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Complying with IEC/EN 61800-3 Good EMC Engineering Practices in the Installation of Power Drive Syst

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REO

Complying with IEC/EN 61800-3 Good EMC Engineering Practices in the Installation of Power Drive Systems

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Good EMC Engineering Practices in the Installation of Power Drive Systems

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1. Introduction

This Guide is for what EN/IEC 61800-3 [1] calls “Power Drive Systems” (PDSs), which are AC or DC motor speed control units more usually called variable speed drives (VSDs) or adjustable speed drives (ASDs). VSDs for AC motors only are often called variable frequency drives (VFDs), adjustable frequency drives (AFDs), or just inverter drives.

EN 61800-3 is listed under the EMC Directive [2], and so may be used for declaring PDSs in conformity with it.

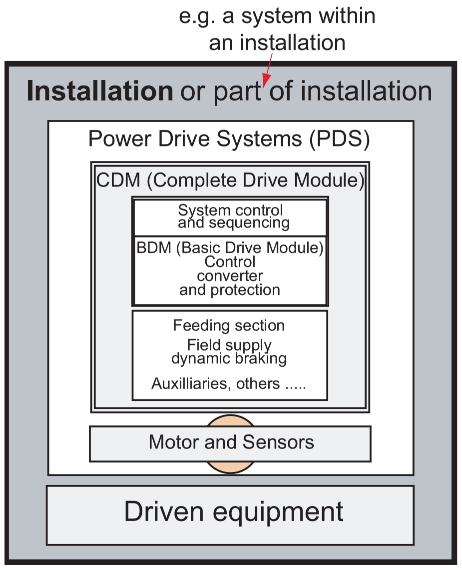
At the time of writing, the EMC Directive has been applying its 2004 version [1] since the 1st October 2007, which means that all PDSs supplied in the EU since then should list EN 61800-3:2004 on their EU Declarations of Conformity, and provide the appropriate test evidence in their “Technical Documentation File” – if they are following the “standards route to conformity” (see [3]).

EN 61800-3:2004 is identical to IEC 61800-3:2004, so this Guide is equally applicable outside of the European Union (EU) where the IEC version – or some national standard based upon it – is applied.

Even where there are no legal EMC requirements, complying with EN/IEC 61800-3 is good engineering practice that will help improve profits overall, over the medium and long term, and will also help increase customer confidence and market share.

1.1. The definition of a PDS

According to EN/IEC 61800-3 [1], a PDS is an adjustable speed AC or DC motor drive, consisting of a basic drive module (BDM), which is part of the complete drive module (CDM), which – when connected to its motor – becomes a PDS, which in turn is part of a system or installation, as shown in Figure 1.



Copied from Figure 1
of EN/IEC 61800-3:2004

Figure 1: Definitions of PDS, CDM and BDM

Figure 2 shows another view of a PDS, this time identifying the various “ports” that are tested by [1].

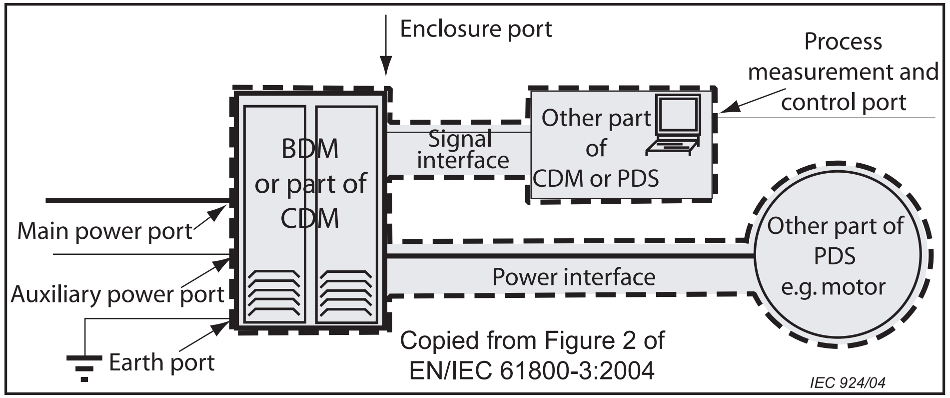


Figure 2: Definitions of PDS, CDM and BDM, showing the PDS’s “ports”

IEC 61800-1, IEC 61800-2 and IEC 61800-4 provide the details for the definitions used in Figures 1 and 2. If the PDS has its own dedicated transformer, this transformer is included as a part of its CDM.

A non-exhaustive list of PDS applications includes:

- Machine tools, robots, test equipment in production, test benches;
- Paper machines, textile production machine, calenders in the rubber industry;
- Process lines in plastic industries or in metal industries, rolling mills;
- Cement crushing machines, cement kilns, mixers, centrifuges, extrusion machines;
- Drilling machines;
- Conveyors, material handling machines, hoisting equipment (cranes, gantries, etc.);
- Propulsion of ships, etc. (but not traction drives or electric vehicles);
- Pumps, fans, etc.

The PDSs may be connected to either industrial or public mains power distribution networks. An “industrial network” is considered to be one that is supplied by a dedicated high voltage (HV) distribution transformer, or its own generator, which supplies only industrial customers or, for example a ship or offshore drilling rig.

A public power distribution network is one that operates at low voltages (e.g. 115/230/400V) and supplies domestic premises. These networks usually have an earthed (grounded) neutral. Where an industrial site is powered from a low voltage mains power distribution, as sometimes happens, the mains distribution network on that site is treated as a public network.

As Figure 1 shows, a PDS may drive some equipment (e.g. a winch, pump, fan, etc.), and/or be part of a system, and/or be part of an installation, but only the PDS is covered by EN/IEC 61800-3 (see 1.3).

1.2. The requirements of EN/IEC 61800-3

[1] includes requirements for PDSs with BDM input and/or output voltages (line-to-line) of up to 35 kV AC rms, rated from a few hundred watts to hundreds of MW, installed in residential, commercial or industrial locations.

It claims to achieve EMC for such applications (but see 1.3) but warns that it cannot cover extreme cases that could occur (but which are assumed to have an extremely low probability). It also warns that it does not cover the EMC performance in the case of faults occurring, which is very relevant for section 2.4 later in this Guide.

[1] specifies emissions limits, immunity levels, and test methods for a PDS according to its intended application and the competency of its installer. It does this by defining two different electromagnetic “environments” or locations, and four different “Categories” of installer competency, as discussed below.

1.2.1. The First Environment

This environment includes domestic premises, and establishments directly connected without intermediate transformers to a low-voltage power supply network which supplies buildings used for domestic purposes.

Houses, apartments, commercial premises or offices in a residential building are examples of First Environment locations.

1.2.2. The Second Environment

This environment includes *all* establishments *other than* those directly connected to a low voltage mains power supply network which supplies buildings used for domestic purposes.

Industrial areas, and technical areas of any building that are fed from their own dedicated transformer are examples of Second Environment locations.

1.2.3. Category C1

This category is for PDSs with rated voltage less than 1,000V, intended for use in the First Environment, permitted to be installed by anyone.

1.2.4. Category C2

This category is for PDSs with rated voltage less than 1,000V, which is neither a plug-in device nor a movable device and, when used in the First Environment, is intended to be installed and commissioned only by a “professional”.

A professional is defined as a person or an organisation having necessary skills in installing and/or commissioning PDSs, including their EMC aspects.

1.2.5. Category C3

This applies to PDSs of rated voltage less than 1,000 V, intended for use in the Second Environment and not intended for use in the First Environment, permitted to be installed by anyone.

1.2.6. Category C4

This applies to PDSs of rated voltage equal to or above 1,000V, or rated current equal to or above 400A, or intended for use in complex systems in the Second Environment, permitted to be installed by anyone.

1.3. Emissions and immunity of PDSs as part of systems or installations

As mentioned above, a PDS may be a part of a system, or part of an installation, but EN/IEC 61800-3 [1] only covers the PDS itself.

However, for compliance with the EMC Directive, customer specifications, or just good EMC engineering practices, the entire system or part of an installation may be covered by other EMC standards – most likely the generic standards:

- EN/IEC 61000-6-1, immunity requirements for residential, commercial and light industrial environments
- EN/IEC 61000-6-2, immunity requirements for the industrial environment
- EN/IEC 61000-6-3, emissions requirements for residential, commercial and light industrial environments
- EN/IEC 61000-6-4, emissions requirements for the industrial environment

In this case, it is possible for a PDS that is compliant with [1] to cause the system or installation that it is part of to fail to comply with the EMC standards that apply to it. There are two reasons why this could occur:

a) The emissions permitted by [1] for the PDS might exceed the emissions limits permitted by other standards for the system or installation containing the PDS. For example, some limits that are permitted by [1] for some PDS Categories exceed the limits permitted by the appropriate generic standard for the same type of environment by more than 20dB.

b) There may be several PDSs in one system (e.g. the sausage machine in

Figure 3), and since their emissions will add up they could exceed the limits for the overall system or installation.

It was because of a) that the European Association of Competent Bodies (ECACB, disbanded since 2004/108/EC, has replaced Competent Bodies with Notified Bodies and changed the compliance methods, see [3]) complained to the European Commission (EC) about the listing of EN 61800-3 under the EMC Directive, and asked that it be removed from that list. It was not removed, but shortly afterwards the EC employed an EMC Consultant with the aim of ensuring they did not make such embarrassing mistakes again.

Figure 3: Example of a machine with a number of PDSs
Part of a complex installation....
The control cubicle for the sausage machine installed at Stork Townsend B.V., The Netherlands, in 2006. 10 metres long; 60 variable speed drives 18 multi-axis servo drives

2. What is <u>not</u> covered in this Guide

2.1. Testing to EN/IEC 61800-3

This Guide is only concerned with the use of good EMC engineering installation practices to help PDSs comply with EN/IEC 61800-3 [1], it does not cover the actual testing techniques that are used by [1].

REO have seventeen Guides [4] that detail how to actually perform the various tests required by [1], including the situation where the test cannot be carried out at a “controlled EMC site”, such as inside a test laboratory’s anechoic chamber.

[1] also includes guidance on what to do when testing has to be done on-site, or when the mains current required by a PDS exceeds 100A. If further guidance is required on on-site testing, [5] may prove useful.

2.2. Complying with the EMC Directive

It is not the aim of this Guide to discuss how a manufacturer should go about legally complying with the EMC Directive [2] [6], as implemented in the various national laws of the European Union’s (EU’s) Member States, such as [7] [8] for the United Kingdom (UK). The compliance methods that are available are discussed in [3].

2.3. Human Health and Safety

The very high voltages and currents associated with high-power PDSs can cause a variety of problems for health and safety. EN 61800-5-1 [l] covers electrical, thermal and energy hazards of PDSs, but does not cover human health effects due to exposure to electric and/or magnetic fields (EMFs).

All PDSs that declare compliance with the Low Voltage Directive [9] must also now declare compliance with the EMF Regulations [10]. While there are no EMF standards specifically for PDSs, it will probably be best to apply the “generic EMF standard” EN 62311 [11].

A workplace Health and Safety Directive on EMF also exists [12], but at the time of writing is not fully in force. Like all Health and Safety directives, it applies to the owners/users of a site or the equipment on it, and not to manufacturers who supply them with equipment.

Neither of these issues are discussed further in this Guide.

2.4. Functional Safety

It is also not the aim of this Guide to discuss the Functional Safety issues of PDSs, other than to say that since electromagnetic interference (EMI) can cause PDSs to suffer errors or malfunctions (e.g. uncommanded changes in speed, torque, direction, etc.) – where these could have consequences for safety risks, complying with EN 61800-3 or any other EMC test standards, even military or aerospace ones, is insufficient for establishing a defence of due diligence.

EN 61800-5-2 [13] applies the basic standard on Functional Safety EN 61508 [14] to PDSs, but – like [14] – does not prescribe what to do about the possibility of EMI. EMI can cause a variety of problems for motor drives, which might be costly (e.g. downtime) or have safety risks, as shown by some of the real-life anecdotes in [15].

To cover EMI it is necessary to apply the basic standard on EMC for Functional Safety [16], for which the IET have produced a helpful and practical 9-step management procedure [17]. EMC tests have a role to play in due diligence for safety, but they cannot be sufficient on their own.

2.5. Machinery Safety

A PDS as defined by the EN 61800 series of standards is not a *machine* as defined by the Machinery Safety Directive [18], and so this directive does not apply to PDSs.

Of course, system integrators and owners of *fixed installations* (using the definition in [2] and [7]) will often use a PDS to provide the motive power for a machine that *does* come under the Machinery Directive, or one of the Health and Safety at Work Directives, in which case it is important that they understand the points made in 2.3 and 2.4. They will find helpful information on EMC in [19] [20] and [17].

2.6. Electronic and mechanical design of basic drive modules (BDMs)

This Guide does not cover the electronic and mechanical design and assembly of the BDM section of PDSs, or its cabinet or other enclosure. But well-proven techniques do exist for these EMC aspects of BDMs, see [21] [22] and [20].

3. Cost implications

3.1. The EMC of PDSs, financial risks, and the perils of short-termism

It is quite practical to design a BDM (see 2.6) so that any PDS using it is *guaranteed* to comply with EN/IEC 61800-3 (and the EMC Directive) regardless of how it is installed and how the PDS that employs it is configured. However, such BDMs will almost certainly cost more.

When using such a BDM, a manufacturer who integrates it into a PDS that he sells to an end-user (or their main contractor) will be able to demonstrate compliance with the EMC Directive [2] [7] without having to test to EN/IEC 61800-3. All they will need to do is to include a few verified EMC documents from the BDM manufacturer, in their Technical Documentation File [3].

Such PDSs will be largely unaffected by EMI in their operational environment, and so will generally operate with greater precision. When used in manufacturing processes they often improve yields and quality, and they often prove to be more reliable. All this will reduce their overall cost-of-ownership for their users, and also generally reduce the warranty costs for their manufacturers, sometimes very significantly.

Such good EMC design increases the bill-of-materials (BOM) cost of the BDM, and most manufacturers would *assume* that they must therefore sell it for a higher price. But this is not necessarily the case, because (for example) their product could have lower warranty costs, and/or might win a much larger market share because of its ease of use [23]. So they might make as much or more profit even when selling it for the same price as a more typical BDM that does not control EMC so well and so requires any PDS it is used in to go through costly tests to EN/IEC 61800-3, to be able to show due diligence in complying with the EMC Directive.

