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EMC design of Switching Power Converters

Part 7 *(continued 2)* —
Shielding (screening) the power converter's output cable

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Contents

Issues 93-99 of The EMC Journal carried the preceding parts of this "Stand Alone" series – my attempt to cover the entire field including DC/DC and AC/DC converters, DC/AC and AC/AC inverters, from milliwatts (mW) to tens of Megawatts (MW), covering *all* power converter applications, including: consumer, household, commercial, computer, telecommunication, radiocommunication, aerospace, automotive, marine, medical, military, industrial, power generation and distribution, in products, systems or installations.

Hybrid & electric automobiles, electric propulsion/traction; "green power" (e.g. LED lighting); and power converters for solar (PV), wind, deep-ocean thermal, tidal, etc., are also covered.

Issues 93-95 used a different Figure numbering scheme from the rest, for which I apologise.

I generally won't repeat material I have already published, instead providing appropriate references to the EMC Journal [14] and my recently-published books based on those articles [15], so that you don't get bored by repetition.

7 Suppressing RF emissions from inputs and outputs

This is the section I began to write in Issue 98 [72] and continued in Issue 99 [84]. Despite my aim in this series to only publish 'stand-alone' articles, each covering a single topic, the issue of suppression is so large that it is impossible to publish it all in a single issue.

The topic of suppression is so large, because it is so difficult and contains so much detail. Please don't forget that it is much better (more cost-effective, shorter time-to-market, see section 7.1 in [72], [11] and Chapter 1 of [5]) to design the power converters in such a way as to minimise their input and output emissions. These design topics were covered in the early parts of this series, [13] [42] [64] [65] and [66] because they are more important for technical and financial success.

My earlier story about suppressing the emissions from a military submarine's winch (page 33 of [84]) was given as an example of filter resonance. But it serves equally well as a story about the cost-effectiveness and development time-savings of designing the noise out of the converter in the first place. Instead of a multi-component mains filter that used costly Y-rated capacitors, and after a day I still hadn't developed well enough to achieve compliance, instead I used a single X-rated 470nF capacitor to adequately suppress the drive's DC Link, and it only took me a few minutes.

Yes, I haven't covered suppressing DC Links yet (it will be covered in the next Issue of the EMC Journal), but this example still proves the general principle that all EMC experts agree with – it is very much better (quicker, less costly, more reliable) to suppress any noise at source, than try to deal with it once it has coupled (escaped!) into other circuits in the same equipment, or any circuits in other equipment.

I keep meeting companies that still design merely to get their circuits working to spec., then have them tested for EMC compliance and iterate the design until it passes the test (ditto, often, for safety compliance too). This approach is *guaranteed* to increase time-to-market and increase overall-cost-of-manufacture (much more important than the BOM cost, see [12]) when compared with using EMC (and safety) skills from the start of the design process.

7.5 Shielding the output cable

The "accidental antenna" effect of output cables should always be reduced by using techniques such as twisted pairs and routing close to a CM return path (see Chapter 4.3.3 of [5] and Chapter 4.4 of [69]). These are helpful and should generally be used, because they reduce the specification of any output filters (i.e. make it easier to pass conducted and radiated emissions tests with a lower-cost output filter).

In fact, some cable suppliers offer specially balanced cables specifically intended for motor drive outputs. These are claimed to be better than twisted pairs, because they are said to convert less of the pulse-width-modulated (PWM) output voltage into common-mode (CM) noise current flowing around the drive system (i.e. they have a lower longitudinal conversion loss, LCL).

It is the CM noise currents that cause most of the conducted and radiated emissions from a motor drive at frequencies above about 1MHz. Below about 1MHz differential-mode (DM) noise from the switching devices can be the dominant cause of emissions, and suppressing this type of noise was discussed in sections 7.1 and 7.2, see [72], and will be returned to again later when I discuss filtering the DC Link.

An alternative to filtering the RF noises from output cables – as discussed in section 7.3.13 of [84] is to shield (screen) them, which is the topic of this article.

Figure 7.5-1 shows the overall current loops when using a shielded (screened) output cable, using the style of drawing I used in [72] to show how filtering should be designed to control the DM and CM current loops.

All currents always flow in loops, including all 'stray' or 'coupled' noise currents, a vital understanding for good EMC design, discussed in detail in [32], [33] and [85], also in [4] or Chapter 2 of [5] (which use the same text).

