PRESENTED BY

interference technology®

2016 EMC FILTERS GUIDE

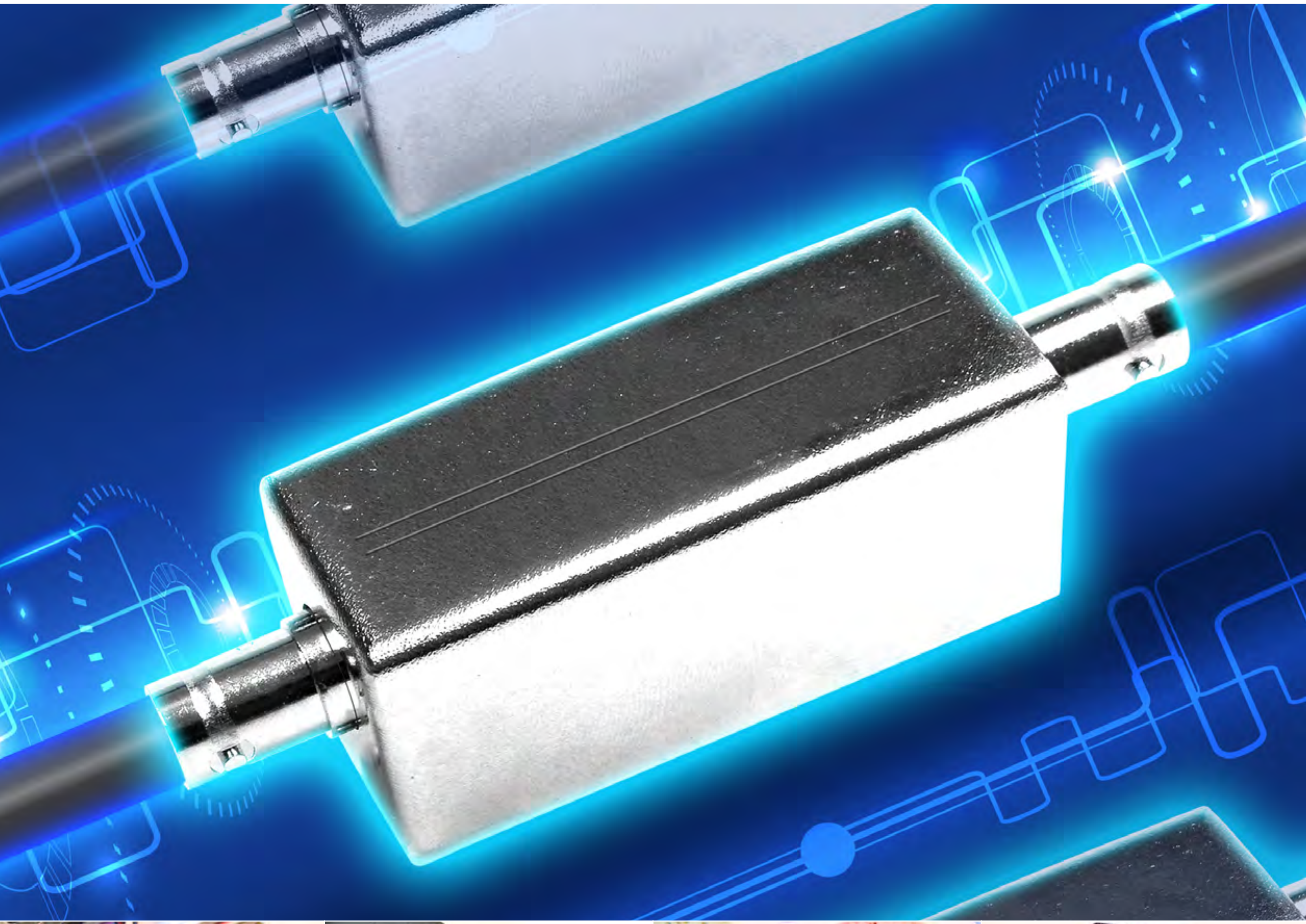


Table of Contents:

INTRODUCTION

Eur Ing Keith Armstrong CEng MIEE MIEEE Partner
Cherry Clough Consultants

This new publication, "2016 EMC Filters Guide", from Interference Technology, deals with the practical issues of EMI filter design and application. Properly designed EMI filters are an important technique for minimizing the inherent radiated and conducted emissions emanating from a product or system. Conversely, they can also provide protection against external radiated or conducted radio frequency transmissions, as well as radiated or conducted transient events, such as power line transients, electrically fast transient (EFT), or electrostatic discharge (ESD).

The content was originally published and copyrighted by Keith Armstrong in the EMC Compliance Journal over the period 2006-2009. Republished with permission.

Keith Armstrong graduated from Imperial College, London U.K. in 1972 with an Honours degree in Electrical Engineering, majoring in analogue circuit design and electromagnetic field theory. He has been a member of the IEE (now the IET) since 1977, a UK Chartered Engineer since 1978, and a European Engineer (Group 1) since 1988.

Between 1972 and 1990 Keith worked for a number of leading companies in three countries, mostly in the power conversion, professional audio and instrumentation fields. In 1985 he was a project manager and principal hardware engineer for Marconi Instruments Ltd (Microwave Division), responsible for a project with 30 staff and spending a budget of one million GB Pounds per year.

Cherry Clough Consultants was started by Keith in 1990 to help companies comply with the emissions and immunity requirements of the European EMC Directive, as well as the emissions requirements of the FCC regulations (USA) and VCCI (Japan) – whilst simultaneously reducing design and development timescales, unit manufacturing costs, and warranty costs.

Keith has been a Chartered Electrical Engineer (UK) since 1978, a Group 1 European Engineer since 1988, and a Fellow of the IET (previously the IEE) and Senior Member of the IEEE since 2010. He has written a great many articles and guides, and presented many papers, on EMC design and testing techniques, and on EMC for Functional Safety. He is a past Chair of the IEE's Professional Group on Electromagnetic Compatibility and a past President of the EMC Industries Association (www.emcia.org). He's also a member of the IEEE's EMC and Product Safety Societies, has chaired the IET's Working Group on 'EMC and Functional Safety' since 1997, and is the UK expert appointed to the IEC standards teams working on 61000-1-2 ('EMC and Functional Safety'), 60601-1-2 ('EMC of Medical Devices') and 61000-6-7 ('Generic standard on EMC for Functional Safety').

He may be contacted at:

Cherry Clough Consultants, www.cherryclough.com
Phone: +44 (0)1785 660 247
Fax: +44 (0)1785 660 247
Email: keith.armstrong@cherryclough.com

INTRODUCTION

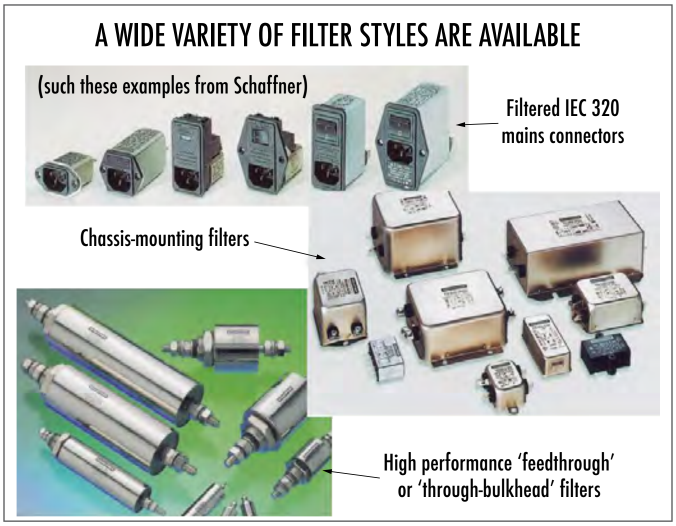


Figure 1 - A wide variety of filter styles is available (such as these mains filters from Schaffner)

Filters are used to attenuate unwanted frequencies travelling along conductors, and are characterised by attenuation versus frequency curves. Transient suppressors, such as surge protection devices (SPDs, sometimes called surge arrestors), attenuate unwanted voltage surges travelling along conductors, and are characterised by graphs of voltage 'let-through' versus time.

Incorrect use of filters or SPDs can make a product's emissions or immunity worse than if they were not used at all. More expensive filters or SPDs are not necessarily the best. You cannot in general choose a filter or SPD from a distributor's catalogue, by simply checking its ratings, performance and intended application, and expect it to provide the benefits you need for your product.

Many books have been written on filter design, such as Arthur B Williams' [3]. No doubt there is a more modern edition available, but filter design has not changed much over the years. There are also now a number of circuit simulators that run on PCs and can be used to simulate filters. This article will not go into poles and zeroes and that sort of detail – instead it will describe the things which need to be taken into account so that filters designed using textbooks, circuit simulators such as Spice, or chosen from catalogues, stand a chance of performing as required, and avoid unpleasant and/or costly experiences.

Filter design or selection is not a 'black art', but nevertheless it is difficult to predict exactly what performance a given filter will achieve when installed in a product, especially at frequencies above 100MHz, so it is often necessary to experiment with different options to find the most cost-effective. Planning and designing for such flexibility from the start of a project is very worthwhile, and an example of what John R Barnes [4] calls "wiggle room" and I call "anti-Murphy design". My approach is based upon the well-known Murphy's Law – I find that designers who try to anticipate the surprises that Murphy might have in store for them reach their design targets and timescales more reliably, and the resulting products have a lower overall cost of manufacture because they have not had to have filters, or larger filters than were hoped for, squeezed in somehow at the end of a project when compliance tests were failed.

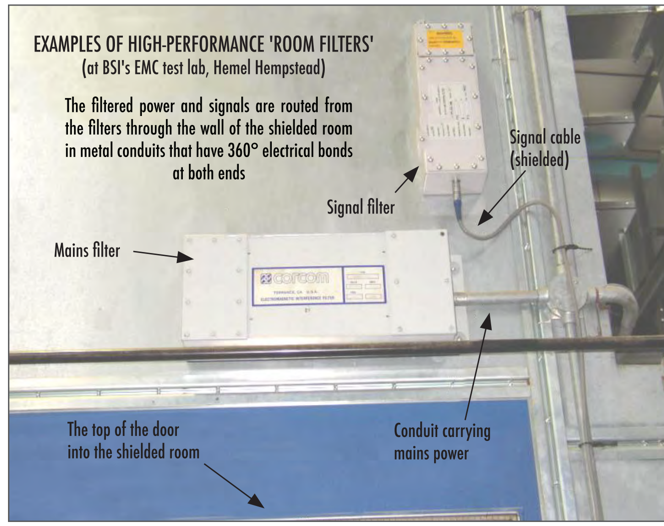


Figure 2 - Examples of high-performance 'room filters' (at BSI's EMC test lab, Hemel Hempstead)

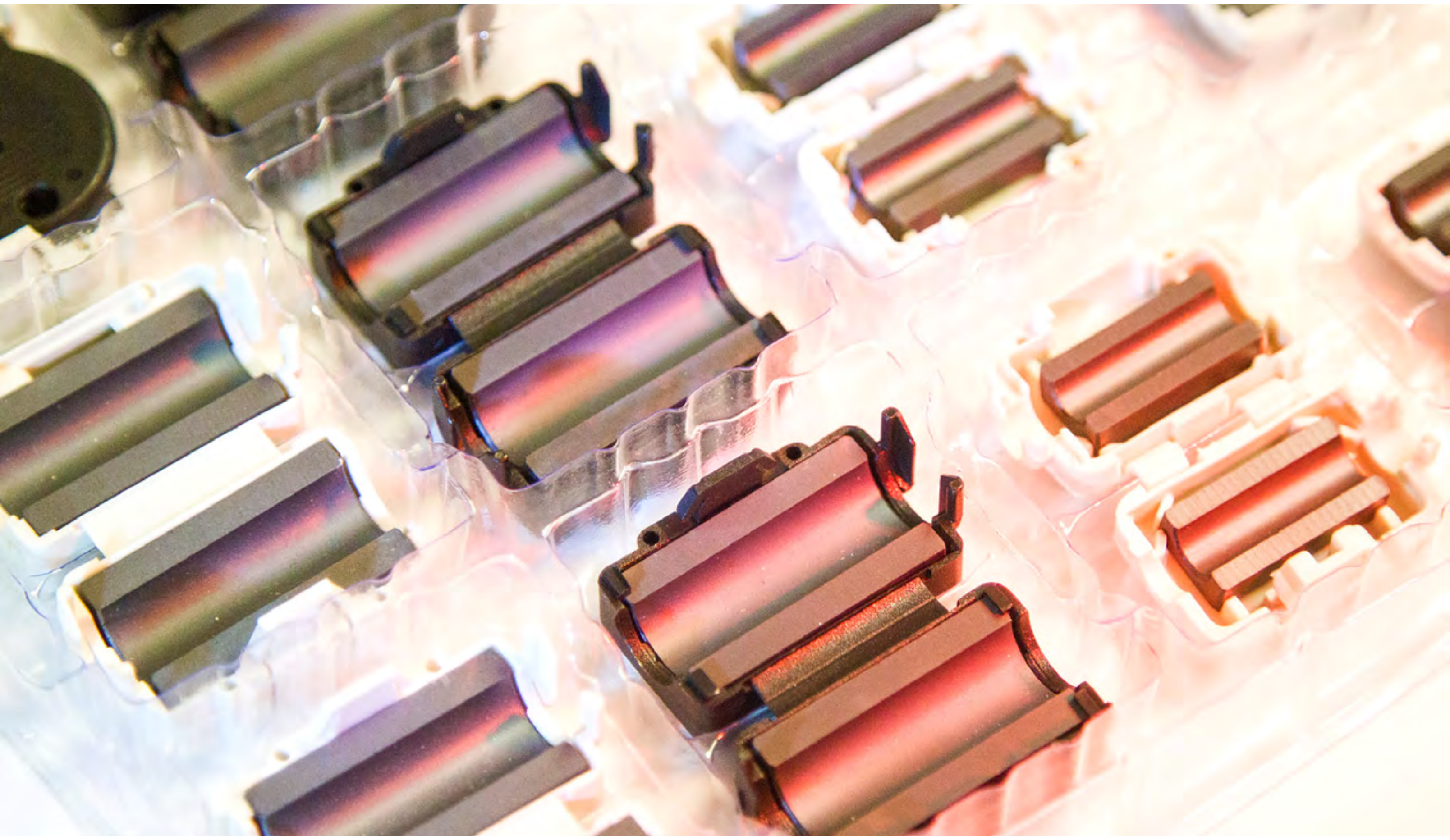
This article considers filters that are fitted at the boundary between a product and its external electromagnetic (EM) environment. Filters used inside an item, for example between a switch-mode power supply and a sensitive analogue circuit, will share most if not all of the same considerations – because filters always separate two areas or zones that should not be allowed to crosstalk or otherwise freely intermingle their signals.

EMC FILTERS MANUFACTURERS GUIDE

Kenneth Wyatt
Sr. Technical Editor Interference Technology

A Guide to Suppliers of EMI Filters

Your quick reference guide by various EMC filter types. The listing includes AC and DC line filters, filters for chambers, feedthrough, board level, coaxial, ferrite, filtered connectors, power converter, EMP/HEMP, TEMPEST, and custom. Applications include commercial, military, medical, and industrial. Also includes contact links for suppliers.



