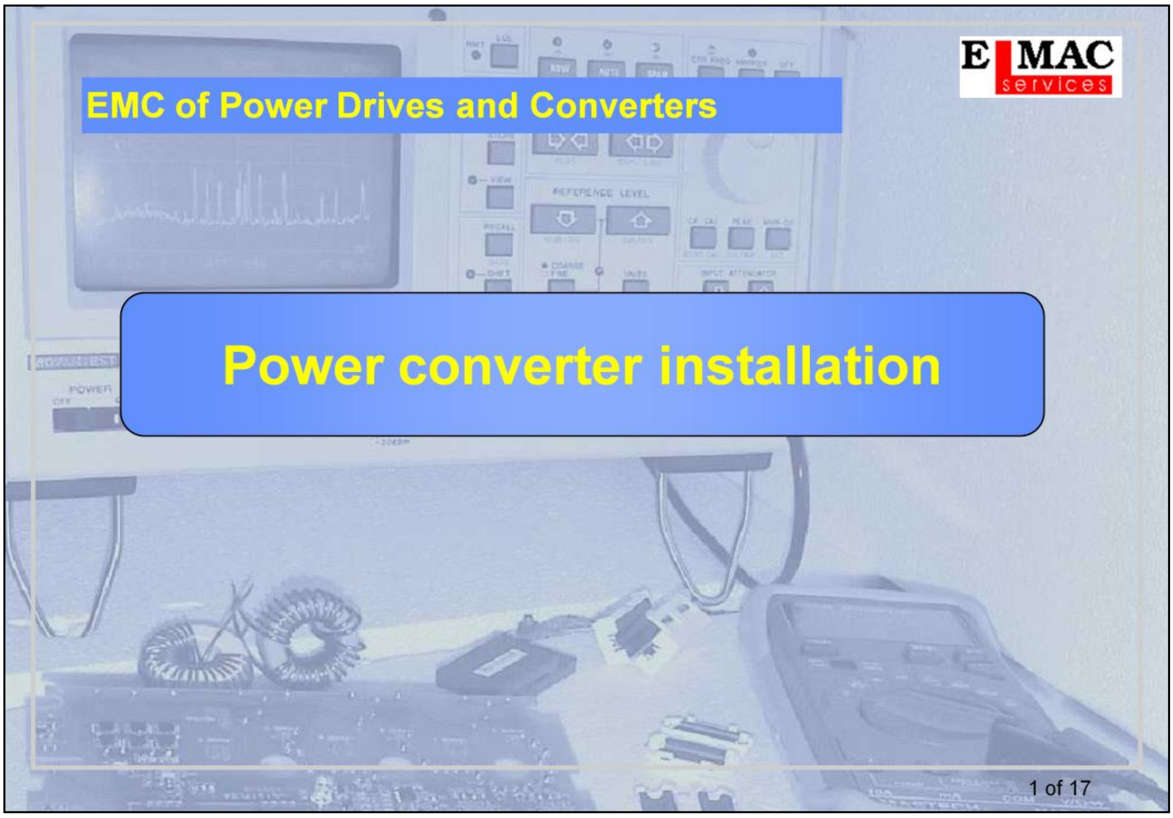
EMC of Power Drives and Converters
EMAC services
Power converter installation
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Outline

- **the emissions threat**
- **coupling paths**
  - differential mode conducted
  - common mode conducted
- **filtering techniques**
- **cabling techniques**

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Recommended reading and acknowledgements:

Control Techniques, *An Installer's Guide to EMC practices and regulations for variable speed drives*, www.controltechniques.com

Schaffner, *Sine wave filter solutions for motor drive applications*

Schaffner, *EMC Installation Guidelines for Motor Drives,* www.schaffner.com

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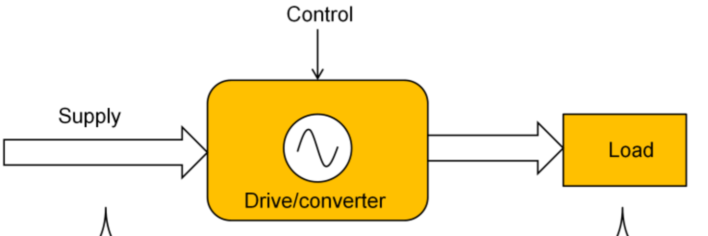
The overall system



Application			
Industrial VS drive	3-ph Mains		3-ph motor
White goods VS drive	1-ph Mains		1- or 3-ph motor
Electric vehicle	DC battery		3-ph motor
Rail locomotive	HV AC/DC		3-ph motor
Wind generator	AC Generator		HV AC grid
Solar energy	Solar panel DC		LV AC mains
Lighting	1-ph Mains		LED/CFL lamps

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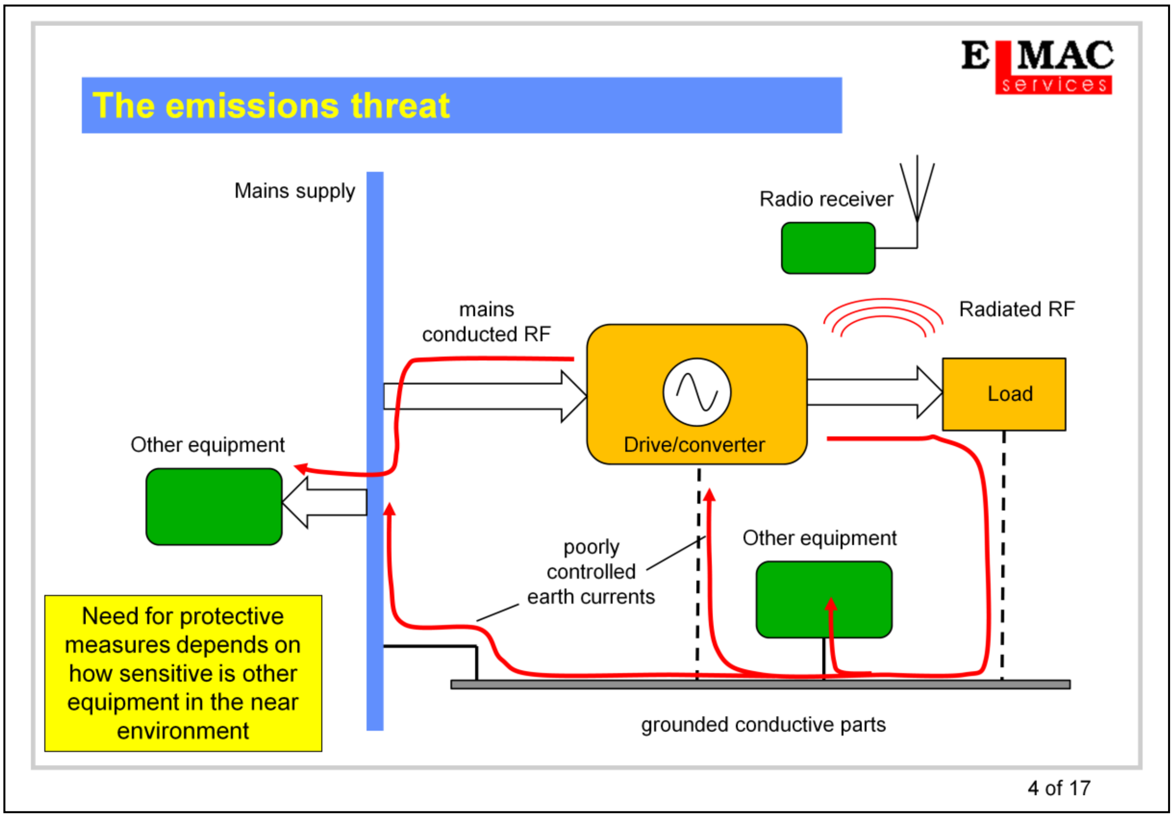
Power switching converters are widely used in many applications. Historically, switched mode power supplies have been used and their EMC implications understood for many decades. More recently other applications of high frequency power switching have become commonplace, as suggested above, facilitated by the development of high speed high power switching semiconductors. The EMC emissions issues discussed here are significant especially when the load is distant from the converter and connected through a cable which carries power **at the switching frequency**.

