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EMC design of Switching Power Converters - Part 1

Helping you solve your EMC problems

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The EMC design of Switching Power Converters

– including:
DC/DC and AC/DC converters, DC/AC and AC/AC inverters,
from milliwatts (mW) to tens of Megawatts (MW)

– in *all* applications, including:
consumer, household, commercial, computer, telecom, radiocom, aerospace, automotive, marine, medical, military, industrial, power generation and distribution, in products, systems or installations;

– including: hybrid & electric automobiles, electric propulsion/traction; green power (LED lamps; solar, wind, tidal power converters, etc.), etc.

– Part 1 –

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Contents

1 Introduction

1.1 Why write about the EMC of switch-mode and PWM power converters?

Switch-mode and pulse-width modulated (PWM) power converter technologies are very electromagnetically noisy – they naturally emit high levels of unintentional EM disturbances.

In fact, these technologies are so noisy that unless good EMC design/construction practices are used, they almost inevitably fail any emissions tests, often by a large margin.

Switch-mode and PWM converters with basic switching rates below 150kHz almost always fail conducted emissions tests quite badly, and lower-power ones with small devices that switch power very quickly can fail radiated emissions tests too. Those with basic switching rates above 150kHz almost always fail radiated emissions tests, often quite badly.

So, to legally sell or use products, vehicles or systems, or construct or operate installations, in almost every country in the world whilst legally complying with their EMI Regulations (e.g. the EMC Directive, 2004/108/EC in Europe) to protect radiocommunications, the designers of switch-mode and PWM power converters *always* have to employ EMC design techniques.

However, complying with standards and regulations is actually the *smallest* part of the issue. If power converters are not designed using good EMC techniques, their manufacturers' financial risks and liability are effectively uncontrolled. This is discussed more in 1.4 below. Using good EMC design to help control financial risks results in products that (almost always) fully comply with all relevant EMC standards and regulations anyway, with no additional work.

Often, designers only use mitigation techniques, (b in the list in 1.2 below) and so waste time, money, weight and volume compared with what they could easily achieve with some attention to designing to reduce emissions (a in the list in 1.2).

And when using mitigation techniques they often don't design them optimally, wasting even more time, money, etc.

Switch-mode and PWM power converters are now almost ubiquitous. Almost every product, system, vehicle or installation now contains at least one switch-mode or PWM converter, even the tiniest iPod, and a typical cellphone or notebook computer has several – switch-mode to power various circuits from low-voltage batteries; PWM (in "Class D" audio amplifiers) to drive headphones or speakers.

At the other extreme, high-power switch-mode and PWM is used to vary the speed of DC and AC motors rated up to tens of MW, for example in the drive-trains of hybrid and electric vehicles; thrusters and propulsion pods on all kinds of marine vessels; and a wide variety of industrial uses including cranes, tunnelling machines and steel rolling mills.

These technologies are now also used for DC/DC conversion in electrical power distribution, allowing the use High Voltage DC transmission lines strung in the air on pylons, or underground/undersea in cables, eliminating the huge energy losses caused by AC distribution.

To reduce energy consumption, all motors in household appliances will soon be driven by switch-mode or PWM converters. Continuing with the theme of trying to save the planet from overheating, these technologies are also used to drive LED lamps and convert the DC and AC power from alternative ("green") sources such as photovoltaic (PV) panels, wind, wave and tidal turbines, to AC mains voltages to input to National Grids.

Figures 1 through 6 show a very few examples of the use of these technologies. The 9 MVA motor drive in Figure 5, and the Type 45 Daring Class destroyer in Figure 6are taken from [1], and the Zytek electric vehicle drive in Figure 6 is from [2].

