emc STANDARDS

Another EMC resource
from EMC Standards

EMC design of Switching Power Converters Part 7 (continued 2)

Helping you solve your EMC problems

9 Bracken View, Brocton, Stafford ST17 0TF T:+44 (0) 1785 660247 E:info@emcstandards.co.uk

EMC design of Switching Power Converters

Part 7 — Suppressing RF emissions from inputs and outputs *(continued 1)*

First published in The EMC Journal, Issue 99, March 2012

Keith Armstrong, Cherry Clough Consultants Ltd, www.cherryclough.com

Contents

Issues 93 – 98 of The EMC Journal carried earlier 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 *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.

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

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

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].

7 Suppressing RF emissions from inputs and outputs

I will discuss suppressing low-frequency emissions (mains harmonics and other noise emissions below 150kHz) in a later article.

7.3 Designing or choosing effective filters

Subsections 7.1 -7.3 of this topic appeared in Issue 98 of the EMC Journal [72], and this Issue completes subsection 7.3 and covers 7.4 too. The remainder of section 7 is intended to appear in a later article.

7.3.5 Combining capacitive and inductive (choke) RF filtering *(continued from [72])*

Sorry, but I forgot to include this in section 7.3.5 in the previous Issue of the EMC Journal [72].

As I mentioned in section 7.3.4 of [72] it is usual to wind CM chokes bifilar, to minimise their DM inductance. But for AC and DC power filtering we often need DM inductance as well as CM inductance, and some manufacturers (e.g. Murata) make “leaky” CM chokes that create high CM and DM (leakage) inductances at the same time, and using them helps save PCB area and cost.

Now we get to the bit that I meant to include last time – it’s the situation that faces many circuit designers when they have to run a number of DC/DC converters to provide power rails at different voltages from a common DC bus (e.g. +5V), or when they have to run a number of DC/DC converters in parallel (e.g. multi-phased, see section 2.10 in [42]) from a common DC bus.

Figure 7.3-9 shows the use of CM + DM chokes to help prevent the emissions from the DC/DC converters from adding up in their common DC bus and making it too noisy.

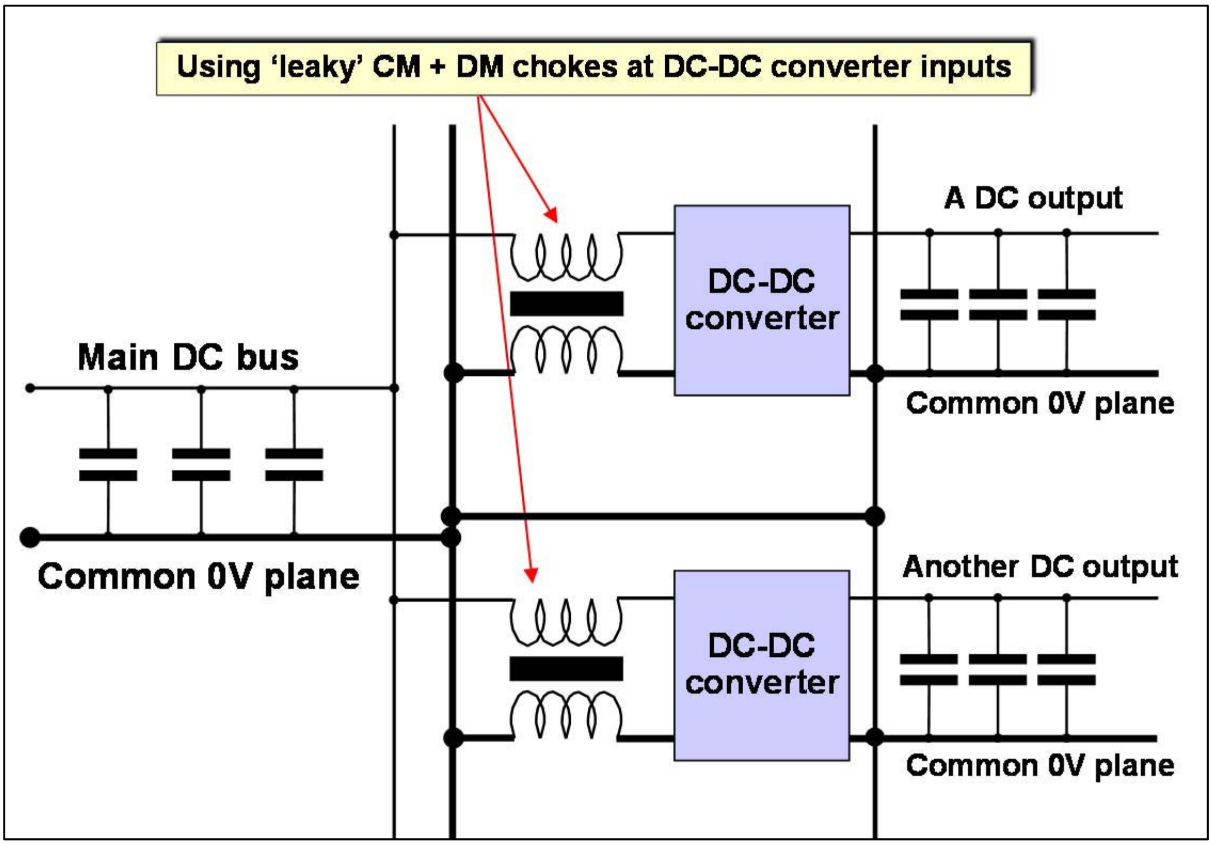

Figure 7.3-9 Example of using ‘leaky’ CM chokes at DC-DC converter inputs

7.3.6 Many different kinds of proprietary mains filters

Figures 7.3-10 and 7.3-11 show a variety of items, all of them different kinds of power filters suitable for AC mains or DC power.

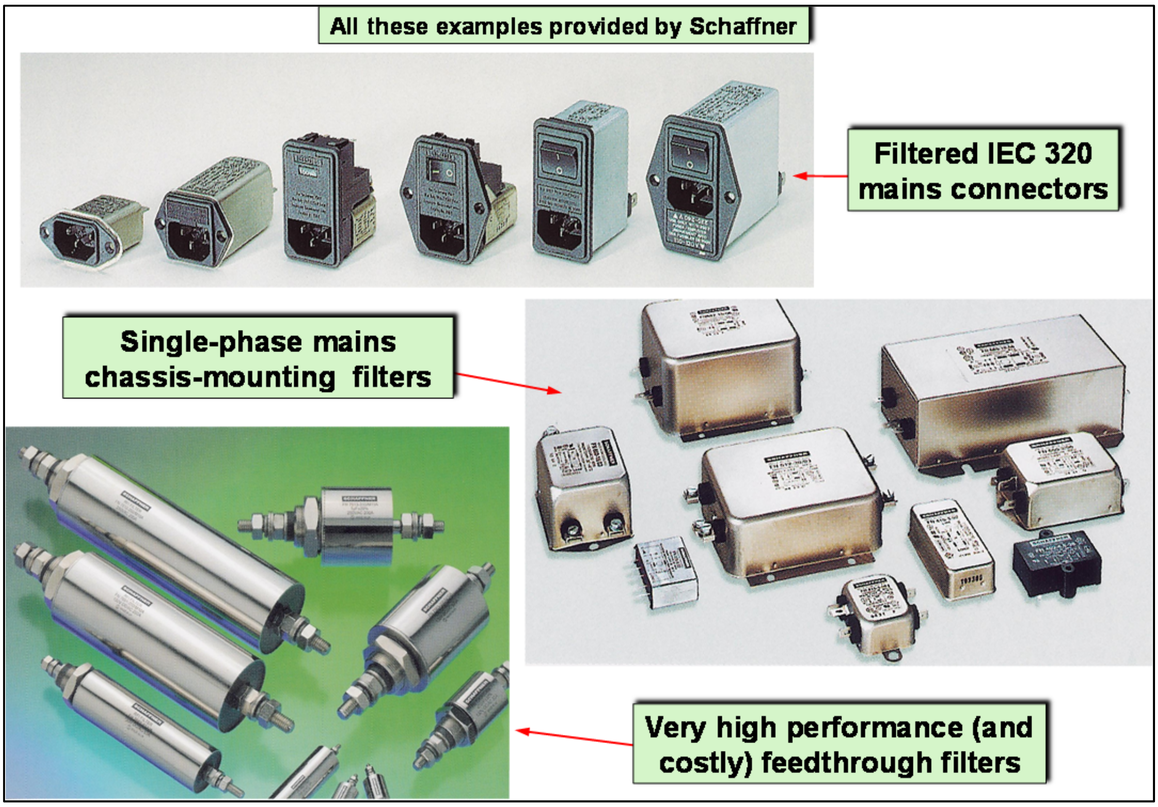

Figure 7.3-10 Some examples of power filters

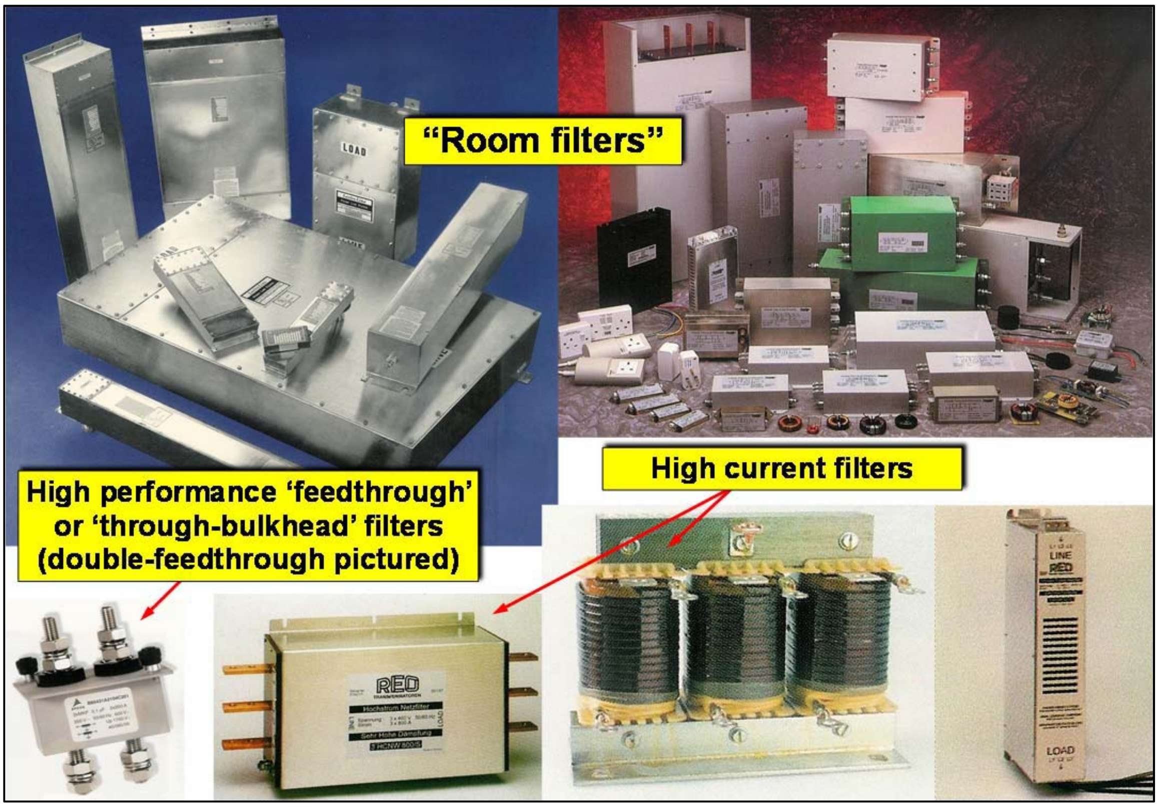

Figure 7.3-11 Some more examples of power filters

Some of the filters in these two figures are very expensive, and some are very low-cost. We would all like to use the low-cost ones, of course, but we can't rely on most filter manufacturer's data sheets to tell us how they will perform in real life.

Sections 7.3.7 through 7.3.9 below discuss the reasons for this, and how to deal them.

7.3.7 Basics of filter resonance and damping

Power input (AC or DC) filters are constructed from inductors and capacitors, so they can all suffer from resonances, amplifying some frequencies instead of attenuating!

Figure 7.3-12 shows a simple low-pass filter made with passive components – the basic building block of most EMI suppression filters intended for AC or DC power inputs or outputs.

A certain value of load resistor (R) is required for critical damping, which has no gain and is -3dB at the resonant frequency f_{res}. Lower values of R cause overdamping, and higher values cause some gain to occur around f_{res}.

Theoretically, an open-circuit for R would mean an infinite gain at f_{res}, but in practice the Ls and Cs have some intrinsic resistance, as do the conductors that connect them together, and the open-circuit has some stray capacitance, so infinite gain is never realised.

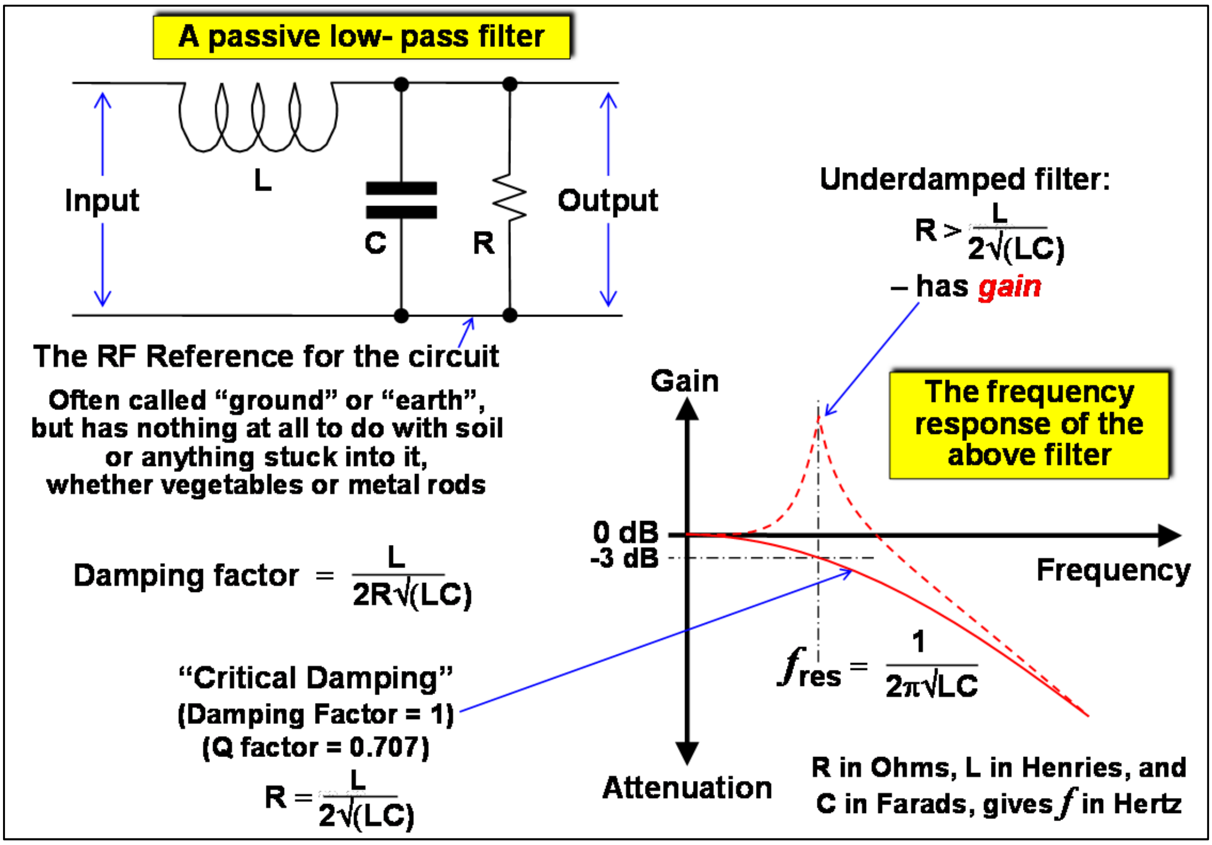

Figure 7.3-12 Underdamped low-pass filters have gain

Circuit values of 1H and 1F give f_{res} = 1Hz, and would be critically damped by a resistance of 0.5Ω. Values of L =1mH and C = 1μF give an f_{res} of just over 5kHz, critically damped by R =15.8Ω.

Filters are generally measured using test equipment with 50Ω inputs and outputs, so filter design usually starts with a load resistor of 50Ω and selects the values of L and C depending on the value required for f_{res} and for the damping factor. So, for example, if we wanted to achieve a damping factor of 1 and an f_{res} of 5kHz with a load resistance of 50Ω, we would choose L = 3.19mH and C = 0.319μF. Of course, in practice we would choose the nearest standard values that got us closest to our design goals. For more on the equations for filter design and damping, see section D.6 of [71] and [73].

In real life, of course, AC and DC power filters are almost *never* working into 50Ω resistive loads. Indeed, their loads are generally complex impedances that vary – and also vary their phase angles between capacitive and inductive – over the frequency range being filtered.

Here are some very generalised examples of AC and DC power source and load impedances (don't use these figures for design!)….

Domestic 50Hz mains supply at wall socket:

Differential Mode (DM): 2Ω to 2kΩ depending on the frequency, varying as other loads on the distribution network are switched off or on.

Common Mode (CM): 1MΩ to 20Ω depending on the frequency, varying as other loads on the distribution network are switched off or on.

Bridge-rectifier and storage capacitor AC power input:

DM: Either <10mΩ or >1MΩ depending on the frequency, switching between them at 100Hz as the rectifiers switch on/off.

CM: 10MΩ to 100Ω depending on the frequency, and varying at 100Hz as the rectifiers switch on/off.

