not allowed for can be very costly (see “anti-Murphy design” at the end of section 4.1 of [5]).

5.2 Suppressing harmonic and interharmonic emissions

5.2.1 Introduction

I have described this topic in great detail for electronic design engineers in Chapter 10 of [5]. So I won’t repeat what it says here. And I also won’t repeat what I have written on this topic for systems and installations engineers in [3], [7] and [8] (which have the great advantage of being free).

When attempting to control the harmonics in systems and installations, most people focus on the larger loads, usually variable speed AC and DC motor controllers rated at 100kW or more (mining industries and the main propulsion of ships can use variable speed drives to 10MW).

A good example of harmonics causing serious safety problems due to interference with control electronics is given in Banana Skin No. 618, published in the January 2011 Edition of the EMC Journal (and available from the archives at www.theemcjournal.com).

But in modern electrical installations *all of the loads can be electronic*, and the aggregation of the harmonic emissions from large numbers of low-power equipment, such as cellphone and laptop chargers; compact and high-frequency fluorescent and LED lighting, etc., can also create significant levels of harmonic distortion, as [53] shows.

So, I always recommend that *all* electronic product/equipment designers reduce harmonic emissions from their mains rectifiers, even where harmonic emissions standards such as IEC/EN 61000-3-2 or 61000-3-12 don’t set any limits, or allow very relaxed limits (as they do for all lighting equipment).

Reduction of harmonic emissions is often known as Power Factor Correction (PFC), but it is important not to get confused with the term ‘Power Factor’ as traditionally used by electrical supply engineers – which simply means the cosine of the phase angle between the sinewave supply voltage and a sinewave load current. This is more correctly called “Displacement Power Factor” and is only relevant for linear loads – which, of course, rectifiers are not.

We are interested in “True Power Factor” – which is simply the ratio of the VA to Watts.

I am always eagerly homing in on advertisements for power factor correction, only to find that they are simply about capacitors and only suitable for Displacement Power Factor correction. We cannot ever correct the mains power factor of rectifiers just by adding a capacitor to the mains (although we can get some improvement by adding a series choke to the mains, see 5.2.6 below).

Another cause of misunderstanding, this time with potentially deadly effect, is that the actual problem of harmonic (and interharmonic) emissions is due to the current noises generated by non-linear circuits, for example measured as I_{thd}. But standards such as IEC 61000-3-2 and -3-12 choose to measure their emissions as the voltage noise that these currents cause (e.g. as V_{thd}) in standard impedances chosen to be typical of AC mains distribution systems.

Because the harmonic/interharmonic measurement standards measure V_{thd}, system and installation designers can be lulled into a false sense of security by thinking that this is what they can expect when an equipment is connected to *any* mains supply.

But in real life, the actual mains distribution systems can have very different impedances, especially when they are powered by a generator. This is because a generator of a given kVA rating typically has a source impedance three or four times that of an HV grid transformer of the same rating, so the same harmonic current noise can cause significantly increased V_{thd}.

So, for example, a hospital might manage a V_{thd} of under 5% when running of the national HV grid – a value generally considered to be acceptable for normal electrical equipment (e.g. motors) and electronic equipment. But they might get many nasty surprises with malfunctioning equipment, flickering displays and lighting, including significant functional safety, fire and explosion risks, when switching to their back-up generators makes the distortion of their AC mains supply jump up to 10% or more.

It seems to me that engineers would be a little more aware, have a little more understanding of the real-life issues of harmonic distortion of the mains supply, if equipment emissions were measured and specified as currents. Then they would have to think about the possible impedance range of their mains power distribution network to ensure that V_{thd} remained under (say) 5% for all reasonably foreseeable operating conditions.

The real-life issues of distorting the mains supply with harmonics/interharmonics are huge, from lighting flicker, through equipment malfunctions, to fire and explosions of any magnitude. [8] has a brief introduction to this on pages 23-26, but [7] goes into much more detail in its pages 7-28 (it's OK, these 21 pages are A5 sized and use large font size – you can read them all in five minutes!).

But something that [7] and [8] don't emphasise enough is that AC motors are designed to operate at up to a specified maximum temperature *assuming* that their AC supply has less than a certain percentage of V_{thd} (usually 5%). If the mains distortion exceeds this they can run hotter than their rated maximum temperature, leading to reduced operational life – if not actual insulation/bearing failure that causes catastrophic failure.

But there is worse. I remember reading somewhere that something like 30% or more of industrial areas worldwide have Explosive Atmospheres, and in these areas a motor that runs excessively hot and above its temperature class, or has bearings that collapse due to the evaporation of their lubrication, can cause fire or explosion. Such fires and explosions can be huge, leading to great loss of life and financial damage to the operating company and their owners. Think of the explosive atmosphere fire and explosion disasters in the UK alone, for example:

Flixborough	(http://en.wikipedia.org/wiki/Flixborough_disaster);
Buncefield	(http://en.wikipedia.org/wiki/Flixborough_disaster);
Piper Alpha	(http://en.wikipedia.org/wiki/Piper_Alpha),
and	
Texaco Milford Haven	(www.hse.gov.uk/comah/sragtech/casetexaco94.htm)

which significantly depressed the UK's gross National Product for a year or more.