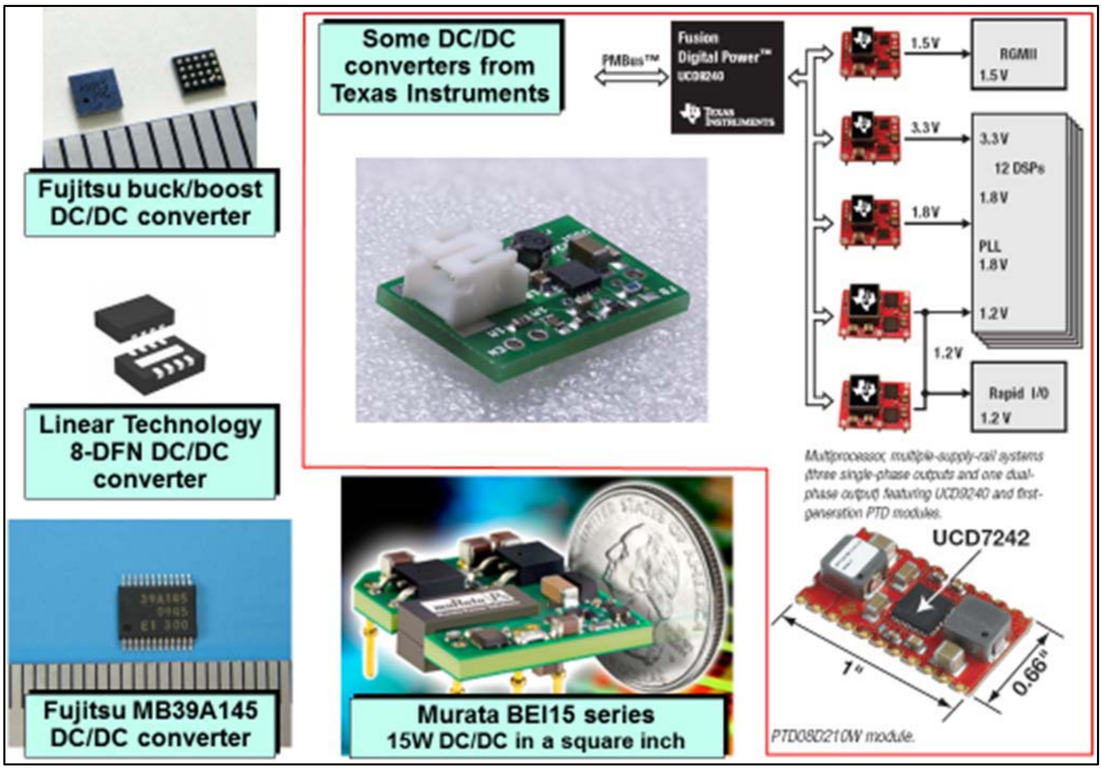

Figure 1 Some of the thousands of very low-power DC/DC converters available

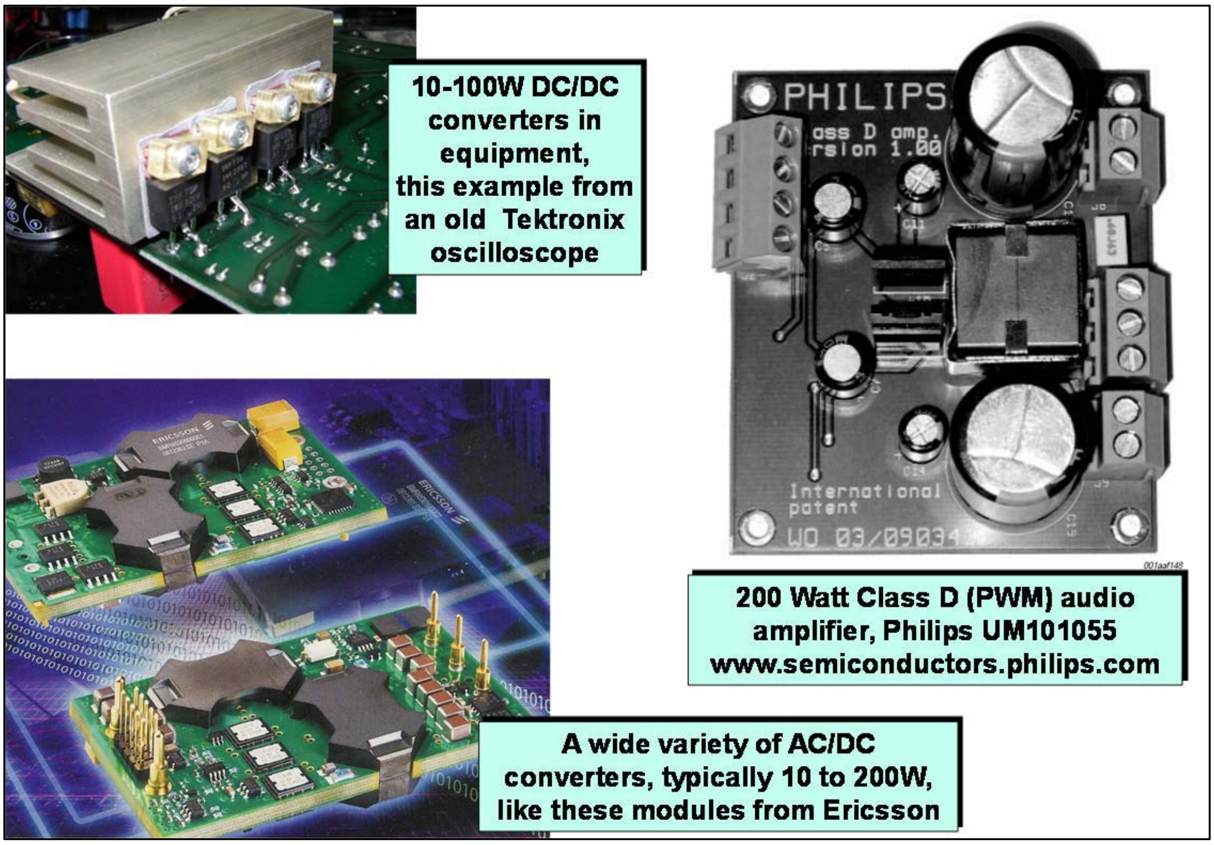

Figure 2 Examples of low-power DC/DC converters and a Class D audio amplifier

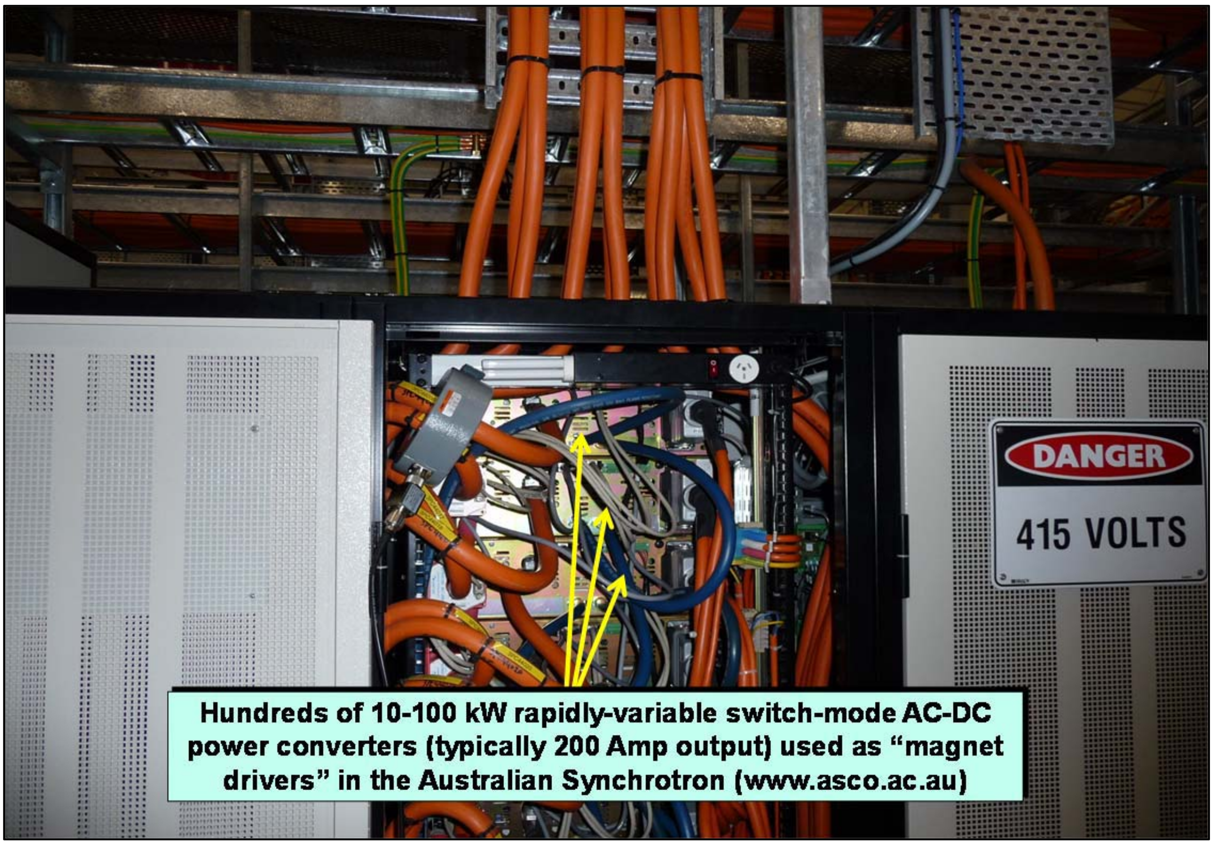

Figure 3 Example of a scientific application of AC-DC converters

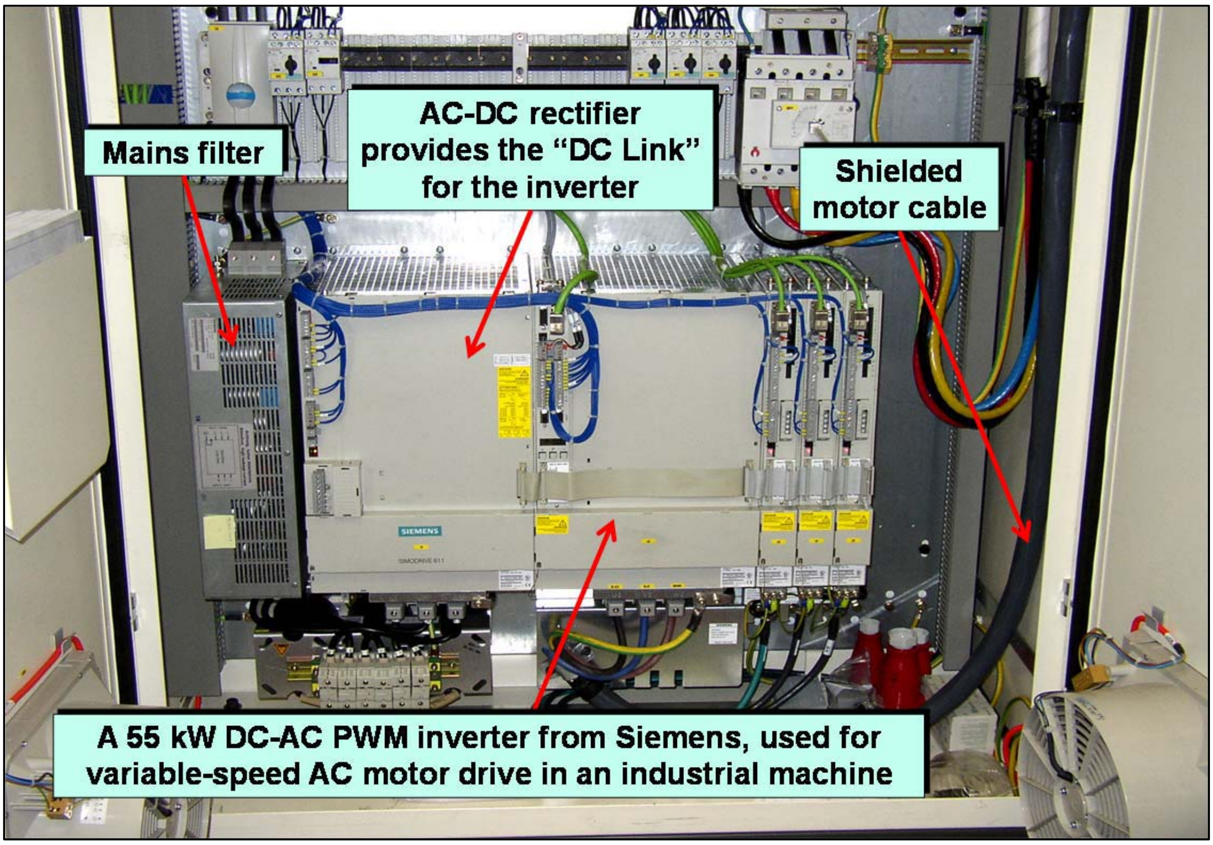

Figure 4 Example of an industrial machine's motor drive

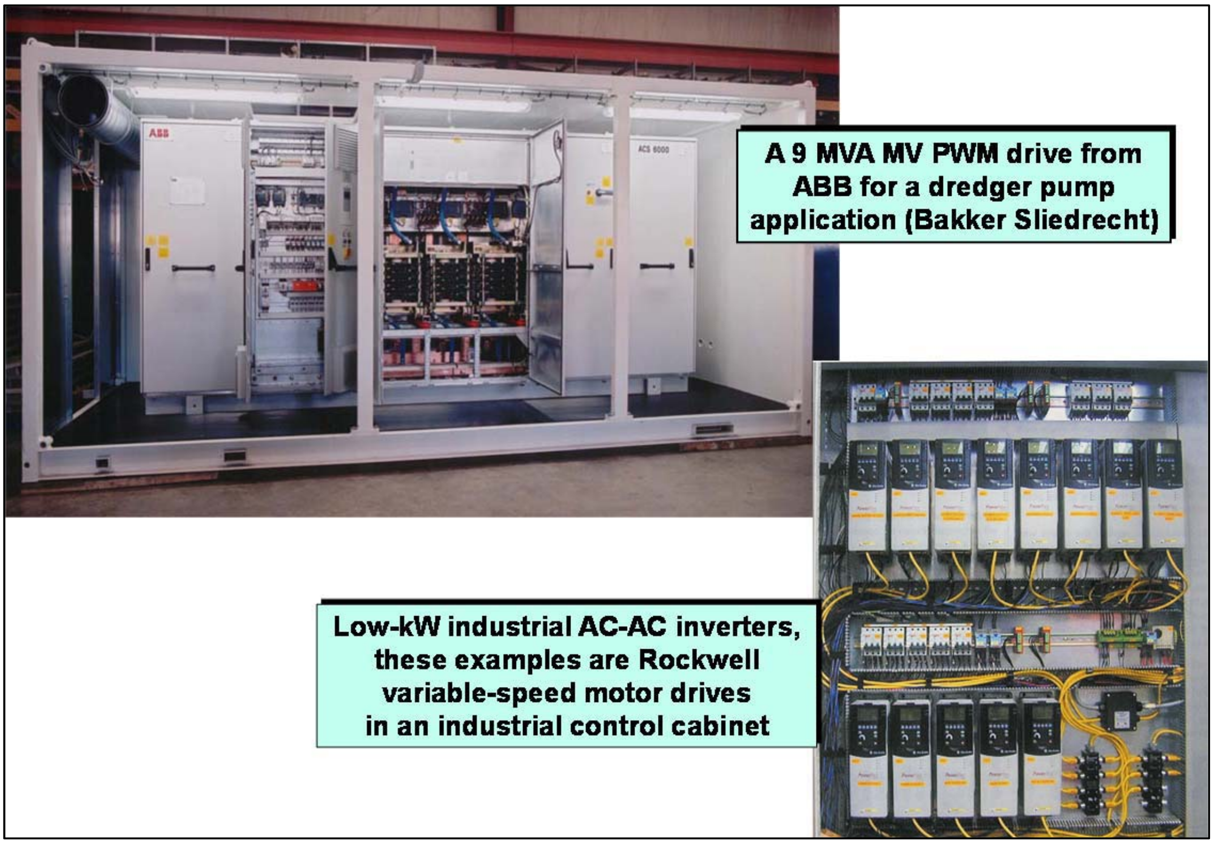

Figure 5 Some more examples of industrial motor drives

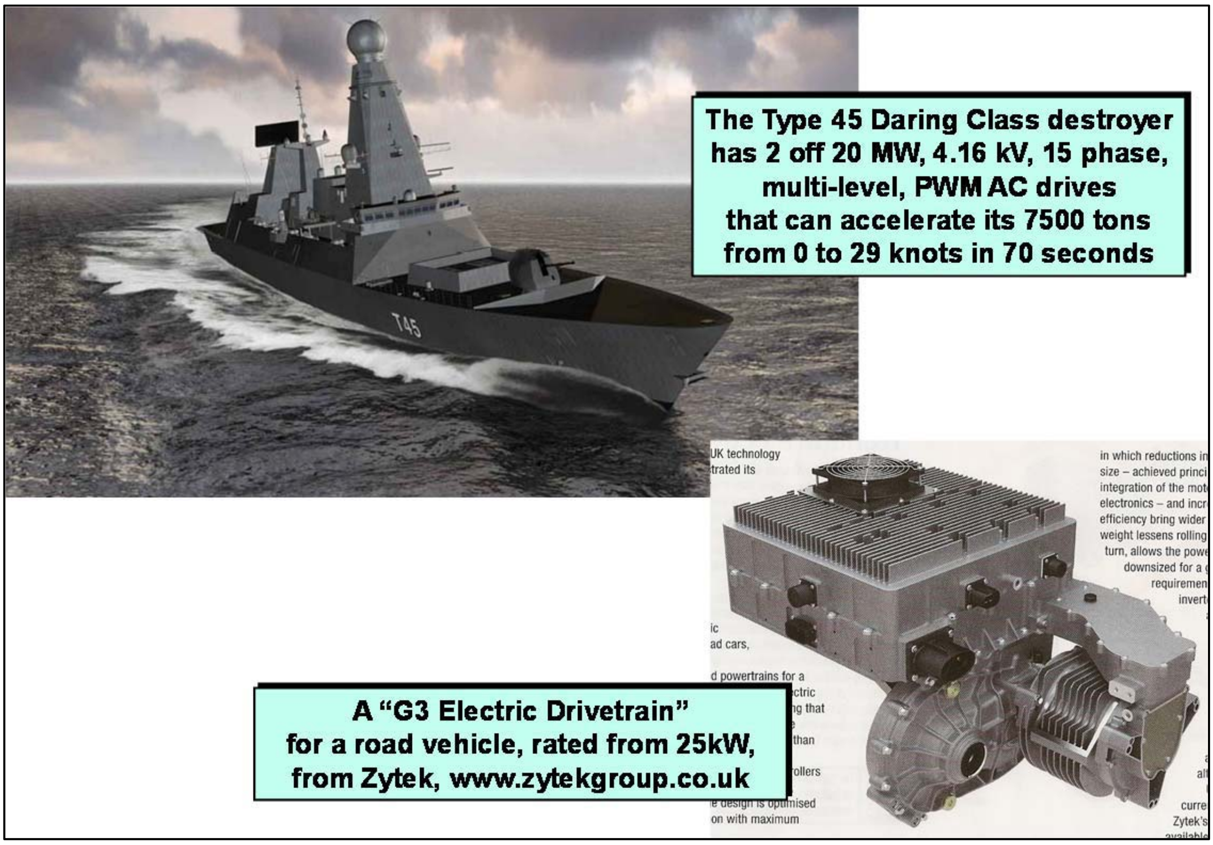

Figure 6 Two examples of vehicle applications: marine and road

This series of articles only addresses switch-mode and PWM converters that employ bipolar junction transistors (BJTs), MOSFETs (PowerFETs), or insulated gate bipolar transistors (IGBTs). It does not address converters that use silicon controlled rectifiers (SCRs), although many of their EMC issues are the same and similar design principles apply, see [3] for their additional EMC characteristics.

This series will cover the EMC issues in converter design, and in the systems and installations that use them, from circuit design and PCB layout, to heatsinking, shielding, filtering, and earthing/grounding in structures of any type, including fixed and mobile systems and installations (e.g. buildings, vehicles) whether they are on land or underground, on sea or subsea, in the air or in space.

From time to time it is inevitable that there will be some overlap between the design guidance in this article, and other articles I have written in the EMC Journal. I will try to deal with these, where they arise, by describing them in brief and referencing a more complete source, otherwise this could be a very long series!