Dedicated traction battery with cables < 2m long:

DM: 1mΩ to 1kΩ depending on frequency and state of charge, temperature and age of the battery.

CM: 10MΩ to 100Ω depending on the frequency.

48V DC supply distribution (e.g. telecoms central office, data centre using blade servers):

DM: 20mΩ to 2kΩ depending on frequency and location in network, and on the state of charge, temperature and age of the battery.

CM: 1MΩ to 100Ω depending on the frequency and location in network.

Both also depend on what loads are connected to the DC distribution, and where they are located, so can change with time.

CISPR 17 [74] is the test standard for the attenuation of mains filters, and requires tests to be done with 50Ω resistive source and load, known as "matched 50/50" tests. Because this is the standard test, filter manufacturers design their filters to look good on this test, and most designers will choose the filters that look the best on these tests whilst costing the least – but this is a big mistake.

Because AC and DC power filters almost never have resistive 50Ω inputs and outputs, we cannot reliably choose cost-effective filters on the basis of their "matched 50/50" measurement data!

7.3.8 How to deal with filters that are insufficiently damped in real life

CISPR 17 [74] recognises the problem of non-50Ω source and load impedances, and includes optional tests using 100Ω source with 0.1Ω load, and 0.1Ω source with 100Ω load, known as "mismatched 100/0.1" and "mismatched 0.1/100" tests respectively.

A complete set of filter attenuation curves covers both DM (known as "symmetrical") and CM (known as asymmetrical"), for all of the CISPR 17 matched and mismatched tests, making 6 curves in all. Figure 7.3-13 shows three of these curves taken from the datasheet of a standard volume-manufactured proprietary single-stage (hence low-cost) mains filter. The single mismatched curve included shows a gain of nearly 20dB around 250kHz.

In general, filters with two or more stages have mismatch resonances that are lower in amplitude and lower in frequency than single-stage filters such as the example in Figure 7.3-12, although this will not be evident from their matched 50/50 test results and they will cost more.

Figure 7.3-13 indicates how to deal with this problem: we obtain all six CM and DM, matched and mismatched attenuation curves, plot their overall worst case, and use that as our guide to the real-life performance of the filter.

The result of this exercise isn't *really* the worst-case, because all the CISPR 17 tests use resistive sources and loads rather than complex impedances, and also they aren't as extreme as what will occur in real life – so it is best to allow an "engineering margin" for filter performance, say by assuming they are worse by a further 10dB.

Some filter manufacturers publish the mismatched figures for their filters as a matter of course, although of course they don't appear in short-form catalogues or distributors' data. Some filter manufacturers will test their products for mismatch upon request.

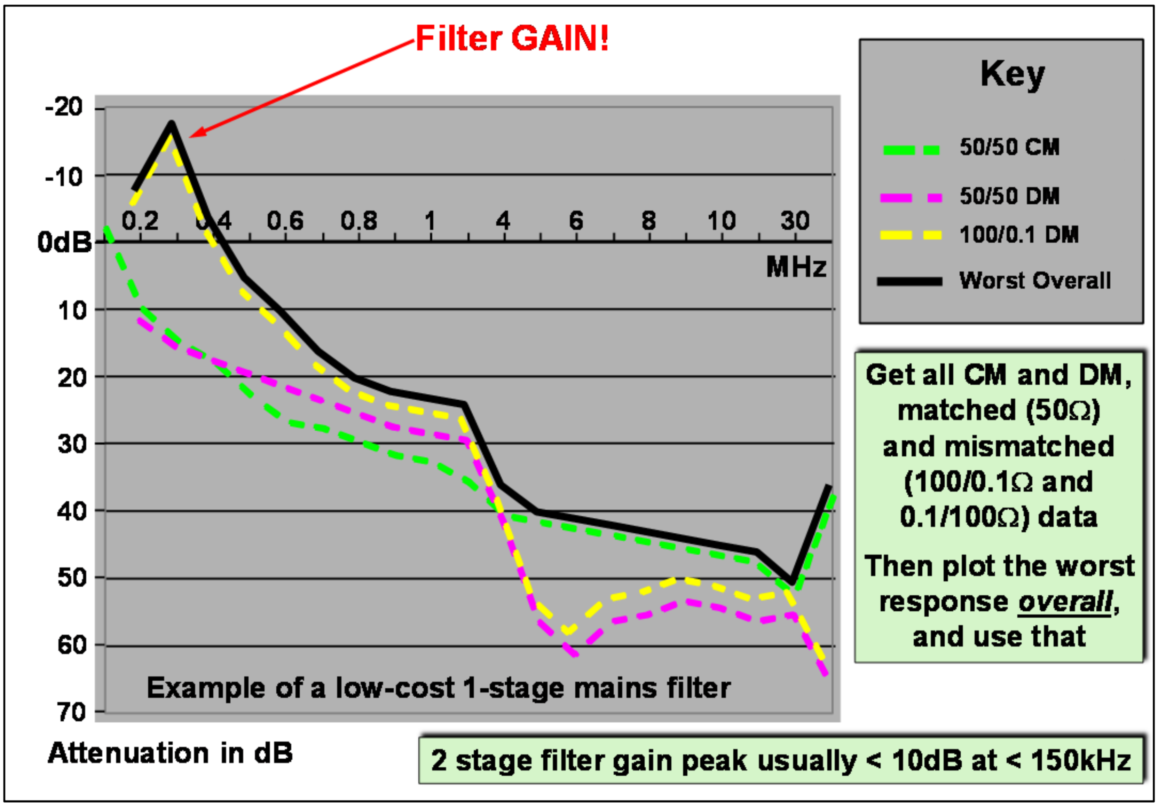

Figure 7.3-13 Example of a single-stage mains filter, matched and mismatched attenuation

Figure 7.3-14 through 7.3-19 shows the results I received in May 2011 from MPE Ltd when I requested a complete set of attenuation full test data for one of their high-performance mains filters whilst choosing the filters for the 2,000 or more control and instrumentation cabinets for ITER [75]. They provided me with the data within 24 hours of my request.