EMC Filters Manufacturers Guide		Type of Filters Available																						
Manufacturer	Contact Information - URL	AC Line	Board Level	Coaxial	Commercial	Common Mode, Power	Custom	DC Line	EMC Chamber	EMP / HEMP / IEMP	Feedthrough	Feedthrough Capacitors	Ferrite Filters	Filtered Connectors	Filter Connector Inserts	Inductors	Industrial	Medical	Military/Aerospace	Power Converter	Signal / Data	Tempest	Tunable	Variable Speed Drive
Americor	www.americor-usa.com	X			X		X											X	X					
Amphenol	www.amphenol.com													X					X		X			
API Technologies	www.spectrumcontrol.com	X	X		X		X	X		X	X								X	X				
API Technologies	eis.apitech.com/power-line-filters.aspx	X																						
Astrodyne (LCR & Radius Power)	www.astrodynetdi.com	X			X													X	X					
Block USA	www.block.eu/en_IN/products/emc-filter	X			X												X							
Capcon	www.capconemi.com			X			X		X								X		X					
Captor Corporation	www.captorcorp.com						X			X	X					X	X		X		X	X		
Coilcraft	www.coilcraft.com		X		X	X		X								X				X	X			
Curtis (TriMag)	www.curtisind.com	X			X			X									X	X	X	X				X
Delta Products Corporation	www.deltaww.com	X	X		X	X					X					X	X				X			
EMI Filter Company	www.emifiltercompany.com							X			X	X							X			X		
EMI Solutions	www.4emi.com				X		X							X	X		X		X					
Emitech Micro Components	www.emitech.co.in	X	X		X												X							
EMP-Tronic	www.emp-tronic.se									X														
ETS LINDGREN	www.ets-lindgren.com								X	X											X			
Genisco	www.genisco.com				X		X		X								X				X			
Heilind (Corcom, Deutsch, TE Connect.)	www.te.com	X			X		X							X			X		X		X			
Jiangsu	www.wemctech.com				X				X		X						X							
K&L	www.klmicrowave.com			X																			X	
Kemet	www.kemet.com	X			X				X		X						X	X						X
Knowles (Syfer)	www.knowlescapacitors.com/syfer		X				X	X			X	X			X			X	X		X			
Mini-Circuits	www.minicircuits.com/homepage/homepage.html			X																				
MPE Limited (in EU)	www.mpe.co.uk	X					X	X	X	X	X								X		X	X		
Murata	www.murata.com	X	X		X	X		X					X			X					X			
OnFilter	www.onfilter.com	X					X	X																X
Qualtek	www.qualtekusa.com/products-emi-filters.php	X			X													X						
Quell	www.quell.com			X	X		X							X	X		X	X	X					
Schaffner	www.schaffner.com	X	X		X	X		X			X	X				X					X			
Schurter	www.schurter.com	X														X								
TDK, EPCOS	www.usa.epcos.com	X	X		X	X		X	X		X	X	X			X					X			
WEMS Electronics	www.wems.com						X		X	X	X			X					X		X	X		
Wurth Elektronik	www.we-online.com/web/en/wuerth_elektronik/start.php				X	X		X					X			X				X	X			

DESIGNING AND SELECTING FILTERS

Eur Ing Keith Armstrong CEng MIEE MIEEE Partner
Cherry Clough Consultants

This next article describes the process for selecting an appropriate filter depending upon the application. It starts by describing how filters work, problems implementing filters, the importance of defining a reference point, differential- and common-mode circuits and the differences in filtering required. The proper application of ferrite materials and core types is also discussed, always with an eye on reducing EMI. The system impedance is very important when specifying filters and various problems with real-life impedances are described. Finally, safety and performance degradation issues are discussed.

DESIGNING AND SELECTING FILTERS

How Filters Work

Ignoring all the poles and zeroes in the filter textbooks: filters work by creating an intentional discontinuity in the characteristic impedance of a current path, reflecting radio frequency (RF) energy away from a protected circuit, or absorbing the RF energy (converting it to heat) – rather like a shield does, as will be described in Part 4 of this series.

The greater the discontinuity, the greater the attenuation. So if the source impedance of an unwanted signal (noise) is 100Ω and we put a 1kΩ impedance in series with it, only about 10% of the signal gets through the high impedance – an attenuation of around 20dB. A similar effect can be created by instead connecting the 100Ω noise to the 'RF Reference' via an impedance that is much lower than 100Ω: for example, 5Ω would provide an attenuation of around 26dB.

Filters use electronic components such as resistors (R), inductors (L), and capacitors (C) to create the desired impedance discontinuities over the ranges of frequencies of concern. R, L, or C can be used as filters on their own, but combining them gives better attenuation. LC types can give better attenuation than RC types, and are often used in power circuits because of their lower losses, but all LC filters are resonators that can produce gain at some frequencies, so they need to be carefully designed, taking their actual source and load impedances into account, to ensure attenuation over the desired range of frequencies. RC types generally provide more reliable filter performance.

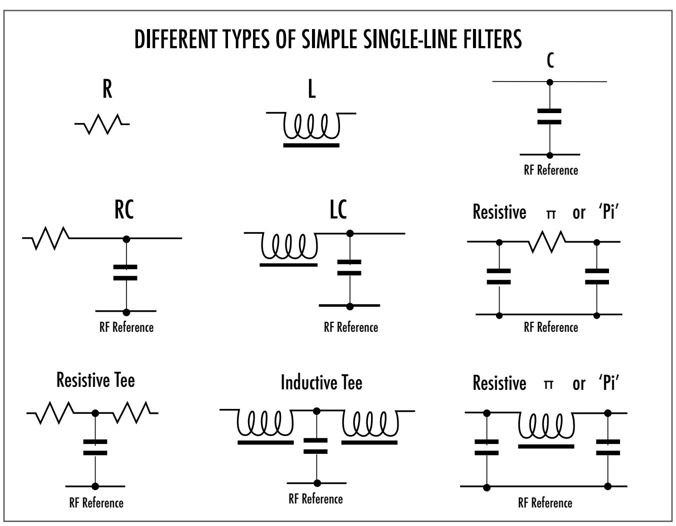


Figure 3C - Different types of simple single-line filters

A range of basic schematics exists for low-pass filters based on R, L and C, and is shown in *Figure 1*. There are high-pass equivalents, and band-pass or notch filters can also be achieved with passive components like these – but the low-pass filter is the one that is mostly used for EMC so that is the type that is shown in *Figure 1* and discussed in this article.

Simple inductive filters (chokes, ferrites, etc.) have no RF Reference connection, so are especially useful where no RF Reference Plane exists, or if it exists but does not have a structure that provides a low enough impedance at the highest frequencies of concern. Unfortunately, such very simple filters are generally unable to achieve very high attenuations – typically between 3 and 20dB, depending on the frequency.

Capacitors can also be used on their own as very simple filters (by creating a 'high-to-low' impedance discontinuity), or as part of a more complex filter circuit that includes inductors and/or resistors. But the effectiveness of a capacitor filter depends upon the impedance of the RF Reference it is using as its 'ground', and also upon the impedance of the interconnection between the capacitor and the RF Reference (e.g. wire leads, PCB traces). As a result, manufacturer's data sheet figures for capacitive filters are rarely achieved in real-life because they were tested with RF Reference Planes that were solid copper sheets covering an entire bench-top, and so had a lower impedance than is usually possible in real life.

Many a well-designed and expensive filter has had its performance wasted by being connected to a poorly performing RF Reference, or by being bonded to an excellent Reference by a short length of wire instead of the direct metal-to-metal contact that was needed.

An example of a common use of RCR filters is to connect computer boards to displays via flexible circuits, to reduce the emissions from the 'flexi'. The resistor values in these filters are often chosen as much for transmission-line matching (see section 2.7 of [6]), as they are for filtering.

Filters must pass the wanted signals/power, while attenuating unwanted 'noise'. So filter specification must begin with knowledge of the full spectrum of the wanted signal or power. It is very common these days for the spectrum of a wanted signal to contain very high frequencies that are not required, caused by the very fast switching edges of modern digital and switch-mode devices. Analogue signals are also polluted with such noise, due to stray coupling from digital and switch-mode circuits nearby. These very high frequencies can be removed by filtering and/or shielding, and it is good EMC practice to remove them at their sources, rather than wait until they have polluted many more conductors, and this was discussed in section 1.1.2 and *Figure 1B* of Part 1 of this series [7].

Active filters can be designed, based upon operational amplifiers (opamps), using feedback techniques to achieve remarkable attenuations. But the phase-shifts inherent in all opamps converts the attenuation of feed back circuits into amplification, above some frequency. So unless you have the experience and skills to really know what you are doing, and unless you are using op-amps with gain-bandwidth products measured in many GHz – always use passive filters based on Rs, Ls and Cs to control frequencies above 1MHz.

Imperfections in the Basic Filter Circuits

All components have imperfections, and these were discussed in section 1.8.1 of Part 1 of this series [7]. These imperfections have a part to play in defeating our attempts to design effective filters quickly and easily. For example: resistors lose attenuation at high frequencies due to their stray parallel capacitance. Inductors lose attenuation when their stray capacitance causes them to self-resonate, and at higher frequencies. Capacitors suffer from self-inductance, causing them to self-resonate and lose attenuation too.

RC filters are the most predictable EMC filters, as they do not resonate strongly. Values of R over the range 1Ω to 10kΩ are commonly used in EMC engineering, with C values typically less than 100nF. RC filters are mostly used where a DC or low-frequency signal from a low source impedance is connected to a high impedance load: the R is connected to the source side, the C connected to the load side, as shown in the lower part of *Figure 5* (below), where they provide very high attenuation at low cost.

LC, inductive Tee and inductive π filters can provide higher attenuation with lower losses than filters using resistors, but are resonant circuits and sensitive to their source and load impedances.

The Importance of the RF Reference

The RF Reference is the node on a circuit's schematic that we define as our reference voltage when designing an RF circuit or measuring its performance. For the most cost-effective EMC, all circuits (digital, analogue, switch-mode, etc.) should now be designed using RF techniques, and this was discussed in Parts 0 and 1 of this series [7].

It is common practice to call the RF Reference 'earth' or 'ground', although it might instead be called 'chassis' or 'frame' in some applications, and in circuits it is usually the same structure as the 0V power supply distribution so it is often called 0V. But all these terms are potentially misleading, because what matters in EMC engineering is the impedance of the conductor structure that is being used as the reference for the RF signals or noises, at the frequencies that you wish to control. The RF Reference is very important indeed, for all filters that are more than simple series impedances. For filters to function as desired, the impedance seen by the return currents as they flow in the RF Reference must be much less than the impedance of any filter elements connected to that Reference.

So, if we are using a 10nF capacitor in an RC filter to shunt the RF noise to 'ground', and we want the RC filter to operate as close to its theoretical performance as possible up to 100MHz, we should realise that the reactive impedance of the capacitor (assuming a self-inductance of 1nH) at 100MHz is approximately 0.65Ω (almost all of which, incidentally, is due to its self-inductance). To create a 'ground' structure that has an impedance of much less than 0.65Ω at 100MHz is quite difficult, because a 10mm length of 1mm diameter wire or 1mm wide PCB trace has an impedance of about 6.3Ω at that frequency. Increasing the diameter of the wire, or the width of the PCB trace, reduces the impedance but not by a great deal – 10mm length of 4mm diameter wire or a 4mm wide trace would still be around 3.2Ω.

A great many earths, grounds, chassis, frames, and 0V systems are made of wire or PCB trace conductors, and designers assume that because they are labelled 'earth', 'ground' or '0V' they actually are at earth, ground or 0V potential – but in fact they have such high impedances at RF that they have significantly different potentials at various points on their structures, depending on the RF currents flowing in them. Above a few tens of MHz, the only conductive structures that can achieve a low enough impedance to be useful as a reference for circuits and especially for filters, are metal areas or planes – which is why RF References are quite often called RF Reference Planes.

The circuits that use a plane as their RF Reference must be located much closer than one-tenth of a wavelength (λ/10) to it, ideally λ/100 or even less – at the highest frequency to be controlled. This helps prevent the connections to the plane from behaving as resonating antennas with impedances possibly in the hundreds of Ω, instead of the plain old low-impedance conductors that they look like to our eyes. At 1GHz this would mean a maximum spacing of 30mm, and better EMC would be achieved by being much closer than that, ideally 3Nm? or less.

Where a circuit is shielded by placing it in a metal box, it can use one or more walls of the box, and/or the rear, base and top as its RF Reference. Generally, this would still be called an RF Reference Plane, despite that fact that they are different sides of a metal box. An important consideration in the design of the structure of an RF Reference is that surface currents must be able to flow freely where they will, all over the area being used. Surface currents are discussed later in the section on Skin Effect.

Many electronic engineers are familiar with the idea of 'single point earths/grounds' – sometimes called 'star earths' or 'star grounds'. In such designs the voltage reference is a single physical point, and everything that needs to use it connects to it by a conductor (a wire or PCB trace). Analysing these conductors in terms of impedance, or in terms of their likelihood of becoming resonating antennas, as discussed in the above paragraphs, quickly shows us that single-point or star conductive structures are no use to us for EMC – their conductors are simply too long.

The continued shrinking of silicon die sizes means that even commonplace digital glue-logic (e.g. HCMOS) now generates significant noise emissions at frequencies up to 1GHz, and modern FPGAs and microprocessors can be very much worse for EMC – both in level and frequency - than such glue logic ICs. To stand any chance of controlling such frequencies requires lengths of wire, PCB traces or via holes, that are no more than a few millimetres long, preferably <1mm. Using flat braid straps instead of round conductors simply raises the useful frequency by a little, but not by enough to control hundreds of MHz. So single-point earthing/grounding techniques are now only of interest to students of the history of technology, regardless of the power or signals involved. All circuits and interconnections now suffer from RF noise that is coupled into them from digital, switch-mode and/or wireless circuits inside the same product, and they also suffer from RF noise coupled from nearby cables and ambient EM fields in their environments.

These coupled noises can cause any circuit or interconnection to be source of RF emissions, and/or a victim of interference, and this is true even for DC instrumentation and low-frequency analogue signals such as audio.

Despite the fact that the design of the RF Reference Plane is crucial to cost-effective EMC design, many engineers (me included) still tend to refer to 'earth' 'ground' or 0V, thereby often leading to confusion and miscommunication with people who think a length of wire can be part of an 'earth' structure as long as it has green/yellow insulation. So it is important to look beyond the terms that are being used to identify the physical structure that will be used as the RF Reference Plane, or to create it if it is not yet there.

Differential-mode (DM) and Common-mode (CM)

Wanted signals are always DM: they flow along the 'send' conductor, and flow back along the 'return' conductor(s). In single-ended signalling, all the return currents share a common conducting structure, usually the 0V of the DC power distribution system. In balanced (or 'differential') signalling there is a dedicated conductor for the return current path as well as for the send path, and for good signal quality and EMC the two are routed together as a twisted pair.

However, unavoidable imbalances in the physical realisations of interconnections in PCBs and cables cause CM voltages and currents to arise, as shown by *4*. CM currents flow out on both send and return conductors at the same time, and return via another route, often the safety earth structure or the mains power distribution network. CM currents are typically measured in µA, whereas DM currents are in tens or hundreds of mA, maybe even Amps – but the much larger loop areas associated with CM noise currents and voltages makes them more important for EMC than the DM signals that originated them. Above about 1MHz most unwanted emissions are mostly CM.

A great deal of RF interconnect design is concerned with making cables and PCB traces that have better balance, to reduce the 'longitudinal conversion loss' (LCL) that converts the wanted signal energy into unwanted CM noise. The better the LCL, the further the wanted signal will propagate with an acceptable quality, or the higher the frequency that can be sent with acceptable quality over the same distance – hence the computer networking industry's progress from Cat 5 to Cat 6 and eventually to Cat 7 cables for Ethernet, each increase in Category is accompanied by better balance, resulting in better LCLs at higher frequencies and reduced generation of CM noise for a given type of signal.

Because of the existence of DM and CM signals and noises, we need to be able to apply filtering techniques to both of them. Below 1MHz, we are more likely to be concerned just with filtering DM signals and noise. But at higher frequencies we can use DM filtering to reduce the amounts of RF present in conductors, so as to reduce the amount of CM noise currents and voltages created by the imbalances in the interconnects. We also use CM filtering to reduce the amounts of CM noise present.

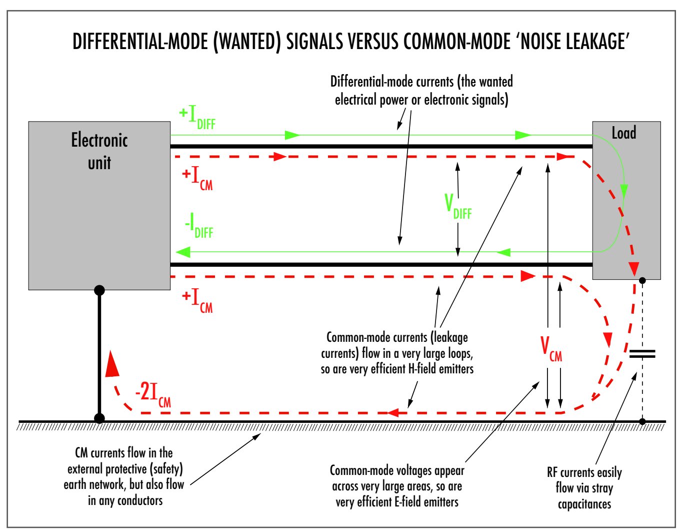


Figure 4 - Differential-mode (wanted) signals versus common-mode 'noise leakage'

Maximising impedance discontinuities

As mentioned earlier, to design effective filters we must maximise impedance discontinuities, at the frequencies of concern for emissions and/or immunity, and *Figure 3E* tries to demonstrate this concept for single-ended signals. Capacitors are used in conjunction with the RF Reference Plane (see *Figure 4*) to create low impedances, applied in shunt, whilst resistors or inductors are used to create high impedances, applied in series.

