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Maxwell's Equations, Quantum Electrodynamics, and good installation practices for SI, PI and EMC

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Maxwell's Equations,
Quantum Electrodynamics,
and good installation practices for SI, PI and EMC

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1 Introduction

This article is about how basic laws of physics result in a few simple and easy to understand engineering principles, allowing us to use good engineering practices in design and installation that automatically result in the best signal integrity (SI), power integrity (PI) and electromagnetic compatibility (EMC).

Some years ago I was asked to help design the Diamond Light Source [1] to help ensure that its instrumentation and control would have such low noise levels that its electron beam would meet its "beam noise" specifications, without requiring the several months of "fiddling about with the installation" that (I was told) has often been needed by other synchrotrons.

Since Diamond's synchrotron is 700m in diameter, its switch-mode beam-bending magnet power supplies consume many MW of electrical power, and its beam accuracy (hence noise specifications) were five times tougher than any previous synchrotron, this was not an insignificant challenge! (Note: I never identify customers unless they have given me permission.)

So I employed my understanding of the physics that underlies electromagnetic (EM) phenomena, which I had been training designers worldwide in for over a decade, to design the site's common bonding network (CBN*), cable routing, and the EMI specifications for the equipment required.

The result was that when built some years later, Diamond met its tough beam noise specifications from the minute it was first switched on.

Figure 1 A view of the Diamond Light Source, Harwell, Oxfordshire, UK

Since then I have been employed by another synchrotron and a large (Tokamac-based) fusion research project, all large scientific projects consuming MW and generating huge amounts of EM noise, whilst also requiring very sensitive and accurate low-noise electronic measurements.

My training course module that covers what was needed to design the Diamond's CBN and cable routing is called "The Physical Basis of EMC", and was recently published as a book [2] of the same name by Nutwood UK, the publishers of the EMC Journal. It is a slim volume that aims to provide an understanding of electromagnetic phenomena, in a way that can be easily understood by practising electronic engineers.

Armed with these few basic principles, EMC issues are easily visualised, and problems more easily solved, using only very simple mathematics and plain English, at any level from printed circuit boards (PCBs) to huge installations.

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Practical experience by myself and many others on many different PCBs, products, systems and installations worldwide (including large professional audio installations in opera houses and the like equipped with powerful variable-speed motor drives (VSDs) for stage scenery and MW lighting control systems) show that this understanding makes solving many types of SI, PI and EMI problems almost a matter of routine, with none of the usual “fiddling about” with cable shields and “earths/grounds” to try to “get the noise out of the system”.

If you prefer a mathematically and scientifically rigorous treatment of the topic of this article, rather than my usual touchy-feely unscientific engineer’s waffle, read [3]. It comes to exactly the same conclusions as to the practical design and construction techniques required for systems and installations.

***CBN:** A building or site has what is commonly referred to as a safety earthing (or grounding) structure or network, comprising of Protective Earth/Ground conductors and much of its metal structure, all connected together and to earth/ground electrodes. In IEC-installations-standards-speak this is more correctly called a common bonding network, CBN.

For electronic functionality (signal integrity, SI, and power integrity, PI) and EMC its connection to earth/ground electrodes is immaterial, and so referring to earthing/grounding in a non-safety situation causes huge confusion, and has delayed many projects and compromised the SI, PI and EMC of many others.

2 External and internal EMC

Apart from DC issues such as the fan-out of DC signals or the voltage drop caused by resistance in DC power conductors, all SI and PI issues are just subsets of EMC, as indicated in Figure 2. We might call them “internal EMC” – the system or installation interfering with itself. For more detail on this, see Chapter 8 of [2].

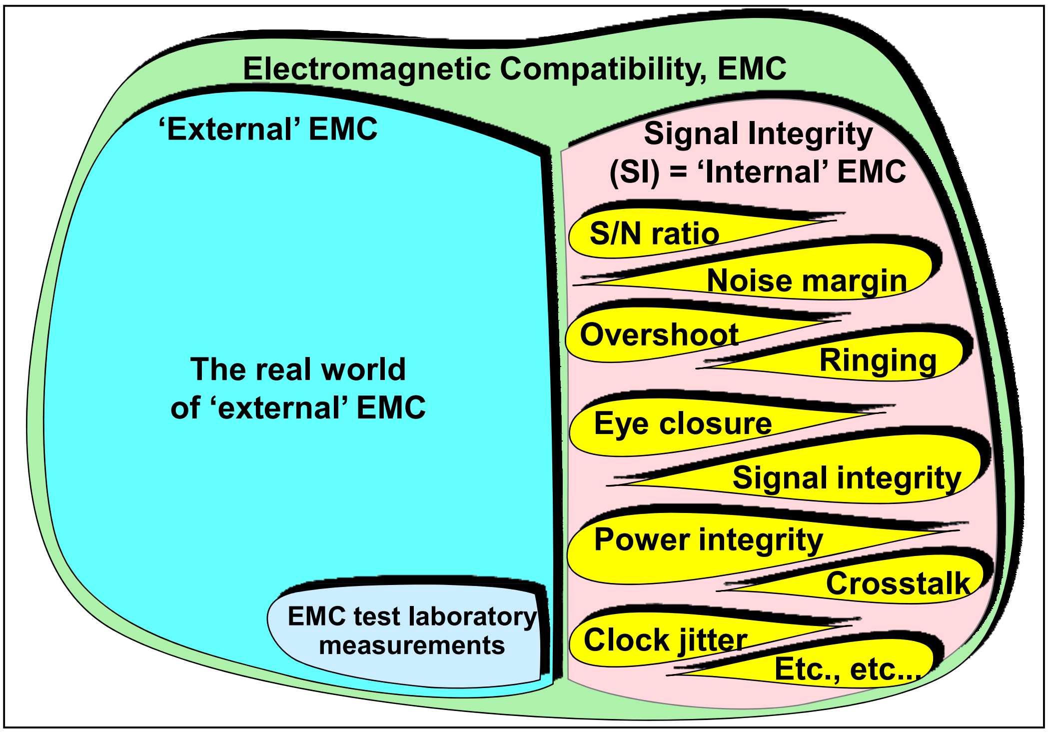

Figure 2 The topic of EMC also covers SI and PI

3 Everything has permeability (μ) and permittivity (e)

All media and materials have conductivity, permeability (μ) and permittivity (e).

In vacuum (and air): $\mu_0 = 4\pi \cdot 10^{-7}$ Henries/metre
$e_0 = (1/36\pi) \cdot 10^{-9}$ Farads/metre

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Other media and materials are characterised by their relative permeability (μ_R) and permittivity (ε_R) – dimensionless numbers, just multipliers for the vacuum permeability and permittivity – so their overall permeability is: $\mu_0\mu_R$ and their overall permittivity is: $\varepsilon_0\varepsilon_R$

Permeability is associated with inductive energy, which we draw as magnetic field lines.

Permittivity is associated with capacitive energy, which we draw as electric field lines.

Conductivity (and its reciprocal, resistivity) is associated with energy loss, i.e. the conversion of EM energy (magnetic or electric) into heat energy.

The shapes of conductors, and the $\mu_0\mu_R$ and $\varepsilon_0\varepsilon_R$ of the media or materials they are embedded in, cause inductance (L) and capacitance (C), respectively. So, whenever there is a fluctuating voltage (V) there is always an associated current (I).

And vice-versa: whenever there is a fluctuating current (I) there is always an associated voltage (V).

In insulators (e.g. air): $\mu_0\mu_R$ and $\varepsilon_0\varepsilon_R$ cause effects similar to inductance and capacitance, so whenever there is a fluctuating electric field (E) there is always an associated magnetic field (H).

And vice-versa: whenever there is a fluctuating magnetic field (H) there is always an associated electric field (E).

Chapter 2 of [2] has more details on the above.

4 Because of Maxwell's equations…

Everything that we call an AC voltage or current is really EM power (Watts, i.e. rate of flow of energy), propagating as a wave in the medium with velocity $v = 1/\sqrt{(\mu_0\mu_R\varepsilon_0\varepsilon_R)}$ m/s ($\cong$ 3.108 m/s in air or vacuum) and creating EM fields as it does so.

This applies to every kind of EM event, whether we call it electrical power; electronic or radio signals; infra-red; light; lightning, etc., and including all mains 50Hz power; analogue, digital and switch-mode power and signals; radio-frequencies (RF) and microwaves, etc., including all electrical, electronic, or radio "noises".

Figure 3 is an attempt at visualising an EM wave at a single frequency, as it propagates in free space, and shows that the E and H fields are perpendicular to each other, and also to the direction in which the EM power is propagating.

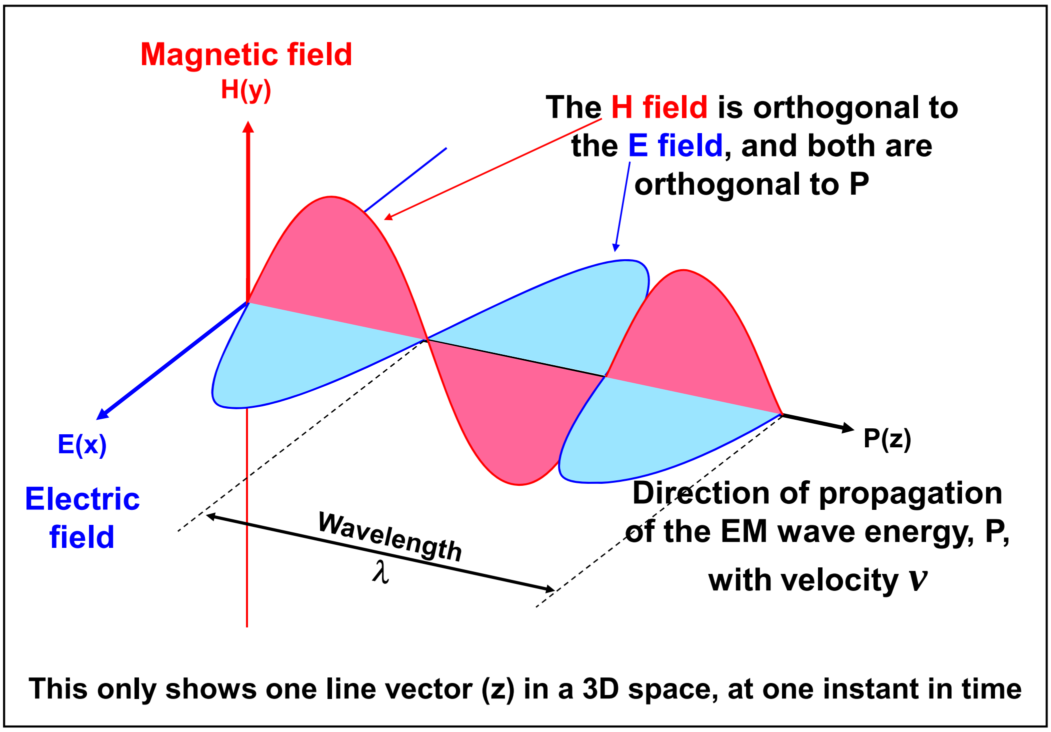


Figure 3 Visualising a linearly-polarised EM wave in free space

A common way of visualising the E and H fields associated with voltages and currents in conductors, is shown in Figure 4, for a send/return pair of conductors shown in cross section. E-field lines always terminate on conductors, perpendicular to their surface, and H-field lines never terminate on anything, and are parallel to the conductor surface.

These lines should be considered like contour lines on a geographical map – they are not real, but their density indicates the strength of the field (like the slope of a hill). So we can see that the E and H field strengths are highest inbetween the send and return conductors.

The electrical power associated with the current in the wires, propagates along the length of the wires, perpendicular to the surface of the page or screen you are reading this from.

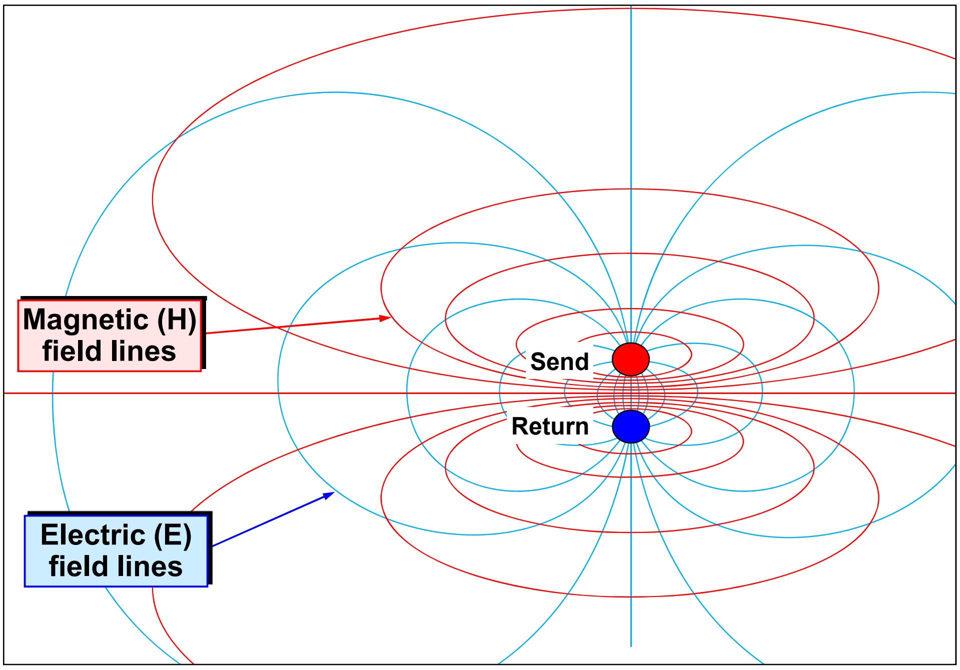


Figure 4 Cross section of fields associated with a pair of send/return conductors

5 Because of the Law of Conservation of Energy...

…there is always zero EM power at any *point* in space. The EM power entering it must be exactly balanced by the EM power leaving it.

If we ignore the reality of EM wave propagation for a moment, we can see that this is Kirchoff's current law, which has been described as: "the sum of the currents at any point equals zero".

Another way of putting this is to say that all currents flow in closed loops. If some current could escape from a loop and go wandering off on its own, never to return, then at the point where it left the main loop there would be an imbalance in the current – current would accumulate at that point, and the Law of Conservation of Energy tells us this can't happen in our universe.

So we see that Conservation of Energy means we could rewrite Kirchoff's current law as: "the sum of the EM power at any point equals zero", hence the title of this section.

The send and return currents (really EM waves) from a circuit node are emitted simultaneously, and propagate through the impedances of the various media (air, conductors, etc.), eventually meeting up and cancelling out to create what we think of as send/return current loops.

All power, signal and noise currents of any kind flow in closed loops.

So connection to the safety earth/ground electrodes has no relevance at all for SI, PI or EMC.

6 But its really all because of Quantum ElectroDynamics (QED)

I met my old Electromagnetics tutor, many years after leaving University, and asked him how the return currents "knew" what routes to follow to exactly match up with the send currents. (I won't mention his name, because I don't want to embarrass him with the physics that I'm mangling in this article.) He recommended that I read [4], so I did.

I learned that propagating EM power (light is EM power) takes the path of least time, which is also the path of least energy, which is also the path that gives the best SI, PI and EMC possible for a given geometry and media/materials (OK, you won't find this last conclusion in [4]).