Although the range of applications, and the range of powers and switching frequencies is so huge, switch-mode and PWM power conversion share certain basic features as far as EMI and EMC are concerned, which is why I believe I can cover them all, from mW to tens of MW, in this series. Wish me luck!

1.2 What are EMI and EMC?

All electrical, electromechanical and electronic activities (voltages, currents, waveforms, spectra, etc.) involve electromagnetic propagation described by Maxwell's Equations, and as such they always cause electromagnetic emissions. There are also several natural sources of emissions (e.g. electrostatic discharge, lightning, etc.) and unnatural sources (e.g. permanent magnets, nuclear bombs, etc.).

Sometimes these activities produce *intentional* emissions (e.g. radio transmissions, radars, diathermic heating, etc.) which can be at very high power and so create great nuisance, and they always have unintentional emissions too. Where design is poor and/or high powers are being used, their unintentional emissions can also be quite powerful.

All electrical, electromechanical and electronic devices and their circuits receive (pick up) electromagnetic "noise" from the electromagnetic environment (EME) they can't help but be immersed in, that is – the totality of all the EM disturbances that can exist at the location(s) where the equipment can be used – consisting of all the intentional and unintentional, natural and unnatural emissions mentioned above.

Physically smaller and/or lower-power devices are generally more sensitive, especially electronics, and particularly integrated circuits, ICs, and devices intended for radio/radar/microwave reception. We say that the electromagnetic energy "couples" into "victim" circuits, and there are four ways in which it can do this, via conduction or radiation.

