REO

EMC Filters

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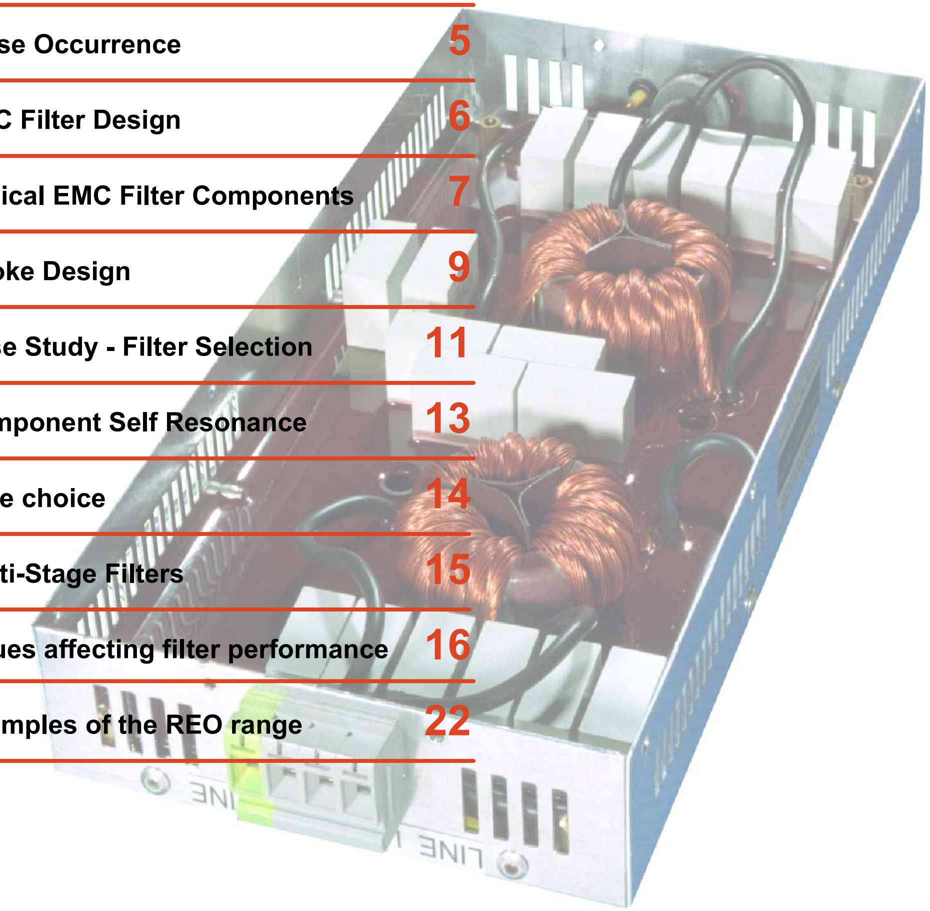


Definition of EMC

The pursuit of smaller and more efficient electronic devices coupled with the proliferation of embedded electronics in all manner of products means that the electromagnetic (EM) spectrum has never been more densely populated, both by intentional sources of EM emissions, such as cellphones and by unintentional EM sources such as Switch-Mode Power Supplies (SMPS), inverter drives, computers, etc..

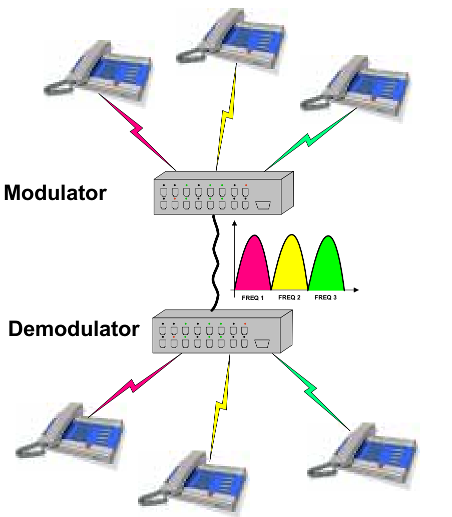
The very nature of these products means that as well as being EM sources they can suffer interference from EM noise, which can be radiated through the air and insulators, and conducted through any wire, cable or other conductor. Immunity to interference from the EM noises that exist in the operational environment, and keeping a products own EM emissions to acceptable levels, is what electromagnetic compatibility (EMC) is concerned with.

This booklet is focused, generally, on suppressing the EM noises that can propagate via actual physical connections and cabling in the mains supply network. Current, conducted emissions legislation dictates that the bandwidth of importance for most products is 150kHz to 30MHz, but EMC compliance relies on achieving adequate performance when tested with conducted *and* radiated emission standards. It is important to realise that any AC current loop can act as an accidental antenna. So any high frequency noise currents flowing in a product's mains input cable, for example, can easily be radiated and cause a radiated emissions test failure. An EMC filter's effective performance should extend beyond the minimum legislative requirements for conducted emissions to aid compliance in other aspects of EMC.

Introduction to Filters

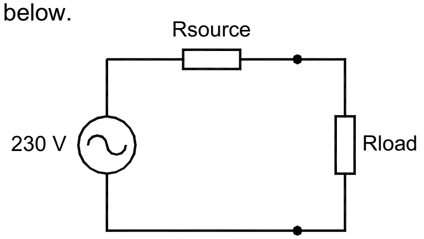
To the world at large, filters are generally considered to be black-box components, where their effect is generally taken for granted. It is understood that one of the first filter applications was in telecommunications, where the number of conversations that could be carried by a transmission cable could be increased, firstly by limiting the bandwidth of the frequencies that were actually used in any one conversation (that's why no-one sounds the same on a phone) and secondly by modulating and demodulating the frequency band used by each conversation using carrier waves at preset frequencies, thereby allowing several simultaneous conversations on the same transmission cable. See diagram below. Filters are now used everywhere from simple tone controls on stereo systems and guitars, to more complex active filters for modern telecommunication and broadcast applications.

Telecomms example



EMC Filters are low pass filters, designed to allow the mains frequency to pass through with very little attenuation, but at the same time attenuating the EM noises at higher frequencies that might cause problems with the connected equipment and the outside world. No economical EMC filter can totally eliminate EM noise, but the purpose of integrating filters into machinery or products is to attenuate EM noises by an acceptable amount, to help ensure compliance with the relevant standards on emissions and immunity, and also to help achieve freedom from interference in real-life operation. See the REO Guidebooks on EN 61000 for information on the various types of EM phenomena, and how they are tested for conformity with the EMC Directive, and on what additional tests may need to be done for real-life reliability

An EMC filter works mainly by reflecting unwanted frequencies back to their sources. This effect can be maximised if the dynamic impedances of the load and the source are different from those of the filter. This can simply demonstrated using Ohms Law. Please see the example below.