This all sounds good, but it rarely happens in real life because of short-termism – managers usually only look ahead as far as the next quarter's financial figures – so even very significant possibilities for medium and long-term financial gains, improving profitability and return-on-investment (ROI) are ignored. Sometimes the benefits of investing in good EMC engineering are discounted because of a lack of appreciation of EMC issues.

Short-termism means that buyers are looking for the cheapest BDM, and often decide solely on the basis of crude "kW versus £" comparisons.

For this reason, and others, most BDM manufacturers' salesmen feel may be unwilling or unable to sell a more costly product on the basis of lower overall cost-of-ownership, especially in regions of the world where EMC regulations are not mandatory or strictly enforced. It isn't helped by the fact that most engineers have difficulty in presenting technical arguments for improved profitability and ROI in a financial manner that can be understood by the people who run their companies. Some remedies for this latter problem will be found in [24].

The inevitable result of this is that, in general, BDM manufacturers aim to make the cheapest products they possibly can, which increases the cost and time burdens for the system integrators and owners of fixed installations (as defined in [2], see [3]), who use their products to construct PDSs. These companies have to use design and installation techniques as described in this Guide, and perform costly testing to EN/IEC 61800-3 *on each PDS they make* (sometimes testing on-site), to be able to declare compliance to the EMC Directive. This increases their overall costs and so significantly increases the price that they have to charge to their customers, above what they would have to charge if they could buy BDMs that had been designed appropriately.

3.2. Mains filters and industrial PDSs

According to clause D.1.2.2 in Annex D of [1], the common practice for many years has been to install PDSs without mains filters. It claims that the general lack of complaints about radio interference from such installations indicates that they achieve EMC – but this is a very risky assumption to make.

There are many reasons why people might not complain about interference, why they might not be able to identify where it came from, why enforcement authorities might not have the resources or expertise to investigate, or why such investigations were not reported to (or remembered by) the people who wrote [1]. Also, there is often an element of (bad) luck in many EMI incidents, which tends to make them hard to reproduce at will, often making EMI hard to "prove" after an incident.

I find that many people who claim their systems or installations don't have EMI problems, actually don't understand how to identify an EMI problem anyway (if they have even heard of it). They may have suffered (or be suffering) from problems that are decreasing yields or increasing downtime – but they never recognised them as being caused by EMI.

For example, some computer experts reckon that as many as one-third of all PC software "crashes" are caused by EMI. We have all experienced these recoverable crashes on our PCs but how many of us have identified the crash as an EMI incident and brought it to the attention of the people who sit on the IEC committee for computer EMC standards?

Another issue is that there is a rapid increase in electronic instrumentation, control and communications in all areas of human activity, including safety-related systems, all brought about by the continual reduction in the costs of semiconductors (transistors).

Also, the reduction in costs of semiconductors is brought about by making them physically smaller and operating them on lower voltages. A state-of-the-art microprocessor (a "silicon chip" on a printed circuit board) at the end of 2008 could contain as many as 1 billion semiconductors and operate from 0.9V DC power. It is unfortunate but unavoidable that these trends inevitably make them more susceptible to EMI.

This rapid increase in electronic complexity, plus the worsening of electronic immunity, might reveal that PDSs previously thought to be EMC compliant (because of no complaints) were not so, in fact. It would be a great pity if the first time this was discovered was an incident that involved a serious injury or death (see 2.4).

In any area where electronic technologies are used, the past is not a reliable guide to the future.

The fact that there is no evidence of a problem should never be taken as proving that therefore *there is no problem*. Although it sounds at first like a reasonable argument, it has been known since the late 18th century that is not a logical conclusion to make (see [25]). It is very disappointing to find such an obvious error in an IEC standard.

3.3. Output filters and industrial PDSs

Very few PDSs use output filters because of their cost, but even if we ignore EMC issues, we have to acknowledge that – without output filters – high-power VSDs suffer from high levels of common-mode (CM) current (see 4.2) flowing through their bearings, which can shorten their life by as much as tenfold.

Another problem is that where long motor cables are used, the "Faraday Effect" causes the motor's drive voltages to rise significantly higher than those output by the VSD, which can degrade the insulation materials in the cables and motor windings, again leading to early failure and increased downtime.

So filtering a VSD's motor output can be an excellent financial investment! For example, the majority of electrical submersible pumps (ESPs) rated up to around 900-1100kW serving the oil industry offshore, would not function unless output filters were installed.

3.4 An example of the financial risks of inadequate EMC engineering

[15] has many examples of costly problems caused by EMI from, or to, PDSs, including industrial ones, and I must say that over the last 20 years, almost all of my work as in independent EMC consultant in solving EMI problems in industrial sites has been caused by two electronic technologies – variable speed motor drives (i.e. PDSs) and personal wireless communications (e.g. private mobile radio, Walkie-talkies, cellphones). Here and in 3.5 are just two examples of costly EMI concerning PDSs, which do not appear in [15]. [37] is another case study of solving a high-power VSD EMI problem that had been very costly for the drive user.

This first example also shows that actual compliance with the test limits and levels in EN/IEC 61800-3 does not automatically ensure compliance with the EMC Directive [2] [7], or ensure low financial risks.

It concerns a UK factory that had a new (and very large and costly) programmable machining centre installed. This used a 50kW PDS (actually a VFD) that complied with EN/IEC 61800-3, so was assumed to comply with the EMC Directive [2] [7]. But when it was operated it put about 15V peak-to-peak at between 10 and 30kHz on the factory's mains supply, causing some packaging machines to malfunction elsewhere on the site. Figures 4 and 5 show the mains voltage I measured on the site when the machining centre was running. When it was not running, the mains supply was a nice clean 50Hz sinewave.

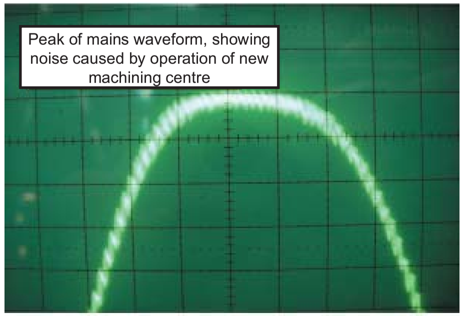


Figure 4: One peak of the mains cycle, showing the 10-30kHz noise

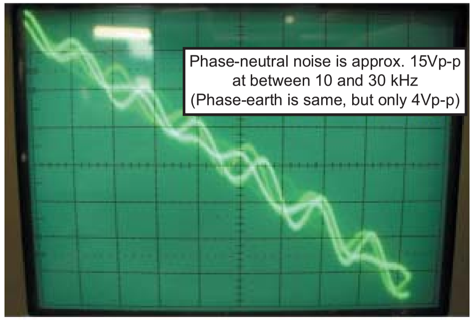


Figure 5: A closer view of the 10-30kHz noise, about 15V peak-to-peak

EN/IEC 61800-3 only specifies limits for conducted emissions over the frequency range 150kHz to 30MHz, and the machining centre met these limits, but since its drive's switching frequency was 2kHz it emitted significant levels of switching harmonic noise into its mains supply from 2kHz at 2kHz intervals all the way up to 150kHz and beyond. At 150kHz and above the mains filter fitted to the PDS attenuated the noise emissions to meet the specification, but it did not provide significant attenuation below 150kHz.

All mains filters resonate at some frequency (see 3.2.9 of [21], 8.1.3.1 of [26] or 5.10 of [19]) and so do all mains distribution networks, due to the combination of predominantly inductive wiring with predominantly capacitive electronic loads (e.g. due to the capacitors in their EMI filters of power factor correction banks, see C.1.3.4 of [1]). Noise currents flowing in them will cause amplified voltages at these resonant frequencies, sometimes as much as ten times higher than would normally be expected. [15] includes some examples of serious problems that occurred because noise was amplified in mains filters or mains distribution networks.

It can come as a big surprise to find that a mains filter is giving gain instead of attenuation, often in contradiction to the suppliers attenuation versus frequency curves! This is due to the fact that mains filters are not tested in situations that correspond to real-life operation. However, in this example, if the mains filter was resonating and giving amplification, it was below 150kHz.

The solution was very simple – the machining centre manufacturer replaced the original mains filter on their PDS with one that provided reliable attenuation down to below 10kHz. This filter was much the same size as the original, but weighed a lot more and was more costly. It was also less efficient, dropped a few more volts and ran hotter. (Incidentally, the replacement filter was the one recommended by the VFD manufacturer, so the fault lay with the machining centre manufacturer, not the VFD manufacturer.)

The manufacturer of the machining centre had saved a few £ by using a cheaper filter than the one recommended, but this caused significant financial losses for their customer, and they also had to spend a considerable amount themselves on field service visits to deal with the customer's complaints over several months, and eventually fix the problem when I showed them what it was. Overall, it would have been much more cost-effective to have shipped the product with the better filter.

Since the machining centre itself sold for over £1 million, why take such a risk just to save one or two hundred £ on the cheaper mains filter? Unfortunately, that is how most manufacturing companies are managed these days, with good engineering practices made subservient to crude analyses of BOM cost [23], often resulting in significant financial risks, as proved by this example.

It is interesting to note that although the machining centre with the original filter met the emissions limits when tested to EN/IEC 61800-3, it did not actually comply with the EMC Directive [2] [7] because it caused unacceptable interference to other equipment when installed as recommended by its manufacturer, and so did not comply with the Directive's Essential Requirements, see [3].

3.5. A second example of the financial risks of inadequate EMC engineering

This example concerns heavy industry, with a company that built, owned and operated installations that used PDSs rated at nearly 1MW. The BDMs they purchased were not fitted with mains filters, and since they had never suffered from any significant problems, which were identified as being caused by EMI, in their installations, they felt that ignoring the costs of suppressing the emissions from these very powerful motor drives was justified.

If they even knew that this was not good EMC engineering practice, they nevertheless ignored it because it was apparently saving them money.

But recently (at the time of writing), one of their new installations *did* suffer from EMI with its control electronics, with potentially lethal safety risks for anyone near to the machinery being controlled. Also, the ground noise voltages exceeded those allowed by safety standards. The site could not be operated until the problem was fixed, which took several months with the cost of lost production running at about £100,000 per week.

Figure 6 shows some of the noises created by these powerful drives, before their mains emissions were suppressed.

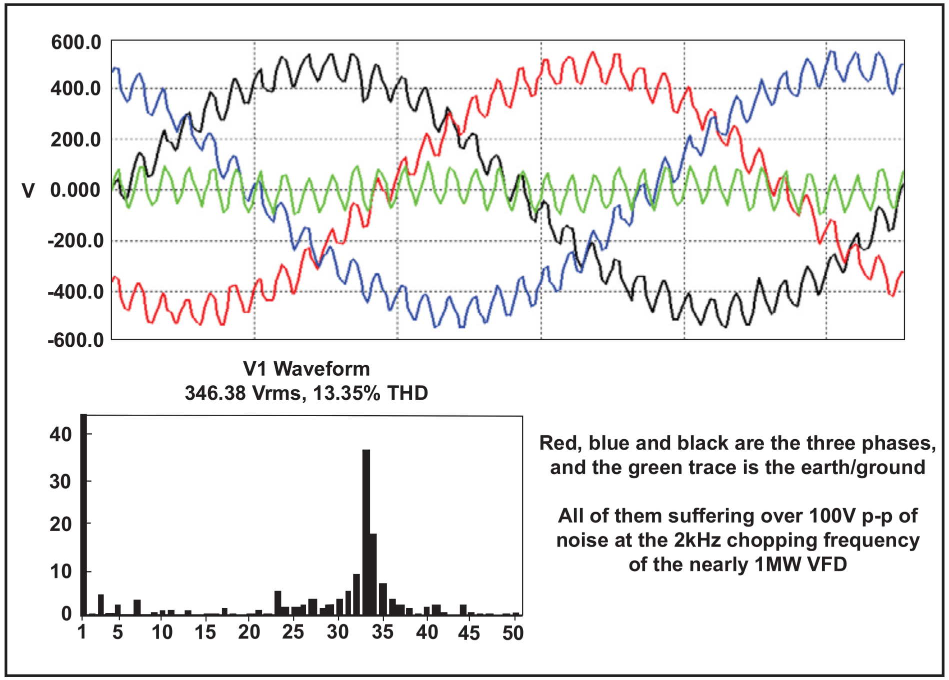


Figure 6:
Voltage noises on the site's 3-phase mains supply, due to one PDS

It turned out that the cost of the lost production on this one new site was many times larger than the company would have incurred if it had *always* installed PDSs using good EMC engineering practices (which means using mains filters, see later). This is still true even when using a discounted cash-flow analysis that takes the cost of borrowing the extra money for the earlier, apparently trouble-free installations into account.

This just goes to show that we can't beat Murphy's Law – "If a thing can go wrong, it will". We might think we are getting away with poor engineering and saving money as a result, but (just like gambling) our luck cannot hold for ever. In the end we will be worse off than if we had always done good engineering. For more on why Murphy's Law is actually true (at least in part), see [27].

The only situation where this "rule" doesn't apply, is if your company has no brand image and is happy to supply people with rubbish and then "disappear" (e.g. by changing names) so as not to have to deal with the resulting high warranty costs. There is always someone willing to buy from an unknown manufacturer, if they have the lowest price, so there is always a market for such manufacturers. I'm sure it will come as no surprise that this Guide is not intended for use by such companies.

4. Emissions

4.1. The basic structure of a BDM

Figure 7 shows the basic "block diagram" of the BDM for a VFD for an AC motor. It is basically just a mains rectifier that produces a DC supply (often called a "DC-Link"), followed by a pulse-width-modulated (PWM) power switching circuit (often called a chopper, switcher or inverter). Sometimes the terms chopper, switcher or inverter are applied to the whole BDM including the rectifier. In a low-power VFD (<10kW), the chopper might use "PowerFET" devices, but almost all higher power choppers use IGBTs (Insulated Gate Bipolar Transistors) instead.

Any DC or AC waveform can be synthesised by chopping at a higher frequency (must be at least twice the wanted frequency) by varying its mark:space (i.e. on:off) ratio. Chopping doesn't waste much energy as heat, which is why PWM drives are much smaller and less costly, and more efficient, than previous motor speed control technologies, and why it is so popular.