This is especially a problem for *offshore* explosive atmospheres, such as gas and oil production platforms and drilling rigs of various types, because they run on generators with a preponderance of their load going to high-power variable-speed motor drives. Their V_{thd}s can be between 15% and 30%, sometimes even more at times, although their V_{thd} limits are supposed to be either 5% or 8%.

The design of EX-rated motors (and the like) is usually based on a harmonic distortion factor (HVF) of 2% (around 5-6% V_{thd}) to limit the temperature rise and to suit their explosive atmospheres, but many operators seem to ignore that they are only EX-rated if their mains supplies have V_{thd}s of 5% or less. It appears that a very important safety risk caused by harmonic emissions is often being ignored, and for more on this and similar problems see [54].

5.2.2 The mains harmonic and interharmonic currents emitted by a bridge rectifier

Electronic engineers should refer to section 10.1 of [5], and systems and installations engineers should see pages 2-7 [7] and page 20 of [3].

The title of this section is a little misleading (but only a little) because bridge rectifiers themselves, with DC storage capacitors and pure unchanging resistive loads can only create harmonic currents. Fluctuations in load current in the frequency range below 10kHz are filtered somewhat by the unregulated DC storage capacitor and then pass through the rectifier and into the mains supply as low-frequency currents that are not harmonically related to the mains frequency of 50 or 60Hz.

So, for example, a very high-power audio system could cause nearby streetlights to flicker in time with the music. And a variable-speed AC motor drive with a PWM output frequency of, say, 39Hz emits interharmonic currents into the mains supply not just at 39Hz, but also at harmonics of 39Hz. It may even be that the emissions of mains harmonics are much less than the emissions of interharmonics.

But the interharmonic situation is actually much worse than this, because bridge rectifiers are non-linear they act as frequency mixers, producing intermodulation products between the mains frequency (50 or 60Hz and all of their harmonics to beyond the 50th) and the load current's spectrum (e.g. 39Hz and all of *its* harmonics to beyond the 50th).

Figure 5 of [7] is reproduced here as Figure 5.2-1, and originally came from Figure 13 of [55]. It shows a spectrum graph of the noise currents emitted from a high power (several hundred kW) AC drive. This is a very rich noise spectrum, with about 120A of current at its output frequency of 39.375Hz and about 30A at its fifth harmonic (nearly 200Hz), but with only small currents (< 1A) at the mains frequency of 50Hz and its harmonics.

It also shows 24A of emissions at 103.75Hz (6th harmonic of 50Hz minus 5th harmonic of 39.375Hz); 12A at 131.25Hz (6th harmonic of 50Hz minus 11th harmonic of 39.375Hz); 7.73A at 260.635Hz (5th harmonic of 50Hz minus 1st harmonic (fundamental) of 39.375Hz), and so on.