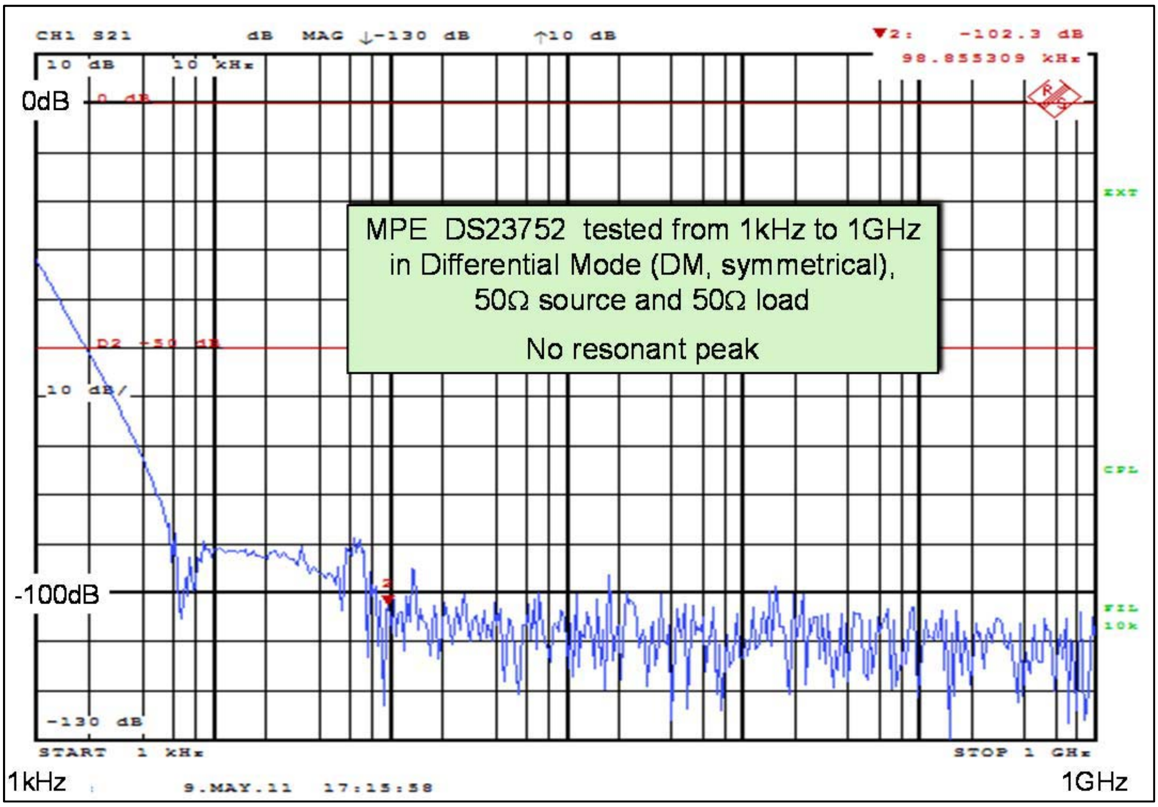

Figure 7.3-14 Example of high-performance mains filter, DM, matched 50/50

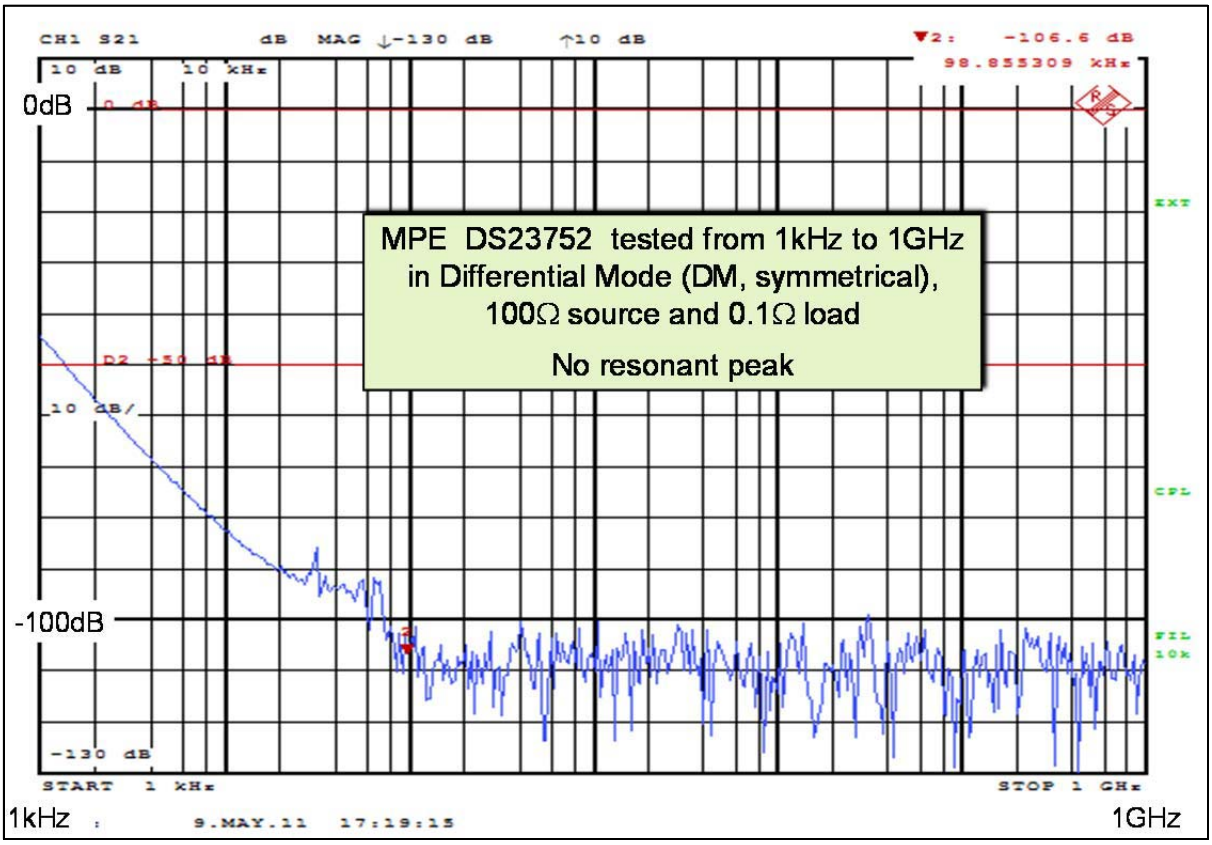

Figure 7.3-15 Example of high-performance mains filter, DM, mismatched 100/0.1

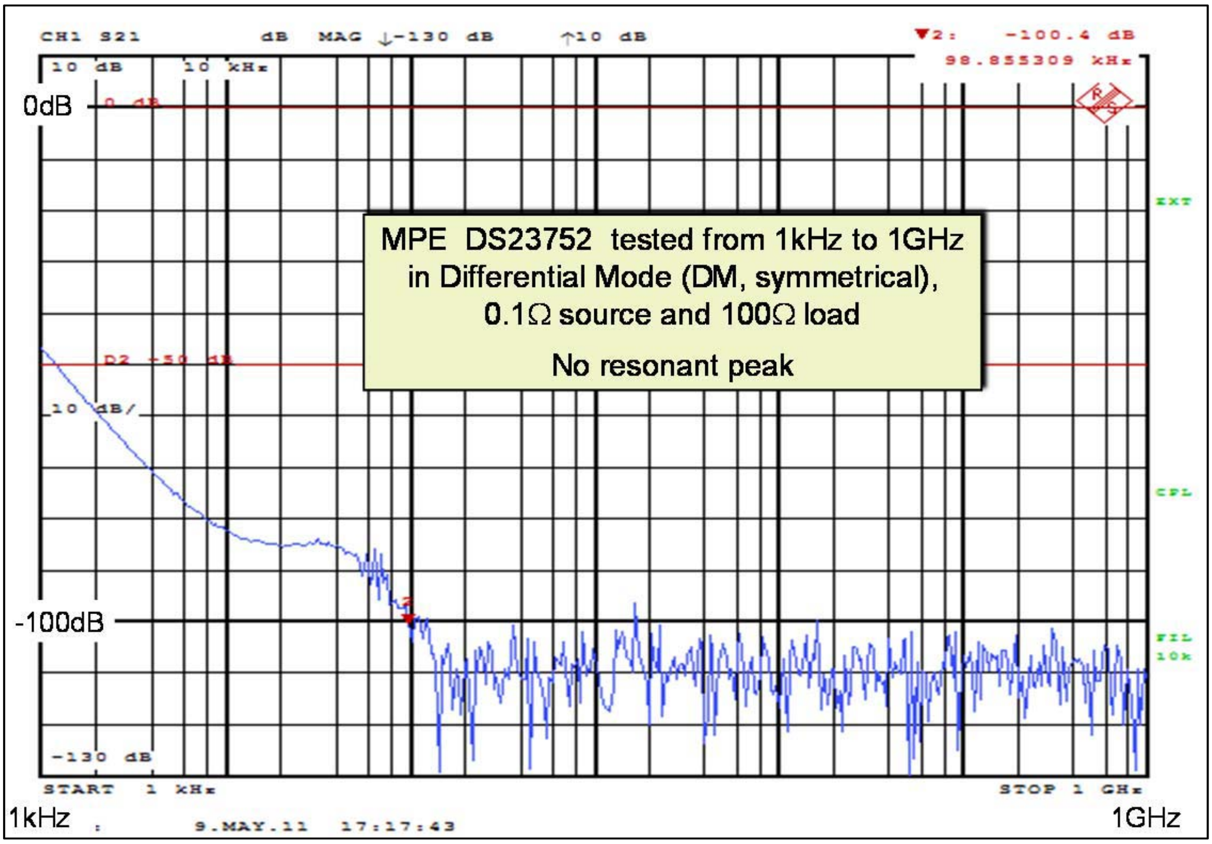

Figure 7.3-16 Example of high-performance mains filter, DM, mismatched 0.1/100

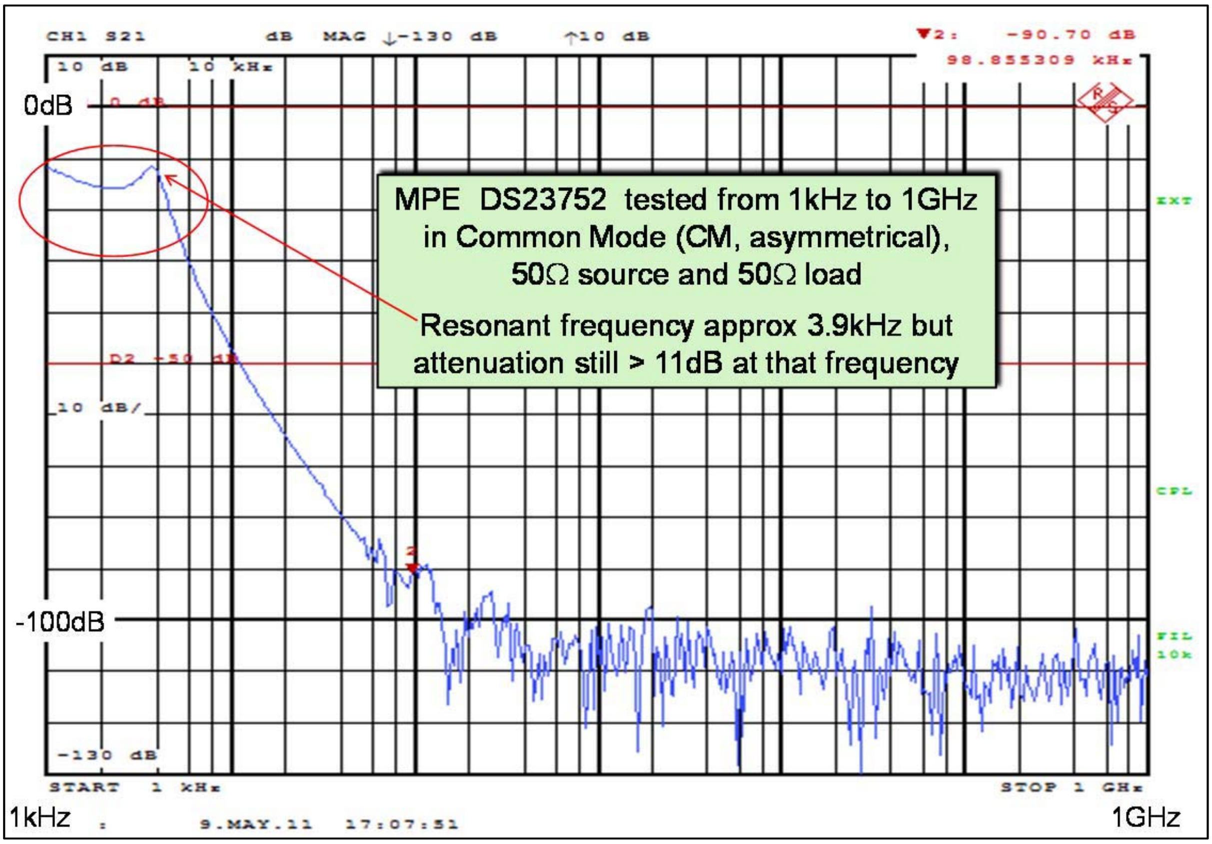

Figure 7.3-17 Example of high-performance mains filter, CM, matched 50/50

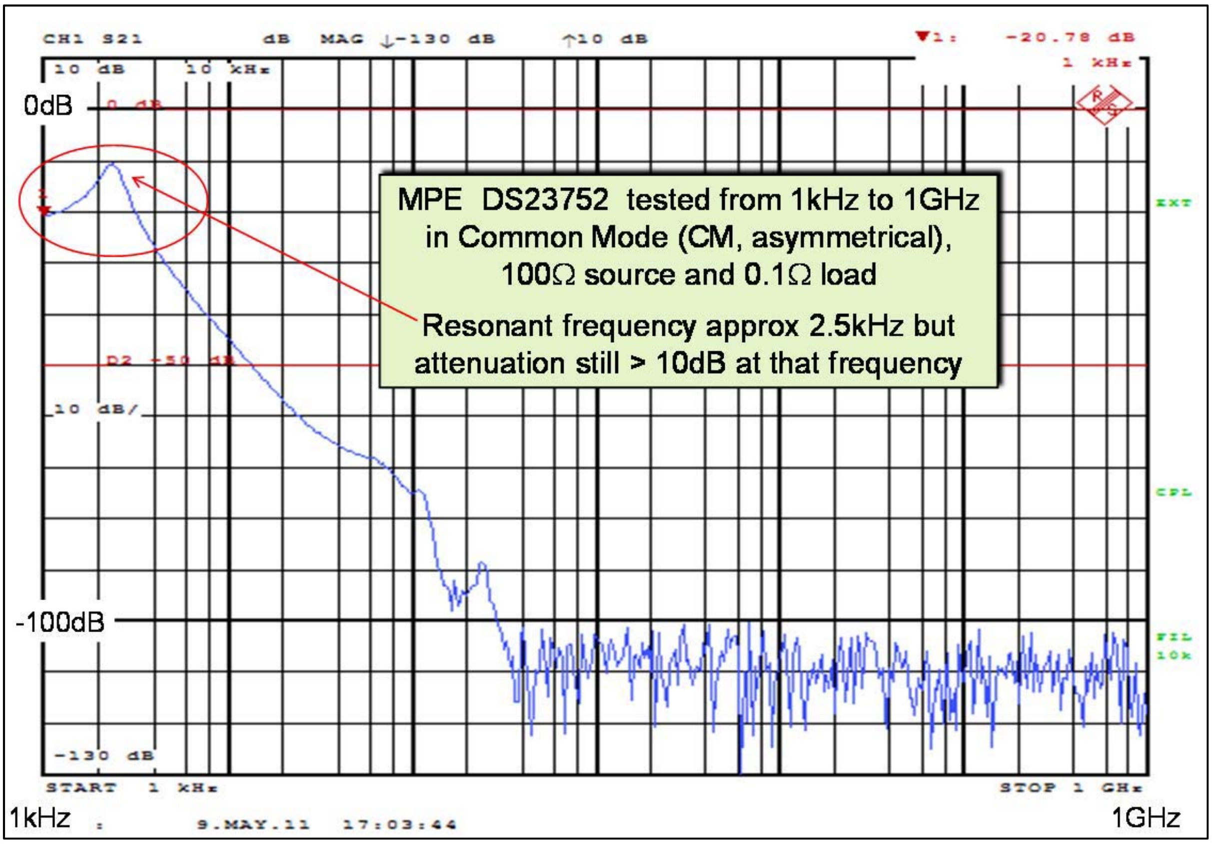

Figure 7.3-18 Example of high-performance mains filter, CM, matched 100/0.1

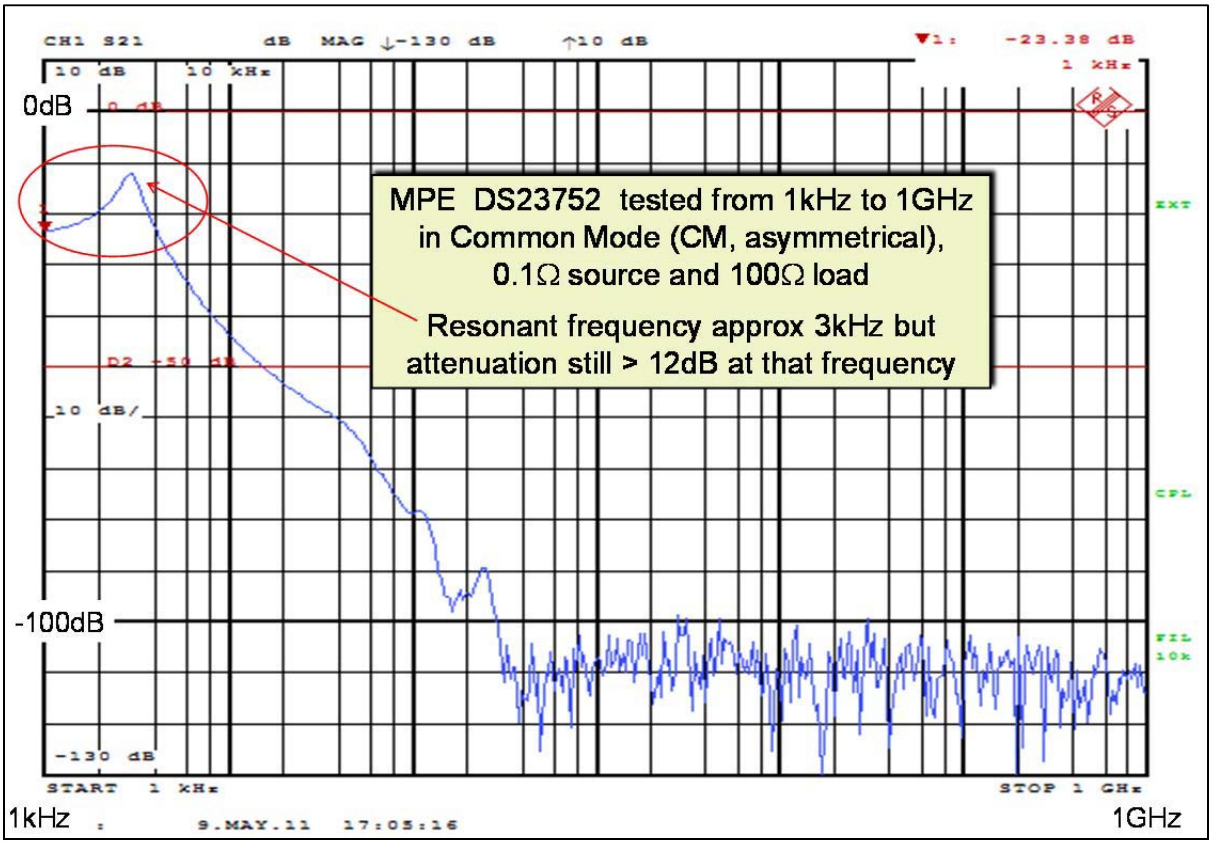

Figure 7.3-19 Example of high-performance mains filter, CM, mismatched 0.1/100

More information on choosing mains filters and dealing with real-life impedances that are not 50Ω *and* resistive is given in Chapters 5.2.8 and 5.2.9 of [5], and its Chapter 5.2.11 discusses how to dampen down mains filters so they don't produce quite so much "negative attenuation" (gain) when mismatched.

I had an interesting example of filter resonances some years ago when I was asked to "fix" the excessive emissions from a winch fitted to the outside of a Navy submarine. The winch was driven by a variable-speed motor and drive that switched at 1kHz, both inside a waterproof pressure housing that mounted on the outside of the submarine's hull.

Full marks to the designers for combining the drive and motor inside one metal box – the DC Link and motor cables were so very short and so well shielded that they were unlikely to cause any problems at the harmonic frequencies created by this drive.

The problem was that the military EMC conducted emissions standard that applied, measured from 200Hz to 100MHz, and the 1kHz drive had a virtually flat emissions spectrum about 10dB above the limit line, for every 1kHz spacing from 1kHz to 100MHz.

Filtering to reduce emissions by 20dB or more is an easy job, so I expected to finish the work in a morning, but by the end of the first day I had gone through dozens of filter designs using nearly all my samples of inductors, chokes and capacitors with no solution in sight.

What was keeping me from a quick solution, was that I could easily make filters that reduced the conducted emissions almost to the noise floor from 50kHz to 100MHz, but they all had a gain peak below that frequency, sometimes as low as a few kHz, and that gain peak boosted the emissions failure from 10dB to 20 or 30dB around its frequency. It was most frustrating!

If the drive had switched at 10kHz I could have arranged the filter resonance to either lie below 10kHz, or mid-way between 10 and 20kHz, but with 1kHz-spaced harmonics I couldn't make the filter's Q high enough not to amplify the harmonics on either side of it. And I didn't have large-enough values of components to get the resonance below 1kHz (nor did I want to use such large and costly parts anyway).

That night, eating dinner in my hotel, I remembered section 7.1 in [72] (well, actually, I remembered its basic premises, because I hadn't written that article at that time).

So at the start of the next day I asked the customer to dismantle the pressure housing so I could get at the drive itself. He wasn't very pleased, because it took over an hour to remove all the bolts and separate the two gasketted halves, but he did it, and it then took me five minutes to solder a single 470nF polypropylene capacitor across the DC link and reduce all the conducted emissions by 20dB. No mains filter was required at all, saving weight and cost. By lunchtime he had reassembled the pressure housing and we had confirmed that from 200Hz to 100MHz all the 1kHz-spaced emissions were now 10dB below the limit line and the winch complied with its conducted emissions standard.

As 7.1 says (see [72]) it is much better in every way to design a converter that has low emissions and only needs a little filtering and/or shielding (if any), than it is to design a converter without using good EMC engineering and expect to be able to suppress its excessive emissions by filtering and/or shielding.

With civilian emissions standards ceasing to measure conducted emissions at frequencies below 150kHz, it is not too hard to design or choose filters with resonances below 150kHz and pass the tests. But where power converters are switching below 150kHz these filters can easily amplify converter noise below 150kHz and risk causing interference problems in real life.

Remember, compliance with the EMC Directive means compliance with its Essential Requirements. Passing tests to all relevant standards listed under the EMC Directive is the usual method of being legally permitted to sign a Declaration of Conformity and applying the CE-Marking (although not the only method) – but if our products cause interference in real life, when used as intended, they don't comply with the Essential Requirements and are not legal to supply or use, even though they pass all the tests.

I had a good example of this a few years ago when a shiny new machining centre was installed in a factory that made metal fixings (nuts, bolts, screws, nails, etc.). The machining centre took sheet metal in, and spat finished fixings out, under computer control. When it was working it sounded like a heavy machine gun, and most of the other equipment on the factory malfunctioned.

A quick look at the mains waveform with an oscilloscope showed that whenever the new machining centre operated, about 20V pk-pk at around 15kHz appeared on the mains distribution for the entire factory.

EMC Directive-listed immunity standards only test conducted RF down to 150kHz, so the equipment had not been designed to withstand significant levels of mains noise at 15kHz.

The machining centre used a 55kW Siemens motor drive, and it was this that was causing the 15kHz mains noise, either the 5th harmonic of its 3kHz switching rate or the 3rd harmonic of its 5kHz switching rate – I don't remember which. The machining centre's manufacturer had not used the drive filter recommended by Siemens, instead they had had a lower-cost one made that still passed the conducted emissions test limits – at 150kHz and above.

But this filter resonated at 15kHz and – being underdamped – *amplified* the already large drive emissions at that frequency, causing mayhem in the rest of the factory.

All we had to do was get the machining centre manufacturer to replace the custom filter with the more costly one recommended by Siemens, which had a resonant frequency below the lowest drive emission frequency, and the 15kHz noise level fell to below 0.5V pk-pk and the rest of the factory was then unaffected.

Figure 7.3-20 is a photograph of this actual drive with its Siemens filter fitted, in its cabinet. I often use it as an example of good EMC engineering in industrial cabinet design, because its manufacturers had done a very good job indeed – except for assuming that complying with the emissions test standards would be sufficient for preventing interference in real life.

7.3.9 Filter resonances caused by the negative impedances of power converter inputs

All types of switch-mode power converters draw more current from the supply as the supply voltage decreases, and this means they have a negative input impedance.

Negative input impedances can cause resonances when the supply is via filters with significant series inductance, and they can be severe enough to damage the converters, and possibly even other equipment connected to the same power supply distribution network.

Solutions are to reduce the series inductance in the filter, and/or increase the value of capacitance that is connected across the power converter's input terminals.

For more on this issue, see [76]. Many more useful references can be found on the Internet.

7.3.10 Filter construction and installation

These issues are fairly comprehensively discussed in EMC Journal articles [14], books and guides I have written, so I won't duplicate their text here, but I have copied some of their figures as 7.3-21 to 7.3-33, covering (in order):

- Filters mounted on PCBs, see Chapters 2.6 of [37] and 5 of [5] for a lot more on these good EMC design techniques
- Filters mounted in the walls of small enclosures, such as personal computers (PCs), see Chapter 3.1 of [37] and 5.3 of [5] for a lot more on these good EMC design techniques
- Filters mounted in equipment cabinets, see [68] and Chapter 5 of [5] for more on these good EMC design techniques
- Filters installed in systems and installations, see Chapter 8 of [70] and Section 5.10 of [69].

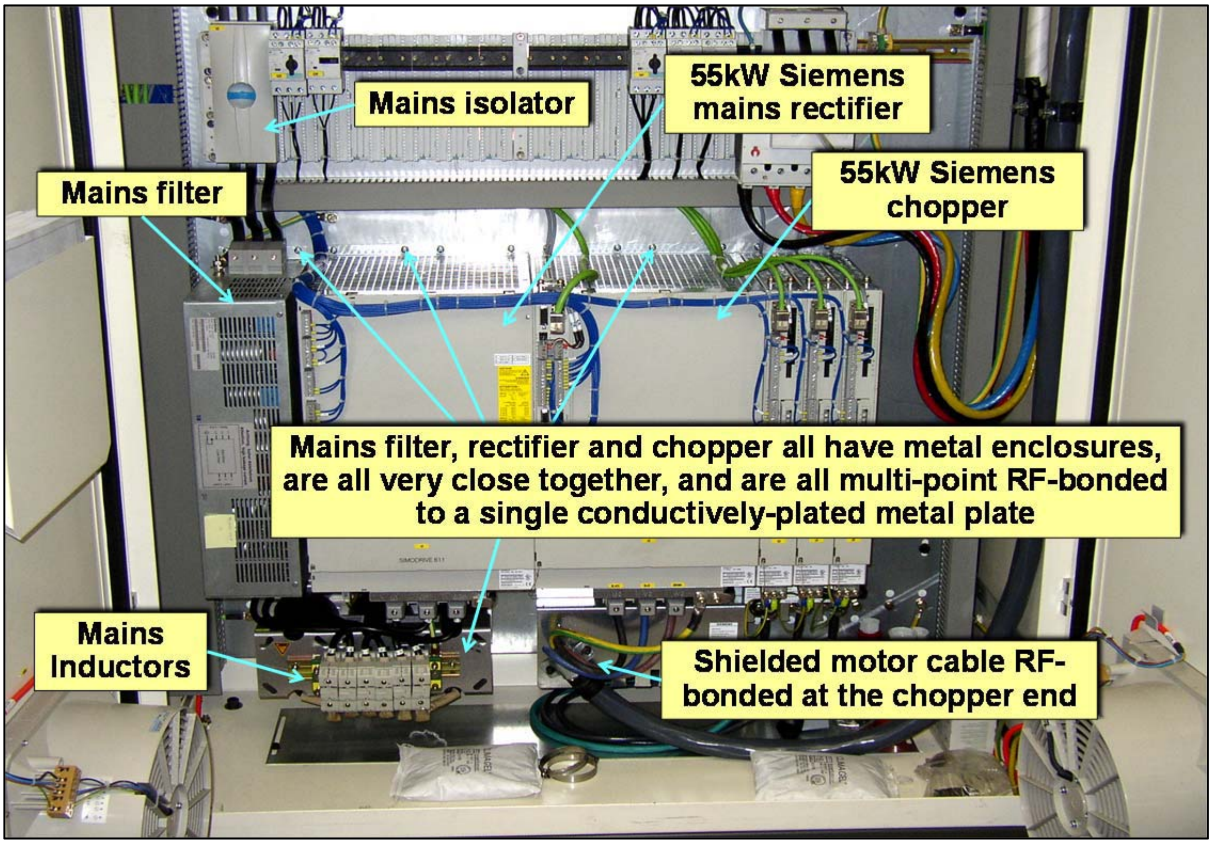

Figure 7.3-20 The Siemens 55kW drive with its associated mains filter, from the story above