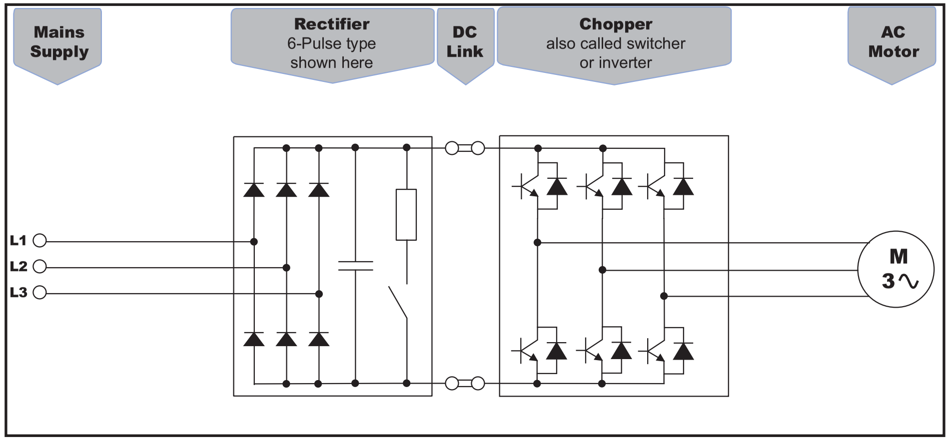


Figure 7:
Block diagram of a VFD for an AC motor

Figure 8 is copied from [28], and shows a simple example of generating a sinewave using PWM. The idea is that when averaged over a few switching cycles, the rapid chopping of the waveform becomes a smooth AC waveform. So when used to drive a motor, the high inductance in its windings causes the motor current to follow the average value of the PWM voltage. In the example of Figure 8, this results in a sinewave at the frequency required to drive the AC motor at the rotational speed required.

Figure 9 shows an example of a PWM motor output measured with a power quality meter, on a 900kW VFD. Because the measuring instrument that was used has a bandwidth of only about 5kHz, the PWM voltage signals in Figure 9 are "averaged" to some extent and do not appear as square or sharp-edged as they really are.

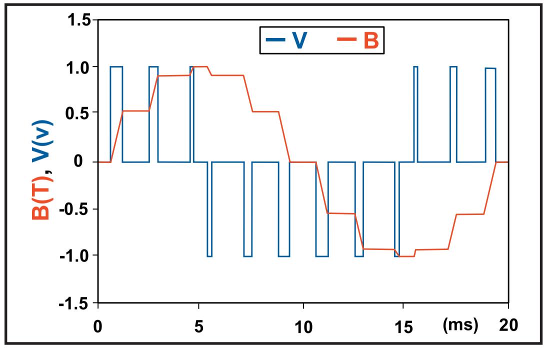


Figure 8:
Example of PWM used to create a sinewave

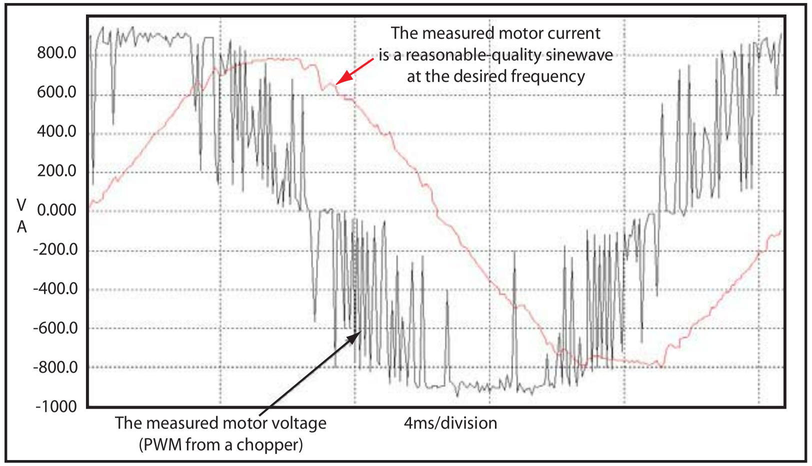


Figure 9:Example of PWM output of a 900kW VFD, measured with a 5kHz bandwidth

The sharper the edges of the PWM, the higher the frequency range of the emissions. Figure 10 shows an example of the waveform and frequency spectrum of a 16kHz squarewave (i.e. a very simple, 1:1 mark-space ratio PWM) with 2µs rise and fall times. The analysis of the squarewave in terms of frequency shows that most of its energy is at the 16kHz switching rate, *and* that it also has significant energy at all the odd-numbered harmonics, for example at:

- 48kHz (3rd harmonic)
- 80kHz (5th harmonic)
- 112kHz (7th harmonic)
- 144kHz (9th harmonic)
- 176kHz (11th harmonic)
- ...etc., all the way to at least 1.616MHz (the 101st harmonic) and beyond

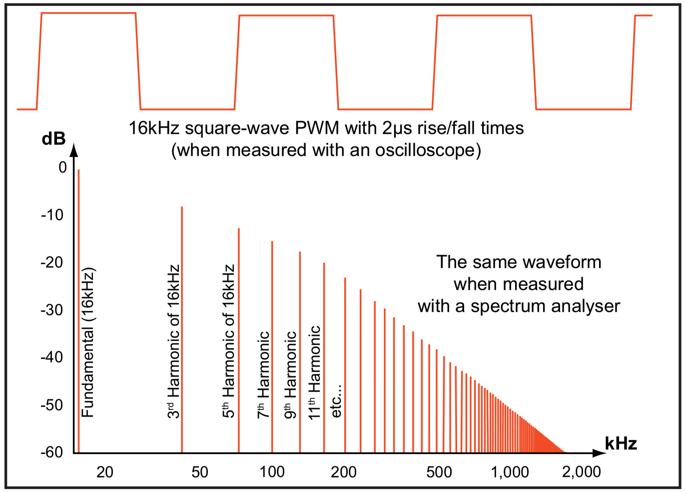


Figure 10:
Example of frequency content of a 16kHz squarewave PWM with 2µs rise and fall times

A squarewave is a special case of a chopper output waveform, and typical PWM waveforms are generally rectangular (i.e. their mark:space ratios are usually not 1:1). This means that their frequency spectra also contain even-order harmonics of their chopping frequency (e.g. 2nd, 4th, 6th, etc.). It also means that the levels of the various harmonics do not show the simple gradual fall-off with increasing frequency that we see in Figure 10. Some high frequency harmonics may have higher amplitudes than lower frequency ones.

A DC motor drive can use PWM just like a VFD, it only requires the PWM waveform to be such that the motor current averages to a DC current instead of to an AC one.

But some types of powerful AC and DC motor drives use thyristor or triac devices switched on and off at the frequency of the mains power, instead of plain rectifiers. They don't need to use a DC-Link or a chopper. Phase-angle-controlled triacs are used to generate a variable DC voltage, and appropriate on/off switching of thyristors can generate AC at frequencies at up to 50% of the mains supply frequency (these are called cycloconverters).

Rectifiers, whether plain or phase-angle controlled, or cycloconverters, generate harmonics of their switching frequency – which is the mains – and so they generate what we call "mains harmonics" to distinguish them from other switching harmonics.

Figure 11 shows the first few harmonics of the current in a single-phase bridge rectifier, whilst Figure 12 shows those for a phase-angle-controlled single-phase rectifier (which could be a VSD for a DC motor).

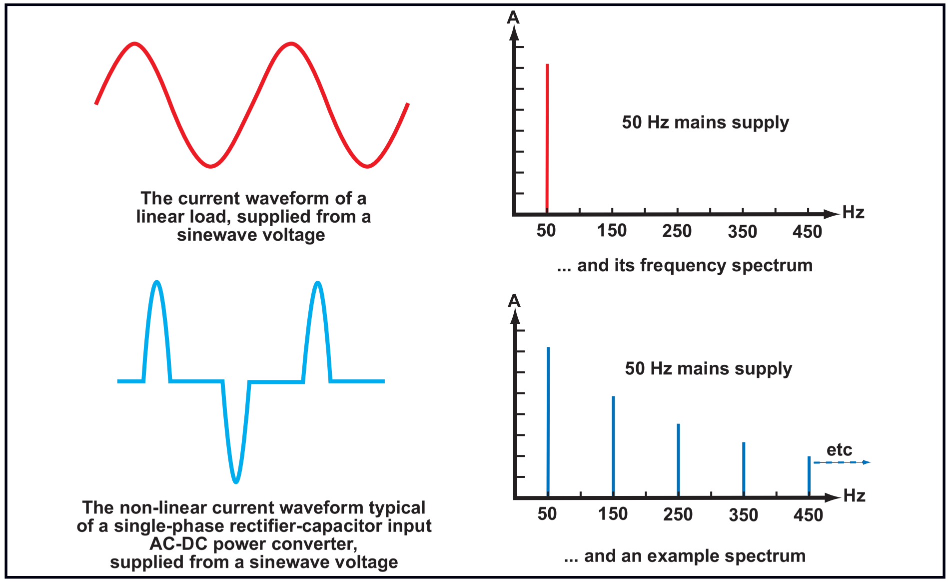


Figure 11: Harmonic currents in a single-phase bridge rectifier

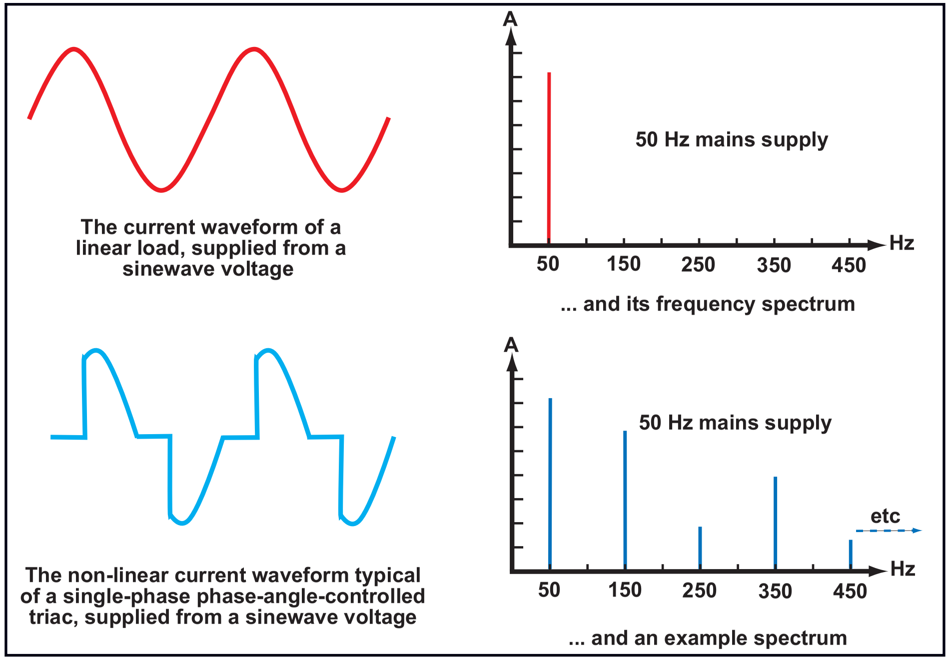


Figure 12:
Harmonic currents in a single-phase phase-angle-controlled triac bridge

In three-phase (often called 6-pulse) rectifiers and phase-angle controlled triacs supplied from a good quality sinewave voltage, the "triplen" harmonics (3rd, 9th, 15th, etc.) cancel out almost entirely in the circuit. However, if there is any imbalance in the supply voltages, triplens are produced. Similarly, for multi-pulse systems (e.g. 12 pulse) any imbalances in the paralleled 6 pulse rectifiers, phase shift transformer secondary windings results in triplens and other unwanted noise emissions being produced.

4.2. The unwanted noise sources in a BDM

The above discussion has shown that, in a BDM, rectifiers generate currents at the mains frequency and its harmonics, and choppers generate voltages at kHz frequencies plus their harmonics – even up to tens of MHz.

The generators used to provide mains power only generate at 50Hz (or 60Hz), so mains harmonic currents are a nuisance. They circulate widely in the mains distribution network causing excess heating of the cables, induction motors, transformers, fuses and circuit-breakers, and as they flow in the impedances of the supply network they cause voltage drops that distort the mains waveform so that it is not a clean sinewave anymore. We say that it is harmonically distorted, and when voltage distortion levels rise too high, many kinds of electronic equipment can malfunction. For more on the problems of mains harmonics, see [29] and [30], and also the REO Guides on EN 61000-3-2 and EN 61000-4-13, from the list at [4].

Since mains harmonics do not contribute to delivered power (they are called “wattless power”, worsening the True Power Factor – combination of the displacement power factor and the distortion factor of harmonics), and since they cause many problems, we consider them to be an unwanted noise emission. EN/IEC 61800-3 [1] defines tests and sets limits for the emissions of mains harmonics from a PDS, as do EN/IEC 61000-3-2 (for ratings up to 15A/phase) and EN/IEC 61000-3-12 (for ratings up to 75A/phase).

Motors have too much mechanical inertia and electrical inductance to respond to kHz chopping frequencies, never mind their harmonics – but they can suffer increased downtime due to their insulation failure, motor bearing problems and cables being degraded by the high frequencies. In addition, induction motors with deep bar or double cage design can overheat significant on heavily distorted supplies. On explosion proof (EExd) motors with these types of rotor design, the flameproof seals on the shaft, which are designed to contain any internal explosion, can become degraded, possibly allowing any internal explosion to be transmitted outside the motor carcass with possibly disastrous consequences.

If the chopping frequencies and/or their harmonics couple with other equipment (via conduction, induction or radiation) they can interfere with its operation. So it is good engineering practice to treat the chopping frequency and its harmonics as potential source of noise or degradation that should be controlled.

[1] specifies tests and sets limits for the amount of conducted and radiated emissions, in common with many other EMC standards, such as the generic emissions standards EN/IEC 61000-6-3 and EN/IEC 61000-6-4.

So, we have to limit our PDS’s emissions of mains harmonics, and chopper frequencies and their harmonics. But this is not all. In a VFD, the motor draws its electrical power at the AC frequency that is synthesised by the PWM of its chopper, and as a result the current in the DC-Link and the mains current demand both follow this frequency. For example, if a VFD is set to 39Hz, then when driving its loaded motor it draws current from the mains at 39Hz. And because mains rectifiers are switching circuits and not linear ones, they generate harmonics of this frequency too.

These low-frequency non-fundamental-related (50Hz in Europe) mains currents are called mains “interharmonics”, and just like mains harmonics they circulate widely in the mains distribution network, causing excess heating and distorting the voltage waveform. DC drives can also generate interharmonics to some degree, when the load on their motors, or their motor speed, fluctuates repetitively and rapidly.