Figure 7 shows the basis of EMI – a source of EM disturbances couples electromagnetic energy into a victim circuit via one or more coupling paths.

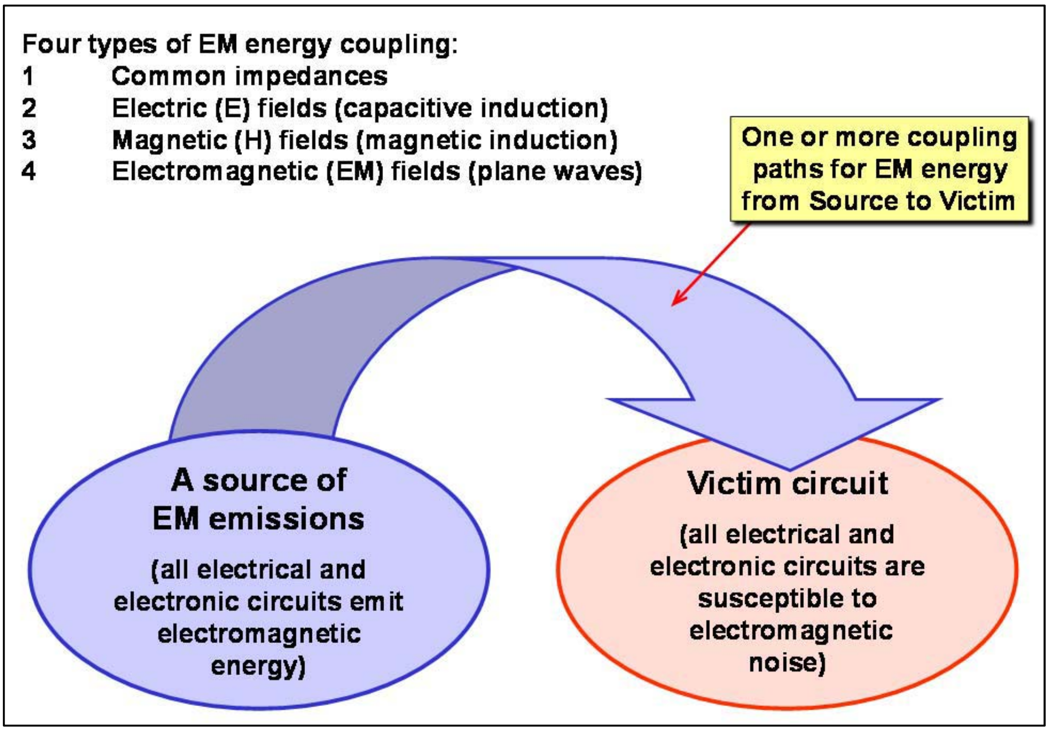

Figure 7 The three parts to every EMI event: Source, Path, and Victim

When the noise picked up in a device or circuit exceeds certain levels, depending on the circuit's design and function, it will experience errors or malfunctions.

Circuits that operate in analogue mode generally suffer errors that increase as the emissions they are subjected to by their environment increase, until functionality is impaired by too much for correct operation. For example, a buzzing noise in an audio system that increases until the audio signal is unintelligible.

Digital circuits (if they are designed correctly) have a "noise margin" and so will be unaffected as the emissions they are subjected to by their environment increase, until the margin is exceeded and they malfunction. Where the digital circuit is running software or firmware, malfunctions may manifest as control errors or malfunctioning code, often mistaken for operator errors or software design errors, respectively. Or the circuit may simply stop operating.

All electrical, electromechanical and electronic devices can be damaged by emissions at too high a level, usually by overdissipation. Some equipment can be damaged too, when an error or malfunction in its control electronics causes moving parts to move inappropriately (for example, if there is an error in the glide path of an aircraft when it is landing).

