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EMC design of Switching Power Converters

Part 7 —
Suppressing RF emissions from converter inputs and outputs

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Contents

Issues 93 – 97 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

Suppression is sometimes called attenuation, and sometimes called EMI mitigation. Suppressing low-frequency emissions (mains harmonics and other noise emissions below 150kHz) will be covered in a later article.

7.1 The necessity of using good EMC design from the start of a project

The design techniques described in the previous parts of this "stand-alone series" [13], [42], [64], [65], and [66] help reduce the RF noises created by rectifiers, switchers or choppers, and are mainly only intended to be effective above the 11th harmonic of the switching frequency, so that the switching is still "hard" enough to be thermally efficient.

But most of these techniques usually cannot provide enough suppression to comply with emissions limits, plus they leave the harmonics below the 11^{th} to create noise emissions. So we need to suppress conducted and radiated emissions using filtering and shielding.

This article focuses on suppression using filtering – but it is important to remember that conducted noise radiates away from the conductors and can cause radiated test failures. Just because a conducted emission test only goes up to 30MHz does not mean that filtering is not required above 30MHz – all conductors connecting to a power converter must be filtered to the highest frequency at which it generates too much noise, whatever the frequency.

The highest frequencies at which a power converter might need filtering (or shielding, which isn't only for radiated emissions) can easily be 2,000 times its switching rate. So a 1kHz switcher or chopper can easily emit excessive noise to over 2MHz (I have seen 5kW 50Hz bridge rectifiers on their own fail emissions tests at over 4MHz), and a 100kHz switcher can easily emit too much at over 200MHz.

For commercial and financial success we want our products to use the least amount of EMI suppression they can, to keep their overall cost of manufacture low.

But it is no use having a low overall cost of manufacture if it means delaying the product launch by months to achieve the most cost-effective EMI suppression! Time-to-market has, since 2000, become the most important issue for a financially successful electronic product.

This is shown by the industry responses to Question 6 in [67], see Figure 7.1-1, and I have seen other reports from similar prestigious organizations that show the same for most electronic applications.

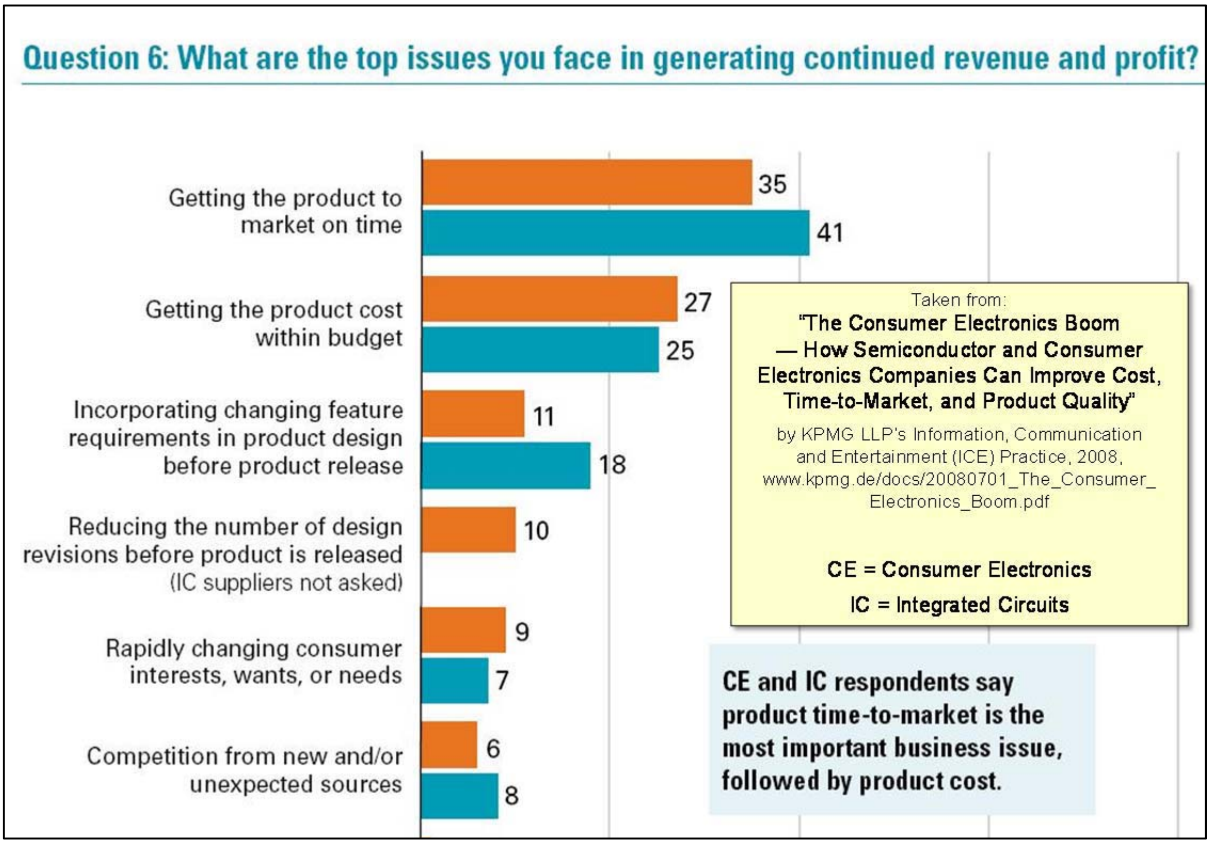

Figure 7.1-1 Time-to-market and cost

Reducing time-to-market (with an EMC-compliant product) whilst simultaneously achieving the most cost-effective EMI suppression, requires the use of good EMC engineering design *right from the start of a new project*.

I have seen switch-mode power converters that required five-stage mains filters that were responsible for more than 33% of the overall bill of materials (BOM) cost, and also about 33% of the converter's overall size (volume) and weight. These filters typically took six months to design before the product could be sold as complying with its relevant emissions standards. The resulting six-month delay in the time-to-market is the sort of delay that can – in these fast-moving times – turn a potentially very profitable product into a loss-making financial black hole.

One thing these power converters had in common was that their designers ignored all the stuff I have been covering in my previous articles in this series. They simply made a power converter that somehow met its functional specifications, then bunged it in a test lab to measure its emissions – which of course it failed – then bodged around with filtering and shielding, cycling repetitively through the test lab, until they managed to get something that passed its emissions tests.

The sad thing is that if they had used the material on good EMC engineering design techniques that I've been describing in the EMC Journal since 1999 (never mind the previous articles in this series), they would have probably met their functional specifications more quickly, would have needed no more than one iteration through the EMC test lab, and their filters would have represented no more than 15% of the product's BOM cost, size and weight. Time-to-market would have been as short as if no EMC compliance was required, and possibly less.

See Chapter 1.1 of [5] for more on how using good EMC design techniques from the start of an electronic design project improves competitiveness whilst reducing financial risks.

Despite the use-good-EMC-design-from-the-start approach being a "no brainer", what I find in practice is that design engineers are increasingly being made to focus on achieving the lowest BOM cost for every tiny part and assembly within a product – an approach that *almost guarantees* difficulties in achieving functional specifications, difficulties in achieving EMC compliance, much delayed time-to-market, and an increased overall cost of manufacture. [12] may be relevant here.

I blame project and other managers who don't take the trouble to learn about EMC, although so few people write about the commercial and financial benefits of good EMC design that I suppose it is not *entirely* their fault.

I suppose it's time I got back to the subject of this article. But first I'll repeat that the design techniques discussed in [13], [42], [64], [65] and [66] all help reduce the cost, size and weight of filtering and shielding, reduce the overall cost of manufacture (even though the BOM costs of some PCBs and assemblies will increase), and considerably reduce time-to-market.

We need to be EMC-savvy from the start of a new project so that we don't have to use more EMI filtering and shielding than is necessary, and so that we save time.

7.2 The DM and CM noise current loops

Figures 7.2-1 through 7.2-4 use the example of an AC-AC inverter variable-speed motor drive with a three-phase (3ϕ) mains supply and a 3ϕ motor, copied from a figure in a REO (UK) Ltd booklet on suppressing motor drives.

This example shows a set of high-value (several milliHenries, mH) inductors in series with its mains input to suppress emissions of mains harmonics up to 5kHz, and this will be covered in a later article in this series. Right now, we are focusing on suppressing RF emissions.

Despite this high(ish) power industrial AC/AC example, the basic noise suppression principles described in this section apply to any/all types of switching power converter, including DC input (which doesn't use an input rectifier) and/or DC output (which might use different types of switching circuits or output rectifiers), for example DC/DC converters on printed circuit boards (PCBs).

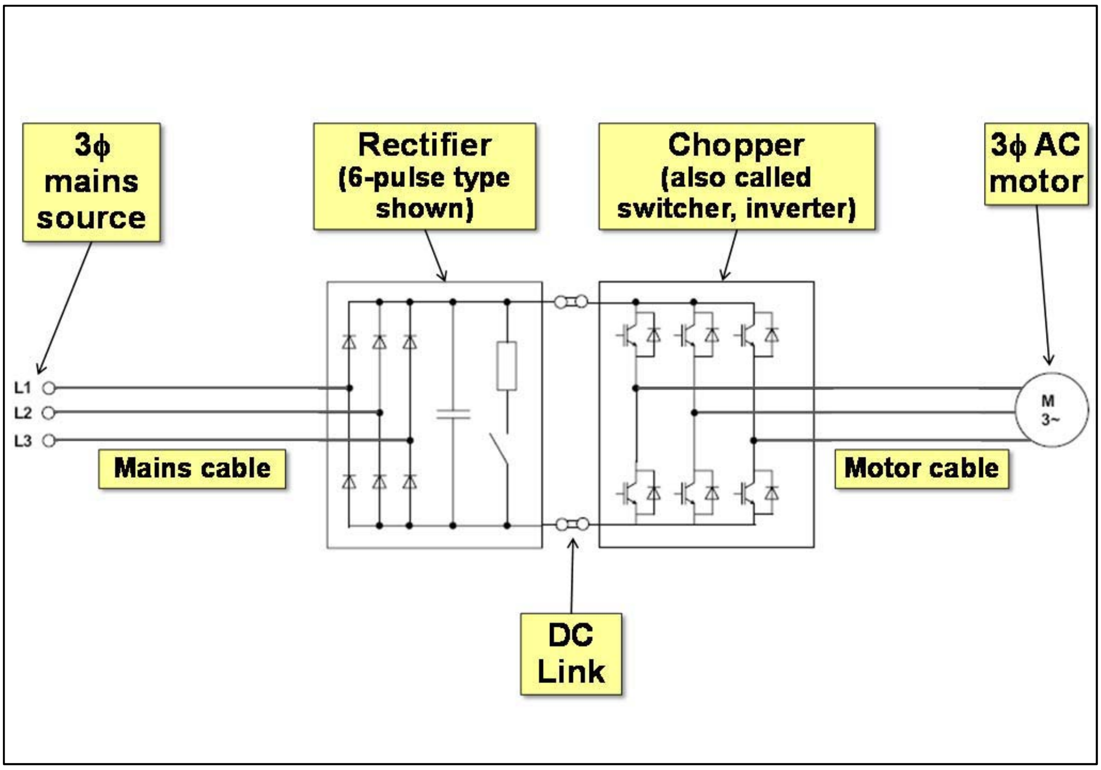

Figure 7.2-1 Example of a variable speed/frequency 3ϕ motor drive (VSD, VFD)

Figure 7.2-1 shows the basics of the system, which – like most high-power VSDs – places its rectifier in a different metal box from that of its chopper, with the connection between them called the DC Link. DC Links can be cables or busbars of any length, although long DC Links are a bad idea for EMC, as discussed later in this section. VSDs or other types of AC input power converters or inverters rated under 10kW usually combine their rectifier, DC Link and switcher or chopper in one box.