Voltage [V]	Rsource [Ω]	Rload [Ω]	Current [A]	Pload [W]
230	50	1	4.51	20.34
230	50	10	3.83	146.94
230	50	50	2.30	264.50
230	50	100	1.53	235.11
230	50	1000	0.22	47.98
230	50	10000	0.02	5.24

Least amount of power transferred to load

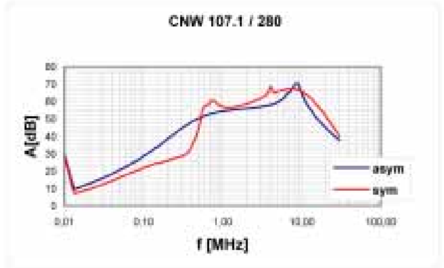
Maximum discontinuity

By creating an impedance discontinuity (often called a mismatch) in the frequency range over which we want to achieve useful amounts of attenuation (typically at least 150kHz to 30MHz), the noise that passes through the filter and reaches the product (or the mains network) is reduced. In the simplified example, the 'noise' would be absorbed, but in an AC circuit, involving reactive elements the EM noise is reflected by the impedance discontinuity in the filter back to its source. A small proportion is absorbed in losses within the filter, so the inductors and capacitors used to construct a filter may have to be made larger to handle this power dissipation. This in turn can decrease their self resonant frequencies, affecting the design of the filter. See the section on Component Self Resonance for more information.

REO provide benchmark test data based on a 50Ω source and 50Ω load impedance, known as a 50Ω/50Ω test. This provides a rudimentary method of accessing the relative merits of one filter range against another. It must be stressed that this is not a satisfactory method of selecting a filter with the intention of ensuring compliance. The explanation of impedance mismatch should provide a reason as to why this is. The impedance of the mains supply network is frequency- and time-dependant. The differential-mode impedance of the UK's 230/400V mains can vary from 2Ω to 2000Ω from 150kHz to 30MHz over a daily cycle. The impedance of the product's mains input could be anything and will almost certainly change with respect to time, due to the characteristics of its power supply circuits; capacitors charging and discharging and semi-conductor activity, for example. The performance of single stage filters, employing just one stage of inductance, in particular is greatly influenced by their source and load impedance. This is why 0.1Ω/100Ω and 100Ω/0.1Ω tests are often carried out to enable more realistic results to be obtained.

REO recommend testing filters when installed in the product as the best option when trying to ensure compliance with the standards. But even this is not without an element of doubt. To try and provide some element of repeatability, it is recommended that conducted emissions tests are carried out using a Line Impedance Stabilisation Network (LISN) between the mains and the product under test. This serves to isolate the equipment from a proportion of unwanted noise already appearing on the mains, but also sets the mains impedance at 50Ω. This means that even a pass, registered by a test-house is not a guarantee that the product will not cause (or suffer) problems in the field due to conducted emissions (or immunity).

Typical Results for REO Filter Type CNW107.1 for 280A per phase



Blue graph 50Ω/50Ω asym. Red graph 50Ω/50Ω sym.

Example of a REO CNW107.1 Filter

Noise Occurrence

EM disturbances in the mains network are typically grouped into two main types, according to their mode of propagation; that is to say the way they actually spread throughout the network.

Common Mode (Asymmetrical Interference)

CM noise appears on all of the conductors simultaneously, with respect to a chosen earth reference point. The voltages and currents associated with this type of noise are all in phase on the conductors concerned, and the current returns via some other path, most often the metalwork and other earthed structures on the site where the equipment is installed.

From the point of view of the mains network, in the case of a single phase mains supply, CM noise voltages appear in-phase on all three conductors in an equipments mains cable (live, neutral and earth) with respect to the networks earth reference point. In a three phase mains network, the noise will appear on all five conductors in the mains cord, (the three phase conductors, the neutral and the protective earth) with respect to the networks earth reference point.

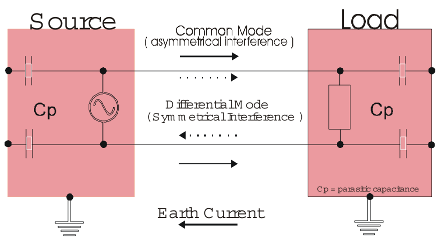
In an item of equipment with an earthed cabinet, chassis or frame, CM noise will appear on all of the phase conductors with respect to the cabinet, chassis or frame.

CM noise is usually the dominant type of noise in the mains network at frequencies above 1MHz (very approximately), and generally has a high source impedance. It is mostly caused by stray capacitances, common impedances (usually due to imperfect earthing systems) and coupling into cables from radiated fields.

Differential Mode (Symmetrical Interference)

DM noise appears between any pair of conductors, its current flows in one direction along one conductor and returns via the other. The voltages and currents associated with this type of noise are all in antiphase on the two conductors concerned. In the case of a single phase mains supply, from the point of view of the mains network or of an item of equipment; DM noise voltages appear out of phase between on all three pairs of conductors in an equipments mains cable (live-neutral, neutral-earth, live-earth).

DM noise is usually the dominant type of noise in the mains network at frequencies below 1MHz (very approximately), and generally has a low source impedance. It is mostly caused by components that abruptly change the power current, for example rectifiers and other types of power switching devices.

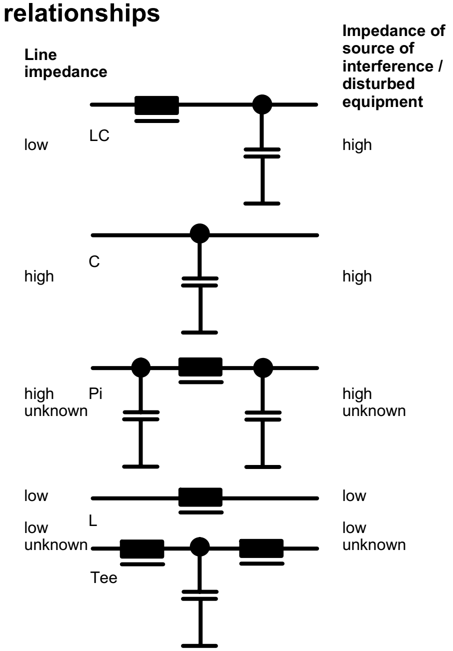


EMC Filter Design

It is clear that any filter must allow the fundamental power frequency to pass without significant impedance, whilst attenuating the unwanted CM and DM noises. Filter circuit design is of the utmost importance and it is helpful to know the principles behind it.