All such undesirable outcomes are called electromagnetic interference, or EMI. Sometimes people use the term EMI to refer to the emissions themselves, and I have sometimes done that intentionally where the intended audience is not as sophisticated in these matters as readers of the EMC Journal.

While we are being correct, the correct term for an electromagnetic emission that could cause interference is an "electromagnetic disturbance", usually abbreviated to "EM disturbance" or just "disturbance", rather than EMD (for reasons that I don't know).

The science and engineering discipline concerned with controlling EMI is called electromagnetic compatibility (EMC). The techniques used in EMC engineering concern each of the three parts necessary for an EMI event, as shown in Figure 7, which is taken from Chapter 5 of [4] and Chapter 2 of [5]:

a) Reducing the level of EM emissions

   This is not usually possible for intentional emitters, in their transmission frequency bands

b) Attenuating (mitigating) the EM energy that flows in the coupling path(s)

   For example by filtering, shielding, overvoltage/current suppression, galvanic isolation, etc.

c) Hardening the victim circuit, i.e. reducing its susceptibility to EM disturbances

   This is not usually possible for receivers in their intended reception frequency bands

For more information on the physics of EMI, read all of [4] or Chapter 2 of [5] (they are the same). For practical information on doing a) – c), read all of [5].

EMC is concerned with ensuring that emissions of EMI are low enough not to upset other equipment, and that immunity to EMI is high enough (i.e. susceptibility is low enough) for equipment to operate tolerably well in its EME.

There are standards and regulations on EMC in most countries, worldwide, at least limiting conducted and radiated emissions to protect their radio broadcasting and communications spectrum.

This article will not discuss EMC test standards or Regulations, just good EMC design and construction techniques. However, a great deal of information on the CISPR and IEC EMC test standards, plus the disturbances they test for, is available from [6].

1.3 Why switch-mode and PWM power converters cause high levels of EMI emissions

Because they are switching power rather than (weak) signals, all power switching technologies generate a lot of electrical "noise", from their basic switching frequency and all of its various harmonics up to radio frequencies (RF), as shown in Figure 8.

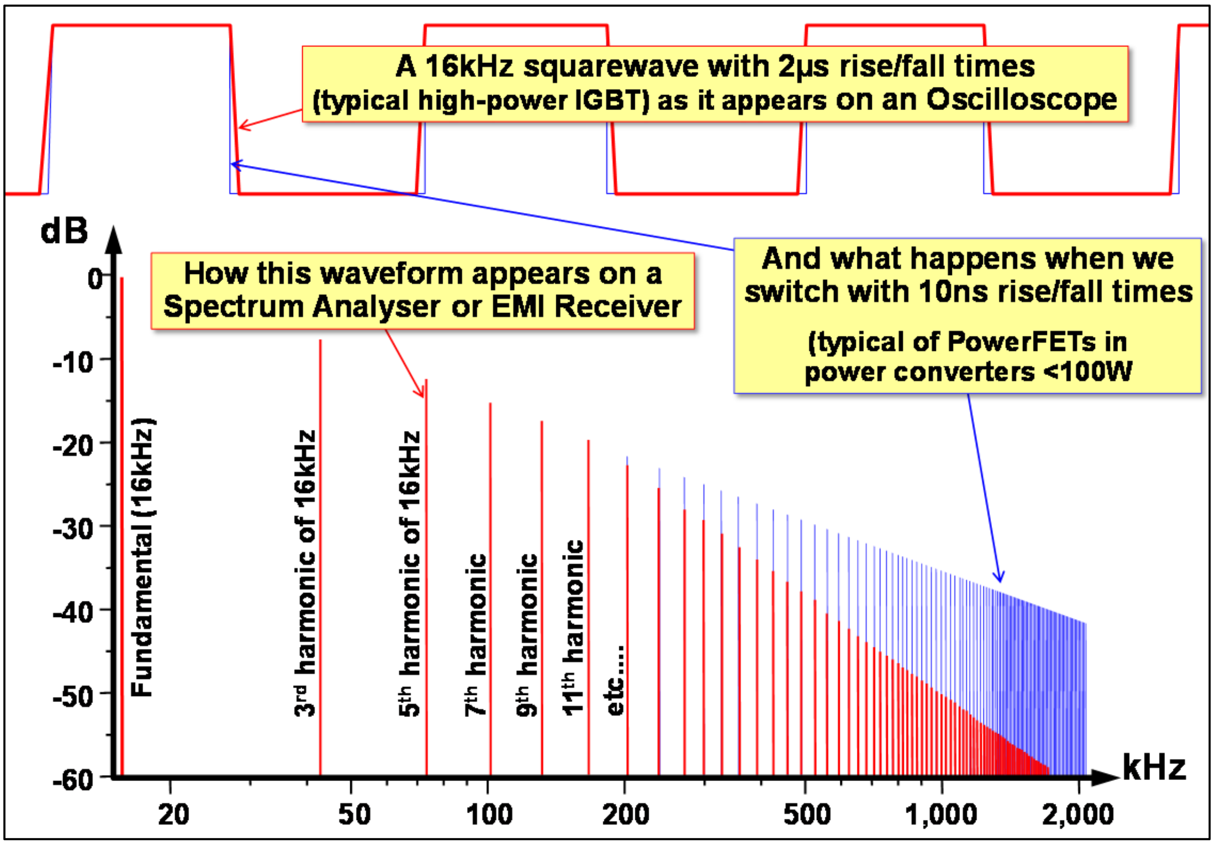

Figure 8 The harmonic content of a 16kHz squarewave, comparing 2µs and 10ns switching times

Figure 8 shows a squarewave, as most such figures do when the issue of the spectral content of a waveform is being introduced for the first time. But the squarewave example is actually quite unusual in the context of this article because it doesn't have any even-order harmonics (2^{nd}, 4^{th}, 6^{th}, etc.), whereas all switch-mode and PWM converters use rectangular waves (their mark:space ratios are not equal to 1, like a squarewave's is, except under special circumstances) and so they exhibit all of the harmonics, even- as well as odd-order.

This noise "leaks out" of the rectification and switching circuits and into the unit's cables, causing high levels of Differential-Mode (DM) and Common-Mode (CM) conducted emissions on the AC or DC power supply, and Figure 9 is a typical result.