Figure 7.2-2 uses the same VSD as 7.2-1, showing the stray capacitances that exist between the units and from them to nearby metalwork. These strays are shown "lumped" for convenience and simplicity of drawing, when in fact they are really distributed all over the length/area of the various parts.

For a powerful VSD installation, the nearby metal structures include cable trays, heatsinks, enclosures (e.g. cabinets), concrete rebars, structural steelwork, cable armour, etc.

For power convertors mounted on a PCB, the nearby metal structures include heatsinks, metal enclosures, and the traces and planes in the PCB's laminations.

I haven't shown any safety earth/ground connections in these figures, because where such connections are used their earth/ground conductors are so long that they have very high impedance at RF, so they don't have much effect on the major paths of the common-mode (CM) RF noise currents – which flow via displacement currents in the stray capacitances shown in Figure 7.2-2.

See Chapters 5.7 of [4] and 2.7.7 of [5] for more details on why connections to the safety earth/ground electrodes in the soil are generally not important for EMC. Chapters 4.6.8 of [5] and 3.1.4 of [37] also show why so-called "earth/ground loops" are not a problem when electronic design is done correctly.

However, the details of the VSD's nearby metal structures and how they are electrically bonded together and connected to the VSD *are* very important for the control of CM current loops, whether these metal structures are connected to safety earth/ground or not, see later.

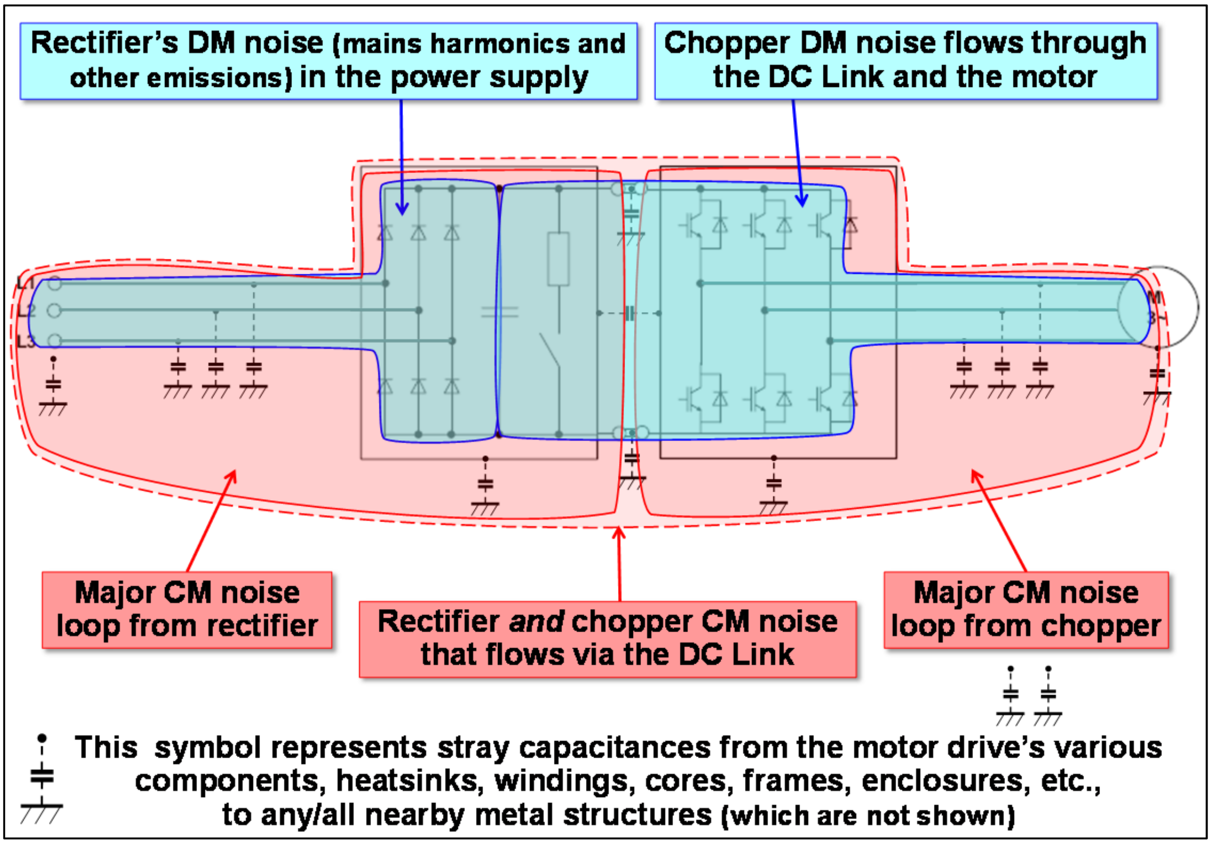

Figure 7.2-2 Example VSD showing noise current loops

Figure 7.2-2 sketches the differential-mode (DM) RF noise currents in blue, and CM RF currents in red.

All currents, including unwanted/stray noise currents flow in closed loops (from Ampere's Law), and I have sketched the DM and CM noise currents flowing in Figure 7.2-2 with simplistic shapes. The coloured areas within these shapes indicate the electromagnetic near-fields associated with each loop. See Chapters 2.4 of [4] or 2.4 of [5] for more on near-fields and far-fields.

Notice that the DM noise current loops are confined to the mains power input and motor drive output cables. But the CM noise current loops flow through various stray capacitances (or direct connections) to all nearby metal constructions (not shown), then along those metal structures until they can return via stray capacitances (or direct connections) to complete their loops – using the smallest loop areas they can find.

The figures in this section (7.2) can be misleading, because they make the mains input and motor output cables appear to be quite short, when in reality they can be very long. The length of the mains cable from the AC power source (generally a large transformer stepping-down from a high voltage, e.g. from 33kV AC rms to 230V rms, but sometimes a generator) to the power converter is almost always several tens of metres, and could easily be a hundred metres or more.

The motor drive cable from the VSD's output could be very short. Shorter is generally better for EMC, with mounting the motor drive directly onto the frame of the driven motor usually the best, but in steel rolling mills I have seen 10MW VSDs driving very large motors over cables much longer than 100m.

The CM currents in the scheme shown in Figure 7.2-2 flow over loops that extend all the way from the source of the AC power (e.g. the HV transformer) through the VSD to the motor. These loops encompass very large areas indeed, with a high probability that they will pass through some other equipment or systems and interfere with them.

I have seen large factories containing dozens of plastic injection machines, each the size of the largest railway locomotive, where the entire metal structure of the factory was "polluted" with CM noise generated by a single 100kW motor drive powering just one of the machine's compressors.

We suppress the DM and CM noise current loops using filters comprising capacitors, inductors, RF chokes, either individually or in combination. The principle of filtering is to provide the DM and CM noise currents with loops that have much smaller areas – which they will naturally prefer to take.

For more on this very important understanding see Chapters 5 of [4] or 2.7 of [5], also [33] (for systems and installations) or [32] (for PCBs).

It is not sufficient just to buy a filter, even a costly high-spec one, and expect it to work in isolation. For filtering to work as expected we need to use "RF Bonding", so that the DM and CM noise currents are diverted by the filter into very small loop areas, which they naturally "prefer", thereby reducing the levels of noise currents flowing in the input and output cables – which we call emissions.

Figure 7.2-3 shows what we aim to achieve with these techniques. Input and output filters provide the DM and CM noise currents in the mains input and motor output cables with low-impedance paths to flow in, and RF bonds between the filters' metal enclosures and the metal enclosures of the VSD (rectifier and chopper) provide the smallest practicable loop areas for them to flow in.

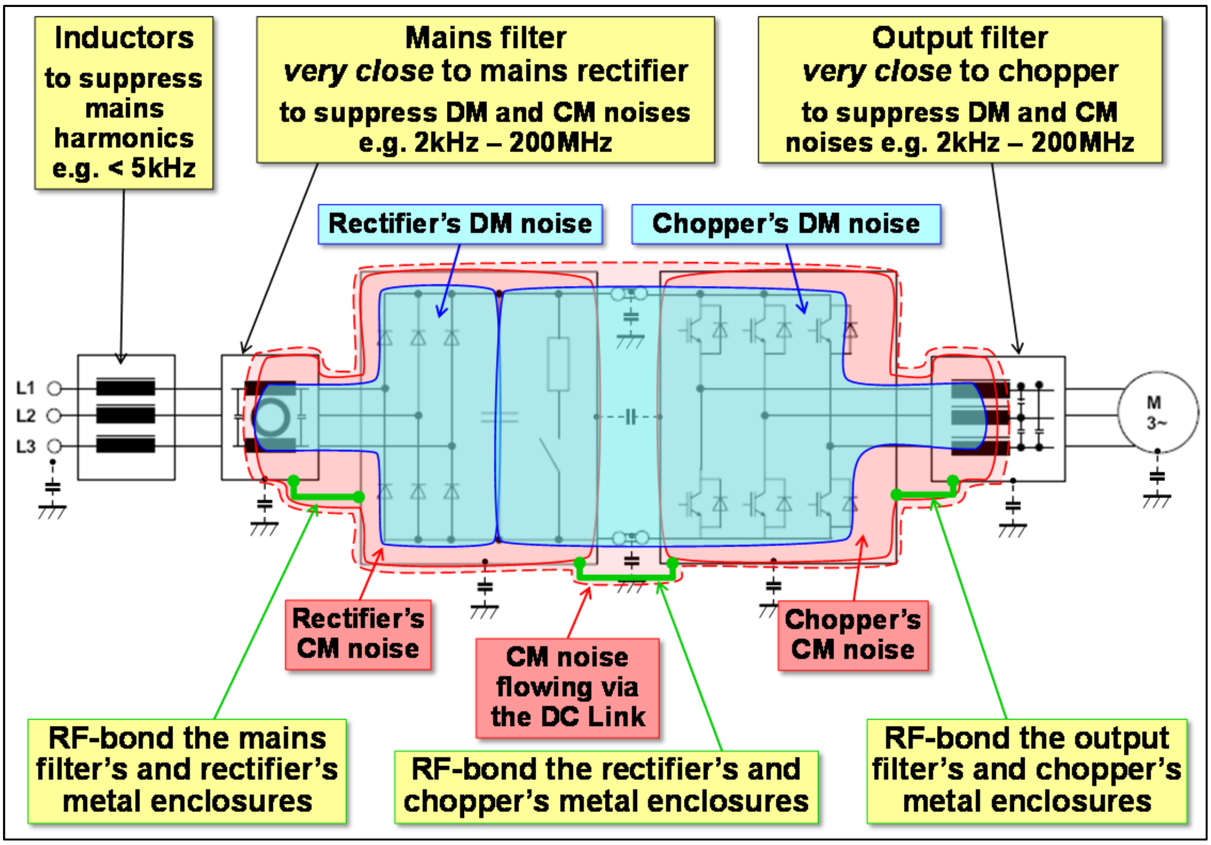

Figure 7.2-3 Example VSD fitted with filters and RF-bonded together

As before, the DM noise current loops are shown as blue outlines filled with light blue, and the CM noise current loops as red outlines filled with light red. When properly designed and assembled, all the noise current loops are contained within the filters and the units comprising the VSD. They do not extend beyond the mains filter into the (long) mains cable that goes to the AC mains source, or beyond the output filter into the (potentially long) motor cable. (Of course, nothing is perfect, see 7.3.)