To find out how EM power knows to do this, we have to integrate over the whole of space and time, including negative time. Apparently this means that with sensitive enough instruments you could hear what the outcome of a horse race would be, by listening to radio broadcasts from the future, but unfortunately it would only get you a few femtoseconds into the future – not far enough to give you the time to place a winning bet!

Also, apparently, QED permits the power budget for a point to deviate from zero for a few femtoseconds, but after that the Law of Conservation of Energy insists that the power books have to balance to zero once again.

7 What does this mean for SI, PI and EMC?

7.1 EM power divides between alternate paths according to their admittances

In the "far field" of an EM source, E and H fields experience the "wave impedance" of the media or materials their EM power is propagating through.

In air or vacuum: $\sqrt{(\mu_0 / \varepsilon_0)} = 120\pi\ \Omega$ (near enough 377Ω)

And in other media (e.g. PVC, oil, fibreglass, etc.): $120\pi\sqrt{(\mu_R/\varepsilon_R)}\ \Omega$

These simple expressions only relate to the "far field", typical for radio transmission and reception, whereas in the "near field" the impedance situation is more complex, and the dominant effects on the impedance of a path through the air or other dielectric are inductive and capacitive coupling – often called "stray" or "parasitic" inductance and capacitance. See Chapter 2.4 of [2] for more on this.

For waves propagating along conductive structures, the medium surrounding them has an important effect on impedance, but so does the shape of the structures carrying the current and the shape and proximity of nearby conductors – most especially the return conductor(s), but any other conductors in the near field will also have an effect. So waves propagating along conductors can experience impedances that are lower, or higher, than the far-field wave impedance of the medium surrounding them.

This means that for an EM wave propagating along a conductor (what we electronic engineers call signals or power) there are always alternative paths, so its send/return current loop is never a simple one.

For example, a significant portion of the wave power might leave a conductor and continue on its path by travelling through the air, if it sees that air path as having impedance comparable with that of the conductor.

In fact, a given current splits to flow in alternative paths in proportions according to their various admittances (the inverse of their impedances). Sometimes just part of a loop will split into several paths. The paths can be along conductors, or through dielectrics or the air – it doesn't matter – to a propagating EM wave they are all just different impedances.

A proportion of the power in an EM wave always "leaks out" of conductors, "escaping" into nearby conductors by stray capacitance and inductance (what we call crosstalk) and also into the air as far-field EM waves (what we call EM emissions). Of course, what we are trying to do for SI, PI and EMC is to minimise the amount of wanted EM power that is "leaked" from our conductors.

Note that all loops, however caused, have to return exactly 100% of the current back to its source, to comply with the law of conservation of energy, so they must all connect at that point at least.

This perspective shows us that – to achieve good SI, PI and/or EMC – all we need do is control the impedances in the various paths that are available to our wanted signals or power currents, so that they travel only in the loops we want them to.

If no signal or power current is "lost" to alternative paths, then we must have no crosstalk, no emissions, and as a direct result our SI and PI must be perfect and our EM emissions must be zero.

And, as I will discuss in the next section, a physical structure that has no emissions, of necessity has no interaction with its EM environment, and so it must have perfect immunity.

Of course, such total perfection is impossible, but if we are careful in what we do we can always reduce emissions to sufficiently small amounts, and improve immunity by as much as is needed.

7.2 All conductors are "accidental antennas"

A transmitting antenna is merely a conductor that *intentionally* leaks its voltages and currents as EM power into the air. A receiving antenna is simply a conductor that picks up voltages and currents from the EM fields around it.

When a conductor is exposed to E, H or EM waves propagating in its insulating medium (e.g. the air), its electrical/electronic circuit experiences the same voltage and current noise as we would need if we wanted to generate the exact same field pattern at the conductors. This is called the ***Principle of Reciprocity.***

When we don't want our conductors to transmit (leak) some of their EM power, or pick up noise from the environment, EMC engineers usually call this "accidental antenna behaviour". Some call it "unintentional antenna behaviour".

The Principle of Reciprocity also applies to accidental antennas, so when a conductor carrying a current has imperfect control of the wanted current loop that results in noise emissions, it will suffer noise pick-up from its EM environment in exactly the same way.

When electronic engineers are discussing SI or PI, they usually call accidental antenna behaviour crosstalk, and they notice that the same techniques that reduce the source of crosstalk "aggressor" (the source), also help reduce the noise picked up by a crosstalk "victim" – another example of the principle of reciprocity.

7.3 Current loop size and coupling

The transfer of EM power from one conductive circuit to another – whether this is intentional or not – is called EM coupling. It can be described by "coupling coefficients" which are, of course, frequency dependent.

The larger the area of the send/return current loop, the larger its impedance (ignoring resonances, see later), and the larger its E and H field patterns.

As shown in Figures 5 for E-fields and Figure 6 for H-fields (and Figure 8, see later) the larger the current loop the higher is the proportion of its wanted current that couples with "victim" circuits, causing higher levels of noise currents flowing in unwanted loops, increasing the waveform distortion in wanted signals, and worsening emissions and immunity.

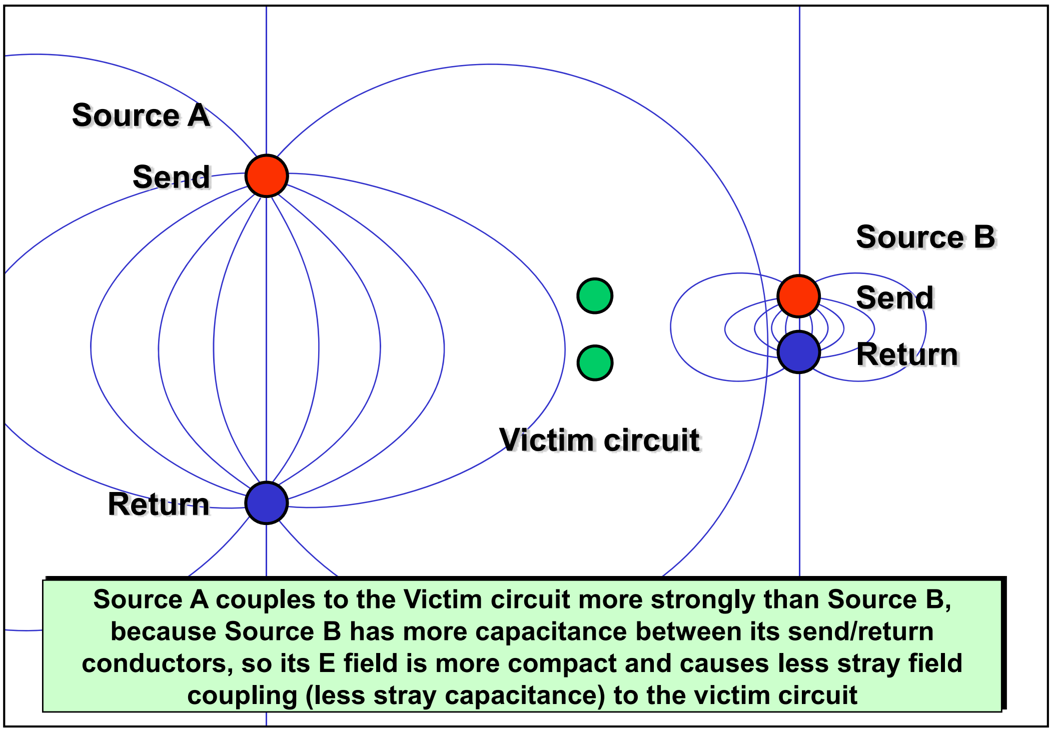
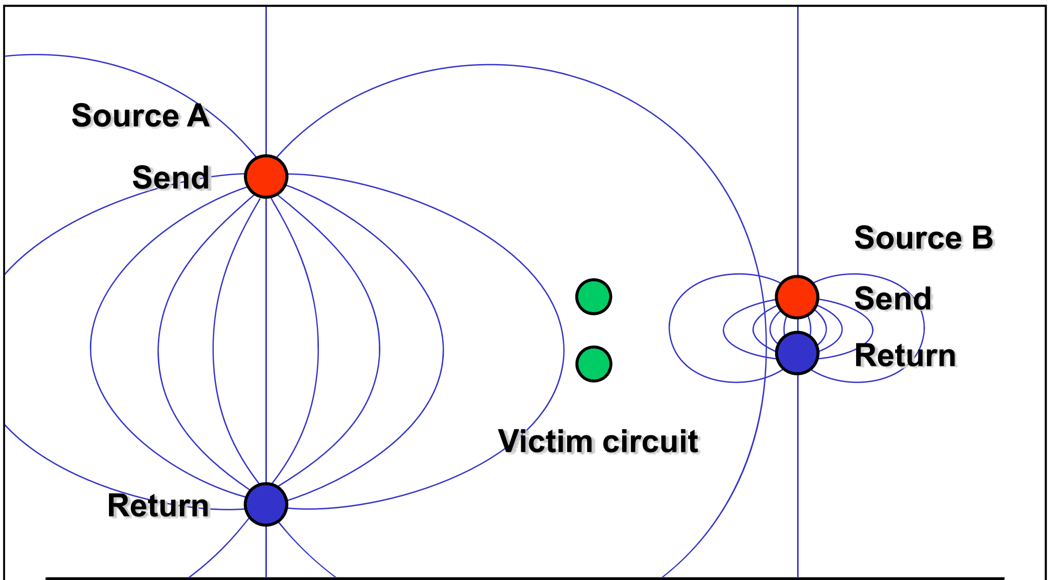


Figure 5 Example of E-field coupling

Figures 5 and 6 show us that it is important to minimise the send/return current loop areas, for all circuits – whether they are accidental transmitters or receivers of EM noise – to maximise their SI, PI and EMC.



Source A couples to the Victim circuit more strongly than Source B, because Source B has more capacitance between its send/return conductors, so its E field is more compact and causes less stray field coupling (less stray capacitance) to the victim circuit

Figure 6 Example of H-field coupling

7.4 Power and signals in conductors have two modes of wave propagation

Differential Mode, DM (also called transverse or metallic mode) is what we call our "wanted" power and signals.

Common Mode, CM (also called longitudinal or antenna mode) is caused by the stray, leaked, "unwanted" EM power when a DM loop's near-field E or H fields meet another conductor, as shown in Figures 5 and 6 above. It also occurs when far-field EM waves couple power from the wanted signal in its intended circuit, to another circuit – accidental radio transmission and reception.

Figure 7 shows the relative paths of the DM and CM currents in a simplified system.

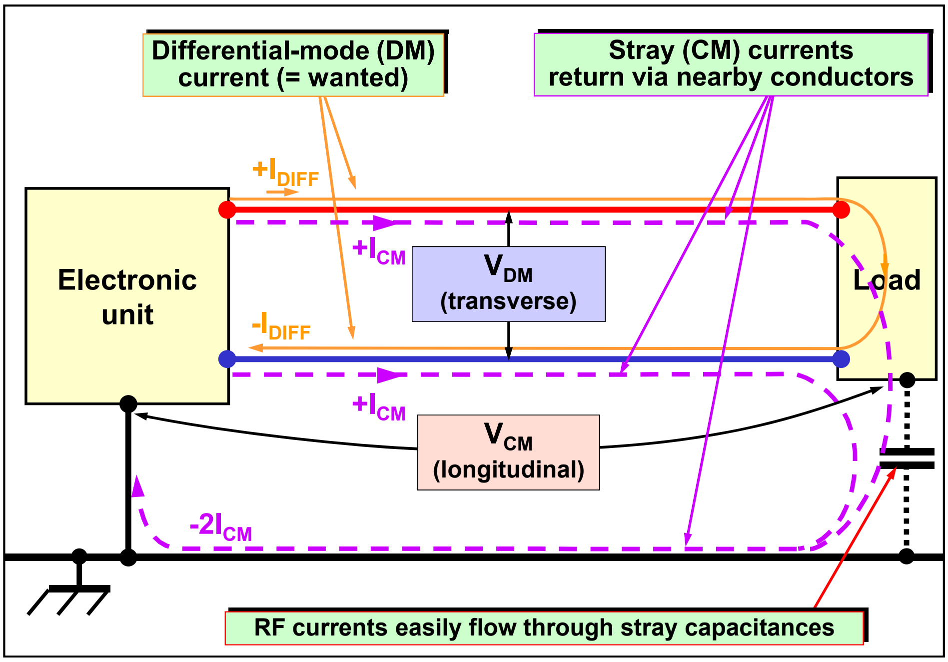


Figure 7 An example of DM (wanted) signals causing CM noises, for a 'floating' load

So our electricity does not all stay in the wire!

Some of it travels as stray CM currents, and like all currents they must flow in closed loops.

Because the CM loop is generally very much larger than the DM loop, and its field patterns are much more widely spread as a result, CM is generally the major cause of "accidental antenna" effects causing EM emissions over the frequency range from 1MHz to 1GHz.

Figure 8 shows that CM currents also couple with "victim" circuits through H-field coupling, just as DM currents do (in Figure 6). I could draw another figure showing how CM voltages couple with victim circuits through E-field coupling, just as in Figure 4, but I'm sure you get the picture.

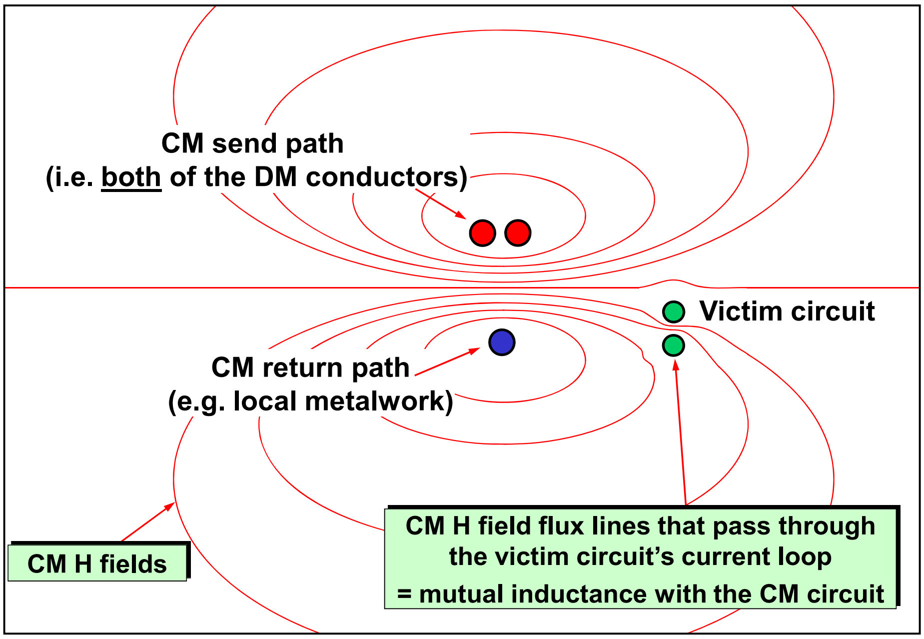


Figure 8 Example of CM H-field coupling

Reducing the size of the CM loop reduces its H-field coupling into the victim, in the same way that reducing the size of the DM loop does in Figure 6. And reducing the size of the CM current loop also reduces the amount of E-field coupling into the victim, in the same way as for the DM E-field in Figure 5.

