Electromagnetic (EMI) shielding

1. The mechanism of Electromagnetic Interference (EMI)

The definition of EMC

The council of the European Union defines EMC in Article 4 of their "council directive on the approximation of the laws of the Member States relating to Electromagnetic Compatibility (89/336/EEC)" as property of an "apparatus":- The apparatus shall be so constructed that: the electro-magnetic disturbance it generates does not exceed a level allowing radio and telecommunications equipment and other apparatus to operateas intended" (emission requirement)- The apparatus has an adequate level of intrinsic immunity of electromagnetic disturbance to enable it to operate as intended" immunity requirement. This is a very broad definition. The customary route to compliance is the application of standards. There are product standards, applicable to a specific product type (e.g. lighting) and, when not available, there are "generic standards" that can be used. When your product passes all required tests this provides the "presumption of compliance".

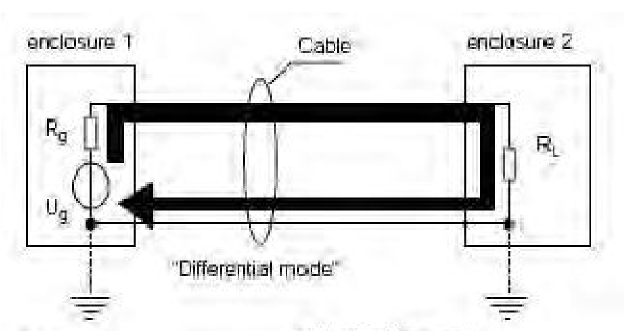
What can you do?

The problem is that there is no direct relation between the tests to establish the fact of "EMC" and the measures you can take to behave satisfactory in that respect. What you need is some basic knowledge on the mechanisms of electromagnetic interference.

Differential and common-mode currents

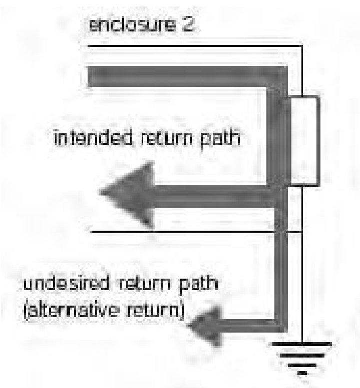
All electric currents run in loops. When you measure current in a wire there must be a return current some whereto the original source. The currents that determine the functional behaviour of a design are called "differential-mode" currents (dm-currents for short). There is another type, however: 98% of all interference problems are caused by common-mode currents (cm-currents).

It depicts an intended o rdesired current loop formed by a cable: a signal and a return line transferring some current from a source Ug to a load RLand back. This is a differential mode current, which means that, if we would use a current probe around the cable to measure the net current passing through the probe, we would find a zero value: all currents going from the source to the load return via the intended return conductor. Consider the circuit in figure 1



F.1

It depicts an intended ordesired current loop formed by a cable: a signal and are turn line transferring some current from a source Ug to aload RL and back. This is a differential-mode current, which means that, if we would use a current probe around the cable to measure the net current passing through the probe, we would find a zero value: all currents going from the source to the load return via the intended return conductor. Complications arise, when there are alternative return pathsavailable e.g. via connections for safety grounding. In that case there is a choice for the return current: Figure 2.



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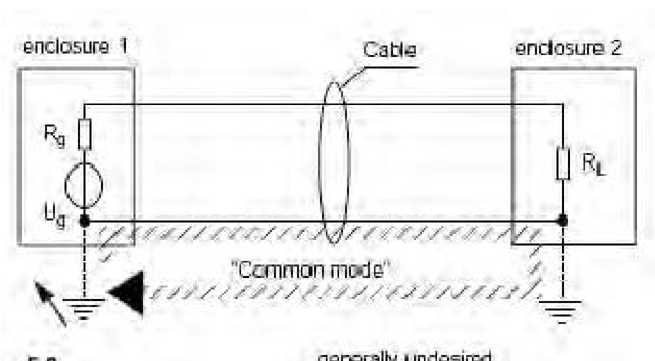
When a portion of the return current takes the alternative path, we will be able to measure a net amount of current with a current probe around the cable. Figure 3.