Because of the way it is drawn, Figure 7.2-3 doesn't visually indicate by how much the area affected by the DM and CM noise has been shrunk by the addition of mains and output filters. Without the filters the noise from the converter extends to the entire branch of the input power distribution system, and the entire route of the output cable to the motor load.

For the example 3ϕ VSD motor drive used here, this could easily include most, perhaps all, of a factory building. And in the case of a PCB mounted DC/DC converter in (say) a Personal Computer (PC) it could cover the whole area served by the input DC rail, plus the whole area served by the output DC rail.

But – with the filters – the area exposed to the DM and CM converter noise is restricted to the area covered by the filters and converter itself. Because all currents (including stray noise currents) flow in closed loops that "prefer" to be as small in area as they can be, best results are achieved by placing the filters and converter circuits adjacent to each other – as physically closely as possible – as shown on Figure 7.2-3.

"RF Bonding" means using electrical connections (i.e. bonds) that have low impedance up to the highest noise frequency to be suppressed. "Low impedance" in this context is always <<1Ω, preferably < 10mΩ.

Effective RF bonding also requires the use of multiple bonds spaced much less than one-tenth of a wavelength (λ) apart from each other at the highest frequency to be suppressed, e.g. << 3 metres apart for filtering up to 10MHz, << 300mm apart for up to 100MHz. If the dimensions of the unit to be RF-bonded is << λ/10 at the highest noise frequency to be suppressed, then a single electrical connection might be acceptable for its RF bond.

For greater suppression at any frequency (up to the highest), the impedance of the RF bonds should be lower, and the spacing between the multi-point bonds should be less.

RF bonding is what almost all EMC textbooks and articles call "EMC earthing/grounding" or "RF earthing/grounding". These are confusing terms because they sound as if they have some relationship with safety earthing/grounding, which they do not.

This confusion of terminology has caused huge problems, delays and costs for very many electronic manufacturing companies, system integrators and electrical installers. This is why I have learnt to use the term "RF Bonding" instead, and strongly recommend it to all.

How to achieve RF bonding in practice is described in detail in the following:

- in general: Chapter 5 of [4] or 2.7 of [5]
- for PCBs: Chapter 3 of [37]
- for complete electronic products: Chapters 4.6, 5.2, 5.3, 6, 7.4.4 and 13.7 of [5]
- for items of equipment comprising several electronic units in one metal box: Chapters 2 and 4 of [68], and 6 of [70]
- for systems and installations of any size: Chapters 5.7 (starts on page 84) of [69], and 5 of [70]

We see from the above references that the length of the conductors used to create RF bonds are very important indeed. For example a typical 4mm diameter conductor (or 4mm wide PCB trace) has an impedance of roughly 0.8µH/metre, so for its impedance not to exceed 1Ω at 10MHz it must not be longer than roughly 20mm, and preferably very much shorter than this.

Replacing our 4mm diameter wire (or 4mm wide trace) bonding conductor with a 25mm wide braid strap (or 25mm wide PCB trace) reduces the inductance to roughly 0.4µH/m, so for suppressing noise up to 10MHz it must be no longer than 40mm, and preferably a lot shorter.

For frequencies of up to 100MHz, our 4mm diameter wire (or 4mm wide PCB trace) must be much shorter than 2mm, and our 25mm wide braid strap (or PCB trace) must be much shorter than 4mm – so the best idea here is usually to screw, bolt, solder, weld or otherwise directly fix together the metal enclosures/chassis/frames/PCB 0V planes/etc. that are to be RF-bonded.

Figure 7.2-3 shows the filters, rectifier and chopper units RF-bonded together, but sometimes this is impractical and it is necessary to RF bond them to their local metal structures instead, usually those that used to support them – such as a cabinet or frame.

In this case it is necessary to convert their local metal structures into an "RF Reference" to carry the CM currents flowing between the units in a way that achieves a very small loop area. This technique is shown in Figure 7.2-4.

When we RF bond together the metal bodies of converter's various units, plus their input and output filters, as Figure 7.2-3, this actually creates an RF Reference without RF bonding to any local metal structures as shown in Figure 7.2-4.

In this situation, the highest frequency up to which this type of RF Reference can maintain << 1Ω is set by its shielding effectiveness.

Where the various units comprising the converter and/or their filters don't have well-enough shielded metal boxes to maintain an impedance of << 1Ω up to the highest frequency to be suppressed, it is usually necessary to also RF bond them to their supporting, and other local metalwork. A combination of Figures 7.2-3 and 7.2-4.

I have spent many happy days in large installations, adding RF bonds all over filtered VSDs and their local metal structures to stop them interfering with sensitive instrumentation (e.g. temperature, weight and flow measurement). The more RF bonds one adds, and the shorter they are, the lower the VSD's EMI.

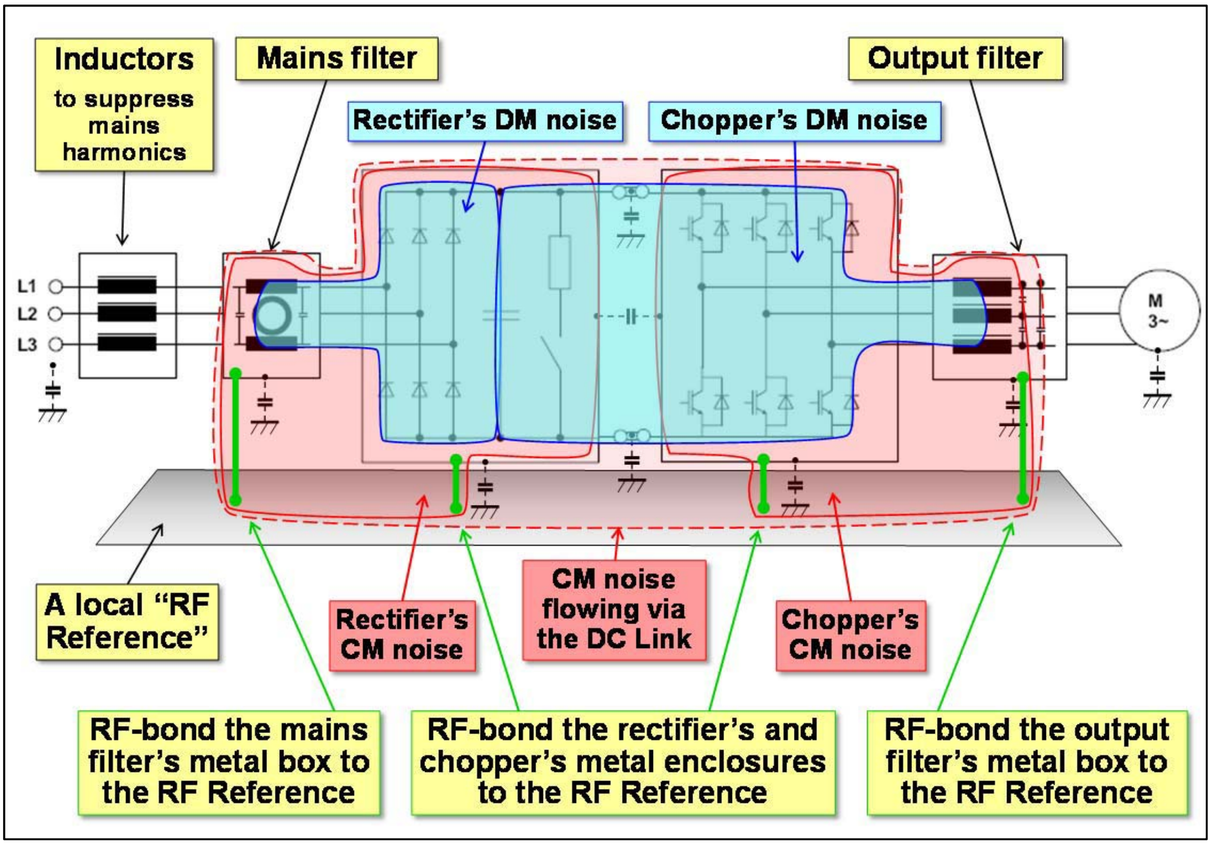

Figure 7.2-4 Example VSD fitted with filters and RF-bonded to an RF Reference

An RF Reference is what almost all EMC textbooks and articles call an "EMC earth/ground" or "RF earth/ground" – confusing terms because people shorten them to just "earth" or "ground", just as they shorten safety earth/ground to "earth" or "ground" despite them being very different things indeed.

As before, this confusing terminology has caused huge problems, delays and costs in the past, so I use the term "RF Reference" instead, and strongly recommend its use.

How to create an RF Reference in practice is described in detail in the following:

- in general: Chapters 5.7 and 5.8 of [4] or 2.7.7 and 2.7.8 of [5]
- for PCBs: Chapter 4 of [37]
- for complete electronic products: Chapters 4.2.3, 4.5, 4.6.2, 5.3 and 7.4 of [5]
- for items of equipment comprising several electronic units in one metal box: Chapters 2 and 4 of [68] and 6 of [70]
- for systems and installations of any size: Chapters 5.5 (starts on page 69) of [69], and 5 of [70]

As the above references show, an RF Reference is a metallic structure that provides a low impedance up to the highest frequencies to be suppressed. This impedance must always be << 1Ω, preferably < 10mΩ, with lower impedances being associated with higher levels of RF suppression. The above list of references describe how to achieve this at low (sometimes no) cost.