So, just as it is important for good SI, PI and EMC to minimise the area enclosed by all wanted (DM) current loops, it is also important for all unwanted, accidental, CM current loops – although in some applications it is not always easy to do.

7.5 Resonating conductors make perfect accidental antennas

There are various causes of resonances in conductive structures, at certain frequencies…

a) When the L and C reactances happen to be equal

b) Due to geometry interacting with wavelength

The second item concerns transmission-line matching. When mismatched conductor characteristic impedances cause propagating waves to be reflected, under certain conditions they can cause standing waves to arise, which are resonances. This is too complex an issue to go into here, but it is described in detail in Chapter 3.2.4 of [2].

At resonant frequencies, loop impedances fluctuate wildly, in the range between the conductor's series resistance (possibly just a few mΩ), up to the stray shunt resistance (possibly a few MΩ).

Accidental antenna effects (stray couplings, whether near-field or far-field) are significantly amplified by resonances, often between 10 and 100 times (20 to 40dB), possibly more, affecting both emissions and immunity equally due to the principle of reciprocity.

8 What does this mean for installations?

8.1 There is no such thing as "earth" or "ground" for SI, PI and EMC

Currents always flow in closed loops. So the idea that the earth/ground electrodes provide a perfect zero-impedance sink for throwing away unwanted electrical power, signals or noises can't possibly be true – it is a total myth, pure and simple, having no basis in reality in this universe.

Even if a zero-impedance earth/ground *could* exist (which it can't, because everything has impedance) – if we sent some unwanted current into it, the current would come back via some other route to complete its loop. So, then: no sinks.

Earth/ground is only a valid concept (can only have any effect) for human safety, where it an issue of preventing electric shock by limiting the maximum potential differences that someone could come into contact with, whether they are caused by mains electricity leakage currents or faults, or lightning strokes.

Even when earth/ground electrodes are doing their thing for safety reasons, the relevant currents still flow in closed loops.

Figures 9 through 12 show some examples of what are commonly called earths or grounds, but are really just elements of a building or site's CBN. I will show that a system or installation's CBN is important for its SI, PI and EMC, by helping return CM currents back to their sources with small loops – but whether it is connected to earth/ground electrodes for safety, or not, is of no consequence for

them.

Figure 9 This copper busbar is not an "earth" or "ground" for SI or EMI

Figure 10 These are not "earths" or "grounds" for SI or EMI either

Figure 11 … these are also not "earths" or "grounds" for SI or EMI

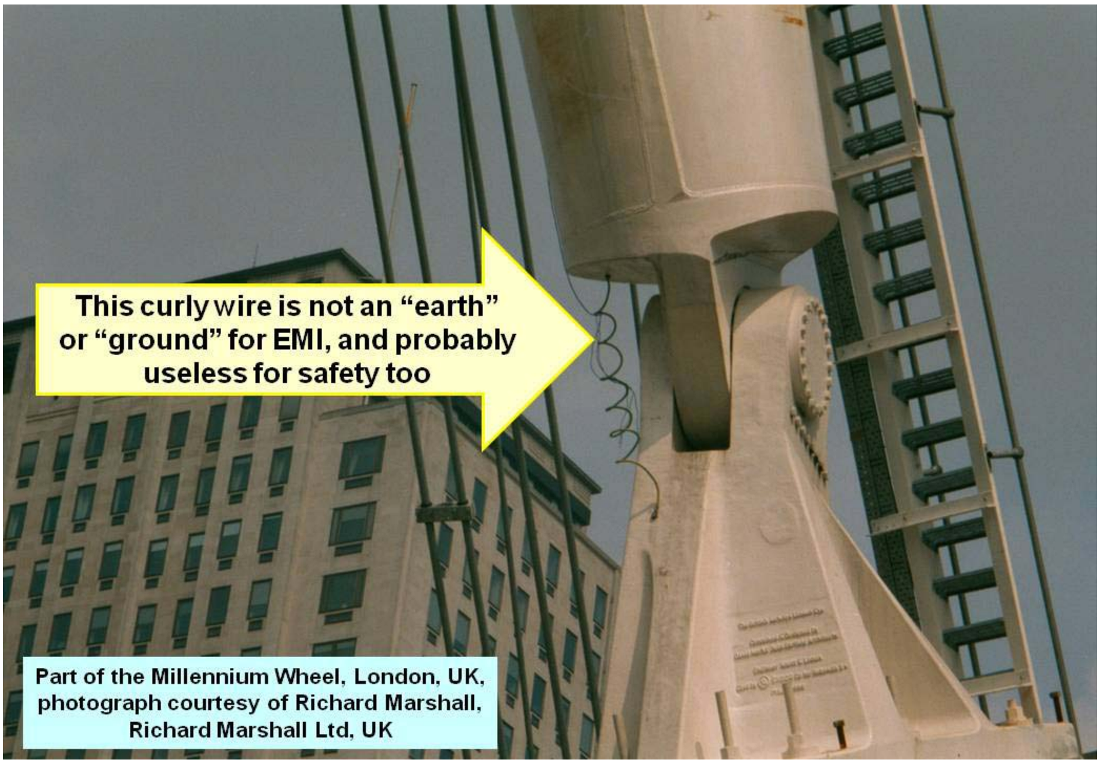


Figure 12 This is not an "earth" or "ground" for EMI or lightning protection, and probably not for safety either!

Of course, I am not the first person to comment on the meaninglessness of earths/grounds for SI, PI and EMC. Dr Bruce Archambeault is an IBM Distinguished Engineer and a mainstay of the IEEE EMC Society, and many years ago he produced the graphic I have used in Figure 13, as a way of making the same point I am trying to make here, only in a rather more amusing way. Unfortunately, I no longer have the original reference for this graphic, but it is used in [3].

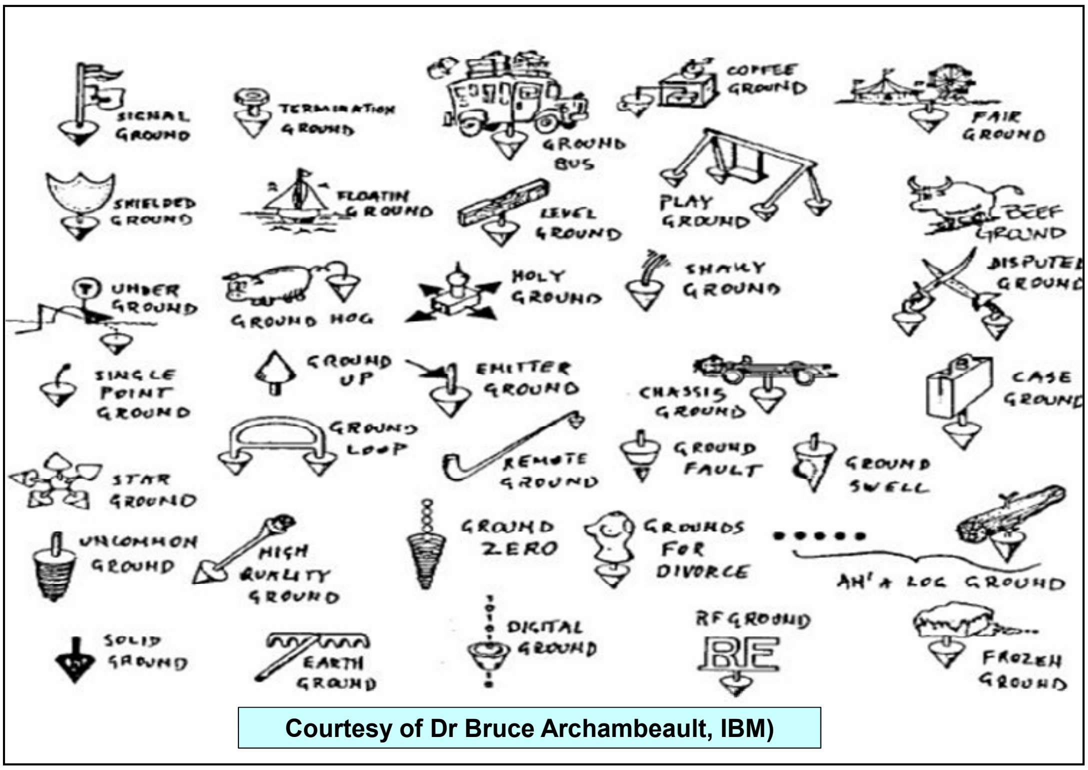


Figure 13 "Ground" is meaningless for SI and EMC

9 Applying these “tools” to a real-life example

I’m going to use the example of controlling the noise emissions from a switch-mode power converter driving a motor with variable speed (a VSD: variable speed drive), a real problem for many installations these days. It is identical to the problem of controlling noise emissions from magnet power supplies in scientific installations such as synchrotrons like Diamond [1], which use pulse-width modulated switch-mode power converter technology too.

(A synchrotron’s dipole magnet power supply, for the magnets that apply the brute force to the job of bending a relativistic electron beam into a circle, often use thyristor power converters instead. These are also a noisy technology and the same good EMC engineering techniques apply.)

Because these techniques control field patterns to minimise unwanted “noise” coupling, because of the principle or reciprocity the exact same techniques also minimise susceptibility, for example minimising unwanted “noise” couplings that add noise into electrical measurements.

9.1 The original installation design and its problems

Figure 14 shows an overview of the example, and Figure 15 shows that everything has stray capacitance to the building’s or site’s CBN. For clarity I have not drawn the stray inductances that also exist, but the same principles apply to their stray couplings as discussed below.

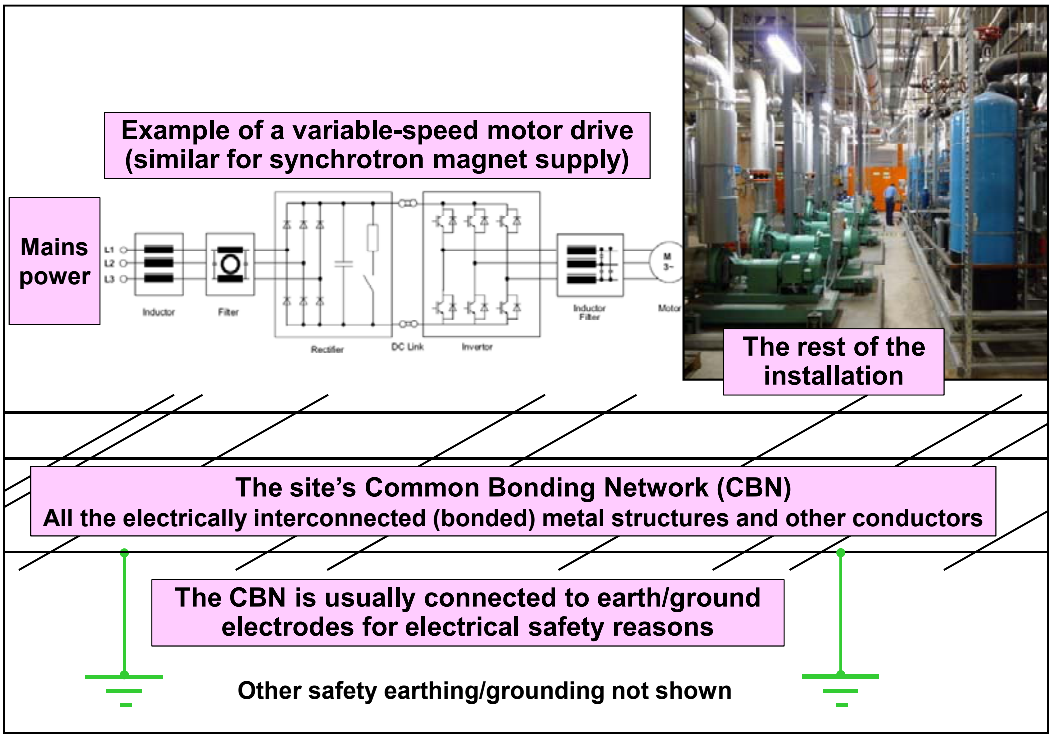


Figure 14 Overview of the example

The rectifier and chopper in the VSD each produce large amounts of noise currents and voltages at their fundamental operating frequency (16⅔Hz, 50Hz or 60Hz for the rectifier, a few kHz for the chopper) and their harmonics, up to at least the 1000th due to their fast switching speeds (i.e. their short turn-on and turn-off times). Figures 16 and 17 sketch the resulting DM and CM current loops for the original installation of Figure 14. It can be seen that they travel widely, in very large loops all over the site.

Figure 18 sketches the sort of field intensity versus location that we would expect to see, on a plan view of the VSD’s installation. Of course, it is only an illustration – a real-life field plot of the “noise fields” would show all sorts of variations that related to details of the site’s structure, electrical installation, etc.