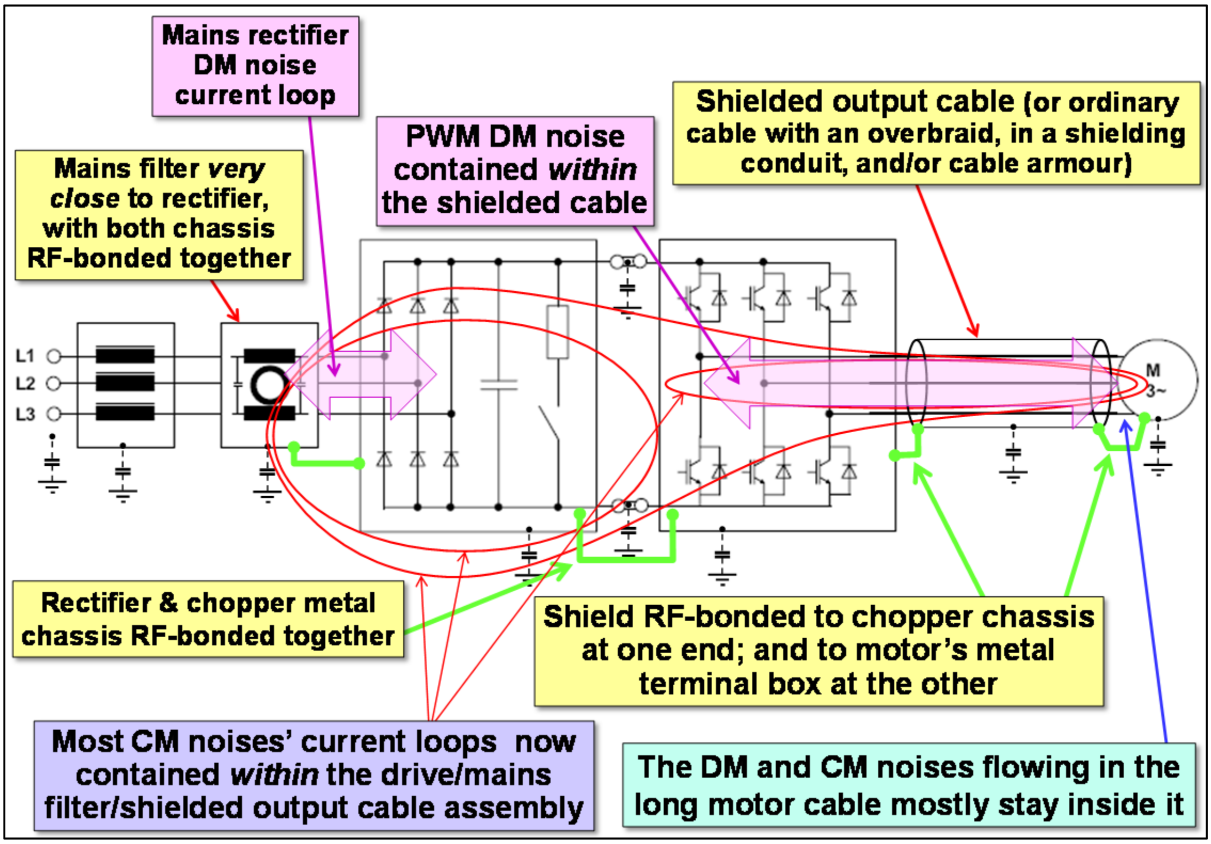


Figure 7.5-1 Example of motor drive noise current loops, filtered mains, shielded output

Converters with fixed DC outputs generally have low-enough output noise (just a little RF 'ripple') that output filtering is easy and low-cost enough, but variable-speed DC or AC motor drives – using PWM – are very noisy indeed.

We can consider an XkW variable-speed motor drive to be the equivalent of an XkW radio transmitter. An XkW radio transmitter emits its RF power at only one frequency, and is connected via a matched transmission-line cable (so that cable emissions are very low) to a transmitting antenna. It is required to give a strong audible signal for radio receivers that may be as much as hundreds, maybe thousands of kilometres distant.

However, an XkW motor drive emits its RF power at a large number of frequencies (the chopper's switching frequency and its first thousand harmonics (at least), and is connected via a variety of types of power cable that are all unmatched transmission lines (making them very effective 'accidental antennas' in their own right) to a motor (which is also an effective 'accidental antenna').

And the motor drive is required to create an inaudible signal on radio receivers that are only 10 metres (in domestic, commercial, light industrial applications) or 30 metres (in heavy industrial applications) distant.

It is little wonder that the introduction of variable-speed motor drives using switch-mode power conversion technology has been accompanied by so many EMI problems, the world over.

But with appropriate use of input and output inductors, filters, cable shielding and RF bonding, as shown in Figure 7.5-1, much reduced harmonics, DM and CM noises flow in the long mains cable and mains distribution network. The output CM and DM noises flow in the whole length of the output cable and the motor, and are made to behave as very ineffective 'accidental antennas' by good cable shielding, plus good shield-bonding (RF-bonding) assembly methods at both ends.

Figures 7.5-2, 7.5-3 and 7.5-4 show how these principles were applied to a moderately-powerful motor drive in an industrial cabinet (simply by following the manufacturers EMC Installation Instructions), but could just as well be an electric traction drive (e.g. hybrid car) instead. (Figure 7.5-2 is a copy of Figure 7.3-20 from [84], repeated here to make it easier to understand the following two figures.)