RF References can be made by RF bonding existing and/or additional metal items together to create some sort of mesh, or (better still) by RF bonding metal sheets together. Ideally, an RF Reference would consist of a single sheet of metal that underlies – and extends beyond by as much as practical – all of the units and filters that are to be RF-bonded to it. Like the sketch in Figure 7.2-4.

Better than the ideal metal sheet RF Reference is to use an internal surface of an overall shielded enclosure that contains all the converter units and their filters, and achieves good shielding effectiveness at least up to the highest frequency to be suppressed. Achieving good shielding effectiveness for a metal box with cables or other types of conductors entering and exiting it, is not a trivial issue, and many people get it badly wrong by missing just one tiny detail.

Shielding will be covered in a later article in this series, but in case you need to know right now, the necessary techniques are fully described in the following:

- for PCBs: Chapter 2.2 of [37]
- for complete electronic products: Chapter 6 of [5]
- for items of equipment comprising several electronic units in one metal box: Chapter 5 of [68] (starts page 55) and 6 of [70]
- for systems and installations of any size: Chapter 5.12 (starts page 133) of [69], and 6 of [70]

Another essential characteristic of an RF Reference is that it must be much closer to whatever is going to use it than one-tenth of the wavelength at the highest frequency to be suppressed. This is often written as $<< \lambda/10$ at f_{max}, but where the surrounding medium is air, gas or vacuum (rather than oil, water, etc.) this can instead be written as $30/f_{max}$. Where f_{max} is given in MHz, the result is metres, but if f_{max} is given in GHz, the result is millimetres. For example, for an f_{max} of 10MHz in air – $\lambda/10$ is 3m, and for an f_{max} of 100MHz in air – $\lambda/10$ is 300mm.

Don't forget these are maximum values, ideally we want to be at least ten times closer to the RF Reference, i.e. < 300mm for up to 10MHz, and < 30mm for up to 100MHz.

RF References that are further away than $30/f_{max}$ or $\lambda/10$ are no use at all as RF References. They might well be a perfect RF Reference for some other item of equipment, but they are too far away to be our RF Reference.

Using metal structures as RF References when they are further away than $30/f_{max}$ (MHz gives metres) or $\lambda/10$ will generally amplify emissions – not what we want.

A particular problem arises with DC Links. They carry quite large amounts of DM and CM noise currents, and some systems use a single high-power rectifier unit to feed DC power to one, two or more power converters some distance away.

But Figure 7.2-3 shows that to suppress the DM and CM noise currents that flow through a DC Link requires RF bonding between the rectifier unit and any/all of the switcher/chopper units it powers. And to achieve $<<1\Omega$ bonding impedance these units would have to be very close together – so such DC Links must be very short indeed.

Ideally, the rectifier and switcher/chopper units would have their metal enclosures directly screwed or bolted together at multiple points $<< \lambda/10$ apart at the highest frequency to be suppressed. Alternatively, they could be RF-bonded to their RF Reference.

Where neither approach is practical, or the DC Link must be long, then the DC Link should be filtered as it exits the rectifier, with this new filter RF-bonded to the rectifier itself, and/or both of them RF-bonded to their RF Reference.

Also, all of the switchers/choppers supplied by this DC Link should each be individually filtered at its DC power input, with each of these new filters RF-bonded to their switchers/choppers, and/or both filter and switcher/chopper RF-bonded to their own RF Reference.

The additional cost/space/weight of the additional filters required for a long DC Link might make it more cost-effective to provide each switcher/chopper unit with its own mains rectifier, to keep the DC Link short and contained within that one unit.

Alternatively, a shielded DC Link could be used, with the shield RF-bonded to the rectifier's RF Reference and also RF-bonded to the RF References of each/every switcher/chopper that is supplied by this DC Link.

Shielding can also be used to replace filtering at a converter's AC or DC output. Sometimes it is most cost-effective to combine shielding with filtering.

Shielding techniques for cables and busbars will be discussed in a later part of this series, but if you can't wait that long, see the following:

- for PCBs: Chapter 2 of [37]
- for complete electronic products: Chapter 4 of [5]
- for items of equipment comprising several electronic units in one metal box: Chapter 3.7 of [68] (starts page 31) and 7 of [70]

- for systems and installations of any size: Chapter 5.7.6 through 5.7.10 (starts page 97) of [69], and 7 of [70]

7.3 Designing or choosing effective filters

7.3.1 An introduction to filter design based on noise current loops

Filters are constructed from capacitors, inductors and chokes, and – as shown in 7.2 above – using filters along with RF bonding and an RF Reference creates small-area loops for the DM and CM noise currents to flow in.

The laws of physics and electromagnetism ensure that the noise currents "prefer" to flow in these small loops, diverting the noise currents away from the much larger loops created by the mains power supply and motor cables. The presence of the small loops significantly reduces the levels of noise currents that flow in these large loops, reducing the likelihood of failing emissions tests and/or causing EMI in real life.

This section (7.3) looks into some filtering techniques. Instead of the complex circuit used as the example in section 7.2, with their complex noise current paths, this section uses figures based on the simple block diagram shown in Figure 7.2-1, and shows the DM and CM current loops as very simple shapes, using blue for DM and red for CM as in section 7.2.

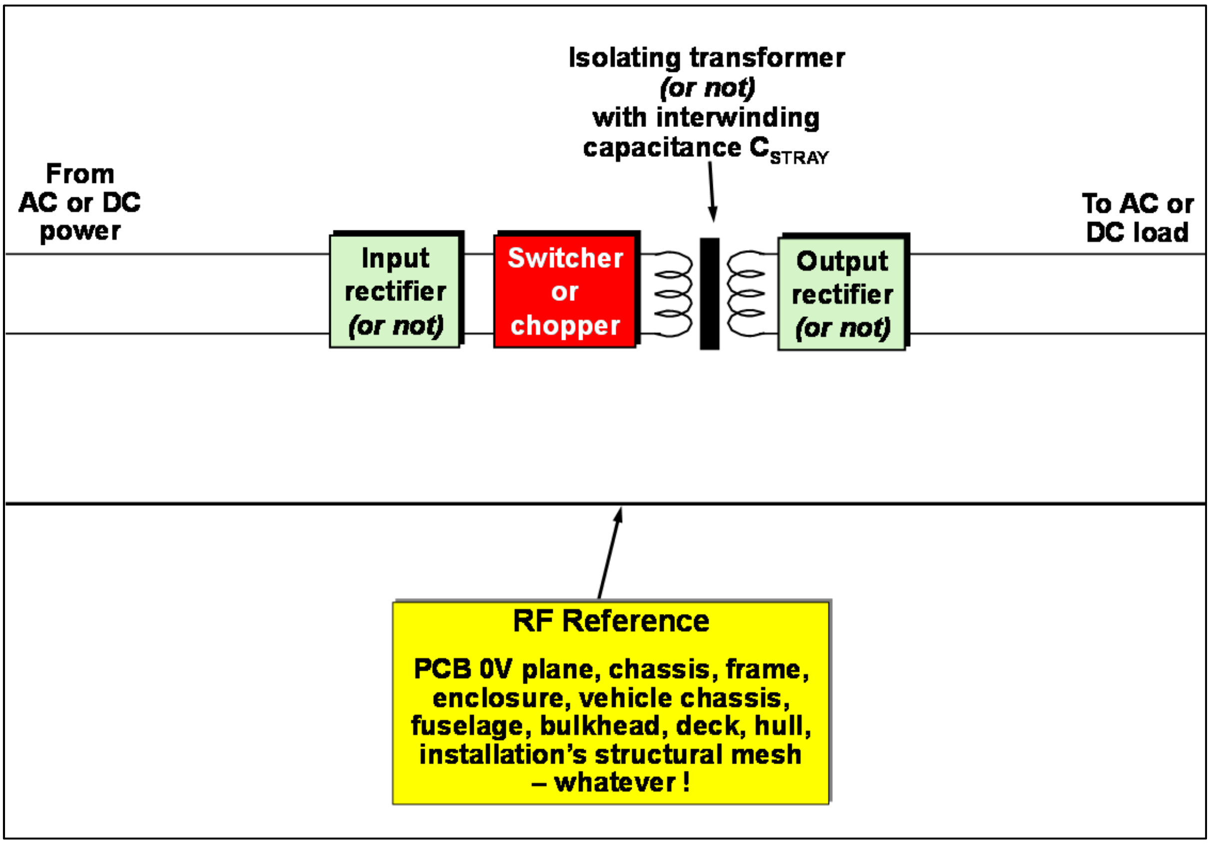

Figure 7.3-1 Example circuit for this section

But, just as in section 7.2, these figures used in this section are equally relevant for all types of switch-mode power converters – from every kind of DC/DC convertor mounted on a PCB, through every kind of AC/DC power supply, to every kind of DC/AC or AC/AC inverter up to any number of MW.

Many of the DC inputs or outputs on low-power converters mounted on PCBs are "single-ended" circuits, i.e. their return paths flow in what is often called the 0V (or zero-volt) conductors.

Where such a converter's PCB has external metalwork, this metal should be RF-bonded directly to the 0V conductors and the whole lot treated as the RF Reference, with the figures in this section (and in 7.2) modified accordingly. (If this text is not clear enough, please let me know and I'll draw appropriate figures in a future article).

But where the PCB's 0V return path must be galvanically isolated from its structural metalwork, then we continue to use three-conductor systems (i.e. separate conductors for the send, return, and RF Reference) like those sketched in Figures 7.2-3 and 7.2-4.

Most EMC books describe EMC filtering, so perhaps I need not go into it in any more detail in this article, in particular:

- in general: Chapters 5.7 and 5.8 of [4] or 2.7.7 and 2.7.8 of [5]
- for PCBs: Chapter 4 of [37]
- for complete electronic products: Chapters 4.2.3, 4.5, 4.6.2, 5.3 and 7.4 of [5], and 13 of [71]
- for items of equipment comprising several electronic units in one metal box: Chapters 2 and 4 of [68] and 6 of [70]
- for systems and installations of any size: Chapters 5.5 (starts on page 69) of [69], and 5 of [70]

However, these books do not describe how filtering achieves noise suppression in terms of current loops and their impedances – so I thought it would be helpful to write a little about filters in that way. Considering the paths taken by currents, whether wanted or stray/noise, is a very powerful way to visualise EMC design issues, and can also be used to analyse EMC design qualitatively, even quantitatively.

AC currents, whether wanted or noise or stray, divide amongst alternative current loops according to their admittances. Admittances are merely the reciprocal of impedance, so the loops with the highest admittance (i.e. lowest impedance) carry the most current.