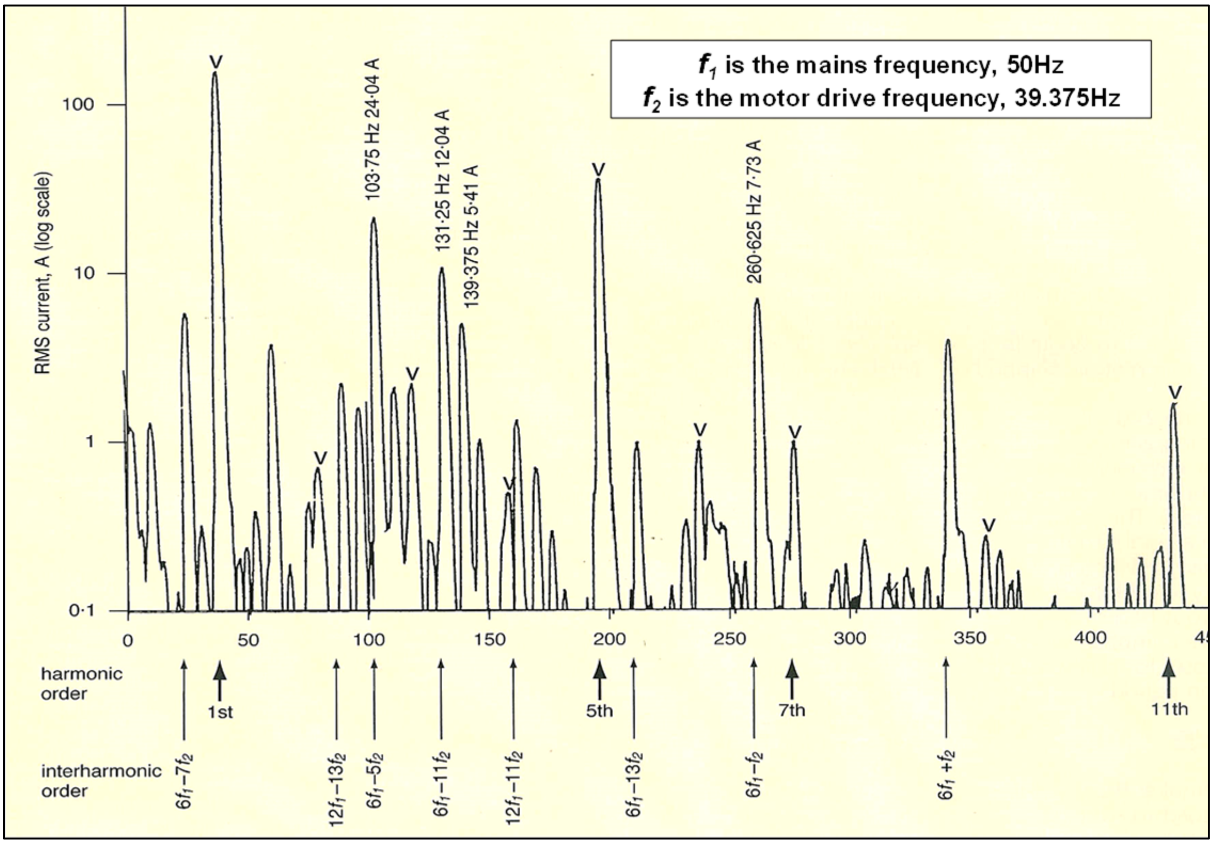


Figure 5.2-1 An example of real harmonics and interharmonics

Interharmonics can extend down to 1Hz or less, and for example Figure 5.2-1 shows about 8A of mains supply emissions at about 25Hz (6th harmonic of 50Hz minus 7th harmonic of 39.375Hz).

It is often assumed that harmonics are the main cause of problems on mains distribution networks, rather than interharmonics, but Figure 5.2-1 shows that, for the inverter measured, mains harmonic emissions are actually very low. Its noise emissions into its mains supply are almost entirely its output frequency of 39.375Hz plus its harmonics, plus intermodulation products between them and the 50Hz mains frequency and its harmonics.

Measuring its mains currents only at the mains frequency and its harmonics, using a very narrowband measuring system, would indicate very low emissions indeed. A practical engineer with some experience would automatically check the consumption at the fundamental frequency, to see if it made sense. He or she would suspect such data because it implies that a motor that was delivering several hundred kW of real work, was consuming less than 1A from the mains at its fundamental frequency of 50Hz!

The first temptation when such things occur is always to want to patent it quickly – energy from nothing! But anything that appears to contradict the Law of Conservation of Energy is *always* wrong, which is unfortunate for global warming (more often called “climate change” in the USA).

Most harmonic measuring systems have measurement bandwidths wide enough to include many of the nearby interharmonics, but only displays the results *as if* the emissions were all occurring at the mains frequency and its harmonics. This may be why it is generally assumed that interharmonics are not a big concern, when Figure 5.2-1 indicates that they may in fact be the greatest concern for power frequency converters.

High-power switching converters can have switching rates of 5kHz or less, and so appear in the same frequency band as mains harmonics, and be measured as such. For example, Figure 5.2-2 shows that the 2kHz switching frequency of the IGBT choppers in a 600Vac 700kW variable-frequency AC motor drive appears as the 40th harmonic of the mains. It just so happens that the 40th harmonic of 50Hz is exactly 2kHz, so when a chopping frequency falls between two harmonics, for example 1.975kHz, whether the full level of the problem is measured depends on the bandwidth of the harmonic measuring instrument at the harmonic frequencies.

5.2.3 Differential Mode (DM) and Common Mode (CM) harmonic emissions

Harmonic current emissions have two modes of propagation:

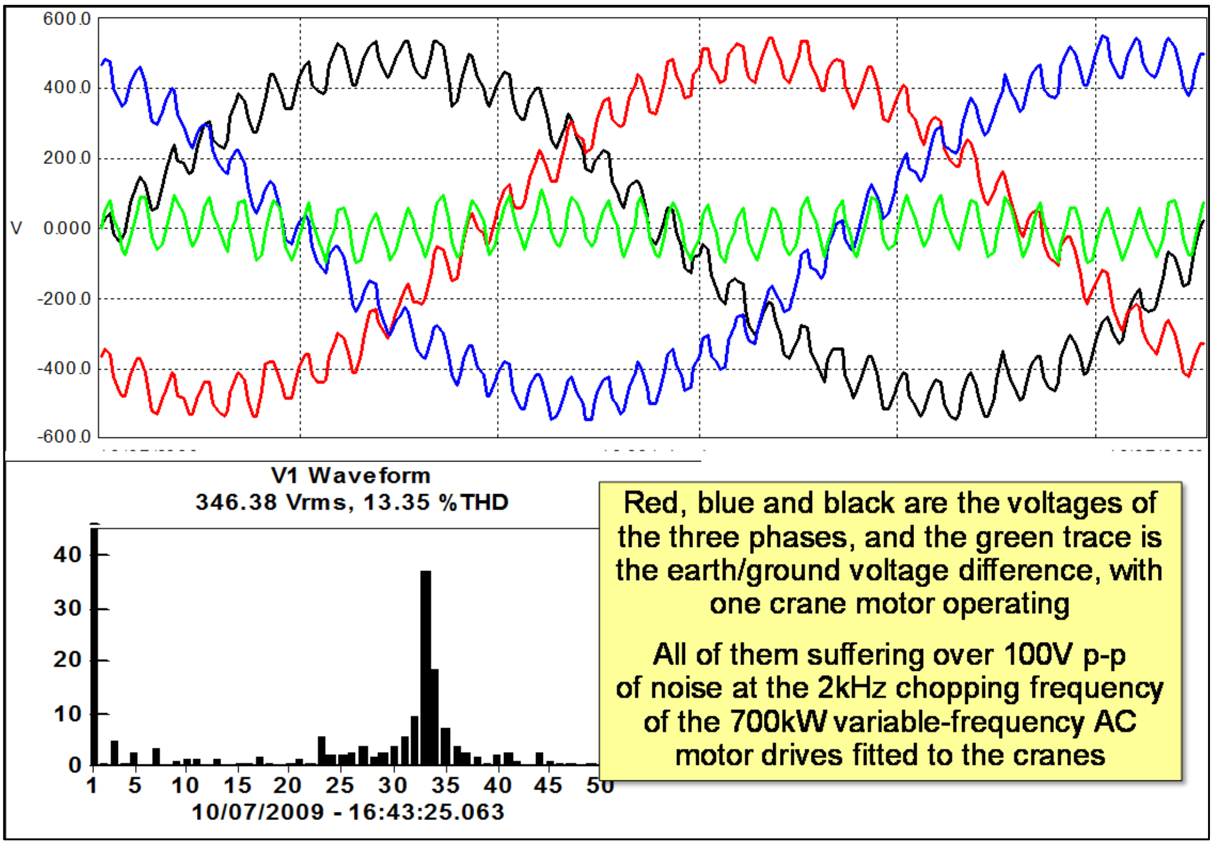
- DM – where they flow out on one phase and back on another (or on a neutral)
- CM – where they flow out as a common current on all phases and any neutral but return via the earth/ground conductor or earth/ground structure

DM currents flowing in the impedances of the phases and neutrals cause the AC mains supply voltage waveform to distort, e.g. V_{thd} (although proper analysis requires that the distortion caused by each harmonic component is measured).

CM currents flowing in the impedance of the earth/ground cause voltage differences between items of equipment, giving rise to so-called “ground loop currents” that cause problems for inadequately designed electronic equipment. (Just because an electronic design meets its functional specifications on a test bench, does not mean it will meet them in a real-life system or installation, but attempting to solve the problem by breaking “ground loops” by using single-point earthing in systems and installations causes all manner of EMC problems, see section 4.6.8 of [5], [61], [62] and [63]).

All of the techniques discussed above will reduce the emissions of DM harmonics – hence reduce the V_{thd} of the AC mains supply. This is often the only thing that anyone thinks about, until they have CM problems in real life. But only some of the techniques work to reduce the CM harmonic noise.

Banana Skin No. 618 (in the January 2011 Issue of the EMC Journal, available from the archives at www.theemcjournal.com) was a CM harmonic problem that cost $54 million before it was solved, and Figure 5.2-2 reveals the scale of the problem on the offshore platform concerned.



Red, blue and black are the voltages of the three phases, and the green trace is the earth/ground voltage difference, with one crane motor operating

All of them suffering over 100V p-p of noise at the 2kHz chopping frequency of the 700kW variable-frequency AC motor drives fitted to the cranes

Figure 5.2-2 Examples of the mains waveforms from Banana Skins No. 618

As the caption on Figure 5.2-2 indicates, the DM noise on each phase of the platform generator's AC mains supply was about 100V p-p (the black, red and blue waveforms), and so was the CM noise in the earth/ground (the green waveform plot), when one of its 700kW crane drives was operating.

This CM noise upset the operation of crane control electronics, causing the crane to flail about with obvious safety problems. Some of the cranes on the platform were more badly affected than others.

The problem of crane control was dealt with by putting isolating transformers in series with the supply to each of the 700kW crane drives – the sources of the CM noise currents – as shown by Figure 5.2-3.

Figure 5.2-3 The fix for the CM noise from the crane motor drives

These isolating transformers did nothing for the DM harmonic currents, and so the V_{thd} of the platform's AC mains supply remained the same when the cranes were operated. But the green waveforms are now almost flat lines – the CM currents, and hence earth/ground noise voltages, having been attenuated by about 20dB by the transformers.

5.2.4 Using smaller values of DC storage capacitor after the bridge

Electronic engineers should refer to section 10.2 of [5]. This is an equipment design technique, not appropriate for systems and installations engineering, and it works on both DM and CM harmonic emissions.

5.2.5 Passive filtering

Electronic engineers should refer to section 10.3 of [5], and systems and installations engineers should see pages 52-54 of [7]. This method works on DM and/or CM harmonic emissions, depending on the design of the filters.