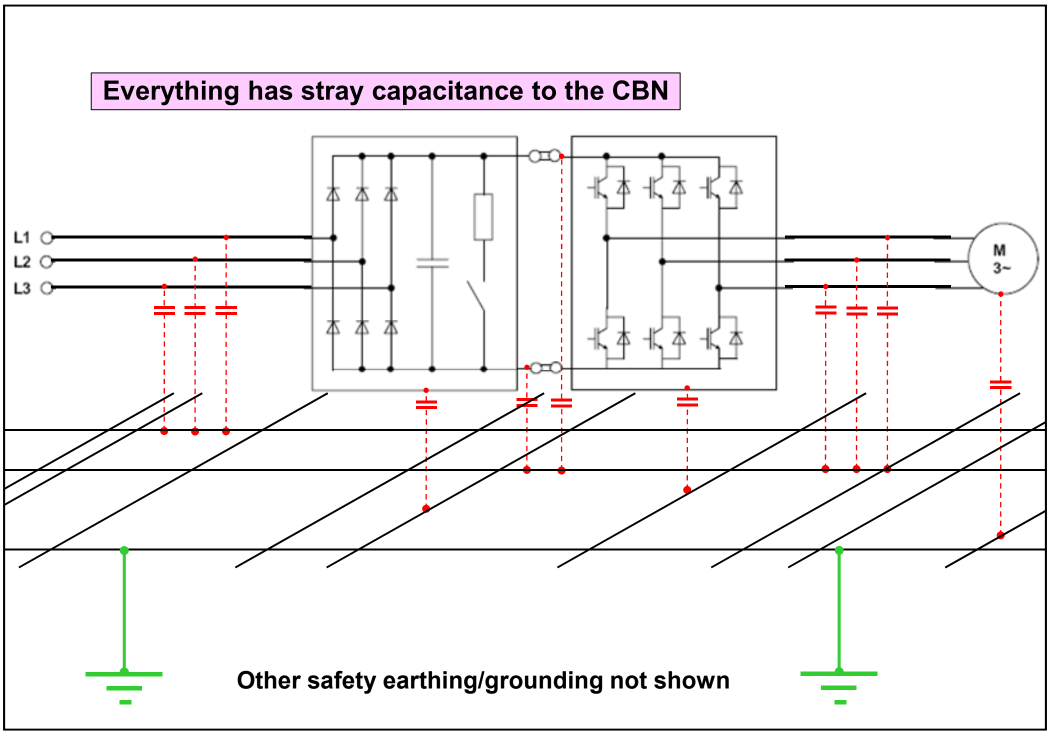


Figure 15 Everything has stray capacitances to the CBN

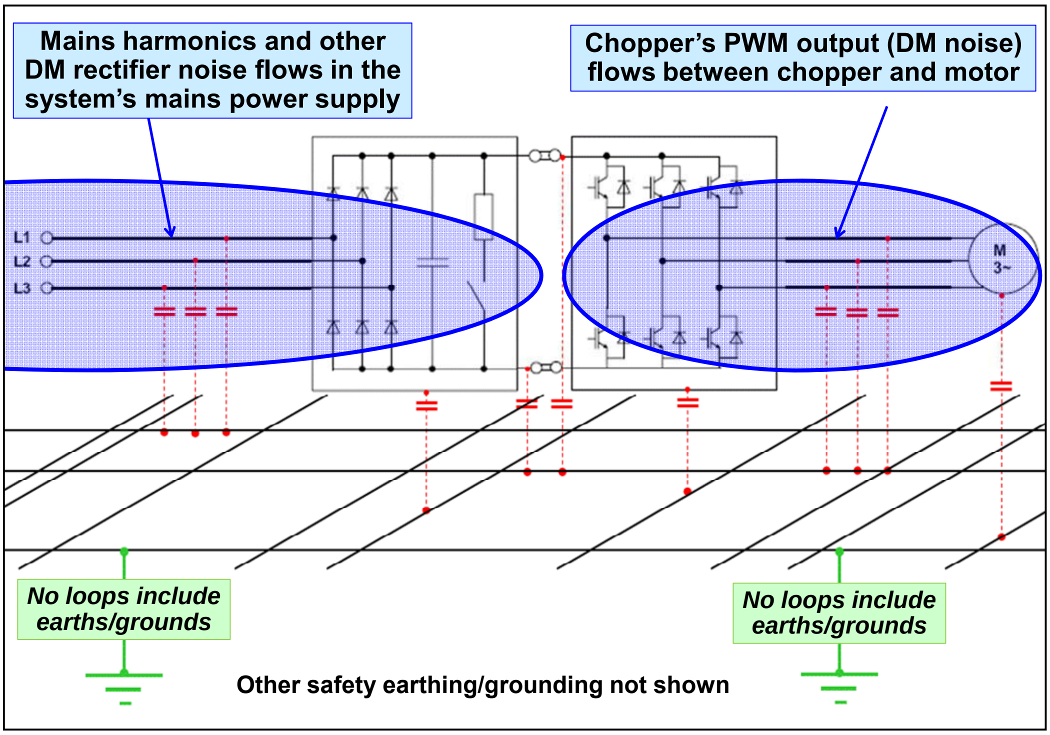


Figure 16 The original DM noise current loops occupy large areas

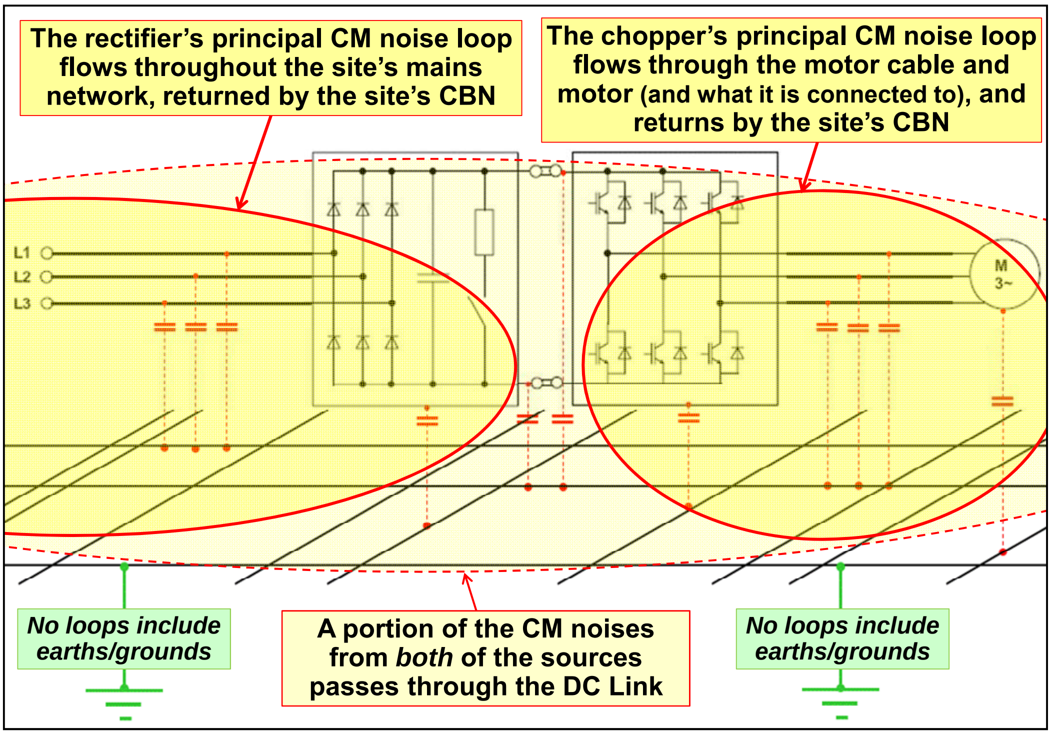


Figure 17 …and the original CM noise current loops occupy very large areas indeed

When earth/ground electrodes and their dedicated conductors take part in a send/return current loop path, they do of course carry currents. In a well-designed installation, these will only be CM (unwanted, stray) currents, and even then they will only be a negligible fraction of the principal CM current loops.

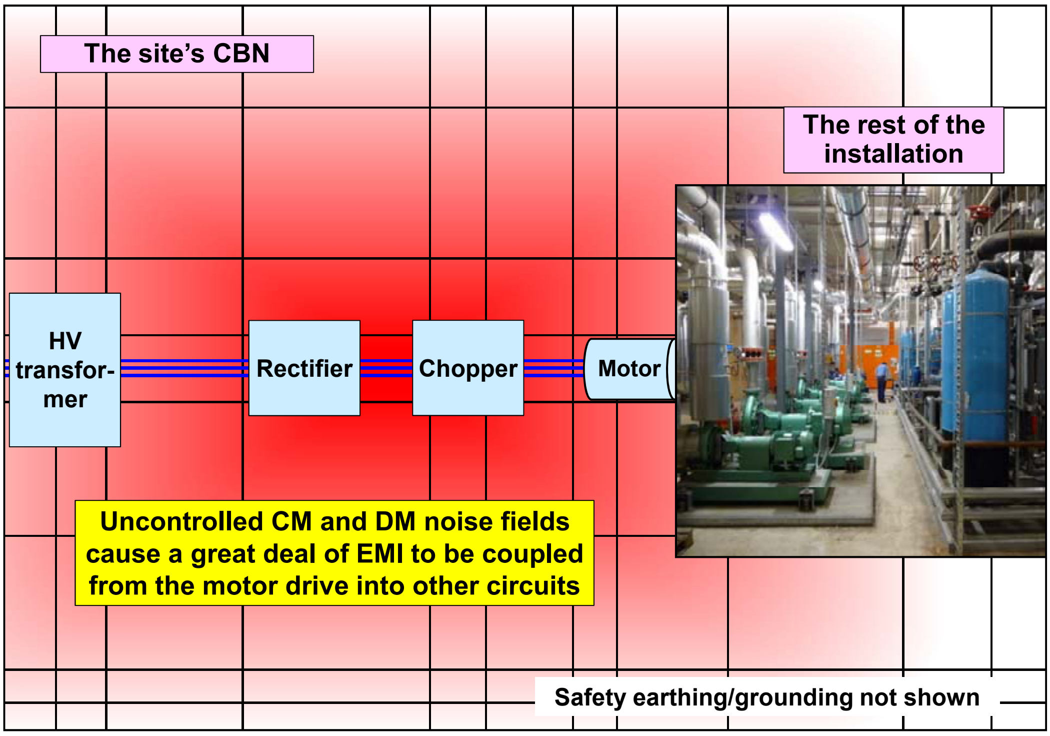


Figure 18 Plan view of the original DM and CM noise field distribution

Where Figure 18 shows a red-hued area, it means that other electrical circuits in that area will be picking up more noise than an area that is less strongly red coloured. Clearly, the original VSD system will inject noise into the many electrical measurements made by instruments on that site.

9.2 Applying the fundamental principles – creating small loops

We can very significantly improve the SI, PI and EMC of the site by creating small DM and CM loops for the VSD's noise currents.

We do this by adding filters that prevent the passage of frequencies (other than the fundamentals) into the mains distribution network and motor cable, for both the DM and CM noises. We also create small, low-impedance loops for the CM currents flowing in the CBN, to keep them local to the VSD.

Just as we need an RF Reference Plane to even begin to control SI, PI and EMC for a printed circuit board [5], or an electronic cabinet [6], we also need an RF Reference Plane for a building or site like the example used here. In a building or site we generally do it by converting the CBN into a MESH-CBN – a CBN that is designed to control up to a given frequency, by creating a small enough size of conductive mesh. This is usually easy and cost-effective, because most of the conductors already exist – we just have to cross-link them at frequent intervals.

[7] describes MESH-CBNs, but [8] and [9] have chapters that describe how to design and construct them in more practical detail, and both include graphics such as Figure 19, the original concept for which was drawn by Alain Charoy of AEMC, France, in the mid-1990s.

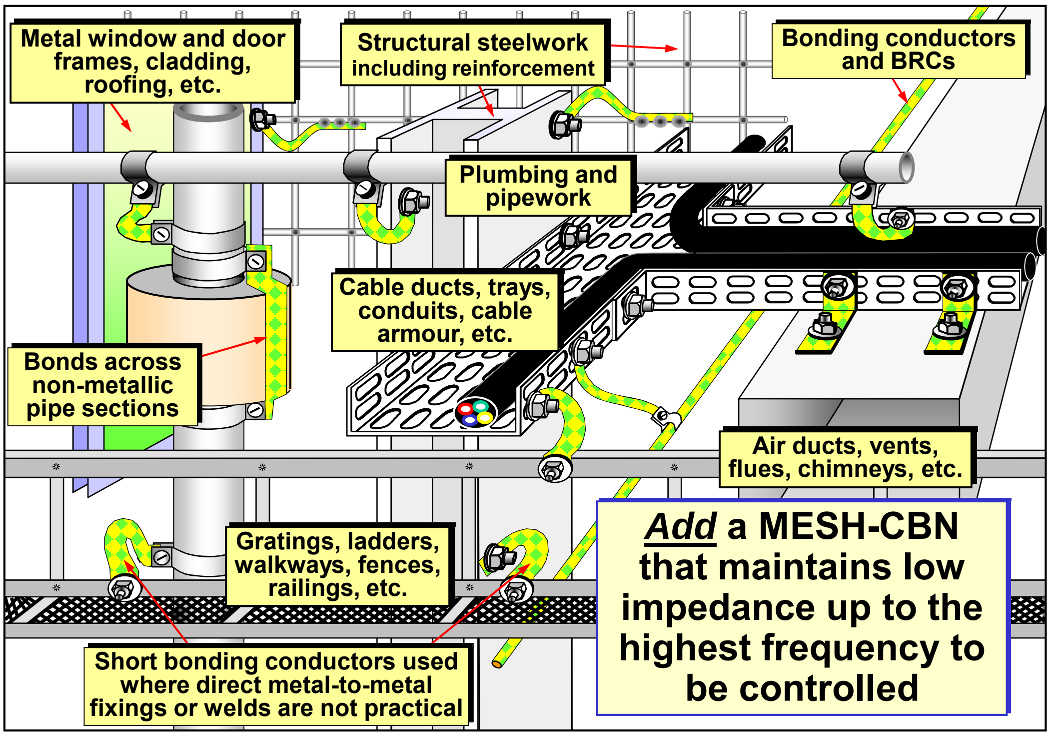


Figure 19 Creating a MESH-CBN

Continuous metal sheet makes the best MESH-CBNs, and provides the lowest possible impedance of any two-dimensional metal structure up to any frequency. Meshed conductive structures are effective only up to about 30/L MHz, where L is the largest diagonal in the meshed structure, in metres. Actually, they are not *very* effective at 30/L MHz, but they are quite effective below 3/L MHz, and much better still below 0.3/L MHz.

However, MESH-CBNs (like any meshed conducting structure) can be as bad as single-point (star) earthing/grounding at frequencies above 50/L MHz – where they start to resonate. So it is important to mesh the CBN finely enough, where it is to carry CM loops with higher frequencies.

[7] shows that we can use different mesh sizes in different areas of a site, to control different frequencies of the CM loop currents flowing in those areas. So for example we can route all our cables in sheet-metal cable trays and ducts (basket and ladder types have restricted frequency ranges, like any mesh), better still in solid metal conduit – multiple-bonding them at all joints and both ends in such a way that they provide the optimum loops for CM currents up to at least 100MHz.

These low-impedance "lanes" for CM currents will generally be embedded in a site's MESH-CBN that has much larger mesh size, that may only be able to control CM currents up to, say, 1MHz. But if we design and construct our high-frequency CM paths correctly, the CM currents will (mostly) flow just where we want them to.

When we have our MESH-CBN, we place our filters, rectifier and chopper units very close together on it, as shown in Figure 20. These units should be so close that we can electrically interconnect their metal bodies with multiple short conductors. Ideally they would be touching each other so that we can bolt their metal enclosures directly together, metal-to-metal.

We then connect each of the units' metal enclosures to the MESH-CBN with multiple short conductors, directly connecting them metal-to-metal where practical.

The purpose of the multiple short bonds and direct connections between the units, and between the units and the MESH-CBN is to provide very low-impedance, very *small* loops for the CM currents.

The CM currents are coupled into the CBN by the stray capacitances and inductances and so are unavoidable (see Figure 15). The CM filters in the mains and output filters inject the CM currents that would have flowed in the wider installation, into their enclosures, adding to the local CM current density. The smaller and lower-impedance the CM loops we create, the less CM current will split off and flow in the impedances of the remainder of the installation, where they can cause interference.