As previously explained a filter will provide higher attenuation the more its mains input impedance is mismatched to the source impedances of the CM and DM noises, helping to protect the equipment from those noises present on the mains network. At the same time the filter should present impedance mismatches to the CM and DM noises emitted by the equipment, to help prevent them from getting into the mains network and causing conducted or radiated interference with other equipment.

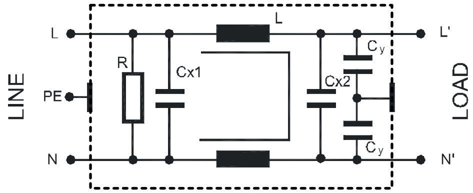
Typical Filter circuits and impedance relationships



The above theory is very generalised and reinforces the argument that filter selection and implementation is a complex issue. REO can offer extensive technical expertise and consultancy in this field, and offer pre-compliance testing to aid selection if required.

A typical EMC filter is designed to economically attenuate both DM and CM noises, and a typical circuit for a single stage, single phase unit is shown below.

REO Filter Type CNW101 20 Amp Single Phase



The basic layout of the REO filter shown on the previous page is along the lines of the 'Pi' filter and so it creates relatively low values of impedance to the mains network and to the connected equipment.

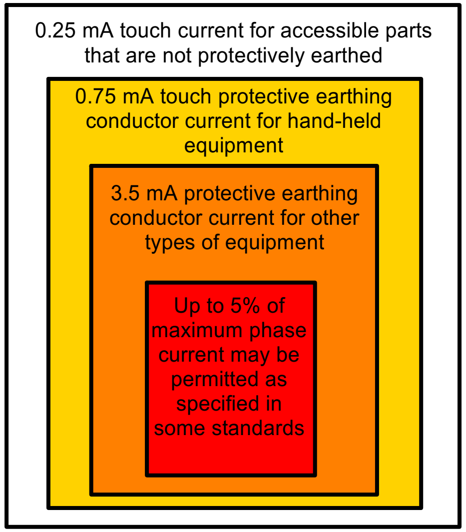
Cx1, is the capacitor which essentially defines the DM impedance for the filter at its mains input. Its value should be sufficiently high to provide significant attenuation in the lower frequency range, where DM noise is the most troublesome. However, the larger the value of capacitance the lower will be the capacitors self resonant frequency (SRF). See section on Component Self Resonance for an explanation of this phenomena. An SRF that is too low can limit the filters effectiveness, and so special extended foil capacitors are used. This construction technique reduces the equivalent series resistance (ESR) and equivalent series inductance (ESL) and helps achieve as high a value of SRF as possible for a given value of capacitance. It is vitally important that a filter capacitors' leads are kept as short as possible to minimise their additional series resistance and series inductance, to help ensure that its SRF is not compromised and the filter in which it is used, will function as required.

Cy are capacitors tied directly between the phase conductors and the earth: these serve to attenuate CM noise. The maximum values of these capacitors are limited due to earth leakage current specifications, for safety reasons. Typical maximum values for earth leakage current are shown in the table.

$$X_C = \frac{1}{2\pi fC}$$

Capacitive impedance decreases as frequency increases

Leakage current table



This diagram is for indication only. Ensure that the standards for the particular application are referred to.

This figure was adapted from Volume 4, of "Safety of Electrical Equipment", York EMC Services 2003, ISBN 1-902009-08-08.

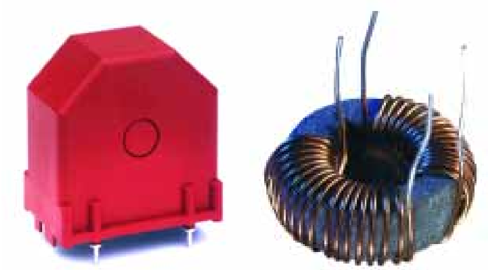
As the value of the Cy capacitors increases, their earth leakage currents at the mains frequency (and noise frequencies) increases. Apart from the safety issues mentioned above, this may cause problems with tripping of residual current detection (RCD) equipment. This is especially a problem when using high current filters in certain industrial applications, which can use filters with high capacitive values. In these types of applications it may be permissible for leakage currents of 5% of the nominal phase current. Such high earth leakage currents could cause dangerous electric shocks if they flowed through a person, so such filters must clearly be physically bonded to earth in such a manner as to make accidental disconnection of their safety earth connection very unlikely indeed.

In more critical applications, it must be ensured that the leakage current calculations take all variables into account; such as the capacitive tolerances, the maximum mains voltage and the highest mains frequency. It is recommended that the leakage current of a system does not exceed 50% of the rated trip value of a connected RCD. The systems leakage as a whole must be taken into account when determining this value, not just the stand alone filter, as there are sure to be other line to ground currents inherent in the system. In practice the most appropriate safety standards must be applied to the application, and their earth leakage requirements adhered to above all other factors, such as EMC filtering issues.

In an inductor (or choke) saturation occurs when the flux density in its core reaches a specified level, at which point the choke will cease to function correctly. However, the current compensated or common mode choke is able to carry large AC currents without saturating, due to the way it is wound. The conductors are wrapped about the core in such a way that the DM currents (including the current at the power frequency) create equal and opposing fluxes, which effectively cancel one another out. The result is a very low impedance to the flow of DM noise currents and the power frequency current. However, when common mode noise currents try to flow, the flux created by both conductors adds up in the core, with no cancellation, so the result is a very high impedance to the flow of CM noise currents.

The benefit of using CM chokes is that saturation due to power frequency current is not easy to induce, so the core can be comparatively small and low cost. They are especially good for applications involving high frequency noise and/or high current AC supplies. Toroidal cores are usually used in the construction of CM chokes because they can have a high flux density before saturation, have a low radiated field and are small and relatively economical to produce.