HF emission occurs as a result of the switching of the power output stage over a wide range of frequencies which are harmonics of the basic switching frequency – that is, six times the supply frequency for a 6-pulse DC drive, and the PWM carrier frequency for a PWM inverter or drive. This covers a range extending from 300Hz, for DC drives, up to many MHz for AC drives. Unwanted electromagnetic coupling reduces below about 100kHz, and so it tends to be the higher order harmonics which are most troublesome.

The power stage of a variable speed drive or converter is the most significant source of electromagnetic emission because of the high voltage and current which is subject to rapid switching. Thyristors are relatively slow-switching devices, which limits the extent of the emission spectrum to about 1MHz, whereas with IGBTs it may extend to about 50MHz, and MOSFETs can produce harmonic content well above this. Without good practice in installation, then interference is likely to occur in the 100kHz-10MHz range where emission is strongest.

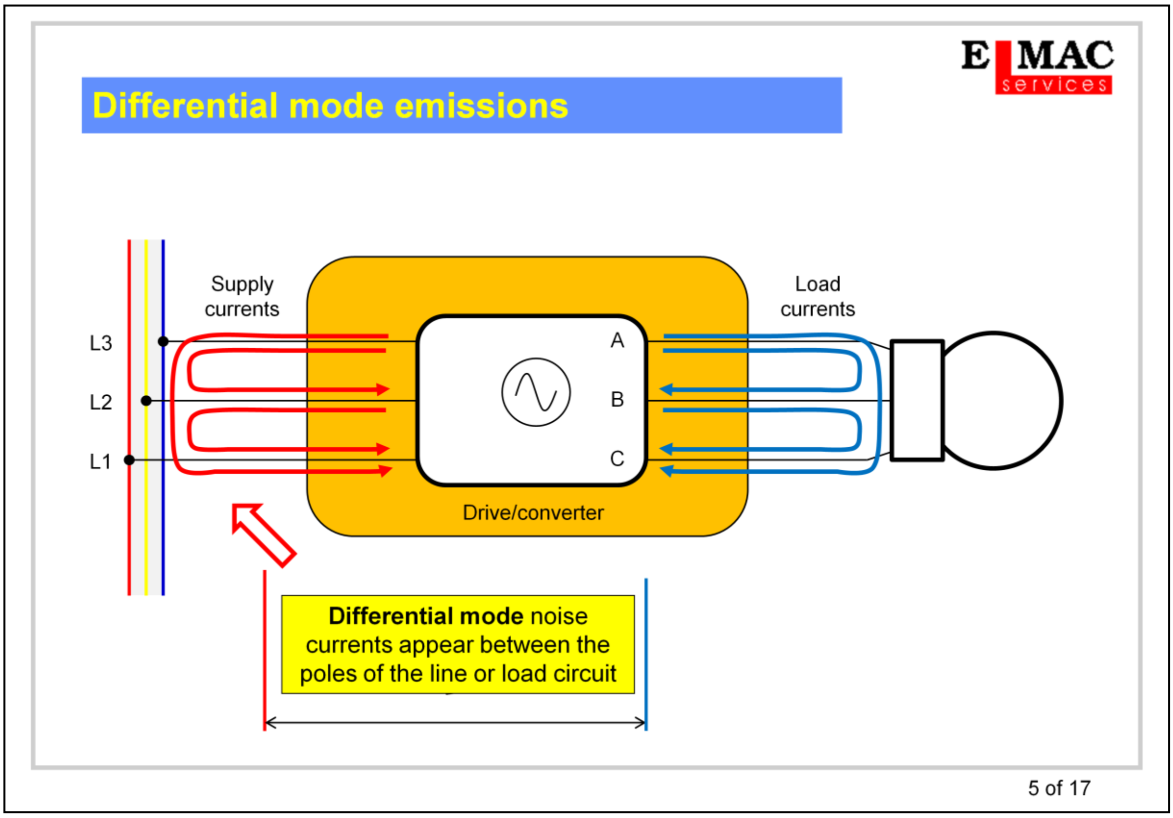


The drive or converter itself is not an important source of direct emission, because its dimensions are much less than a half wavelength over the relevant frequency range. There may be strong fields close to the unit's housing, which can be seen by near-field probing, but they diminish rapidly with increasing distance. On the other hand the power wiring can be extensive and may form an effective antenna for the generated frequencies.

The power **output** connections carry the highest level of high-frequency voltage. But since the cable connecting the unit to its load is a dedicated part of the installation, its route can be controlled to avoid sensitive circuits, and it can be screened. Provided the screen is connected correctly at both ends, emission from this route is then minimised.

The power **input** connections of a drive or converter also carry a high-frequency potential which is mainly caused by the current flowing from the output terminals to earth through the capacitance of the output cable and load parasitics, and then returning via the supply side network. Although the interference voltage level here is lower than at the output, control measures may be needed because these terminals are connected to the extended mains supply network. Most commonly a radio frequency filter of some kind is installed here.

Note that the current paths are in the common mode, i.e. the current flows in the power conductors and returns through the earth. Differential mode paths are less important in high-frequency EMC. Since the return currents in common mode flow in the earth wiring and structure, installation earthing details are particularly important for good EMC. Much of the installation practice aims at controlling the earth return paths and minimising common impedances in the earth system which cause unwanted coupling.