When the source and load impedances seen by a current (DM or CM) are both low – also taking into account the impedances of their current loops including their return paths – a 'Tee' filter (with either R or L) is preferred. When the source and load impedances seen by a current (DM or CM) are high – also taking into account the impedances of their current loops including their return paths – a π ('Pi') filter (with either R or L) is preferred. When the source impedance for a current (DM or CM) is low, and its load impedance is high (or vice-versa) – also taking into account the impedances of their current loops including their return paths – an RC or LC filter (with the R or L connected to the low impedance side) is preferred.

For low-power circuits with low-frequency wanted signals and high impedance loads, it is often possible to replace the inductors in these simple circuits with resistors of between 100Ω and 10kΩ to save cost and even sometimes achieve higher attenuations over wider frequency ranges.

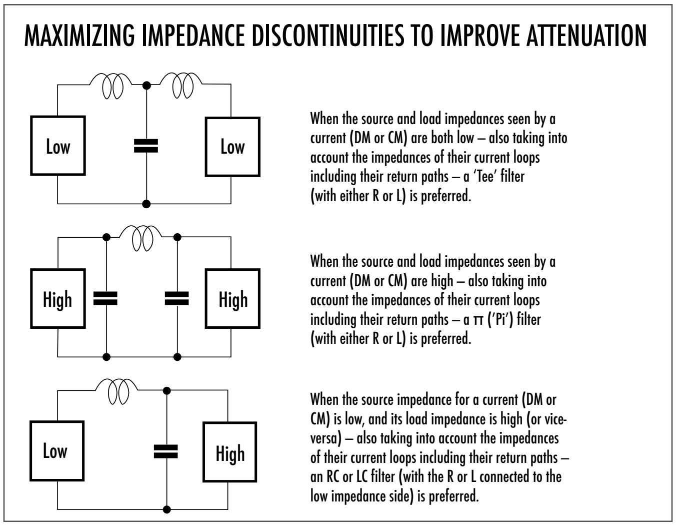


Figure 5 - Maximising impedance discontinuities to improve attenuation

When the source impedance of the noisy current (DM or CM) to be filtered is low, fitting a simple C filter will increase the noise currents flowing in the circuit, increasing H field emissions, and will also increase the noise voltages across the circuit's 0V plane, increasing its CM emissions. Preventing DM or CM noise currents from increasing is another reason why we always follow a low impedance source with a series resistor or soft ferrite choke (to create an RC, LC or Tee filter).

For balanced (differential) signals the RF Reference in *Figure 5* is replaced by the return conductor for the conductor pair – but only for DM filtering. For CM filtering we need two circuits as shown in *Figure 3E* – one for the send conductor and one for the return conductor, both of them connecting their capacitors to the RF Reference Plane. CM filtering can also benefit greatly from the use of 'CM chokes' – described later and shown in *Figures 12, 13* and *14*.

Using Soft Ferrite Cores

All inductors (L) suffer from RF resonances, and are only effective in filters at frequencies not far above their first (parallel) resonance (see section 1.8.1 of [7]). But so-called 'soft ferrites' behave resistively at RF, and the resulting lack of RF resonances helps make filters that use them have better and more predictable performance at RF. For example, a typical small 'soft ferrite' bead a few millimetres in diameter will have around 1µH of inductance and 0.1Ω of resistance at DC, but around 80Ω of real resistance (not inductive reactance) at frequencies from 30MHz to 1GHz or more. Some leaded soft ferrites are available with resistances of over 1kΩ at 100MHz, but a much wider range of surface mounted device (SMD) soft ferrites is available with resistances up to 1kΩor more at selectable frequencies from 30MHz to 2GHz.

Soft ferrite components are known by a variety of names, including 'RF suppressers', 'Interference suppressers', 'Suppression chokes', and 'Shield Beads'. *Figures 6* and *7* show some of the cable-mounted soft ferrite parts available. A very wide range of PCB-mounted soft ferrite components is also available, but not shown in these figures. *Figure 7* includes a standard VGA cable, showing the standard soft-ferrite CM choke that all VGA cables are required to have at each end, for the products they interconnect to meet emissions regulations in Europe and the USA (at least).

Figure 6 - A wide variety of soft ferrite cores is available
(these examples of toroidal and cylindrical types are from Philips)

The bottom right-hand-side of *Figure 3G* shows a toroidal soft ferrite core used as a CM choke, in this case with '4½ turns' of cable wrapped around it. As will be described below, the attenuation of a filter at the highest frequencies is governed by the stray coupling between its input and output conductors – so it is important that the input and output conductors of a CM choke, such as the one in this photograph, are as far apart from each other as possible. This results in the winding format that can clearly be seen in the figure – only half the core is wound and the input and output cables are on opposite sides from each other, the perhaps odd description of it as having '4½ turns' is a common way of making clear that input and output conductors are on opposite sides.

Figure 7 - Some more examples of soft ferrite cores

A useful soft ferrite component is a cylinder split lengthways and held in a plastic clip-on housing, and some examples of this are also included in *Figure 7*, for round cables as well as for flat cable styles. Such split ferrites are very easy to apply to cables (and to remove if found to be ineffective), and EMC engineers tend to carry many of these around with them, using them for the diagnosis, isolation and curing of EMC problems, both DM and CM. A ferrite cylinder clipped around an entire cable or cable bundle, including all the send and return conductors, is a CM choke, but if clipped over just a send or return conductor it is a DM choke.

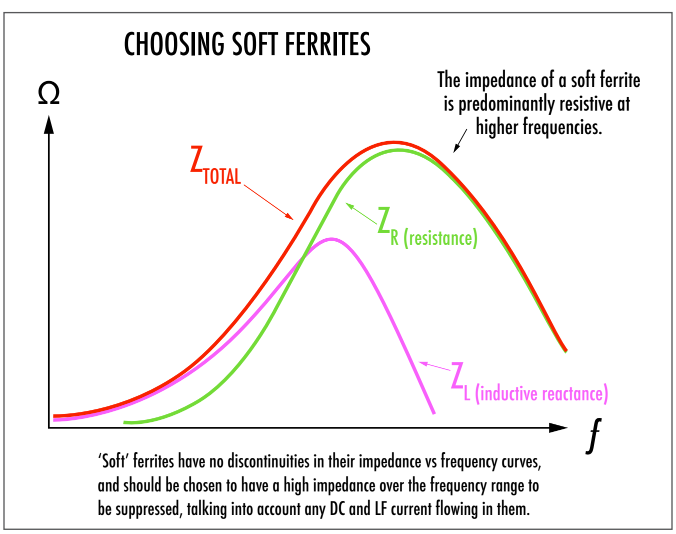


Figure 8 - Choosing soft ferrites

Choosing soft ferrites involves checking that their impedance is as high as required over the frequency range for which significant attenuation is required. Soft ferrite components *always* have impedance versus frequency curves that are smooth and not discontinuous, whereas the curves for inductors will show one or more discontinuities (changes in slope from positive to negative, or vice-versa, that occur at a point) that reveal the presence of resonances.

Some data sheets only provide impedance data for a portion of the frequency range you are concerned with. But it would be a mistake to assume anything about the impedance they will achieve in the frequency range for which no data is provided – always make sure you have manufacturers data on the impedance over the entire frequency range that you wish to control.

An aspect of choosing soft ferrites that is often overlooked, is that their impedance versus frequency curves vary with their DC and/or LF current. Typical data sheet curves assume zero current in the device, but as the current increases the frequency at which the peak impedance occurs will also increase, and may not be as high as it was with no current. Often, when an emissions or immunity test is failing at some frequency (e.g. a clock harmonic at 228MHz), a soft ferrite will be chosen that has a very high impedance close to this frequency, and it will be added in series with traces on the PCB that are thought to be the cause of the problem.

But the DC or LF current in those traces could make the frequency of the peak impedance increase by enough that the actual impedance achieved at the problem frequency is not high enough to provide significant attenuation and pass the test. Instead, the currents in the traces and the frequency/current variation of the type of devices to be used should have been taken into account, to select a device that would have its peak impedance at the problem frequency when the trace current is passing through it.

Several manufacturers offer wide ranges of soft ferrite RF suppression components, and are continually adding to them. Recent additions include SMD parts rated at 3A continuous current at DC and low frequencies; yet provide 1kΩ or more around 100MHz. Other recent additions include parts that provide impedances of 1kΩ or more over the range 100MHz to 2GHz.

Curves such as those in the two top graphs in *Figure 9* are most suitable for filtering low-frequency signals, whereas the two bottom curves show devices that have been tailored for filtering unwanted harmonics from digital waveforms whilst leaving sufficient lower-frequency harmonics to create reasonable digital waveforms that have rise and fall-times fast enough to reliably meet the maximum skew requirements of the circuit. CM ferrites tend to have impedance versus fre quency curves similar to the top left-hand graph, since there is no need for any CM currents at any frequencies.

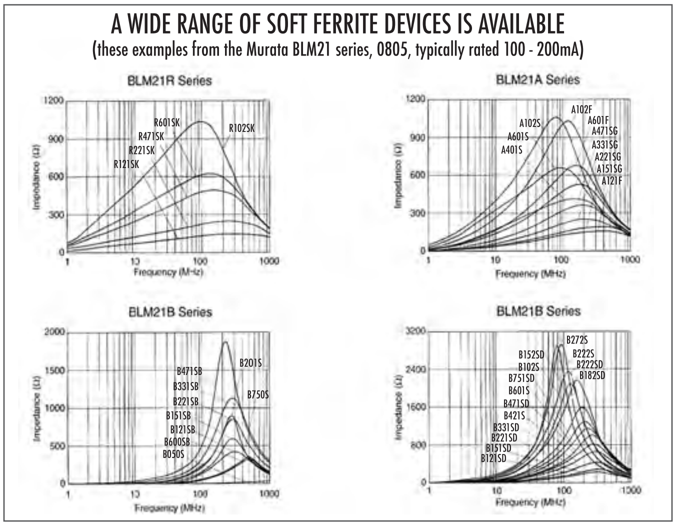


Figure 9 - A wide range of soft ferrite devices is available
(these examples from the Murata BLM21 series, 0805, typically rated 100 - 200mA)

When simulating filters or other circuits using soft ferrite components, a simple device model cannot be used – the parameters are frequency-dependant and current-dependant, and may also be temperature dependant, and should be modelled as such to achieve any accuracy in the simulation over a range of frequencies. Some circuit simulators may be unable to handle models with such complex parameters.

Issues With Wound Components (Inductors, Transformers, Chokes, etc.)

Three main issues of concern for wound (inductive) components are the control of their stray magnetic fields, the variability of their parameters with current and temperature, and their resistivity.

Closed Magnetic Circuits Are Preferred, to Reduce Stray Fields

If the path of the magnetic field includes air, the component can be a significant cause of emissions, and can also pick up ambient magnetic fields and cause noise in the circuit. As a result, the EMC of wound components benefits from having a closed magnetic circuit, such as a ferrite bead, cylinder or toroid. This is important for filters, and also for chokes and transformers in switch-mode power converters, whether AC-DC, DC-AC (e.g. inverters) or DC-DC.

For example, an inductor wound on a rod core is essentially the same as a ferrite rod antenna in a typical AM radio. Many types of low-current inductors (up to about 1mH) or ferrite suppression components are available as axial components, essentially ferrite rods with a winding on them. While they can be perfectly acceptable in some applications, in others they can pick up noise from ambient fields and cause or suffer from crosstalk and/or emissions or immunity problems – so it is generally more reliable to use types based on ferrite cores that are beads, cylinders or toroids, which have closed magnetic circuits. *Figure 10* illustrates this issue.

This can be a significant problem for DM chokes carrying higher currents, because they have large magnetic fluxes and rely on air gaps to prevent their cores from saturating. Where an air gap is unavoidable, solutions include applying a shield over the component to contain its stray fields, or else use a core made of iron or iron oxide powder in an epoxy binder, or a similar distributed-air-gap material.

Close proximity of a shield reduces the component's inductance – and the shield might become saturated from the high field strength and no longer provide shielding – so the shield should not be too close to the core or the windings. Iron powder or similar cores have no discrete air gaps, relying instead on hundreds of millions of microscopic air gaps between the magnetic particles in their cores, with much smaller stray magnetic fields as a result.

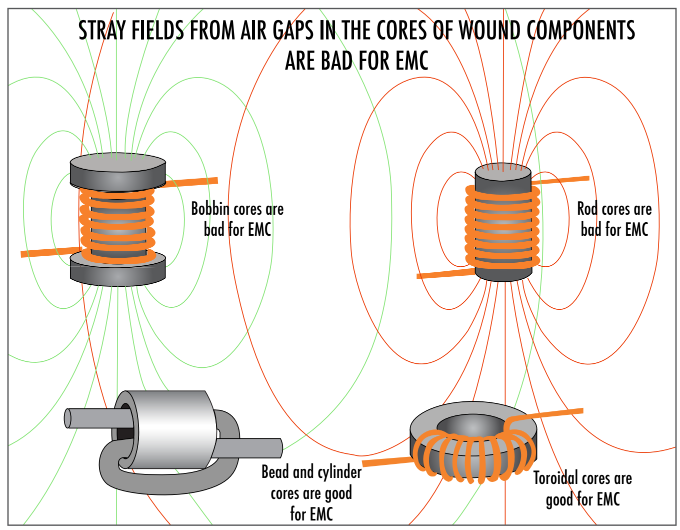


Figure 10 - Stray fields from air gaps in the cores of wound components are bad for EMC

Allowing for the Variation of Parameters Due to DC and/or LF Currents, and Temperature

As the DC and/or low-frequency current in a filter increases, the inductance value of all the series inductors falls, affecting the filter performance and resonant frequencies. Also – for all soft ferrites – the frequency at which the peak impedance occurs increases. Sufficient levels of current will saturate the magnetic circuit, causing the inductance/impedance to fall to practically zero. This is a common cause of the differences between simple calculations or simulations and real-life filter performance.

Variations in temperature have a similar effect. Above about 25°C, the inductance of a magnetic core reduces, falling more rapidly as the 'Curie Point' is approached, and zero above that point. The Curie Point depends upon the type of material, but is generally between 100 and

200°C. An experiment that showed how the performance of a mains filter could be reduced by as much as 20dB, by variations in current loading and ambient temperature that remained within the operational ratings of the filter, is described in [8].

So if designing a filter, get all the appropriate graphs of current and temperature dependency from the core suppliers and take this effect into account during the filter design for the full range of currents and temperatures they are required to operate over. And if choosing a filter from a supplier, make sure you understand what its minimum performance will be over the range of currents and temperatures (simultaneously) that it will experience in operation.

A particular problem is AC-DC mains power supplies that do not meet EN/IEC 61000-3-2 Class D. They draw their mains currents as peaks that are many times higher than their rated or measured RMS supply current. These peaks will degrade the attenuation 100 times per second (120 times/second in 60Hz countries) and might even cause momentary saturation of filter inductors and seriously compromise the filtering performance achieved.

CM chokes aim to balance the send and return currents so there is no net magnetisation of their cores by the wanted DM currents. But because no windings can be perfect, there is always some imbalance, which manifests itself as a DM choke in series with the CM choke. The resulting imbalance currents can saturate the cores of CM chokes, especially because their cores are made as small as possible to save space and reduce cost.

If designed carefully, CM chokes always run cool. Saturated inductors run warm, and if used on power frequencies they may be heard to hum or buzz, or felt to vibrate, both of which are clues to possible errors in design.

Resistivity of Ferrite Cores

All ferrites are ceramics, but they are not insulators – different types of material have differing resistivities. So if the insulation on the winding wire is inadequate for the stresses and strains imposed by winding it on the core, the core can ‘short-out’ the windings, or at least provide a parallel resistance that affects performance. If the winding is carrying a hazardous voltage, failed insulation can result in a ‘live’ core that can be a safety hazard to service personnel, or even to a user.

There is always stray capacitance between a winding and its core, and because ferrites are ceramics their dielectric constant is high so the stray C is increased. RF voltages on the windings will therefore induce RF currents in the core, and because ferrite is conductive, these currents can flow out of the core into other conductors via stray capacitance or resistive contact.

Service personnel could get shocks and RF burns from the cores of wound filter components or transformers that are handling large amounts of RF. These stray RF core currents are CM, and so can cause significant problems for EMC. It is important either to insulate the cores to help inhibit the flow of stray CM currents, or else to provide a connection to the core that returns the stray current to the appropriate part of the circuit.