Typical REO common-mode chokes

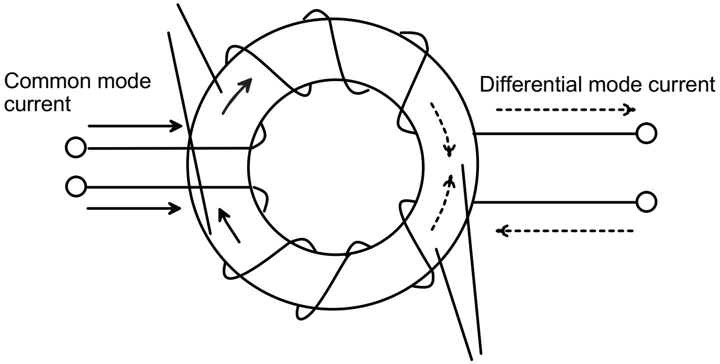


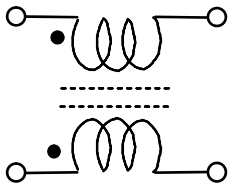
An ideal common mode choke would not offer any impedance to DM noise currents, but no real component is ever ideal so we must now consider the equivalent circuit of a typical *real* filter choke, see figure below

(a) Structure

(b) Circuit

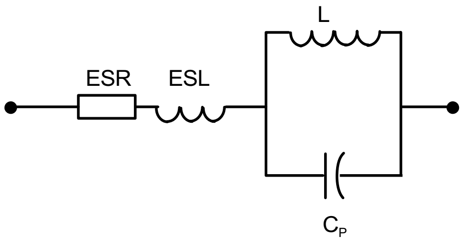
Magnetic flux caused by common mode current is accumulated producing impedance



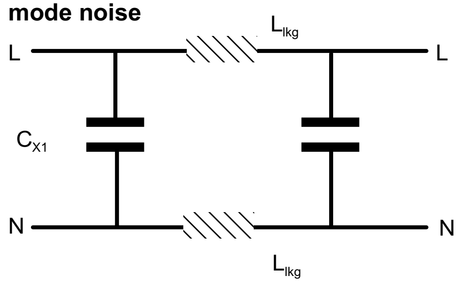


Magnetic flux caused by differential mode current cancels each other, and impedance is not produced

Equivalent circuit of common mode



Equivalent filter circuit for differential mode noise

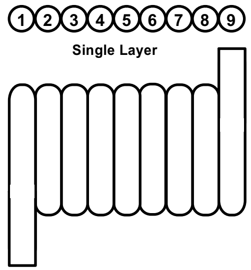


The equivalent circuit of a common mode choke shows the main inductance in parallel with a small parasitic capacitance, and both of them are in series with a small leakage inductance plus a small resistance. The leakage inductance appears in differential mode and so helps to impede DM noise. This is shown in the equivalent filter circuit. It is very convenient to use the 'free' leakage inductance to help reduce DM noise but one of the disadvantages of using toroidal cores is that this leakage tends to be small. However, manufacturing steps such as increasing the spacing between windings (so the lines of flux are not cut by the opposing winding) can increase the leakage inductance. Care must be taken not to increase the leakage inductance by too much, as this can also reduce the power frequency current at which saturation of the core occurs, making larger and more costly components necessary to achieve the desired filter performance.

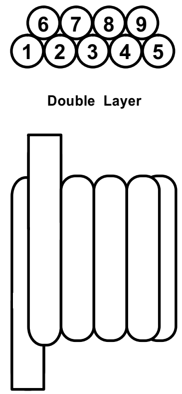
The parasitic capacitance shown in parallel with the choke winding is largely due to stray capacitance between windings. This depends upon the manufacturing processes and in particular the winding method employed. Typical winding methods are shown in the diagram opposite.

Capacitance can only exist between conductors of different potential, so using a progessive technique reduces the p.d. between adjacent conductors and hence minimises interwinding capacitance, but also allows a higher value of inductance (more turns) for a given core size.

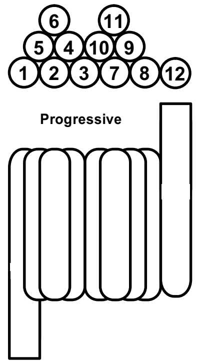
Choke winding methods



This provides relatively low levels of capacitance as adjacent windings are at similar potential and the start and finish are divided



This has capacitance between windings and layers and as such will affect the high frequency performance of the choke



The is a compromise used when many windings are required on a core. The capacitance that exists between adjacent windings is reduced improving choke performance

Case study - Filter Selection

The inductances and capacitances associated with a real choke cause it to behave like a tuned circuit at some self resonant frequency (SRF). See the section on Component Self Resonance for more information. Generally speaking; the more windings a given choke has, the higher is its inductance, series resistance, parasitic capacitance and leakage inductance. The lower the SRF, the more likely it is to have a detrimental effect on the performance of the filter in which the choke is employed.

REO utilise a number of methods to keep choke SRF high, but typically a progressive winding technique is employed. This keeps the capacitance between adjacent windings to a minimum. Manufacturing steps such as insulating the core, and fitting insulating dividers between windings also help reduce the amount of parasitic capacitance and keep SRF as high as is practical.

Too many windings, poor winding methods and the use of small cores, increase the leakage inductance of the choke. That is the inductance caused by uncoupled windings and uncancelled flux in the core. This series inductance does add to the filters DM noise performance but also increases the likelihood of choke saturation that would limit the maximum current it could handle at the power frequency.

You can easily measure a chokes leakage inductance by applying a short circuit across one side of its windings and measuring the inductance at the other side. In an ideal CM choke the measured inductance will be zero but this never happens in real life.

As previously mentioned there are many reasons why 50Ω/50Ω test data should not be used as the only selection criterion for a mains filter and that perceived performance benefits do not always manifest themselves in real-world applications.

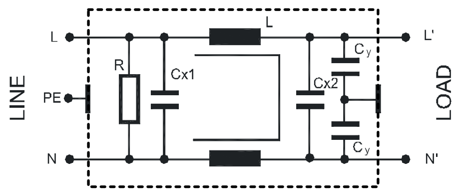
The diagram shown opposite shows a typical choice facing a customer when specifying an EMC Filter. Filter 1, is a single stage unit type CNW101 as manufactured by REO, whilst Filter 2, is a 2-stage, single phase unit from another reputable manufacturer.

If we were to use the 50Ω/50Ω test data as the main selection criteria, then Filter 2 would appear to be the better option. However, what the manufacturers test data does not show is that chokes employed in Filter 2 use a small core packed with windings to achieve the required inductance value, ensuring a low SRF and a high leakage inductance. When tested with a typical load (a thyristor control unit in this example) Filter 2 exhibits very poor low frequency performance as a result of choke saturation, caused by uncoupled windings. This is demonstrated by the test plot for Filter 2 and explained in more detail overleaf.