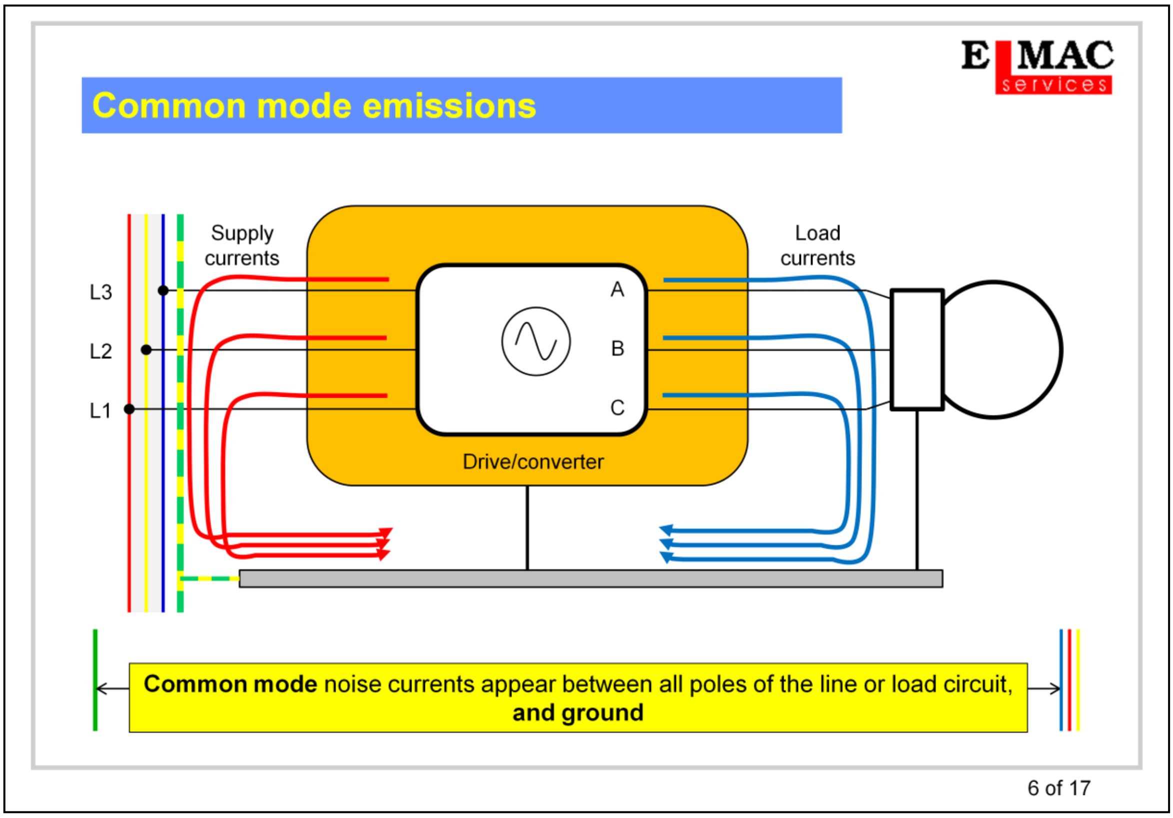


Before considering mitigation measures, it is necessary to be clear on the difference between differential and common mode emission paths. Mitigation for one mode will be ineffective for the other; sometimes both modes must be treated by separate methods.

In the differential mode, the noise currents are generated between the active supply input or output terminals without reference to earth. For a three-phase input connection this means that a voltage will appear between L1 and L2, L2 and L3, and L3 and L1, and the currents will flow in the supply network returning through their respective phase conductors. It is not necessarily the case that the noise sources will be balanced in the same way as the power supply currents are, but if they are, and if the supply network is balanced at high frequencies, then these differential currents are relatively benign in EMC terms. The same is true of the output connections, where good balance of the load at high frequencies will help control the emissions. The balance requirement includes the cable used for input and output connections, that is, all three conductors must be closely coupled in the same cable loom.

For single phase or DC supplies and/or loads, then the differential currents flow in the loop formed by live and neutral or DC plus and DC minus. The source for the noise is fairly easily traced to the ripple voltage across the input DC link capacitor, and the output switching voltage.

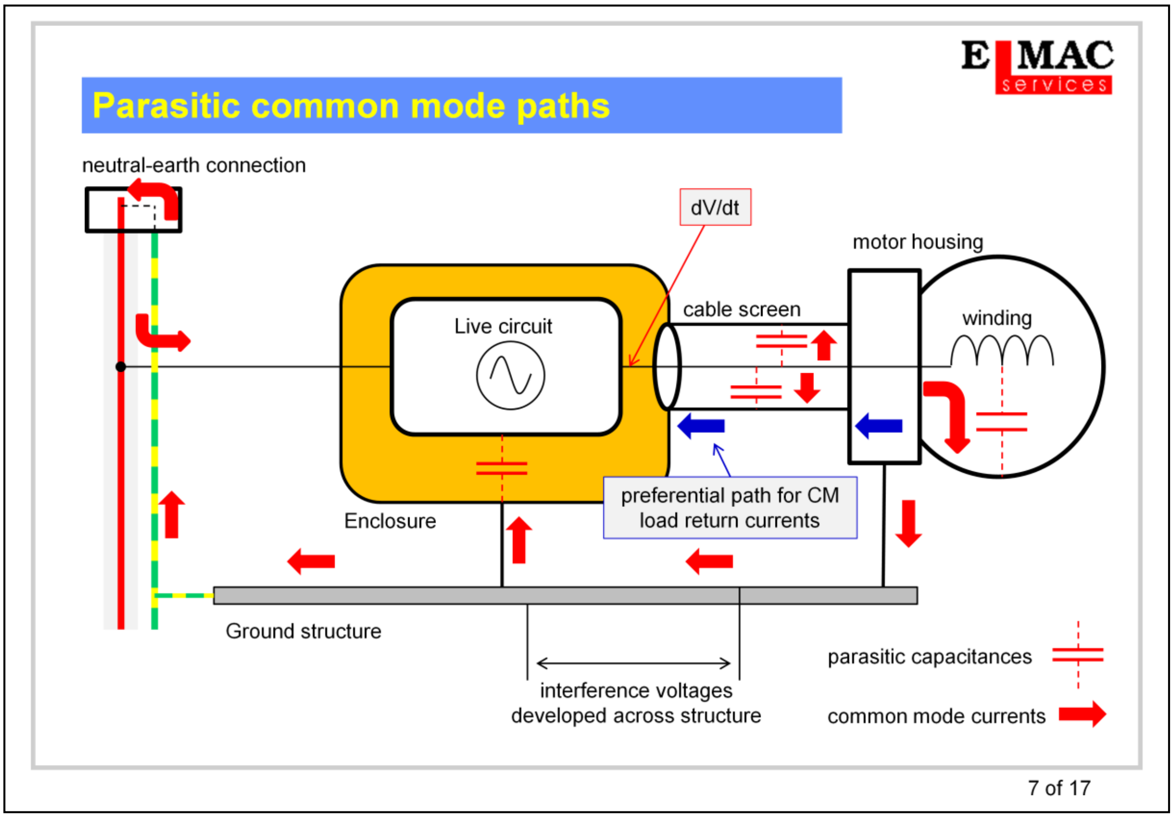
In all cases, the important distinction versus common mode currents (next page) is that the differential path **does not include the earth structure**.



By contrast, common mode currents **do** flow in the earth structure. It is harder to see the coupling path and the source for these currents, until you realise that both the drive or converter and its load exhibit parasitic coupling components to the earth structure (next page).