Just as for mains harmonics, [1] and other standards specify tests and limits for interharmonic emissions.

Interharmonic emissions are made more complex by intermodulation within the mains rectifier. The mains voltage frequency and its harmonics (distorted waveform) intermodulates with the AC motor drive frequency and its harmonics, to create a huge number of “Intermodulation Products”. Figure 13 shows a measurement that was made on the current spectrum of a 700kW VFD, and shows significant current levels at, for instance 24A at 103.75Hz, which is six times the mains frequency (near to 50Hz) minus five times the motor frequency of 39.4Hz.

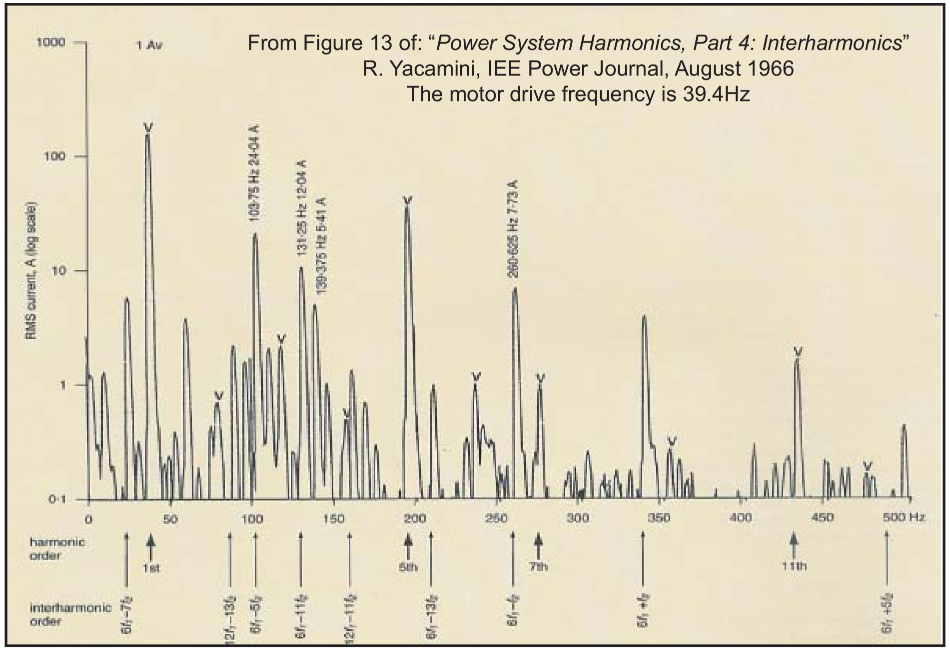


Figure 13:
Example of intermodulation increasing the interharmonic levels in a VFD

The remainder of this Guide will focus on VFDs and VSDs that use PWM, because these are the worst for creating high-frequency noise emissions. This is because their choppers use very fast-switching PowerFETS or IGBTs, which are operated at kHz switching rates – as low as 1kHz for MW power ratings; as high as 50kHz for ratings around 1kW. We can expect to have to control noise at frequencies of up to 1,000 times the switching rate (e.g. 1MHz for a 1kHz chopper, 50MHz for 50kHz).

Thyristors and triacs switch much more slowly than PowerFETS and IGBTs, and their switching rate is no higher than the mains frequency. As a result they produce significantly lower levels of high-frequency noise emissions than a PWM drive of the same power rating. However, since they are often used at very high powers, their high-frequency noise emissions can be significant and should not be ignored.

All types of VSDs create low frequency emissions at harmonics of the mains supply, interharmonics, and voltage fluctuations due to load current changes; so this Guide will describe the techniques that are used to control noise emissions for VFDs that use PWM. The same techniques also work for thyristor and triac drives, which will probably need more attention paying to suppressing noise emissions in the lower frequency range (i.e. below 150kHz).

Variable speed motor drives are also used to drive various kinds of motors in servo systems, and to drive stepper motors. These use the same DC or AC PWM motor drive technologies described above, so their EMC should be treated the same way.

Figure 14 shows how the noise currents flow in the BDM example previously used in Figure 7.

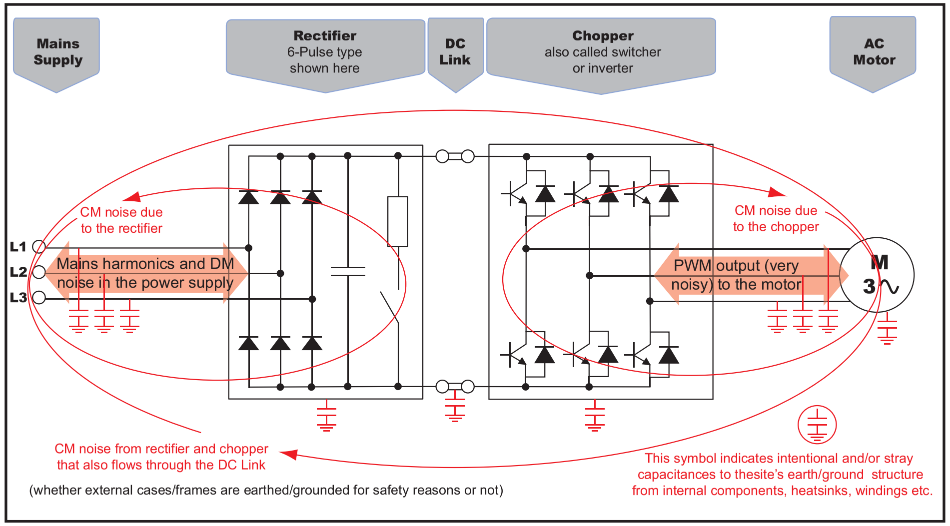


Figure 14:
How the noise currents flow in a BDM

To understand Figure 14, we have to understand that there are two kinds of noise currents – differential-mode (DM) and common-mode (CM). All currents flow in loops, and DM noise currents flow in loops within a single cable (or cable bundle). In the case of a three-phase delta connected VFD like that shown in Figure 14, DM currents flow out and back along the three mains phase conductors, and they also flow out and back along the three motor phase conductors.

However, CM noise flows out along all of the conductors in a cable or cable bundle at the same time, and returns via a different path to complete its loop. Any path will do, but the one that always exists is via the earth/ground structure of the site or vessel the PSD is installed in. Even where no conductive path exists, high-frequency currents can easily flow through the air or insulators, via stray mutual inductances and stray capacitances.

Figure 14 indicates some of the stray capacitances that exist in a typical PDS, which can carry CM currents.

CM currents are caused by imbalances between stray capacitances and stray inductances, for example, the stray capacitance of Phase 1 to earth/ground, versus that of Phase 2. These imbalances are small, so CM noise currents are small when compared with the DM noise currents, but since CM currents travel in very large loops, which can encompass a whole site or vessel, they have the potential to cause as much (or more) interference as DM currents.

Figure 14 shows (as a double-headed arrow) the DM noise currents associated with the rectifier – consisting of mains harmonics and interharmonics plus high-frequency switching noises from the rectifiers themselves – flowing in the three-phase mains cable's conductors.

It also shows (also as a double-headed arrow) the DM noise currents associated with the chopper – consisting of the set motor frequency and its harmonics, plus the chopper frequency and its harmonics – flowing in the three-phase motor cable's conductors.

Figure 14 shows – as red ellipses – the CM noise current loop associated with the rectifier and mains supply, and the loop associated with the chopper and the motor. It also shows a larger ellipse indicating that rectifier CM noise *also* flows in a loop that comprises the motor, chopper and DC-Link; and that chopper noise also flows in a loop that comprises the mains supply, rectifier and DC-Link.

I'm sure the reader will appreciate that Figure 14 is a gross simplification for the purpose of illustration, and that its simplified analysis can equally well be applied to VFDs using single-phase, or six (or more) phase rectifiers.

Currents flow according to the impedance that they experience around their entire loop, and where there is more than one alternative path they will take all of them, dividing between them in a ratio that depends upon the impedances of each, and the frequency concerned.

Stray capacitance ensures that there are always many alternative loops for CM currents to flow in, and since there are very many noise frequencies associated with rectifiers and choppers (see Figures 10, 11, 12 and 13) the ratios of currents between the loops is frequency-dependent. Simply put, we should expect the CM noise from a PDS to flow all over the earth/ground structure of a site or a vessel.

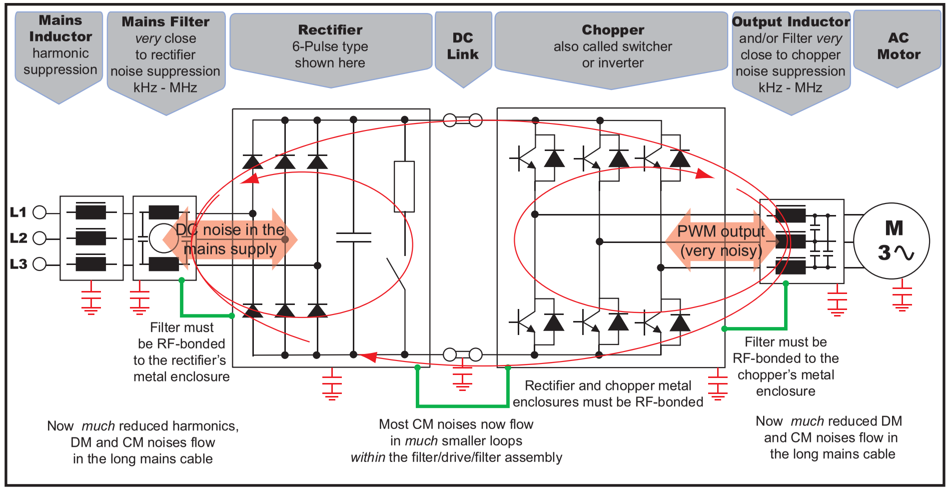


Figure 15: Using inductors and filters to suppress noise emissions

4.3. Suppressing the noise sources

Figure 15 shows the use of filters at the BDM's rectifier's input, and at its chopper's output, to suppress the DM and CM noise emissions.

The best way to understand how a filter suppresses DM and CM noise emissions, is to regard it as a means of providing a return path for the noise current loops that has a much lower impedance than the other loops. The noise current will then automatically split so that most of it flows in the path provided by the filter. Filters generally use capacitors to provide these low-impedance loops.

Most filters also add inductors and chokes to increase the impedance of the mains or motor cables on "the other side" after the provision of the low-impedance return path, to help encourage most of the noise currents to flow in the new path provided by the filter and not out into the installation's cables where it might cause interference.

Figure 15 shows the mains harmonic emissions from the rectifier being suppressed by a three-phase inductor, a common technique often called a line reactor (or just reactor). Other methods are discussed later.

Note that Figure 15 shows line reactor fitted to the *supply side* of the mains filter, not to its BDM side, because this helps prevent resonances in the mains power distribution network. Connecting capacitors directly to a supply network, without series reactors between them and the supply, has been seen to cause resonances that caused costly damage to equipment, with even higher costs due to its downtime.

Providing a low-impedance path for DM noise currents is easy – simply connect capacitors between the phase conductors in each cable. These will tend to "short out" the DM currents, so they don't get out into the supply or motor cable, but of course no capacitor is perfect so the noise current redirection is not perfect either and some DM noise current will still flow in the long cables.

Redirecting the CM currents also uses capacitors, but they have to be connected to the earth/ground structure, so to be effective the impedance in the earth/ground structure between the filter and the rectifier or chopper must be very small indeed. This essentially means:

- **Locate the inductors and/or filters physically as close as practicable to the unit whose noise it is to suppress** (i.e. the rectifier or the chopper)
- **RF-bond the metal bodies of the inductors or filters to the metal body of the unit whose noise it is to suppress.**

(Even though an inductor has no *intentional* path to earth/ground, like the capacitors in a filter, its windings have significant stray capacitance which will help control CM currents, providing the inductor is RF-bonded.)

"RF-bonding" means providing a conductive path that has a very low impedance, <<100mΩ, at the frequency concerned. Ideally, the conductive path should have an impedance of 1mΩ or less at the highest frequency that it is desired to control. Remember that this is the *impedance* of a bond, not simply its resistance.

Wires or braid straps are ineffective for RF-bonding purposes, because their impedance is too great. The inductive impedance of a straight wire is $2\pi f L$, where f is the frequency to be suppressed in Hertz (Hz) and L is the inductance of the wire in Henries (H). We can assume about 1µH/metre for a long wire and about 0.3µH/metre for a wide braid strap, so, for example, at 1MHz a 25mm wide braid strap just 100mm long that might have a resistance of 1mΩ has an impedance of nearly 0.2Ω at 1MHz – 20 to 200 times too high to be a good RF-bond.

Figure 16 shows an example of a 50kW VFD assembled in an industrial cabinet with its mains filter. Note how close the mains filter is to the VFD's rectifier, and also how both the conductively-plated metal bodies of the filter, rectifier and chopper units are all multi-point bonded to the cabinet's conductively-plated backplate, to provide good RF-bonding up to several 10s of MHz.

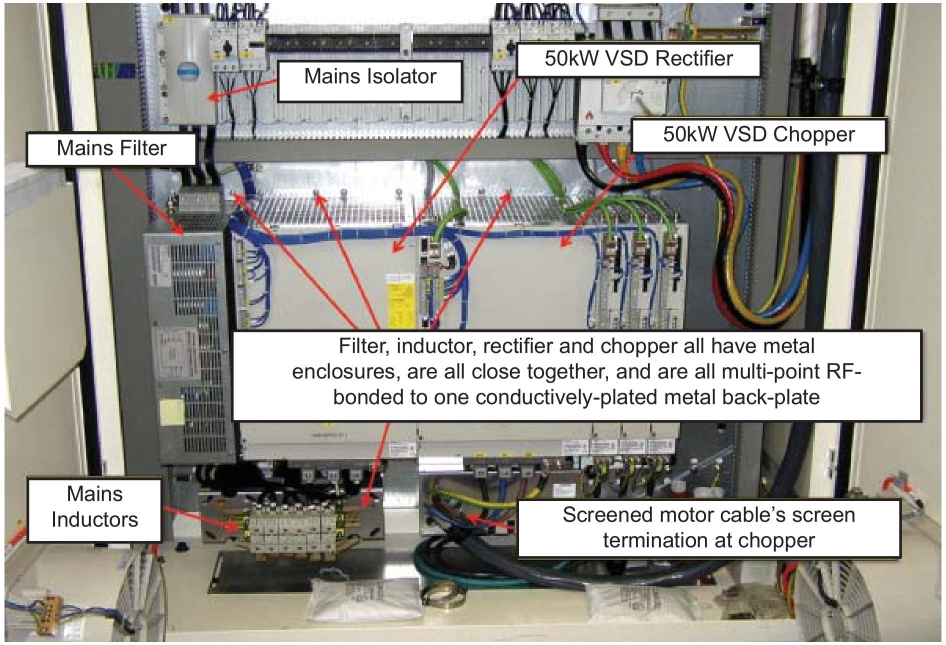


Figure 16:
Example of a 50kW drive with filtered mains and screened motor cable

Figure 15 shows how this approach reduces PDS emissions, by showing that the double-headed arrows of the DM noise currents, and the red ellipses of the CM noise currents, are all now contained within the assembly comprising the mains filter, VFD and output filter. They are not showing as flowing in either the mains supply or motor cables.