The most appropriate part of the circuit to return the core current to is not necessarily the ‘earth’, ‘ground’, ‘chassis’, ‘frame’ or ‘0V’. All currents flow in loops, and for good EMC the loop areas must be minimised – so the correct technique is to figure out where the stray RF core currents originally came from, and return them back to their source by the path that encloses the smallest area. For the filters in ‘typical’ electronic products there is usually no need to worry about the RF currents and voltages associated with ferrite cores. But control of core currents can be important for achieving EMC in the ferrites associated with switch-mode power conversion (flyback chokes, transformers, etc.) because switch-mode waveforms contain a great deal of energy in the RF spectrum. But this article is about filters so will not go any further into switch-mode EMC design issues. But this article is about filters so will not go any further into switch-mode EMC design issues.

Stray Capacitance and its Effect on High Frequency Impedance

Stray capacitances between the input and output of a choke limits its high-frequency impedance, by acting as a ‘bypass’ in parallel with the choke. This effect can be seen in the impedance versus frequency curves of all of the ferrite chokes shown in *Figure 9* – as frequency increases their impedance increases, but eventually a point is reached when their impedance starts to decrease as frequency continues to increase. In this region the impedance of a choke is dominated by the stray capacitances between its windings, and also between its input and output terminals and/or leads.

For this reason it is very important for high-frequency performance to keep the input and output terminals of series filtering elements (such as chokes or resistors) – and any leads, circuits or PCB traces attached to those terminals – as far apart from each other as practical. For good performance at 100MHz and above it can even be important to shield the input circuit from the output circuit – a topic discussed below.

Surface mounted ferrite beads can achieve high impedances at very high frequencies, because their parasitic capacitances are so small. But it is easy to ruin their performance above 100MHz by routing their input and output traces near to each other, increasing the stray input-output capacitance, so PCB layout is very important (see Part 2 of [9] for more on PCB design and layout techniques for EMC filters).

To obtain increased attenuation, it is tempting to wind the conductor(s) several times around the same magnetic core to increase its impedance. But this might not be as effective as required at higher frequencies, because of the increase in the stray capacitances created by the extra windings. The higher the number of windings on a core, the closer their proximity to each other, and the higher the stray capacitance between them. This effect is very strong with multilayer windings, especially if they are pile-wound – as this winding technique does not control where the windings lie with respect to each other, from one unit to another.

Chokes with multiple winding layers, including pile-winding, can achieve very high impedances at lower frequencies, and in some applications this is all that is required, for example when suppressing the RF noises emitted by a phase-angle controlled triac in a lighting dimmer, where significant levels of attenuation may only be needed up to a few MHz. Interestingly, at least one manufacturer of such lighting dimmers has found that chokes with layered or piled windings do not always provide the same attenuation performance when the chokes are reversed in the circuit. This is because of the complex nature of the stray capacitances in such a choke.

To improve the impedance at higher frequencies with highly-wound or multilayer chokes, it is better to use sectional winding techniques to reduce the overall input-output stray capacitance. One example of this type of choke is the 'super-toroid' winding shown in *Figure 11*. The aim of this technique is to split the winding in half – each half being wound on different portions of the toroid to reduce the stray capacitance coupling between them and increase the impedance of the choke at higher frequencies. Notice that each half of the winding is wound in the opposite direction to the other half – but because these halves are wound in different directions their fluxes do not cancel out, they add together to maximise impedance.

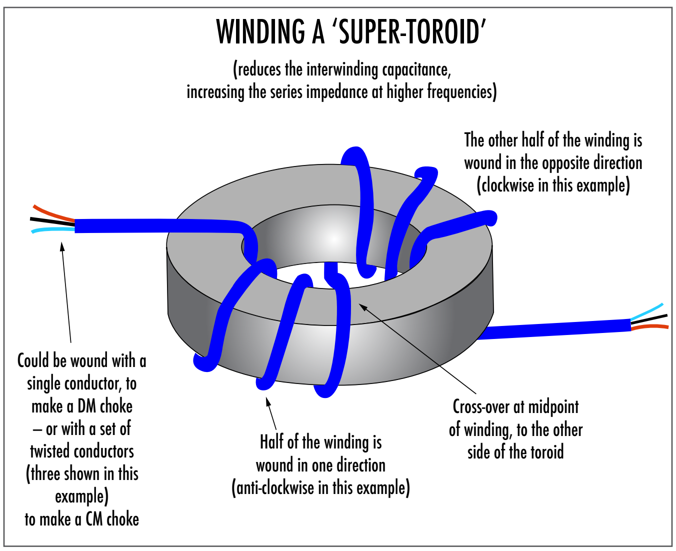


Figure 11 - Winding a 'super-toroid'

A super-toroid wound with a single conductor is a DM choke, whereas one wound with a multi-filar twisted cable, as shown in *Figure 11*, is a CM choke (see later).

Another way to improve the impedance at higher frequencies is to string a number of ferrite tubes or toroids in series along a cable. However, it is possible that their impedances and stray capacitances could interact to create resonances that will defeat the aim of this technique. So when using this technique it is best to simulate all such designs, using reasonably accurate estimations for the stray 'components' (or extract them from a 3-dimensional field simulation of the physical structure), or simply to build them and test their transfer function with instruments.

One way to reliably achieve a choke that has a very low stray interwinding capacitance and hence the very highest series impedance that the ferrite material is capable of, is to string a number of ferrite tubes or toroids along a conductor, with all of the ferrites touching each other. Instead of multiple windings around each ferrite core, the conductor is only passed once through the centre of each core. Of course this makes a very large or long device overall.

Specifying and Designing Filters

When specifying a filter prior to design or selection, it is necessary to know the spectrum of the wanted signals, so that the filter's response can be tailored to pass the wanted signals whilst impeding unwanted noises (interference). It is easy to specify 50 or 60Hz mains filters, because the RF noises to be filtered are at a much higher frequency than the wanted 50 or 60Hz sinewaves. But it is not so easy to specify a filter when the signal and noise spectra overlap, as they do for most digital signals and interconnections.

However, most emissions and immunity problems are caused by CM noises, whereas wanted signals are DM – so we can use CM filtering on noise that is within the signal's spectrum without attenuating or distorting the signal. Of course, nothing is perfect, so CM filtering will have some effect on the wanted DM signals, and it is part of the design to make sure that the attenuation and/or distortion of the DM signals are within acceptable limits.

The key component for CM filtering is the CM 'choke', which generally uses a soft ferrite core with the send and return conductors for the DM signal wound together on the choke's ferrite core, usually wound bi-filar, tri-filar, etc. with the input and output leads/pins on opposite sides of the core, to reduce the stray input-output capacitance that limits the performance at the higher frequencies.

When a magnetic circuit is wrapped around both (or all) of the send and return conductors associated with a signal or power circuit, it will only attenuate CM currents.

The magnetic fluxes created by the send and return current paths of the wanted DM signals cancel out, so they experience no effect from the magnetic circuit. In practice there is always some leakage inductance, caused by imbalances in the send/return windings, hence there is always some DM attenuation. This inevitable leakage can be turned into a benefit by providing both CM and DM filtering in one component. In ordinary CM chokes, the DM leakage is not controlled, and can vary considerably, but some EMC filter component manufacturers (e.g. Murata) offer ranges of CM chokes with specified DM impedances. Some aspects of CM choke filtering are shown in *Figure 12.*

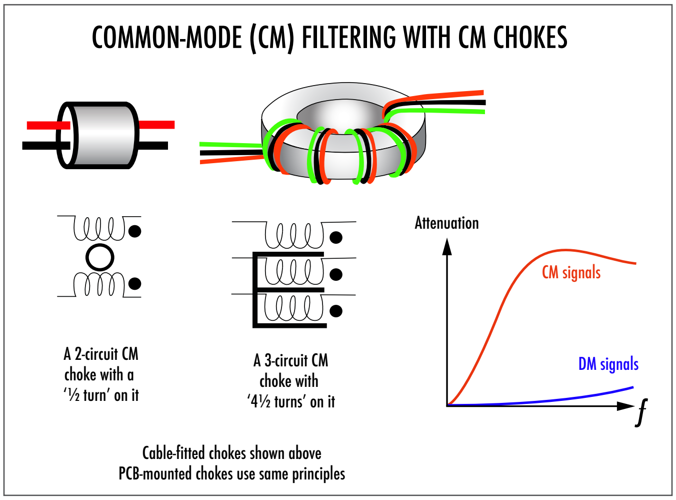


Figure 12 - Common-mode (CM) filtering with CM chokes

The cancellation of DM flux in CM chokes (sometimes called 'current-balanced' chokes) allows large inductance values (e.g. milliHenries) to be achieved with small components, whereas DM chokes of the same physical size achieve much lower inductances (e.g. microHenries) and must become physically larger as DM currents increase.

Of course we want to design so as to have confidence in passing EMC tests the first time – to avoid delays caused by iterations and retesting – but for volume-manufactured products we also do not want to add too much cost by over-engineering. Designing CM filters creates some difficulties here, because CM voltages and currents are mostly unknown in both frequency and amplitude until the product is EMC tested.

Computer-aided EMC simulation packages are now available that allow CM effects to be predicted. To give sufficiently accurate results the simulator must model all of the stray (parasitic) parameters of the components (which can be done in any circuit simulator), but it must also solve the fields associated with the components, conductors and other physical structures, in three dimensions. These simulators require powerful computers with a great deal of memory, such as modern 64-bit PCs, and the software packages can cost as much as a top-of the range luxury car, but they can be very effective if sufficient effort is put into learning how to use them, modelling the components and digitising the actual physical design. Computer simulation offers the possibility of designing EMC right first time with the lowest component cost – or at least getting much closer to the optimum EMC design more quickly.

In the absence of an accurate computer simulation, it is best to design prototypes for a range of filter component or packaged filter options, and keep a stock of all the filter components or packages that could be needed, from the lowest-cost to the highest-specification (often available as free samples from their manufacturers). In the case of PCB-mounted filters, 'universal filter pad patterns' can be developed that can accommodate from zero-ohm links through individual resistors or ferrite beads to CM chokes, plus two or three-terminal capacitors, to create a wide range of filter types including RC, LC, Tee, and π filters.

EMC pre-compliance testing begins with the lowest-cost filter options fitted, and if these turn out to be inadequate different components or higher-specification filters are fitted until the tests are passed. An alternative and arguably better approach starts off with the highest-specification filtering, to make sure no other problems exist – and when the tests are passed the filters are then reduced in cost to what works well enough. For products containing digital and switch-mode electronics, it is usually enough to use pre-compliance emissions tests – low emissions usually being a sign of adequate immunity, but only the full suite of emissions and immunity tests will prove whether adequate filters have been employed.

Such approaches help avoid the 'no room for the filter' problem, which could require a complete redesign of the product. Most engineers soon gain experience with their own technologies and applications, permitting smaller-sized filter pad patterns – but the resulting design rules must be considered afresh whenever construction, ICs, or technology changes (e.g. due to a die-shrunk microprocessor, see Part 1 of [7]).

It is best if filter performance provides an 'engineering margin' of at least 6dB beyond the emissions or immunity requirements of the test standards, to allow for device and assembly tolerances, measurement accuracy, etc. If the EMC tests are less accurate than those achieved by nationally accredited laboratories (e.g. by [10]) it is best to allow even greater margins for error, remembering that EMC test repeatability at a given test laboratory is usually no better than ±4dB, and repeatability between test laboratories that have been accredited by the same accreditation body is often no better than ±10dB.

Some types of interconnections, such as ribbon cables using single-ended signalling, suffer from high levels of DM emissions and immunity, and it might prove impossible to achieve adequate EMC by using filtering alone

– because the necessary filtering attenuates the wanted signals by too much. In such cases it may be necessary to use shielded interconnections (see Part 1 of [7]) to attenuate frequencies that can't be filtered sufficiently without damaging the wanted signals. Sometimes it is most cost-effective or necessary to use filtering and shielding at the same time.

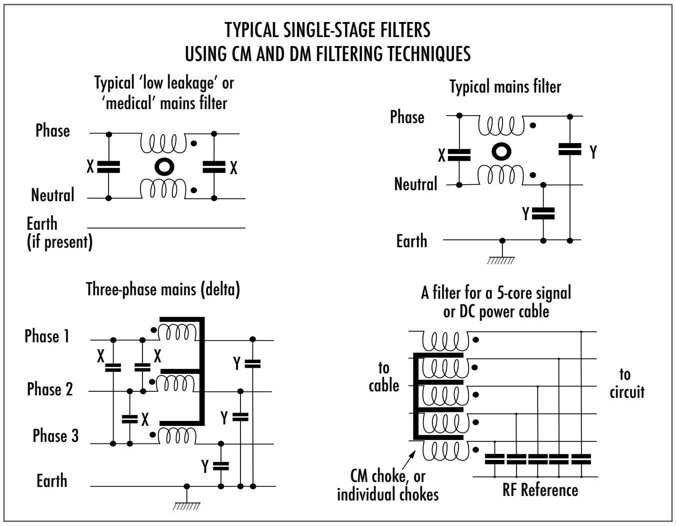


Figure 13 - Typical single-stage filters, using CM and DM filtering techniques

Figure 13 shows how CM and DM filtering techniques are combined in three examples of simple mains filters. These are called single-stage filters, because they only use one inductive element. Because mains-powered products must isolate the hazardous mains voltages from any touchable parts of its body for safety reasons, their CM emissions will generally have a high source impedance, so they are firstly attenuated with capacitors between phase and the RF Reference, and subsequently with a CM choke, to maximise the impedance discontinuities for the CM noises (see *Figure 5*).

Because products draw power from their phase and neutral conductors, their DM emissions tend to have low impedance. So they are firstly attenuated by a DM choke (maybe the leakage inductance of a CM choke), and subsequently by a capacitor between the phases, to maximise the impedance discontinuities for the DM noises.

The low leakage (often called 'medical') filter shown in *Figure 13* has no capacitors between phase and earth, so that it may be used in medical applications where very low earth leakage currents are required to protect patients (maximum 50 or 60Hz leakages for some medical products can be as low as 10μA). This type of filter tends to rely on larger, higher-impedance CM chokes, and its lack of 'earthy' capacitors can sometimes make it useful in applications other than medical.

Figure 13 also shows an example signal filter using a CM choke in an LC filter type. Military signal cable filters tend to rely on C-only and π types, probably because most traditional military equipment has a substantial and well-engineered RF Reference Plane between items of equipment (die-cast metal boxes electrically bonded by multiple mounting bolts directly onto metal surfaces in metal-bodied vehicles) and between items of equipment and their electrical power sources (generators and/or batteries).

Some civilian applications (such as digital telecommunications exchanges, computer rooms, and semiconductor manufacturing) achieve or approach such high-performance RF References in systems and installations, but most domestic, commercial, and industrial products are used in systems and installations that rely on networks of green/yellow insulated 'safety earth' wires for their reference, which of course have very high impedances and resonances at RF frequencies. The most predictable signal filters in such applications tend to be R, L, RC, LC, or Tee types (using soft ferrites for any Ls). These types of filters impose lower levels of RF currents on the RF Reference than C-only or π filters, reducing the RF potential differences between different parts of the RF Reference and helping to reduce CM emissions as a result. As military vehicles use new materials such as carbon fibre, their RF Reference Planes suffer higher impedances, and they may find R, L, RC, LC, or Tee filters more cost-effective than C or π.

The use of a CM choke as shown in *Figure 13*, instead of a series of individual ferrite beads, can allow substantial CM filtering to be achieved at frequencies as low as 150kHz, whilst allowing wanted (DM) signals of 15MHz or more to pass through unattenuated. There are inevitable tolerances between individual components of the same type, so (all else being equal) the CM attenuation of a filter that uses a single CM choke for all the conductors in a cable will give superior CM attenuation than one using a row of individual ferrites. However, CM chokes are often more costly than the equivalent number of single ferrites, and careful PCB layout and component choice can achieve a design that can be fitted with a CM choke if the single ferrites aren't adequate, with just a few minutes with a soldering iron, instead of a PCB design iteration.

It is best if filter performance provides an 'engineering margin' of at least 6dB beyond the emissions or immunity requirements of the test standards, to allow for device and assembly tolerances, measurement accuracy, etc. If the EMC tests are less accurate than those achieved by nationally accredited laboratories (e.g. by [10]) it is best to allow even greater margins for error, remembering that EMC test repeatability at a given test laboratory is usually no better than ±4dB, and repeatability between test laboratories that have been accredited by the same accreditation body is often no better than ±10dB.