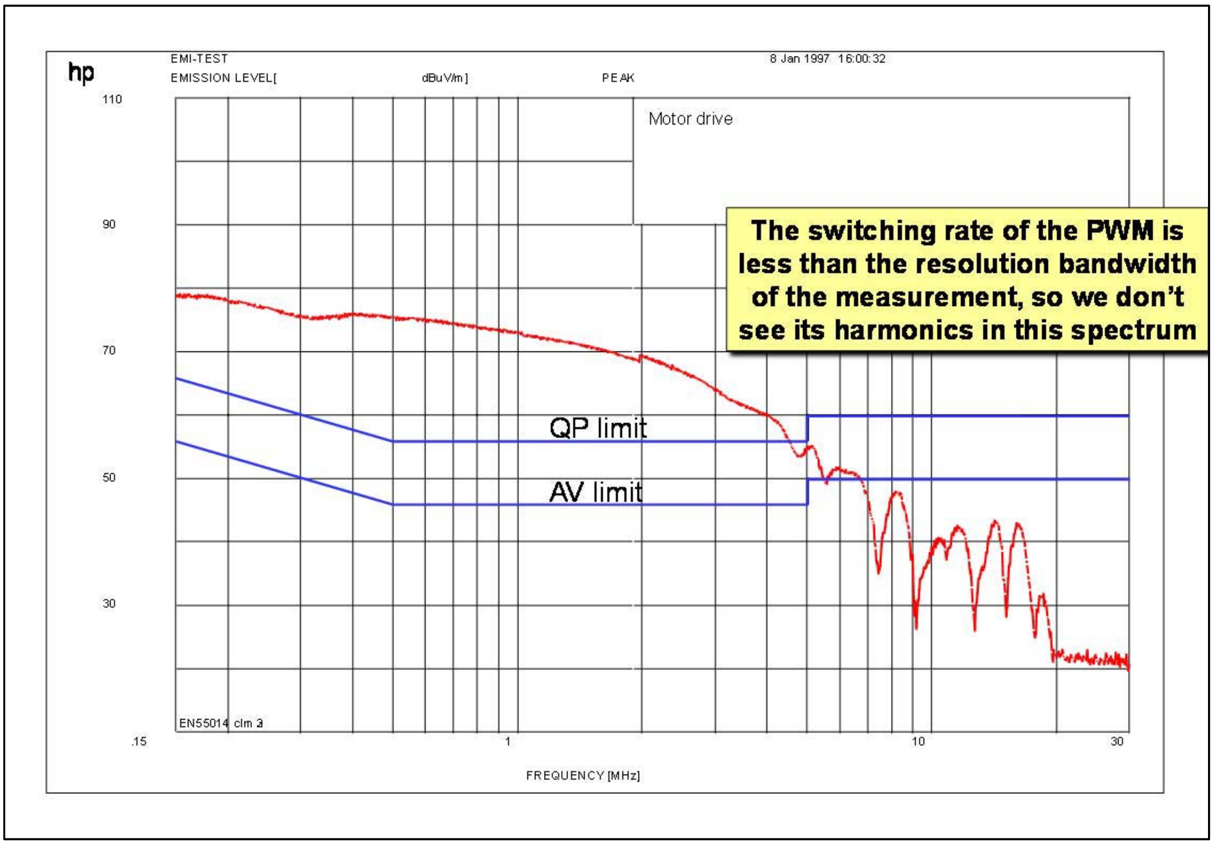

Figure 9 Example of the conducted emissions from a small PWM motor drive, compared with the limits in the Generic Emissions standard, EN 61000-6-3

The design of the example PWM motor drive whose test results (from 1997) are shown in Figure 9 already includes some EMC measures, so is not as bad as it could be. I have often seen quite small switch-mode and PWM converter emissions vanish over the top of the screen when measured in the standard way. We would sit in the test laboratory wondering why the test was taking so long to get started, until, as the measured frequency got above, say, 3MHz, the measured emissions became low enough for their display line to become visible at the top of the screen.

Conducted emissions of 50dB or more above the Quasi-Peak (QP) detector's limit line are not that unusual, when designers have not used any EMC techniques, or not used them correctly, even from very small converters.

Conducted tests like Figure 9 are only performed on mains cables, but DM and CM noises also appear on heatsinks, chassis members, output and control cables, and because all conductors naturally behave as "accidental antennas" a proportion of the *conducted* DM and CM noises "leak" from the conductor into the air, causing high levels of *radiated* emissions. (Another name for CM is "antenna mode", giving some idea of its much greater propensity for "leaking" from cables into the air than DM – for frequencies below 1GHz, at least.)

All CM noise current loops include the chassis/frame/earth/ground/common bonding network (CBN) structures, and so CM noise is one of the causes of "ground noise", that effects other equipment via common-impedance coupling.

Figures 10 through 12 attempt to give some idea of the accidental antenna behaviour of cables – also all other types of conductors, for example printed circuit board (PCB) traces, busbars, heatsinks, etc. – and why they create so many problems for modern electronics.