See 4.4.4 for using an isolating transformer to improve the CM performance of mains filters, and – where CM noise is the only significant problem – possibly replacing the mains filter entirely.

I don't have a real-life photograph of an output filter installed on a VFD, but the principles are exactly the same as for the mains filter in Figure 16. The output filter should be one that, like the mains filter, redirects both the DM and CM noise currents that would otherwise flow in the motor cable and motor, such as the REO "Sinus ++", otherwise known as filter type CNW 961. Figure 15 does not show it, but CM + DM output filters like the CNW 961 generally require a connection to the DC-Link as well.

Figure 17 shows some real-life measurements on a VFD fitted with series inductors to limit emissions of mains harmonics, then with an additional filter to suppress emissions

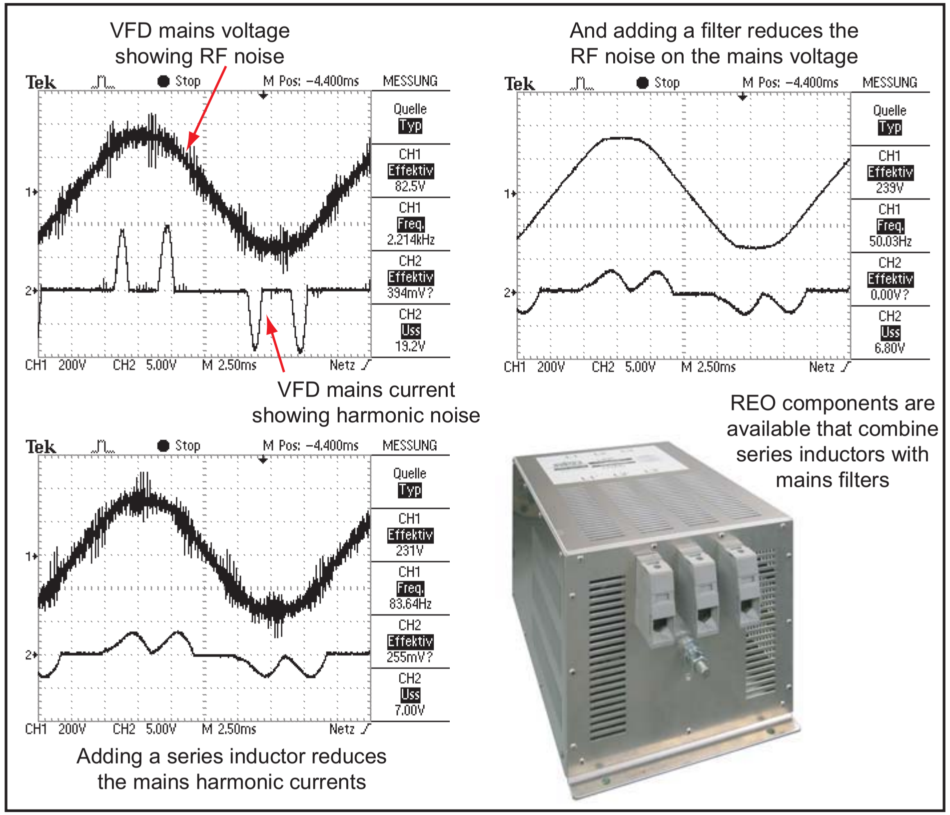


Figure 17:
Examples of suppressing mains noises

of high-frequency noises.

Even where the chopper does not cause interference problems, there is the problem of bearing life, and of the degradation of the insulation in motor cables and windings when long motor cables are used (see 3.3).Figure 18 shows an alternative to the output filter shown in Figure 15 – a screened motor cable. As this figure shows, if the screened motor cable has its screen correctly RF-bonded at both ends, the CM current loops associated with the VFD's motor output prefer to flow inside the cable screen. This is because the impedance of the CM loop path down the inside of the cable screen is so much lower than the alternative CM loops that exist in the earth/ground structure.

For example, when a number of resistors are connected in parallel, it is the one(s) with the lowest value that carry the bulk of the current. The impedance of the CM loops at frequencies above a kHz or so are dominated by inductive and capacitive reactances, rather than resistance, but the same principle applies – the bulk of the CM current automatically

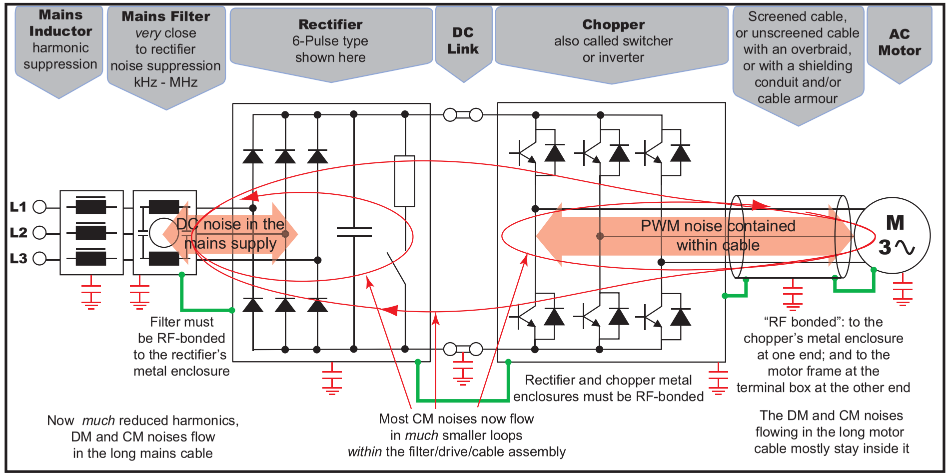


Figure 18:
Suppression with mains inductors and filters, and screened motor cables

takes the loop that presents the least overall impedance.

To achieve the low impedance necessary to control the motor output's CM currents:

- **At the chopper end, the motor cable screen must be RF-bonded to the chopper's metal enclosure, chassis or frame. At the motor end, the motor cable screen must be RF-bonded to the motor's metal terminal box, which in turn must be RF-bonded to the motor's enclosure or frame** (e.g. by seam-welding or multiple spot or tack welds).

Note: Figure 18 does not show an earth/ground cable between the motor body and the chopper, although one will almost certainly be required. This is because some VFD manufacturers require it to be contained *within* the screen of a screened motor cable, whereas other manufacturers require it to be routed outside the screen (but still close to the motor cable along its route). These requirements come from the electronic design of the VFD, so it is important to obtain the manufacturer's EMC instructions for the exact model of motor drive, and follow them.

A good way to prevent noise from the chopper which is causing EMC problems, is to make the motor cable very short indeed – less than one-tenth of the wavelength at the highest significant chopper harmonic frequency (e.g. 1m for 30MHz, 10m for 3MHz, 100m for 300kHz). The very best is to combine the BDM with the motor, with their metal frames multi-point RF-bonded together, or combined in a common casting, so there is no external motor cable at all. This technique has been very successfully used by some manufacturers, including Danfoss.

All VFD and VSD manufacturers should provide detailed EMC instructions for their products. I do not recommend using any manufacturer who does not (or will not) provide them. They will often be different for different models and ratings of drives, and for example, higher rated drives will generally require different filter specifications.

Cable screen RF-bonding is sometimes called 360° termination or 360° bonding, because it should ideally make electrical connection all around the circumference or periphery of the braid screen. Alternatives, such as multi-point bonding, may be used providing the bonding points surround the cable.

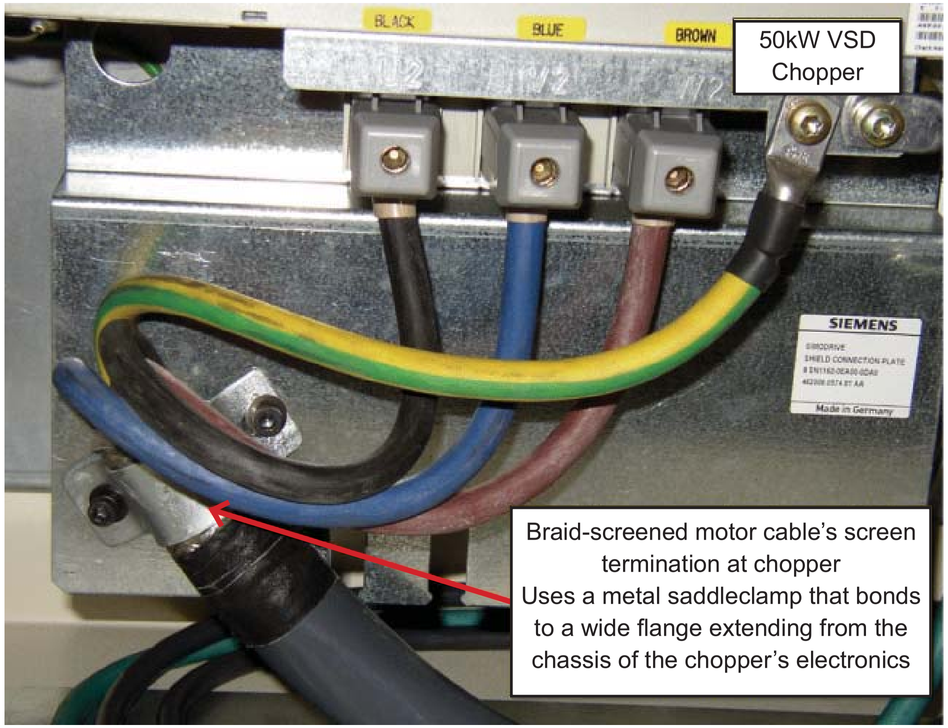


Figure 19:
Detail of the motor cable connection to the chopper in Figure 16

Figure 19 shows an amplified detail of Figure 16, where the motor cable connects to the 50kW VFD's chopper unit. It shows that the cable's braid is clamped to a flange protruding from the chopper's chassis, using a metal saddleclamp.

Figure 20 shows the other end of the motor cable in the system driven by the VFD in Figure 16. Here the motor cable's braid uses an "EMC Gland" to 360° bond to the motor's terminal box. Figure 21 shows a variety of types of EMC gland, the top left-hand one being the preferred type. Where connectors are used instead, they should terminate the cable screen in 360° just like an EMC gland.

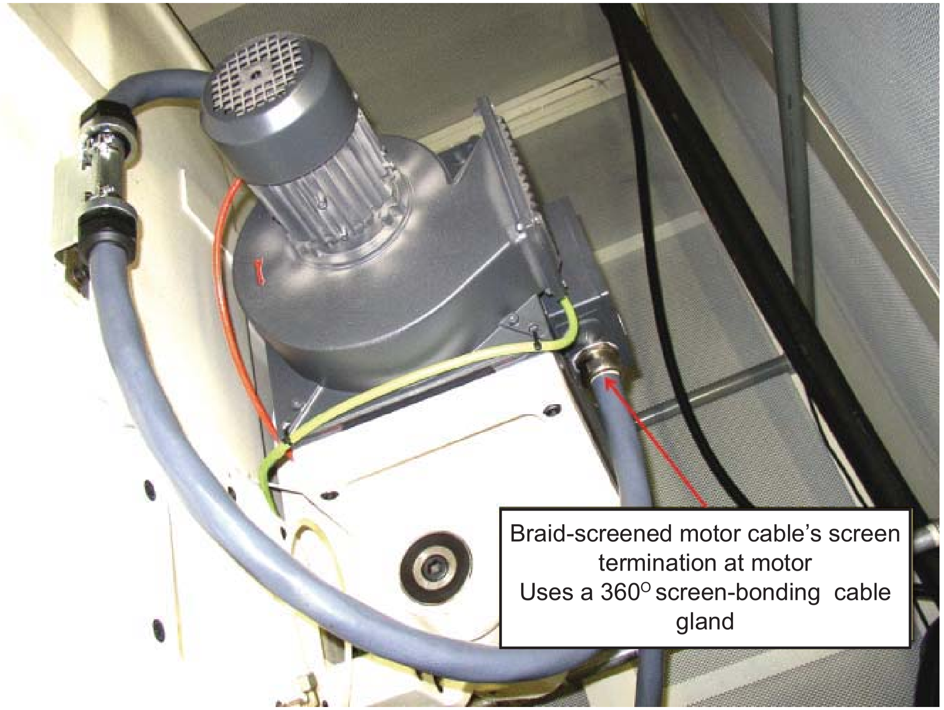


Figure 20:
Detail of the cable connection to the motor driven by the VFD of Figure 16

Figure 21:
Examples of three kinds of EMC cable gland

Figure 22:
Examples of screened flexible conduit and overbraid

Where it is difficult to source high-current cables with good quality screens, or when suppressing the noise from a legacy system that used an unscreened motor cable, overbraids or shielded flexible conduit can be used, as shown in Figure 22. When choosing either, make sure that appropriate 360° glands or connectors are available for it.

Solid conduit makes the best screen for a motor cable, but the usual "banjo" washers are useless for suppression purposes because they rely on lengths of wire to bond them to an earth/ground terminal, and so have too high an impedance at RF. Figure 23 shows one manufacturer's solution – a conduit nut that makes a multi-point 360° bond between the solid conduit and a metal enclosure at the point of penetration of the enclosure.