Some types of interconnections, such as ribbon cables using single-ended signalling, suffer from high levels of

DM emissions and immunity, and it might prove impossible to achieve adequate EMC by using filtering alone – because the necessary filtering attenuates the wanted signals by too much. In such cases it may be necessary to use shielded interconnections (see Part 1 of [7]) to attenuate frequencies that can't be filtered sufficiently without damaging the wanted signals. Sometimes it is most cost-effective or necessary to use filtering and shielding at the same time.

Mains filters with more than two stages are frequently used, and *Figure 14* shows two typical designs. The multiple filter stages provide more impedance discontinuities for DM and CM noises, hence more attenuation. Standard filter products are available with up to four stages, and with ratings of up to 100 Amps, single or three-phase. These are the types of filters that are often required for use with high-power variable-speed AC motor drives, uninterruptible power supplies (UPSs), or other powerful switch-mode power converters.

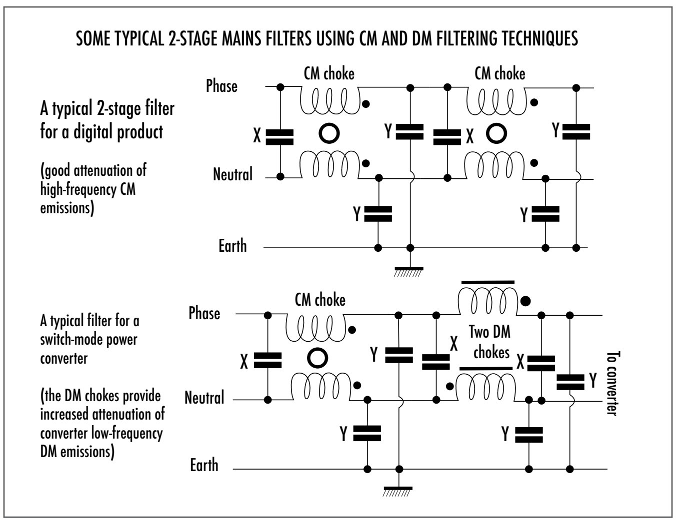


Figure 14 - Some typical 2-stage mains filters using CM and DM filtering techniques

Problems with Real-Life Supply Impedances

The CM and DM impedances of the public AC mains supply can vary from about 2Ω to 2,000Ω depending on the frequency and time of day. All filters that use inductors and capacitors are resonant circuits, with their resonant frequencies and hence their attenuations depending critically on their source and load impedances. But most filter datasheets are based upon CISPR17 measurements taken with 50Ω source and load impedances, which means that their specifications are always better than their real-life performance.

Single-stage filters are very sensitive to source and load impedances, and have a resonant peak that provides gain, rather than attenuation, when operated with certain source and load impedances. Single-stage filter gain usually pops up in the 150kHz to 10MHz region and can be as bad as 20dB, so it is possible that fitting a mains filter with a good (50Ω/50Ω)specification can actually increase emissions and/or worsen susceptibility. It is not uncommon to have a switch-mode power supply or inverter motor drive with excessive emissions between 200kHz and 1MHz, and fit a low-cost filter with a data sheet that shows sufficient attenuation to pass the tests – only to find that the filter increases the emissions!

To avoid this situation, only consider filters whose manufacturers specify both CM (sometimes called 'asymmetrical') and DM (sometimes called 'symmetrical') performance, for both matched 50Ω/50Ω and mismatched sources and loads. Mismatched figures are taken with 0.1Ω source and 100Ω load, and vice versa, using the CISPR17 test standard that is also used for 50Ω/50Ω tests. Drawing a line that represents the worst-cases of all the different datasheet curves results in a filter specification that can generally be relied upon – providing the filter is not overloaded or overheated (see earlier) and is installed correctly (see later). *Figure 3Q* shows an example of estimating a filter's worst-case attenuation curve.

Mains filters with two or more stages (some examples are shown in *Figure 14*) have at least one internal circuit node, and these have impedances that do not depend as much on the source or load impedances. As a result, when installed correctly and not overloaded or overheated, they are more likely to provide real-life attenuation that approaches their 50Ω/50Ω datasheet specifications. Of course, they are larger and cost more than simpler single-stage filters, so if they might be required – the design should allow sufficient room.

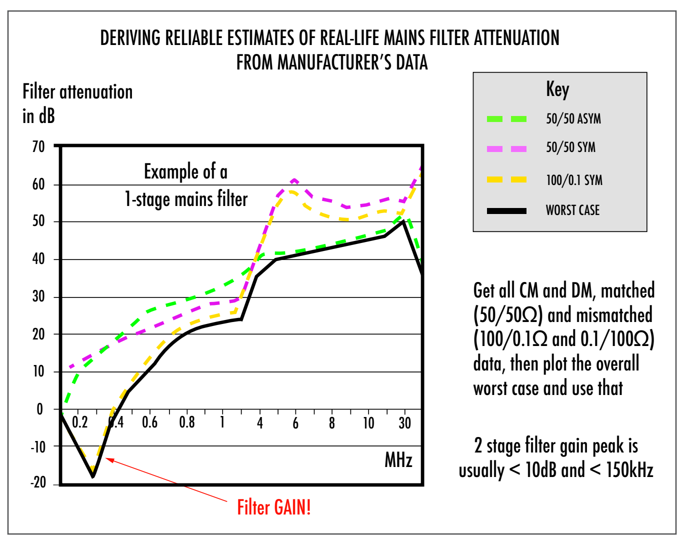


Figure 15 - Deriving reliable estimates of real-life mains filter attenuation from manufacturer's data

Figure 15 and the above discussion concerned mains filters, but exactly the same resonant gain issues arise for signal filters that use Ls and Cs, at frequencies below about 30MHz. Signal filters almost always use soft ferrites, which are resistive in the upper part of their frequency range and so do not cause resonances there – but they are inductive in the lower part so can cause resonances at those frequencies. Unfortunately, few if any signal filter manufacturers provide attenuation figures for source or load impedances other than 50Ω – so if RC, resistive Tee or π filters are not good enough and inductive components must be used, it might be best to experiment.

Experiments should take place at an early design stage, using sample filters and an RF signal generator and oscilloscope or spectrum analyser (if you don't have a network analyser), to see what attenuation can realistically be expected when used with the actual source and load impedances in your application. The differences between data sheet figures and real-life attenuation can be dramatic, and you do not want to discover such interesting effects during the EMC testing of a supposedly finished design!

Problems with Real-Life Switch-Mode Converter Input Impedances

Switch-mode power converters (e.g. switch-mode regulators, switch-mode amplifiers, DC/DC converters or DC/AC inverters) can have a negative dynamic input resistance at their power input terminals. This can interact with the impedance of an input filter, resulting in instability and even oscillation that can destroy the switch-mode converter and/or other equipment connected to the same power source. The problem is mainly caused by the series inductance in the filter, which can be compensated by using a larger value of capacitance connected across the input terminals, and also by damping the inductance (see below).

[5], written in 1973, describes these issues, and defines the conditions required for oscillation to take place. It also describes methods for preventing the instability and/or oscillation. Many more references can be found on the Internet, by searching with appropriate terms.

Damping Filter Resonances That Cause Gain

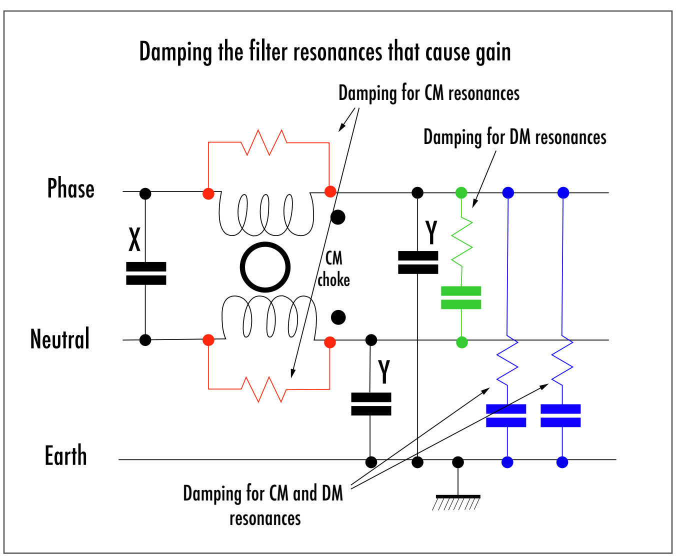


Figure 16 - Damping the filter resonances that cause gain

All LC filter circuits resonate, and at resonance they have a gain that depends upon the amount of loss in the circuit. 3.2.9 discussed resonances that can be caused in power supply filters by variations in their input (power source) impedances, whereas 3.2.10 discussed resonances that can be caused by the negative input impedance characteristics of switch-mode power converters. Filter resonances can amplify surge overvoltages, as discussed in 3.5.5, increasing their potential to cause damage.

Loss is caused by resistance, but most L and C filter components are designed to have low internal resistances to minimise their internal heating – so their resonant gain can be high. *Figure 16* shows how resistors can be added to an example mains supply filter circuit to provide damping that reduces the resonant gain. Such circuits cannot eliminate resonance entirely in any practical filter, but in some applications they can tame the resonances sufficiently well.

Although a simple single-stage mains filter is shown in *Figure 16*, the resistive damping techniques it shows can also be used for other types of power and signal filters containing inductors.

Filters and Safety

Class 1 products have a protective (safety) earth conductor connected to their metal structures, which are also their RF References, and mains filter capacitors connected to the filter's earth/ground cause leakage currents in the safety earthing/grounding system that can be dangerous. The maximum limits for these currents should be no larger than those specified by the appropriate safety standard(s) for the type of product concerned, e.g. IEC/EN: 60950, 61010-1, 60601-1, 60335-1, 60204-1, etc. Typically: double insulated products (no protective earth connection) must have <0.25mA, Class 1 protectively-earthed portable products must have <0.75mA and fixed ones must have <3.5mA. Class 1 protectively-earthed industrial fixed products might be permitted to have earth-leakage currents up to 5% of the rated phase current – when specified warning labels are fitted – but at the other extreme patient-connected medical products can be limited to <0.01mA.

In systems and installations the earth leakages from numbers of filters can build up to create large earth currents that can be very dangerous indeed. Tens of amps of leakage current is not unusual in the main protective earth terminal of a modern office building, due to its very many PCs and PC monitors, each with their mains filters leaking up to 3.5mA.

Mains filtering is an area where EMC requirements can often come into conflict with safety needs, and of course safety must always come first. So always take the relevant safety standards into account when designing or selecting mains filters, remembering that most X and Y capacitors have tolerances of ±20%.

Mains filters sold for 50Hz use may generally be used on supplies from DC to 400Hz with the same performance (but check with their manufacturers). Also remember that the earth-leakage currents caused by filter capacitors connected to the earth/ground will increase as the supply frequency increases, so filters that meet the relevant safety standards at 50Hz might not comply at 60Hz, and may be decidedly dangerous on 400Hz.

Capacitors connected between the phases and RF Reference should always be approved to all relevant safety standards for both the application and the voltage. They will usually be Y1 (for double insulated products) or Y2 (for Class 1 products with an earthed protective bonding network). Capacitors between phases should also be safety approved, e.g. types X1 and X2, more to prevent fire hazards than to prevent shocks.

It is always best to use mains filters (or components) for which third-party safety approval certificates have been obtained and checked for their authenticity, filter model and variant, temperature range, voltage and current ratings, and the application of the correct safety standard. Forged safety approval certificates are not unknown, even from manufacturers who might be expected not to run such risks, so I always recommend that certificates are checked with their issuing Approvals Bodies, who in my experience are always happy to help, to make sure they are not forgeries.

Filter Capacitor Degradation with Time and Over-Voltage

Metallised-film mains capacitors lose their value with age, when used on voltages close to their maximum ratings. This is a real problem for filter capacitors used between phases or phase-to-neutral, which should be X-rated and approved as such (see 3.2.12).

The standard IEC tests for approving X-rated capacitors allow them to lose 10% of their capacitance value every 1000 hours of operation. So, for example, after 3 years continuous use they could be down to 6.5% of their original value, e.g. a 100nF capacitor could be as little as 6.5nF.

I was alerted to this by Daniel Elser, of Lumatec SA, Geneva, Switzerland, who measured 100nF capacitors that have been running on the mains continuously for 3 years and now measure under 10nF. His capacitors were metallised film types from a reputable European manufacturer.

The problem is due to ionization with the capacitors, that erodes the metallisation. The solution (or, at least, a way of extending their life) is to use capacitors that are rated at twice (or more) the peak value of the mains. Or else use two regular capacitors in series – but then they'd each have to have twice the value, so the material cost would be four times the price of just one capacitor (that could of course be <10% of its value after 3 years continuous). Some types of Y-capacitor actually have two capacitors in series inside their single case, each one rated for the mains voltage, so they should last a little longer than their single-capacitor X counterparts.

Another problem is that mains surges and other transients can damage mains filter capacitors so severely that they go open-circuit. This applies to X as well as Y capacitors.

Sometimes when surge testing a product, you will hear a bang. But since the product works just fine afterwards the bang is regarded as being unimportant.

But if the bang is caused by a flashover to the chassis, when connected with signal cables to other equipment in a system a chassis flashover causes a "ground lift" that can blow up the I/O drivers. And if the bang is caused by the X or Y capacitors failing, the product's emissions and immunity can be very poor afterwards.

I'm told that some test labs are familiar with this problem, and either do emissions testing after immunity, or else recheck emissions after surge testing. But I've never been in a test lab where they did this!

Anyway, these problems with mains filter capacitors means that emissions will generally increase with age, and immunity will decrease. Some product manufacturers might not care about this – after all, the EMC Directive only applies at the point of supply to the distributor or end-user – and any serious problems are likely to arise outside of the warranty period.

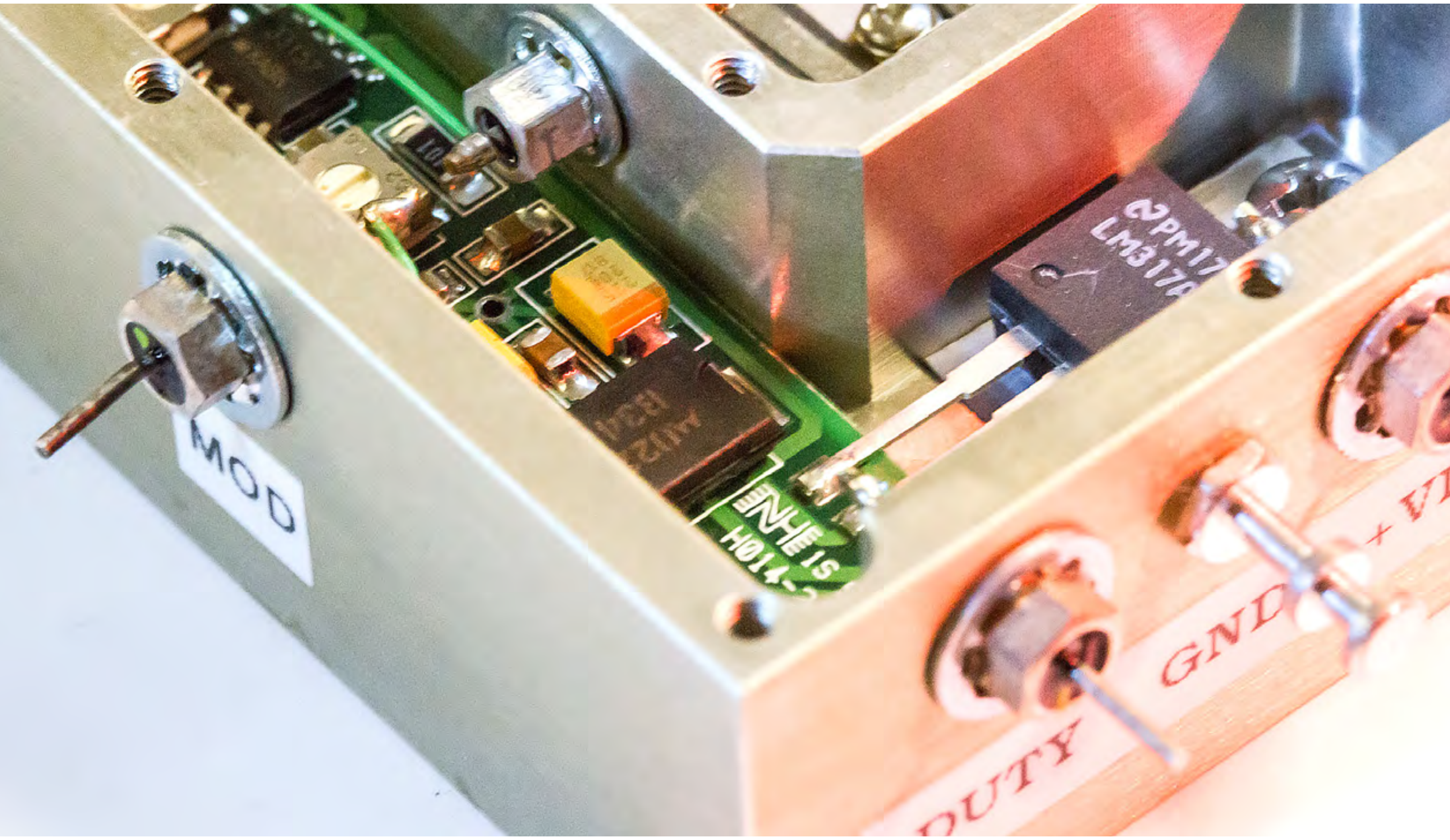
Now, it's not for me to talk about the ethics of supplying products whose performance is bound to degrade. But where errors or malfunctions in electronic products could increase safety risks, or where they are used in environments where excessive emissions could cause other equipment to cause increased safety risks, the designer must ensure that the safety risk targets are met over the anticipated lifecycle of the product. A good example of this would be medical devices, used in a hospital.