The common mode voltages appear on, and the currents flow in all of the input and/or output lines together, **in the same direction** – compare this to the differential case, where the balance of these lines means that an outgoing current in one line is balanced by its return in another line, so that keeping the lines closely coupled allows good control of the net emission. In the common mode case, close coupling between the individual lines is irrelevant because the return path may not include these lines at all. Equally, differential mode mitigation measures on input or output, which address voltages and currents between the lines, have no effect on the common mode situation since the lines are regarded as one.

Because the common mode currents flow in the earth/ground structure, which may involve earth cables but is equally likely to include any metalwork in the installation, these currents can not only induce radiated fields to nearby receiving victims but can also affect other instrumentation which includes an earth connection.



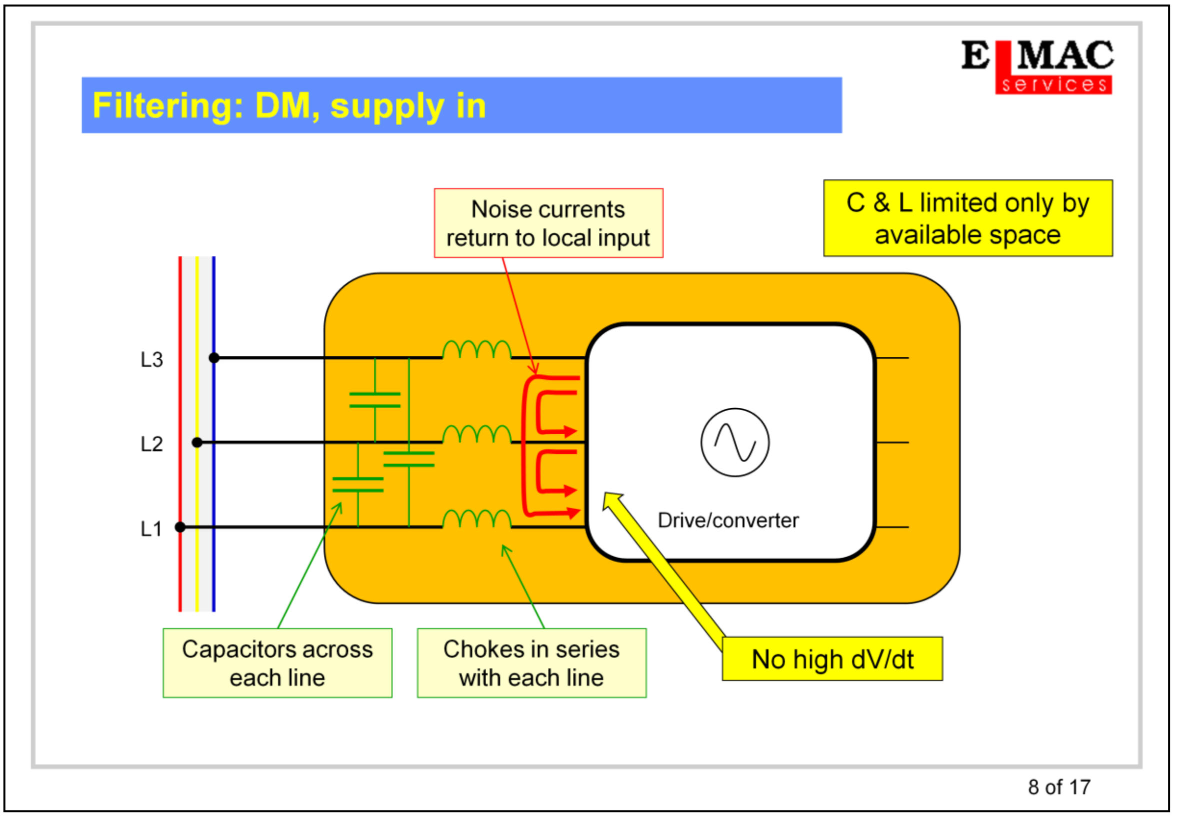
The main cause of high frequency common mode emissions is the current flowing from the output terminals to earth through the capacitance of the load cable and the load parasitics (in the case of a variable speed drive, the motor winding-to-case capacitance) to earth. In many converter and drive applications, the output is switched in PWM fashion with the full dV/dt being passed to the load.

The diagram above summarizes the main emission routes for high-frequency emissions. The capacitance of a motor winding to its frame may be in the range 1nF to 100nF, depending on its rating, and the capacitance from the cable power cores to the screen is generally between 100pF and 500pF per metre. These values are insignificant in normal sinusoidal supply applications, but will cause large current pulses at the edges of the PWM waveform where there is a high dV/dt. The peak current can to a first order be estimated from the standard equation for capacitive coupling:

$$I = C \cdot dV/dt$$

so for example, with 5nF of capacitance and voltage waveforms of 400V peak with a risetime of 50ns, the peak current pulse at each edge of the waveform is 40A. If all of this current is forced to flow in the ground structure and the supply earth network it can cause serious interference with other equipment. It can also be seen why cable length is an important installation parameter, since it directly influences the total capacitance from the cable cores to earth.

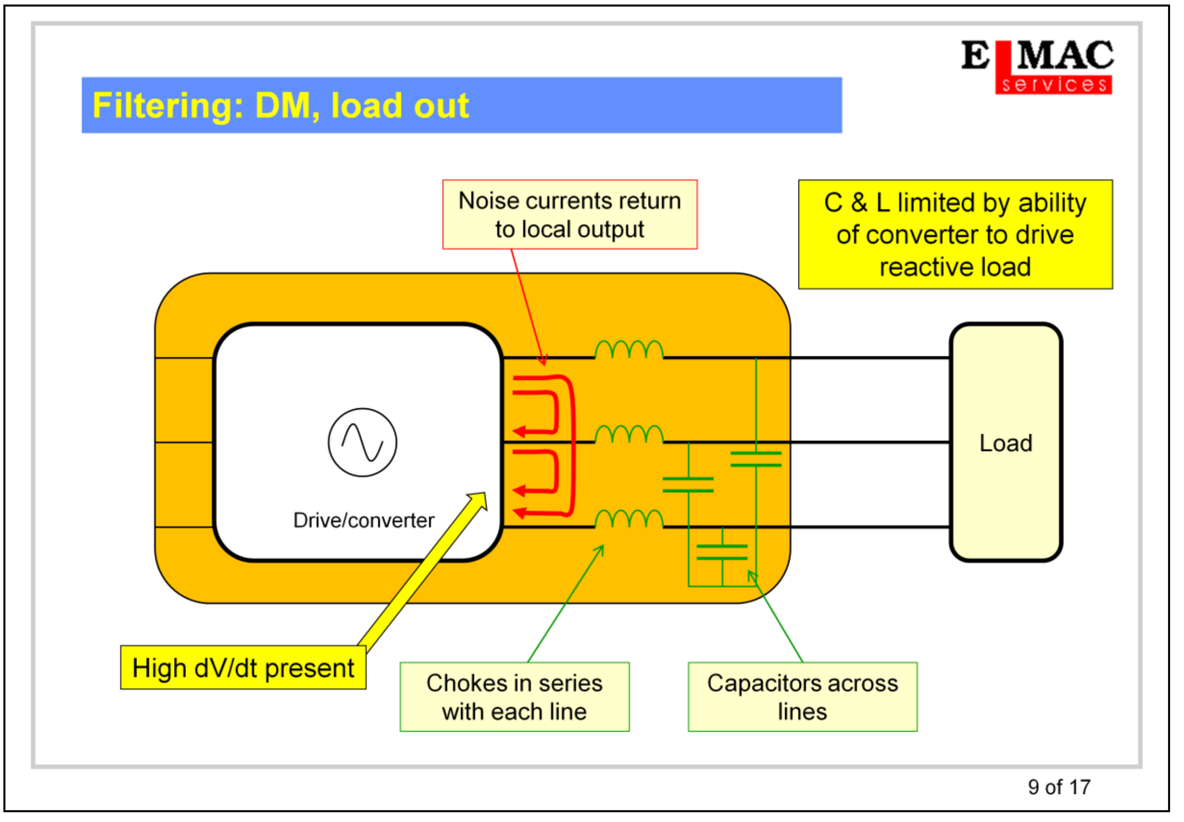
To control the return path of the common mode current, and pass it preferentially directly back to the converter, we use a combination of filtering and screening.