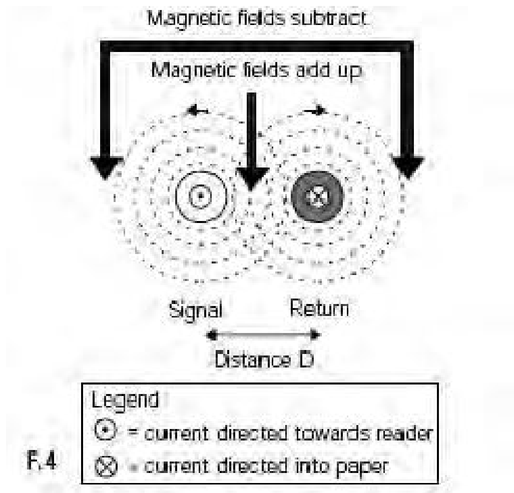
F.3

These undesired currents are not intended by the designer of the equipment and, worse, usually not included into hisan alyses. It is these "forgotten" currents that create most of the sometimes damaging interference in electronic systems.

Cables convert from dm to cm and back

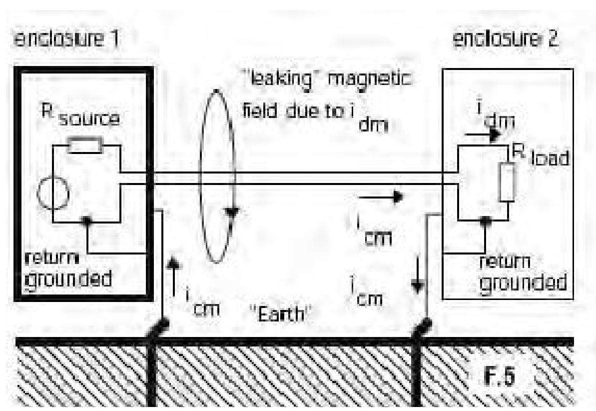
Cables or, more generally, interconnections have the property to convert differential mode currents into common-mode currents and vice-versa. This property is called "transfer-impedance". This is the basic phenomenon which is responsible for electromagnetic interference.

The rest is "related topics". For instance: all currents are accompanied by a magnetic field. The picture in figure 4 shows a two wire cable. Each wire carries the same current but their directions are opposite.



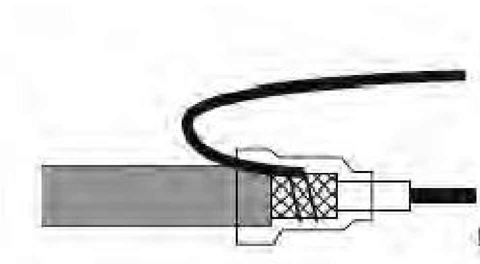
The magnetic field lines belonging to each of them "add up " between the two wires and "subtract" outside that area. Assuming ideal conditions, the combined magnetic field magnitudes could be reduced to zero if it were possible to position the two wires "on top of" each other, exactly centred. The then equal but opposite fields at any position would exactly cancel ("coax" situation)!

In any practical situation there will, however, be some distance between the two wires. This means that some amount of field will be measurable outside the cable. This field in turn induces currents in any conducting loop in the neigh-bourhood. This includes the loop formed by the cable itself and any alternative return conductor (a "common-mode" or ground-loop)! Figure 5.



This alternative conductor could be the machine' s structure, safety grounding provisions, the enclosure wall or other cables. This (induced) current in the usually larger loop is a common-mode (cm) current. Transfer impedance is aproperty of a complete interconnection: cable plus connectors, patch panels etc. from source to load!

The properties of a very good cable can be ruined by a lousy finishing e.g. the infamous "pig-tail" construction on shielded cables. Figure 6.