Because it is impossible for a low-pass filter to get high levels of attenuation of low-order harmonics without wasting a lot of power at 50 or 60Hz and running hot, where high attenuation is required it is normal practice to use "resonant trap" filters, tuned to the 3rd and other low-order harmonics.

They are used in parallel with the mains, to provide very low impedances at their tuned frequencies; and/or in series with the mains supply, to create very high impedances at their tuned frequencies. Traditional low-pass filters are generally used for attenuating all the harmonic emissions above the 7th.

Where resonant trap filters are used to reduce harmonics in installations, it is normal practice not to tune them exactly to the harmonic frequencies. Based on a detailed site survey that covers all modes of site operation, the filters are tuned to one side or the other of the harmonic so as not to increase the risks of voltage instability due to system resonances (see pages 44-46 of [7]).

So, if you want to use passive harmonic filters on your system or installation, I always recommend employing professionals with a proven track record in your type of system or installation (ask for references), instead of trying to do it yourself.

There is another type of passive harmonic filter that is unlike traditional passive filters, typically used in large systems and installations worldwide, including offshore. Called a "wide spectrum filter" it uses a proprietary design based on multi-limbed inductors (chokes) wound on a common core and fitted with a small bank of capacitors.

These filters are connected in series with the load(s) and – depending on manufacturer – can reduce I_{thd} to around 5%. One manufacturer supplies these filters with ratings up to almost 3,000kW for use with both AC and DC motor drives. Being passive and linear, they do not add to any EMI emissions. A Google search for these wide spectrum filters turns up www.mirusinternational.com/pages/lineator.htm and www.harmonicsolutions.co.uk/solutions/solutions1.html, probably good places to start learning about this proprietary technology.

Passive filtering of interharmonics gets progressively more difficult/costly at frequencies below 100Hz due to the physical size of the components, plus it is difficult to filter interharmonic frequencies that are within ±20% of the mains frequency due to power losses in the filter.

5.2.6 Series chokes ("reactors") in the DC or the AC supply

A warning about terminology

I tend to use the word "choke" as a synonym for (means the same as) inductor, and most electronic designers would find this unexceptional. But in electrical systems and installations they tend to refer to inductors as "reactors".

This seems very odd to me. I think of an electrical reactor as a component that produces reactive impedance, which means that capacitors are reactors as well as inductors. But the common usage in systems and installations is that a "reactor" means an inductor (a choke) and "reactance" is inductive impedance, whereas a capacitor is a capacitor and creates capacitive impedance. It is faulty terminology that can lead to misunderstandings, so beware!

Now back to the plot….

Electronic engineers should refer to section 10.4 of [5], which concerns adding chokes in the DC rails between the bridge rectifier and its unregulated storage capacitors. This method works on DM and/or CM harmonic emissions, depending on the design of the chokes.

Of course, systems and installation engineers cannot add series chokes in the DC power rails of purchased equipment without invalidating their warranties (and probably also considerably reducing their reliability).

But they *can* (and do) add series chokes in the AC mains supplies to the purchased equipment, and this common technique is discussed on page 392 of [5], pages 51-52 of [7] and page 49 of [3].

Although not as powerful as adding DC chokes in series with the DC supplies inside an equipment, it is nevertheless a useful technique when we are struggling to ensure that an upgrade to the motor drives in our plant room does not prevent our site from complying with G5/4-1 (see [56], [57], [58]), so that it is still permitted to be connected to the national HV grid.

It is also a useful technique when struggling to prevent the motors in our Explosive Atmosphere areas from running so hot that they can ignite the flammable gasses or vapours present and cause fire/explosion that could kill many people and significantly harm our company's income for a year or three.

Series chokes cannot be expected to significantly reduce interharmonics at frequencies below 100Hz.

I am old enough to have cut my teeth on thermionic valve circuits (i.e. "vacuum tubes", for our readers across the Atlantic) in my teenage years. Valve (tube) rectifiers were always designed with a series choke between them and their unregulated voltage storage capacitors, because they could not handle the current peaks that would otherwise occur. These chokes would typically be about half the size of the equipment's mains step-up/down transformer.

I can still remember the thrill of replacing big hot valves (tubes) with little black epoxy blocks – the first silicon rectifiers – and how we immediately stopped using the series DC chokes, because they were big, heavy and expensive and the new silicon rectifiers would handle the peak currents without them. If only we had all kept using the series chokes, we would not now be having to control harmonic emissions!

5.2.7 Charge-pump switch-mode technique

Electronic engineers should refer to section 10.5 of [5]. This equipment-design technique is not appropriate for systems and installations engineers, and it works on both DM and CM harmonic currents.

5.2.8 'Active' PFC circuits

Electronic engineers should refer to section 10.6 of [5], which describes an equipment design technique that is not appropriate for systems and installations engineering. It suppresses both DM and CM harmonic currents.

5.2.9 Interleaved active PFC

This is an equipment design technique that uses two boost converters operating 180° out of phase with each other, so the ripple currents in their boost inductors – which, after passing through the bridge rectifier, result in harmonic currents in the mains supply – are (almost exactly) 180° out of phase, and so (mostly) cancel out in the mains input.