Differential mode filtering at the input of a switching converter is straightforward to implement, involving capacitors between each line and separate chokes in series with each line, without any connection to an earth point. Here, the filter capacitors are subject only to the input voltage waveform, which may be DC or 50/60Hz AC in most applications.

The chokes may be combined into one unit on a single core, but this should be distinguished from the common mode choke as described later; a differential mode choke is designed to provide impedance to the differential mode current path, whereas a common mode choke is configured such that the differential currents cancel and the choke has only a very small impedance to them. The consequence is that for a given supply input current and a given size (and weight) of choke, the differential mode component cannot provide much more than 3-4% of the impedance of a common mode component.

Generally, capacitors across the input are the preferred solution and the series choke(s) are only used in particularly severe cases of differential interference.

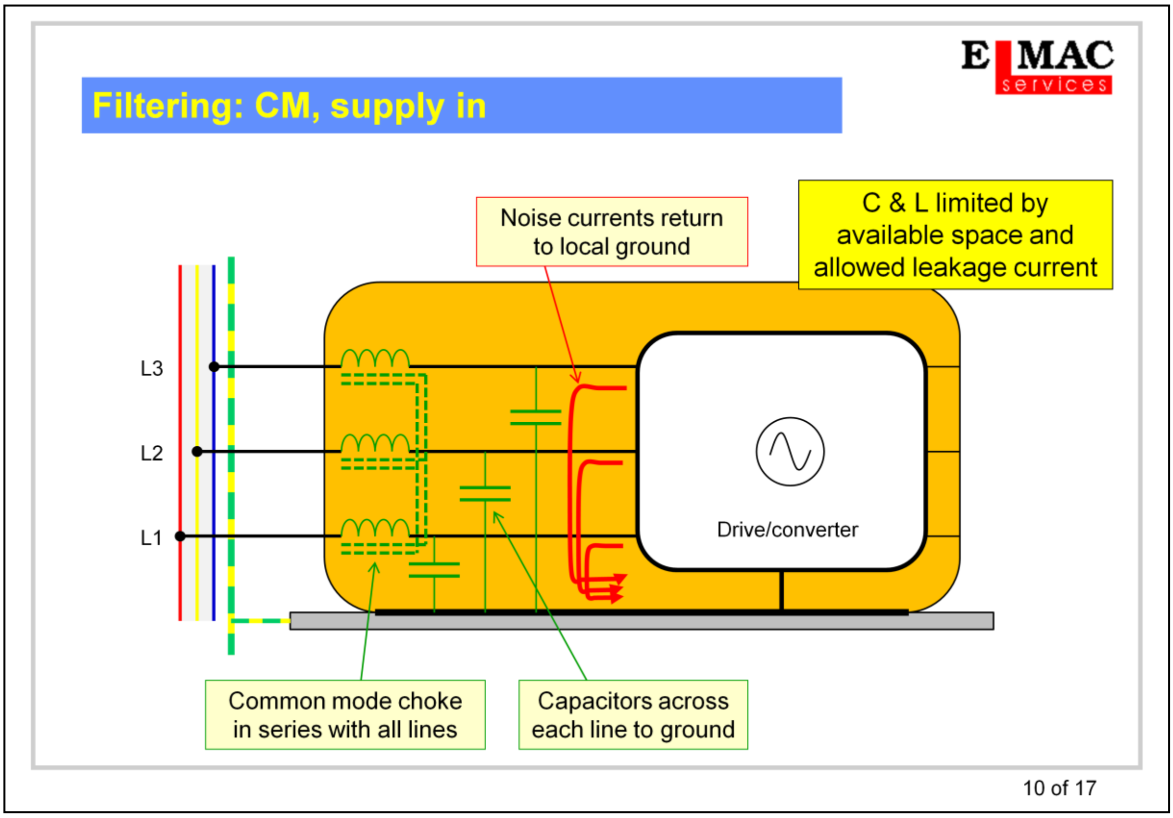


Output filtering in differential mode follows the same circuit approach as for the input, with capacitors between each line and, if desired, separate chokes in series with each line, and no connection to an earth point. The significant difference here is that the filter components are subject to the full dV/dt of the output switching waveform, and the converter or drive output circuit is subject to the extra reactive impedance of the capacitors and chokes. This may well put a limitation on the maximum values of such components and it is necessary to carefully match the chosen components with the capabilities and limitations of the converter.

Depending on the need for control of the differential circuit, the output filtering can take one of three forms:

- dV/dt reactor: chokes alone in series with each line; reduces the dv/dt at the load but is limited by resonances between the choke and the load and cable capacitance
- dV/dt filter: chokes and capacitors with a cut-off frequency above the operating frequency of the converter, which maintains the PWM output but softens the rising and falling edges of the waveform; helpful both for EMC and load reliability issues due to ringing on the switching edges
- sinusoidal filter: cut-off frequency below the operating frequency, so that the waveform to the load is no longer switching but is transformed to a near-sinusoid; requires larger components than the dV/dt filter