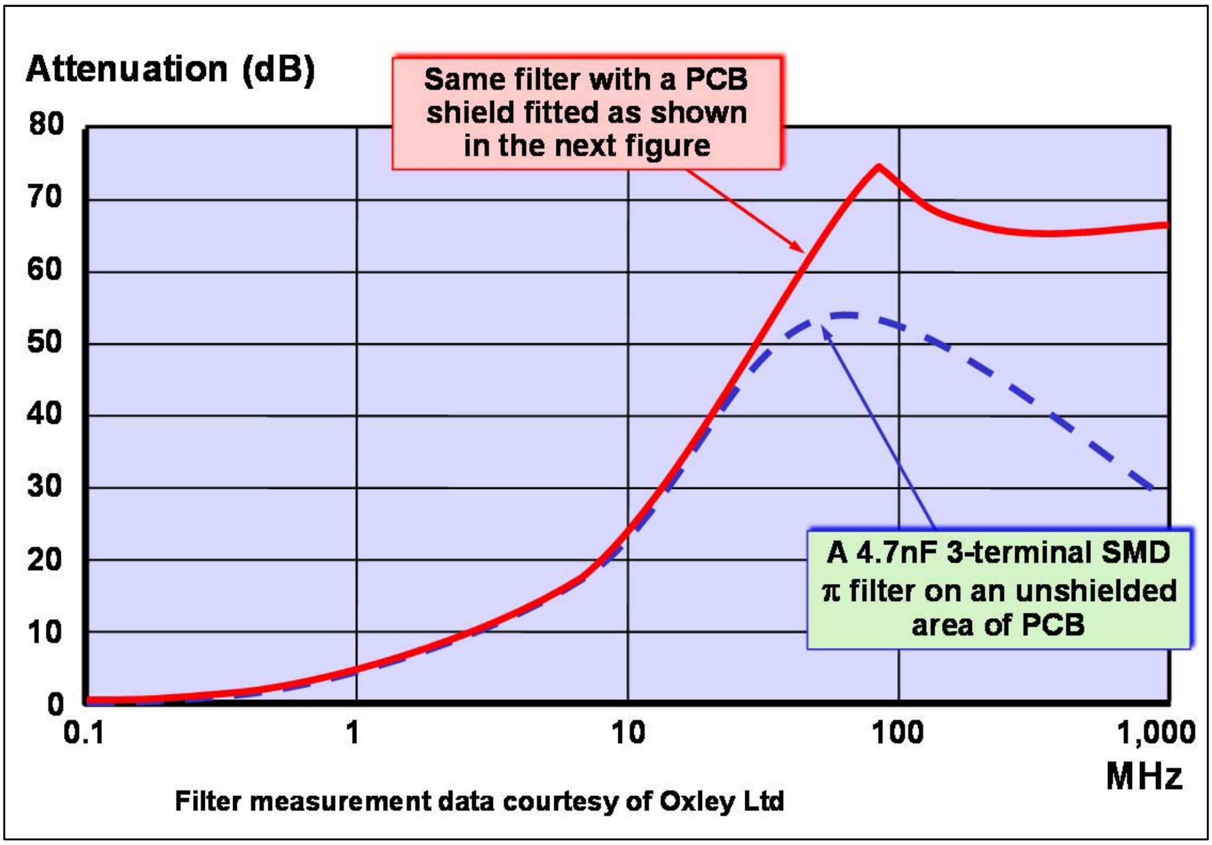

Figure 7.3-21 PCB filters benefit from shielding

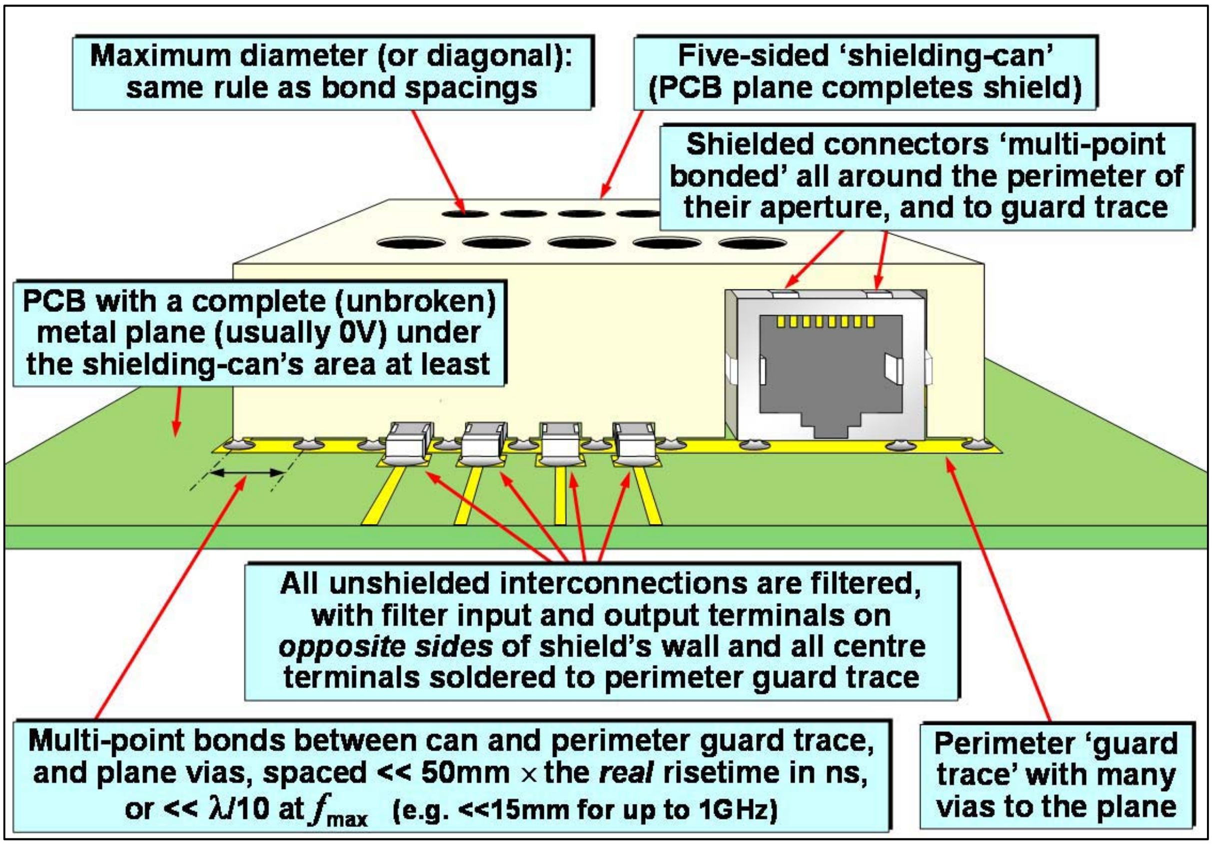

Figure 7.3-22 Overview of good EMC design by combining PCB shielding with filtering