It used to be necessary to use discrete components for this, but now there are some PFC controllers available that have been specifically designed for this technique, including: UCC28070 and UCC 28060.

This is not a suitable technique for systems and installations engineering, and works on both DM and CM harmonic currents.

5.2.10 6-phase (or more) rectification

Electronic engineers should refer to section 10.7 of [5], which works for both DM and CM harmonic currents.

It is also an appropriate technique for systems and installations engineers who specify/purchase rectifiers separately from the power converters. The rectifiers provide a "DC Link" that is a common DC bus for a number of power converters, for example a single 10kW rectifier might power a DC Link that feeds a dozen or more 1kW motor drives. The relevant references for systems and installations are pages 58-60 of [7] and the small comment on page 21 of [3]).

Single-phase VSDs and VFDs suffer from emitting all of the odd-numbered mains harmonics, including triplens as mentioned earlier. On four wire systems (i.e. 3 phase + N) the triplens add arithmetically in the neutral conductor, and can cause significant problems with localised power quality and equipment operation.

However, three-phase (6-pulse) drives running from reasonably low-distortion mains supplies have very low levels of "triplen" harmonics, of which the most important are the 3rd and 9th. Losing the 3rd makes it significantly easier to use series inductors in the AC supply (see 5.2.6 above) to get good reductions in a rectifier's harmonic emissions.

Transformers with star and delta secondaries have a 60° phase-shift between their star and delta windings, so feeding two 3-phase bridges from each secondary and then linking their unregulated DC outputs creates a 6-phase (often called 12-pulse) rectifier.

12-pulse rectifiers have significantly reduced emissions of 5th and 7th harmonics, and their first significant emission of mains harmonics is the 11th.

So-called "Zig-Zag" transformers [59] can be used to create phase shifts other than 60°, allowing the creation of bridges with more than 12-pulses (6 phases). For example, a 24-pulse rectifier is created by using a mains transfer with windings giving 30° phase shifts, and four sets of 3-phase rectifiers feeding a common DC rail, and has significantly reduced emissions of 11th and 13th harmonics.

However, for the technique to be effective the requirement for well-balanced, low-distortion mains supplies increases as the pulse number of the rectifier increases. Vehicles, ships and offshore platforms often operate with their AC generators highly loaded by non-linear loads, and as a result often have severely distorted mains supplies, making it difficult to use this technique, but with appropriate filtering they can successfully use 12-phase (24-pulse) rectifiers – refer to the American Bureau of Shipping's guidance [60].

The DC choke method of 5.2.6 can be used to great effect with rectifiers having three or more phases. For a given harmonic attenuation it will generally be a lot smaller than would be needed for a single-phase rectifier of the same rating.

5.2.11 Active front end (AFE) rectification

Electronic engineers should refer to section 10.8 of [5]. This is not a technique that can be applied at the system/installation level, and it suppresses both DM and CM harmonic current emissions.

Some of the techniques described above have been used for many decades, but the "active front end" (AFE) technique, which uses IGBTs instead of plain old rectifiers, is a relatively recent development at the time of writing (September 2011).

The IGBTs are switched at a high rate, just like a chopper that drives PWM into a motor, but powerful signal processors and their controlling software arrange the sequencing and timing of their switching so that – after passing through a series inductor to average out the high-frequency PWM – the result is a rectifier that appears to the mains supply as a substantially linear (i.e. resistive) load. AFEs are claimed to be able to achieve low emissions of mains harmonics (< 5% I_{thd}).

However, AFEs achieve this at the cost of significant high-frequency harmonic currents in the supply at the switching frequency of the AFE bridge, higher EMI emissions between 10kHz and 100kHz, and a number of other EMC issues.

AFE rectifiers, being series devices, have to be dimensioned for the total load. This, of course, is a matter of equipment selection, and is not otherwise under the control of a system integrator or installer.

It is always great fun to read the various articles in the industrial press, in which the suppliers of motor drives and other products using AFE and the suppliers of other techniques for harmonic reduction, argue the toss over whose approach is better, or more cost-effective. Sometimes one can even learn something from such exchanges.

An interesting aspect of AFE technology is that it can also – with suitable IGBT gate switching patterns – provide bi-directional power transfer. For example if used in a motor drive it can transfer power from the motor back to the AC mains supply, i.e. regenerative braking.

I have worked on converters for solar photovoltaic panels that used such technology to add mains power to the PV power when the sun was not bright enough for the PV to supply the full load, which could also export power to the national grid when the solar power available exceeded the load's requirements.

5.2.12 Anti-harmonic injection, usually called "Active Filtering"

Electronic engineers should refer to section 10.9 of [5], and systems and installations engineers should see pages 54-55 of [7] and 50-51 of [3]. This technique is used to suppress DM harmonic emissions, but there seems to me to be no reason why it could not be used to suppress CM currents instead (or as well).

I call this an anti-harmonic injection technique, but the manufacturers of products intended for cleaning up harmonic pollution from mains distribution networks generally call them "active filters". This is despite the fact that neither the technique nor the products have anything at all to do with *actually filtering* the mains supply, see Figure 5.2-4.