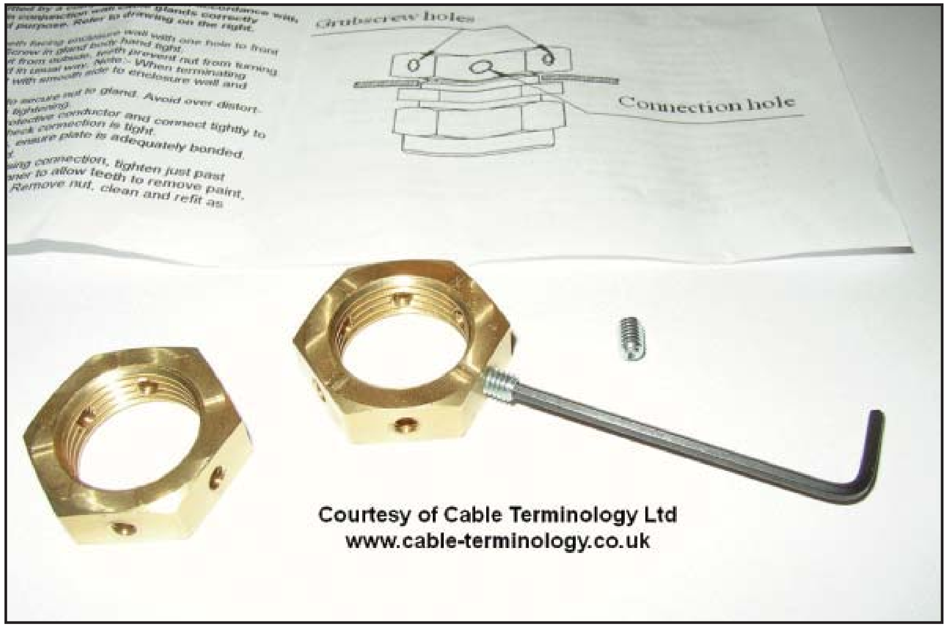


Figure 23:
Example of a suitable 360° bond for solid conduit

Figures 15 and 18 show the DM and CM currents flowing entirely within the VSD assembly, which includes any mains chokes or filters, and any output filters and/or motor cable screen bonds (at the chopper end). However, electrical installers often seem to be of the opinion that all earths or grounds are equivalent, and also that it does not matter exactly where the various components associated with a VSD are installed ([37] records some difficulties with this). So, in practice, the electrical installation of a VSD and/or its associated components (chokes, filters, isolating transformers, motor cable screen bonds, etc.) might not be compact, and its earth/ground conductors may connect all over the place.

It is however very important indeed that the following two general installation rules are followed:

a) All of the component parts of a VSD, plus its associated suppression components (chokes, filters, isolating transformers, motor cable screen bonds, etc.) <u>must</u> be in very close proximity, ideally all contained within one metal enclosure.

b) All of the earth/ground conductors associated with the component parts in a) above must connect to one point, ideally the chassis, frame, backplate or surface of the metal cabinet they are all contained within. This one point must then connect to the site's or vessel's safety earth/ground structure via one conductor – following all the necessary safety codes taking the earth/ground leakage current into account (it could be several amps, due to the mains filtering).

I make no apology for repeating some of the points already emphasised in the earlier text. Electrical installers must be controlled very carefully to ensure that these rules are met in full – otherwise all the time and cost of determining how to suppress the drives will be wasted, and the EMC engineers involved will be blamed for getting it wrong, when the problem is incorrect installation.

I strongly recommend to all EMC engineers associated with such projects, that they write down mandatory requirements for the installation of their suppression devices, using as much detail as needed to communicate with the electrical installers in terms that they will clearly understand – and insisting that the contract with the customer includes an item covering their inspection and approval of the final electrical installation.

Some readers might contrast point b) above with other REO Guides, books and articles I have written (e.g. [19] [26]) in which the virtues of meshed common-bonding networks (MESH-CBNs) are extolled at length. Note that these also allow the possibility of combining single-point bonded systems with mesh-bonded ones, so there is no conflict. However, if a MESH-CBN or MESH-IBN (see [19] or [26] for definitions) that can control up to 30MHz, at least, exists in the area where the VSD and its suppression components are located, then b) can be modified to read as follows:

b*) All of the earth/ground conductors associated with the component parts in a) above must connect to their local meshed CBN or IBN structure, using very short electrical bonds. Follow all the necessary safety codes taking the earth/ground leakage current from each into account (could be several amps, due to the mains filtering).

4.4. More details on suppressing PDS emissions

A little Guide like this cannot be a textbook and provide everything one might need to know, but at least it can provide the basics, and this has been done above. This section provides a few additional notes, and many references, on suppressing PDS emissions.

4.4.1. Obtain manufacturer's EMC instructions and follow them

VFD and VSD manufacturers EMC design/installation guides should always be obtained, and their advice followed accurately. However, they may not aim to achieve the degree of noise suppression that is needed (for example when installing many PDSs in one system, such as the example of Figure 3).

There are many general guides and textbooks on suppressing emissions from motor drives, including [31], [32], [33], [34], [35] and [36], and these might provide sufficient information to overcome any shortcomings in the drive manufacturer's EMC installation instructions. If even more information is required, see the following subsections.

4.4.2. Filtering

The specifications for the filters should be obtained from the VFD or VSD manufacturer's detailed EMC instructions for exactly the model of drive being used. When not using an output filter, longer motor cables – or screened or armoured motor cables – will have more stray capacitance, causing an increase in the magnitude of the chopper's CM currents, and may therefore need to use higher-specification mains filters for the same level of emissions (all else being the same).

So the mains filter specifications in a properly documented EMC installation guide should show how the filter specifications depend on the length of the motor cable, and in some cases on the type of cable too (e.g. screened cable, or cable routed in conduit, will have higher stray capacitance than the same length of unscreened).

For more information on EMC filtering, and how to assemble it in cabinets, systems and installations to get maximum benefits, see section 5.10 of [19], 4.7 of [20] and Chapter 8 of [26].

Mains harmonics can be filtered, instead of simply reduced by line inductors. However, because of their low frequencies special passive and/or active filtering techniques are used, and these are discussed in pages 51 through 55 of [29].

Where RF interference is suspected from a mains or output cable, it will usually be the CM currents that are to blame. Clamping a ferrite toroid around ***all*** of the phase and neutral conductors in the cable or bundle, with or without including their associated protective earthing (safety grounding) conductor, can sometimes be enough to stop the interference, and is especially effective at frequencies above 30MHz. At frequencies below 30MHz two or more ferrite toroids may be needed in series on the cable.

Distributors stock many suitable ferrite toroids, and the split versions are better for retrofitting (all EMC engineers carry many kilograms of various types of ferrite when visiting a site to try to solve a problem). It is important to ensure that all of the power conductors associated with a mains supply or motor load pass through the ferrite toroid, and it may be necessary to wind those conductors two or even three times on the toroid. Always check that – when installed on a cable – the ferrites do not get too hot to hold your hand on for several minutes, when the drive is running at full power. Ideally, they would hardly get warm at all, and if they do it usually means that a much larger ferrite is required.

For even better performance from a ferrite CM filter at low frequencies, wound single-phase and three-

phase CM choke components can be connected in series.

When trying to specify your own mains filter in the absence of guidance from the drive manufacturer (or when that information proves inadequate) it is important to understand that, in real life, mains filters operate with "mismatched" input and output impedances – i.e. they are not both 50Ω, or even both the same. All mains filters resonate and provide gain rather than attenuation at their resonant frequencies, and especially so when operated mismatched – as they always are in real-life. But attenuation data from most distributers and some manufacturers do not show this, because they only show the results of "matched" tests (i.e. 50Ω input and output).

How to deal with the problems of filter resonance is discussed in detail in section 5.10.1 of [19], 4.7.1 of [20] and Chapter 8.1.3.1 of [26]. These all basically recommend getting all the CM and DM, matched and mismatched test data from the filter supplier (6 curves in all), drawing the worst case of all of the attenuation curves, and assuming that a filter's real-life performance will be no better than that.

Cascading mains filters is generally a bad idea. Resonances can occur that make the attenuation of the combination worse than any of the filters on their own, so great care should be taken when a VFD is fitted with an internal mains filter, but its performance is not enough and you are tempted to add another filter in series with it.

However, multi-stage filters are available that have excellent performance, although the more stages they have, the larger, heavier and more costly they tend to be. But the author knows custom-engineering control cubicle manufacturers who automatically fit a 100A 3-phase 5-stage mains filter to the incoming supply of their cabinets. Although over-specified in most cases, they reckon that it saves them time and cost overall, by avoiding the need to spend time choosing and proving which is the most cost-effective filter for each cabinet.

Most standard mains filters sold as 'EMC filters' will not provide much attenuation for the VSD's emissions below 150kHz (see the case study in 3.4). Filters suitable for VSDs must provide good attenuation down to the chopper's fundamental frequency (i.e. switching frequency) for both the DM and CM noise emissions. The CM attenuation is especially important.

CM + DM <u>output</u> filters convert the PWM output into a relatively "clean" DC or AC waveform, that can be sent significant distances, over perfectly ordinary cables to the motor, without causing interference problems – incidentally improving cable and motor life as mentioned earlier. But because they are costly, such output filters will probably not even be mentioned in most drive manufacturers' EMC instructions.

Where using screened motor cables is impractical for some reason, CM+, DM filters like REO's Sinus ++ series may be the only solution. The manufacturers of the filters should be able to tell you which VFDs or VSDs they are suitable for.

In between low-cost ferrite toroids and expensive CM + DM motor output filters, there are various medium-cost alternatives. So-called dV/dt filters "round off" the edges of the motor output PWM waveforms, which – in the frequency domain – attenuates the higher frequency noise spectrum. Figure 24 shows the effect of applying a REO dV/dt output filter to a VFD.

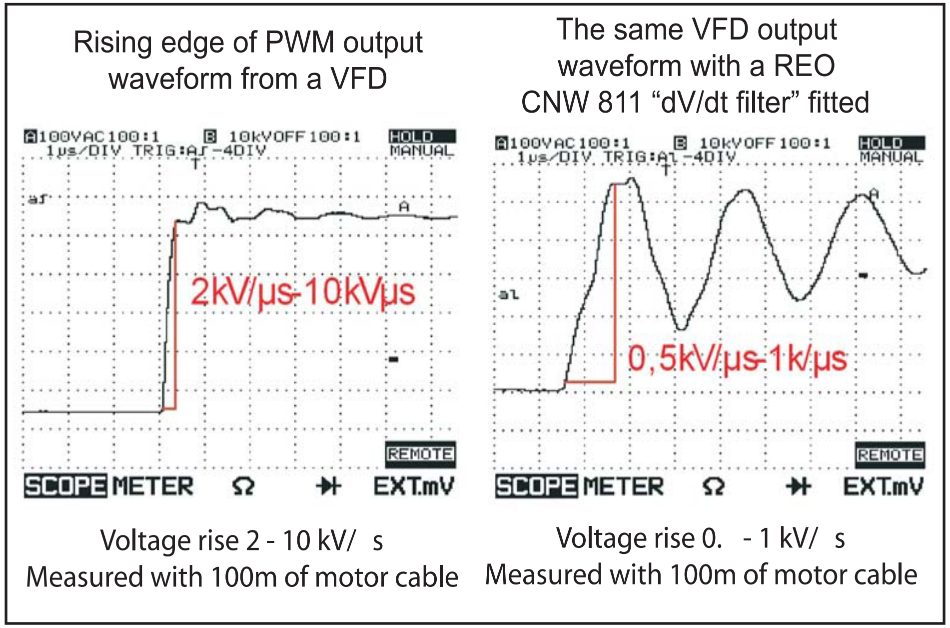


Figure 24:
"Rounding off" the PWM waveform with a dV/dt filter

Ships and other vessels generally use mains supplies that do not have their neutral directly bonded to their earth/ground structure [35], and some land-based installations also use this practice. This situation is discussed in Section 4.5.

4.4.3. Safety issues with filtering

Filters contain capacitors from the phase conductors (mains or motor) to the earth/ground, and these increase the current in the protective earthing conductor (the green/yellow striped wire in the mains supply). Safety standards and electrical wiring codes set quite low limits on this current, to help prevent electric shock hazards, but they will allow any amount of earth/ground leakage current when high-integrity earthing/grounding systems are used with a fixed VSD installation (i.e. one that does not have a flexible mains lead or mains plug, sometimes called "non-pluggable" equipment.).

The high earth/ground leakage currents caused by filters can also make it impossible to use residual-current circuit breakers (RCCBs), earth leakage circuit breakers (ELCBs) or ground-fault interrupters (GFIs).

Where the mains system is isolated from the safety earth/ground (see 4.5), or when it is "corner-grounded" (one phase connected to earth/ground, rather than the neutral), all capacitors connected to the earth/ground (e.g. in a filter) should be safety-rated for the full phase-to-phase voltage, rather than phase-to-neutral.

4.4.4. Benefits of isolating transformers

Where a BDM is *not* powered from a co-located dedicated step-down isolating mains transformer, *and* where the mains power supply that feeds it is shared with other electronic equipment (which may include other BDMs) that are *not* co-located with the BDM concerned – then a number of EMC issues arise that may be best dealt with by fitting the BDM with a dedicated co-located isolating transformer.

Isolating transformers are large and costly components, especially for high-power BDMs, but omitting them or trying to use less costly alternatives can prove to be more costly overall (see section 3).

In situations where a mains power supply feeds two or more items of equipment spread over a site or vessel, the DM impedances of the phases can become different from each other due to unequal loading, and the CM impedance between the phases and the earth/ground can become quite low due to the stray capacitances of the long cables and the CM filters in other equipment. These impedance effects negatively affect the performance of a BDM's mains filter (see [36]). Fitting an isolating transformer restores the balance to the DM impedances, and also restores a high CM impedance, helping the mains filter achieve its designed potential.

Earlier, I discussed how a BDM's CM return currents were 'steered' by capacitors in its input and/or output filters and their low-impedance bonding to the BDM's chassis/frame, so that they flowed mostly in the BDM's assembly. But when the CM impedance of the mains supply is low the ratio between the path impedances provided by the mains filter and that provided by the mains supply might not be as high as we would like. For example, where there are two or more equipments fitted with mains filters connected to a mains supply, their low CM impedances encourage the CM currents of each item of equipment to flow in the other's mains filter – encouraging CM currents to flow widely, which is not what we want.

Where a BDM's mains filter does not include a CM choke on the supply side of its CM capacitors, this problem can be reduced by fitting a CM choke in that position, co-located with the mains filter. But all chokes cause some voltage drop and so this might cause an increased rate of tripping due to sags or dips in the supply. Another possibility is to fit an earth/ground choke to the BDM, which of course will only work if it is fitted to the single conductor that connects the BDM's earth/ground to the earth/ground structure of the site or vessel (see item b in Section 4.3).

But an isolating transformer dedicated to the BDM and co-located with it (see item a in section 4.3) will provide much better control of CM currents than any chokes.