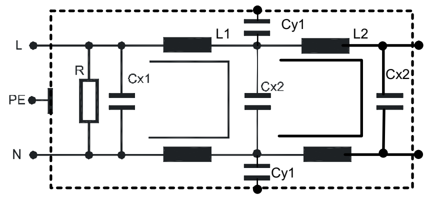
The test data for REO Filter 1 demonstrates a conducted emissions pass using the same test load. This reiterates the fact the 50Ω/50Ω is not an effective measure of filter performance and that two stages are not always better than one.

Diagram showing 1-stage vs 2 stage

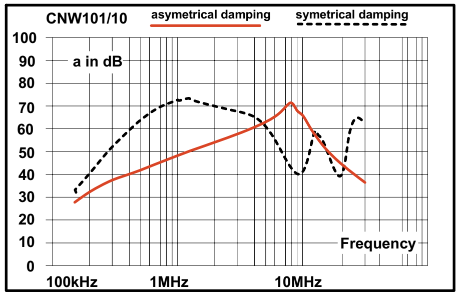
REO Filter Circuit 1



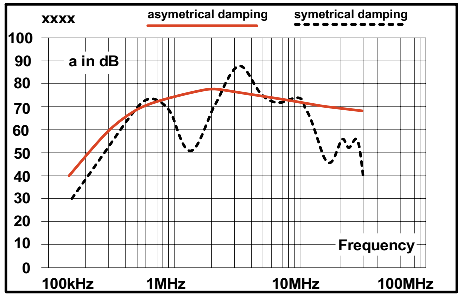
Competitor Filter Circuit 2



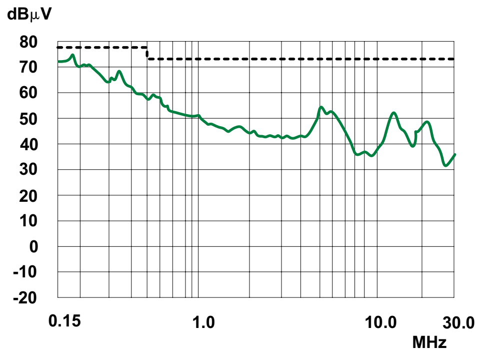
No load attenuation (Higher the better)



No load attenuation (Higher the better)

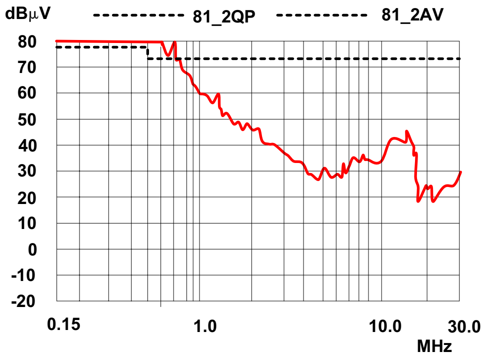


EMC Measurement (Lower the better)



REO Filter Test PASS

EMC Measurement (Lower the better)



Competitor Filter Test FAIL

Component Self Resonance

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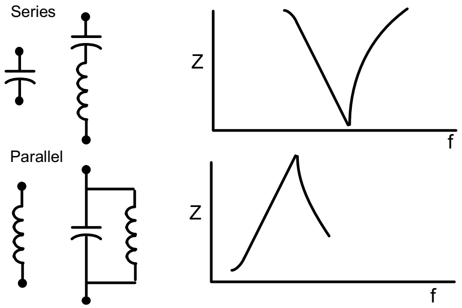
The issue of Self Resonance has been mentioned before and this phenomenon is further explained in this section.

In a circuit containing capacitance and inductance there is a resonant frequency, at which the electrical energy in the circuit is transferred between the capacitor and inductor in an oscillatory manner. The energy stored in a capacitor is in the form of an electric field, created by a voltage across its terminals, whilst the energy stored in an inductor is in the form of a magnetic field, created by a current flowing through it. Every electrical circuit contains reactive elements, whether intentional or stray (parasitic) and so has the capacity to self-resonate. The frequency at which this occurs, the self-resonant frequency (SRF), depends on the values of the capacitances and inductances in the circuit, and not upon the applied voltage or current.

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}}$$

In theory this transfer of energy between the reactive elements can continue indefinitely, however, due to the imperfect nature of electronic components, internal resistance (ignored in the above equation) dissipates the energy (as heat), so the resonance gradually decays until its amplitude is negligible.

It should be noted, that in theory at least, a parallel resonant circuit has very high impedance at its SRF, whilst a series resonant circuit has a very low one.



The resonant impedances can be used intentionally to construct a tuned frequency amplifier, for instance, but when they are not part of the intended operation of a circuit they can cause problems. For instance, in an application involving an electronic motor starter and power factor correction capacitors, unintentional self-resonances can cause the current consumption to be higher than expected, blowing fuses and possibly damaging the semi-conductors used within the motor starter.

Previous sections discussing capacitors and chokes also showed how self-resonances within the components, due to parasitics such as series inductance or interwinding capacitance, can alter the behaviour of the components from what was required.

The effects of self resonance can cause problems with filter performance, particularly at higher frequencies. These are usually shown as performance dips in a filters test results, and the lower the frequency at which they occur the more chance there is of them affecting the EMC performance of connected equipment. Inductors are usually wound so their first resonance occurs at least at 150kHz. At frequencies below its SRF, a chokes EMC performance is not maximised and its filters performance at lower frequencies is diminished.

Core choice

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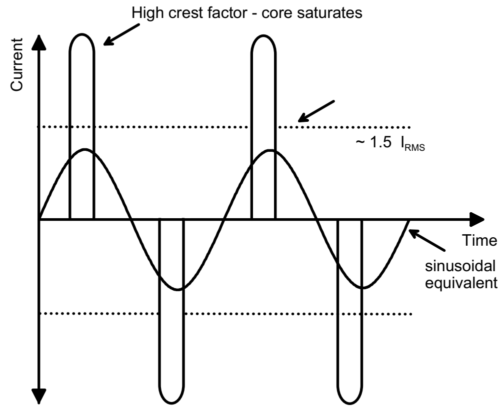
As you may expect, the actual cores used in the inductors play a large part in the performance of the EMC filter. Different core types are essential for common and differential mode chokes. Common mode chokes tend to use high permeability cores (usually ferrites) allowing them to be much smaller than similarly rated differential chokes. Differential mode chokes use cores that are larger and made from a material which is less likely to saturate, but which as a result has much lower permeability so the values of inductance are lower, for a given size of core.