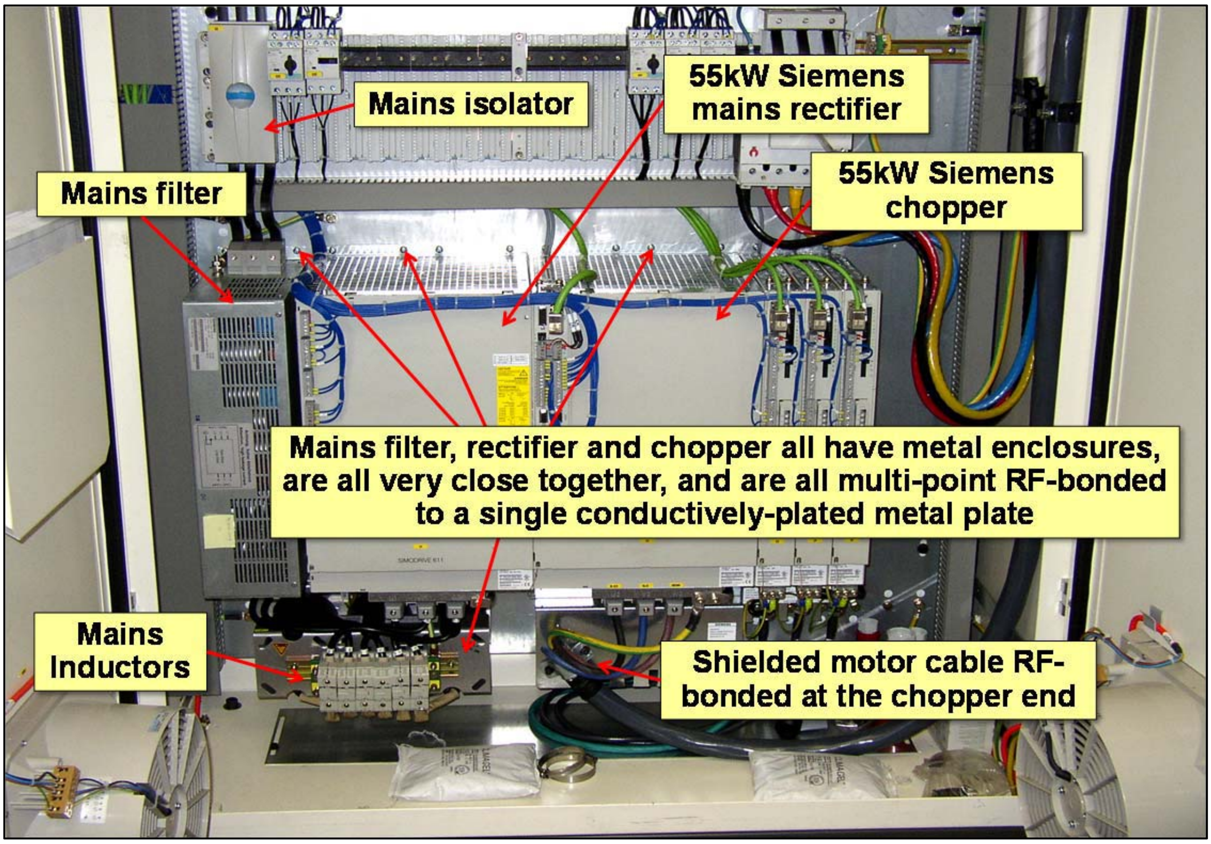


Figure 7.5-2 Example of a 55kW motor drive in an industrial cabinet

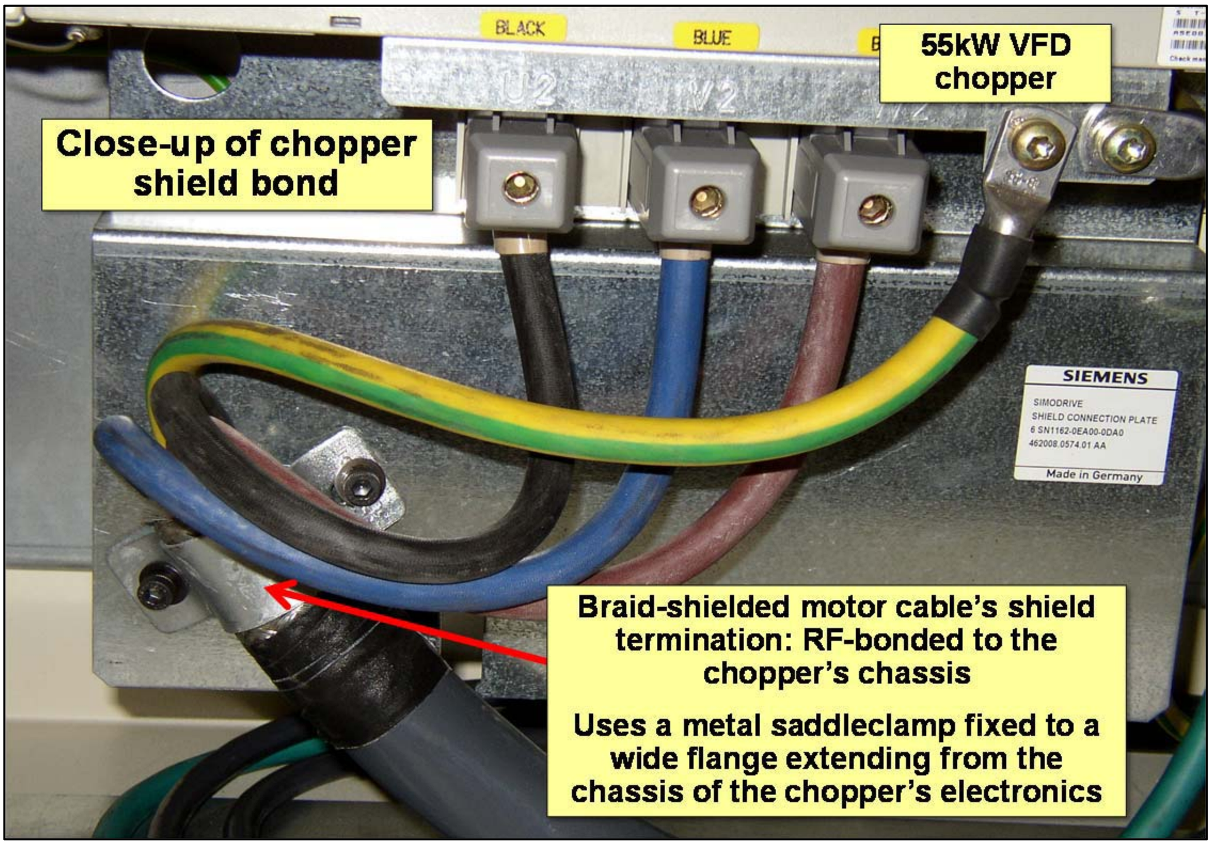


Figure 7.5-3 Close-up view of the 55kW drive in the previous figure, showing the good shield bonding of its drive output cable