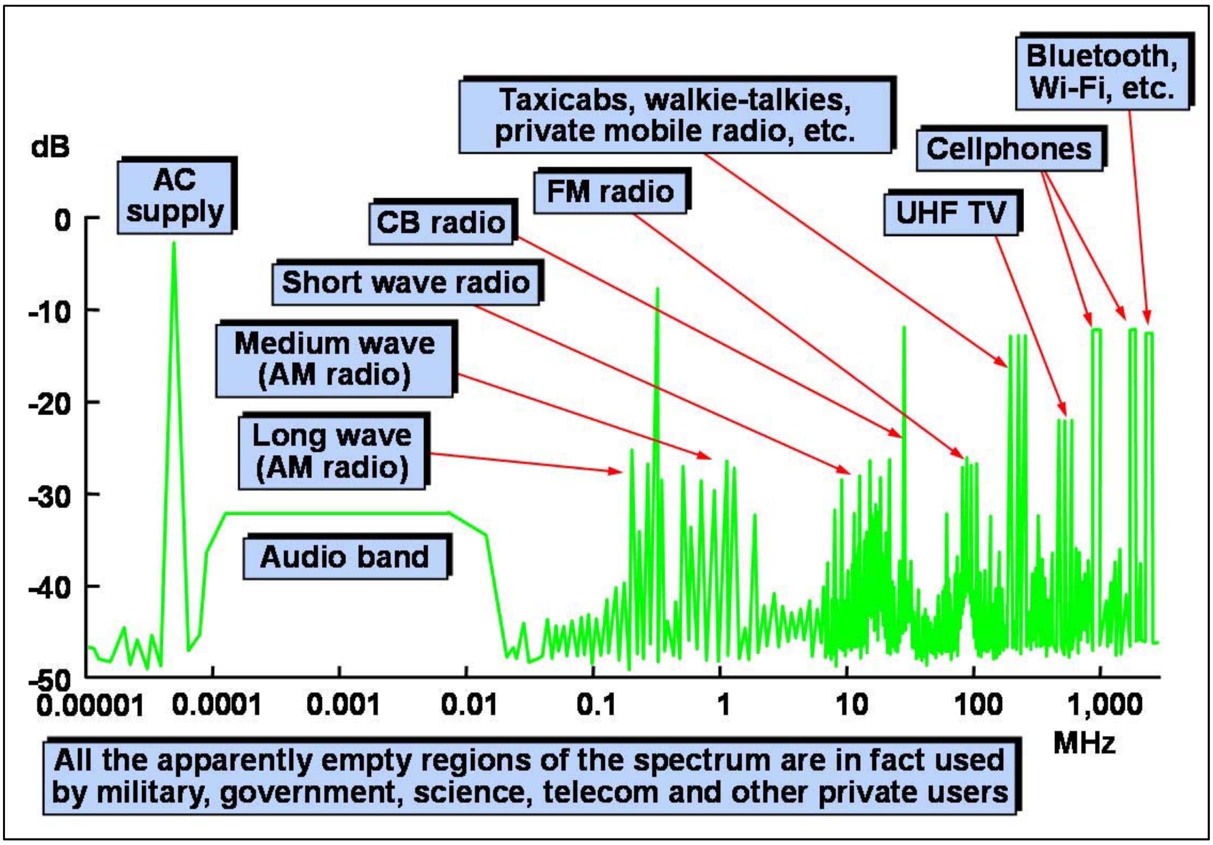

Figure 10 The frequencies we most often use, from 10Hz to 3GHz

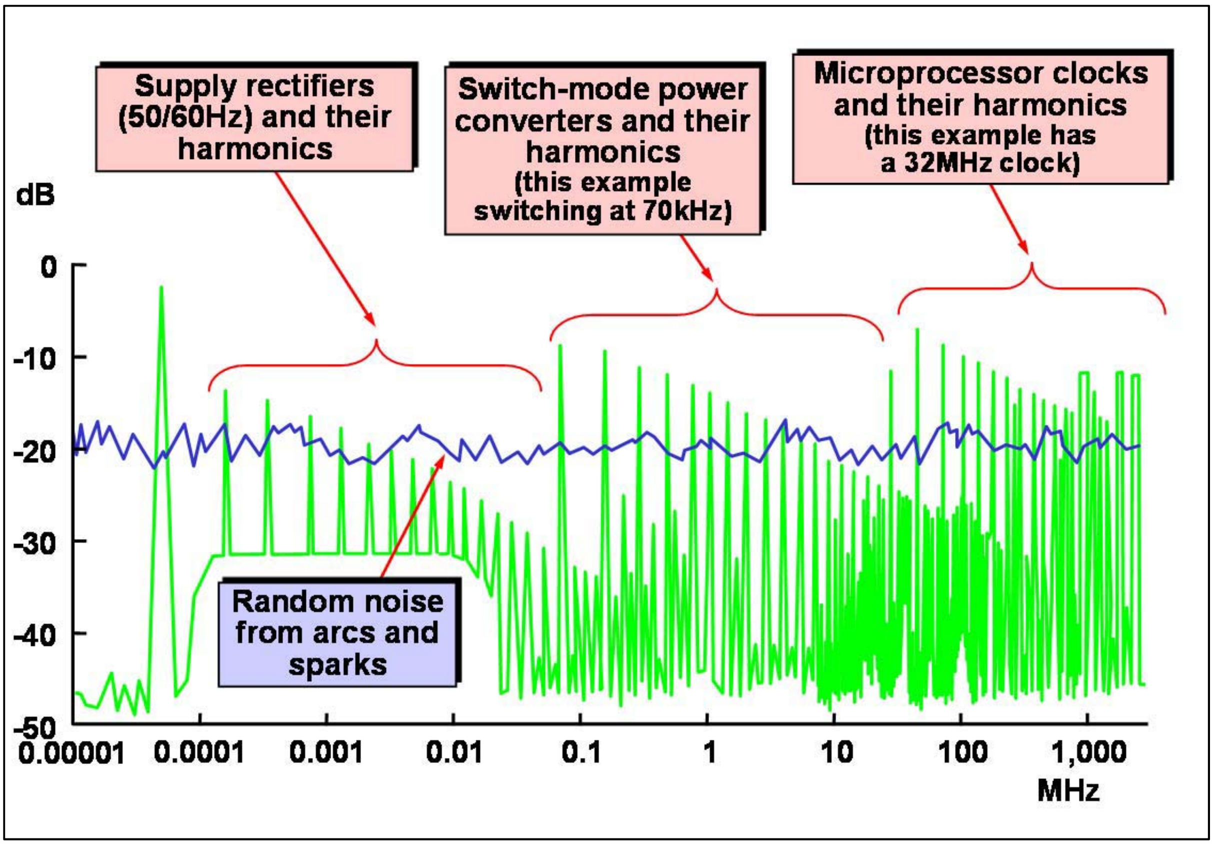

Figure 11 The frequencies we use, plus typical electrical/electronic noise emissions

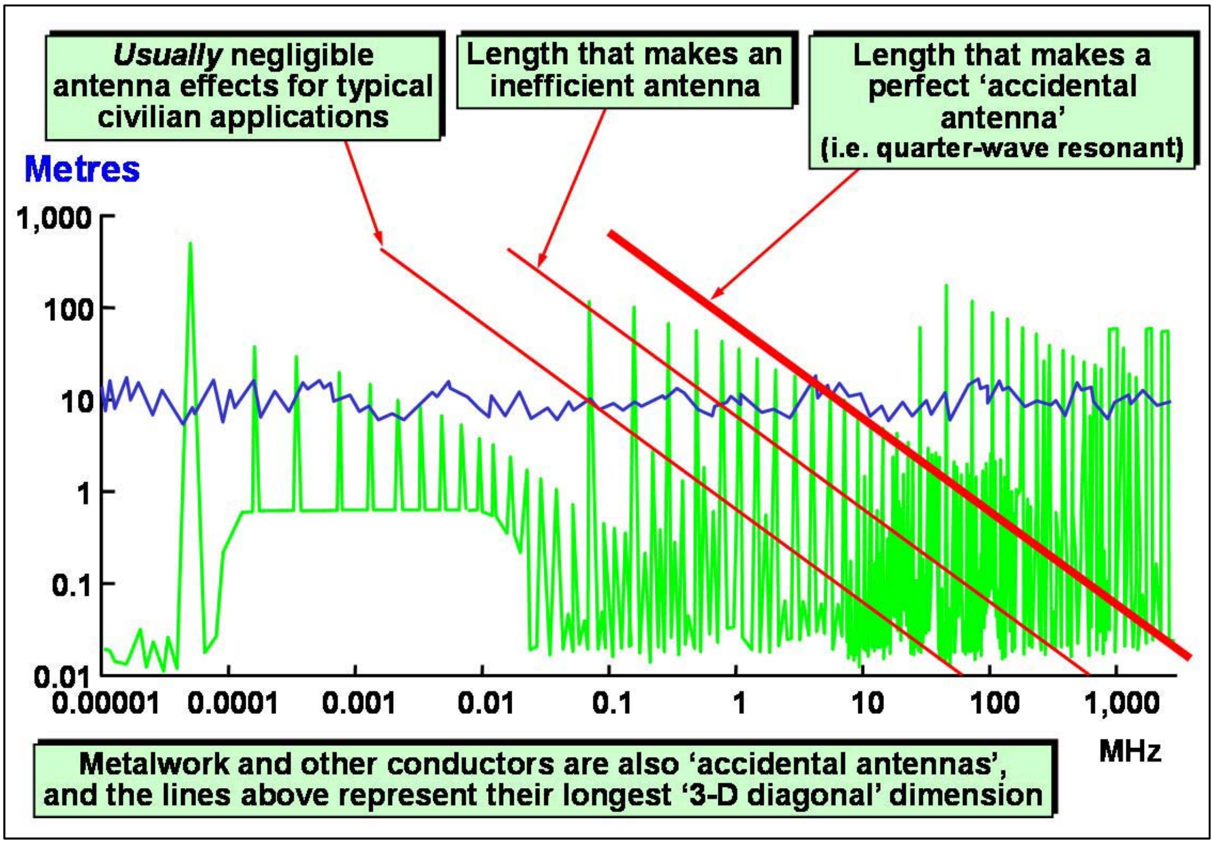

Figure 12 Comparing frequencies with the accidental antenna behaviour of conductors

A piece of metal, such as a wire or cable, is a linear element and so works just the same "backwards" as "forwards", so the accidental antenna behaviour that causes conductors to radiate a proportion of the DM and CM currents that flow in them into the air as electromagnetic energy, means that they also "pick up" EM fields in the air and convert a proportion of them into DM and CM noise currents. This is known as the Principle of Reciprocity, and is discussed in more detail in [4] and Chapter 2 of [5].

This natural EM pick-up behaviour of all conductors is one of the main causes of immunity problems. It is often thought that because power converters operate with high voltages and currents, they are naturally immune to typical levels of EMI, but the switching devices that carry the high currents and voltages are controlled by microprocessors or other IC controller devices made using similar semiconductor technologies, and these are easily upset by EMI.