Manganese Zinc ferrite material is usually used to construct common mode chokes for EMC applications, because these provide high permeability at lower frequencies and exhibit useful, lossy characteristics at higher frequencies ensuring that their performance is useful to at least 50MHz. Iron-powder cores, manufactured from fine iron particles insulated from one another by a non-magnetic binder are usually used for differential mode chokes. The continuous or distributed air-gap which exists between each and every magnetic particle ensures that they have a low permeability and high flux density before saturation.

It is important to be aware that all magnetic materials cease to be effective at a certain temperature, this is known as the Curie temperature (Tc) and is usually in the range 100-300 °C for ferrite materials. So it is important to ensure that the ambient temperature plus the operational temperature rises within the core do not approach Tc. Also, ferrites are susceptible to the mechanical stresses caused by winding or mounting methods, and their permeability can alter under some circumstances, for example if the expansion coefficient of an encapsulating material is greatly different to that of the core.



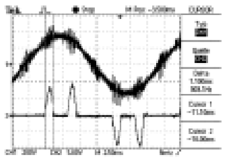
The crest factor, or peak factor of a waveform is simply its peak value divided by its rms value. The ideal AC mains voltage (and subsequent current) is a sine wave, which has a crest or peak factor of 1.41. The non-sinusoidal current draw of the capacitors that follow a mains rectifier increases the crest factor of the current and so increases the saturation of the cores in the filter inductors that carry this current. Selecting a core with a higher permeability will usually solve this problem, either by allowing a higher initial inductance, ensuring that the value at saturation is high enough to maintain filter performance or (for a common mode choke) by allowing a reduction in the number of windings employed hence decreasing the filters leakage inductance. REO can provide assistance if a particular application is likely to require a special choke construction. The differential mode performance of a filter can be further increased by incorporating differential mode chokes into its design. These are straightforward inductors, which must be rated at the peak of the mains current, taking into account the crest factor of the current and possible transients and surges.

Multi-Stage Filters

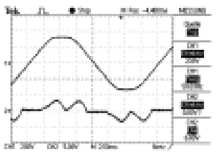
Larger capacity chokes placed on the mains side of the filter can attenuate harmonic peaks and are a useful aid to compliance with mains harmonics standards. See REO guidebook on Mains Harmonics and Interharmonics for further details. Differential-mode chokes usually have a single winding, and must be able to support significant mains flux density without saturating whilst impeding the flow of high frequency noise current.

REO manufacture a range of three phase EMC Filters with integrated differential mode choke for use with Variable Speed Drives. This is useful for ensuring EMC compliance and reducing harmonics.

REO Combi Filter, Type CNW307



Voltage/current trace at input of frequency drive without CNW307

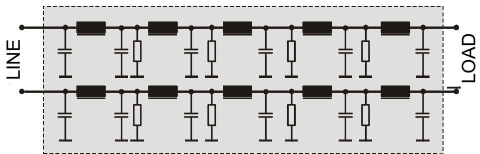


Voltage/current trace at input of frequency drive *with* CNW307

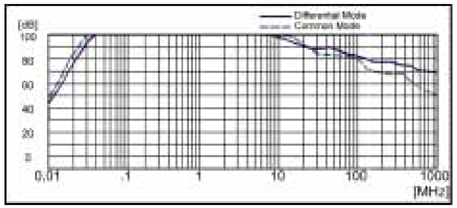
A multi-stage filter uses more than one inductive element in the design, to achieve a higher level of filtering performance. Two-stage filters are the most common multi-stage types, but designs incorporating up to five (or more) stages are not unknown. In fact the REO range CNW140 uses 5 stages to achieve very high levels of attenuation in the bandwidth 10kHz to 1GHz. It is available in 1, 2, 3 and 4 line versions.

REO CNW140 Range

Typical Circuit



Typical Performance



In general a multi-stage unit will provide real-life attenuation that is closer to its published performance, because the internal mismatch between filter stages can be incorporated into the design and so the unit is less susceptible to the issue of source or load impedance.

A correctly designed multi-stage filter will generally provide better levels of attenuation than a single stage unit. However issues like SRF, leakage inductance and physical layout, plus other variables like installation methods can compromise the performance. See the case study on page 12 for an example of a high quality single stage filter, providing better EMC performance than a 2-stage unit.

Of course, adding more stages to a filter design adds to its cost and size. REO recommend testing, not only to ensure compliance, but also to help minimise unnecessary costs by making the filter no more complex than is necessary.

Issues affecting filter performance

As stated previously, the test data that REO publish for comparison purposes is generated in an EMC test laboratory. These tests are carried out in a screened room and the filter is bonded securely to a large metal ground plane. The mains impedance is defined using an artificial mains network, called a LISN, which sets the impedance of the source. The design of this LISN or Line Impedance Stabilisation Network is defined in CISPR 16 and is the benchmark that has been adopted by filter manufacturers. The connection cables are segregated and are as short as possible. Unfortunately, these lab conditions do not have a lot in common with the real world conditions under which the filter may be used.

Physical location and routing of connection cables is of the utmost importance and care must be taken to avoid undesirable cross coupling between cables and internal components. Generally there are three types of noise coupling that occur in an AC electrical system.

Conductive Coupling

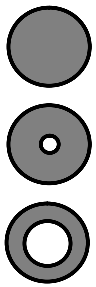
Earth systems in machines and in fact layout in general are usually not done with EMC in mind. This often means that the internal segregation between noise sources such as Switch Mode Power Supplies and sensitive equipment is not as good as it might be. This situation is made worse still by the use of poor earthing practices (from an EMC point of view).

The Earth (or Ground) connection, serves two purposes, firstly it is the primary safety measure, but also it serves to conduct unwanted interference into and out of the system. It might be acceptable to connect an earth cable or braid to something for safety purposes, but from an EMC point of view this is unlikely to be effective, especially in the frequency range that we are concerned with these days, which might extend to 100`s of MHz, or even GHz.

For EMC reasons, direct metal-to-metal connection at multiple points, between the metal body of the filter and the earthed metal backplate, wall or floor of the equipments metal enclosure, or the metal bulk of the system or installation is best. A green/yellow insulated earth wire might need to be added as well, between the filters earth terminal and the protective earth system, for safety reasons.