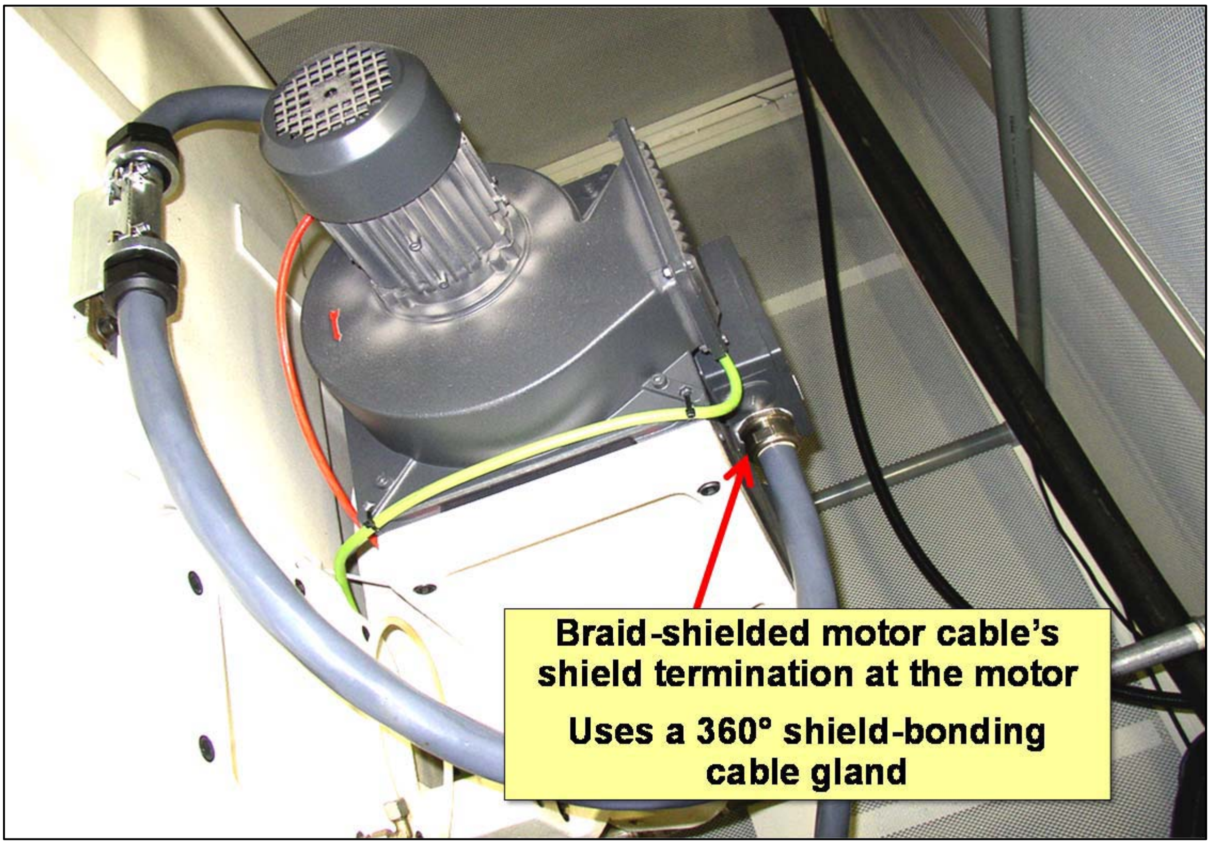


Figure 7.5-4 Example of the motor driven by the 55kW drive in the previous figure, showing the good shield bonding of its drive cable

As the above figures show, if the shielded motor cable has its shield correctly RF-bonded *at both ends*, the CM current loops associated with the drive's motor output 'prefer' to flow inside the cable's shield. By following this path, the area enclosed by their current loop is very much less than that of all the other paths available to the CM current, making its loop impedance very much lower than the alternatives (for example the CM loop paths that exist in the earth/ground structure outside of the cable shield).

If it seems difficult to understand why an RF current should prefer to flow in a particular loop (the one with the least impedance), think of a number of resistors connected in parallel – it is the resistor with the lowest value that carries the bulk of the current.

The impedance of the CM loops at frequencies above a few 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 'prefers to flow in the loop that presents the least overall impedance, which is the loop with the least inductance, which is the loop that creates the smallest surrounding magnetic field, and is therefore the loop that provides the lowest emissions, see [85], also in either in [4] or Chapter 2 of [5] (which use the same text).

To achieve the low impedance necessary to ensure that the motor drive's output CM currents 'prefers' to flow in paths that cause the least emissions:

- At the chopper end, the motor cable shield must be RF-bonded to the chopper's metal enclosure, chassis or frame.
- At the motor end, the motor cable shield 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).

There are many good design and assembly practices associated with cable shielding, and they have all been addressed in Chapter 4.3 of [3], Chapter 4.6 of [5], Chapter 5.11 of [69], and in [61] and [70].

Notice that for a cable shield to act as a shield at RF frequencies, it must be 360° RF-bonded at both ends. Never use a pigtail, or 'take the shield through a connector pin'. Of course, this causes potential equalising currents to flow in the shield, which have been demonised as 'ground loops', 'earth loops', 'hum loops' etc. ever since the first electronic systems were built to add sound to movies, which had previously been silent.

In fact, these loops are a positive advantage in improving the signal-to-noise ratio of correctly designed electronic equipment, and they also help reduce the common bonding impedance of a site and so help achieve EMC specifications.

Also, 360° RF-bonding at both ends is the only way to maintain the RF shielding performance of shielded cables that are longer than $\lambda/100$ (for example, that are up to 0.3 metres long, about a foot, at frequencies below about 10MHz). And as Figure 7.5-1 showed, not RF-bonding the motor cable's shield at both ends would result in high levels of emissions, because the shield would not then provide the CM current loop with the path of least impedance (= the path of least external field, = the path that causes the least EM emissions).

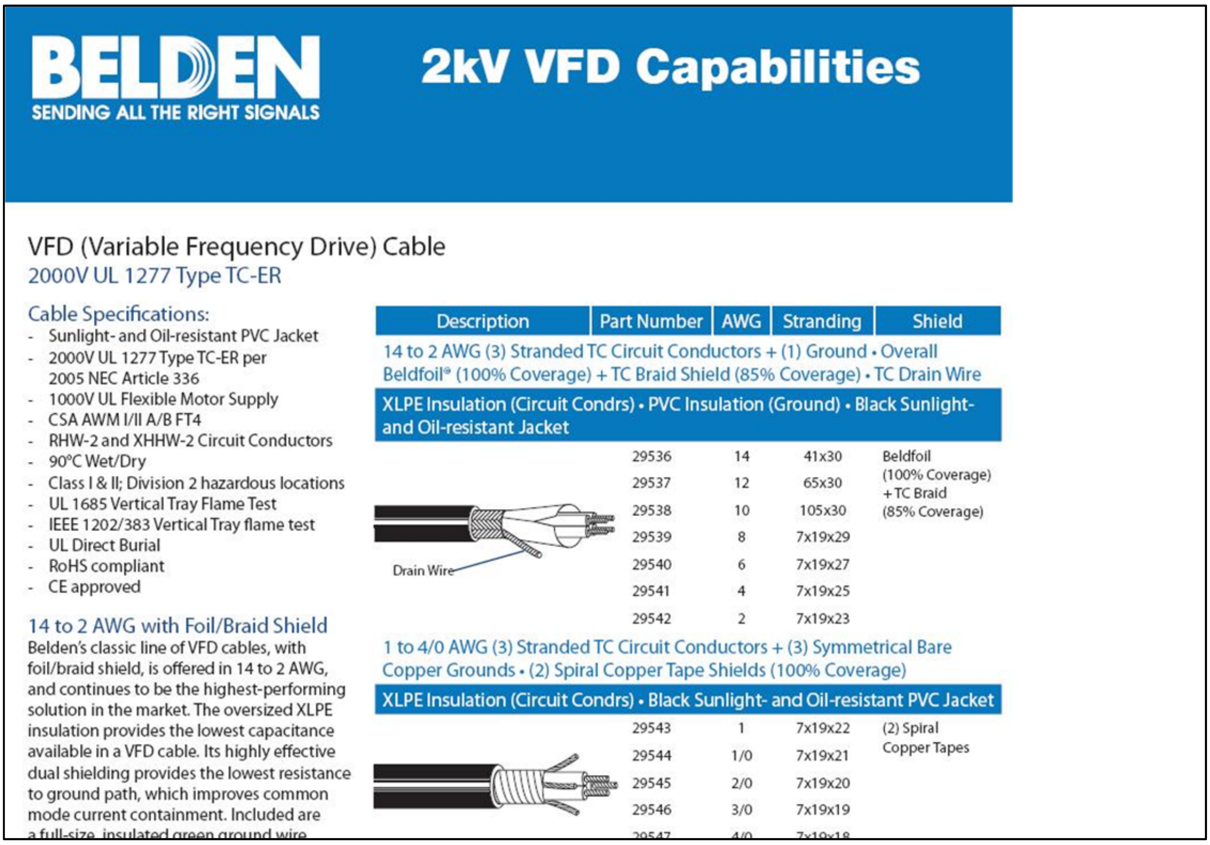
The problem with so-called earth/ground loops arises because most electronic circuit boards and their resulting equipment are specified (and thus designed) to work well when tested on a bench, rather than in a real-life system or installation.