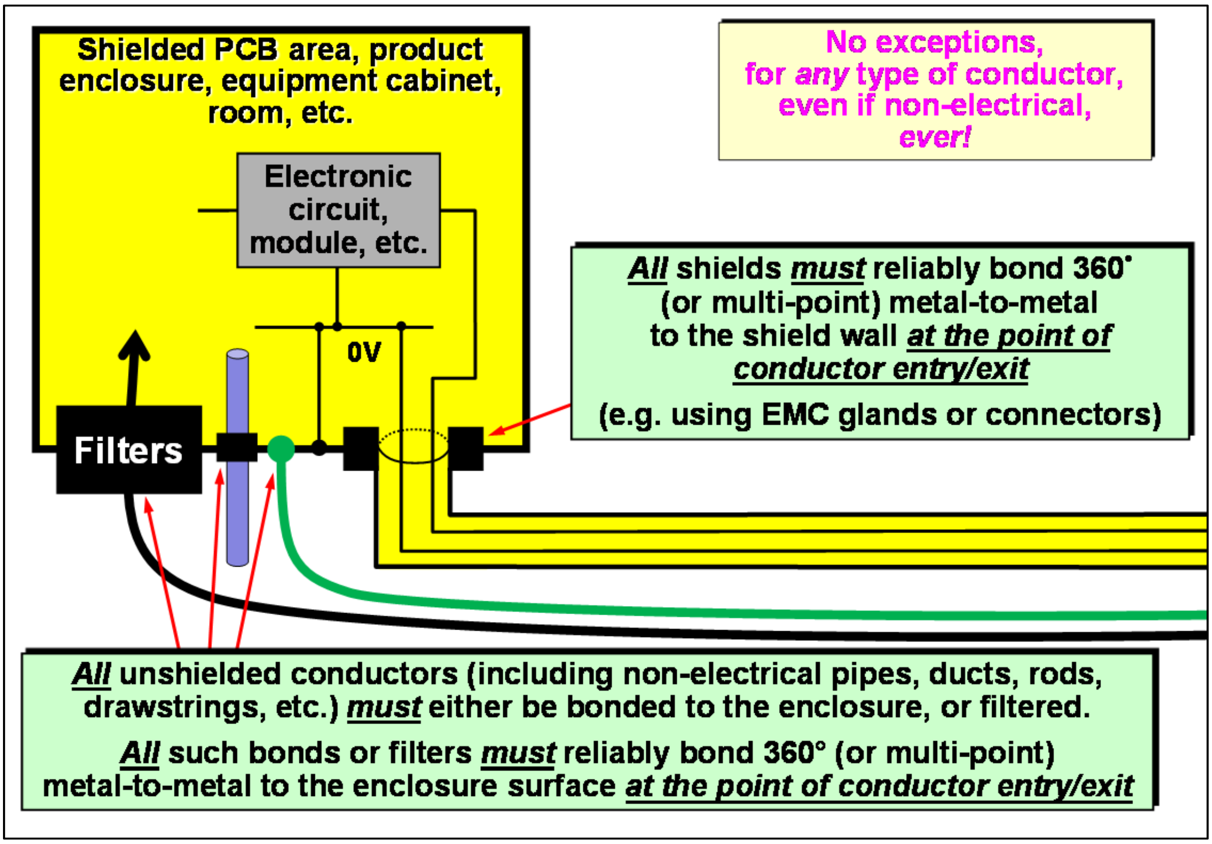

Figure 7.3-23 Dealing with conductors entering shielded enclosures/areas

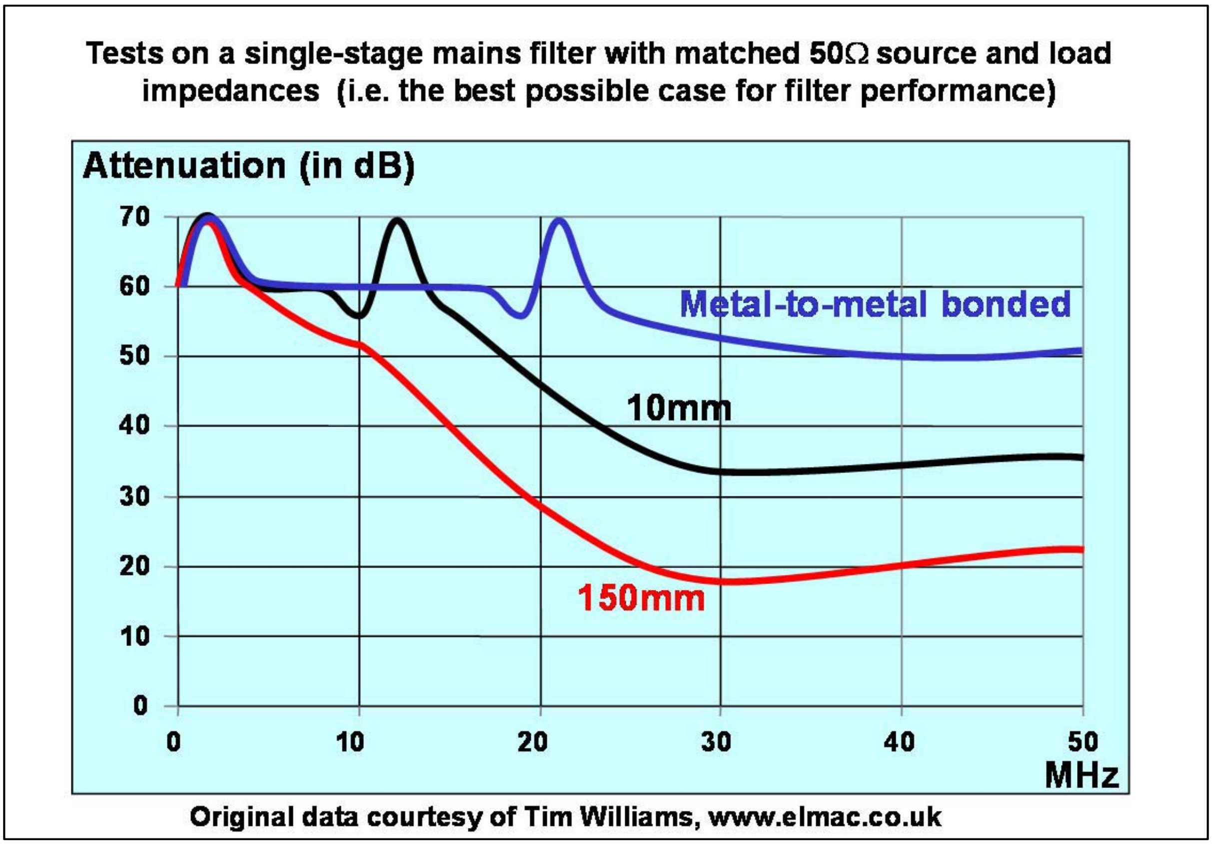

Figure 7.3-24 Comparison of two lengths of filter RF-bonding "earth" wire

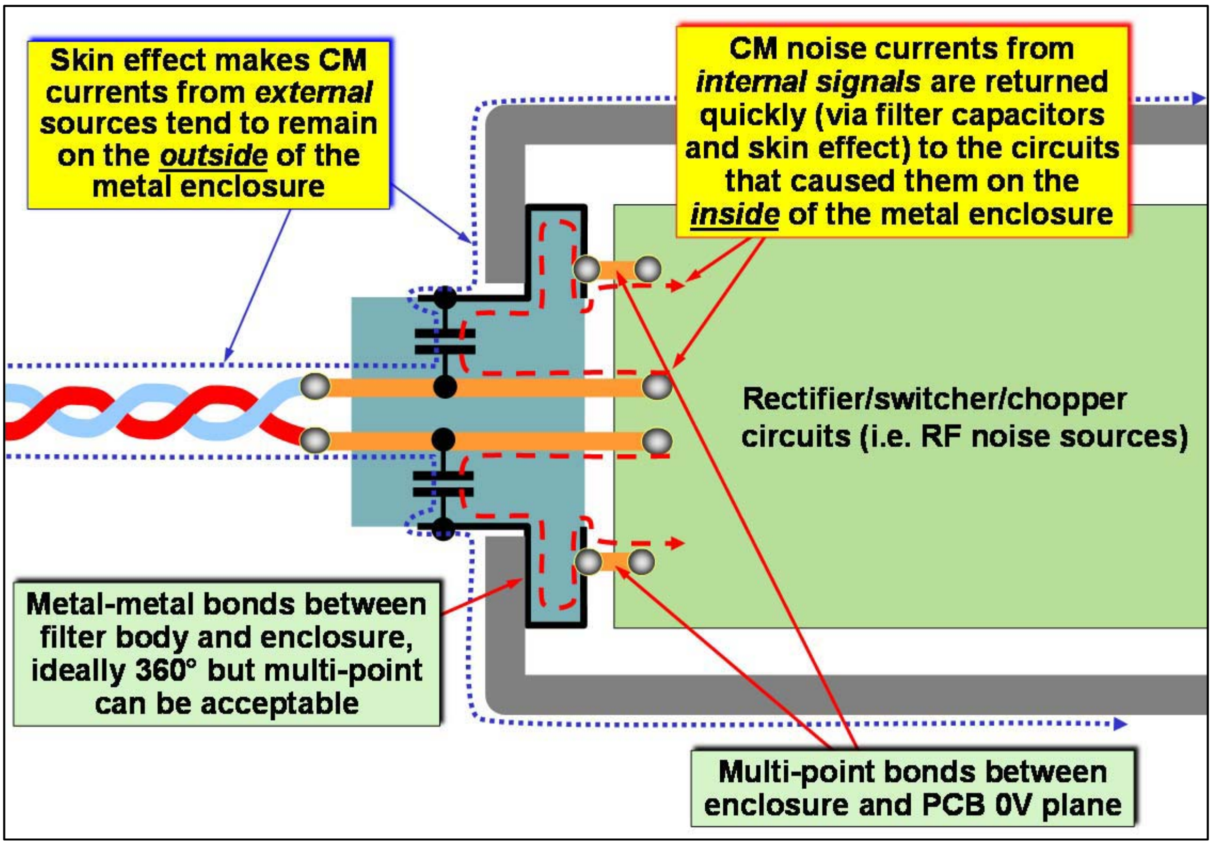

Figure 7.3-25 Example of filter RF-bonding to control surface currents

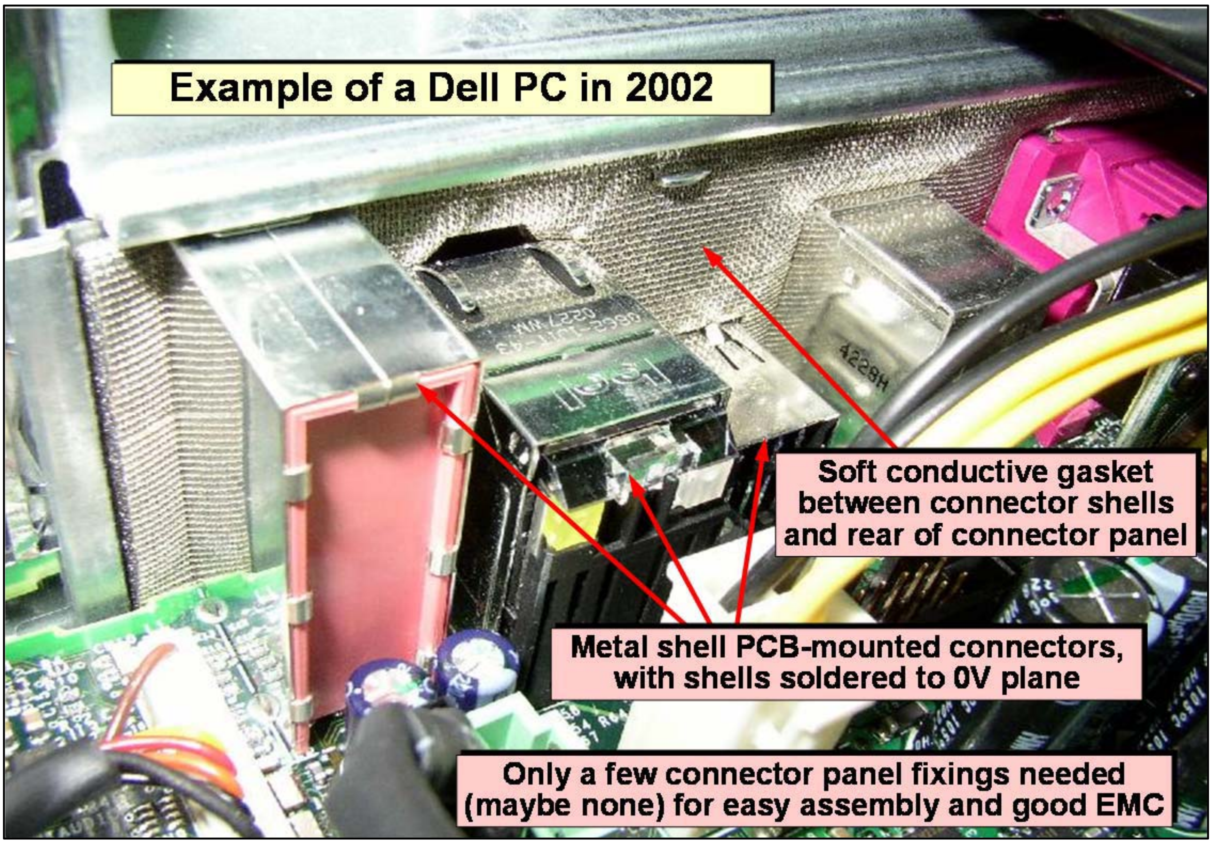

Figure 7.3-26 Easily making good 0V plane – chassis bonds by using conductive gaskets

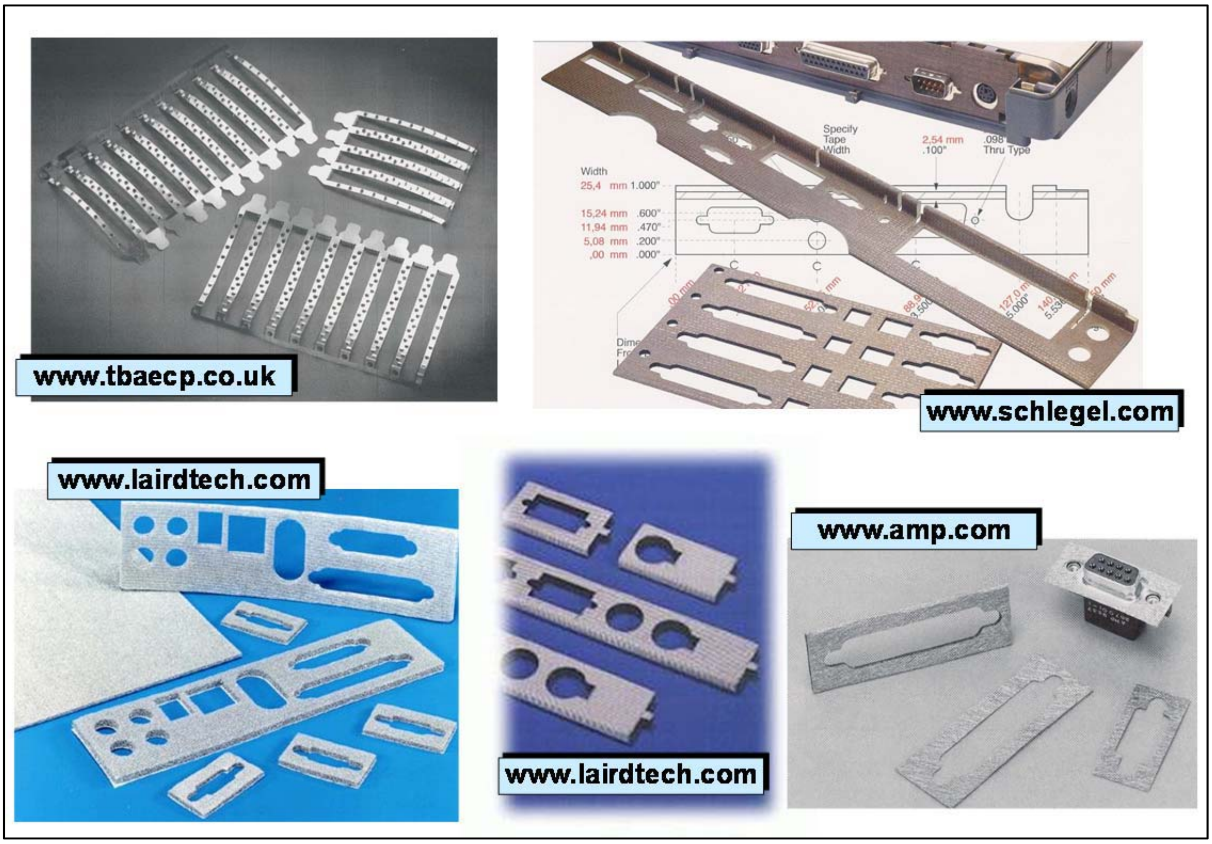

Figure 7.3-27 Examples of die-cut conductive gaskets suitable for bonding to PC chassis

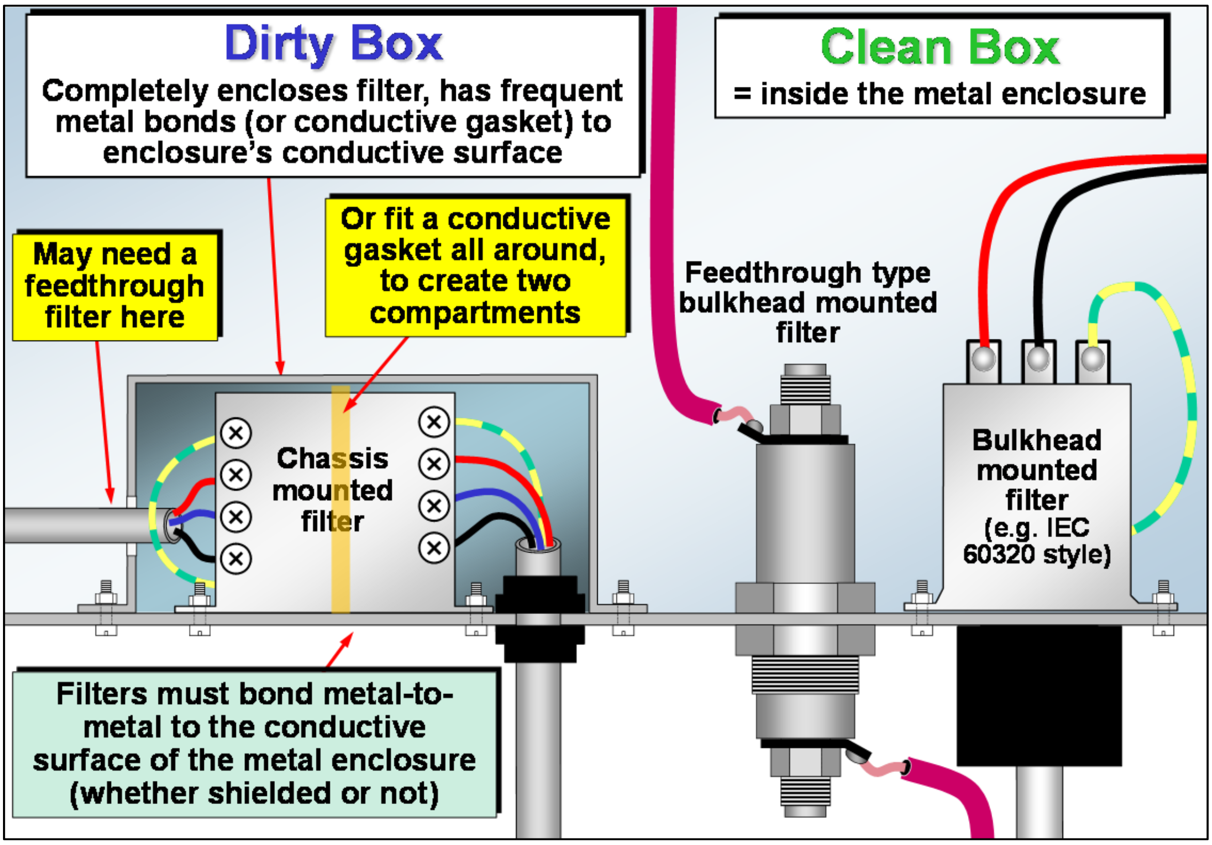

Figure 7.3-28 Good assembly techniques for filters in metal enclosures

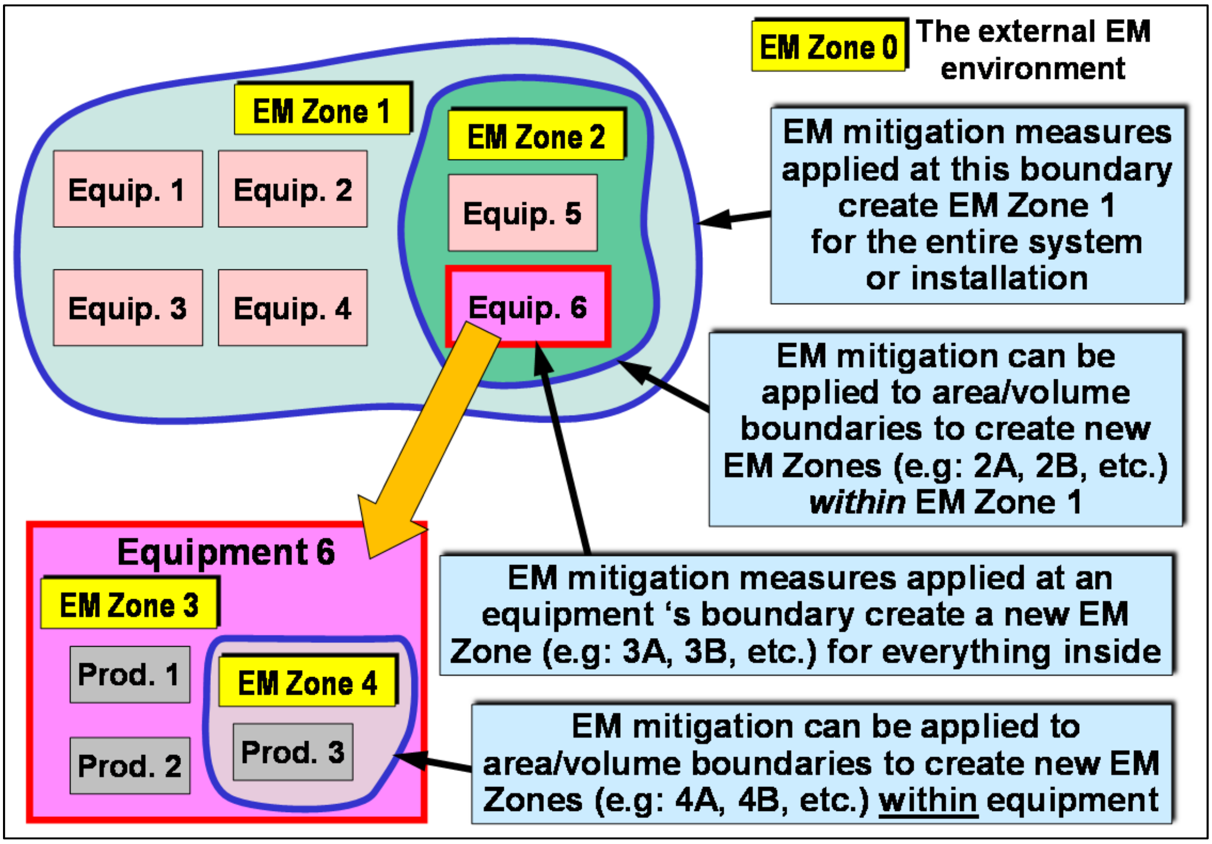

Figure 7.3-29 Using EM Zoning techniques to control EM environments

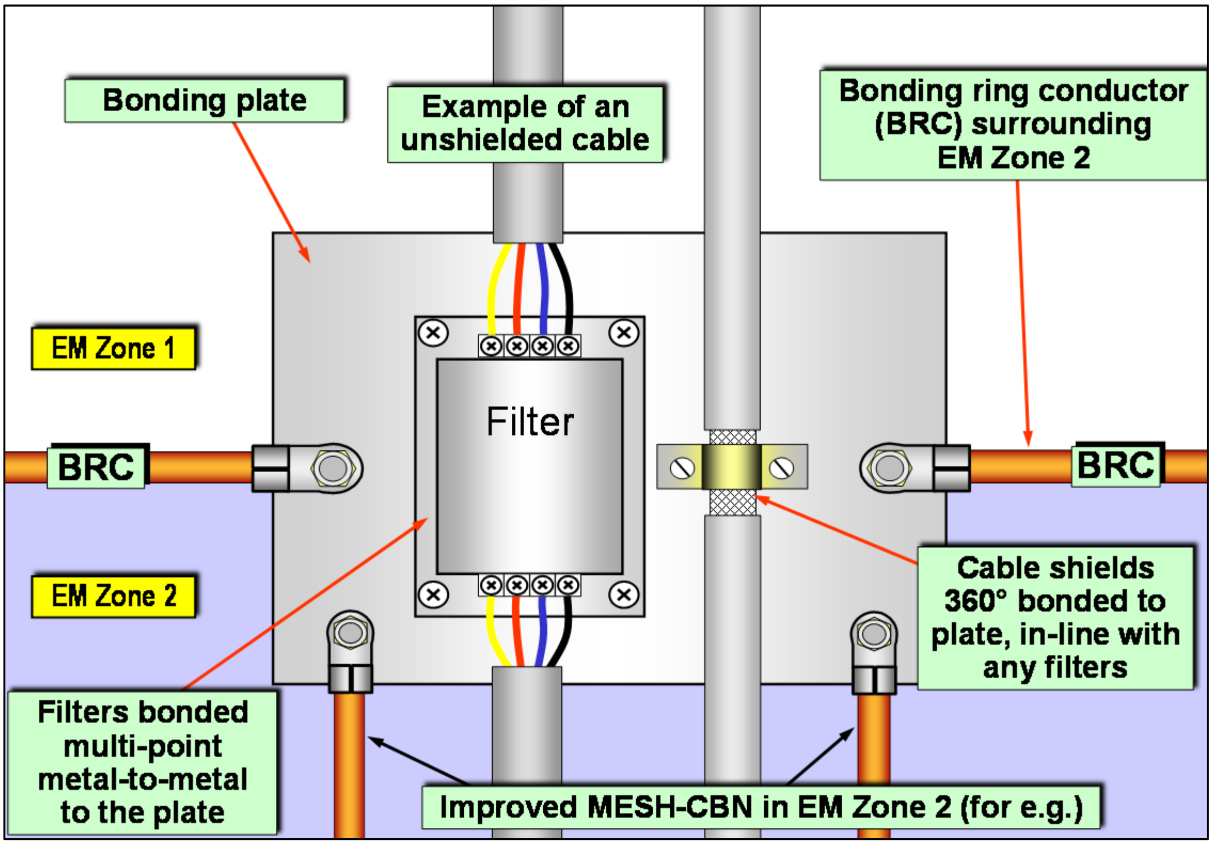

Figure 7.3-30 Example of direct and indirect RF-bonding (via a filter) at a Bonding Ring Conductor, using a bonding plate