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2. Interference sources and susceptibility threats

Thus, interconnections are our sole concern for all EMC related issues. From printed circuit board traces to system cabling! We can divide the threats to our systems into "man-made" and "natural". Actual interference is always a susceptibility problem: the disturbed system is unable to cope with the fields or currents that threaten it. Whether the system should be able to cope with them is determined by the prescribed levels in the EMC standards! If the system is too susceptible (civil standards call it "insufficient immunity") you will have to improve it by working on the various interconnections by improving their transfer-impedance. If the system is ok., the interference source has to be located and a similar process must be carried out to reduce its "emissions"

Man-made threats

Interference with a continuous character

Most interference emerges from equipment either your own system or the neighbour' s. Well known sources of high frequency fields are transmitters from public services to GSM telephones. Notably the portable telephones are a threat since they are mobile and can get very close to the susceptible equipment. Fields related to transmitters and other high frequency equipment are in the range from 1 to 100 Volts per meter (Electric field value). Typically 10 V/m or an industrial environment (but: no guarantee)! As a rule of thumb each ltper-meter of field gives rise to a common-mode current of 10 mA in an unprotected able.100 mA of cm-current is considered a critical value in process control installations. Apart from intentional transmitters there are the unintentional transmitters formed by interconnections hich generate common-mode currents and corresponding fields. A high-frequency current in a cable with inadequate transfer-impedance is the common cause.
This common-mode current can either flow directly on a sensitive cable (e.g. from analogue sensors) or create a high frequency electromagnetic field which induces common-mode currents in sensitive cables. Interference with an intermittent character A

special type of interference are "impulsive disturbances" caused e.g. by switching inductive loads.
Examples are relays, frequency converter/motor combinations and switched mode power supplies. When inadequately "snubbered", high peak values in voltage and current are reached when the load is switched. These currents travel through the interconnecting cables and are converted into common-mode currents. The interference mechanism is, of course, identical to the continuous case but due to the intermittent character, it can be more difficult to locate the source of the problem. Common-mode currents from these sources can be considerate: several hundreds of millions amperes especially when relay contacts degrade over time.

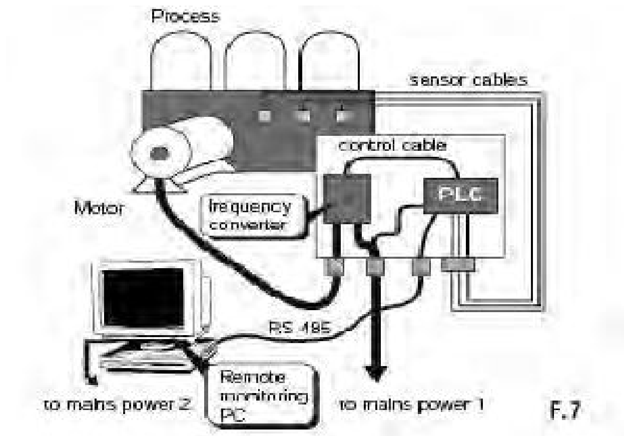
Natural sources of interference

Natural sources are lightning and electrostatic discharge (ESD). The phenomena are related. In either case a (static) electric discharge occurs. In the lightning case a large circuit is involved with dimensions reaching many kilometers. In the ESD case, there is usually a person carrying the charge and discharging into a piece of equipment by touching it. The lightning stroke is a high-energy phenomenon with a relatively low frequency character. Consequently most interference is transferred by conduction. ESD is a high frequency phenomenon with a lower energy content. High frequencies, however, can travel "through air" (capacitive effect) and the corresponding damaging current in the equipment cannot easily be diverted. If there is a susceptible component in its path: too bad for the component. Common-mode currents as a result from these natural sources can reach very high values. Amperes are not uncommon. (A direct lightning stroke typically has 50 kA -i.e. 50000 A-, ESD from 5 -40 A)

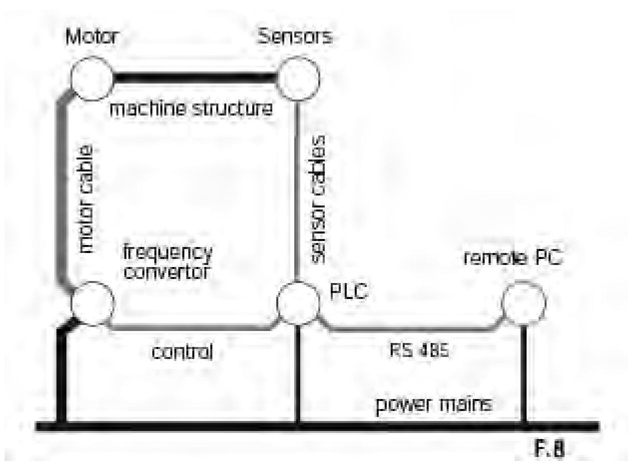
3. Measures to improve compatibility

Packaging of equipment can have a major effect on the behavior in electromagnetically "hostile" environments. In the following sections several approaches are shown. Most of them are very cheap when considered at the design stage. Later in the lifecycle protective measures become scarce and more expensive.