When circuits and equipment are designed correctly for use in real systems/installations, with their inevitable potential equalising currents, it is found that RF-bonding cable shields at both ends always provides very positive benefits, from DC to RF frequencies, well beyond what is possible with any type of system that uses single-point earthing/grounding (sometimes called star earthing/grounding), which requires cable shields to only be connected at one end. [62] and [63] have much more detail on this, as does Chapter 4.6.8 of [5].

The installation method known as meshed earthing/grounding (more correctly – meshed bonding) – which benefits from RF-bonding cable shields at both ends – has been proved conclusively over many years in numerous installations, including those as large as the Diamond Light Source at the Rutherford-Appleton Laboratory in Harwell, Oxfordshire, UK (http://en.wikipedia.org/wiki/Diamond_Light_Source), the Singapore Opera House, and the huge new Danish Radio City. Systems and installations designed and constructed using this good installation engineering method almost always fully meet their signal-to-noise specification from the instant of switch-on, and they are safer, too.

(I am allowed to talk about 'correct electronic design' for real systems and installations, because 30+ years ago I used to design circuits that tested very well on a bench, but proved difficult to install and meet their specifications in real systems – though in my defence I must add that every other circuit designer in the companies I worked for were no better. Later, I learned how to design circuits so that they met their specifications when tested on a bench, and also without any fuss when installed and used in real systems and installations. No prizes for guessing that the much-preferred latter designs RF-bonded their cable shields at both ends.)

It can seem difficult to find shielded cables with the appropriate voltage and current ratings for high-power motor drives, but figure 7.5-5 shows a cable type from Belden that has excellent shielding characteristics (when RF-bonded properly at both ends, of course) and is rated for up to 2kV and is available with conductors of up to 2AWG (i.e. 6.5mm in diameter, with a current rating of 94A).


BELDEN
SENDING ALL THE RIGHT SIGNALS

2kV VFD Capabilities

VFD (Variable Frequency Drive) Cable
2000V UL 1277 Type TC-ER

Cable Specifications:
- Sunlight- and Oil-resistant PVC Jacket
- 2000V UL 1277 Type TC-ER per 2005 NEC Article 336
- 1000V UL Flexible Motor Supply
- CSA AWM I/II A/B FT4
- RHW-2 and XHHW-2 Circuit Conductors
- 90°C Wet/Dry
- Class I & II; Division 2 hazardous locations
- UL 1685 Vertical Tray Flame Test
- IEEE 1202/383 Vertical Tray flame test
- UL Direct Burial
- RoHS compliant
- CE approved

14 to 2 AWG with Foil/Braid Shield
Belden's classic line of VFD cables, with foil/braid shield, is offered in 14 to 2 AWG, and continues to be the highest-performing solution in the market. The oversized XLPE insulation provides the lowest capacitance available in a VFD cable. Its highly effective dual shielding provides the lowest resistance to ground path, which improves common mode current containment. Included are a full-size, insulated green ground wire

Description	Part Number	AWG	Stranding	Shield
14 to 2 AWG (3) Stranded TC Circuit Conductors + (1) Ground • Overall Beldfoil® (100% Coverage) + TC Braid Shield (85% Coverage) • TC Drain Wire				
XLPE Insulation (Circuit Condrs) • PVC Insulation (Ground) • Black Sunlight- and Oil-resistant Jacket				
Drain Wire	29536	14	41x30	Beldfoil (100% Coverage) + TC Braid (85% Coverage)
	29537	12	65x30	
	29538	10	105x30	
	29539	8	7x19x29	
	29540	6	7x19x27	
	29541	4	7x19x25	
	29542	2	7x19x23	
1 to 4/0 AWG (3) Stranded TC Circuit Conductors + (3) Symmetrical Bare Copper Grounds • (2) Spiral Copper Tape Shields (100% Coverage)				
XLPE Insulation (Circuit Condrs) • Black Sunlight- and Oil-resistant PVC Jacket				
	29543	1	7x19x22	(2) Spiral Copper Tapes
	29544	1/0	7x19x21	
	29545	2/0	7x19x20	
	29546	3/0	7x19x19	
	29547	4/0	7x19x18	

Figure 7.5-5 Example of shielded cables for variable frequency (VFD) motor drive outputs

Where higher-power output cables are required, or to save cost, unshielded cables may be used and fitted with an overbraid or shielded flexible conduit, like the examples shown in Figure 7.5-6.

Solid round metal conduit could of course be used instead, and if fitted with appropriate 360° RF-bonding at all joints and both ends – for example by using the RF-bonding 'earthing nuts' in Figure 7.5-7 – can provide the ultimate in output cable shielding performance up to a few hundred MHz. Higher frequencies would need a complete 360° electrical connection at the equipment and motor ends of the conduit, instead of the multi-point bond provided by the component shown in Figure 7.5-7.