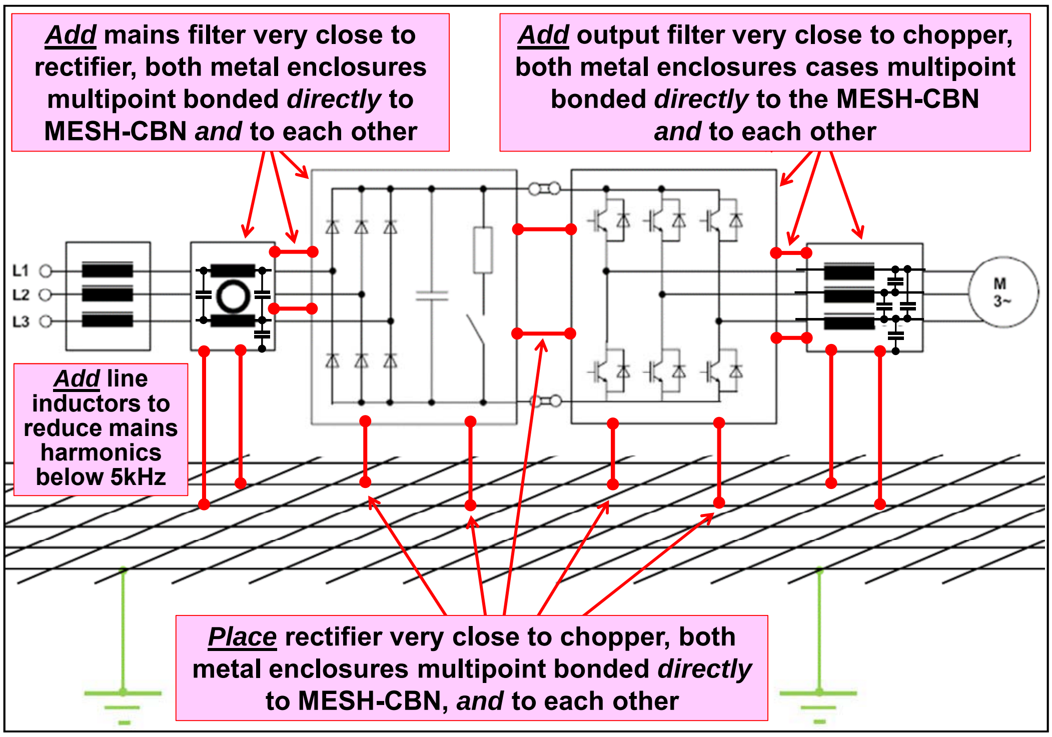


Figure 20 The example with input and output filters, plus multipoint bonding

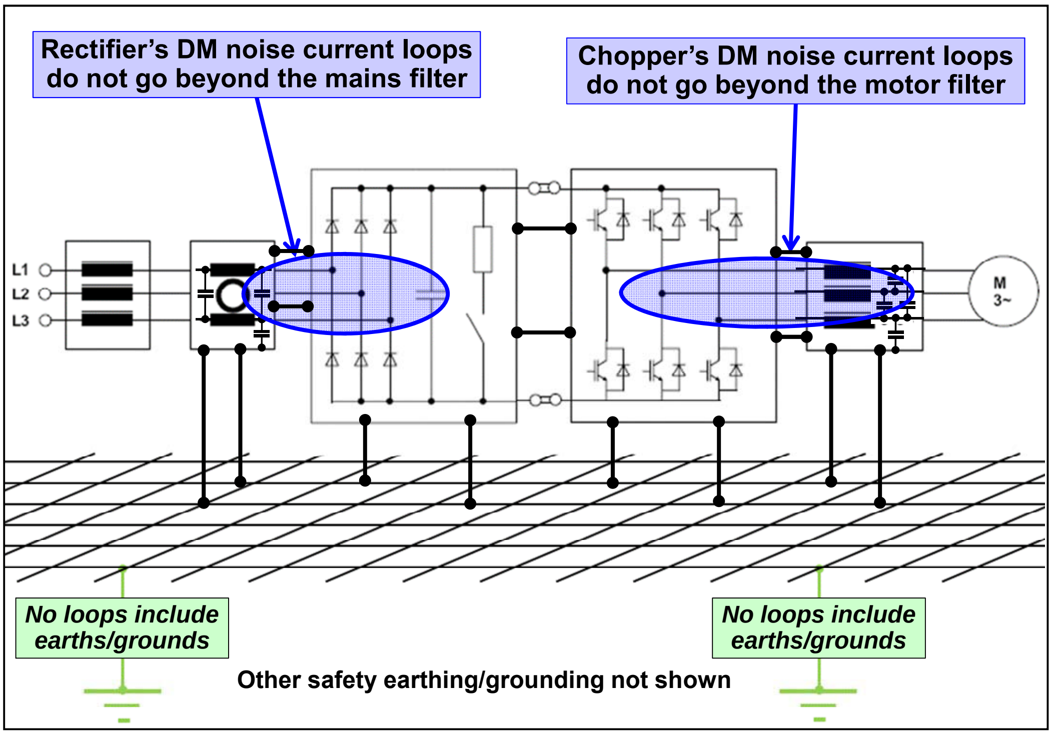


Figure 21 The DM noise current loops are now much smaller

Figures 21 and 22 show the effects of our modifications on the DM and CM current loops, and Figure 23 illustrates the new DM and CM field intensity versus location in the plan view of the site.

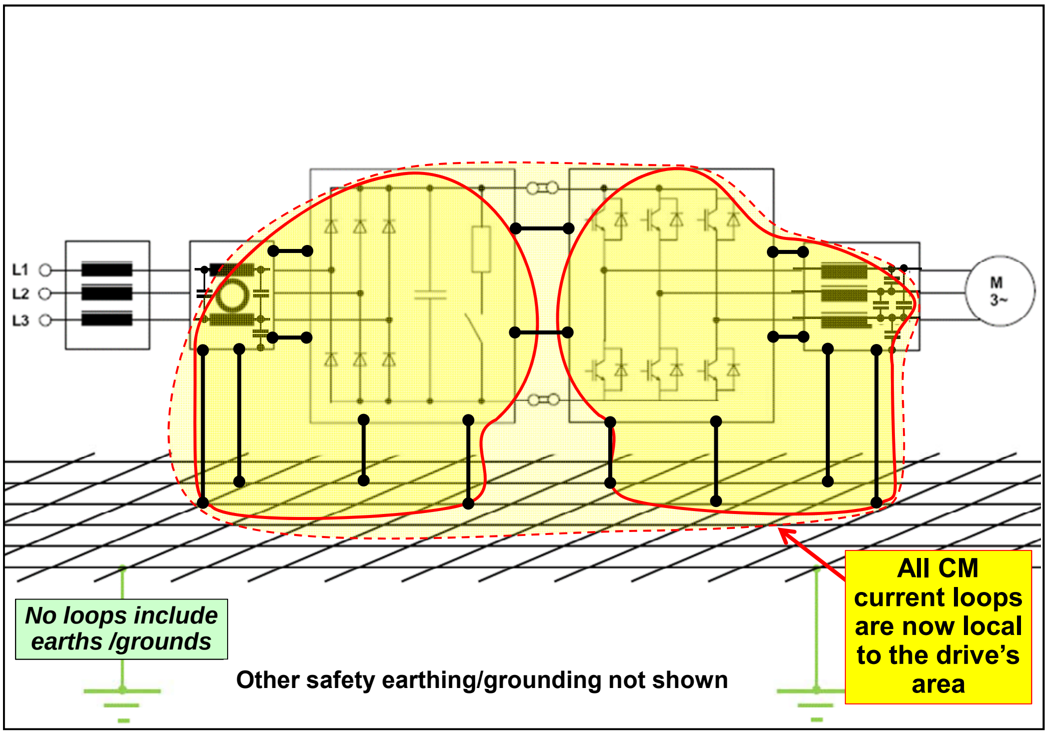


Figure 22 …and so are the CM noise current loops

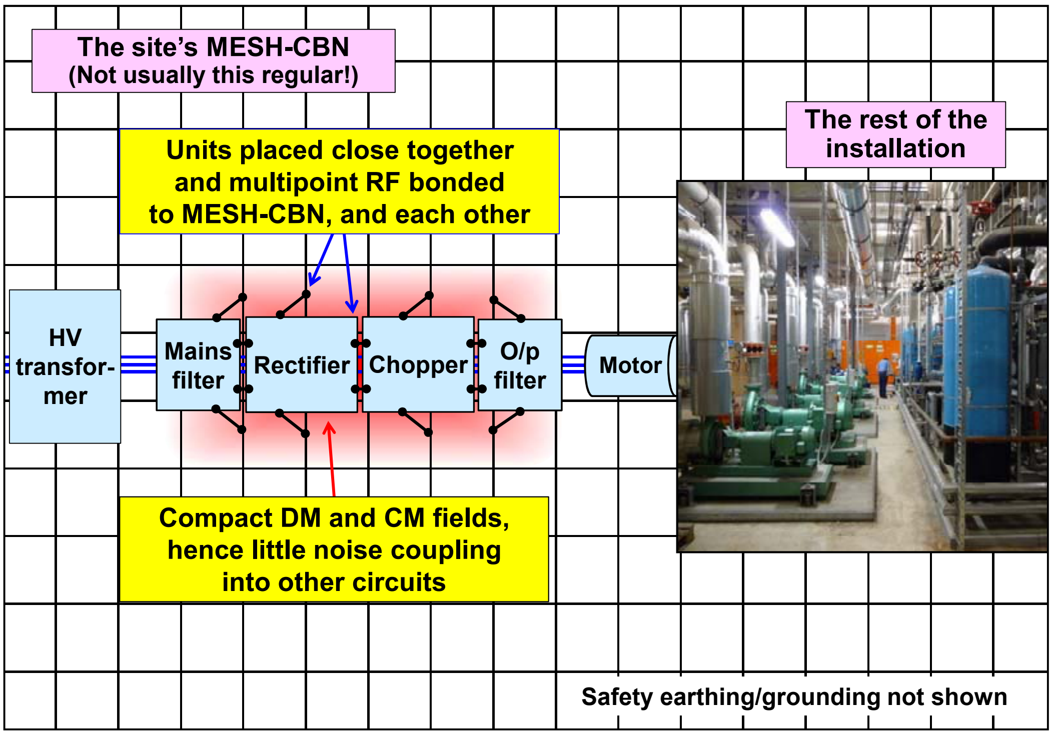


Figure 23 Plan view of new DM and CM noise field distribution

The CM currents automatically prefer to flow in the loop(s) with the lowest impedance, so they automatically prefer to flow in the route with the smallest loop area – the path with the most compact field patterns – which is also the path with the least "accidental antenna" effects.

These are the loops we created with our MESH-CBN, mains input and motor output filtering and bonding. These loops couple least into other circuits, and achieve the best SI, PI and EMC.

9.3 All we have to do is provide low-impedance paths for return currents

The fact that currents prefer the path with the smallest loop area and lowest impedance, is the only way that I know in which the laws of physics work *with* a designer, instead of against him or her.

Computer field solvers show this phenomenon very clearly. For example Figures 24 and 25, copied from [10] show that when a bent wire carrying a current is routed close to a sheet metal chassis that it is using as a return path (20mm in this example) the return current flows almost exclusively in the metal that lies underneath the wire, following its bent path, at frequencies above 10kHz.

This is because the return path in the metal sheet below the bent wire has the least overall impedance, even though it goes around a bend.

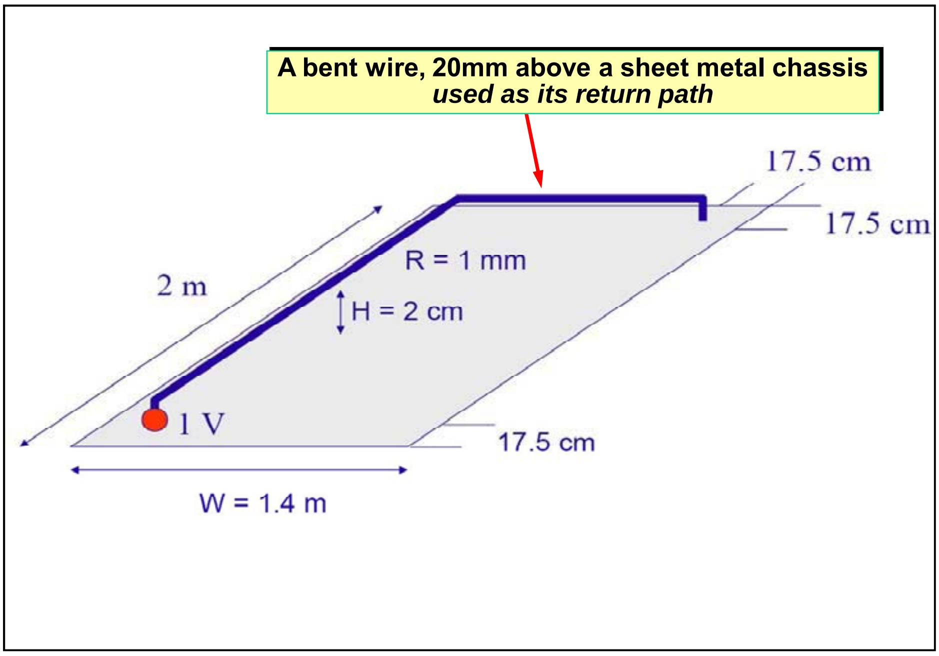


Figure 24 Example of a bent wire with a sheet metal chassis for its return current

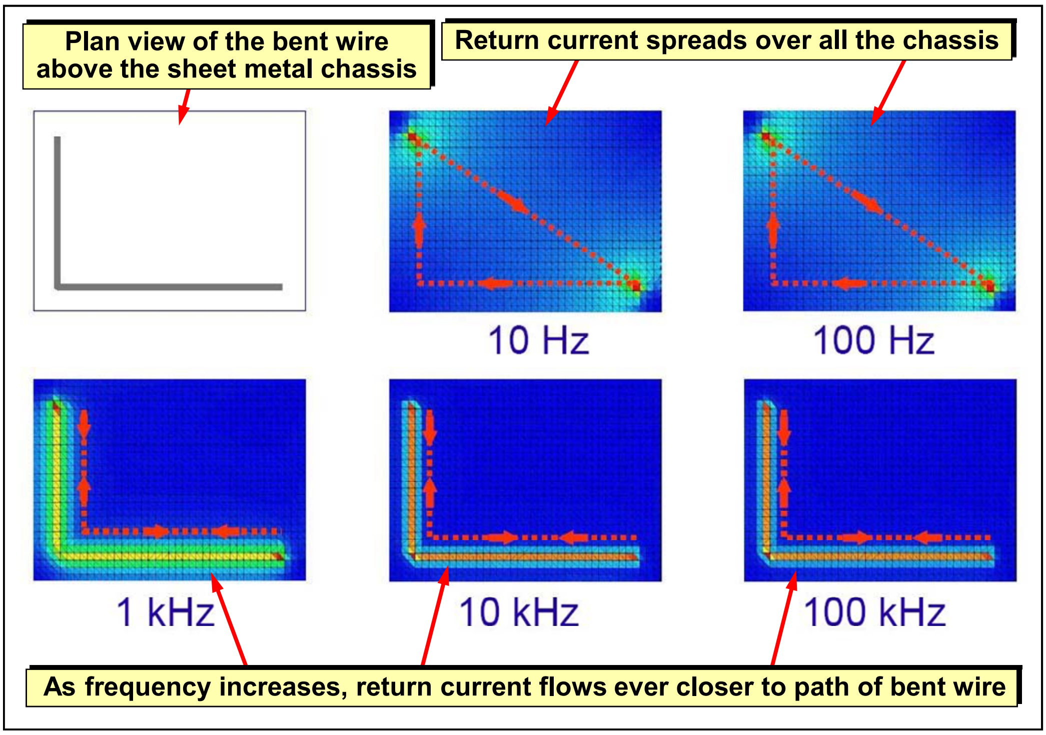


Figure 25 Computer simulations of the return current path for a wire above a plane

The red dotted lines in Figure 25 were drawn by hand by the original authors, to help understand where the mean or average current return path lies, from the colour gradients in the field solver's plot.

It is important to notice that although the return current is flowing in part of the metal sheet, the rest of the sheet is "quiet", and circuits using those parts of the sheet do not suffer any noise from the bent wire current loop at frequencies above 10kHz. (and below 10kHz the impedance of the sheet is so low that the voltage noise caused in the other circuits by the widely-spreading return current are generally negligible).

The shortest DM loops are provided by:

- Twisting the send and return conductors…
- A coaxial return path around the send path (e.g. cable shield)

The shortest CM loops are provided by:

- A return path in very close proximity to the send path (e.g. routing all DM conductors along elements of a MESH-CBN designed/constructed to have low impedance for the frequencies to be controlled)
- A coaxial return path around both of the DM conductor (e.g. a shielded twisted-pair cable)

For these techniques to control noise emissions and susceptibility, any metal elements in the return paths (DM or CM) must be directly connected to the equipment at both ends, in a way that achieves low impedance at the frequencies to be controlled.