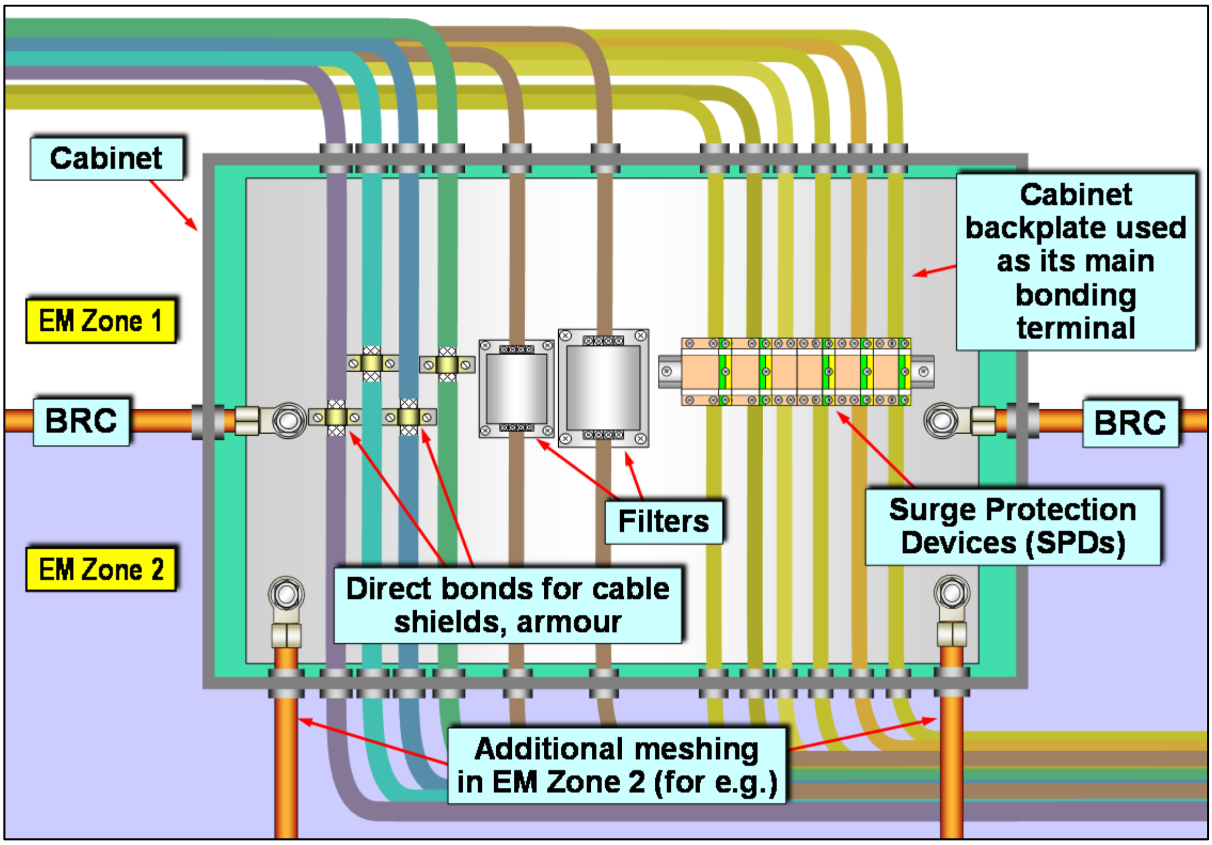

Figure 7.3-31 Example of direct and indirect RF-bonding (via filters and/or surge arrestors) at a Bonding Ring Conductor, using a cabinet backplate

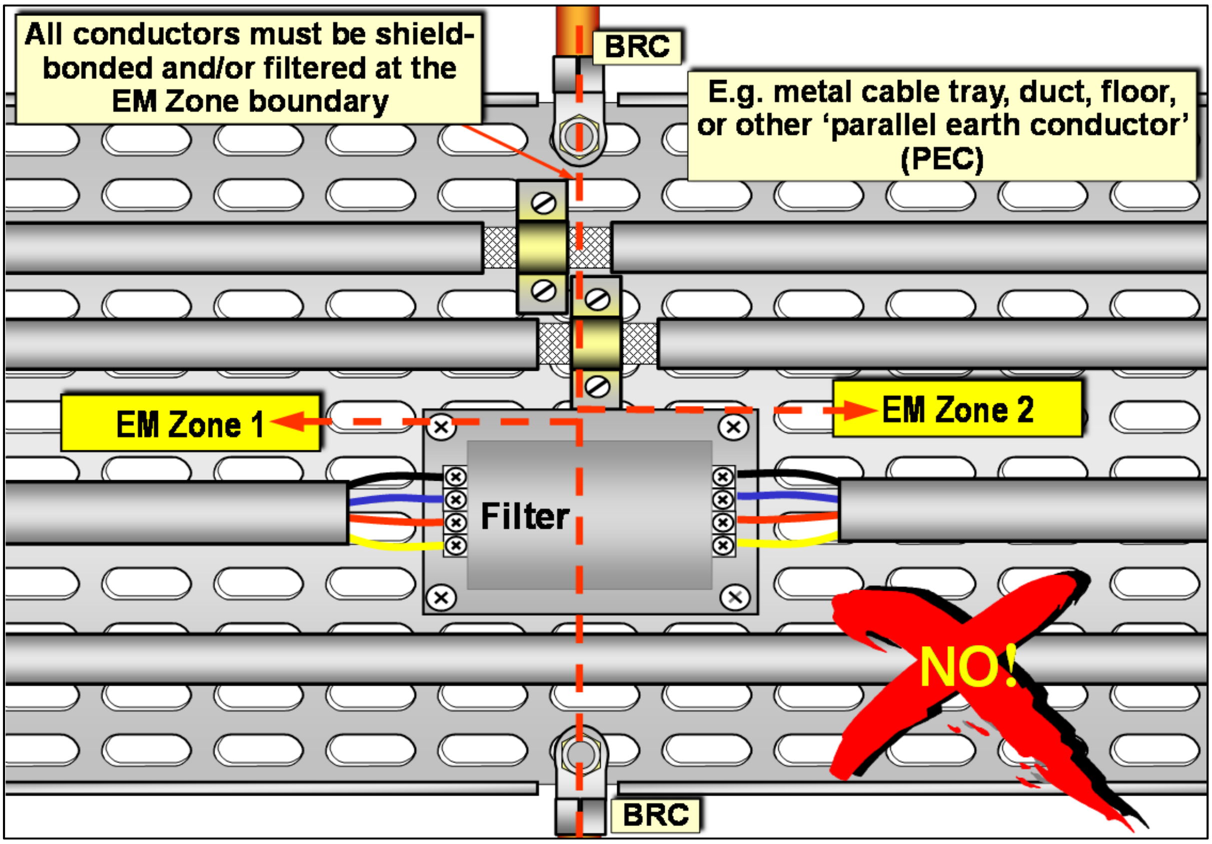

Figure 7.3-32 Example of direct and indirect RF-bonding (via a filter) at a Bonding Ring Conductor, using a cable tray

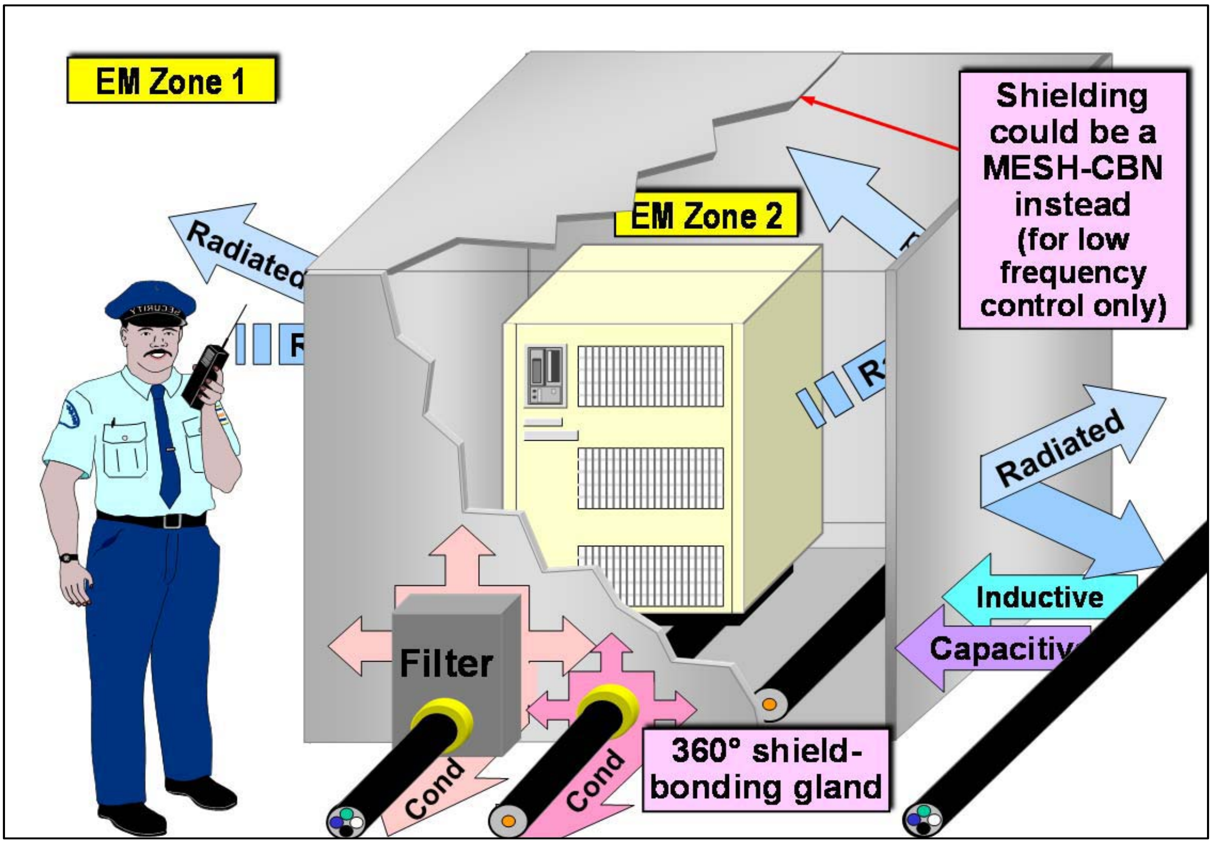

Figure 7.3-33 Shielded EM Zones need filtering too, for all unshielded cables

7.3.11 Filter reliability over time

Issues covered in the text of the articles, books and guides that are not covered in the above figures include the variations in component values (hence filtering effectiveness) and reliability with variations in temperature, voltage and load current. Getting this wrong has been shown to reduce the attenuation of filters by 20dB, when they are used within their maximum ratings (see [78]).

So it is necessary to ensure that, for worst-case combination of load current, supply voltage and ambient temperature, the current rating is adequate, and the attenuation and expected lifetime of the filter remains adequate.

Surge transients can damage power supply filter capacitors, so it is best to complete all surge tests before testing RF emissions and immunity. Real-life surges on all 115/230/400V single-phase supplies worldwide can exceed 6kV (line-line and line-earth/ground) [79]. For three-phase supplies that power only three-phase distribution systems with IEC 60309 or similar three-phase mains sockets, anecdotal evidence suggest allowing for surges of up to 15kV.

Some X2 capacitors lose 10% of the value every 1000 hours of operation, which means they can lose 90% over just 3 years (100nF capacitors degrading to 9nF over 3 years of continuous use have been seen in practice, and were not considered unusual by their manufacturers), and it might be thought surprising that this is permitted by their safety test standard, IEC 60384-14.

This loss of capacitance value is caused by "inception" (i.e. partial discharge or corona discharge that eats away at their very thin metallised layers) – which would start at 200V AC rms unless the air in the capacitor was replaced by resin or oil – or by using two capacitors in series.

IEC 60384-14 requires using two capacitors in series for all Y1 caps – but not because of inception – so that if one goes short-circuit there is another in series to prevent safety risks caused by high levels of earth/ground leakage current. Of course, it has the benefit that all Y1 capacitors used on their rated mains supplies do not suffer inception.

To achieve very high reliability, capacitor manufacturers such as MPE make all their filter capacitors (X and Y) as two capacitors in series, so they suffer no corona discharge and hence no reduction in capacitance value over years of use. As an example, MPE recently received over 20 of their mains filters from a military base that was being refurbished after nearly three decades of continual use, and found by re-measuring them, that they all still met their original specifications.

So, because we want our filters to maintain their performance for their operational lifetime, we should choose X capacitors that are rated for twice the AC voltage, and/or that have an acceptable specification for their rate of capacitance loss based on the results of actual tests performed by their manufacturers.

7.3.12 Filter attenuation depends upon the impedance of its RF Reference

A filter's RF Reference is a conductor that is shared with the circuit to be filtered, to control the RF surface currents so they flow in smallest size current loops and so create the least efficient "accidental antennas".

An RF Reference is generally at a circuit's 0V potential, and/or at earth/ground potential (but not necessarily!), and its impedance should be <<1Ω (preferably <10mΩ, ideally <1mΩ) over the entire frequency range to be suppressed by filtering and/or shielding (which often need to be used together, as figures 7.3-21 – 7.3-33 above show.

What should we use as the RF Reference?

- For a single PCB

  At least a "solid" (i.e. continuous copper with no gaps) 0V plane, better still a 0V plane that is RF-bonded to a metal chassis/enclosure, with the best performance achieved using a well-shielded metal enclosure. For more detail, see Chapter 4 of [37].

- For a product containing several PCBs

  At least a metal chassis/enclosure, better still one that is RF-bonded, with the best performance (once again) achieved using a well-shielded metal enclosure. For more information, see Chapters 5.2 of [5] and 2 of [68].

- For an electronic cabinet

  Its metal backplane area, or its metal cabinet (shielded cabinets being the best). For more detail, see Chapter 2 of [68].

- For a distributed system, installation or site

  Its "common-bonding network" (CBN), which means the site's metal structure, which is usually (although not necessarily) safety earthed/grounded. Two-dimensionally-meshed areas are better, with three-dimensionally-meshed areas being better still. A shielded enclosure, room or building (yes, they are used) is the very best. For more detail, see Chapters 3.4 and 5.5.3 of [69] and 5.3 of [70].

When using a metal volume (box) as a filter's RF Reference, it only provides a low enough impedance over the frequencies for which its RF-bonding and/or shielding has been designed to be effective (see later).

Poorly shielded / unshielded boxes create impedances that depend upon their detailed design, and *will* suffer from high-impedance resonances at some frequencies (see our module on shielding) at which filters will not work well at all.

Shielding techniques are described in more detail for PCBs in Chapter 2.6 of [37]; for products in Chapter 6 of [5]; for equipment cabinets in Chapter 5 (starts on page 55) of [68], and for systems and installations in Chapters 5.12 (starts on page 134) of [69] and 6 of [70].

When using a metal area as a filter's RF Reference, a single sheet of metal (one with no seams or joints) maintains low impedance to many GHz, but suffers "patch antenna" high-impedance resonances at some frequencies due to its dimensions, and at these frequencies filters will not provide much attenuation.

A seamed or jointed metal area will suffer from high-impedance resonances at frequencies that depend on detailed design aspects, once again degrading filter attenuation at these frequencies.

A larger metal area and thicker material extends an RF Reference's low impedances to lower frequencies (but its patch antenna frequencies will also reduce).

PCB 0V planes and other metal sheets or meshed-conductor area structures are only effective as RF References, for components/conductors closer than $\lambda/10$ to the plane, preferably $< \lambda/100$, and further from any plane edge than their height above the plane.

λ is the wavelength of the frequency to be filtered, and we generally base our designs on the highest frequency, f_{max} (i.e. the shortest λ) at which we want out filters to be effective – which is almost always the same as the highest frequency we need to suppress by any means, whether by filtering or shielding. It is easy to calculate λ for conductors in air or vacuum, as $300/f_{max}$ metres, where f_{max} is given in MHz (f_{max} in GHz gives λ in millimetres).

When using a metal mesh or meshed structure of any size as a filter's RF Reference, for example perforated metal sheet, "weldmesh", wire mesh, electrically-bonded conductors and/or metal structures, etc., they are only effective at all up to 30/L MHz, where L is the dimension of the largest mesh diagonal in metres (if L is given in mm, 30/L gives results in GHz).

Meshes only provide a good low-impedance below 3/L, and 0.3/L is much better (sheet metal is best).

All meshes *will* suffer from high-impedance resonances at frequencies above 50/L, where filter attenuation will be significantly degraded.

For more information on using meshes or meshed structures as RF References, see Chapter 5.5.3 (starts on page 71) of [69] and Chapter 5.3 of [70]. Figures 7.3-34 through 7.3-27 are examples taken from [69].