Figure 7.5-6 Examples of overbraids and shielded conduits

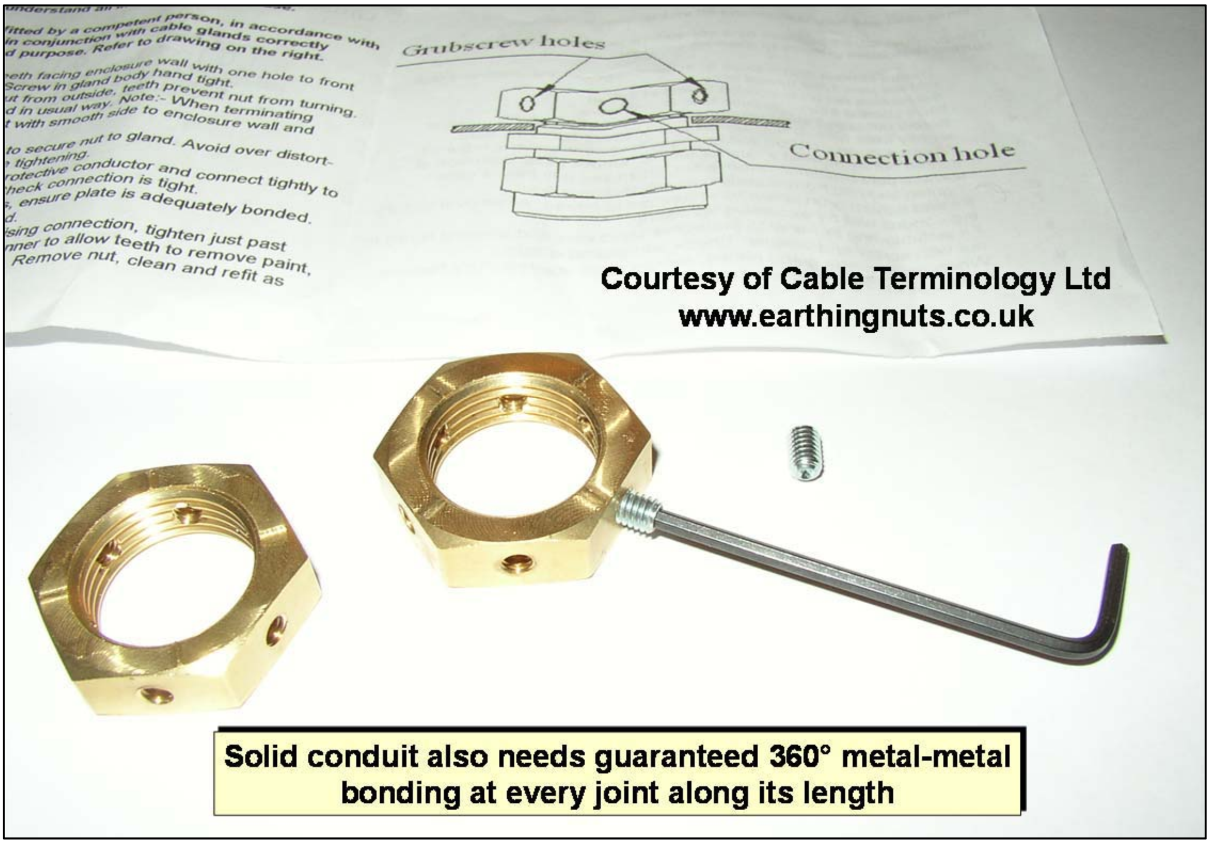


Figure 7.5-7 Example of an RF-bonding ‘conduit-to-enclosure’ component

When the switch-mode converter is in a shielded enclosure, filter and shield bonds must be to the enclosure wall, or its floor, top, or back surface, as shown in Figure 7.5-8.

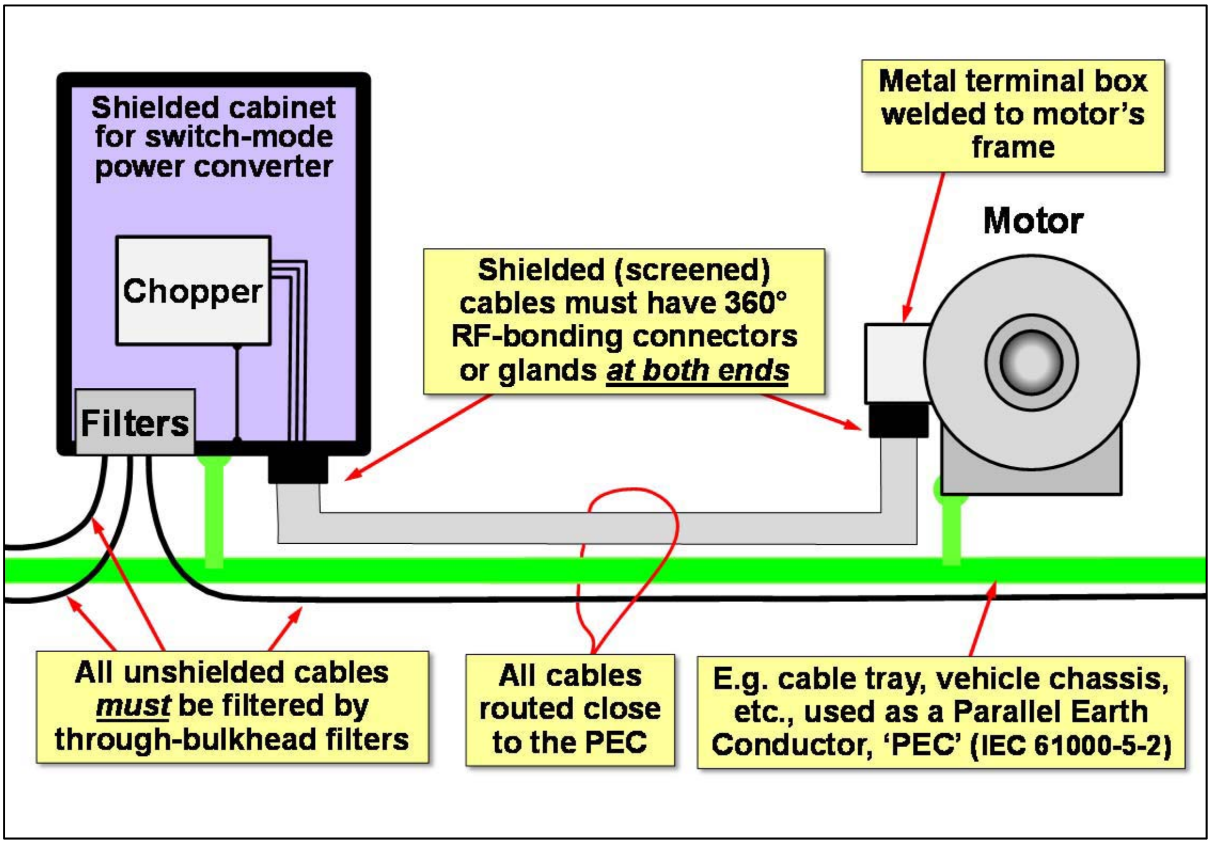


Figure 7.5-8 Design principles for connecting a shielded motor drive cabinet to a motor, using a shielded cable

In accordance with the good shielding practices described in Chapter 4.4.7 of [3], Chapter 4.6 of [5], Chapter 5.12 of [69], and [70], anything that is conductive that passes through the wall of a shielded cabinet, must be RF-bonded to that wall, using either 360° direct bonding, or filtering, at the very point where it penetrates the wall.