Recognize common-mode or ground loops
Split up cables into categories
All EMC problems (well, 98%) are common-mode problems. Try to develop an instinct for common-mode or ground-loops. Once found, they can be treated following the systematic approach given below. A first example was given in figure 5, a slightly more complex example is shown in figure 7.



Several cable types can be observed in this diagram. It is usually helpful to draw a simplified diagram showing equipment as circles with interconnecting conductors.
Do not forget to include power, "ground" and machine structure as conductors! In the diagram of figure 8, several cable types can be recognized:



- Cables with large and/or high frequency currents. Indicate this type using a red color or the letter "E" for Emission: due to transfer-impedance it will generate possibly large common mode currents.
Example: the cable between frequency converter and motor

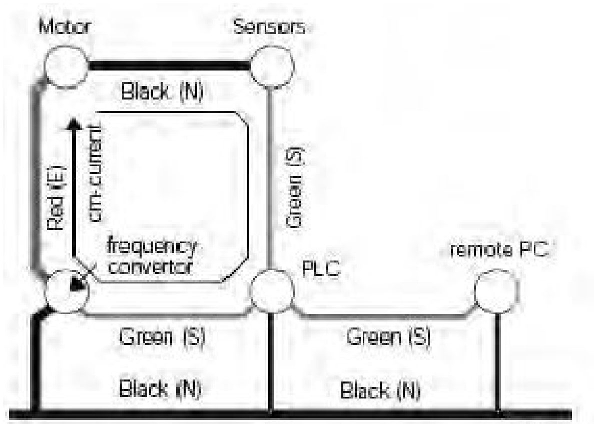
- Cables that neither generate nor are susceptible to common mode currents. Indicate them using a black color or the letter "N" for Neutral.
Example: power cables, machine or building structure, metal piping etc.

- Cables that carry small analog signals or are otherwise sensitive to interference by common-mode currents across them. Indicate this type using a green color or the letter "S" for Susceptible.
Example: sensor cabling, RS-485 line, PLC/frequency converter control cable. Figure 9. Of course, more detailed distinctions can be made. Books on EMC generally use five to seven cable categories.

The RS-485 cable in our example can be susceptible to cm currents from the motor cable but could be an interference source to sensitive analog signals! The three categories used here are only used to demonstrate the principle: our effort should be focused on keeping the emission sources separated from the sensitive cables!

Reduce your sensitivity to cm-currents

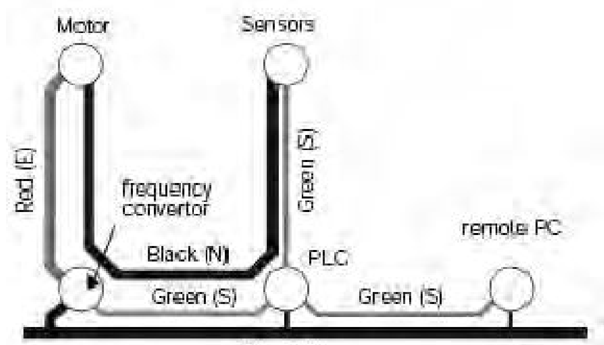
Keep interconnections short
The first thing we can do is keep cable lengths short. All interference is ultimately coupled through transfer-impedance the cable property that converts common-mode currents to differential and vice versa. This effect increases with cable length!
The shorter the cable, the smaller the effect. For that reason interference risks in our example in figure 8 and figure 9 would go down dramatically if we could manage to build the frequency converter right down on the motor! No cable length to speak of, no generation of common-mode currents. Of course, external fields remain as threats to our sensitive cables.