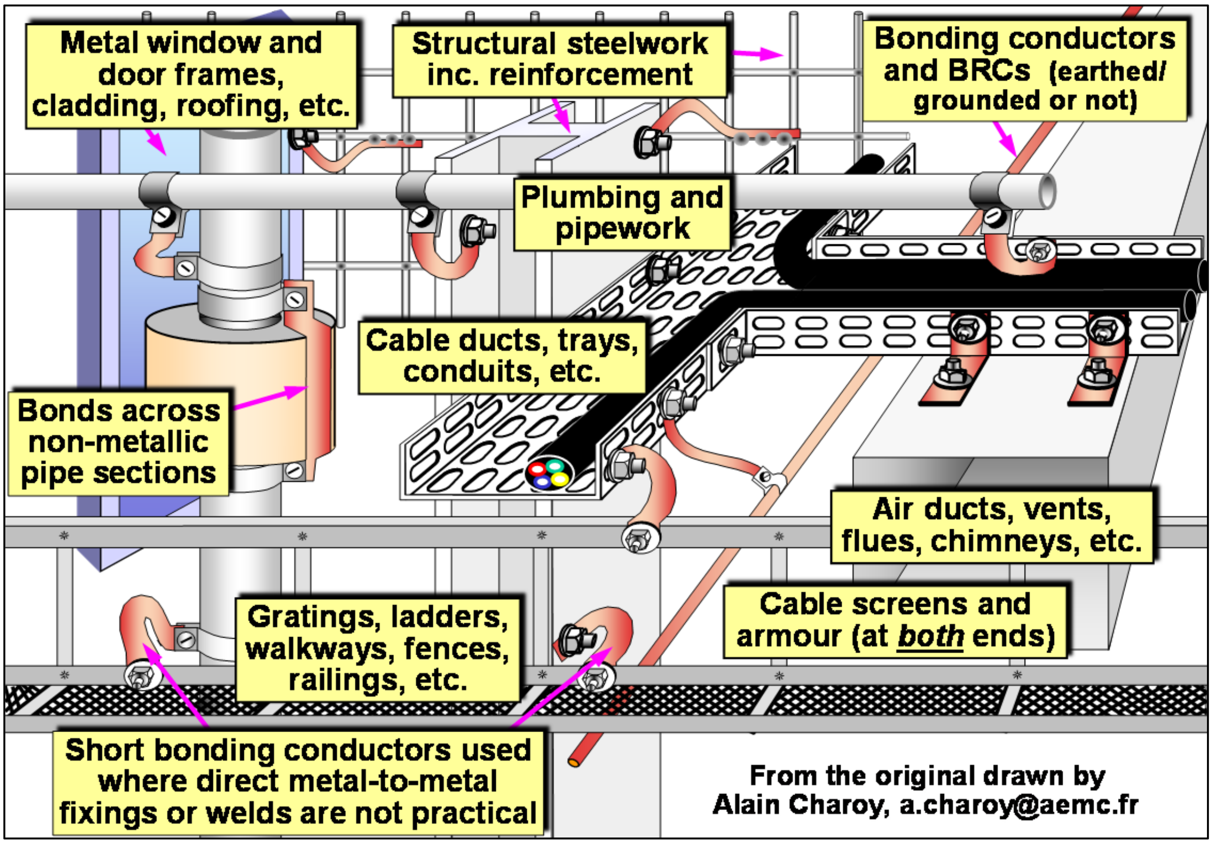

Figure 7.3-34 Creating a meshed RF Reference using existing ("natural") metal structures

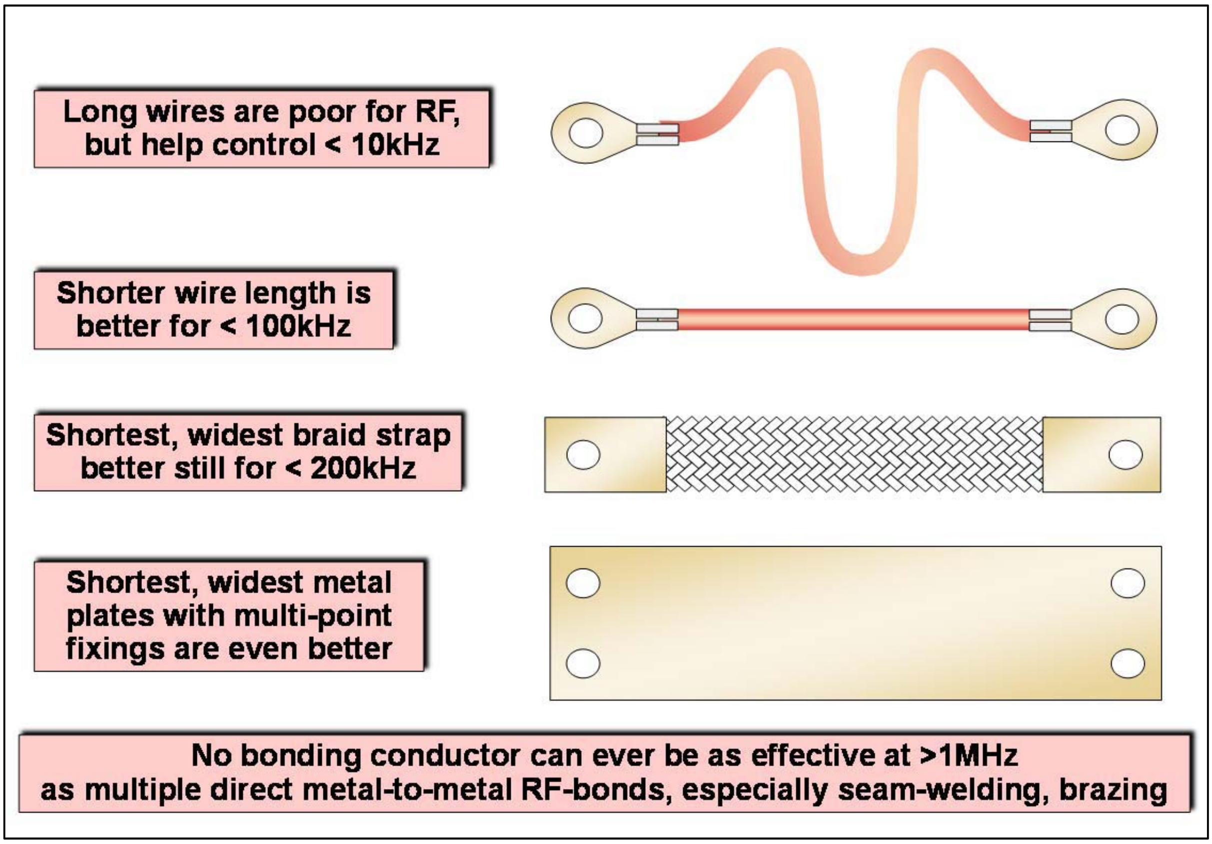

Figure 7.3-35 Some RF-bonding conductors

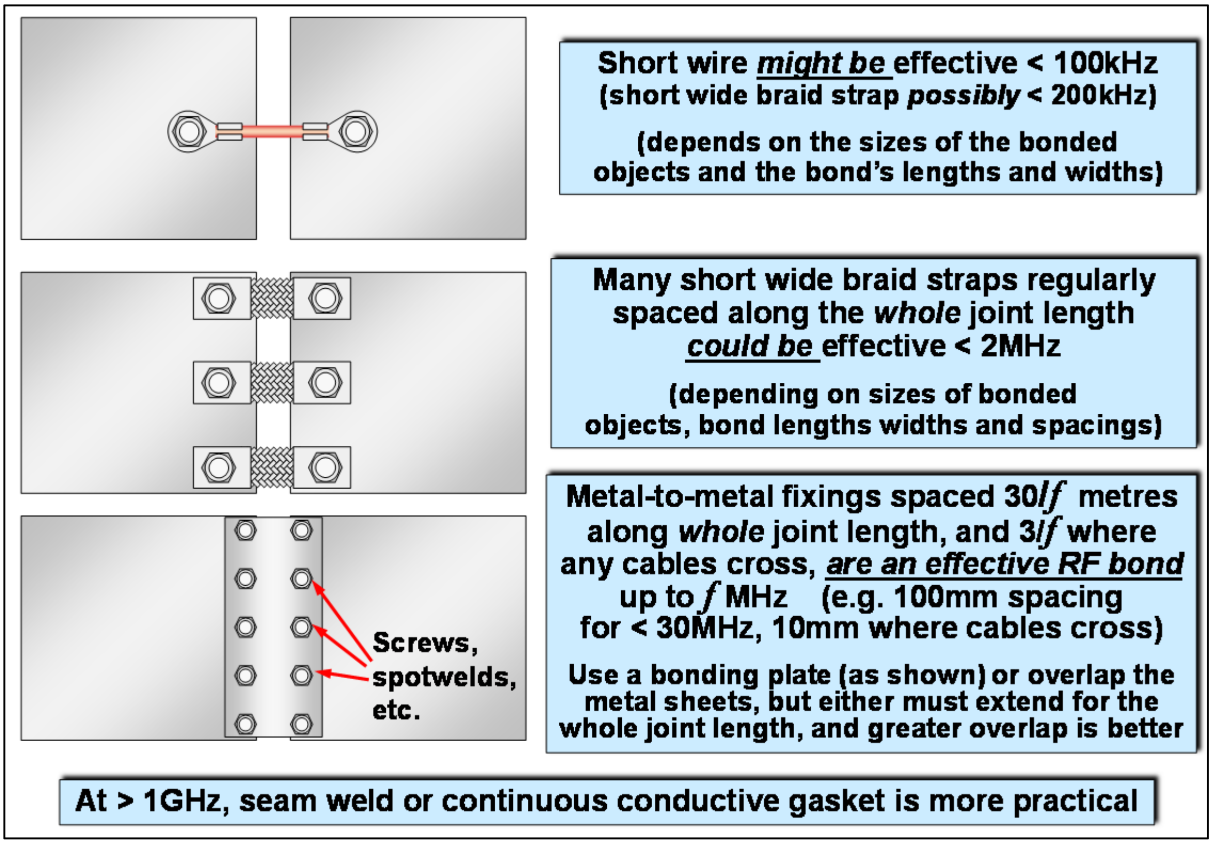

Figure 7.3-36 Some RF-bonding methods

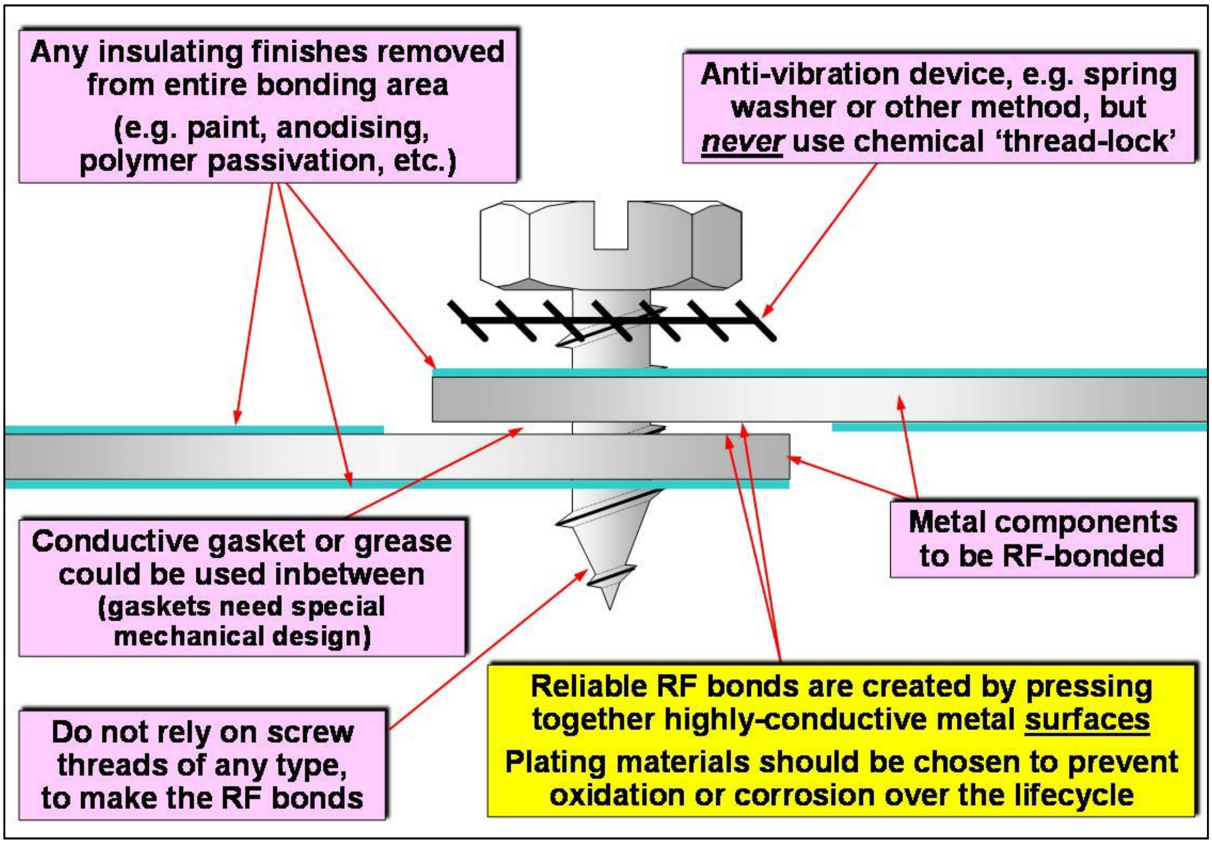

Figure 7.3-37 A direct metal-to-metal RF bond
(using a self-tapping screw as an example, and shown partially disassembled)

7.3.13 Filter attenuation also depends upon the impedance of its bond to the RF Reference

A filter's RF bonding to its RF Reference (see 7.3.12) must *also* be <<1Ω (preferably <10mΩ, ideally <1mΩ) over the range of frequencies it is to suppress – and this applies also to the circuit being filtered.

The RF bonding method used must control the surface currents so they flow in smallest loops, hence creating least efficient "accidental antennas". Ideally, we use 360° direct metal-to-metal contact or multipoint direct metal-metal contacts with spacing <<λ/10 at f_{max}, preferably < λ/100. However, bonding with a few millimetres of wire or braid might be acceptable where the frequencies to be filtered are <100kHz and the filter attenuation required is <20dB (see figure 7.3-24).

The green, green/yellow or clear insulated, or plain, metal wires or braids used for filter safety earthing/grounding are almost always unsuitable as their RF bonds, because they are much too long.

(Braids or straps with a length-to-width ratio of less than 5 are often mentioned in texts on EMC as if they have magical low-inductance properties. Trying to discover where this fallacy originated leads to military documents that appear to have been written before 1980, but can no longer be identified. Anyway, there is no physical basis for this ratio being special in any way. The most important thing with any conductor used for RF bonding is to make its length as short as possible. The next most important is to increase its surface area to as large as practicable, a 5:1 length to width ratio is OK, but 3:1 is better and 2:1 better still. And where the dimension of the joint that is being RF-bonded is longer than λ/10 at f_{max}, use multi-point bonding with such conductors spaced <<λ/10 at f_{max} apart.)

RF-bonding techniques are described in more detail for PCBs in Chapter 3 of [37]; for products in Chapter 5.3 of [5]; for equipment cabinets in Chapter 4 (starts page 45) of [68], and for systems and installations in Chapters 5.7 of [69] and 5.2 of [70].

7.3.14 Filter frequency range and shielding

I must mention a very important point here, which is that a converter's AC or DC power input or output cables contribute to radiated emissions, and "leakages" from imperfect shields contribute to conducted emissions. So any filtering and/or shielding has to be effective over the full range of frequencies that need to be suppressed.

Many designers think that mains cables only need filtering over the range of conducted emissions to be tested (typically 150kHz to 30MHz for the EU's EMC Directive), so they think they only need filters that attenuate to 30MHz, which means that most low-cost filter manufacturers only design and specify their filters to be effective up to an f_{max} of 30MHz – causing many problems for radiated emissions above 30MHz. They know that good filtering is required to higher frequencies than this, but can't justify the added cost when their customers can't see the need.

If radiated emissions are to be measured to, say, 1GHz, then the mains cable filters generally need to be effective up to 1GHz too. This is why the mains filters in figures 7.3-14 to 7.3-19 were tested from 1kHz to 1GHz.

However, power converters that do not incorporate microprocessor circuits, and are not enclosed in the same boxes as microprocessors, generally have a limited ability to generate frequencies above a few hundred MHz, meaning that their input and output filters do not have to provide much attenuation at higher frequencies. High-power converters use larger switching devices that switch more slowly, and might not emit much noise above, say, 20MHz.

7.3.15 Special issues for filtering power converter *outputs*

Converter AC or DC power output filters are similar in construction to their power input filters, and all of the previous good EMC design and installation practices for power input filters apply in exactly the same way to power output filters, and ordinary mains filters can be used for DC outputs.

But there are some special considerations for converters with AC outputs (e.g. PWM). Mains filters designed for 50Hz can generally be used with little/no derating up to 400Hz sine-wave (it is best to check with the manufacturer) but some power converters directly output kHz rectangular waves or PWM, that have switching rates from up to several hundred kHz with harmonics up to more than 100 times higher.

Variable-speed motor drives for AC motors are often described as having outputs from 0Hz to 100Hz (say) but in fact these numbers refer to the sine-wave modulation frequency of the PWM waveform. They rely on the integration of the PWM waveform in the magnetic core of the motor's stator to create the sine-wave flux at 0 to 100Hz that spins the rotor.

Similarly, variable-speed DC drives output a PWM waveform with a mark-space ratio that corresponds to the DC voltage specified when the PWM has been integrated by the motor winding's iron core.

Similar issues apply to other motor drives, for example for stepper-motors or reluctance motors, because they all use rectangular output waveforms generated by power switching semiconductors.

It is not surprising that the PWM outputs of choppers (and the like) are extremely large sources of EMI. A 10kW variable-speed motor drive connected to an AC or DC motor is essentially a 10kW radio transmitter emitting its RF power at many dozens of discrete frequencies into a mismatched cable connected to a mismatched motor, so exceeding emissions limits is easy!

PWM and similar types of converter outputs are generally suppressed by shielding, which I intend to cover in a future article. But filtering is a powerful technique that is generally not used enough. [82] might be interesting here.

PWM (and similar) converter output filters must be designed or chosen for the PWM frequency taking account of the chopper's design, so as not to make the chopper unreliable, so where a proprietary chopper is to be filtered I always recommend checking with the manufacturer whether the type of filter that is proposed is acceptable. Some converter manufacturers might list suitable output filters in their EMC installations manuals.

When we are designing our own power converters, we should ensure that any output filters we add do not cause the voltages/currents in the power switches to behave in ways that might cause unreliable operation – over the whole range of operating conditions that are possible.

Output filters can be used to just "round off" the sharp edges of the output waveform and thereby reducing levels of RF emissions at higher frequencies. These are often called dV/dt filters, and they are available in different strengths – providing greater or lesser degrees of rounding. These filters are often used to assist output cable shielding in meeting emissions specifications.