This is the case for any type of signal or power conductor (even for a mouse cable) and also when the conductor is not an electrical conductor, for example if it is a metal pipe for hydraulics or pneumatics. I often see costly shielded cabinets ruined despite the use of good shielding practices, because the mouse cable has not been RF-bonded as it passes through the wall of a shielded cabinet wall.

The PEC referred to in Figure 7.5-8 is the 'Parallel Earth Conductor' that is described in the standard on good practices in cabling and earthing: IEC 61000-5-2. This is an unfortunate term because it gives the impression that good EMC design for systems and installations has something to do with metal rods stuck into the ground (earth). Some product-specific installation standards and national wiring regulations call it a Parallel Bypass Conductor instead, which is better, although in my view the best term for it would be Parallel Bonding Conductor, PBC. The usefulness of PECs, and how to design installations with them, is covered in Chapter 5.9 of [69], and in [70].

There are two downsides with using shielded cables for power converter outputs, which sometimes create very real problems for motor drives.

The first issue is that allowing RF currents to flow in the load can be harmful to it. In particular, the stray capacitance between a motor's windings and its rotor encourages stray RF current to flow through the motor's bearings. All motor bearings are insulating, even if they use steel rollers or balls they are always coated with an insulating film of oil or grease when the motor is turning, so this stray rotor current can only flow through its insulating bearings as spark discharges.

This causes two undesirable effects. The sparks inevitably erode any metal surfaces and degrade the quality of the oil or grease. Some motor bearings have been known to last for a tenth of their expected lives, due to the effect of stray RF bearing currents from variable-speed motor drives, and they are quite costly to replace.

Correct RF design and assembly of shielded motor cables provides the optimum low-impedance path for stray RF currents in the motor's stator, but the bearings present an essentially infinite resistance – until they spark over when the voltage across them is high enough. When the voltage across the bearings is less than what is needed to break down the gap and spark over, stray rotor current will tend to flow in other paths, which is much less desirable for achieving good EMC.

Oil or grease that has been degraded by bearing currents will contain free carbon, which – when above a certain particle density, basically black sludge – will develop a resistance and thus reduce the currents flowing into whatever the rotor is coupled to. Of course, but the time this occurs the bearing is probably grinding away at the premature end of its life, so it is not a desirable situation. However, it does show us that using a conductive oil or grease in the first place, when the bearings are assembled, should reduce (possibly eliminate) the damage caused by sparking in the bearings, and also reduce the emissions by providing a more optimal current loop path for the stray RF rotor currents.

Where a suitable conductive oil or grease is not available with the specifications required for a bearing, rotary conductive gaskets are an alternative. These are metal springs or carbon-fibre brushes that are electrically bonded direct to the motor frame or stator close to the motor's metal driven shaft, and press against it. They wear and so require maintenance, but they provide much lower resistance than conductive oils or greases and so can help reduce RF emissions.

The second problem with shielded power converter output cables, is that they are not matched transmission lines (see Chapter 4.7 of [5]), and as a result suffer from overvoltages caused by the reflection of electromagnetic waves at the load end.

It is worth reminding ourselves at this point that all electrical activities (power, signals, data, wireless communications, etc.) are really electromagnetic wave propagation rather than electrons speeding down conductors, as discussed in [32], [33], [85], and also in [4] or Chapter 2 of [5] (which use the same text).

Connect an LED to a battery and it will light up almost immediately regardless of the length of wire (although if the wire went right around the earth at the equator, it would take about an eighth of a second). But if you could somehow follow the movement of a single electron as it flowed in that wire, you would find that you could easily jog faster than it was travelling.

If we use a cable that is made to provide constant characteristic impedance (called Z_0) we can then 'match' it by providing source and load impedances that equal the cable's Z_0. This is why all general-purpose RF test equipment has 50Ω outputs and inputs, provided by connectors that have 50 Ω characteristic impedances, and we connect them together using cables that also have 50 Ω characteristic impedances. In this way we don't measure erroneous voltages at frequencies that depend on the cable lengths.

The same 'impedance matching' methods are used for radio and television broadcast antenna, where it is especially important because any mismatch at any point along the antenna cable, or at the antenna itself, reflects power back from the antenna into the transmitter, which can be damaged as a result. The overvoltages arising in such situations can also cause very dangerous and damaging arcs.

However, no motor matches the characteristic impedance of its motor cable, so the high frequencies (actually, RF) present in a converter output, especially those with PWM outputs, reflect back from the motor, causing overvoltages and ringing on the switching edges. [86], [87] and [88] provide a wealth of detail on this problem.

The peak value of these overshoots are generally considered to reach as high as double the voltage on the converter's DC Link, but no higher, and the insulation ratings of motors and motor cables are set accordingly. However, since the mid-90's it has been known that they can be higher still, up to three, even four times the DC Link voltage, as shown by [89] and [90].

If the insulations of the motor cable and the motor itself are not rated for continuous operation with the high voltage peaks caused by the motor-cable mismatch, they will degrade, reducing the operational life of the system. Also, the corona discharge (and even sparking) caused by inadequate insulation will increase RF emissions and help cause EMC test failure, as well as increasing the possibility of interfering with other equipment.

The height of the overvoltages that arise at a motor cable's connection to its motor depend upon the *dV/dt* of the power converter's chopper output, and the length of the cable connecting it to its load.

Developments in the power switching semiconductors themselves are generally in the direction of shorter switching times, to reduce thermal losses, increase electrical efficiency, and use smaller heatsinks to pack more converter power into smaller packages that cost less. The result is that, as time progresses, new motor drives have PWM outputs with ever-higher values of *dV/dt* that can cause damaging levels of overvoltages with ever-shorter lengths of cable.

The switching edge rates can be reduced by *dV/dt* filtering as mentioned in 7.3.13 and figure 7.3-38 in [84], so here we would be using output shielding and filtering together, to minimise costs and maximise performance.

Of course, using a sinewave filter at the output of a PWM filter, as described in 7.3-13, totally removes the PWM waveform, along with all its nasty RF.

In [91] Gary Skibinski proposes fitting a termination network to the motor, to match the motor's connection to the surge impedance of the cable – a sort of transmission line matching method.

Well, that's it for converter output cable shielding. The next issue will discuss suppressing RF noise in converter's DC Links.

References (for this article only)

[3] "Complying with IEC/EN 61800-3 — Good EMC Engineering Practices in the Installation of Power Drive Systems", Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase

[4] "The Physical Basis of EMC", Keith Armstrong, Armstrong/Nutwood UK October 2010,
ISBN: 978-0-9555118-3-7, from www.emcacademy.org/books.asp. The same material is presented as Chapter 2 in [5].