F.9

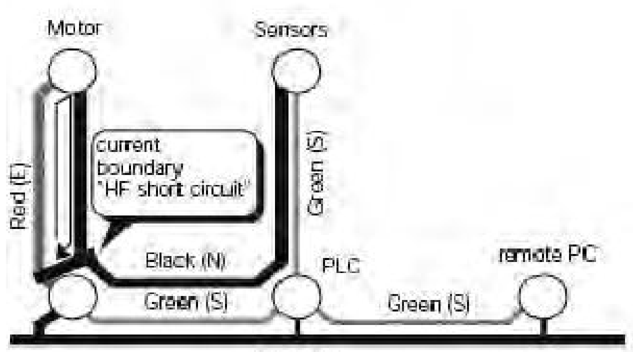
Shield cables
The conversion of differential-mode to common-mode currents and vice-versa can be reduced considerably by shielding the cables. In other words, this reduces their transfer impedance. It is important to connect the shielding on both ends to the equipment the cable connects. The best way to do this is using an EMC gland (discussed later) or metal connector shell i.e. by providing a contact over 360° between the braid and the enclosure wall It enters. The measures described below are, nevertheless, appropriate when considerable distances have to be covered.

Reduce common-mode loop areas
As a next step it is useful to reduce the areas of (all) common mode loops detected. This does not readily remove the common-mode currents in our loops but at leastthe field outside the loop will be reduced by this action. Further, it makes the loop less sensitive to external fields. The reduction can be achieved by routing the category marked "black" or "N" along side the green and red ones. Figure 10.



F 10

In our specific situation the black conductor between motor and sensors is the machine structure! It is cumbersome to bend it alongside the cables so a solution where the cables are routed along the structure is more appropriate here! But, as long as the enclosure containing the PLC and frequency converter cannot be built on the machine structure itself, this will remain difficult. So we will have to look for other alternatives.
EMC grounding: current boundaries
For that we will take our next step first: try to divert the threatening common-mode currents away from the sensitive cables i.e. provide an alternative path for them. This alternative is called a "current boundary" or reference conductor. Figure 11.

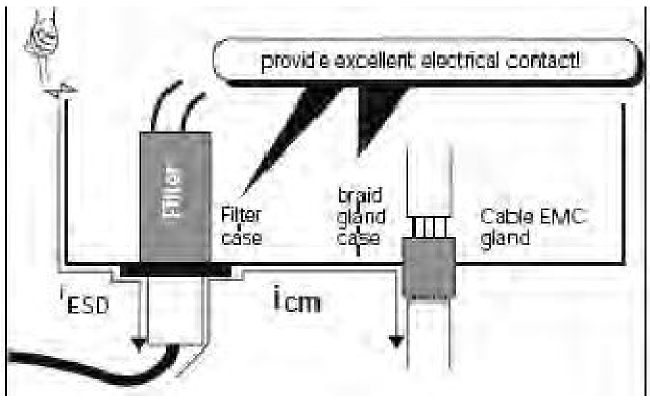


F.11

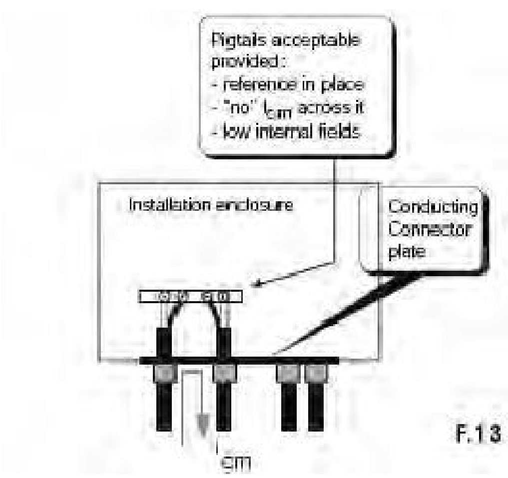
In the situation of figure 10, this would call for a (high frequency) connection between the bottom end of the red cable and the black conductor next to it. Of course, the closer the current boundary is to the end of the cable, the larger the effect will be.
The construction of current boundaries

The current boundary is defined as a path for at least the high frequency part of the common-mode currents. In case the red cable is a shielded type cable (highly recommended, see below), the cable shield could be connected to the black conductor. If this is the machine structure, a bracket could be used to electrically connect the braid

to the structure. If it is another cable with shielding, the two shields could be bracketed together. In any case: keep this connecting device as small as possible.
Whatever the construction, the obvious spot to locate it is at the interface with our equipment (the circles in figure 11). It is practical to always use "natural boundaries" for this purpose. A natural boundary that is obvious in figure 7 is the enclosure containing PLC and frequency converter. Assuming it is a metal case, the interconnections between the various cables could be made at their entry point. Special EMC glands are commercially available for this purpose. Figure 12