It is exactly the same way that DC currents divide amongst parallel resistor loads – the highest currents flowing in the highest conductance (in Siemens, S) i.e. the lowest resistance (in Ohms, Ω).

But for AC currents the important issue is the admittances (reciprocal of impedances), which of course vary with frequency.

7.3.2 Filtering with capacitors only

Figure 7.3-2 shows an example of filtering using only capacitors, which aim to create low impedances for the noise currents, to provide them with small loop areas.

Capacitors between the send and return conductors for a converter's input (or output) aim to provide lower impedance loops for the DM noises than if they flowed in the cables all the way to the power source (or load).

Capacitors from the send and return conductors to the RF Reference, aim to do the same for the CM noise currents – provide lower impedance loops for the CM noises than if they flowed in the input (or output) conductors all the way to the to the power source (or load) and back via various metal structures (chassis, frame, installation structural metalwork, etc.).

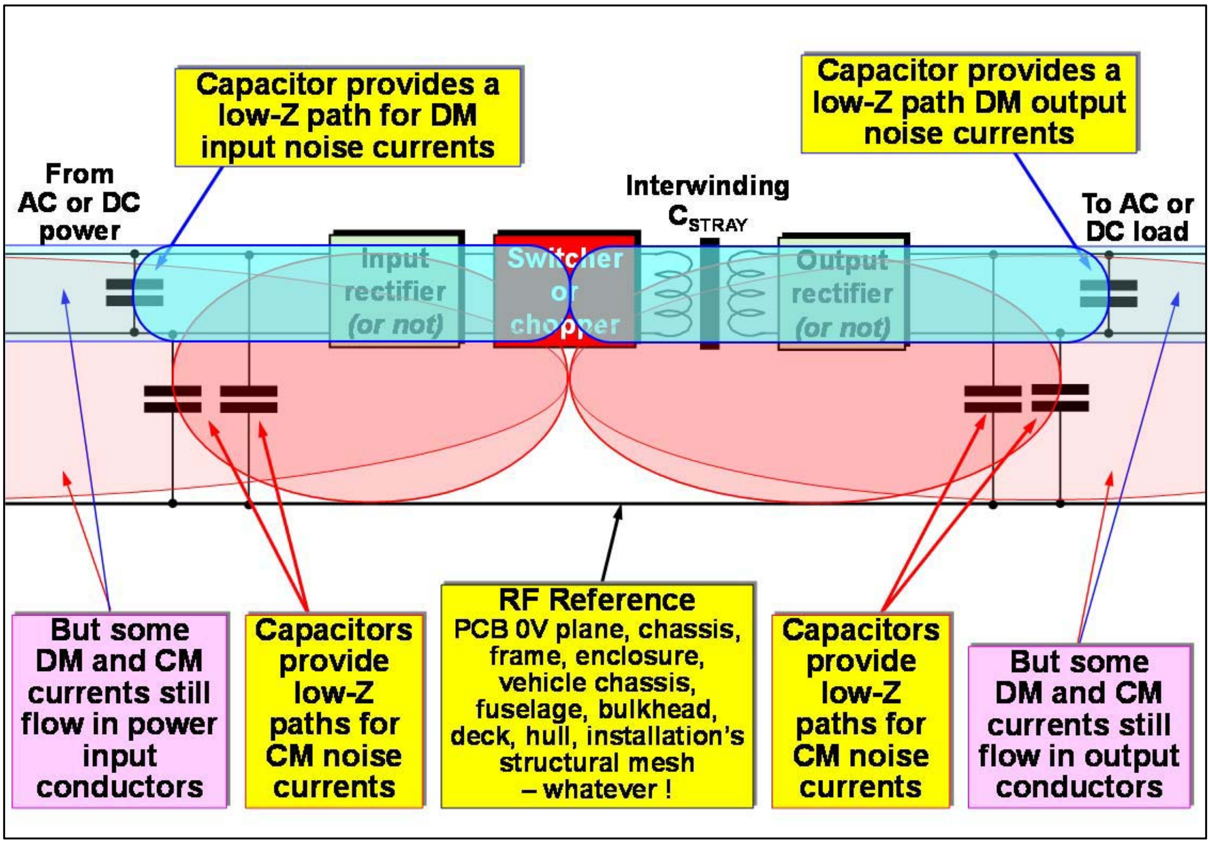

Figure 7.3-2 Example of capacitive filtering

Both DM and CM filtering capacitors need to have low impedances over the noise frequency range to be suppressed – which means they must have a high-enough value of capacitance to create a low-enough impedance at the lowest noise frequency, plus a low-enough value of ESL (equivalent series inductance) to have a low-enough impedance at the highest noise frequency to be suppressed.

(Chapter 3.8 of [5] describes the stray (sometimes called parasitic) impedances associated with capacitors, which limit their usefulness for RF suppression above some frequency. Other limitations of capacitors (e.g. ripple current, temperature) are also covered.)

The way the filter capacitors are connected to the circuit conductors is also important, because all leads, traces, busbars, etc., have inductance. Their inductance adds to the ESL of the capacitors themselves, increasing the overall impedance at the highest noise frequency and making it less effective as an alternative current path.

Figure 7.3-3 sketches various types of capacitors used in filters, with varying effectiveness as filter capacitors depending on the inductive impedance created by their method of assembly.

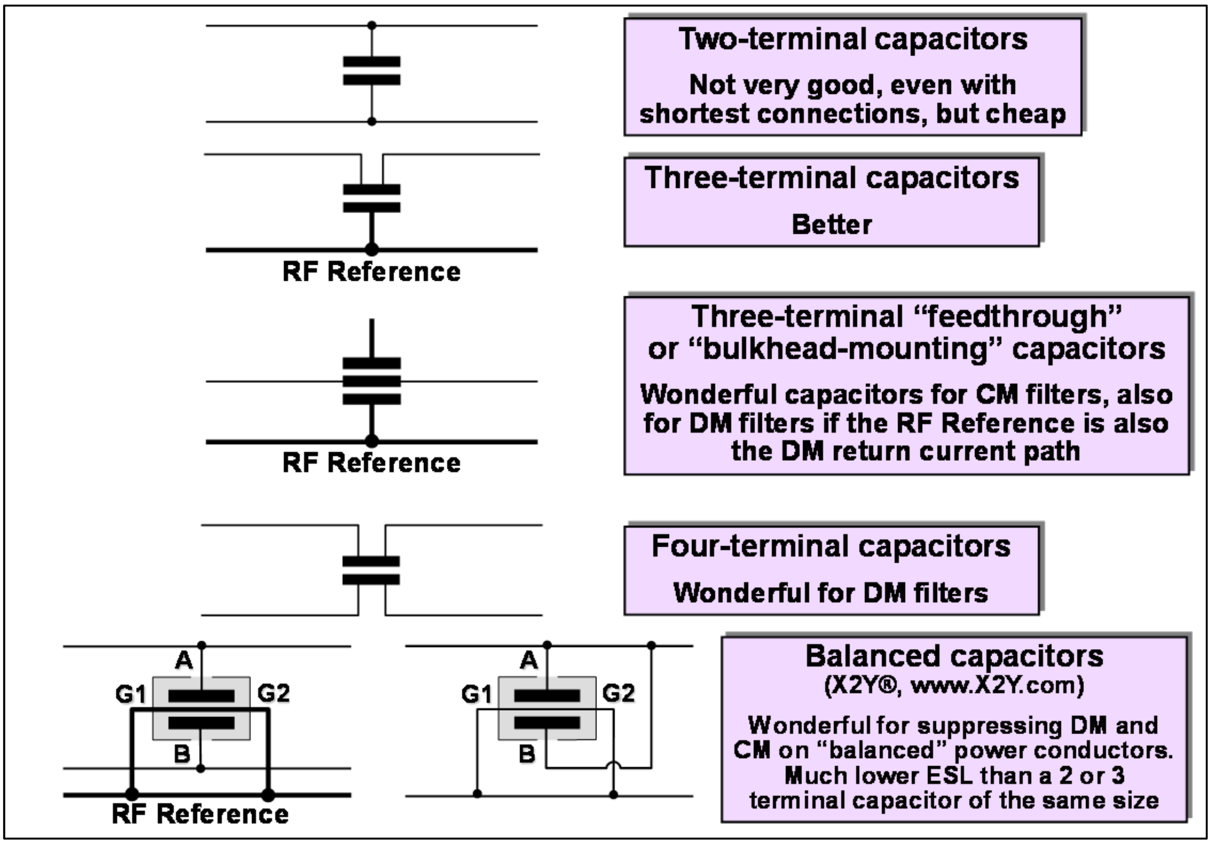

Figure 7.3-3 Examples of types of filter capacitor

For example, if we assume that the typical impedance of the CM noise current loop for a long cable is 150Ω, and if we wanted to achieve a 20dB reduction in emissions at the highest frequency of 100MHz, we need to use a filter capacitor that achieves a total loop impedance of 15Ω. (I am ignoring the source impedance of the noise for the sake of simplicity, as it does not alter the point I am trying to make with this example.)

This total loop impedance is the vector sum of the capacitor's own reactance and the overall inductance and resistance in the current loop. A 10nF capacitor at 100MHz has a reactance of about 0.16Ω, but a 10mm square current loop has an inductance of about 0.04μH and a reactance at 100MHz of 25.2Ω. The vector sum of both reactances is about 25Ω – dominated by the loop inductance

Clearly, the most we can expect from this capacitor filter assembly is an attenuation of roughly 25/(25 + 150) – i.e. about -14dB, and not the 20dB we wanted. To get 20dB we'd have to reduce the loop's inductance by about a half.

This example shows that once the easy job of choosing a capacitor value is done, it is the total loop inductance that really matters when filtering with capacitors. To get a 20dB reduction in emissions at 100MHz we must provide a current loop that – including the size of the capacitor – is equivalent to a square of side 7mm.

It would be the same for 40dB at 10MHz, 60dB at 1MHz, or 80dB at 100kHz – using capacitive filtering they would all require current loops that were equivalent to a 7mm square current loop, or smaller.

Similar examples show that current loop inductance is a problem when capacitively filtering DM noise sources too.

Filter manufacturers are well aware of this issue, and for good performance use three-terminal feedthrough or through-bulkhead types. These have very low ESL and when mounted on a metal wall or bulkhead that is part of their RF Reference (for CM noise) – and for DM noise also acts as the return conductor. Their overall loop impedance is set by the impedance of the RF Reference and any RF bonding.

Providing they are mounted correctly on well-designed and correctly assembled RF Reference, three-terminal feedthrough or through-bulkhead capacitor filters can achieve very high levels of attenuation to well beyond 1GHz.

For good suppression at frequencies of 100MHz and above, the metal plate through which the feedthrough filters are mounted, will almost always need to be a shielded enclosure as well as the RF Reference.