Where safety is an issue, the designer of the mains filters needs to ensure that they are still filtering much as intended, after a period of use at least equivalent to the intended life of the product. Maybe this would be done by choosing more costly filter capacitors, or fitting surge suppressors (which also wear out over time!), or by a planned maintenance programme that checks/replaces degraded capacitors and/or surge suppressors - but it does need to be dealt with.

FILTER INSTALLATION ISSUES

Eur Ing Keith Armstrong CEng MIEE MIEEE Partner
Cherry Clough Consultants

Real-life filter performance is totally dependant on how they are installed, especially on the impedance of the RF Reference and the impedance of the method used to electrically bond the filter to its RF Reference. Not only should these impedances be much lower than that of the shunt capacitors in the filters, they should also allow the internal and external CM surface currents to find their optimum return paths. This section discusses these issues, and the practical installation guidance that results.



FILTER INSTALLATION ISSUES

Input and Output Conductors

Stray RF coupling between the conductors associated with their unfiltered and filtered sides easily degrades filter attenuation. This problem is generally worse at higher frequencies, because the impedances of stray capacitances and stray mutual inductances reduce as frequencies increase, increasing the amount of stray coupling bypassing the filter. Many engineers have been very surprised by the ease with which high frequencies will bypass ('leak around') a filter, given half a chance.

In an unshielded enclosure, filters should be positioned as near to the point of entry of the cable as possible. The maximum possible separation distances should be maintained between the filter's external and internal cables, and between all of the conductors associated with the circuits on either side of the filter. Conductors in air should be spaced at least 100mm apart, more if they are routed in parallel for more than a few centimetres. Closer spacings might be acceptable for PCB traces and components – but only if they are much closer to the PCB's RF Reference Plane than the spacing between them. Filter input and output conductors should never, ever, be bundled together, or share the same cable or cable route, unless they are each well shielded. See [6] for how to shield conductors effectively.

Where the enclosure is shielded, it is essential to mount the filter in the wall of the enclosure, with the filter's body electrically bonded directly to the shielding surface of the wall, otherwise both the filtering and shielding performances will be degraded by stray coupling around the filter. The type of filter required is often called a bulkhead-mounting, or through-bulkhead filter, because it fits through the metal wall (bulkhead) that it is mounted upon. The shielded enclosure considerably reduces the stray coupling between the filter's input and output. It may even be necessary to fit a conductive EMC gasket around the aperture in the shield where the filter is mounted, for the maximum possible filtering and shielding. Issues of filtering with shielded enclosures are covered in more detail below.

Skin Effect and the Flow of Surface Currents

Where the frequencies to be attenuated are not very high, it could be acceptable to use a few direct bonds, or a few millimetres of wire or braid to provide the electrical bonding to the RF Reference, providing the impedance of the bonding method is much less than that of the filter's shunt capacitors at the highest frequency of concern. But to understand how to assemble/install filters correctly for good RF performance at high frequencies, we need to understand 'skin effect'.

All RF currents travel as surface currents, because all conductors have a skin effect that effectively causes them to shield their inner depths from RF currents. *Figure 3S* illustrates the general principle, and shows that as the frequency increases, the current is constrained to flow closer to the surface, increasing the current density at the surface of the conductor. One skin-depth is the depth into the conductor by which the current density has decreased to 1/e of what it was – about 0.368. By two skin-depths into a conductor the current density has reduced to $(1/e)^2$, or 0.135, by three skin-depths it has reduced to $1/e)^3$, or 0.05, and so on.

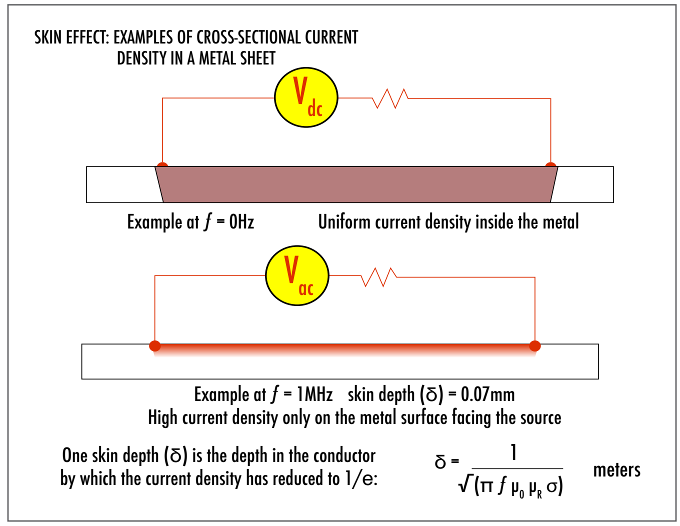


Figure 17 - Skin effect: examples of cross-sectional current density in a metal sheet

Figure 17 gives the formula for calculating one skin-depth δ, where μ_0 is the permeability of free space ($4\pi.10^{-7}$ Henries per metre); μ_R is the (dimensionless) relative permeability of the conductor material (most common conductors, such as copper, aluminium and tin, have a μ_R of 1.0) and σ is the conductivity of the conductor material in mho/metre. Copper has a nominal volume resistivity ρ_v of 1.72.10-8 Ω-m, giving it a nominal conductivity of 58.10^6, so one skin-depth in nominal copper is given by $\delta = 66/\sqrt{f}$ (δ is given in millimetres when f is in Hz). For example, at 160MHz: one skin-depth is 0.005mm, so 0.05mm below the surface of a copper conductor, the RF current density is 0.0025 of the density at the surface, an attenuation of 52dB.

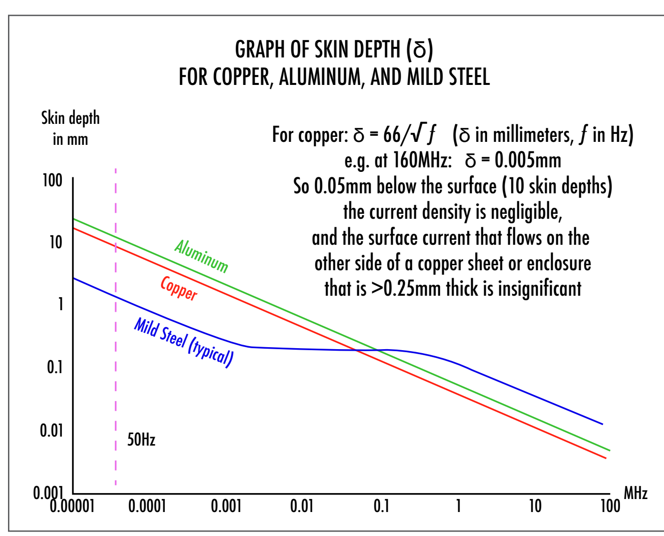


Figure 18 - Graph of skin-depth (δ) for copper, aluminium, and mild steel

Figure 18 shows graphs of skin-depth versus frequency for some common materials, to save having to find out the values of their conductivity and calculate δ. Mild steel is shown as an example of a ferromagnetic material (nickel is another), and to show that their high values of μ_R result in smaller skin-depths, but also that their permeability is frequency-sensitive and disappears above some critical frequency.

[11] contains information on the material properties of a wide range of conductors, for calculating skin depth, and also a great deal of other useful information for designers. [12] is a useful source for information on skin-depth.

Above a few tens of MHz most conductors and metal items (such as the cases of filters) are several skin-depths thick, so RF currents travel as surface currents in them. Taking this phenomenon into account in the design of a filter's assembly/installation is essential for the achievement of good emissions and/or immunity performance.

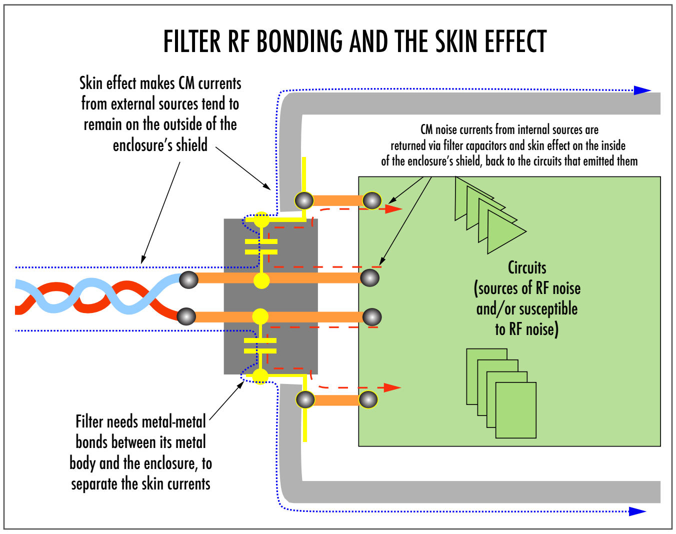


Figure 19 - Filter RF bonding and the skin effect

Figure 19 shows how providing a continuous metal bond between a filter and the shielding enclosure of a product ensures that the external CM noise currents do not enter the enclosure and cause interference and immunity problems, and the internal CM noise currents remain inside the enclosure and do not escape to cause emissions problems. *Figure 19* shows a simple capacitor filter, but the principle applies to all types of filters.

As a result, the optimum way to bond a filter to its RF Reference Plane, for the best performance at the highest frequencies, is what is often called '360° direct metal-metal contact' – meaning that the filter's metalwork and the RF Reference Plane are in direct contact with each other all around the periphery of the filter (hence the term 360°).

Commercial and industrial conducted emissions standards generally only measure up to 30MHz, and at such low frequencies it is often sufficient to bond a filter to an enclosure with a single direct metal-to-metal connection between the filter's case and the enclosure. Where the filter is only required for low frequencies, e.g. below 1MHz, it may even be possible to use a very short length of wire or braid to connect its metal case to the enclosure metalwork, plus of course the enclosure will not need to be a proper shield either. But there is a synergistic relationship between filtering and shielding, discussed in more detail in the following section.

Filters that employ capacitors connected between power or signal conductors and the RF Reference depend upon the RF Reference – and their connection to it – having a much lower impedance than the filter capacitors, at all of the frequencies to be attenuated. The connection between the capacitors and RF Reference should be very short and direct, less than one-hundredth of a wavelength long at the highest frequency to be attenuated, and should also have a very low inductance. This usually means that wires or even braid straps cannot be used to electrically bond filters to the RF Reference Plane, except for low frequencies (say, below 1MHz).

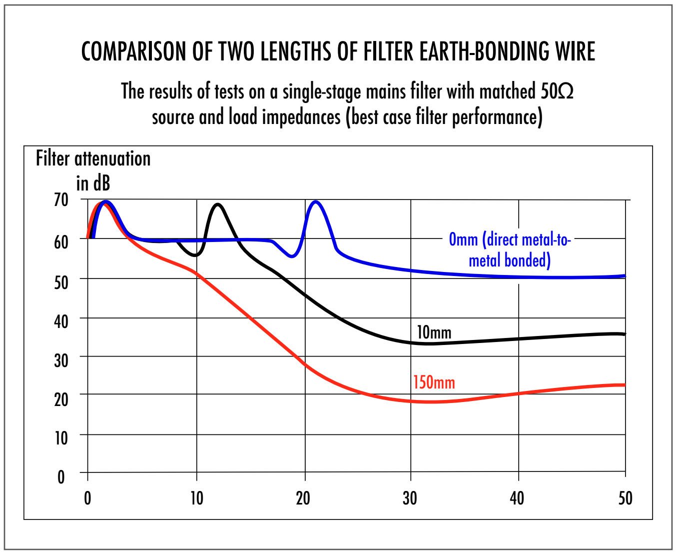


Figure 20 - Comparison of two lengths of filter earth-bonding wire

Figure 20, which is taken from [13], shows the sorts of bad effects that even a short length of interconnecting wire can have on a standard single-stage mains filter even when measured with 50Ω/50Ω source and load impedances – its best possible case. If the 10mm wire were replaced with at least one direct metal-to-metal bond, performance at 30MHz and above would improve dramatically.

It is acceptable to fit green/yellow wires of any length to mains filters, for safety reasons, as long as there is also at least one direct metal-to-metal electrical bond between the filter's metal case and the product's RF Reference. When a mains filter's metal-to-metal bonds have been designed to maintain a very low impedance over the lifecycle of the product, there is no need for a green/

yellow 'safety earth' wire as well – but safety inspectors are generally much more reassured when they can see a green/yellow bonding wire with anti-vibration anti-corrosion connections at both ends. (But, as discussed above, it would be a mistake to assume that the green/yellow safety wire was adequate for achieving the filter's EMC performance.)

The Synergy of Filtering and Shielding

Some mains filter manufacturers only design and specify their filters to provide attenuation over the frequency range of the conducted emissions tests (typically up to 30MHz for commercial and industrial products), to keep costs low. Unfortunately, if such filters have poor attenuation above 30MHz, they will degrade the shielding effectiveness (SE) of a shielded enclosure above that frequency by permitting RF signals to leak out via the filtered cables – resulting in problems for both emissions and immunity.

It does not matter what is the ostensible purpose of a conductor, e.g. mains or DC power, audio, whatever – if its filtering and/or shielding provides less attenuation than is required for the shielded enclosure, it will degrade the SE of the enclosure. The filtering and/or shielding of cables used for audio, mice or keyboards are often ignored when they exit a shielded enclosure. The assumption is usually that the signals they carry will not cause a problem for EMC. But this overlooks the fact that all conductors or whatever type or signal designation always behave as 'accidental antennas' (see [6]), very readily picking-up EM noises on either side of a shielded barrier and retransmitting them on the other side – unless specifically prevented from doing so by the application of shielding and/or filtering.

If good high frequency shielding is required, all unshielded cables that enter the enclosure (including mains) must be filtered with good attenuation at the highest frequency of concern for shielding purposes. So where shielding is required up to 1GHz (for example), only employ filters with data showing good attenuation up to at least 1GHz. Few mains filters intended for commercial and industrial equipment specify attenuation above 100MHz, so additional high-frequency filtering might be needed. However, some filter manufacturers (e.g. EMC Solutions) specify their filters up to 1GHz.

Assembly and Installation Techniques For Filters That Penetrate Shields

As discussed above, the performance of shielded enclosures can easily be degraded by RF noise that 'leaks' out along the cables that enter and exit the enclosure. The shielding/filtering synergy issues discussed above are vital considerations when high levels of shielding or filtering are required (e.g. >40dB) at frequencies >100MHz.

The design of shielded cables was covered in [6], and the design of shielded enclosures will be covered in Part 4 of this series. This section discusses how filters should be installed in shielded enclosures so that they do not permit RF noises to pass through them that could compromise the SE of the enclosure.