If direct connection is impractical, a conductor should be used to connect the filters earth terminal to the equipments earth reference point. This conductor should be as short as possible, but even so the filters performance at frequencies above a few MHz will be significantly reduced, compared with direct metal-to-metal mounting. If using a conductor to earth the filter, it is best to use a braid instead of a plain conductor. Braid has a lower impedance at high frequencies, because of something called skin effect.

Skin Effect



Conductor Cross Section at DC and low frequency. Minimum resistance.

Conductor Cross Section at increased frequency. Increasing resistance.

Conductor Cross Section at increased frequency. Further increased resistance.

Skin effect is where high frequency signals avoid using the centre of a solid conductor, as shown by the figure below left. Interestingly, this is used to advantage in domestic radio and TV aerials which are usually made hollow to save weight. At the high radio frequencies involved the centre of a solid aerial would be ineffective, and would just add cost and dead weight.

Braided conductors provide a larger surface area for the skin currents, hence a lower series resistance at high frequencies, than the same cross-sectional area of copper in plain conductor. Because they are wider they also have a lower series inductance than plain conductors.

An earthing/grounding system that has significant impedance will suffer from different potential differences at different locations, as currents flow through it. The resulting voltages can cause interference, so steps should be taken to reduce the impedance of the earth/ground system at the frequencies of concern. The skin effect and inductance of individual earth/ground conductors that are longer than a metre or so, even braids, makes them little use at frequencies above a few tens of kHz. So good earthing/grounding practices from an EMC point of view concentrate on providing a mesh of conductors, since a conducting area or volume can be made to have a low impedance at very high frequencies. Refer to IEC 61000-5-2 for further guidelines or to “EMC for Systems and Installation" ISBN 0-7506-4167-3.

A capacitor relies on low impedance connections to be effective, and a capacitor in an EMC Filter similarly relies on a low impedance earth connection. This is why high value capacitors used in high frequency applications have their leads cut to an absolute minimum length, to reduce series inductance. REO filters are usually provided with Earth terminals for Safety Earth as well as sturdy mounting points to enable them to be directly bonded metal-to-metal to the backplate, wall or floor of metal enclosure, or the metal bulk of the system or installation, minimising the high frequency impedance between the filters body and the earth, and maximising the performance of the filter.

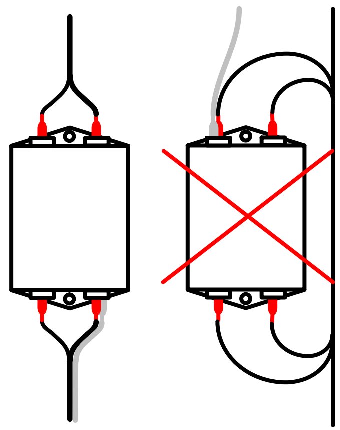
The earth/ground connections for sensitive equipment may need to be segregated from those of less sensitive equipment, and in turn separated from the earth connections of items which may actually cause interference.

Inductive and Capacitive Coupling

Stray or parasitic inductive and capacitive coupling occurs between one area of a circuit and another, even though there is no direct electrical connection. Inductive coupling is where a magnetic field caused by current flow in one area of a circuit causes a voltage to be induced in another area of circuit this is essentially an accidental transformer. Capacitive coupling is where an a.c. potential difference between two areas of a circuit causes a current to flow in the inevitable stray capacitances between them. The magnitude of the coupled voltages and currents increases as the frequency increases. Coupling can be reduced by increasing the distance between the two areas of circuit, increasing or improving the shielding between them and/or reducing the magnitude and/or the frequency of the signals in the circuits that are being coupled into the other areas.

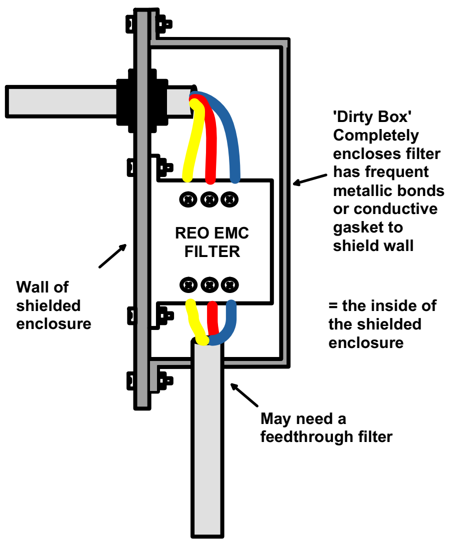
Stray coupling can ruin the performance of a filter, especially at higher frequencies. To minimise the effects of coupling care must be taken when designing and installing a filter. For example, the input and output cables must be segregated to minimise coupling between them (which would bypass the filter) both inside the filter and outside it. The filter should also be installed as near to the point of the mains entry into the equipment's enclosure as possible. If this is not possible then the unfiltered mains input cable should be routed in such a way to limit coupling to the output cable. Running the cable in earthed metal conduit or keeping it as far from the internal circuitry and wiring as possible will help reduce coupling and so help to maintain the performance of the filter.

Filter Cable Segregation



In a shielded equipment enclosure the method of connection of the mains filter should not compromise the shielding performance of the housing. Through-bulkhead mounting filters are the best, because their method of mounting places their mains input cables outside the shielded enclosure, and their filtered mains cables on the inside, so they are shielded from each other by the wall of the enclosure.

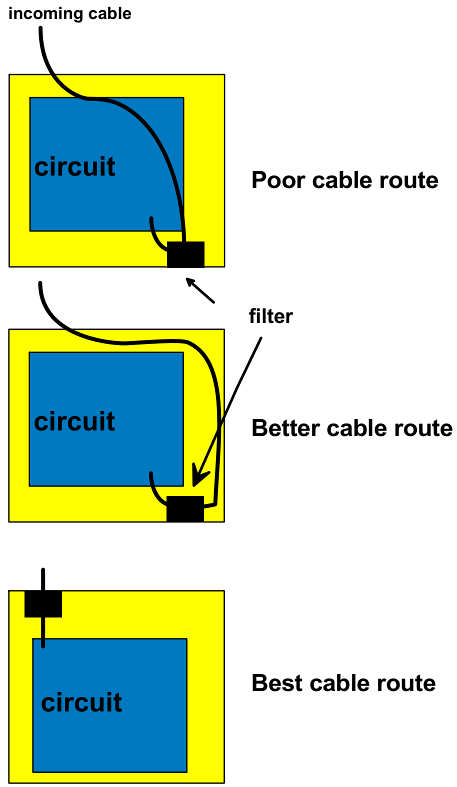
The mounting of the filter must not create any gaps in the shielding of the enclosure; otherwise it will compromise its shielding performance. So, conductive gaskets may be needed when installing the filter in the wall, floor or top of an enclosure.