Clearly, component choice, and the design of RF bonding and the RF Reference are very important for capacitive filtering! For full details on these important issues, read the Chapters on filtering listed in 7.3.1 above.

Capacitive CM and DM filtering is especially effective when the conductors they are suppressing have high-Z resonances, and especially useless when their conductors have low-Z resonances.

Even feedthrough filters can struggle to divert noise currents away from the external conductors, when those conductors are suffering low-Z resonances. So we now need to discuss conductor resonances.

7.3.3 Resonances in Input and Output conductors (PCB traces, cables, busbars, etc.)

In real life, the CM impedance of a long conductor (e.g. a cable) varies considerably depending on its proximity to conductors and dielectrics, and both CM and DM impedances in conductors vary greatly when they resonate. Their first resonance is generally when they are a quarter of the wavelength long, for example: at 100MHz, the first (quarter-wave, i.e. high-Z) resonance occurs in conductors just 750mm long, at 10MHz in conductors 7.5m long, and at 1MHz in conductors 75m long.

Remember, when a converter is powered from an AC or DC power distribution network, its power input cable is as long as the network itself. It is not merely the length of the cable used to connect to that network. So almost all AC mains power input conductors are longer than 75m.

Exactly the same situation applies to converter AC or DC *outputs* that provide power to AC or DC distribution networks – the actual conductor length is much longer than the cable used to connect the converter to the network.

Chapters 4.7 and 7.6 of [5] shows how to design conductors as matched transmission lines, which do not resonate. Resonances occur in all transmission lines that are not correctly terminated, but few people (if any) design their converters' AC or DC inputs or AC or DC outputs as matched transmission lines, so they all suffer from unwanted (and unhelpful!) resonances.

Chapters 3.2 of [4] or 2.5.2 of [5] show how mismatching causes these resonances, but does not give a range for the impedances this causes. In fact, conductor resonances can produce impedances as low as their overall resistance (usually tens or hundreds of mΩ) and as high as their leakage resistance (usually tens of MΩ).

For example, a typical straight 10m length of cable connected to the input or output of a power converter, on its own in free space, will resonate with high and low impedances alternately, at 7.5, 15, 22.5, 30, 37.5, 45, 52.5, 60, 67.5, 75, 82.5, 90, 97.5……etc. MHz, all the way to well over 1000MHz (1GHz).

Bending or coiling the cable, or routing it near metal or near (or in) damp soil (or other dielectric materials) will "tune" all of its resonances to different frequencies. Also, in the case where AC or DC power is supplied from a distribution system shared with other equipment, the connection and disconnection of the other equipment (e.g. switching lights on or off) will tune power cable resonances to different frequencies.

And don't forget that power conductors can have other resonances in their DM and CM noise current loops, as their series inductance interacts with their shunt capacitances, "tuned" in this case by any filter capacitors connected to them. With the large values of capacitors connected to power distribution networks these days – mostly to reduce the RF emissions of switch-mode power converters – these resonances generally occur in the range up to about 100kHz.

The result is that – unless the input or output conductors have a fixed relationship to each other and to nearby metalwork (including other conductors) and dielectrics, and a fixed configuration and characteristics for all supplies and/or loads – we should assume that we can get low-Z or high-Z resonances at *any* frequency.

Unfortunately, when converters are tested for their EM emissions, they use a standardised AC or DC power supply impedance, a standard length and layout of cables, and they might replace the intended reactive load (e.g. motor, solenoid, PCB with decoupling capacitors, etc.) with a resistive load (this is almost always done for DC-output convertors). So we cannot be confident that we have tested for resonances that could occur in real life and possibly cause big problems.

There are ways of making emissions (and immunity) testing more realistic, to reduce project and financial risks. Some of them (e.g. using the real load instead of resistor bank) can be used within the standard test methodology, but many of the other ways would mean deviating from the standard test.

7.3.4 Filtering with inductors/chokes only

So now let's look at filtering with inductors, or "chokes" as they are usually called when suppressing RF.

Figure 7.3-4 shows our example block diagram fitted with inductive (choke) filtering only. RF chokes aim to create high impedances at the noise frequencies we want to suppress. We put them in series with the external conductors we are trying to suppress, to reduce the amount of noise current that flows in them.

A big advantage of choke filtering, is that it doesn't need an RF Reference. However, as we will see below, choke filtering on its own is almost never provides the noise suppression we need over the whole frequency band, so we need to combine it with capacitive filtering as described in 7.3.4 – which *does* need an RF Reference, if only for suppressing CM noise.

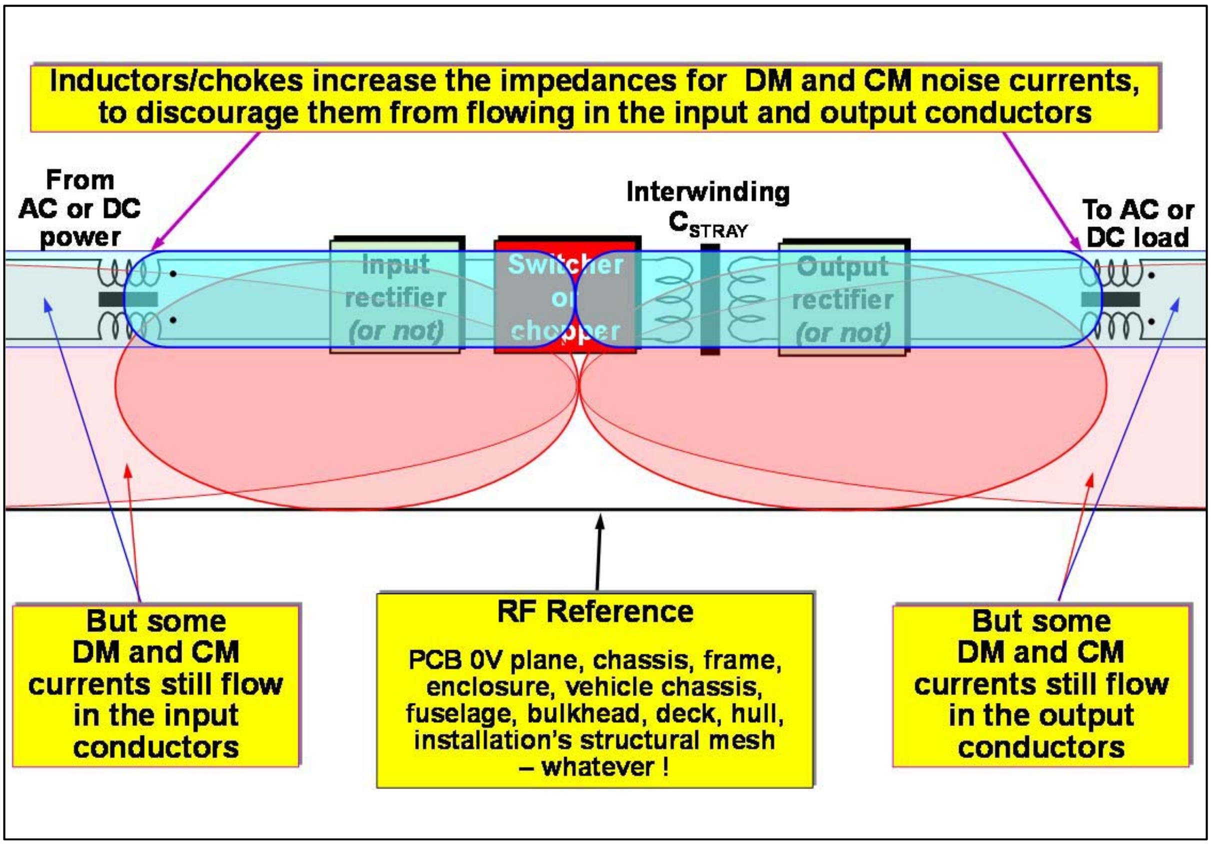

Figure 7.3-4 Example of inductive (choke) filtering

Figure 7.3.4 shows CM chokes and says that they filter DM and CM. An ideal CM choke only creates impedance for CM currents, and has no DM impedance. But all *real* CM chokes have some leakage inductance that creates impedance for DM currents, and for well-made wound CM chokes this is typically 1% of the CM inductance.

Some manufacturers of RF power chokes make CM chokes that have large DM inductances, sometimes called CM+DM chokes. Their big advantage is that where both CM and DM chokes are required – as they often are on the power inputs of switch-mode power converters – they can save a component (or two).

To have any appreciable effect, a choke must create an impedance at least as large as that seen by the noise current loop including the impedance of the noise source itself.

For example, if the impedance of the noise source plus the loop to be suppressed was 50Ω, then to achieve 20dB of suppression the choke must have sufficient self-inductance to create at least 500Ω over the range of frequencies to be suppressed.

For high levels of suppression and/or very high frequency suppression, the stray capacitance from a choke's input to its output can significantly reduce its effectiveness. For example, just 3pF of stray input-to-output capacitance will have a reactance of about 530Ω at 100MHz, and because this appears in parallel with the choke's self-inductance it limits the choke's impedance to no more than this, no matter how high the value of its inductive reactance.

(Chapter 3.8 of [5] describes the stray/parasitic impedances associated with inductors and chokes that limit their ability to suppress RF above some (often surprisingly low) frequency. Other limitations, such as peak current and operating temperature are also covered.)

Inductors (chokes) are wound components that inevitably suffer from stray capacitance. For this reason, most RF chokes for use on conductors carrying power struggle to achieve more than 1kΩ over more than a decade of frequency.

Clearly, component choice, and the design of metalwork, are very important for choke filtering at RF. For full details on these important issues, read the Chapters on filtering listed in 7.3.1 above. Chokes intended for use below about 10MHz are often specified by their CM and DM inductance values, but chokes for use above about 10MHz tend to show their CM and DM data as graphs of impedance versus frequency.

Conductor resonances were described in 7.3.3, and whilst their low impedance resonances cause difficulties for capacitive filtering, their high-impedance resonances cause difficulties for choke filtering.

Also, real noise sources might have impedances of between 10mΩ (or less) and 10MΩ (or more). For example, below 1MHz, the DM noise emitted from a rectifier's mains power input is generated mostly by the ripple voltage on the rectifier's storage capacitor. In the case of a DC input converter, it is the ripple on its DC input capacitor.

These ripple voltages have very low impedances, comparable with the ESL and ESR of the capacitors, which are usually just a few tens of nH and a few tens of mΩ respectively. The result is that the DM noise source impedance for the AC or DC power input is usually around a few tens of mΩ at 100kHz, and around a hundred mΩ at 1MHz (or more).

At the other extreme, in an isolating power converter the CM noise emitted by a rectifier's mains power input comes from stray capacitances between the AC rectifier and off-line switching devices, and their metal enclosure or other nearby metalwork. These strays can be as low as 100pF, which would create a CM noise source impedance of around 15kΩ at 100kHz and 1.5kΩ at 1MHz.