THREE-ELECTRODE ('THREE-TERMINAL') AND FEEDTHROUGH CAPACITORS

Traditional high-performance 'feedthrough' capacitor filter
(these examples from Oxley)

SMD 3-terminal capacitor filter
(this example from AVX)

Figure 21 - Three-electrode ('three-terminal') and feedthrough capacitors

Figure 21 shows an example of a 'feedthrough' capacitor specifically designed for use where unshielded conductors penetrate a shielding enclosure, which could be a product's enclosure or an internal shielded volume. Another, higher current style of feedthrough capacitor was shown in *Figure 1*. Feedthrough capacitors have three terminals, for input, output and 'ground'. The signal to be filtered enters at one side of its electrodes and exits at the other, having to pass the ground electrode as it does so. The middle 'ground' terminal connects directly to the shield, using a 360° electrical bond so that the internal and external surface currents stay separated on either side of the shield, as shown in see *Figure 19*, allowing the shield to function correctly. If designed correctly, the shielded enclosure prevents stray coupling between the capacitor's input and output terminals, and also provides the filter with an RF Reference Plane with negligible impedance at the highest frequency of concern, all of which helps the filter employing the feedthrough capacitor to achieve the best performance it is capable of.

When used as (or in) filters, traditional feedthrough capacitors such as the ones shown in *Figures 21* and 1 provide much better attenuation, at much higher frequencies, than is possible by using ordinary two-terminal capacitors. Traditional feedthrough capacitors are soldered or screwed into a shield wall and connected to the circuits on either side by wire conductors. They are often used between shielded compartments within RF equipment, e.g. to filter the DC power that passes between the RF, IF and digital sections of an RF receiver or spectrum analyser.

Traditional feedthrough filters, such as those shown in

Figure 3W, are also available as 'filter pins' in some standard connectors, such as some D-types and military circular connectors. (Note that not all connectors with built-in filters use feedthrough filter pins, some use discrete components on miniature internal PCBs, which will not achieve as good an attenuation at the highest frequencies.)
Traditional feedthrough filters are not favoured for modern volume-manufactured products because of their high component cost, and the high cost of their manual assembly and the assembly of the wires they connect to. Volume-manufactured products prefer to use SMD components automatically assembled on PCBs – but since a true feedthrough capacitor cannot be automatically assembled, three-terminal capacitors have been developed to fulfil this purpose.

Figure 21 includes an example of a three-terminal capacitor intended for SMD assembly processes, and *Figure 22* shows an example of how it is used in conjunction with PCB shielding. The capacitor is aligned with the shield wall so that its input and output terminals are shielded from each other by the PCB-mounted shielding-can, and the capacitor's centre 'ground' terminal is soldered directly to a guard trace that follows the wall of the shield-can and connects it to a PCB plane (almost always 0V) with a wall of via holes.

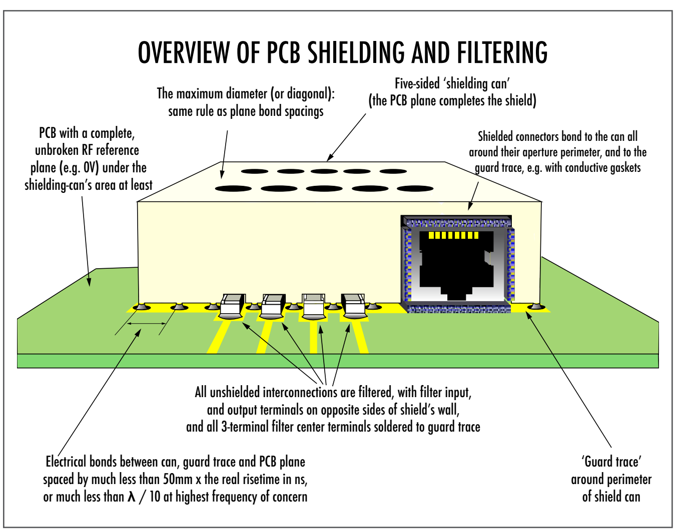


Figure 22 - Overview of PCB shielding and filtering

The gaps that are cut out of the shield-can's wall for the bodies of the filters are known as 'mouseholes' (for reasons that should be obvious to anyone who enjoys 'Tom and Jerry' cartoons). Three-terminal capacitors and the filters that use them cannot be as good as proper 360° shield-bonded feedthrough types, because there will always be some stray coupling through the mouseholes in the shield. But careful control of the maximum dimensions of the mouseholes, and of the spacing between the via-holes connecting the shield wall to the PCB plane that provides the shield's sixth side, can nevertheless achieve excellent performance. For more details on this, see Part 2 of [9].
Figure 23 shows attenuation of a three-terminal SMD π filter assembled on a PCB, and the effect of adding a PCB-mounted shielding-can in the manner shown in *Figure 22*. Without the PCB's shield-can fitted, the filter performance is quite respectable at about 50dB at 100MHz, but above that frequency it falls off at 20dB per decade, so that it is only about 30dB at 1GHz, and it would presumably be about 10dB at 10GHz.

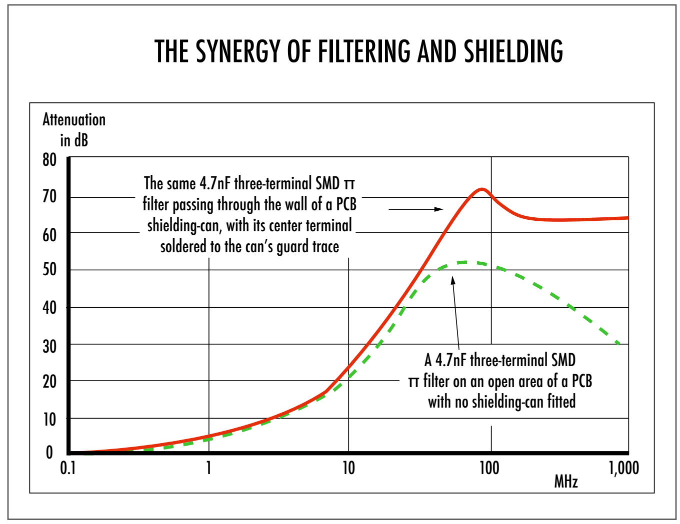


Figure 23 - The synergy of filtering and shielding

But the addition of the shielding-can reduces the stray coupling bypassing the filter very considerably, and also allows correct separation of internal and external surface currents and provides an RF Reference Plane that has a much lower impedance over the frequencies measured. The result is an attenuation of around 70dB at 100MHz, and a more-or-less flat attenuation that maintains about 65dB up to 1GHz – easily 35dB more attenuation than was achieved without the shield. It is not clear what the performance with the shield-can would be above 1GHz, but as there is no sign of any roll-off even at 1GHz it is likely that an attenuation of at least 45dB would be achieved at 10GHz.

As described in section 2.6 of [6], shielded cables exiting a shielded PCB region require shielded connectors or glands that are electrically bonded to the shield-can's wall by mechanical fixings, soldering or gasketting that makes multiple connections around its periphery – preferably full 360° bonding.

The experiment whose results are shown in *Figure 23* reveals two important things:

a) Filters that must provide significant levels of attenuation at frequencies above 100MHz, must employ shielding techniques as well. They will not be able to achieve the required performance otherwise.

b) Modern digital ICs produce large amounts of CM and DM noise at frequencies above 1GHz, and products supplied to the USA already have to comply with

FCC emissions limits above this frequency. The EN standards used to achieve a presumption of conformity with the EMC Directive for products supplied to Europe will soon be changing to include emissions and immunity requirements above 1GHz – at least to 2.7GHz and maybe higher. To comply with these requirements using low-cost SMD PCB assemblies will require the use of shielding wherever GHz frequencies need to be filtered.

There are now many suppliers of PCB-mounted shielding-cans that can be used with three-terminal filters, and they have many types that can be automatically assembled like any other SMD component. Part 2 of [9] has more details on these shield-cans, and also describes a number of different PCB layouts appropriate for filtering off-board connectors. An example of one of these layouts is shown in *Figure 24*.

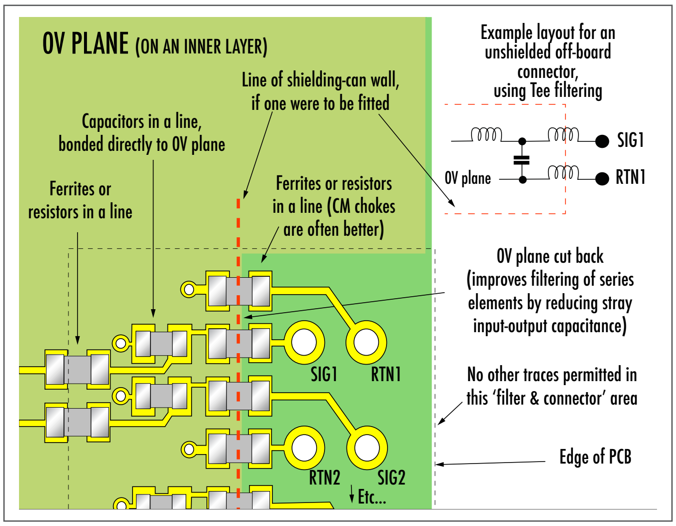


Figure 24 - Example layout for an unshielded off-board connector, using Tee filtering

Where filters must penetrate the shield of a product's overall enclosure, and PCB-mounted components are not suitable, more traditional feedthrough or 'bulkhead-mounted' filters in metal cases are the best. A point to watch out for is whether the metal cases of such filters are seamless – good filters are enclosed in what are actually well-shielded enclosures themselves. Filters that have metal cases with apertures, seams or gaps in them give poor attenuation at high frequencies regardless of what their data sheet says, because they compromise the attenuation of the shielded enclosure they are assembled/installed onto.

'Chassis mounted' filters include types with screw terminals, spade or blade terminals, or flying leads (*Figure 1* shows some examples of chassis mounted filters with spade terminals) and cost less than proper bulkhead or feedthrough types, but cannot be assembled to shields so as to reduce stray coupling between their inputs and outputs. The result is that they are not as effective as feedthrough or bulkhead mounting types at higher frequencies, especially above about 10MHz. Their performance can be maximised by mounting them with multiple direct metal-to-metal bonds to an RF Reference Plane that is a shielded enclosure wall, or at least a very large metal plate, plus routing their input and output cables very close to the RF Reference Plane and keeping them and any circuits or components they connect to very far apart. However, their performance can be significantly improved by the use of what is known as the 'dirty box' shielding technique illustrated in *Figure 25*. This figure shows a shielded enclosure, and an example of the correct installation of a traditional high-performance feedthrough filter. It also shows an example of an IEC 320 appliance mains inlet connector with an internal filter. The important issue with such inlet filters is that they should have seamless metal bodies that make a direct metal-to-metal connection to the wall of the shielded enclosure.

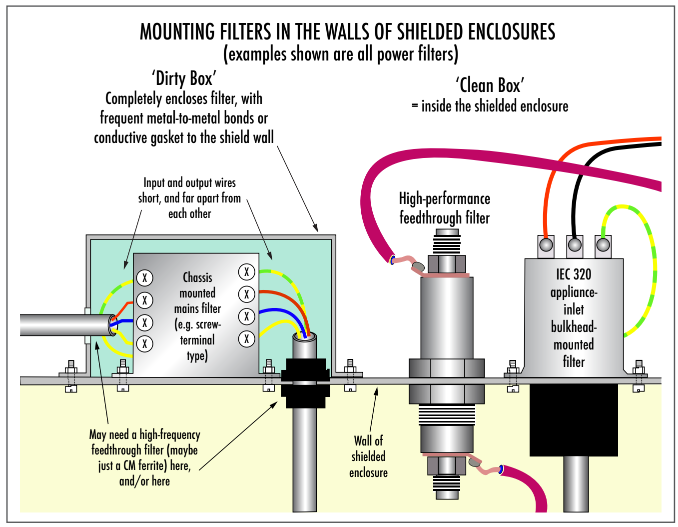


Figure 25 - Mounting filters in the walls of shielded enclosures (examples shown are all power filters)

Many manufacturers have fitted mains connectors with built-in filters, relying on their mounting screws and green/yellow safety earth wire to make the necessary electrical bonds, and have found the EMC performance to be almost useless. As discussed above, the length of the green/yellow safety wire is simply too long, and a problem with most built-in filter connectors is that their mounting screws bear onto plastic mouldings, so they don't provide any metal-to-metal connections. The correct way to install such filters is to ensure that an area of the enclosure's shield wall is free from paint or anodising, and has a highly conductive surface that will be pressed firmly against the filter's metal body when it is assembled. Sometimes it may even be necessary to bond the bodies of such filters 360° to the shield wall all around the perimeter of the filter's metal case, requiring high surface conductivity for the metalwork on both sides of the gasket, and protection from corrosion (see on the right).

When chassis-mounted filters are applied to cables entering or exiting a shielded enclosure, the portion of the cable that enters the enclosure to connect to the filter de grades the attenuation of the filter by causing stray coupling to its other terminals. This portion of cable also degrades the SE of the enclosure by acting as an accidental antenna (see [6]), especially at higher frequencies.

To maximise the high-frequency performance of such filters and prevent degradation of the enclosure shielding, such filters should be installed using the 'dirty-box' method illustrated in *Figure 25*. The Dirty Box is a five-sided shielded cover that fits over the filter and the external cable entry, within the overall shielded enclosure. It must have metal-to-metal bonds at multiple points between its walls and the wall of the shielded enclosure, spaced apart by much less than λ/10 at the highest frequency to be controlled, and covering the entire perimeter of the Dirty Box's walls. Conductive gaskets might help reduce assembly time by reducing the number of fixing screws, or might even be necessary to achieve sufficiently good bonding to the enclosure wall.

The filter is mounted inside the Dirty Box, with its input and output conductors kept as short and as far apart from each other as possible, to reduce their stray coupling – but even so the higher frequencies will still couple between them. If the resulting high-frequency stray coupling is problematic and cannot be reduced by careful cable routing within the Dirty Box, soft-ferrite CM chokes and/or high-frequency feedthrough filters may be needed on either (or both) the input and output cables, fitted at the point where they enter or exit the Dirty Box.

'Shielded room' filters are also available, and although intended for EMC test chambers (as shown in *Figure 2*) they can be used for shielded equipment cabinets as well. These are essentially screw, spade or blade terminal filters with two Dirty Boxes, one over the input terminals and their conductors, and one over the output terminals and their conductors, to minimise the stray coupling between input and output.

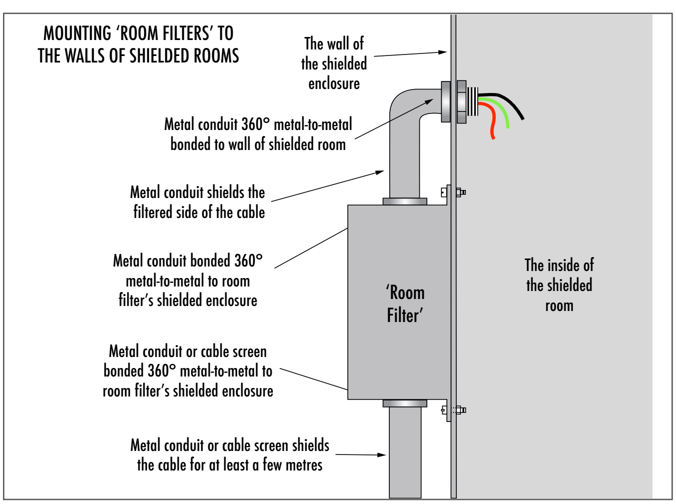


Figure 26 - Mounting 'room filters' to the walls of shielded rooms

Conduit fittings are usually provided for the filtered side of room filters, to provide shielding for their conductors whilst they enter the shielded room or enclosure. Where the conduit enters the shielded room or enclosure it must electrically bond 360º at the shield wall, as illustrated in *Figure 26*. Shielded cables may be used instead of conduits, as long as they bond 360º at both ends, to the filter's case and the shielded room or enclosure wall using appropriate glands or connectors.

Figure 27 shows an overview of shielding and filtering at the level of the final system or installation. Where an electrical/electronic product has an overall shielded enclosure, all of the conductors that enter or exit that enclosure must be shielded, and/or filtered, at the point where they enter/exit the enclosure. There are no exceptions to this rule, whatever the purpose of the conductors, including safety earth wires: metal armour or draw-wires for cables, fibre-optics, or hydraulic hoses; metal pipes for gasses or liquids; metal ductwork for cables, air-conditioning, etc. Conductors permitted to be connected directly to the shield wall should be so connected, using 360° bonding techniques just as if they were cable shields (see [6]).