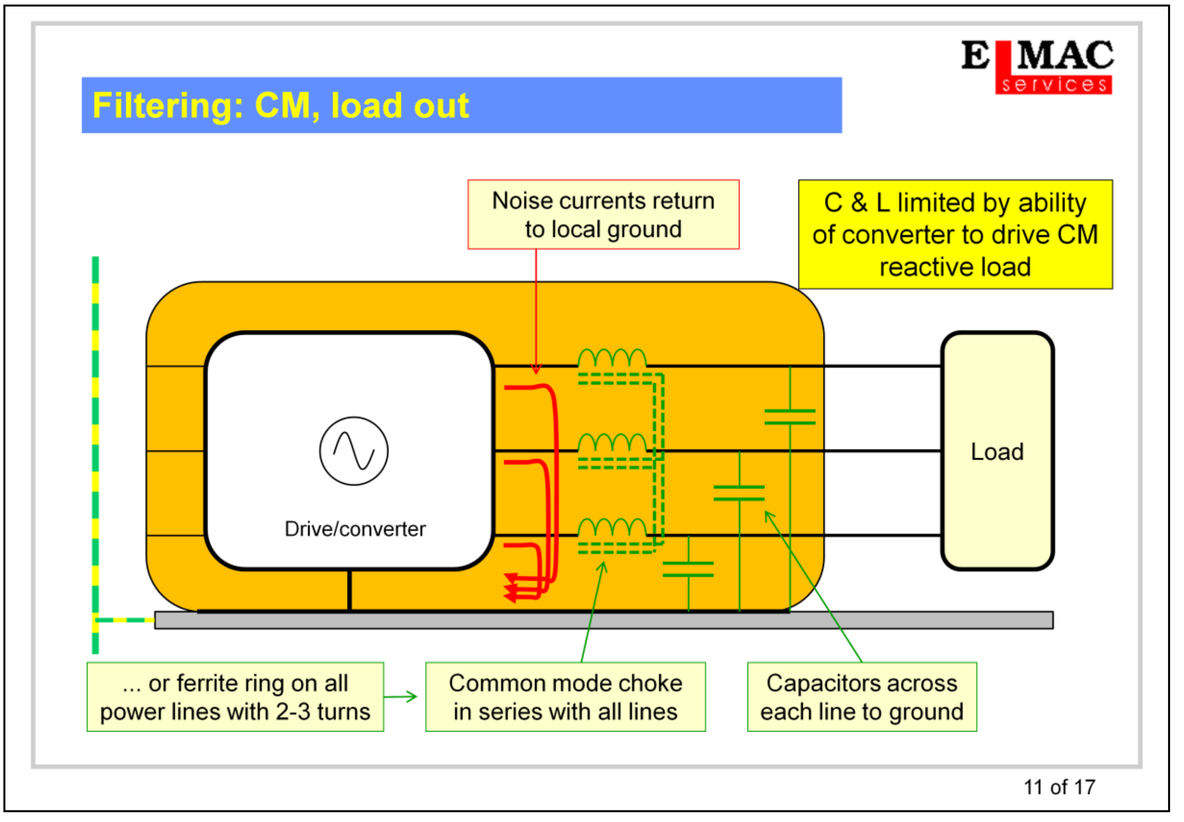
As well as controlling the high frequency emissions from the output side, such filters can also reduce the stress on the load; particularly, large electric motors driven by variable speed drives may suffer reliability problems from the fast switching edges as well as acoustic noise from the PWM frequency. The sinusoidal filter tends to be used to address these latter issues.



Conventional mains filters almost always will incorporate a common mode choke and capacitors from each line to the earth return, and supply filters for power drives and converters are no exception. In fact, if the module itself does not contain adequate filtering then a significant improvement in EMC performance can be obtained just by including capacitors to earth from each supply line, directly at the input terminals of the unit.

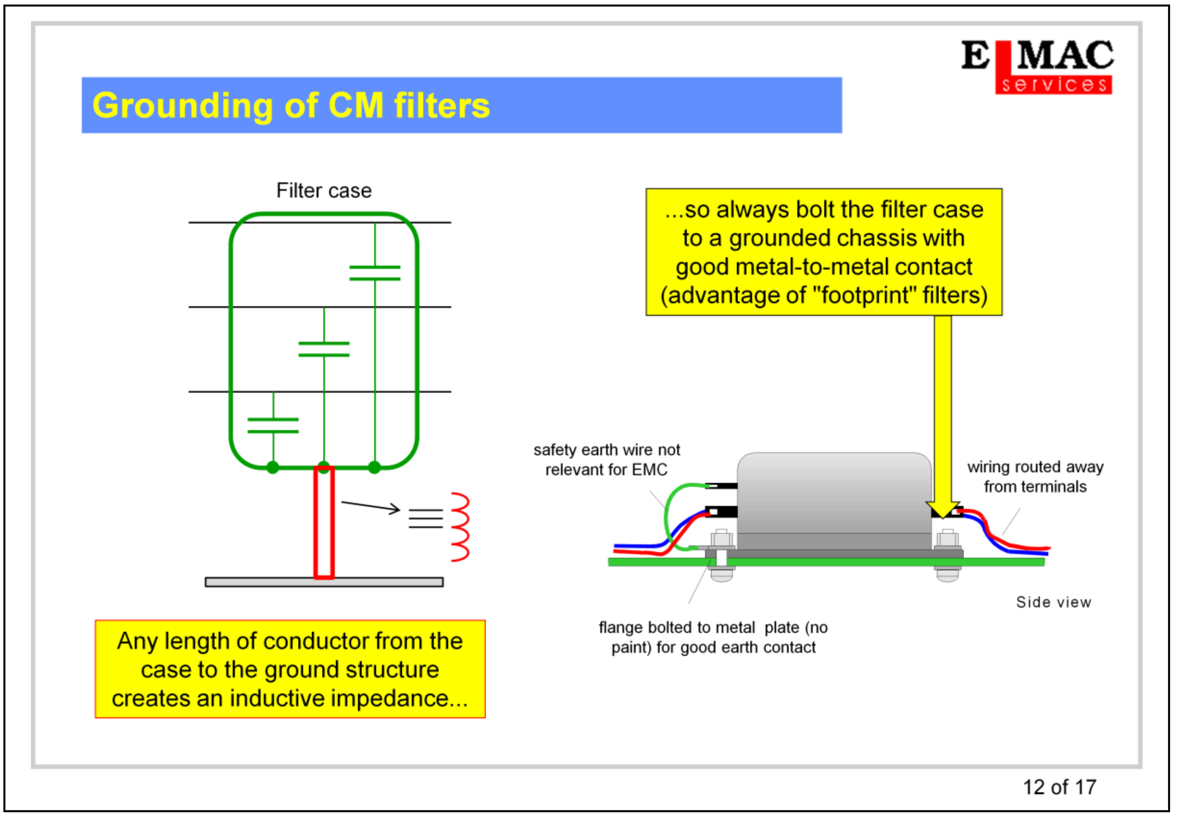
Emission from the motor cable is not affected by this measure, so output cable segregation must be observed. The capacitors must be safety types with voltage rating suited to the supply voltage with respect to earth. Earth leakage current will be high, so a fixed earth connection must be provided – if the application is for AC mains with a user-removable connection (the typical 13A mains plug) then the capacitor values are severely limited by earth current constraints, but otherwise values in the range 100nF to 2.2µF can be used.