These figures were adapted from Volume 4, of "Safety of Electrical Equipment", York EMC Services 2003, ISBN 1-902009-08-08.

Where lower-cost chassis-mounted filters are to be used instead, it may be necessary (to preserve the shielding performance of the housing) to totally enclose the EMC filter and its terminations within an additional shielded housing, within the primary shielded housing. This box should be securely fixed to the shielded wall of the enclosure using electrical bonding at multiple points and/or a conductive EMC gasket for better shielding performance.

Cable routes to filters



Common impedance coupling

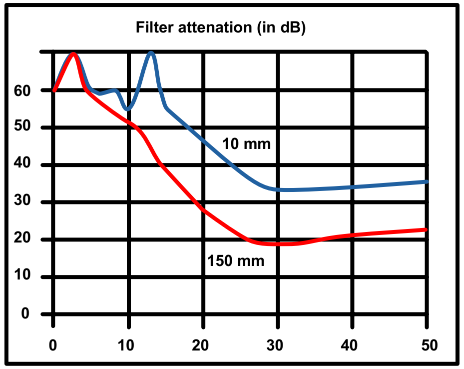
This is where noise is generated in a system and conducted between noise source and noise victim through their common connections, typically the earth connection. The primary function of a safety earth connection in a mains application is to provide equipotential bonding to ground. This provides a basic level of protection in the event of a fault condition. However, an efficient bonding scheme does not necessarily constitute an effective earthing system from an EMC point of view.

For example; in a control cabinet, all the individual earth connections from a number of DIN rail mounted components, like Power Supplies and PLCs will often be run through the trunking to a central Earth stud within the housing. Each of these connections will have different impedances and so any noise currents flowing through them will appear as a noise voltage between different nodes in the earth network. If these coincide with areas of the circuit where the ground is used a reference point for a common mode signal, for example in a inverting op-amp circuit, where the inverting input is tied to earth, then it is likely that this noise will cause spurious operation. This can be overcome by segregating the earth connections of noise sources from those of potential noise victims.

Keeping the impedance of earth connections as low as possible was discussed earlier. Where conductors are used (whether braid or plain) it is also important not to route them near areas where they may suffer inductive or capacitive coupling from noisy currents or voltages. As previously mentioned, direct mounting of components to an earthed backplate, enclosure wall, floor or bulkhead, or to the metal bulk of system or installation will usually provide the best results.

Filter earth bonding

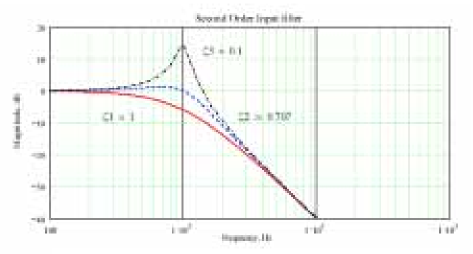
The table below shows a comparison of two lengths of filter earth-bonding wire for a single-stage mains filter with matched 50Ω source and load impedances (the best possible case for filter performance).



Direct metal-to-metal bonding at multiple points to the reference potential plane is very stongly recommended.

This figure was adapted from Figure 8.7, Chapter 8, of "EMC for Systems and Installations", Newnes, 2000, ISBN 0-7506-4167-3

Connecting several filters in series



Filters are usually designed to work independently and great care should be taken where several filters are to be used in cascade. Whilst it is unusual and uneconomic to use several EMC filters connected directly in series it is easy to envisage a situation where a large input filter is connected at the mains input of an item of equipment, and this is in turn connected to a footprint EMC filter for a variable-frequency drive, and this may also be connected to the drives own integral EMC filter.

Ordinarily a filters equivalent values for L and C are chosen so that the cut-off frequency, or frequency at which attenuation is desirable, occurs at a frequency which is high enough above the fundamental mains frequency not to dissipate too much power at the fundamental frequency, but not so high that the filter will be ineffective at 150 kHz or less.

The combination of L, Frequency and Load Resistance gives a damping factor for the filter, which is usually optimised to give a value of 0.707 leading to the performance characteristics shown by the blue line in the diagram above

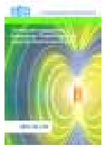
For EMC Filters the damping factor is signified by the Greek letter zeta.

$$\zeta = \frac{L}{2R\sqrt{LC}}$$

A filter with a low damping factor of much less than one (such as the blue line in the diagram) may cause ringing in the filter and may result in worse EMC performance than if the filter was not in circuit, whilst a high damping factor (shown by the red line in the diagram) reduces the cut-off frequency and will increase the losses in the filter.

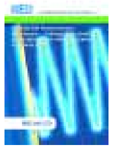
Series connection of filters that were never designed to be used together can cause overdamping or underdamping to occur, making it possible to achieve a worse overall EMC performance than if no filter were used at all. So the cascading of filters should in general be avoided.

REO have published a series of mini guides relating to EN standards that are called up by Directives or are required for immunity testing. These can be downloaded from the REO website at www.reo.co.uk or hard copies can be sent on request by phone or email.



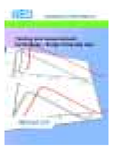
Magnetic Field

Harmonics

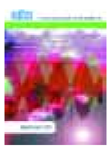


Sags & Dips

Flicker



Surges



Conducted RFI

Examples of the REO range

CNW102

Single phase,
250 V,
high performance unit suitable for most applications

CNW104

3 phase,
3 x 440 V,
3 line mains filter with very high attenuation

CNW114

3 phase,
3 line mains filter with increased attenuation

CNW203

3 phase,
3 x 480 V
bookcase style filters, with very high attenuation

CNW204

3 phase,
3 x 440 V,
2 stage bookcase style filter.

CNW811

3 phase,
3 x 440 V,
dV/dt filter

CNW854

3 phase,
motor choke
upto 1200 A

CNW933

400V,
3 line sinusoidal filter for use with VSD.

View further products on-line @ www.reo.co.uk