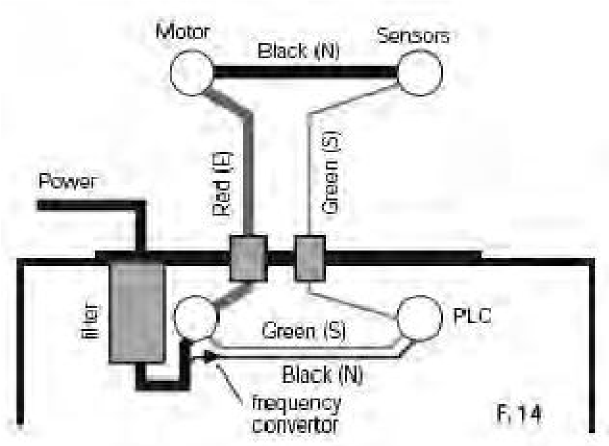


They connect the cable shield electrically to the metal of the enclosure. For cables without shields, filters are the available option. Filters are insulators for mains frequencies (50 - 400Hz) while forming a short circuit to the enclosure from, say, 100 kHz upward. Actually, what happens at the current boundary (=enclosure wall) is that an originally large common-mode loop is cut into a very small enclosure-internal one and a large outside version. Figure 13.



The small portion of the red cable remaining inside will cause only a small common-mode current. In many cases, small pigtails (figure 6) may even be acceptable inside the enclosure!
To enable an excellent electrical contact between EMC glands, filters and other current boundary techniques, the enclosure entrance plate for cabling is often given a lasting

conductive finish. If not, the locations for your EMC glands should be thoroughly ground or polished bare before mounting them.
Afterwards a protective layer of paint can be applied.
Use metal cable guides
Let us assume these provisions have been made on our enclosure of figure 7. Our diagram would look like the one below. Figure 14.



Objections may be brought in to the mounting of the filter in the enclosure wall. From an EMC point of view this is, however the best option. If mounted inside, place it as close as possible to the entry point of the power cable (no EMC gland here) and keep the wire between the entry point and the filter very close to the enclosure wall. Make sure the filter has very good electrical contact to the enclosure. It is advisable to check all current boundaries using a milli-ohm meter. Measure between the metal case and each cable braid or to the filter.

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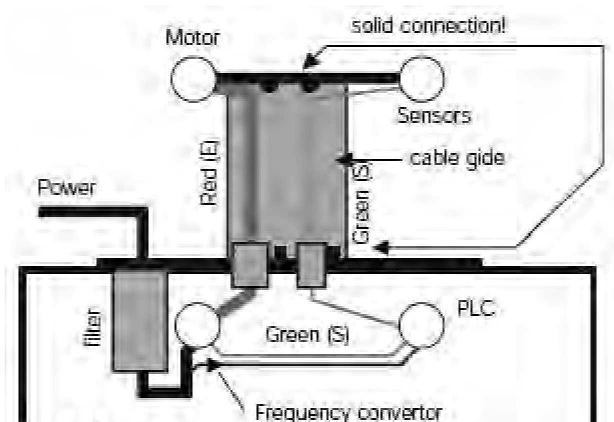
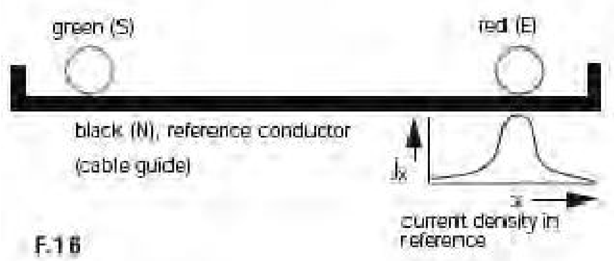
Having done all this, we are faced with a new problem: running between instrumentation enclosure and machine are two cables: the motor cable (red) and the sensor cable (taken together, green). No black conductor to protect them! The solution is: the cable guide. To be effective, it should be made out of metal (conducting). This cable guide is connected (directly or with very short litz wire straps) to the instrumentation enclosure and to the m\a chine structure. The red and green cabling is then placed against the metal of the cable guide with some distance between red and green. Figure 15.