The common mode choke provides extra impedance between the supply and the module input. Because the windings are arranged on a common magnetic core such that the DC or LF AC supply current passes through all of them in the appropriate sense, the fluxes created by this current cancel in the core. This means that the choke provides very little attenuation to differential mode noise but its full attenuation appears for common mode noise. The advantage of this is that much higher impedance is available to the common mode noise for a given choke size, weight and current rating.



Common mode filtering can also be applied to the output. As with the differential mode filter it is necessary to be sure that the filter parameters are matched to the output of the drive or converter module. The principle is that common mode currents are returned to the module's local earth terminal before they pass out into the cable to the load, by the capacitors; and the choke offers a higher impedance to these currents before they pass to the cable, attenuating them further.

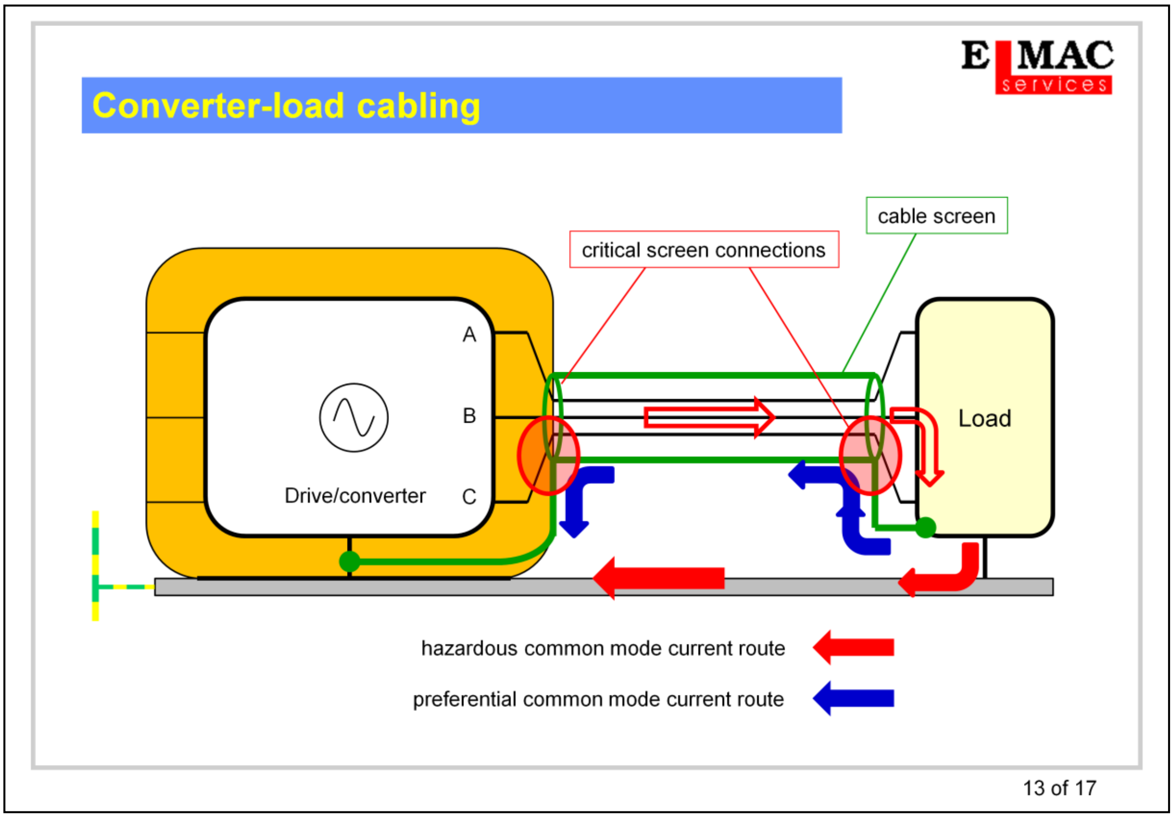
A simple method of implementing a common mode choke, rather than using and wiring in a discrete component or a complete filter, is to apply a ferrite ring around all the output conductors together. The ring fits around the power cores but not the earth, and is most effective if the conductors pass through the ring multiple times – two or three times is typical. The ferrite should be a manganese-zinc type; it is adding resistive loss rather than inductance to the common mode path at higher frequencies, particularly in the 1-10MHz frequency range where motor cable resonance occurs, and this gives useful damping of the resonance. It absorbs the common mode power, and as such may get quite hot. The temperature rise depends on the current at the switching edges and therefore higher common mode capacitance, as created by a long cable or high load parasitics, will increase the size of core that you have to use.



The earth return point for the common mode capacitors is particularly critical: it should be as close to the earth terminal for the module as possible, since we are trying to return the noise current via the shortest possible path. The filter must at least be mounted on the same panel as the converter module, and both units must be HF connected to this panel. If the separation between filter and converter exceeds around 30 cm then a flat cable should be used for the HF connection between filter and drive; the optimum technique is to use the "footprint" filters which mount directly underneath the converter module and bond to it.

Any paint or passivation coating between the filter case and the ground plate must be removed to ensure contact. A back-plate of galvanised steel, or other corrosion-resistant bare metal, is preferred.

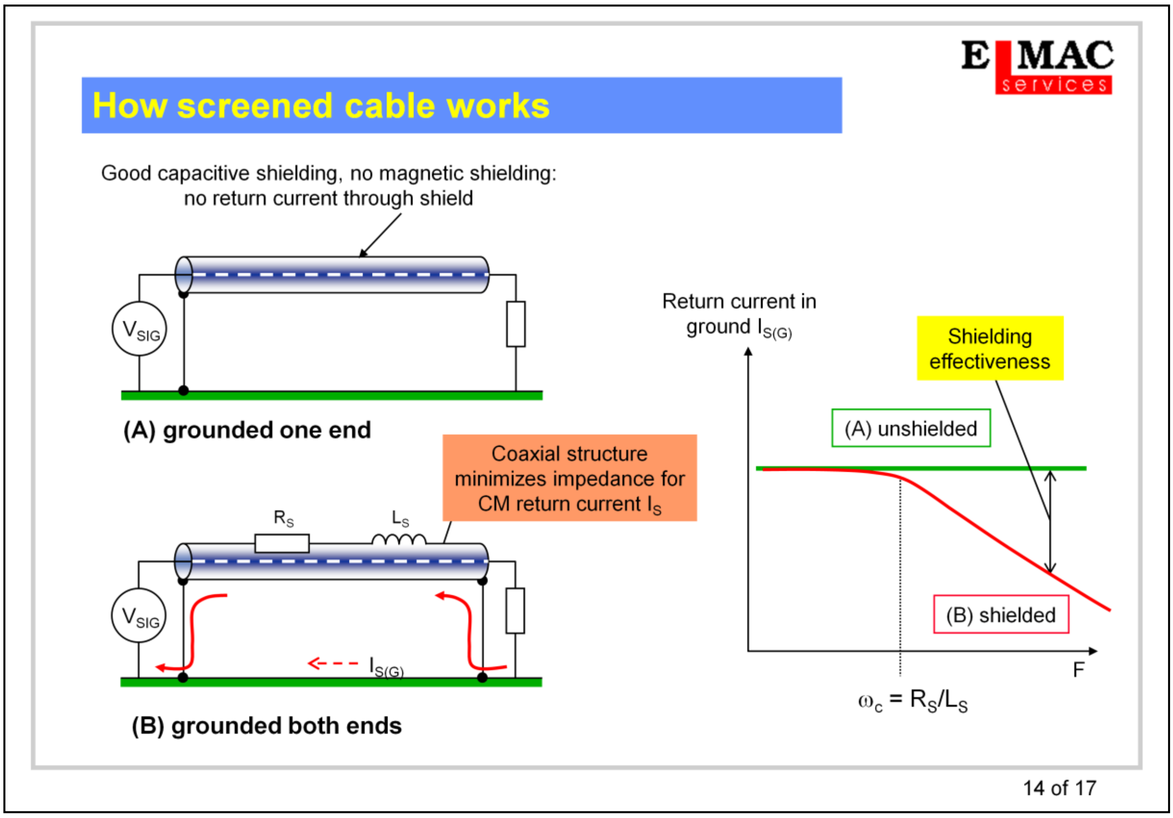
Note that there may be a high current flowing through these capacitors in operation and therefore there are safety implications to their mounting. In this respect, although for safety purposes a visible green-and-yellow wire may be required to a safety earth terminal such as a busbar in a cabinet, this does not form any part of the EMC (high frequency) earth. The EMC earth invariably has to be placed in parallel with this safety wire and is effective for both purposes; the safety earth wire is for backup but has no useful function in normal operation.