[5] "EMC Design Techniques for Electronic Engineers", Keith Armstrong, Armstrong/Nutwood UK Nov. 2010, ISBN: 978-0-9555118-4-4, from www.emcacademy.org/books.asp.

[11] "When the going gets tough – smarter design wins", Keith Armstrong, The EMC Journal, Issue 81, March 2009, pages 21-24, available from the archives at wwww.theemcjournal.com.

[12] "BOM cost and profitability", Keith Armstrong, The EMC Journal, Issue 82, May 2009, pages 32-34, available from the archives at www.theemcjournal.com

[13] "The EMC design of Switch-mode and PWM power converters", Keith Armstrong, The EMC Journal, Issue 93, March 2011, pages 26-34, available from www.theemcjournal.com

[14] Keith Armstrong's earlier articles are available from the archives at www.theemcjournal.com

[15] Textbooks by Keith Armstrong and others are available from www.emcacademy.org/books.asp

[32] "Key knowledge for the efficient design of electronic products and their EMC – that we were never taught at university", Keith Armstrong, ANSYS Next Generation Signal Integrity and EMI Simulation Seminar, 23rd March, De Vere Milton Hill House, Oxford, download via http://www.ansys.com/en_uk/Downloads/SIUK, or direct from: www.ansys.com/staticassets/ANSYS%20UK/staticassets/Keith_Armstrong_Presentation_ANSYS_March_23%202011.pdf

[33] "Maxwell's equation, Quantum Electrodynamics, and good installation practices for SI, PI and EMC", Keith Armstrong, The EMC Journal, Issue 91, November 2010, pages 32-46

[42] "EMC Design of High-Frequency Power 'Switchers' and 'Choppers'", Keith Armstrong, The EMC Journal, Issue 94, May 2011, pp 39-50, available from the archives at www.theemcjournal.com

[61] "Terminating cable shields (screens)", Keith Armstrong, The EMC Journal, Issue 82, May 2009, pages 19-23, available from the archives at www.theemcjournal.com

[62] "Designing I/Os so they will not suffer from 'ground loop' currents in cable shields (screens)", Keith Armstrong, The EMC Journal, Issue 83, July 2009, pages 38-42, available from the archives at www.theemcjournal.com

[63] “Bench testing individual PCBs for immunity – to reduce financial risks”, Keith Armstrong, The EMC Journal, Issue 92, January 2011, pages 24-30, available from the archives at www.theemcjournal.com

[64] “EMC Design of High-Frequency Power ‘Switchers’ and ‘Choppers’ – Design techniques for HF isolating transformers”, Keith Armstrong, The EMC Journal, Issue 95, July 2011, available from the archives at www.theemcjournal.com

[65] “EMC Design of High-Frequency Power ‘Switchers’ and ‘Choppers’ – Design techniques for LF (mains) rectifiers”, Keith Armstrong, The EMC Journal, Issue 96, September 2011, available from the archives at www.theemcjournal.com

[66] “EMC Design of High-Frequency Power ‘Switchers’ and ‘Choppers’ – Design techniques for high frequency (HF) output rectifiers”, Keith Armstrong, The EMC Journal, Issue 97, November 2011, available from the archives at www.theemcjournal.com

[69] “Good EMC engineering practices in the design and construction of fixed installation”, Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase

[70] “EMC for Systems and Installations”, Tim Williams and Keith Armstrong, Newnes 2000, ISBN: 0-7506-4167-3, www.bh.com/newnes, RS Components part number: 377-6463

[72] “EMC Design of High-Frequency Power ‘Switchers’ and ‘Choppers’ – Suppressing RF emissions from converter inputs and outputs”, Keith Armstrong, The EMC Journal, Issue 98, January 2012, pages 27-38, available from the archives at www.theemcjournal.com

[84] “EMC Design of High-Frequency Power ‘Switchers’ and ‘Choppers’ – Suppressing RF emissions from converter inputs and outputs”, Keith Armstrong, The EMC Journal, Issue 99, March 2012, pages 30-42, available from the archives at www.theemcjournal.com

[85] “Fundamentals of EMC Design: Our Products Are Trying To Help Us”, Keith Armstrong, Interference Technology Magazine, 04/03/2012, www.interferencetechnology.com/fundamentals-of-emc-design-our-products-are-trying-to-help-us-3

[86] “Effects of AC Drives on Motor Insulation - Knocking Down the Standing Wave”, ABB Technical Guide No. 102, 1997, http://www05.abb.com/global/scot/scot239.nsf/veritydisplay/fec1a7b62d273351c12571b60056a0fd/$file/voltstress.pdf

[87] “Riding the Reflected Wave – IGBT Drive Technology Demands New Motor and Cable Considerations”, L A Sanders, G Skibinski, *et al*, IEEE IAS-Petroleum & Chemical Industry Conference, Philadelphia, PA., Sept 23-25, 1996, p. 75-84, http://abweb.rockwellautomation.com/support/abdrives/documentation/techpapers/ieee/pcic.pdf

[88] “Evaluating Inverter-Duty Motor Insulation Systems Using Corona Inception Voltage”, Technical Brief 100, Lincoln Electric Company, Motor Division, 1997, http://shared.a2zinventory.com/mfg/LincolnMotors/Library/tb-100.pdf

[89] “Interaction of Drive Modulation and Cable Parameters on AC Motor Transients”, R J Kerkman, D Leggate, and G Skibinski, IEEE Transactions on Industry Applications, Vol. 33, No. 3, May/June 1997, www.bhelpswr.co.in/Technical/Electrical/Arvind%20gupta%20Papers/VFD_paper_13.pdf

[90] “Assessing AC motor dielectric withstand capability to reflected voltage stress using corona testing”, G Skibinski, J Erdman, J Pankau, and J Campbell, IEEE Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS '96., 6-10 Oct 1996, pages 694-702 of Vol.1 of the Conference Record, http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=557114&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel3%2F4112%2F12151%2F00557114.pdf%3Farnumber%3D557114

[91] “Design methodology of a cable terminator to reduce reflected voltage on AC motors”, G Skibinski, IEEE Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS '96, 6-10 Oct 1996, pages 153-161 of Vol.1 of the Conference Record, http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=557009&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel3%2F4112%2F12151%2F00557009.pdf%3Farnumber%3D557009