This means multiple-bonding the metal enclosures, frames or chassis of all items of equipment directly to the MESH-CBN, and bonding cable shields at both ends as discussed next.

10 Skin effect and its importance for shielding and filtering

10.1 Basics of skin effect

Another basic principle that we need to understand, to complete our "tool kit" of techniques, is called the "Skin Effect", described in Chapter 3.1.1 of [2].

We need to understand skin effect to make sure that what *appears* to be a low-impedance path in a MESH-CBN really is a small current loop, so that CM currents are encouraged to flow mostly in the path(s) we want them to.

We also need to understand skin effect to be able to use shielding and filtering most effectively – to increase the impedances in the paths we *don't* want DM or CM currents to take.

Skin effect arises because E-field coupling results in displacement currents flowing on the surface of a metal, and because H-field coupling results in an eddy current flowing inside the metal, creating a field opposing the incoming field (Lenze's Law). In both cases, the currents flow mostly on the side of the metal where the E or H field impinges.

The coupled currents from the E or H fields (whether they are near fields, or the constituents of a far-field EM wave) flow mostly near the surface of a metal conductor, depending on its resistivity and permeability. The higher the frequency and/or conductivity and/or permeability – the thinner the "skin" carrying the majority of the coupled current.

Figure 26 shows an example of a copper sheet seen edge-on, in cross section. For a DC source, the current density between the two connection points on the copper is uniform throughout its thickness (although a plan view would show some "current crowding" around the contact points, as can be seen in Figure 25 for the DC and low-frequency cases.)

But for a 1MHz AC source the current has to flow all around the edges of the plate to get to the contact point on the other side.

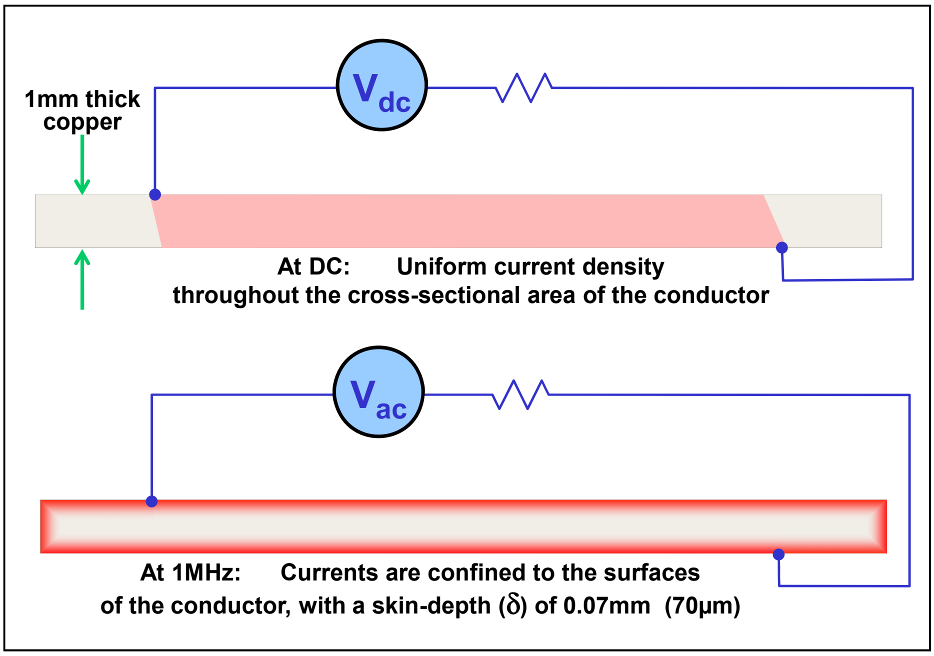


Figure 26 Examples of cross-sectional current density in a copper sheet

In annealed copper, the skin depth formula (see [2]) tells us that the current density in the metal reduces by $1/e$ (about 0.368, or -8.7dB) for every $66/\sqrt{f}$ millimetres below its surface, when f is in Hz. At 1MHz in copper, this means that one skin depth (δ) is about 67μm, so if the copper sheet is 1mm think it represents about 15 skin-depths at that frequency, attenuating the current density by 0.368^{15}, 130dB, or to about $0.3\cdot10^{-6}$ of the current density on the other side.

So only about one-third of a millionth of the current injected by the contact on the top surface would penetrate through the thickness of the metal sheet to the contact point on the bottom surface. Instead, this DM current loop has to flow around the edges of the sheet as shown in the bottom part of Figure 26, to get to the other contact and complete the circuit.

If we were to drill a hole in the sheet, some of the current would "pour" from the top to the bottom surfaces by flowing around the edges of the hole. If it had a large enough diameter, it might divert most of the surface current away from the edges, by providing a lower-impedance path.

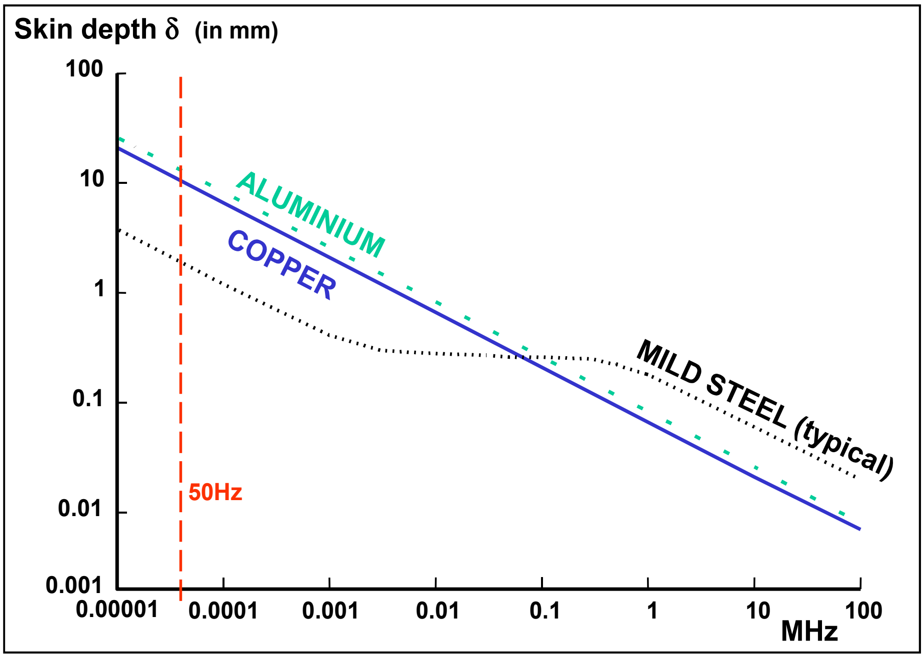


Figure 27 Graph of skin depth (δ) for copper, aluminium, and mild steel

[2] provides sufficient information and references for accurate calculations of skin depth for any conducting materials, but Figure 27 provides some quick references for good conductors like copper and aluminium.

Skin effect means that RF currents can't flow through metal. Above a certain frequency, most of the current has to flow around the edges of a metal object, including the edges of any holes, apertures, joints, gaps, seams in the object.

Now that we have added skin effect to our EMC toolbox, we can use it to help constrain DM and CM current loops to flow where we want them to go, to minimise the leakage into alternative loops, and hence further minimise field patterns.

10.2 Skin effect and good practices for cable shielding and filtering

Figure 28 shows how skin effect keeps the internal and external CM currents apart, in a well-constructed cable shield termination.

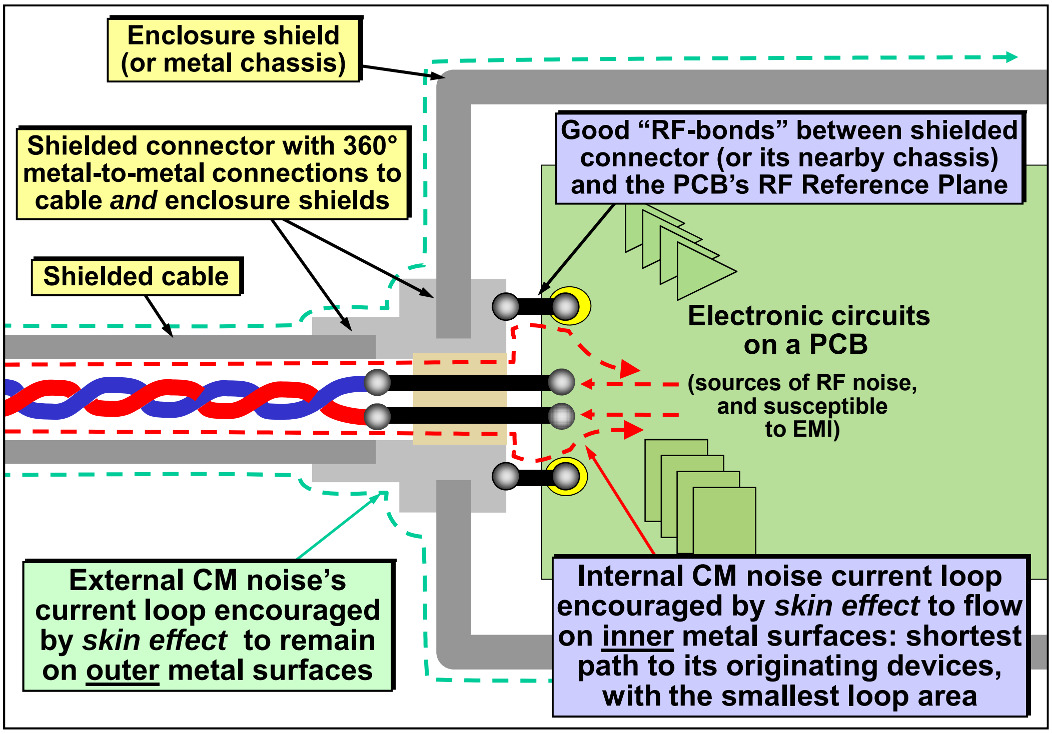


Figure 28 Skin effect and good-practice cable shielding

Figure 28 shows us why the practice of terminating cable shields with wires or via connector pins – generally called "pigtailing" ruins shielding effectiveness above a few kHz.

Without the benefit of the skin effect, a larger proportion of the internal CM currents will flow in alternative loops on the outside of the enclosure or cable shield, and cause EM emissions. It may not be a very large proportion, but it only takes 15μA of internal CM current on the outside of a cable shield to fail the Class A emissions limits for industrial environments – and a VSD can generate several amps of CM current.

Also, without the benefit of skin effect, any external CM current that gets onto the *inside* of an enclosure or cable shield will cause noise in the circuits.

Pigtails are deprecated by [7], and Figures 29 and 30 are different ways of showing how bad they are. Figure 29 was very kindly provided to me recently by Alain Charoy of AEMC. Alain is an independent EMC consultant based in France. Figure 30 is taken from [11].

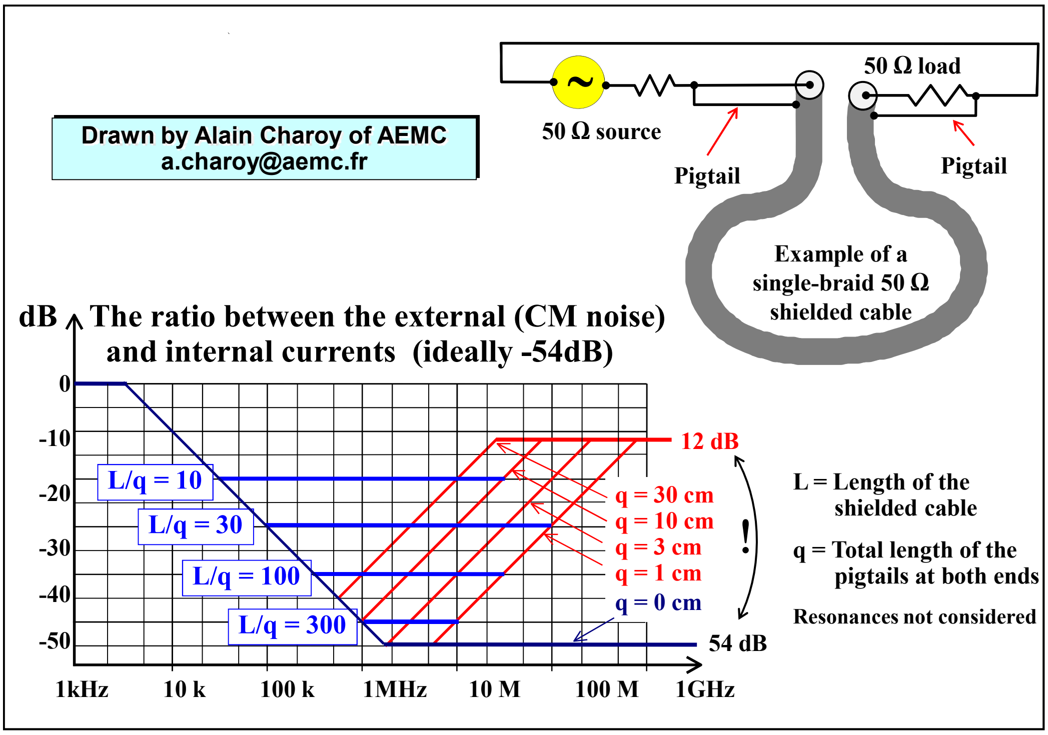


Figure 29 Pigtails are very bad for cable shields!

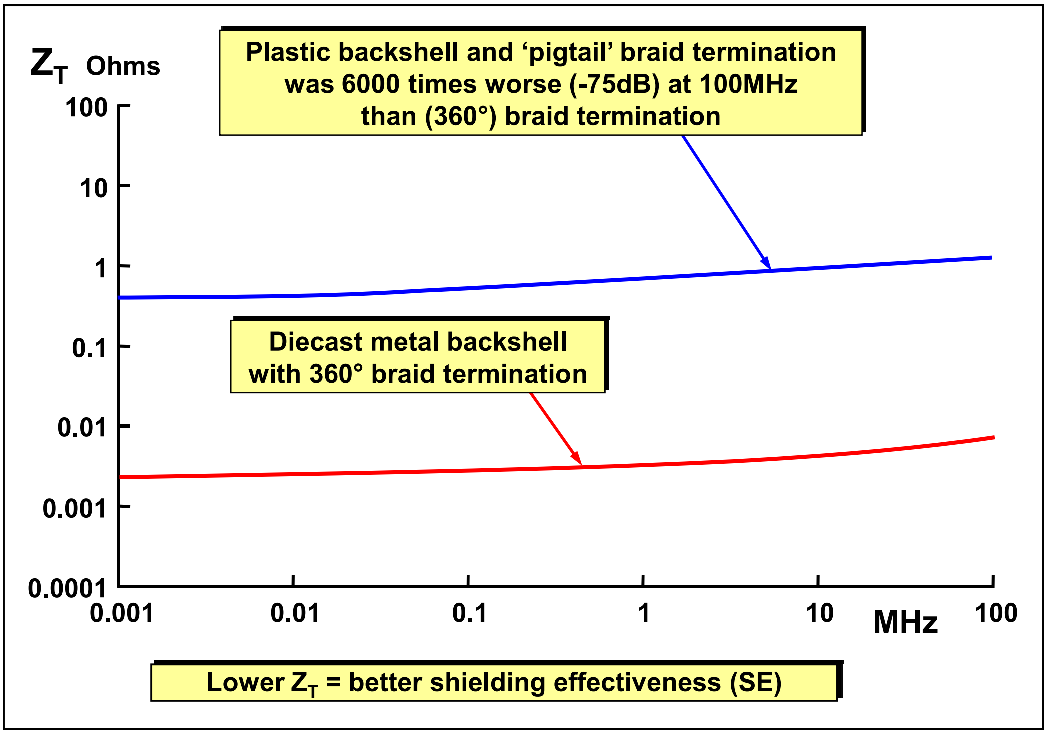


Figure 30 Pigtails are *really* very bad for cable shields!