F.15

The cable guide provides the alternative path for the common mode current. It separates the two cables by virtue of the proximity effect: a current will always take the nearest possible conductor as return conductor (provided it is connected electrically!). For high frequencies, the return current (our common-mode current) will concentrate under the conductor that generates the current. Figure 16.



F.16

The distance between the red and green cable (-sets) should be between 5 and 10 times the diameter of the larger cable.
Note: Cabling should always be routed along wide metal surfaces. A separate construction is not always needed though. Any wide metal can be used! The machine structure already mentioned is fine but the metal enclosure wall is excellent for this purpose too!

4. The final option: shielding equipment against electromagnetic fields

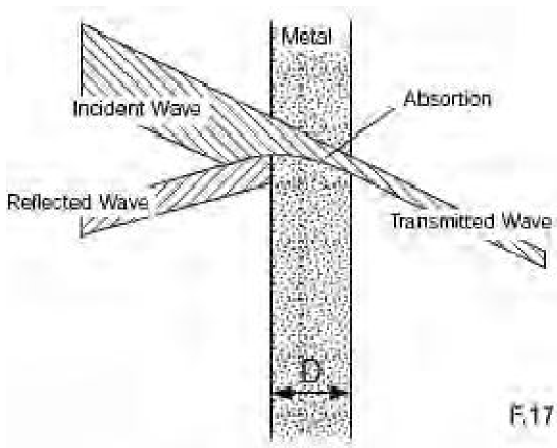
The effects of shielding

Shielding is a means to keep electromagnetic fields out of an enclosure.
For that purpose the enclosure should, theoretically, be completely made out of metal and be "gas-tight". The enclosure wall can then, more or less, be considered to extend infinitely. A model often encountered for an infinite shielding wall is the transmission line model given in figure 17. When an electromagnetic wave encounters a metal wall, some

of the energy is reflected and some passed into the metal. At the other side of the wall, a similar process again reflects part of the transmitted wave and passes the rest. This final wave which emerges from the inside of the wall in relation to the original incident wave on the outside is called the shielding effectiveness (SE).

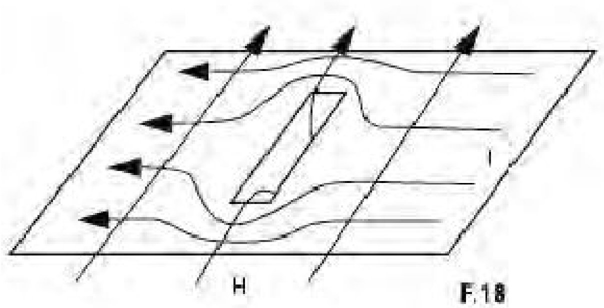
SE = 20 log incident wave transmitted wave (db)

It is generally expressed in dB' s. The absorption which reduces the intensity of the wave on its path through the wall is a phenomenon called the skin effect. Important parameters in this mechanism are wall thickness and material properties like the conductivity of the metal and its magnetic permeability property.



F.17

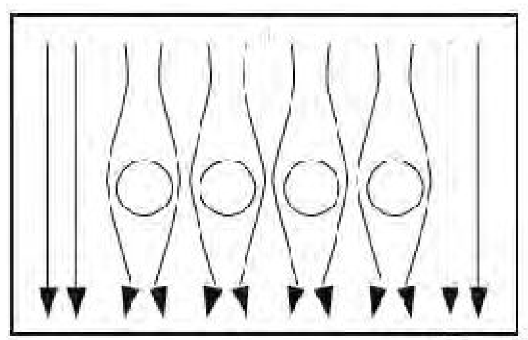
Treatment of apertures in shielding
The effect of a hole in a shielded enclosure
Practical enclosures, however, are never "gas-tight"!
They have apertures, slits and seams which "leak" electromagnetic energy. These apertures determine the entire shielding behaviour of the enclosure. The effect can be imagined with the help of figure 18.



F.18

The effect of the field is a current in the shielding. This current generates a field which opposes the incident field. That way even non-magnetic materials can be used as shielding. When an aperture is encountered, the current has to flow around it.
This deflects the external field into the aperture!