A mains isolating transformer might also prove to be sufficient, on its own without a mains filter, for preventing the CM noise from a BDM's mains input from circulating widely. It would do little or nothing for the BDM's DM noise emissions, or the resulting waveform distortion, but this is often not as much of a problem as the CM noise emissions anyway.

Where a BDM is fitted with a mains filter that deals with CM noise as well as DM, the majority of problems with widely-circulating CM currents occur at lower frequencies, below 150kHz. In this case experience seems to show that the normal type of construction for an isolating transformer is adequate for controlling CM currents in this frequency range.

However, there are techniques available for decreasing the stray primary-secondary interwinding capacitance, and for adding interwinding screens. These can be used to provide better isolation performance and higher CM source impedance, from DC to radio frequencies, which may be needed on occasion, for example when a mains filter is not fitted at all.

4.4.5. More detail on RF-bonding techniques

Figure 25 shows the basics of the ideal method of RF-bonding two metal items together (e.g. RF-bonding the metal bodies of the mains filter, rectifier and chopper to the backplate in Figure 16).

But there are many more details that could be important, and in some cases alternatives might be appropriate, so the information in

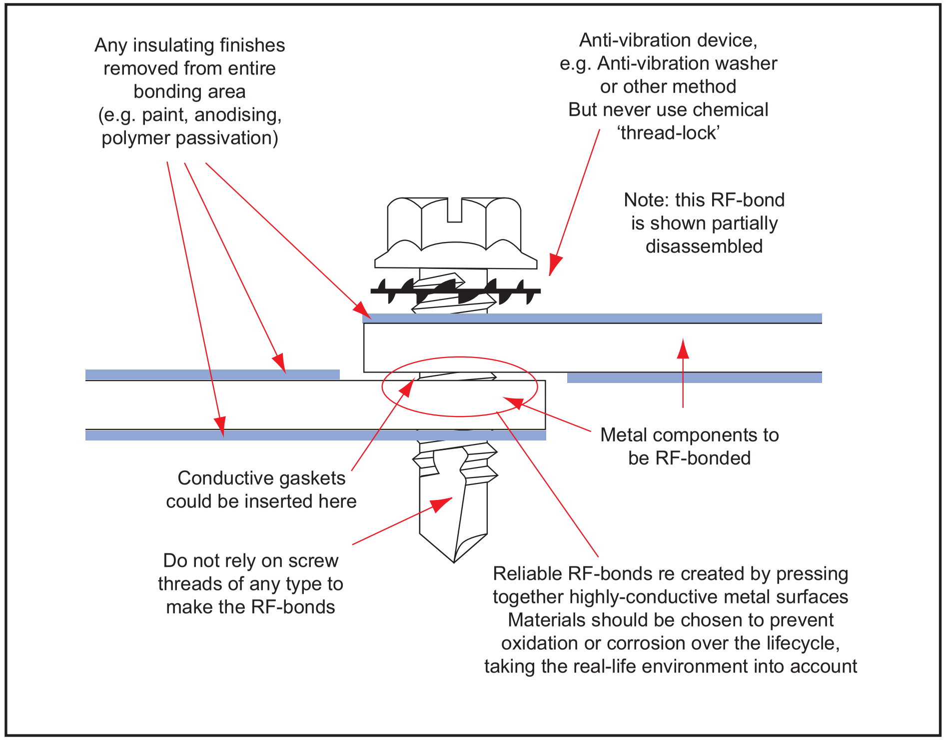


Figure 25: RF-bonding two metal surfaces

section 5.7 of [19], 2.2 through 2.5 of [20] and Chapter 5 of [26] may be useful.

4.4.6. More detail on cable screening (shielding) techniques

This will be found in sections 5.7.6 through 5.7.10 and 5.11 of [19], 3.7 of [20] and Chapter 7.2 of [26].

Screen bonding need not be costly, especially where there are number of cables screens to be bonded (e.g. to a cabinet backplate) as shown by the DIY screen-bonding technique of Figure 26.

However, where a screened enclosure (e.g. cabinet, room, etc.) is used (see 4.4.5), “proper” glands like the top left-hand side on in Figure 21 should always be used (or connectors with similar screened braid terminations).

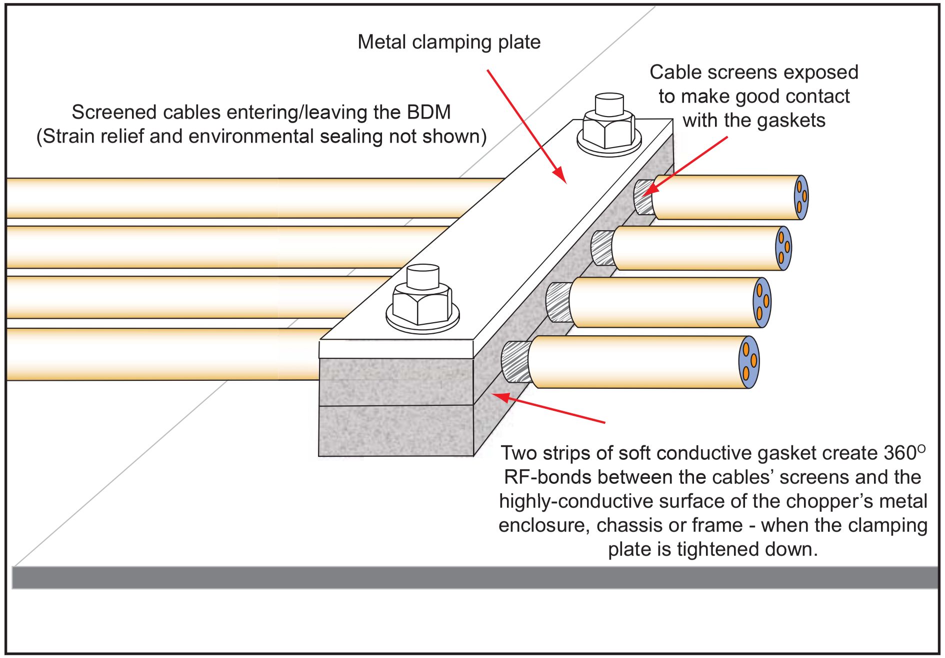


Figure 26:
A low-cost way to RF-bond multiple cable screens

4.4.7. Screened (shielded) enclosures

EN/IEC 61800-3 is rather dismissive of the potential of PDSs to interfere with radio reception through radiated emissions. However, VFDs – especially low-power ones switching at over 20kHz – have been known to interfere with radiocommunications, as some items in [15] show (e.g. No. 24).

As long ago as the early 1990s I have had to improve the shielding of industrial control cabinets that contained several VFDs, to pass the radiated emission tests to the generic emissions standard for the industrial environment (which was EN 50082-1, but is now EN/IEC 61000-6-4). Each VFD complied on its own, but when all the drives in the cabinet were running, their aggregate emissions were significantly above the limit line.

As PowerFETs and IGBTs develop, they are designed to switch faster to reduce heat losses and increase efficiency, so the prospects for radiated interference can only worsen. And as mentioned in section 3, more radiocommunications are being used everywhere, which also increases the potential for radiated interference from PDSs.

Designing and/or installing shielded enclosures requires a lot of attention to detail, but the basic principles are outlined in Figure 27, which shows

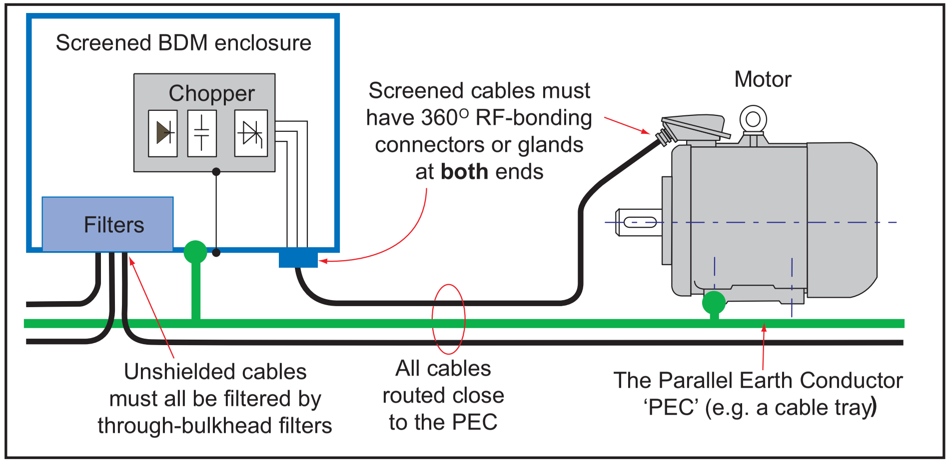


Figure 27:
The basic principles of employing a screened enclosure

that no conductor of any type (even a mechanical push-rod or metal pipe) can enter/exit a screened enclosure without either:

a) Being RF-bonded to the enclosure's metal wall at the point of entry/exit, or

b) Being filtered to an appropriate specification, with the filter RF-bonded to the enclosure's metal wall at the point of entry/exit, or

c) Being a screened cable with an appropriate specification, the screen being RF-bonded (i.e. 360° bonded) to the enclosure's metal wall at the point of entry/exit.

No alternatives are ever permitted, for any reason. I am often asked to solve real-life problems in which expensive shielded cabinets are found to be "leaking", and the usual problem is that some conductor assumed to be insignificant (e.g. hydraulic pipe, mouse cable, etc.) has been allowed to enter/exit the enclosure without one of the above three methods being applied.

However, sometimes the problem has been that the system integrator has simply cut a large hole in the wall or door of the screened enclosure, to mount their human-machine interface, destroying the screening effectiveness in the process.

A great deal of detail on the design and installation of shielded enclosures, of all sizes from just large enough for one small VFD, up to screening an entire room or even a building, will be found in the following: section 5.12 of [19], section 5 of [20] and Chapter 6 of [26].

4.4.8. Other EMC techniques

The above discussion has not addressed all the EMC techniques that will probably be required, for which read [31] [32] [33] [34] [36] and [19] [20] and [26].

For example, most (if not all) VFD manufacturer's EMC installation instructions, as well as [33] [34] and [36] will include the requirement to classify the cables associated with a PDS according to some rules, and then to route these "cable classes" separately from each other, with certain minimum spacings to be maintained between cable classes where they are routed in parallel.

This acknowledges the fact that no cable screens or filters are perfect, so it helps to reduce the crosstalk between the cables, especially from the motor output to the mains supply or control cables. It also helps ensure low crosstalk to cables that are not associated with the drive, such as telephone cables, which can suffer dramatically from audio-frequency

whines and whistles if routed too close to cables associated with a drive, and are a matter of some concern to EN/IEC 61800-3 (see 6.2.5 in [1]). For a real-life example of serious telephone interference from a high-power drive, see Item 1 in [15].

Cable classification and segregation is covered in section 4.8 of [19] (4.4 is also important); 3.3 of [20] and Chapter 7.4 of [26].

4.4.9. Commutation notches

Voltage "notching" is an emission problem caused by naturally commutated thyristors/triacs in DC drives. The cross-conduction when one thyristor or triac turns on before another has finished turning off, momentarily shorts-out their phases causing a dip with a depth of 100%.

Although this is a low-frequency noise, it is very severe and can interfere with other equipment that is using those phases. However, a "3% inductor" such as is often fitted to reduce emissions of mains harmonics and interharmonics (see 4.4.8), will generally provide adequate suppression.

[1] calls this series inductor a "decoupling reactance" and requires that its size be specified.

4.4.10. Mains harmonics and interharmonics

These are typically suppressed by using a "3% inductor" in series with the rectifier, as shown in Figures 15 and 16. The 3% refers to the fact that when carrying its full rated current, its internal impedance reduces the mains voltage by 3%. This is considered to be a cost-effective compromise, but sometimes it is necessary to go as high as a 4% inductor. Increasing the impedance even further is not advised, so if series inductors have not managed to reduce the harmonic and interharmonic emissions by enough, other techniques must be used instead of, or as well as, series inductors.

Single-phase VSDs and VFDs suffer from emitting all of the odd-numbered mains harmonics, including triplens as mentioned earlier. On four wire systems (i.e. 3 phase + N) the triplens add arithmetically in the neutral conductor causing significant problems with localised power quality and equipment operation. However, three-phase (6 pulse) drives running from reasonably low-distortion mains supplies have very low levels of "triplen" harmonics, of which the most important are the 3rd and 9th. Losing the 3rd makes it easier to use series inductors to get good levels of mains harmonic reduction.

Phase-shifting mains transformers can be used to create six-phase (often called 12-pulse) rectifiers, which has the effect of causing the 5^{th} and 7^{th} harmonics to be substantially cancelled out in the rectifier's circuits, so that its first significant mains harmonic is the 13^{th}. Increasing multiples of three phases (or six pulses) attenuates even higher-order harmonics, but the specification on the purity of the mains supply's sine waveform and equipment and phase shift transformer quality (internal imbalance tolerance levels) must increase with the number of phases for this to be effective. However, using large or multiple-phase-shift transformers, as is typical of oil production platforms, can still reduce this excessive voltage distortion, especially at higher order where they are both most problematic and difficult to treat.

Ships and other vessels often have very distorted mains supplies because their electricity generators have much higher (about 3 times) the source impedance of a landlubber's HV transformer of the same VA rating, and also because of the increased use of powerful VFDs in "electric thrusters" and even electrical propulsion. For this reason, 6-phase and higher (12-pulse and higher) rectifiers are often unsuitable for ships, because they rely on low-distortion mains for their harmonic improvements. So ships and vessels often use special harmonic suppression techniques that are not commonly used in land-based installations, see [35] for details.

A reasonably new design technique, at the time of writing, is the "active front end" (AFE), which uses IGBTs instead of plain old rectifiers. These are switched at a high rate, just like a chopper that drives PWM into a motor, but control software arranges the sequencing and timing so that, after passing through a series inductor to average out the PWM, the result is a rectifier that appears to the mains supply as a substantially linear (i.e. resistive) load, which as a direct consequence is claimed to achieve low emissions of mains harmonics (<5% I_{thd}).

However, AFEs achieve this at the cost of significant harmonic currents in the supply at the switching frequency of the AFE bridge, higher EMI emissions between 10kHz and 100kHz, and other a number of other issues. AFE rectifiers, being series devices, have to be dimensioned for the total load. This, of course, is a matter of drive selection, and is not otherwise under the control of a system integrator or installer.