Figure 31 shows how we should use skin effect to optimise filtering, by (once again) making it more difficult for the external CM currents to flow in alternative internal loops and inject noise, and for the internal CM currents to flow in alternative external loops and cause emissions.

It only shows the filter as consisting of a capacitor, which is typical of many signal filters, but mains and other power filters will also have chokes, and may have two or more stages of choke/capacitor combinations in series.

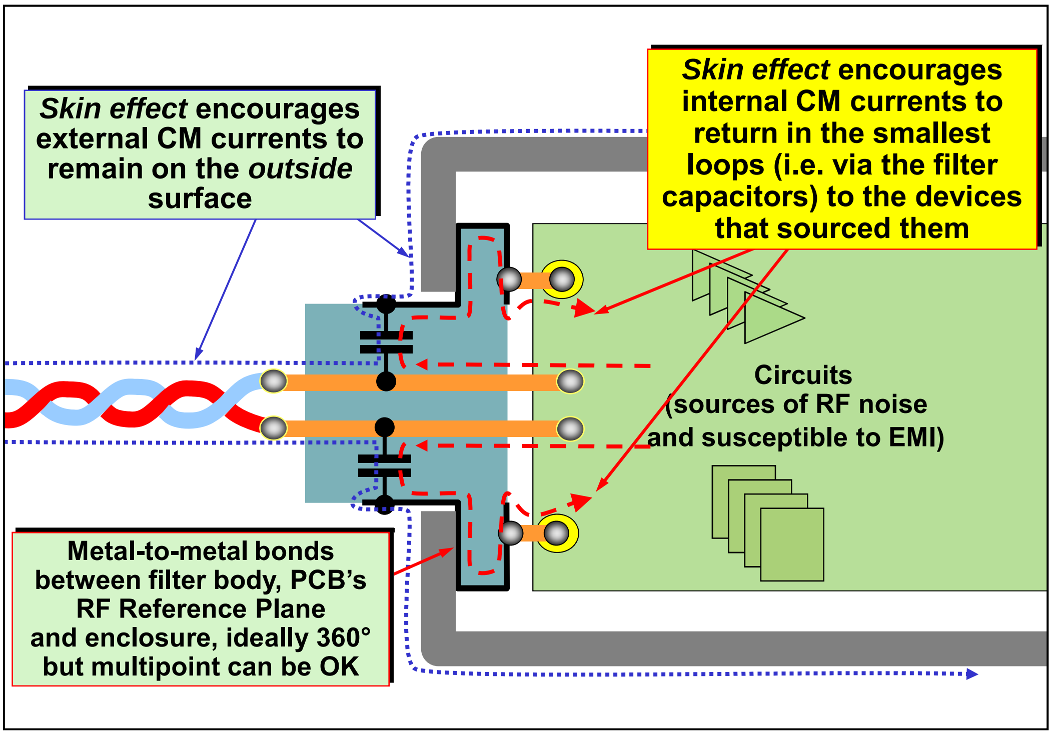


Figure 31 Skin effect and good-practice filter assembly

10.3 Applying shielding to the example installation

Now that we've added skin effect to our EMC toolkit, we can investigate how to use cable shielding most effectively in our example VSD installation.

Figure 32 shows our example with the mains filter that was used before, but without the output filter and with a shielded motor cable instead, with the shield terminated correctly at the VSD and the motor frame (see [8] or [9] for details).

Most VSD installations use shielded motor cables, but it is not unusual to find them using pigtails, single-ended shield termination, and other very bad SI, PI and EMC engineering techniques.

(Almost the entire electrical installation industry worldwide believes – with an almost religious fervour – that cable shields must absolutely <u>not</u> be connected at both ends, and that it doesn't matter how long a pigtail is, as long as it uses wire with green/yellow striped insulation and is connected to something (like a water pipe) that eventually finds its way into the soil and so is earthed or grounded.

Documented good EMC installation practices are now mandatory in all EU Member States under the EMC Directive 2004/108/EC, and the next edition of the IEE Wiring Regulations will require electricians to employ good EMC engineering practices. So if any electrical installers read this article, could I ask them to please bring it to the attention of all the others, worldwide?)

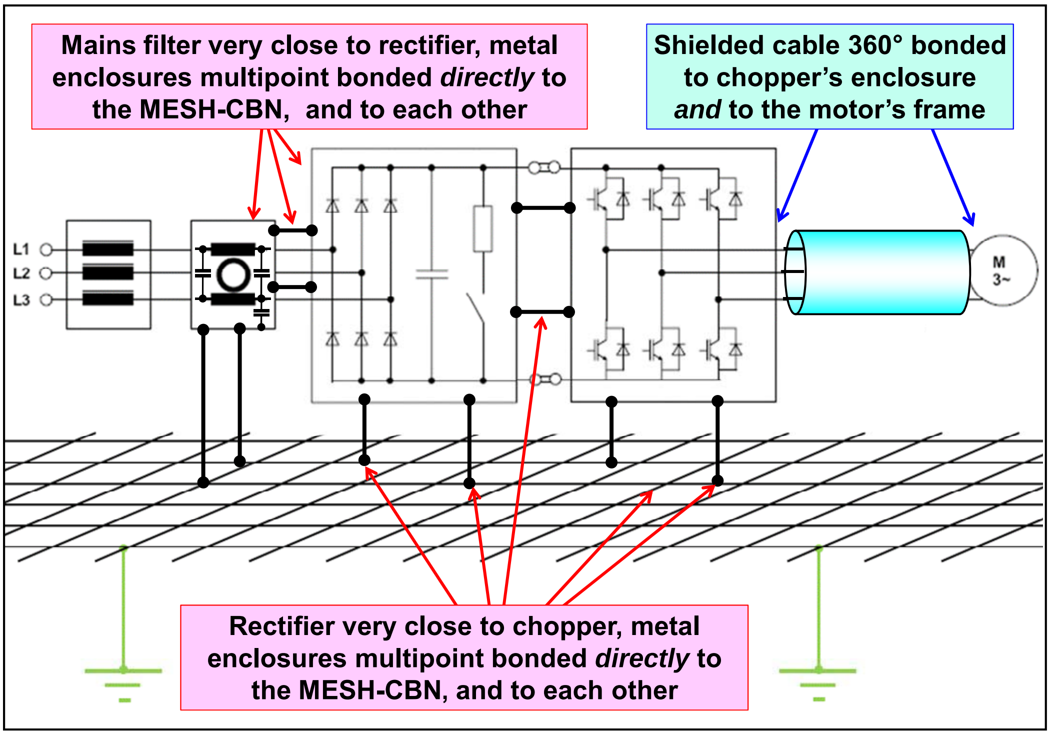


Figure 32 The example, with a mains filter and shielded motor cable

Figures 33 and 34 show the effects of this new design, on the DM and CM loops in our example VSD installation, and Figure 35 shows a plan view of the sort of "noise field" distribution we can expect when we do a proper job.

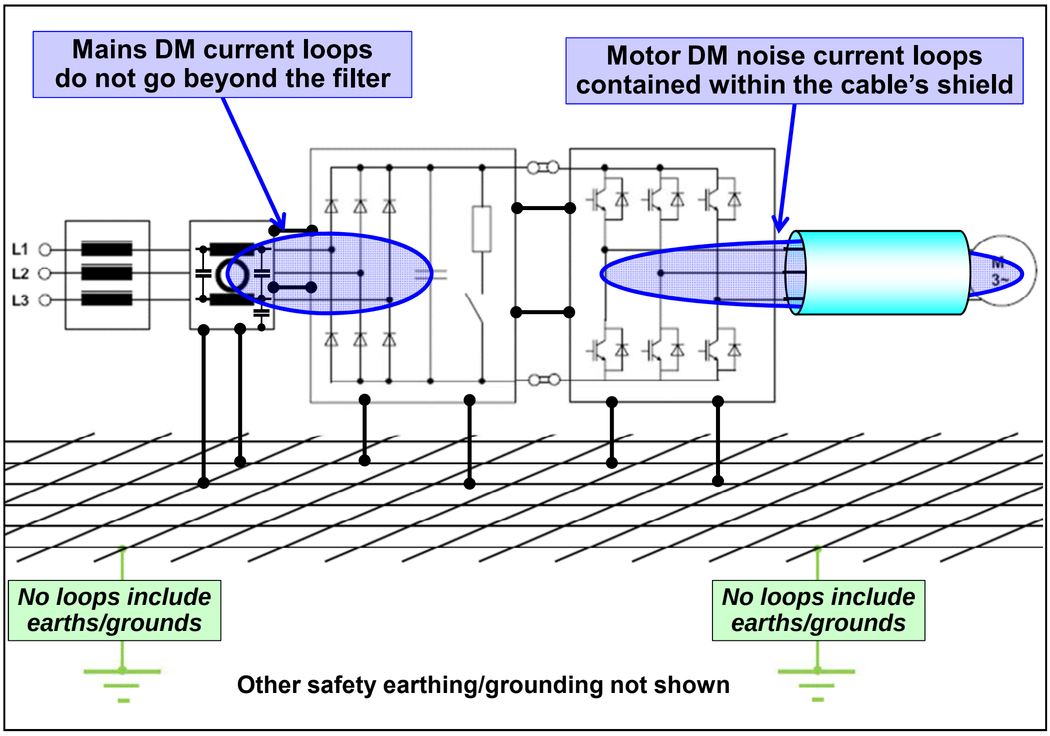


Figure 33 The DM noise current loops are now even smaller

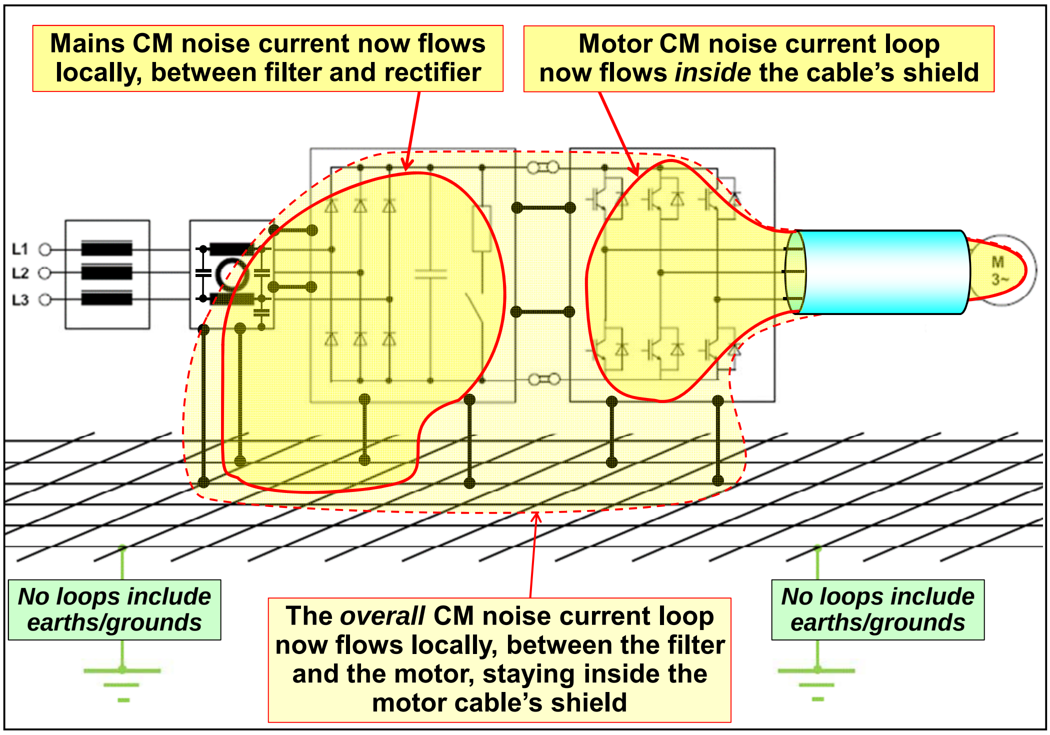


Figure 34 …and so are the CM noise current loops

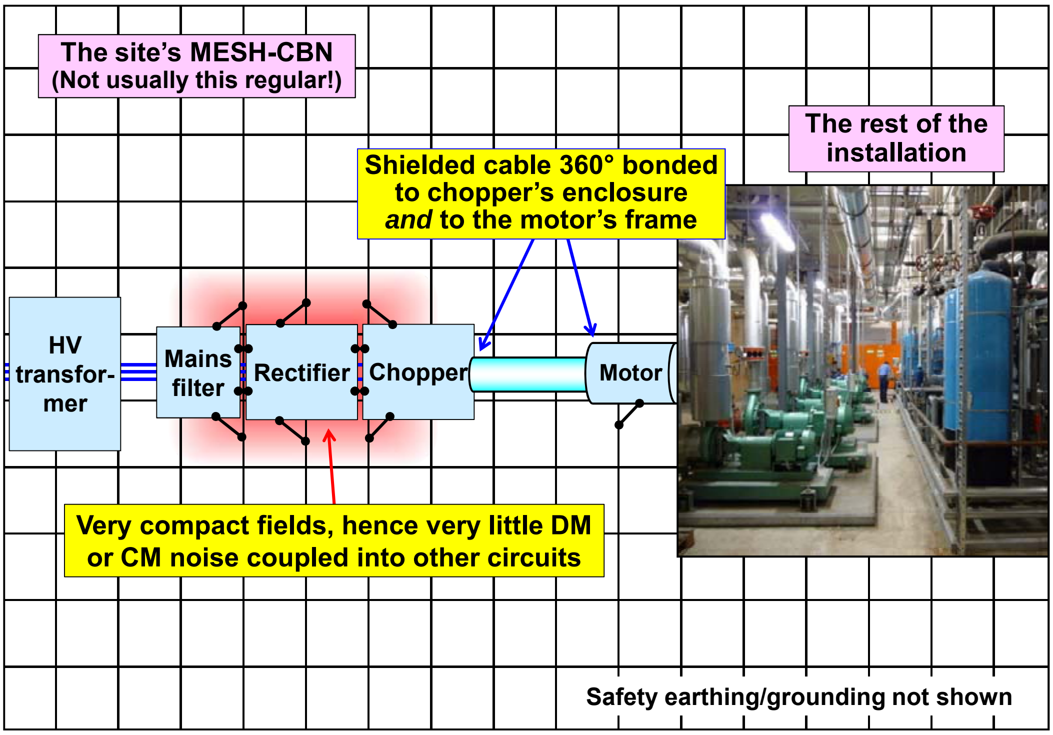


Figure 35 Plan view of new DM and CM noise field distribution

10.4 Earth/ground loops aren't the problem they might seem to be

Connecting cable shields to the metal enclosure, frame or chassis of the items of equipment at both ends allows the unavoidable voltage differences around an installation's CBN to drive potential equalising currents through them. This causes what are usually called "earth loop", "ground loop" or "hum loop" problems for badly-designed electronics, usually because they do not connect their cables' shields to their metal enclosure, frame or chassis, but to their internal circuits instead.