One way to reduce this effect is to replace one large aperture by a number of small apertures. This technique can be applied for apertures to allow light and air into an enclosure. Figure 19.



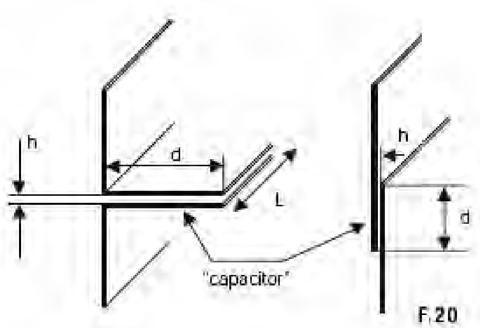
F.19

The effect of slits and seams

EMC enclosures built out of sheet metal are usually spot welded.
In that way small slits are formed which potentially leak electromagnetic energy. This leak is small when the slits are much smaller than one half wave length of the highest frequency to be shielded.

For GSM telephone fields (900 MHz), the slits would have to be considerably smaller than 16 cm (approximate half wavelength). Enclosures not originally intended for EMC can be improved by connecting the various metal panels using litz wire straps (short)! The number of straps can be determined using the same rule given for seam widths (between straps) above.

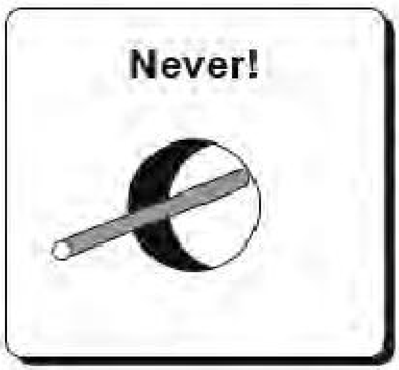
Overlap in seams can help to reduce higher frequencies too (e.g. with wavelengths shorter than the seam width). This measure works due to the effect of the so created capacitor. Figure 20.



F.20

Cabling of shielded enclosures

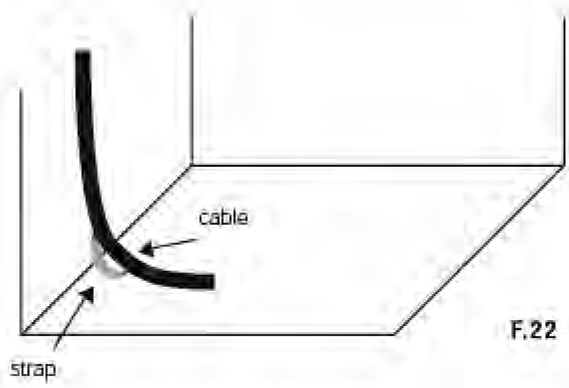
Never should a conductor be allowed to enter an enclosure unhindered: no cables or other conductors like shafts of controls or metal tubing. Figure 21.



F.21

There should be a direct electrical connection to the enclosure wall. If it is a cable, an EMC gland should be used (see figure12). If you would allow the cable to pass the hole insulated while connecting the cable braid via a (long) cable, the loop formed by it would pick up electromagnetic energy (a common mode current) and it would be conducted over the braid to the inside of the enclosure.

There it would reradiate, forming a leak! An unshielded cable passing an enclosure wall intended for shielding, should be filtered, if possible, directly on the wall. Figure 22.



F.22

Almost as bad as an unfiltered cable through an EMC shield is a cable crossing a slit in the enclosure wall.
When this is necessary, it is good practice to connect both sides of the slit electrically using a short strap of litz wire.

When is an EMC enclosure needed?

Most installations can be made to comply to the EMC directive using the measures described in section 3.

As long as the distances between cabling and protecting machine-structures or cable guides is much smaller than a half wavelength of the highest frequencies, few problems will be encountered. Field levels in an industrial environment are in the order of 10 Volts per meter (E-field) while the domestic value hardly exceeds 3 Volts per meter. Be aware though that the external threats like GSM telephones are everywhere and their frequency will go up to 1800 MHz (half wavelength 8 cm)!

The most sensible approach is to shield at the smallest possible scale: at the printed circuit board (PCB) level or at the PCB-rack level. The larger the enclosure (with respect to the wave length of the field) the more difficult shielding will be.