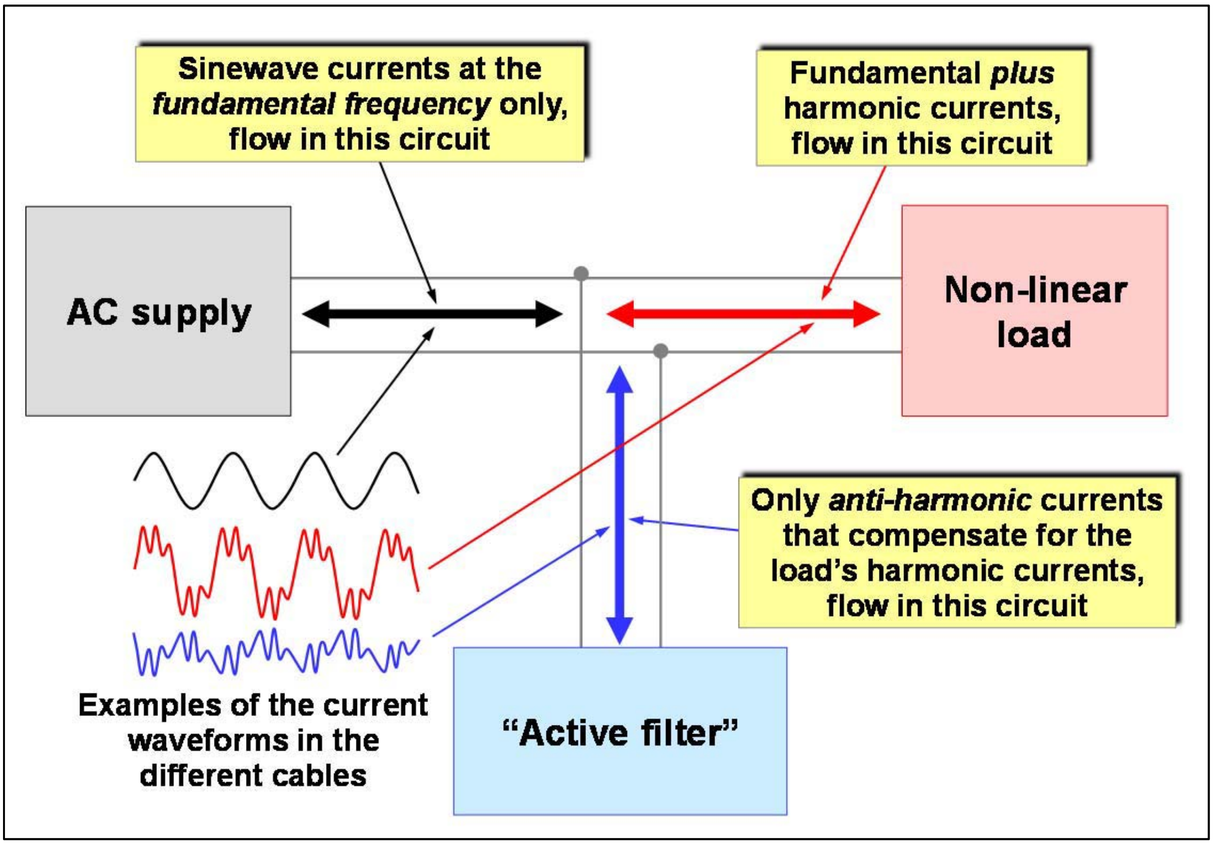


Figure 5.2-4 Principle of operation of so-called "active filters"

The technique uses switch-mode AC-AC power inverter technology, and can be applied in a way that makes it relatively immune to phase imbalance and distorted supply waveforms – so it acts on the emissions from an item of equipment and does not try to correct the entire mains distribution network it is connected to.

Active filters can be designed into products to reduce their harmonic emissions into their mains supplies, but are more commonly used to reduce the levels of harmonic currents (and hence the levels of harmonic voltage distortion) for systems and installations. For example, like passive harmonic filters, they can be applied to:

- A whole building or site, to reduce its harmonic emissions at its point of common connection to the MV or HV supply. (For example to help comply with the G5/4 requirements [56], [57], [58] for connection to the MV or HV grids in the UK. Other countries have similar harmonic requirements.)
- A whole building or site, to reduce the exposure of its MV or HV transformer to harmonic currents that would cause it to overheat (or else require costly over-rating).
- A whole vehicle, ship or offshore platform to reduce the exposure of its generator to harmonic currents that would cause it to overheat (or else require costly over-rating).
- A branch circuit (e.g. one floor of a tower block) to reduce the harmonic levels elsewhere in the mains feeder and other branches of an LV distribution network. (Has little/no effect on the harmonic distortion of that branch itself)
- A single item of equipment (typically a large machine or power converter) to keep its harmonics out of all of the LV distribution of its ship, platform, vehicle, building or site.