This range of noise source impedances means that, for the example isolating power converter input circuit at frequencies below 1MHz, choke filtering is generally most effective on DM noise emissions, and capacitive filtering is generally most effective on CM noise emissions.

Figures 7.3-5 and -6 give examples of different ways of using chokes in RF filters, and are (hopefully) self-explanatory. Please let me know if they are not and I'll write some text about them in a future article.

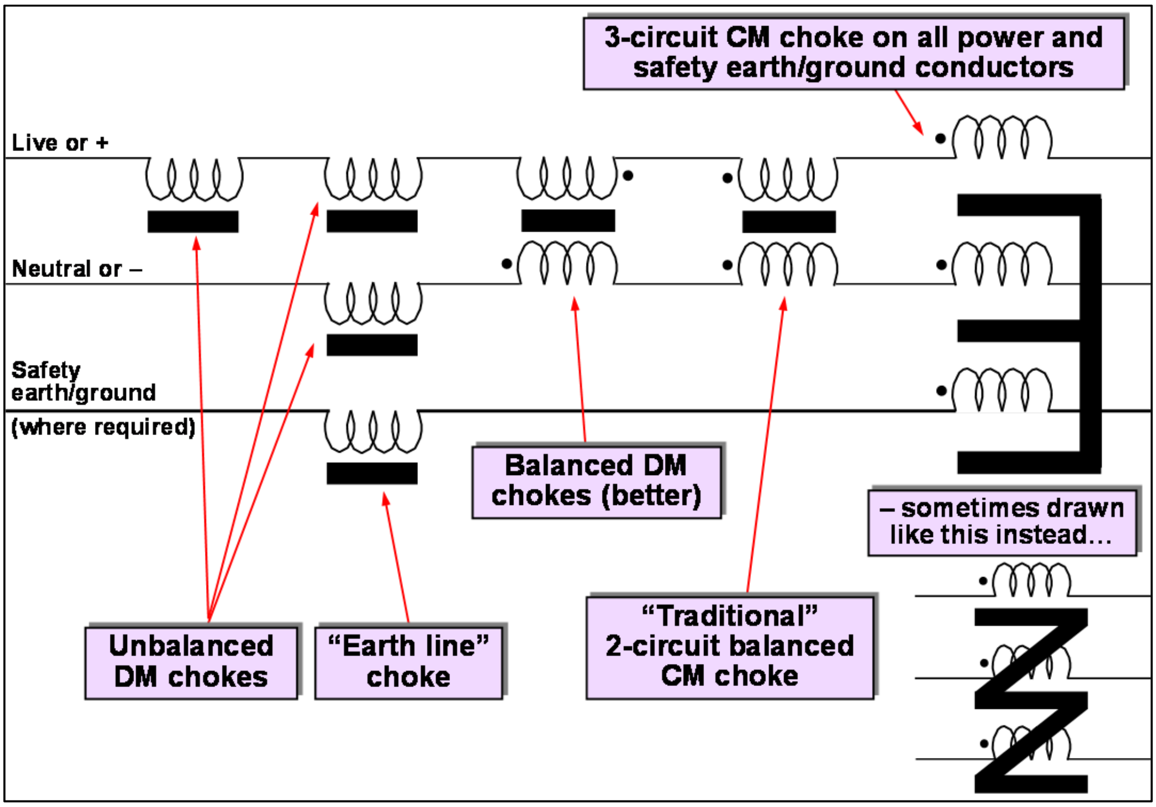

Figure 7.3-5 Different kinds of inductors (chokes)

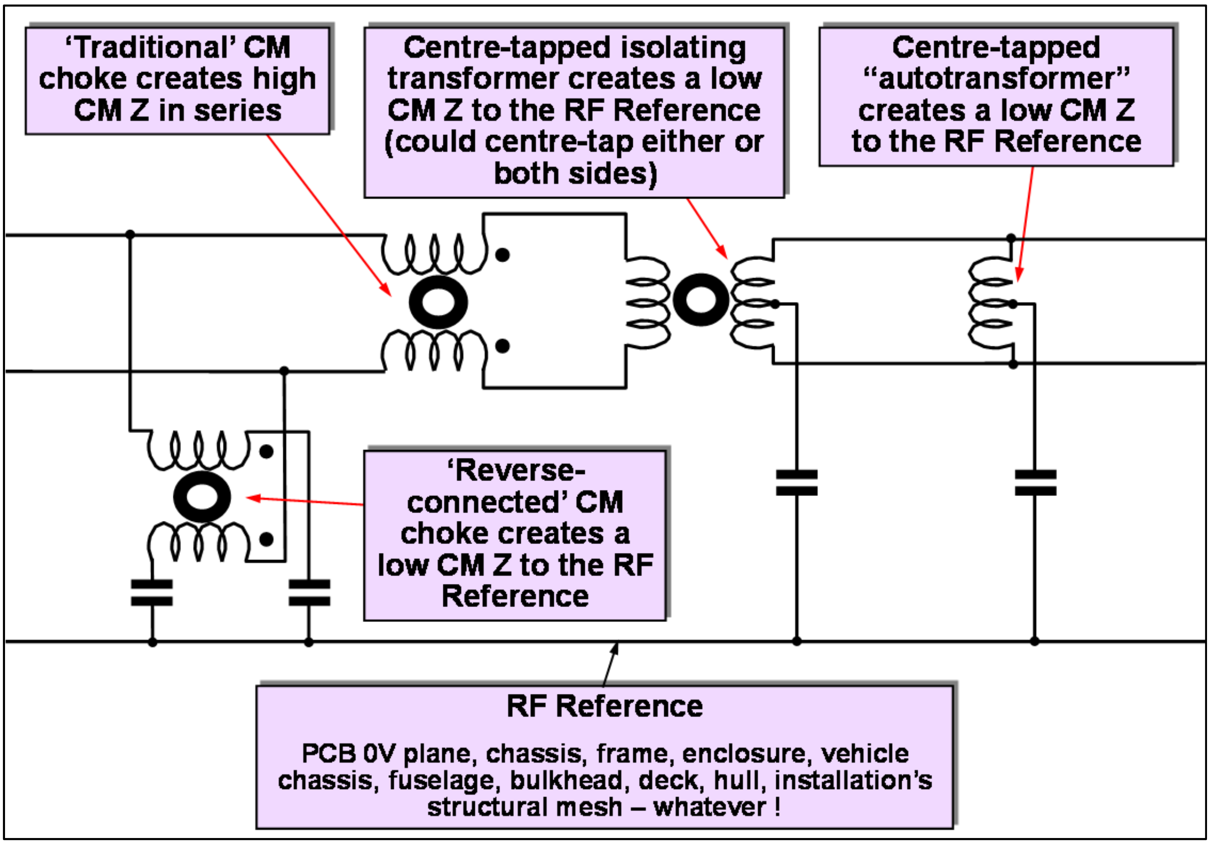

Figure 7.3-6 Examples of alternative CM chokes

7.3.5 Combing capacitive and inductive (choke) RF filtering

CM currents are often the main causes of emissions problems above 1MHz, and Figure 7.3-7 shows the use of so-called "earth-line chokes" to add extra impedance into the unwanted CM noise current loops in the external cables.

At frequencies where the CM filter capacitors don't achieve a very low impedance alternative internal noise current loop, or where the external conductors are for some reason creating a low impedance, this choke will help divert more of the noise current through the internal loop created by the filter capacitors.

Although an "earth-line choke" is a single circuit (i.e. unbalanced) DM choke, because it is in series with the safety earth/ground conductor it can help to suppress the CM noise that is returning from long external conductors via the safety earth/ground conductor.

However, where a converter has many return current paths for its external CM noise current, adding an earth-line choke into its safety earth/ground conductor may have disappointingly poor results.

A good way to increase the impedance of the external CM noise current loop, is to remove all connections to the safety earth/ground – creating an (effectively) infinite series impedance. Of course, we only do this where it cannot compromise safety compliance!

I have often done this, with good effect, where designers had assumed that the safety earth/ground electrodes created a sort of "infinite sink" for RF noise, so they had connected their product to the external safety earth/ground network in the hope that their RF noise emissions would be somehow absorbed in this sink. Of course, as 7.2 shows, all currents (even stray noise currents) flow in closed loops, so it is impossible (in this universe) to create any kind of current sink.

Understanding this, I was able to remove the safety earth/ground connections and significantly reduce CM emissions, to the amazement of the designers, who had assumed it would make CM emissions worse.

It's a good feeling to be able to amaze people in this way, especially when solving EMC problems in a few minutes that they had been wrestling with for weeks, sometimes months. But in fact everyone reading this article can easily learn to understand how Maxwell's equations relate to good practical EMC engineering design techniques, and then work *with* the laws of physics to quickly get wonderful EMC (and SI and PI) performance whilst reducing the overall cost of manufacturing EMC-compliant products, equipment, systems and installations. For more on this see [4] (general), [32] (for PCBs) or [33] (for systems and installations).

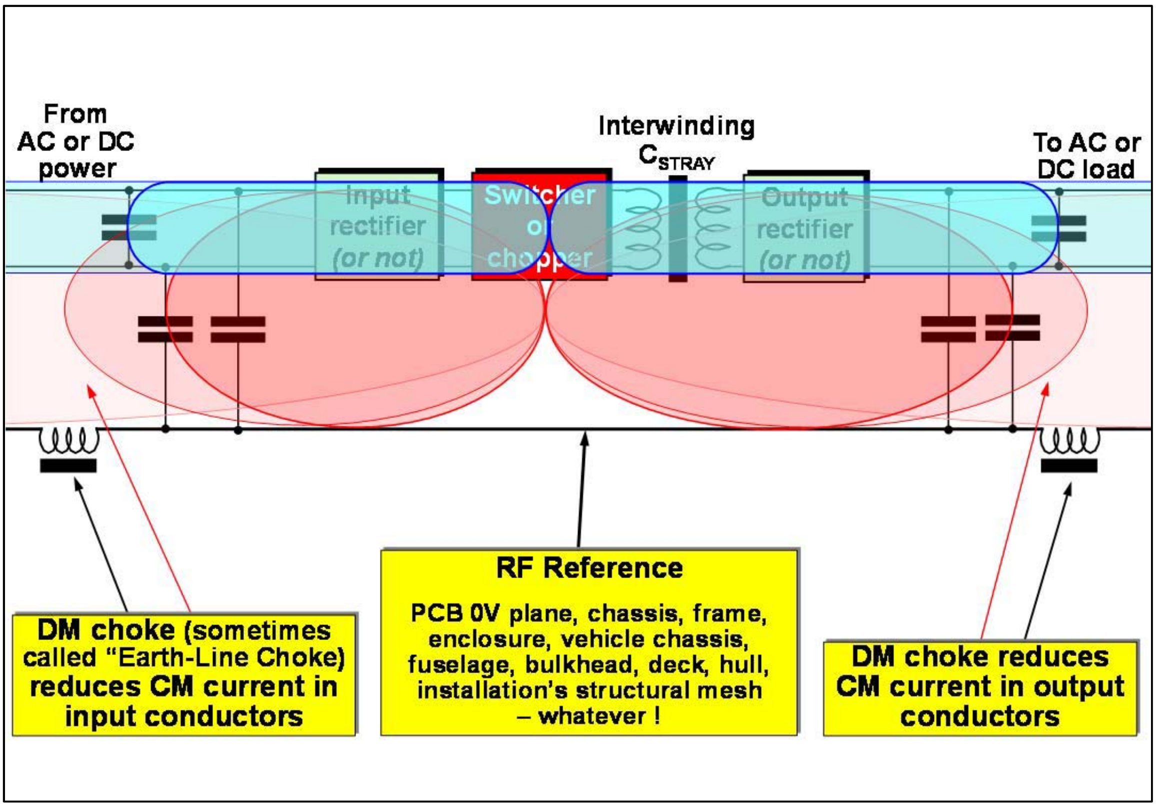

Figure 7.3-7 Example of combined capacitive and inductive filtering using "earth-line chokes"

Figure 7.3-8 shows a different way of achieving the same effect as using earth-line chokes – by fitting CM chokes into the input and output conductors. Because there are often many alternative routes for stray CM currents in external conductors to return, using CM chokes in this way generally provides better suppression than using earth-line chokes.