Because the common mode return currents between the drive/converter and its load are so important, the cabling between the two is a critical part of the system design. For all but the least onerous of installations a screened cable will be needed. The purpose of the cable screen is to provide a preferential return path for these currents. It is not, primarily, to actually "screen" the cable from radiating emissions, although the effect of return current in the screen is largely to cancel these emissions.

It is often assumed that the return current will take the route of least **resistance** back to its source. This indeed occurs at DC and low frequencies, but as the frequencies increase so inductance becomes more important, and a coaxial screen around the inner conductors creates a preferential path due to mutual magnetic coupling. The better the coaxiality, the more effective is the mutual inductance and the lower the apparent impedance of the screen to the return currents.

But to achieve this the low impedance must be continuous through the whole circuit: there must be a low impedance connection at each end of the screen, as well as at any junctions along its length. A low impedance connection **doesn't** include a length of safety earth wire: for the best performance even a short length (a "pigtail") should be avoided. Saddle clamps to a backplate are often the most convenient, and the optimum is a true conductive circular gland which makes 360° contact all around the cable braid. The point of connection at the load end will be any metalwork enclosing the load, such as a motor housing; at the source end, it should be an earth terminal local to the converter or drive.



For low frequencies an overall screen, grounded only at **one** end, provides good shielding from capacitively coupled interference. In the case of high dV/dt on the inner wires this may be useful in some circumstances but it doesn't prevent earth currents, and the extra capacitive load on the output has to be accounted for.

To shield against a magnetic field, **both** ends of the screen must be grounded. This allows an induced current (I_S) to flow in the screen which will oppose the current induced in the centre conductor(s), effectively minimizing the loop area seen by the complete signal circuit. This effect begins to become apparent only above the cable cut-off frequency, which is a function of the screen inductance and resistance and is around 1 - 2kHz for braided screens or 7 - 10kHz for aluminium foil screens, which have a higher resistance per unit length. Above about five times the cut-off frequency, the current induced in the centre conductor is constant with frequency.

The same principle applies when shielding a conductor to prevent magnetic field emission. The return current must flow through the screen, and this will only occur (for a circuit which is grounded at both ends) at frequencies substantially above the shield cut-off frequency.

In many installations the cable to the load has to be carried in armoured cable for mechanical reasons. The common steel wire armouring (SWA) has a higher DC resistance than a copper braid and so its shielding effectiveness in this sense is less than a braid screened cable. On the other hand, the higher permeability and resistivity cause a greater high frequency loss in the armour conductors which damps the wavelength-related resonances along the cable. This has a beneficial effect. Overall, SWA as the screen of a cable is useful and acceptable, provided that it is treated as an electrical conductor and fully electrically bonded at each end.

Summary: simple cases

- **Identify a low threat environment:**
  - no sensitive victims nearby
  - short output cable, low power load
- **Precautions:**
  - earthed backplate for the converter, and a properly designed earthing network
  - filter capacitors to earth at input, or minimal supply filter
  - ferrite ring on output cable
  - output cable segregated from all others

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In practical installations it is necessary to identify the degree of threat which may exist from a power converter to other apparatus in the same environment. If there are no sensitive transducers such as proximity sensors or low-level analogue instrumentation, video links or long wave/medium wave/short wave radio receivers, then a relatively high level of emissions can be tolerated. A low power converter with a short cable to the load, or one in which the system is entirely housed in one enclosure such as white goods, may need little more than simple measures to control them.

These include:

- Good quality earthing structures at the cabinet housing the converter, to which the converter's ground terminal is bonded; the complete earthing network for the system should be designed and implemented to prevent common impedances between the noise source paths and any other equipment
- As a minimum, capacitors in the range 0.1 to 2.2µf rated if necessary for mains-to-earth use should be placed at each terminal of the supply input to the ground plate; a simple filter could also be used
- The output cable can be wound two or three times through a ferrite ring as it leaves the converter
- The output cable should be segregated from all other cables in the installation; a practical rule of thumb has been found to be: no parallel run to exceed 1m in length if spacing is less than 300mm

Summary: critical cases

- **Identify a high threat environment:**
  - High power system, long output cable or
  - Sensitive victim equipment in the environment
- **Extra precautions:**
  - input filter: matched to converter/drive, bonded to metal backplate
  - output cable: must be screened, continuous screen bonded at either end using conduit glands or saddle clamps to backplate and load housing
  - input, output and signal cables must be segregated
  - consider output filter esp. for long cables

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In a more complex environment or with high power systems then full precautions need to be taken. A complex victim environment includes AM broadcast and short wave radio receivers, analogue instrumentation using very low signal levels (thermocouples, resistance sensors, strain gauges), wideband/fast circuits such as audio or video systems, or unscreened digital data links. All such items are likely to be affected by the harmonic noise generated by the switching converter output.

Precautions now include:

- Earthing and segregation arrangements as per previous page
- An input filter which is designed specifically for the drive or converter to control supply emissions to a specified level
- A screened output cable that doesn't exceed the maximum length allowed for the converter; the screen must be low-impedance bonded to the earth structure at both ends
- Interruptions to the output cable, e.g. for isolators or other switches should be avoided if possible; if unavoidable then the screen connections should be made with glands or clamps to an earthed metal plate or bar to give a minimum inductance between screens. The unscreened section should be kept as short as possible, and run close to the earthed plate
- Any deviation from the optimum screening of the output cable, or a breach of limits on its length or capacitance, should trigger the need for an output filter on the same baseplate as the converter

Power converter installation

Thanks for your attention!