Active filters are expensive but widely used. Depending on the type, they can reduce emissions of harmonic voltage distortion to below 5%. They are connected in parallel with the mains supply and so only need to be rated for the harmonic current, unlike series-connected passive filters – which have to carry the whole of the load current (see 5.2.5 above).

5.2.13 Other techniques for systems and installations

If the above techniques don’t provide enough harmonic reduction in a system or installation, or are impractical for some reason, we are left with the following techniques:

- Isolating an especially “noisy” or “sensitive” branch of the mains distribution by isolating and regenerating the mains power that supplies it, to remove all DM and CM harmonic currents.
- Isolating the mains power with a transformer that has a Delta winding for its primary and/or secondary, to remove DM triplens and all CM harmonic currents.
- Ignore harmonic suppression and simply uprate cables, transformers, motors, overcurrent protectors and other mains-powered components to be able to handle the distorted mains supply and/or harmonic currents without compromising reliability.

Isolation for a distribution network branch was traditionally achieved by using a motor-generator set, and many scientific survey vessels have used them to generate “clean” sinewave power for their sensitive instruments. These days an uninterruptible power supply (UPS) would most likely be used instead, but it must be an isolating continuous on-line double-conversion type.

Beware of M-G sets and UPSs that have such high emissions of harmonics that they make the problem worse, or create new problems due to their poor EMC, or are too unreliable.

The side of the M-G set or UPS that has to deal with highly-distorted mains must be appropriately rated for the harmonics, and up-rating is discussed last in this section.

Single-phase rectifiers generate triplen harmonics, which add constructively in 3-phase AC mains distribution systems, so in installations where most of the load is single-phase, the 3rd harmonic generally has the highest levels and causes the most overheating problems.

An example of this exact problem affecting a major road tunnel lighting scheme is given in Figures 11 and 12 of [7] and their associated text, and it is only one of the road tunnel lighting scheme harmonic problems that I have worked on over the last 21 years.

Passing the 3-phase through a star-delta transformer attenuates the DM triplen harmonics, and the better the balance of the triplens on the phases, the better the attenuation.

But the energy in the triplen harmonics circulates as a zero-phase flux in the transformer’s Delta windings, so it is important to uprate the transformer so that it can handle the additional iron and related losses without overheating or otherwise compromising its reliability.

For legacy systems and installations, uprating is the costly option that we are left with when all else fails. However, for a new build it can sometimes be the easiest and most reliable method of dealing with harmonics, possibly even the lowest-cost (although it won’t help you win any carbon credits).

Essentially, all we do is calculate the harmonic current loading on the various branches and the whole AC supply distribution network, then design our cabling, transformers, motors, overcurrent protectors and other mains-powered components to handle the additional heat generated by the harmonic currents and by the harmonically distorted mains supply voltage.

Pages 9, 19 and 20 of [7] provide some simple formulae for calculating how to uprate conductors and transformers.

But *never uprate overcurrent protection devices*, except when uprating everything else accordingly, see 5.2.14 below.

5.2.14 Overcurrent protection, safety, and the effects of harmonics

Although not an EMC issue, I feel that it is important to add a final note about overcurrent protectors, such as fuses and thermal and/or magnetic circuit breakers, because of the very significant safety issues that often arise with them as a result of harmonic current "pollution".

Electricians are often supplied with low-cost multimeters, which with the addition of current clamps can measure currents up to kA. It is often found with legacy installations that, as the old energy-inefficient plant is replaced by shiny new electronically-controlled plant, fuses and circuit breakers can start to open when measurements of the currents in the cables show that they are still within their current ratings.

The usual solution is to uprate the overcurrent protection, so we might find that a 100A cable carrying 100A of current (as measured with the low-cost multimeter and its current clamp) and protected by a 130A circuit breaker, because it only opens when the meter shows the current exceeds 100A.

The next thing that we find is that the cable insulation is starting to degrade through overheating, in certain places. If we are lucky we will discover this before we have a (possibly major) fire or explosion.

The problem is that the low-cost multimeters are average-responding types, calibrated as measuring RMS by using a pure sinewave. When measuring a real-life *impure* mains waveform, for example one that has significant levels of harmonic distortion, they can measure as much as 30% low, and so underestimate the real heating effect of a real-life voltage or current by nearly 70%.

These days, _*all*_ electrical measurements on equipment, systems and installations _*must*_ use true-RMS meters that have a frequency range of up to at least 2kHz (preferably 5kHz or more).

Thermal overcurrent protectors, whether they are fuses or circuit breakers, automatically respond perfectly correctly to any distorted current waveforms. But magnetic and other types of overcurrent protection will have trip responses that change with the level and type of distortion – unless they use electronic circuits that have a true-RMS response to at least 2kHz (preferably at least 5kHz).

So whenever we have problems because a thermal fuse or thermal circuit-breaker (or true-RMS electronic protector) is opening when the current in the cable, transformer, motor or other equipment it is protecting appears to be lower than should be needed to open it – we must always believe the overcurrent protector and question why it is that we think the current is too low.

See pages 15 to 19, and 43-44 of [7] for more detail on this important reliability and safety issue.

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