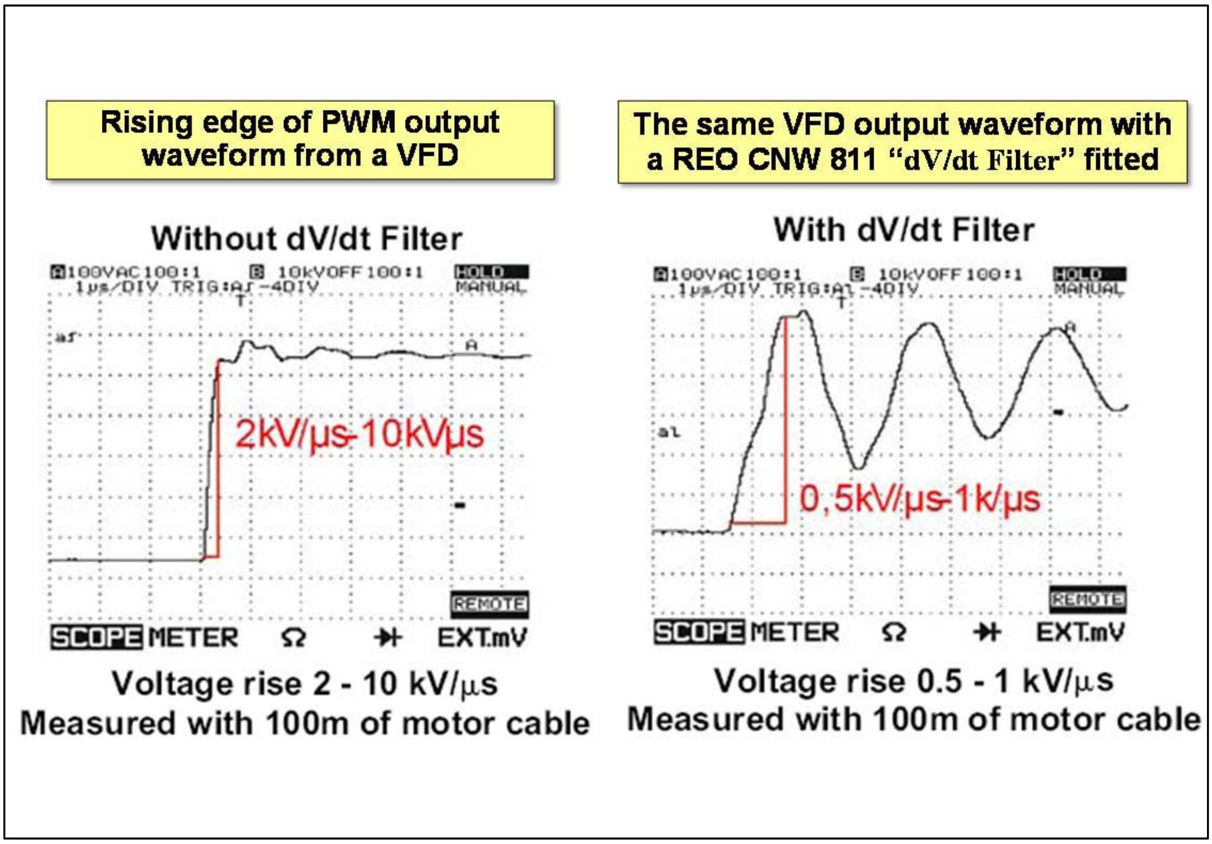

Figure 7.3-38 Example of the effect of a dV/dt output filter (courtesy of Steve Hughes of REO (UK) Ltd)

Figure 7.3-38 shows a proprietary dV/dt filter slowing the rising edge of a converter's output waveform from 2kV/µs to 0.5kV/µs, thereby reducing the levels of high frequencies in its emitted spectrum. Note that the dV/dt filter causes strong ringing at about 350kHz, that was not present in the original waveform, and which might possibly cause a new problem at that frequency.

One important purpose of dV/dt filters has nothing to do with suppressing EMI – they can be used to reduce the overshoot voltage that occurs at the motor terminals due to the impedance mismatch between the cable and the motor windings – the "Faraday Effect" – and can damage the motor winding's insulation.

Modern choppers switch so rapidly that motor overvoltages of 200% of the nominal motor AC voltage rating can now arise with cables as short as 13 metres or less [80] – which is a problem, because most AC motors use insulation that is only rated for twice the nominal 50 or 60Hz AC rms voltage and so can be damaged by such high levels of overshoot. [81] shows that overvoltages of 300% or more can also be caused in situations where 200% at most might be expected.

DV/dt filters also help reduce the level of RF "bearing currents" – caused by the stray capacitance between the stator windings with their PWM waveforms and the rotor, that can cause sparking in the bearings that wear them out in one-tenth the normal lifetime.

We can go a long way beyond dV/dt PWM filters, to use what are often called "output reconstruction filters".

These integrate the PWM in their inductors and capacitors, instead of leaving it to the motor or other load, at the end of a long and mismatched cable, to do the integration. The output of a reconstruction filter is the low-frequency sine-wave or variable DC level that the converter's front panel controls say it is providing (e.g. 0Hz to 100Hz).

Most filter manufacturers who supply output reconstruction filters, supply types that reconstruct only the DM waveform, and this is very good for entirely preventing overvoltaging motor winding insulation. They also have *some* benefits for reducing bearing RF currents and suppressing EMI.

But to greatly reducing bearing currents and greatly suppressing EMI requires output reconstruction filters that that reconstruct both the DM *and CM* waveforms from the PWM. These are costly filters, and at the time of writing are only available from a few manufacturers, but they are generally cost-effective (especially so when long output cables are necessary) because the Faraday Effect and EMI emissions become much worse with longer cables, and the only alternative method – shielded cables – is even more expensive.

Reconstruction filters for variable-speed AC motor drives are sometimes called "sine-wave output filters", or "Sinus output filters", and are available from REO, Siemens, and a few other filter manufacturers. Some of them require a connection to the converter's DC Link.

Types that reconstruct the DM and CM waveforms are given a variety of unhelpful names by their manufacturers, which do not help when web searching for their suppliers. I tend to call them "sine-wave CM + DM PWM output reconstruction filters" so that their design and purpose is evident, but this description isn't very helpful as a search term either. [83] is a guide to their use, from REO (UK) Ltd.

7.4 Filters and safety

A very important issue associated with AC mains filters is the safety of the earth/ground leakage currents caused by their filter capacitors – *which might continue to flow even when the equipment is switched off by its front panel control*.

Figure 7.4-1 is the filter for the Dipole Magnet Power supply for a synchtrotron. Its leakage current of 3A meant that special safety precautions needed to be taken to prevent electric shock in the case of a broken protective earth (safety ground) conductor.

The safety issues associated with filter earth/ground leakage currents are all discussed in Chapter 5.2.12 of [5], and I won't duplicate its text here other than to say that most (if not all) national wiring/installation regulations, such as the UK's BS7671 [77], require items of equipment with excessive earth/ground leakage currents to be installed in a special way.

(There is an interesting non-safety story associated with the 3A leakage current from the filter in figure 7.4-1. Because the system used single-point earthing (ugh!) and the safety earth/ground cable from the dipole magnet power supply was routed back to the distribution room with a 500mm spacing from the three-phase AC supply cables, the resulting magnetic field from the leakage current coupled with the beam position monitor cables and put a lot of 50Hz noise onto the synchroton's electron beam position, reducing the synchrotron's usefulness for the science experiments it was intended to perform for several years. Of course, the electrical installers had no idea that this could be the result, they just routed the cables where they seemed easiest. They also didn't fit any mains filters to the dozens of 100kW inverter drives in the plant room, despite them being required by the drive manufacturer's installation instructions, resulting in high levels of noise up to 10MHz all over the large site, with a peak at 2MHz – the site's resonant frequency. But these are stories for a different article!)

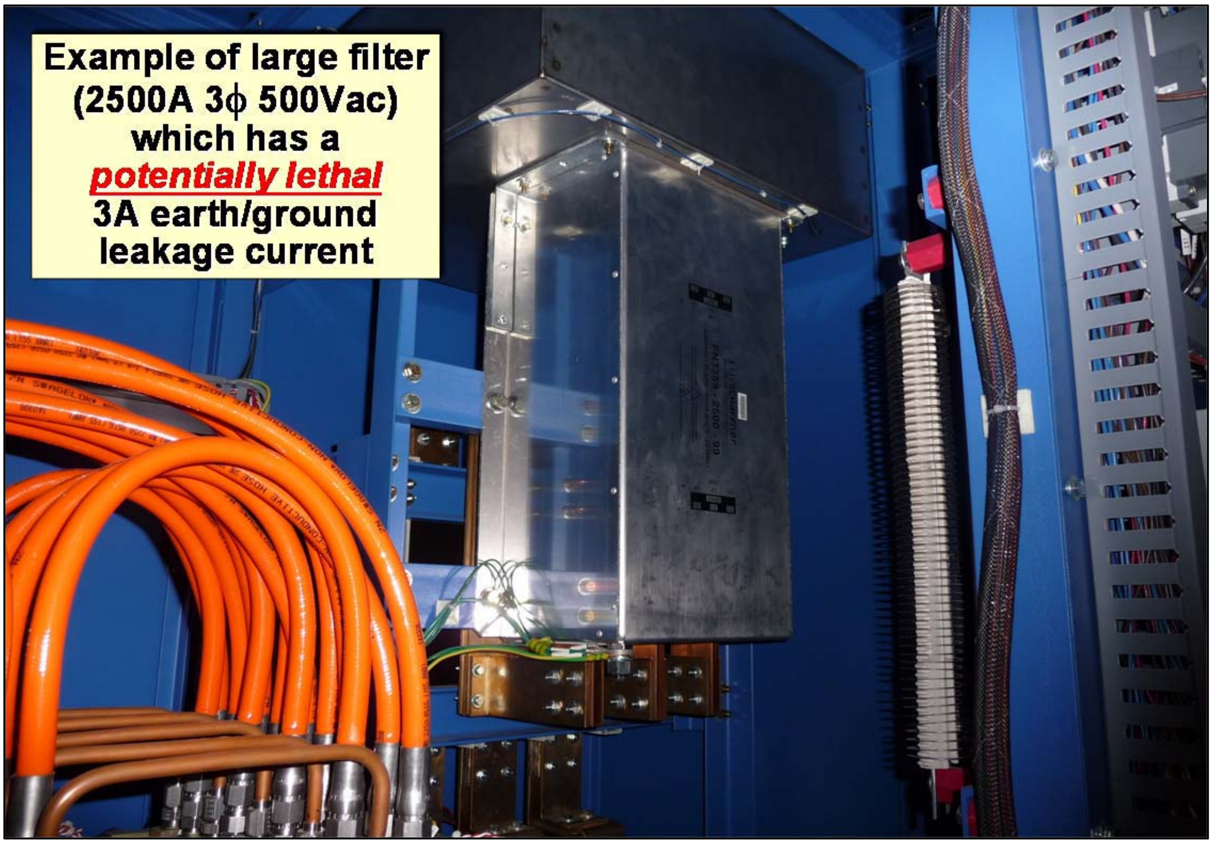

Figure 7.4-1 Example of a filter with a very dangerous earth/ground leakage current

Mains distribution systems protected by residual current circuit breakers (RCCBs), sometimes called earth-leakage circuit breakers (ELCBs) , residual current detectors (RCDs) or ground-fault interrupters (GFIs), will have reliability problems when using mains filters.

Transients and surges on the mains cause unbalanced transient currents in the filters, which can trip the breakers, as can the higher leakage currents of larger filters, which can also trip main breakers during switch-on or transients/surges.

The lowest-cost solution may be to omit the RCCBs (ELCBs, RCDs, GFIs, etc.), and use high-integrity safety earthing/grounding techniques instead.

But it is possible to use RCCBs (ELCBs, RCDs, GFIs, etc.) with mains filters (however high their leakage current) by passing the mains power through an isolating transformer before the mains filter. The isolated neutral should not be earthed/grounded, or else the centre tap should be grounded (e.g. supplying 230V as 115-0-115), and the same safety earth/ground must be used for both sides of the transformer.

As mentioned in 7.3.9 above, power converters work best when their supply comes from big fat capacitors, which is also best for EMC too, but Chapter 5.2.12 of [5] doesn't discuss the design of the discharge resistors needed for filter capacitors that can be charged at hazardous voltage.

When designing and building our own mains filters and off-line rectifiers we mustn't forget to fit all capacitors over 0.1µF with discharge resistors independently safety-approved to IEC 60065 clause 14.1.a), so that they will handle the peak value of voltage surge expected on the mains supply without damage or safety problems. Filter manufacturers should be well aware of this (but it is worthwhile checking with them, to make sure).

I have always used VR37 resistors for discharging all mains filter and off-line storage capacitors, regardless of value, but I often see products that use a single 1206 resistor for this purpose. Of course, when they have been used for a few months these resistors are always failed open-circuit, having been destroyed by mains surges, exposing users to dangerous shocks from the pins of their mains plugs – possibly for days or weeks after disconnection from the mains supply.

How did such products ever pass their surge tests to IEC 61000-4-5? Well, when these surge tests are done, the functionality of the product is checked afterwards – no-one checks that the mains filters are still discharging as they should when unplugged from the supply.

Test labs should now perform a quick re-check of the conducted and radiated emissions after a surge test, to check that the mains filter is undamaged, but it seems that some EMC test labs don't always do this. But even when they do, they don't check that the filter capacitor discharging resistors have not been damaged by the surges, and even if they were not damaged by the standard surge test, it only tests with surges to a kV or two, whereas we know that real-life surges can exceed 6kV a few times each year.

Inadequate mains filter discharge resistors should, of course, have been identified during product safety testing, but many manufacturers do their own safety tests. It appears that the necessary ruggedness (and standards compliance) of mains filter discharge resistors is an issue that is sometimes overlooked.

References (but only for *this* article)

[5] "EMC Design Techniques for Electronic Engineers", Keith Armstrong, Armstrong/Nutwood UK Nov. 2010, ISBN: 978-0-9555118-4-4, from www.emcacademy.org/books.asp.

[14] Keith Armstrong's earlier articles are available from the archives at www.theemcjournal.com

[15] Textbooks by Keith Armstrong and others are available from www.emcacademy.org/books.asp

[37] "EMC for Printed Circuit Boards – Basic and advanced design and layout techniques", Keith Armstrong, Armstrong/Nutwood UK 2010, ISBN: 978-0-9555118-5-1, from www.emcacademy.org/books.asp (note, this is the same text as the 2007 edition, ISBN: 978-0-9555118-0-6 or 978-0-9555118-1-3, repackaged in a different style of book).

[42] "EMC Design of High-Frequency Power 'Switchers' and 'Choppers'", Keith Armstrong, The EMC Journal, Issue 94, May 2011, pp 39-50, available from the archives at www.theemcjournal.com

[68] "Good EMC engineering practices in the design and construction of industrial cabinets", Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase. (Applicable to any metal box that contains two or more electronic units interconnected by wires or cables, not just industrial cabinets, but also, for example: some domestic appliances; some IT and telecomm's equipment; and most road, rail, aerospace and marine vehicles.)

[69] "Good EMC engineering practices in the design and construction of fixed installation", Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase

[70] "EMC for Systems and Installations", Tim Williams and Keith Armstrong, Newnes 2000, ISBN: 0-7506-4167-3, www.bh.com/newnes, RS Components part number: 377-6463

[71] "EMC for Product Designers, 4th Edition", Tim Williams, Newnes 2007, ISBN 0-7506-8170-5

[72] "EMC Design of High-Frequency Power 'Switchers' and 'Choppers' – Suppressing RF emissions from converter inputs and outputs", Keith Armstrong, The EMC Journal, Issue 98, January 2012, pages 27-38, available from the archives at www.theemcjournal.com

[73] "RLC Circuit", http://en.wikipedia.org/wiki/RLC_circuit

[74] CISPR 17 Ed.2:2011, "Methods of measurement of the suppression characteristics of passive EMC filtering devices"

[75] ITER, www.iter.org

[76] "System Oscillations From Negative Input Resistance at Power Input Port of Switching-Mode Regulator, Amplifier, DC/DC converter, or AC/DC Converter", Sokal, N.O., IEEE Power Electronics Specialists Conference (PESC) 1973 Record, pp. 138-140

[77] BS7671:2008 incorporating Amendments No 1:2011, "Requirements for Electrical Installations, IET Wiring Regulations Seventeenth Edition", ISBN: 978-1-84919-269-9

[78] "EMC Performance of Drive Application Under Real Load Condition", F Beck and J Sroka, Schaffner Application Note 11 March 1999; EMC Zurich 2001; Power Quality magazine June 2001.

[79] "Handbook on EN 6000-4-5, Testing and measurement techniques – Surge immunity test", Keith Armstrong, REO (UK) Ltd, free download from www.reo.co.uk/knowledgebase

[80] "Effect of Surge Voltage Risetime on the Insulation of Low Voltage Machines Fed by PWM Converters", Gary Skibinski *et al*, IEEE Transactions on Industry Applications, Jul/Aug 1998, Volume: 34 Issue: 4, pp 766 – 775, ISSN: 0093-9994, available from: www.ab.com/support/abdrives/documentation/techpapers/ieee/05_7.pdf

[81] "Interaction of Drive Modulation & Cable Parameters on AC Motor Transients", Gary Skibinski *et al*, IEEE Transactions on Industry Applications, May/Jun 1997, Volume: 33 Issue: 3, pp 722 - 731, ISSN: 0093-9994, available from: http://ieeexplore.ieee.org

[82] "Part 4: Output Issues with VFDs", Siemens, http://northerncanada.ieee.ca/ias-pes/Events/2006_03_16/Presentation.pdf

[83] "Sinus Filter Plus ++® (Output filter for common-mode high-frequency interference)" from www.reo.co.uk/files/cnw961_td_1.pdf