Filtering was mentioned earlier as a means of suppressing mains harmonics, using passive filters such as resonant traps. Another technique is the so-called "active filter", which

is really a chopper that is controlled to source or sink mains currents in antiphase to those that are causing problems, and – despite its name – is not a filtering technique at all. Passive and active harmonic filters are often used where it is desired to deal with the harmonics of all the equipment on one floor of a building, or even an entire building, site or vessel, instead of dealing with them at the level of individual items of equipment.

Active filters, introduced some 10 years ago, are expensive but widely used. These electronic 'filters' provide a very low impedance source (<1%) for the harmonic currents. Therefore, if rated correctly, the load(s) draw the harmonic currents from the active filter whilst the source provides only the fundamental current. Depending on the type, active filters can reduce harmonic emissions to below 5%. Active filters are parallel devices, and so only need to be rated for the harmonic current.

The other type of harmonic filter which is very popular is worldwide the passive "wide spectrum filter". These are multi-limbed reactors wound on a common core, fitted with a small capacitor bank (not like traditional passive filters). They are connected in series with the load(s) and – depending on manufacturer – can also reduce the I_{thd} to around 5%. One manufacturer supplies these filters up to almost 3,000kW for both AC and DC drives. Being passive and linear, they do not cause EMI emissions.

Cost-effectiveness calculations may show that it costs less to allow all the PDSs on a site or in a vessel to emit their harmonics, and to clean them up with a single filter (passive or active) so that they do not cause too much distortion of the mains voltage waveform.

These and other "installation level" techniques are discussed in pages 42-62 of [29], and [35].

4.4.11. Mains voltage fluctuations

[1] sets limits for the generation of mains voltage fluctuations, for which there are only a few installation-level mitigation techniques, such as Dynamic Voltage Restorers (DVRs) see pages 36-49 of [30].

At the level of the motor drive, the major benefit comes from using "soft-starting", especially for AC motors because they can draw very large magnetising currents when switched Direct-On-Line (DOL) near the zero-crossings of the mains voltage. Using VFDs solves this problem automatically.

Where high-powered drives have a rapidly fluctuating load, the fluctuating motor currents can also give rise to significant mains voltage fluctuations. This may be able to be cured by adding inertial energy storage (e.g. a larger flywheel) or by installing a DVR with an adequate rating, see 5.3.9 on page 48 of [30].

4.4.12. Radiated EM disturbances – low frequency H-fields

These are suppressed by the filtering and cable screening methods discussed earlier, and by ensuring that all conductors carrying DM loops are in close proximity, preferably twisted together, along their entire route, see section 4.4 of [19].

Where cables carry currents that are too large to permit them to be twisted or placed close together, because of the physical damage that would occur to their insulation due to the electro-motive forces acting on their conductors, it may be possible to arrange for external shielding around the bundle of conductors to protect nearby equipment from the magnetic fields (see 5.12 in [19]).

But shielding can be very costly, especially in the case of very low frequencies – say below 1kHz – where it can also be very difficult to do at all. Where problems arise with low-frequency magnetic field emissions, for instance in a ±8kA DC drive I saw in a steel mill, often the only solutions are either to make sure that sensitive equipment is located far enough away not to be effected, use equipment that is not sensitive (e.g. use plasma or LCD computer screens instead of cathode ray tube (CRT) types), or fit localised screening to the affected items of equipment.

Screening for very low frequencies can be passive (e.g. using MuMetal™); or active, in which metal frameworks are driven with currents to create magnetic fields that “cancel out” the local ambient magnetic field.

Where there are powerful currents there is always the possibility that human exposure to the resulting magnetic fields could be too high, see [10] and [11] for limits, and methods for testing and calculation.

4.4.13. Emissions from the DC-Link

DC-Link conductors can carry as much noise as the output cables. Figure 14 shows that there is some stray capacitance to earth/ground from the DC-Link conductors, so the noise voltages and currents on the DC-Link can couple noise into other equipment and radio receivers by induction or radiation.

The DC-Link should therefore be treated like a motor cable: made as short as practicable, and then (if

necessary) either filtered or screened. When filtering techniques are used, filters may be needed at <u>both</u> ends, because the DC-Link carries noises generated by both the rectifier and the chopper.

4.4.14. Neutral shift can stress motor insulation

Section 4-12 of [36] discusses the problems of increasing neutral-earth/ground voltage caused by VSDs with Wye-connected inputs. It also discusses solutions that can be used when a Delta connected mains input cannot be used. These include using an isolation transformer at the mains input and floating the neutral connection to the VSD.

4.5. Insulated Neutral, “floating” mains power systems

Ships and other vessels generally use mains supplies that do not have the neutral of their mains power supply directly bonded to their earth/ground structure [35], and some land-based installations also use this practice. This is known as an IT power network (nothing to do with Information Technology!).

EN/IEC 61800-3 [1] assumes (D.1.2.2 and D.2.2) that filtering is an unsuitable technique where the mains power network is isolated from ground, and says that in such situations the only mitigation possible is to ensure that all the other equipment on the site is immune enough to the noise emitted by the PDS. But this ignores the possibility of interference with equipment off-site, and with radio receivers, so is not a complete solution.

However, if filters are fitted to individual BDMs as recommended in this Guide, all that is necessary is to “float” the chassis, frame or enclosure of the BDM. Since the mains and output filters (if used) will be RF-bonded directly to the BDM’s chassis, frame or enclosure they will not increase the leakage current into the earth/ground. Of course, this will mean protecting the BDM from being touched, to prevent personnel from suffering electric shocks if there is a phase-to-earth/ground fault in the system.

When using cable screens and/or armour instead of output filters, a capacitive RF-bond could be used at one end of the motor cable, either at the BDM or in the motor’s terminal box. This will not be as effective as a proper 360° RF-bond, but may be good enough if their lead lengths are kept very short. For safety, such screen-bonding capacitors should be safety-rated for the full phase-to-phase voltage, and of course their effect on the amount of earth/ground leakage current must be taken into account.

Another technique for reducing the earth/ground leakage of filters and cable screen/armour bonds, is to fit a co-located isolating transformer to the PDS so that it can be bonded directly to the earth/ground without compromising the rest of the system. Of course, if the PDS is powered from a dedicated and co-located step-down isolating mains transformer, a separate isolating transformer is not required – its EMI suppression function is provided by the step-down transformer.

5. Immunity

As well as dealing with emissions, EN/IEC 61800-3 [1] specifies test methods and test levels for immunity. The issues it is concerned with are:

- Power quality issues, including:
  - Distorted mains supplies (including harmonic distortion and commutation notches)
  - Supply voltage deviations, variations, changes, fluctuations, dips, dropouts and short interruptions
  - Three-phase voltage unbalance
  - Mains frequency variations
- Magnetic fields
- Conducted continuous EM disturbances (150kHz to 80MHz)
- Fast transients
- Radiated continuous EM disturbances (80MHz to 1GHz)
- Surge transients
- Electrostatic discharge

Most of these are best dealt with by the design of the equipment, as described in [21] and [22], and so not in the scope of this Guide.

To discuss what *can* be done to improve the immunity of a PDS by using installation techniques, the immunity problems can be broken down into four groups, see below.

5.1. Power quality issues

Section 5 of [30] is the most relevant reference for installation-level methods for dealing with poor power quality, and 4.2 of [19] will also be useful.

Part 6.5 of [21] describes a number of ways of designing equipment to improve its immunity to power quality issues, and some of those techniques can also be applied “stand-alone” to a PDS, system or installation.

And the techniques for dealing with commutation notching and other low-frequency emissions such as harmonics and interharmonics described in section 4 above, may also be able to be used to improve immunity to those electromagnetic disturbances.

5.2. Magnetic fields, conducted/radiated disturbances, fast transients

Where a PDS has problems complying with the tests for immunity to magnetic fields; conducted continuous EM disturbances (150kHz to 80MHz); fast transients, and/or radiated continuous EM disturbances (80MHz to 1GHz) – the usual solutions are to use the filtering and screening techniques discussed in section 4 above for suppressing emissions of low and high frequencies.

A technique that attenuates an equipment’s emissions of a particular electromagnetic disturbance, generally provides a similar level of attenuation when protecting equipment *from* interference by that same type of disturbance.

5.3. Surge transients

Series inductors used for suppressing emissions of harmonics or commutation notches also help increase a drive’s immunity to surge transients. Other techniques are galvanic isolation and surge protection devices (SPDs), which are discussed in sections 4.3 and 5.13 of [19], respectively.

These techniques can be used individually, or together in any combination.

5.4. Electrostatic discharge (ESD)

ESD techniques for equipment are covered in part 6.1 of [21], and they can be applied to a complete BDM by enclosing it in either a plastic enclosure (to prevent ESD from occurring at all) or in a shielded enclosure (to divert ESD disturbances away from the BDM’s electronics within).

Plastic enclosures do not protect

from the radiated fields of a nearby discharge, so it may turn out that a shielding solution is better. This is then just a matter of applying the shielding techniques briefly introduced in 4.4.5 above, usually aiming for the upper frequency to be controlled to be at least 1GHz, ideally 3GHz.

To suppress ESD within an installation means preventing it from happening by using static control measures: dissipative flooring and other surfaces, dissipative clothing, ionising blowers, control of relative humidity etc., all very familiar to anyone who has worked in semiconductor manufacture or light electronic assembly.

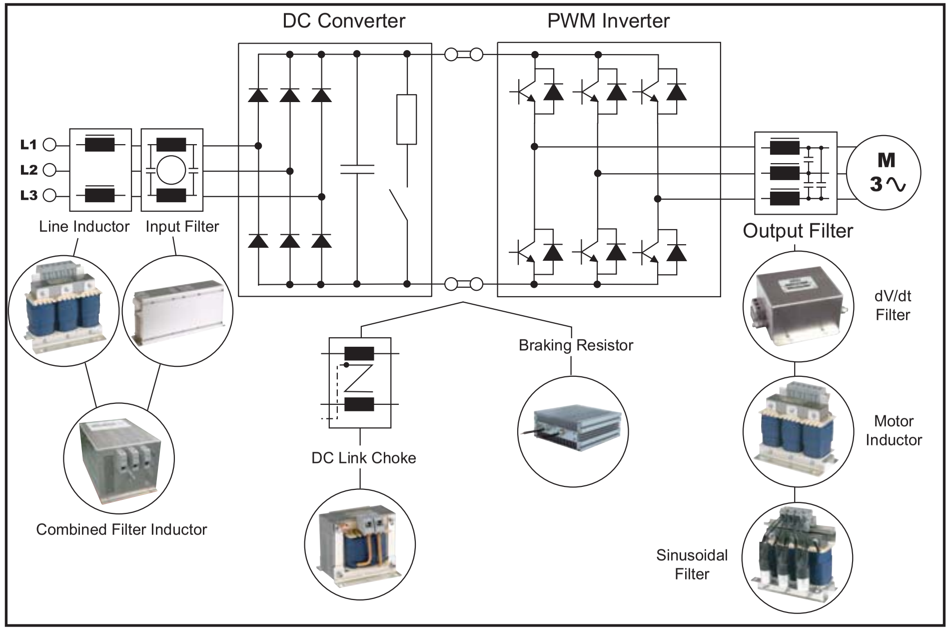


Figure 28: REO's motor drive products

6. EMC suppression products from REO

Figure 28 shows the range of products that REO provides for suppressing and/or protecting motor drives.

7. References and further reading

[1] EN 61800-3:2004, "Adjustable Speed Electrical Power Drive Systems – Part 3: EMC requirements and specific test methods". Identical to IEC 61800-3:2004.

[2] European Union Directive 2004/108/EC (as amended) on Electromagnetic Compatibility (2nd Edition) in English: http://eur-lex.europa.eu/LexUriServ/site/en/oj/2004/l_390/l_39020041231en00240037.pdf

– in any EU language: http://ec.europa.eu/enterprise/electr_equipment/emc/directiv/dir2004_108.htm

The Directive's official EU homepage includes a downloadable version of the current EMC Directive and its successor; a table of all the EN standards listed under the Directive; a guidance document on how to apply the Directive; lists of appointed EMC Competent Bodies; etc., all at: http://europa.eu.int/comm/enterprise/electr_equipment/emc/index.htm.

[3] Keith Armstrong, "Complying with the EMC Directive (2004/108/EC), Second Edition", Conformity, March 2008, pages 12-22, http://www.conformity.com/PDFs/0803/0803_F1.pdf. Also published in a slightly amended form in Conformity's 2009 Annual Reference Guide.

[4] Seventeen EMC Guides on EM phenomena, legal compliance and EMC testing have been written by Keith Armstrong and published by REO (UK) Ltd. They are very readable and practical, and can be downloaded from www.reo.co.uk/knowledgebase.

They are also available from REO (UK) Ltd and Cherry Clough Consultants as a CD-ROM that contains all 17 of them plus two other REO EMC Guides and a great deal of other useful information on EMC.

[5] "On-Site EMC Test Methods", Keith Armstrong, EMC Test Labs Association (www.emctla.co.uk) Technical Guidance Note No. TGN 49, also available from the "Publications and Downloads" pages at www.cherryclough.com.

[6] The EC's official Guide to 2004/108/EC can be downloaded from: http://ec.europa.eu/enterprise/electr_equipment/emc/directiv/dir2004_108.htm#guide

[7] The EMC Regulations 2006, United Kingdom Statutory Instrument 2006 No. 3418: http://www.opsi.gov.uk/si/si2006/uksi_20063418_en.pdf, implementing 2004/108/EC in UK law.

[8] The official guide to the UK's 2006 EMC Regulations is posted under "Related Documents" at: http://www.berr.gov.uk/dius/innovation/regulations/ecdirect/page12469.html

[9] The consolidated version of the Low Voltage Directive, 2006/95/EC, replaces 73/23/EEC and its amendment by 93/68/EEC, http://europa.eu.int/comm/enterprise/electr_equipment/lv/index.htm

[10] 1999/519/EC, "Council recommendation 1999/519/EC on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)", from: http://ec.europa.eu/enterprise/electr_equipment/lv/emf.htm

[11] EN 62311:2008, "Generic standard to demonstrate the compliance of electronic and electrical apparatus with the basic restrictions related to human exposure to electromagnetic fields (0 Hz - 300 GHz)" (a modified version of IEC 62311:2007, it replaces EN 50392:2004).

[12] 2004/40/EC, "On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)", dated 29 April 2004. From: http://www.hse.gov.uk/radiation/nonionising/l184emf.pdf

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