These naturally-occurring currents do not cause problems when electronics are properly designed for systems and installations, and it is usually possible to modify problematic equipment by adding galvanic isolation such as transformers and optical isolators.

But creating a MESH-CBN generally reduces the common-impedance of the CBN by so very much that the potential-equalising shield currents are reduced to the point of insignificance. See Chapter 5.1 of [2] for more on this topic, and [9] for more detail on solutions.

11 These principles and techniques work as well for immunity as emissions

These techniques employ the fundamentals of electromagnetism, to make field patterns and wave propagation as compact as possible – dramatically reducing EM coupling, reducing emissions, and (by the principle of reciprocity) improving immunity – helping to keep noise out of measurements and making more precise control possible.

Some installations (e.g. Tokamacs used for fusion experiments; powerful radio transmitters, etc.) create very powerful high-frequency fields that can't be reduced without compromising their operation and functionality, and these can create DM and CM noises in all conductors, especially problematic for sensor cables. This kind of problem has been met many times before, and Eindhoven University of Technology has been solving them for many years using the techniques described above, see [12], [13] and [14] from the 1980s and 90s.

Figure 36 is a photograph of a circuit breaker opening a high-voltage power line under full load. Such electrical events generate huge amounts of arcing, with correspondingly huge levels of conducted and radiated noise emissions.

Figure 36 A high-voltage power line's air circuit-breaker opening under full load

[12] describes a number of case studies including that of oscillations of 250A at 400kHz when a 150kV HV line was open-circuited. The oscillations are caused by the resonance of inductance of the HV conductor with the stray capacitance between the HV transformer and its tank, excited by the energy released during the arcing when the circuit-breaker was opened. Figure 37 attempts to reproduce the situation described in [12].

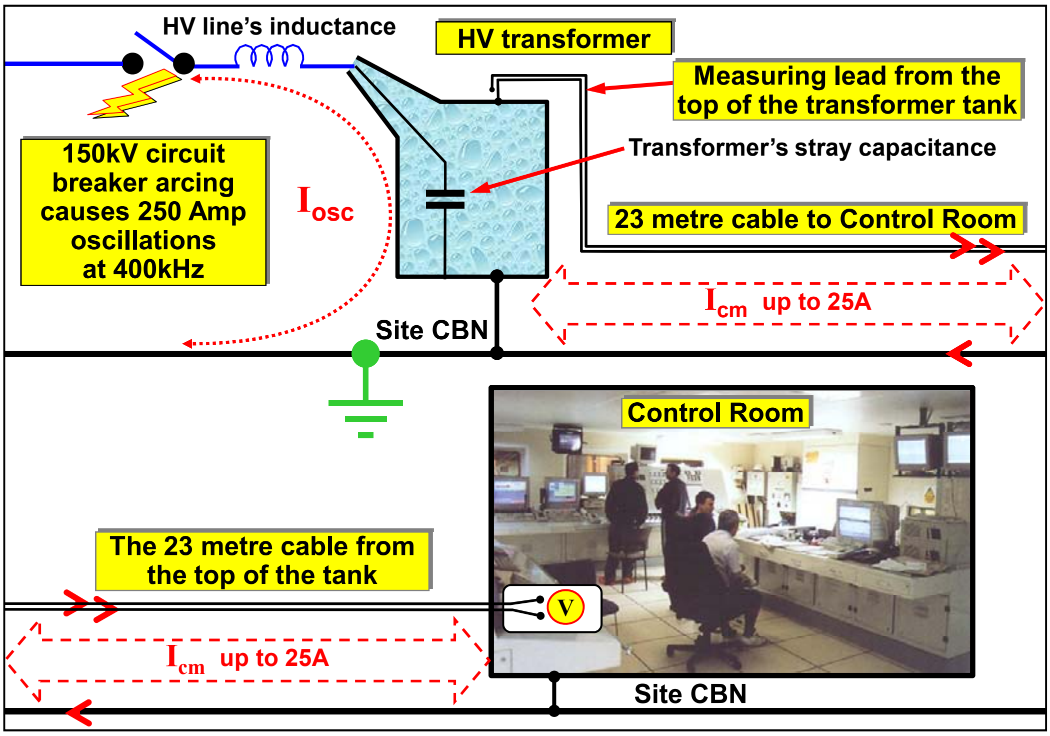


Figure 37 The HV oscillation problem

Such high levels of noise can damage the electronic measuring instruments in the control room, and a typical measuring lead from the top of the transformer tank to the control room, 23 metres long, was found to experience voltages with respect to the Control Room's CBN of about 2.3kV when the HV due to the oscillation when the circuit breaker was opened. This is caused by the noisy CM current flowing in the measuring lead during the powerful oscillation caused by the arcing.

Figure 38 shows the progressive reduction in the transient oscillation voltage at the control room, as the usual techniques for reducing the effects of CM noise were applied. A two-conductor steel-wire-armoured (SWA) cable was installed in place of the measuring lead, in a rectangular steel conduit open at the top.

With just one conductor used as the measuring lead, the peak noise voltage during arcing was the same, at 2.3kV. Then the parallel conductor in the cable was bonded to the top of the tank at one end and to the control room's CBN at the other, and reduced the noise voltage on the measuring lead to about 600V.

Then the SWA was bonded to the top of the tank at one end and to the control room's CBN at the other, using circumferential (often called 360°) bonding at each end (no pigtails!) and this reduced the noise voltage on the measuring lead to about 20V peak.

Finally the metal duct was bonded at both ends, tank and control room, too, and the peak noise voltage during HV arcing and its resulting 400kHz oscillation was only 1V.

What was happening, was that the powerful fields from the 400kHz oscillation were coupling CM current into the measuring lead, which due to its high impedance was causing a high voltage to appear in the control room 23m away. All the improvements had the effect of providing alternative paths for the CM current, with progressively lower impedances than that of the measuring lead.

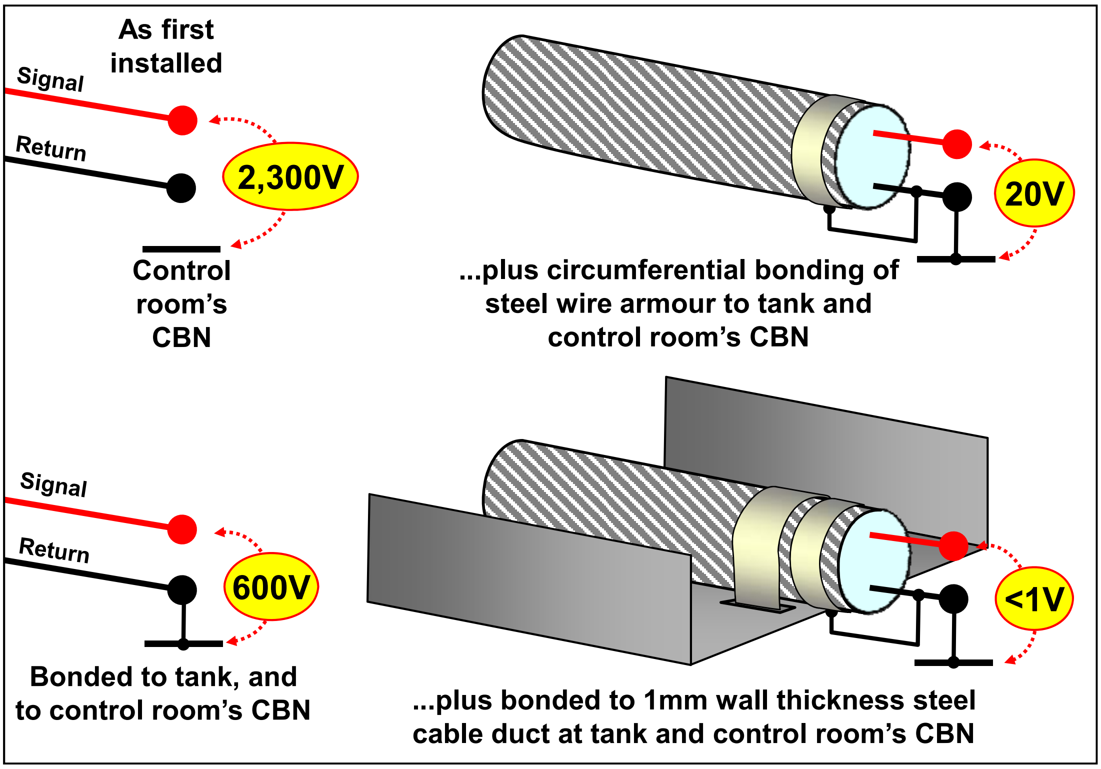


Figure 38 The peak voltages at control room when circuit-breaker opens

In the end, with the cable duct bonded at both ends, the total CM current flowing in the two conductors, SWA and cable duct was about 25A peak – but the proportion of the CM current flowing in the measuring lead itself had dropped to about 1/2300 of its original value, had been attenuated by about 67dB, because 2299/2300ths of the CM current preferred to flow in the new lower impedance paths.

Finally, Paul Bellomo of the Stanford Linear Accelerator facility, SLAC, in California sent me some photographs of one of their installations, one of which is reproduced in Figure 39.

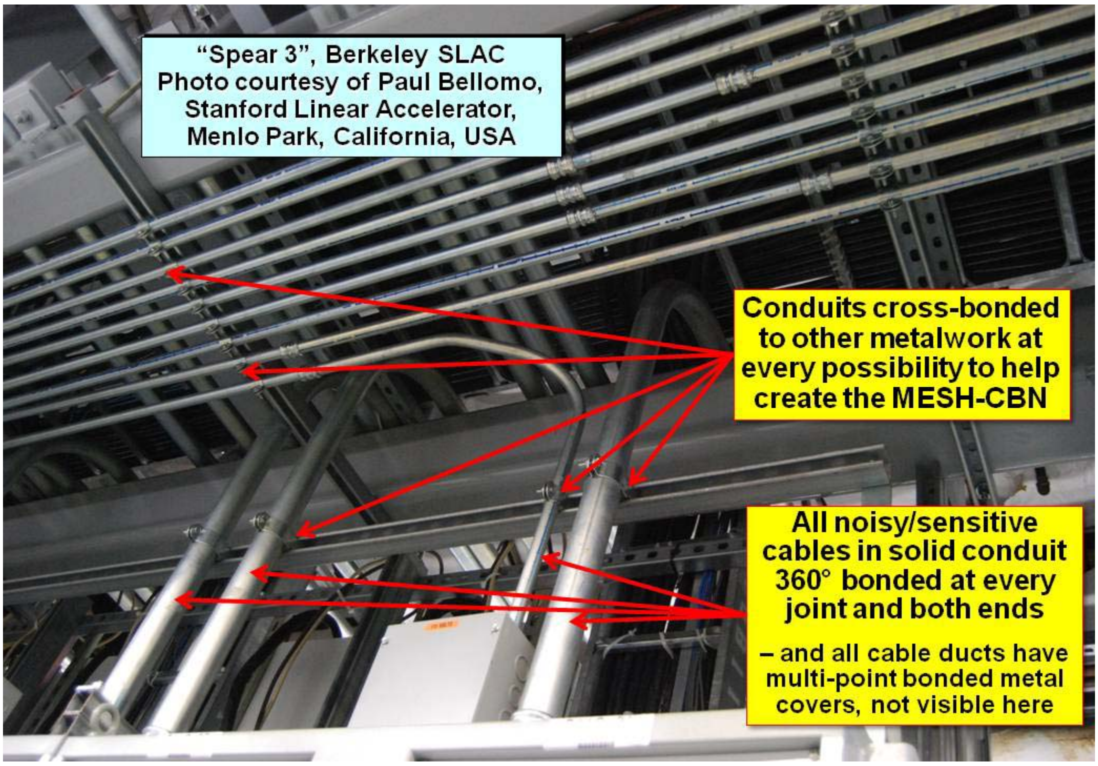


Figure 39 Example of good installation

Paul and his colleagues at SLAC have always had very firm rules about creating "Facility Meshed Earths" that have very low impedance, and routing all "noisy" cables in solid round conduit or rectangular metal ducts with multiple-bonded metal covers. All very good practices for the reasons described in this article. As a result, they have rarely had any new accelerators that suffered from noise causing SI, PI or EMC problems.

Clearly, construction methods such as those recommended here add to the cost of building a new scientific experiment, industrial plant, opera house or other installation, but this must be weighed against the lack of delays in bringing it into service and meeting all its design specifications, the downtime while it is fixed, and the uncertainty of not knowing what modifications are going to be necessary. Often, the cost of the modifications alone costs much more than it would have done to construct the installation correctly in the first place.

Of course, no-one has ever done a controlled experiment, but all experiences so far indicate that it is reasonable to say that – in general – by using existing metalwork as the basis for a MESH-CBN, the additional cost of constructing new high-power installations using the good EMC practices outlined in this article is significantly outweighed by the reduced financial risks.

12 Conclusions

Maxwell's Equations, the Law of Conservation of Energy, and Quantum Electrodynamics show us that all electrical and electronic power and signals (and their associated noises) are not simply voltages and currents but are in fact propagating EM waves, with E and H field patterns that couple with nearby conductors causing noise.

They also show us that all conductors are accidental antennas, that everything has impedance – including the air – and that all currents flow in multiple closed loops, splitting between the various loops according to their admittance (reciprocal of impedance).

So in practical situations in installations, a wanted (DM) power or signal current flowing in a wire will never all stay in the conductor loop the designer has created for it – portions will flow in unintended (stray, CM) loops involving the air and other conductors, including metal structures, causing noise currents to flow.

The smaller the area of the wanted (DM) current loop, and the lower its impedance, the less CM current will couple noise into other conductors and contribute to radiated and conducted EM emissions. Likewise, smaller-area and lower-impedance DM loops will pick up less noise from a given EM environment, providing better immunity.

CM currents cannot in practice be reduced to zero, but applying the same techniques of providing them with small-area low-impedance current paths also reduces the noise they couple into power and signal conductors, and their conducted and radiated EM emissions.

Connection to earth/ground electrodes is unimportant and unnecessary for SI, PI and EMC (but not necessarily for safety), and all green/yellow insulated and other protective conductors should form part of the site's meshed common bonding network (MESH-CBN) that is designed and constructed to provide very small loop areas and very low impedances for CM currents.

The fundamental laws also cause the skin effect, which can be used to increase the impedances of inappropriate CM current loops, encouraging more of the CM current to flow in small-area low-impedance loops that are best for SI, PI and EMC.

The words "earth" and "ground" and their corresponding graphical symbols should *never* be used in electronic and EMC engineering, in equipment and installation design and construction, because of the confusion this causes with electrical safety provisions.

This very confusion has for many decades resulted in, and continues to encourage, bad EMC practices that have damaged economic performance at every level in the supply chain, from warranty claims to downtime and poor quality audio, video and electronic control.

But the principles of good installation design and construction for SI, PI and EMC are very clear, easy to understand, and easy for everyone to implement at low cost in practice, as I hope this article has shown.

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