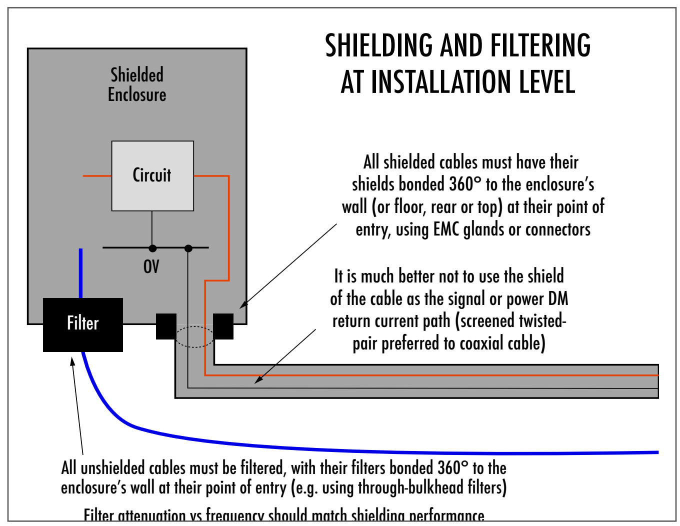


Figure 27 - Shielding and filtering at installation level

Unshielded conductors that are not directly bonded to the enclosure at point of entry/exit must be filtered, taking into account all of the techniques discussed above concerning the synergy of filtering and shielding.

Designing to Prevent Corrosion

All metal-to-metal bonds associated with filters (and shielding), and all conductive gaskets, must be designed to provide low impedance for the anticipated lifecycle of the product, despite the mechanical, climatic, biological, chemical and other physical environments the product is exposed to. This generally means choosing metals, platings and gasket materials that resist oxidation, and it also means ensuring that the materials in contact are sufficiently close in the galvanic series so that they don't suffer unduly from galvanic corrosion. IEC 60950 is a safety standard but provides some useful guidance on these issues, and there is also a lot of information available freely on the Internet.

Effective 'vapour-phase corrosion inhibition techniques' are claimed to have been developed in recent years, by Cortec Corporation (http://www.cortecVpCI.com), and should be investigated, especially where corrosion is a significant problem.

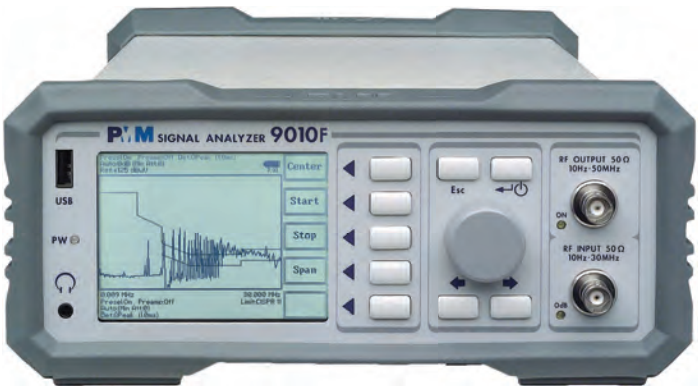
Filters Connected in Series

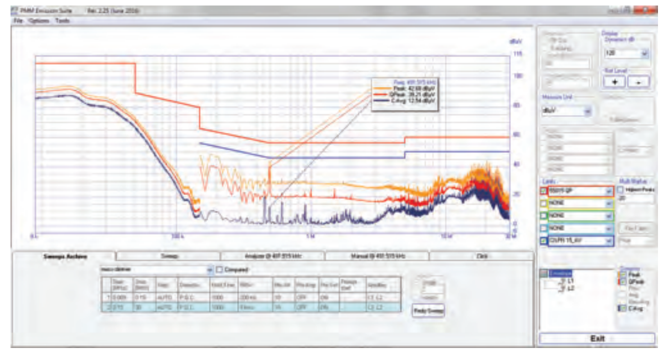
It sometimes happens that a product is supplied with mains filtering, but its RF emissions are too high (or its immunity too low) for the equipment, system or installation it is used in. This is often a problem where a large number of identical or similar devices are used in one product or system, for example a number of low-power inverter motor drives in one industrial cabinet. Each product may meet the relevant emissions limits individually, but when a number are all operating at once the aggregate of their emissions might exceed the permitted limits. In such situations it is tempting to simply add another mains filter, which would then appear in series with the mains filters already fitted in the products. Often a single-stage filter is chosen because the filtering requirements are only modest. The gain problems that can occur with filters with 'mismatched' source/load impedances, especially single-stage types, were discussed earlier – but sometimes connecting filters in series can result in resonances that are not present in any of the filters when they are tested individually. So adding the extra filter can sometimes create worse emissions or immunity than before.

Solutions include replacing the original filters in the products with ones that achieve higher performance, or experimenting with different types of additional filters to find ones that work well when connected in series with the filters in the products. If the circuits of the filters involved (product and additional) are known, circuit simulators such as Spice should be able to predict resonance problems in advance, and guide the choice of appropriate devices.

Advanced solutions for testing EMI filters applications in few seconds

Saves time and money!

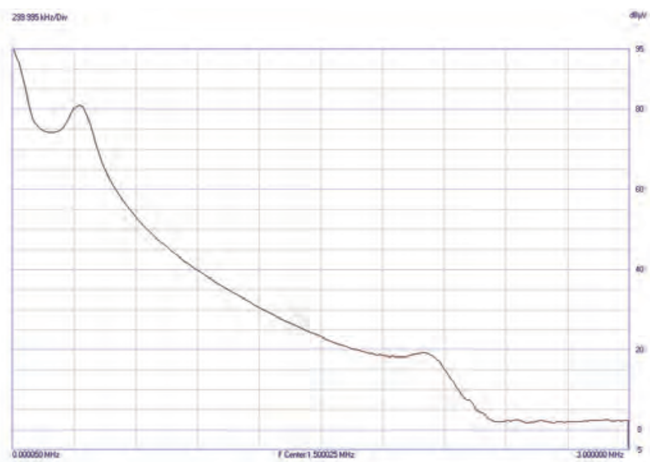




PMM Emission suite: measure, analyze, report

FFT GAPLESS EMI RECEIVER MODEL 9010F

- Frequency range 10 Hz— 30 MHz
- Full CISPR and MIL-STD compliance
- All detectors simultaneously
- Scan, spectrum and manual modes
- Scans 9 kHz—30 MHz in 24 seconds
- DC and battery powered
- Internal tracking generator
- Auto switching of LISN lines (PMM LISN)
- Robust, portable: 4 kg only
- Free, powerful PMM Emission Suite
- Expandable to 3, 6, 18 GHz on site

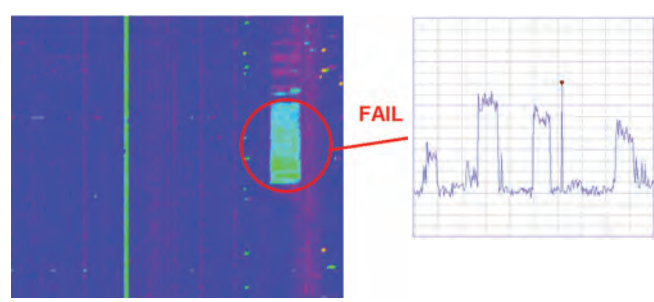


Amplitude response of filters

COST-EFFECTIVE, UNCOMPROMISED QUALITY AND PERFORMANCE!

Other valuable PMM accessories and solutions from Narda:

- Single and 3-phase LISN up to 500 A
- Antenna sets for emission tests
- RF immunity systems



Long run test with spectrogram and time history

PMM A BRAND OF narda Safety Test Solutions® an L3 Communications Company

E-Mail: nardait.support@L-3com.com
Internet: wwwnarda-sts.it

References

1. Keith Armstrong, "*Design Techniques for EMC*", UK EMC Journal, a 6-part series published bimonthly over the period February – December 1999. An improved version of this original series is available via the "Publications & Downloads" page at www.cherryclough.com

2. "EMC for Functional Safety", The IET, 2008, a 180-page practical guide suitable for all industries and applications, available for free download from www.theiet.org/factfiles/emc/index.cfm or as a colour printed book for £27 from: www.emcacademy.org/books.asp

3. Arthur B Williams, "*Electronic Filter Design Handbook*", McGraw Hill, 1981, ISBN 0-07-070430-9

4. John R Barnes, "*Robust Electronic Design Reference Book, Volume I*", Kluwer Academic Publishers, 2004, ISBN: 1-4020-7737-8

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

6. Keith Armstrong, "*Design Techniques for EMC, Part 2 – Cables and Connectors*", The EMC Journal, May and July 2006, available from www.compliance-club.com.

7. Keith Armstrong, "*Design Techniques for EMC, Part 0 – Introduction and Part 1 – Circuit Design and Choice of Components*", The EMC Journal, January 2006 pp 29-41, plus March 2006 pp 30-37, available from www.compliance-club.com.

8. F Beck and J Sroka, "*EMC Performance of Drive Application Under Real Load Condition*", presented at the Industrial Forums in EMC Zurich 2001, and also a Schaffner EMV AG application note dated 11th March 1999. It was also presented by W L Klampfer at the 8th International Conference on Electromagnetic Interference and Compatibility, INCEMIC 2003, ISBN: 81-900652-1-1, publication date: 18-19 Dec. 2003.

9. Keith Armstrong, "*EMC for Printed Circuit Boards – Basic and Advanced Design and Layout Techniques*", February 2007, www.emcacademy.org/books.asp, £47 plus p&p, perfect bound: ISBN 978-0-9555118-1-3, spiral bound (lays flat): ISBN 978-0-9555118-0-6

10. The United Kingdom Accreditation Service, www.ukas.com

11. John R Barnes, *Robust Electronic Design Reference Book, Volume II, Appendices*, Kluwer Academic Publishers, 2004, ISBN 1-4020-7738-6

12. RF Café, *Skin Depth*, www.rfcafe.com/references/electrical/skin_depth.htm

13. Tim Williams and Keith Armstrong, "*EMC for Systems and Installations"*, Newnes 2000, ISBN 0 7506 4167 3, especially chapter 8, www.newnespress.com, RS Components Part No. 377-6463

14. ITI (CBEMA) Curve and Application Note: www.itic.org/archives/iticurv.pdf

15. "*PCB Layout: The Impact of Lightning and Power-Cross Transients*", Milton Hilliard, Compliance Engineering, January/February 2003 pp 25-30, available from the archives at http://www.ce-mag.com

16. MIL-STD-275 "*Printed Wiring for Electronic Equipment, Revision: E, Dated: 31 December 1984*", available via: http://www.dscc.dla.mil/Programs/MilSpec/ListDocs.asp?BasicDoc=MIL-STD-275

17. Akihiko Yagasaki, *Characteristics of a Special-Isolation Transformer Capable of Protecting from High-Voltage Surges and Its Performance*", IEEE Trans. EMC, Vol. 43, No. 3, August 2001, pp 340-347

18. Daniel Dunlap, *Protection of SPD Products*, ITEM 2000, pp 148-157, visit www.interference-technology.com and search by 'Daniel Dunlap'.

19. Keith Armstrong, *The Benefits of Applying IEC 61000-5-2 to Cable Screen Bonding and Earthing*, IEE Seminar entitled: "EMC – its nearly all about the cabling", The IEE, Savoy Place, London, January 22nd 2003.

20. IPC-2152, "Standard for Determining Current-Carrying Capacity in Printed Board Design", September 2009 (replaces IPC 2221).

Acknowledgements

I am very grateful to the following people for suggesting a number of corrections, modifications and additions to the first series published in 1999 [1]: Feng Chen, Kevin Ellis, Neil Helsby, Alan Keenan, Mike Langrish, Tom Liszka, Tom Sato, and John Woodgate. I am also indebted to more recent input from Richard Marshall.

Author Contact

Eur Ing Keith Armstrong CEng MIEE MIEEE
Partner, Cherry Clough Consultants,
www.cherryclough.com, Member EMCIA
Phone: +44 (0)1785 660 247
Fax: +44 (0)1785 660 247
Email: keith.armstrong@cherryclough.com

Originally published in the EMC Compliance Journal in 2006-9, and available from www.compliance-club.com/KeithArmstrong.aspx

Modified 9 April 2010 by adding new section 3.12.3, and last updated on 11 Dec 2010

INDEX OF ADVERTISERS

Captor Corporation
5040 South County Road 25A
Tipp City, Ohio, 45371

t: (937) 667-8484
e: sales@captorcorp.com
w: www.captorcorp.com

Coilcraft Inc.
1102 Silver Lake Road
Cary, IL USA 60013

t: (800) 322-2645
e: sales@coilcraft.com
w: www.coilcraft.com

WEMS Electronics
4650 West Rosecrans Ave.
Hawthorne, CA 90250

t: (310) 644-0251
e: salesinfo@wems.com
w: www.wems.com

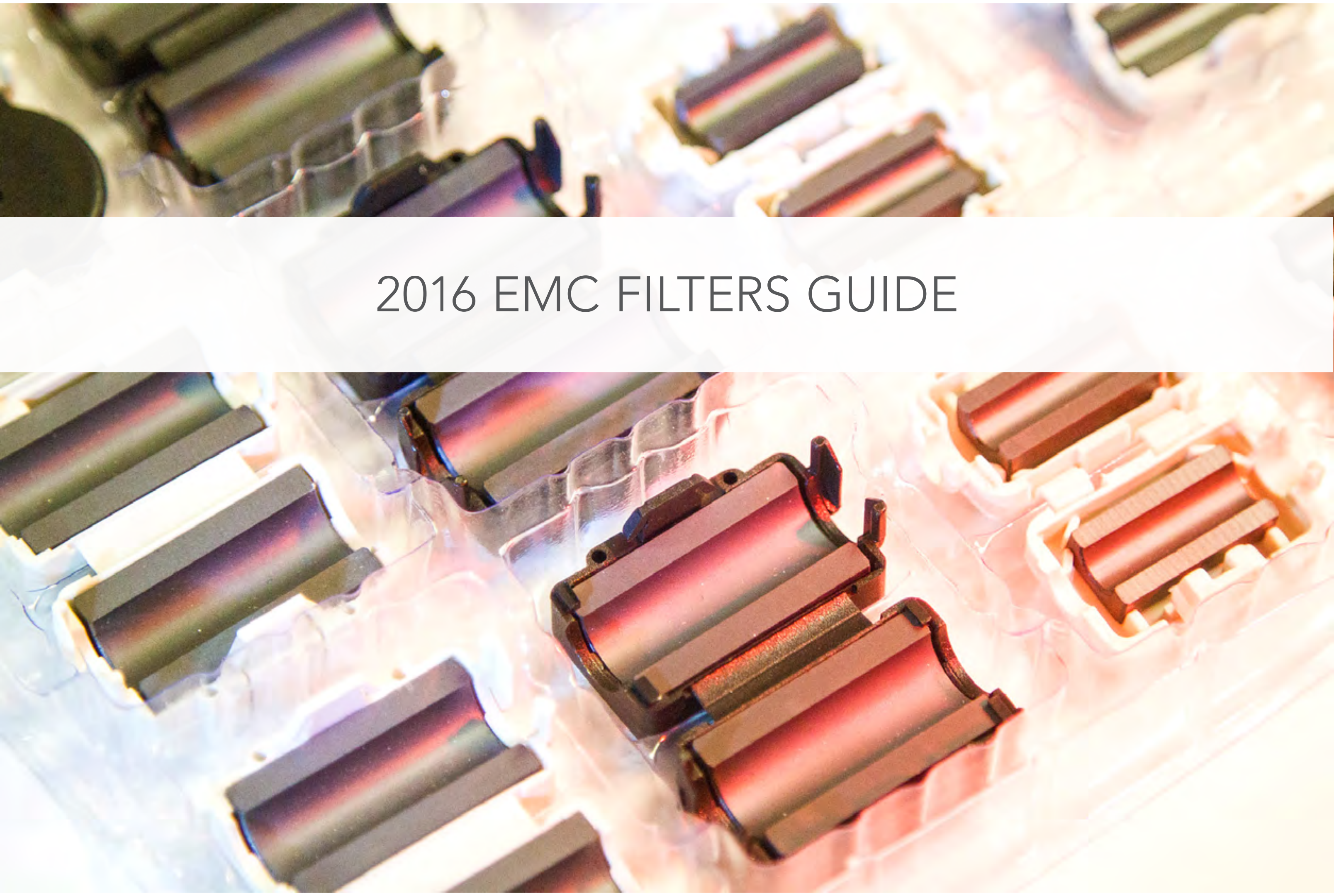
Narda Saftey Test Solutions
435 Moreland Road
Hauppauge, NY, USA

t: (631) 231-1700
e: nardasts@l-3com.com
w: www.narda-sts.com

Quell Corporation
5639 Jefferson NE
Albuquerque, NM 87109 USA

t: (505) 243-1423
e: nardasts@l-3com.com
w: www.eeseal.com

2016 EMC FILTERS GUIDE



INTERFERENCE TECHNOLOGY GUIDE SERIES
www.interferencetechnology.com