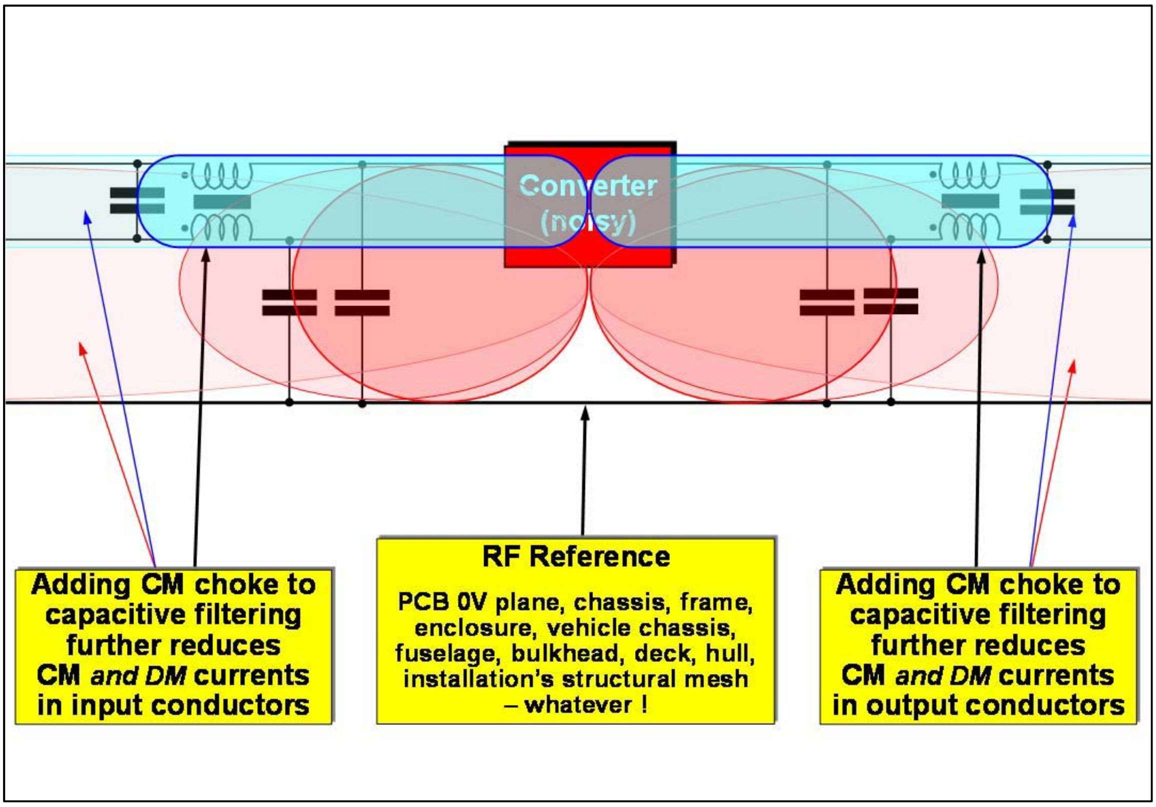

Figure 7.3-8 Example of combined capacitive and inductive filtering using CM chokes

Notice that in Figure 7.3-8 the DM capacitors have been moved to the other side of the CM chokes from the CM capacitors. This is so that the DM inductance inevitably provided by real CM chokes adds some impedance to the DM noise sources in the converter. Where these DM sources have very low impedance (as they usually do below 1MHz, see above) this small but significant additional DM noise loop impedance increases the suppression achieved by the DM capacitor.

However, for high levels of DM suppression below 1MHz it is usually necessary to fit a DM choke as well as a CM choke, to increase the DM noise loop's impedance by a lot more than can be had from a CM choke. Alternatively, we might use a CM+DM choke if we can find one with the CM and DM inductances and other characteristics we need (there is not a great deal of choice).

The noise current paths sketched in blue and red on Figures 7.3-7 and -8 show the combined effects of using capacitive and inductive filtering. As discussed earlier, when using ordinary low-cost components (e.g. wired or PCB-mounted, rather than feedthrough types), neither method is capable of achieving very high levels of suppression on its own and combining them generally achieves higher levels of suppression.

But we see the major benefits of combining capacitive and inductive (choke) filtering when we consider the problems of resonances: in the sources of the DM and CM noise currents, and in the external input and output conductors. Where there are low-Z resonances (e.g. mΩ) capacitor filters are more ineffective, but choke filters are more effective. And where there are high-Z resonances (e.g. MΩ) choke filters are more ineffective, but capacitor filters are more effective.

Combining capacitive with choke filtering therefore helps us suppress emissions over a wide frequency range despite the inevitable resonances in both the noise sources and conductors. Where we can't get sufficient suppression from the simple combined filters shown in Figures 7.3-7 and 7.3-8, which we call "single stage" filters, we can cascade any number of filter stages to achieve the suppression we need.

Figure 7.3-9 shows an example of a three-stage filter, and most filter manufacturers offer AC and DC power filters with one, two and three stages as standard products, with some offering even more stages. Multi-stage filters can have advantages over single-stage filters that I will discuss in a later article.

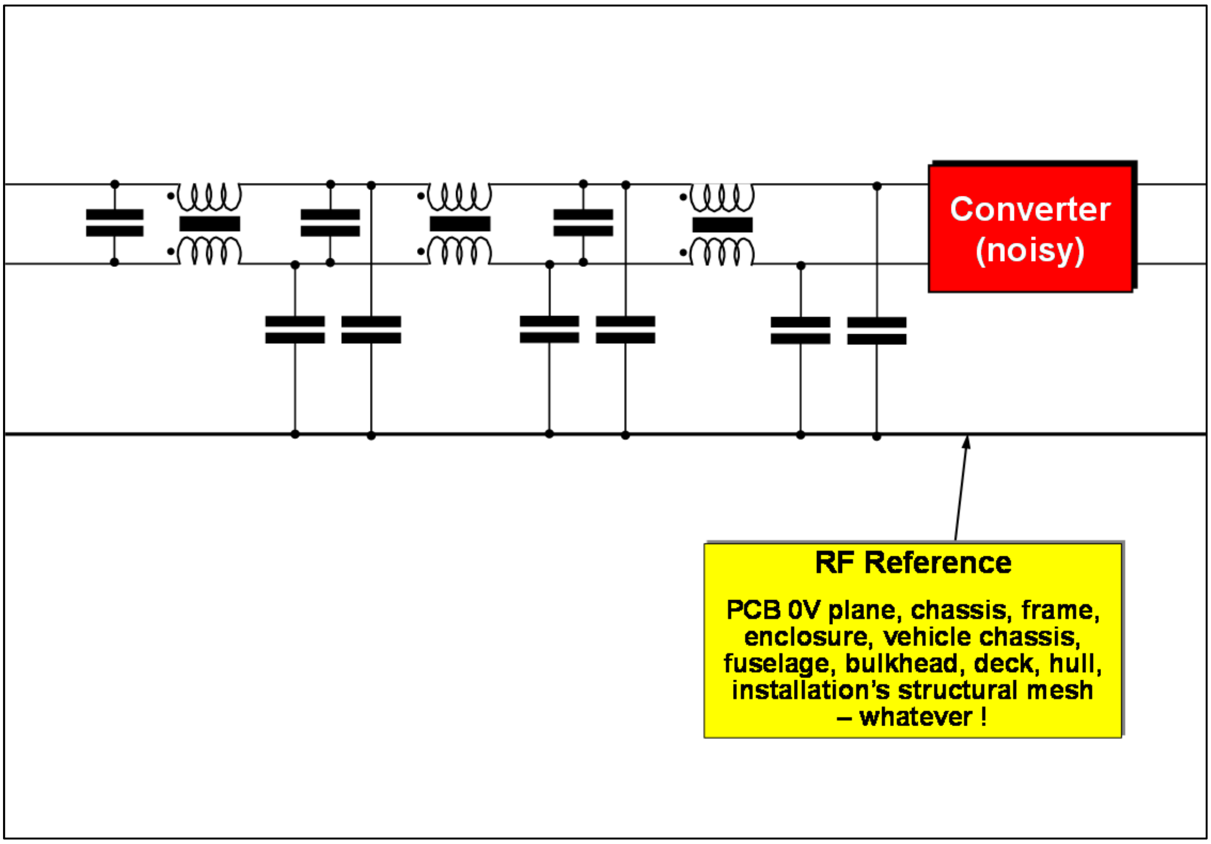

Figure 7.3-9 Example of a 3-stage mains input filter

It is worth pointing out that having more stages in a filter does not (on its own) automatically achieve higher levels of noise suppression at least cost. A filter made with high-performance high-cost components, such as feedthrough capacitors, can provide the same (or better) suppression at the same (or less) cost as a filter with more stages that uses "ordinary" low-cost components.

All mains filters intended for use on 50/60Hz supplies can be used with the same ratings on 16⅔Hz or DC (but not "PWM DC"), at a power converter's input or output. They might also be able to be used with reduced ratings on AC supplies at frequencies above 60Hz, usually up to at least 400Hz (e.g. aircraft generators). Ask the supplier if he can specify the filter's ratings for the power frequency required.

However, 50/60Hz mains filters are all unsuitable for any pulse-width-modulated (PWM) outputs, whether they are AC or "DC".

In future articles in this "stand alone" series, I will delve into good EMC filtering design practices in more detail.

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