A lack of immunity can make bridge-type power converters explode violently due to the high energies they handle, and higher-power converters can explode as violently as some military ordnance – and cause similar injuries from shrapnel. I have narrowly missed being injured by such converter explosions myself, and know of one military supplier who had to hire a million-frames-per-minute camera to photograph his power converter as it was "self-disassembling" to find out which part failed first (i.e. the most likely cause), because all he had to analyse after the event was a smoking pile of ash; blackened and distorted metalwork, and shards of components.

Immunity is outside the scope of this series, because it focuses on controlling emissions. However, most of the EMC design techniques for reducing emissions also improve immunity, because of the Principle of Reciprocity.

All the terms and concepts introduced so far in this subsection are described (using hardly any mathematics, and that very simple) in [4] and Chapter 2 of [5].

In addition to the above noises caused by the active power switching devices, AC mains-powered switch-mode converters generate mains-frequency-related harmonic noise emissions, and PWM inverters generate non-mains-frequency-related noise emissions (known as "interharmonics"), and both can cause problems, for example by:

- Overheating cables and transformers (fire is a real possibility)
- Making it difficult or impossible to run equipment at full power.
- Distorting the mains distribution voltage waveform so it isn't a sinewave, possibly interfering with or damaging other equipment connected to the same mains network

These are examples of what are called “power quality” problems, which will be addressed in later issues in this series. If you can’t wait, [7] and [8] discuss these problems and their solutions from the point of view of systems and installations, and [3] tackles the EMC and power quality issues of power drive systems and installations, including marine and offshore applications.

1.4 Reduce financial risks by using good EMC engineering from the start

Unless low-enough emissions and high-enough immunity is designed-in from the start of a new product’s design/development project, it will take a long time before they work well enough to sell, customers will suffer interference and downtime, warranty costs will be high, and repeat business will suffer. There are many examples of this in [9].

Product liability claims are also a possibility where the poor EMC of the product causes financial losses (e.g. excessive downtime) or causes injury or death.

Injury and death is especially a problem as vehicles and medical equipment employ more electronic control, using ICs with ever-smaller silicon features which are therefore more susceptible to EMI.

(Note: where errors or malfunctions in electrical, electromechanical or electronic items could cause significant financial or safety risks, complying with EMC Regulations such as the EMC Directive 2004/108/EC and passing all of its emissions and immunity tests is (almost always) insufficient to demonstrate that the risks are at acceptably low levels. See [10] for more on this, plus detailed practical guidance.)

A recent example of this was reported in the “Banana Skins” column of the EMC Journal in the previous issue, as Banana Skin number 618. A new offshore gas drilling rig had cost US$ 500 million to build but suffered from two EMC problems, one of which caused its large and powerful (700kW variable-speed motor drive) cranes to go out of control, causing very real safety hazards. After four months without drilling, independent consultants were called in and fixed the problems, which were caused by the complete lack of mains filters on all of the many switch-mode and PWM converters on the rig, even the 700kW ones.

The rig’s manufacturer counted the final, real costs of the EMC problems, which amounted to over US$ 54m. They had made several similar offshore drilling rigs beforehand, and had never fitted them with mains filters – despite this being good EMC engineering practice, especially when running on generated power – because, they said: “they were not needed”.

In other words, because they saw no obvious EMI problems on the rigs and because the rigs were operating in international waters where no country applied EMI Regulations, they imagined that they were saving money by saving the cost of the mains filters, a few tens of thousands of US dollars per rig (certainly much less than 0.1% of the overall cost of manufacture).

However, like most such bad EMC engineering decisions, it ended up costing them hugely much more than they had ever “saved”.

The Banana Skins column (and [9]) has many similar examples of what I call “saving money at any cost”, and I – and most EMC consultants – know many more such stories that have never been published, and never will be for reasons of commercial confidence.

So good EMC engineering is always required, to help control a manufacturer’s financial risks, whether there are EMC standards or regulations to comply with, or not. See Chapter 1 of [5] for more on this, and [11] and [12] may also be interesting – why not print them out for your financial director?

1.5 The “building blocks” of switch-mode and PWM power converters

Figures 13 through 24 show the full range of types of switch-mode or PWM power converters, showing how they can be seen to be based upon a number of circuit “building blocks”, each with its own EMC characteristics:

- High-frequency (HF) power switchers (various types)
- High-frequency (HF) PWM power choppers (full-bridge or half-bridge)
- Low-frequency (LF) isolating transformers (typically 50/60/400Hz but in fact quite happy at any AC power frequency)
- High-frequency (HF) isolating transformers
- Low-frequency (LF) input rectifiers (typically 50/60/400Hz but in fact quite happy at any AC power frequency)
- High-frequency (HF) output rectifiers

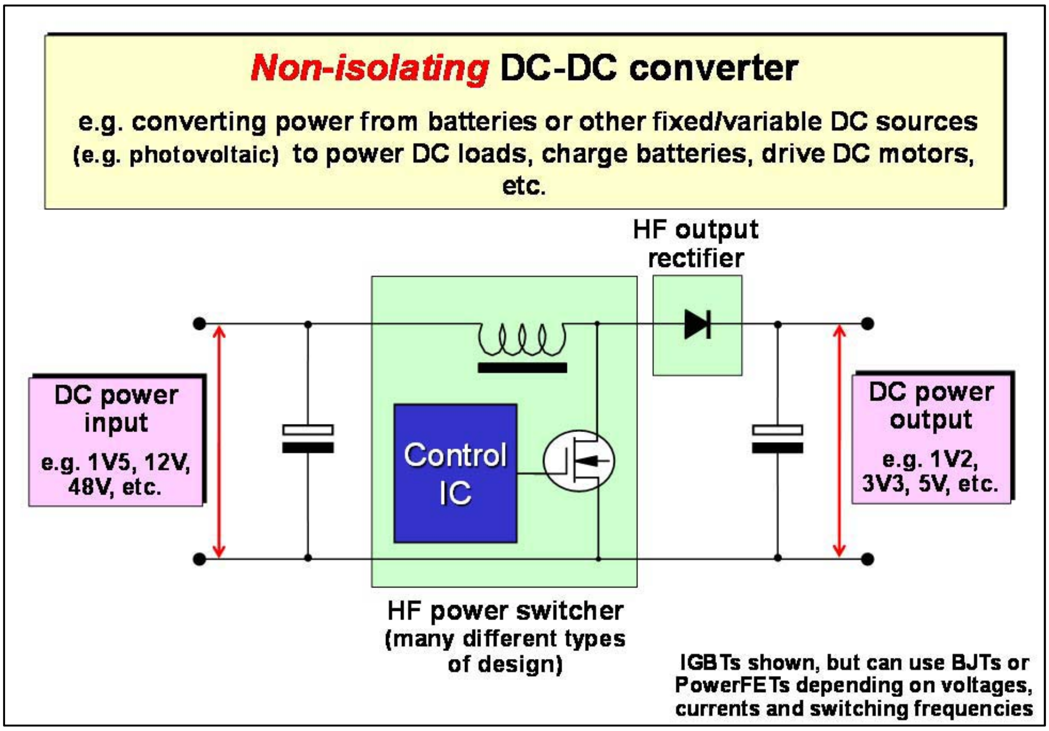

Figure 13 Non-isolating DC-DC converter

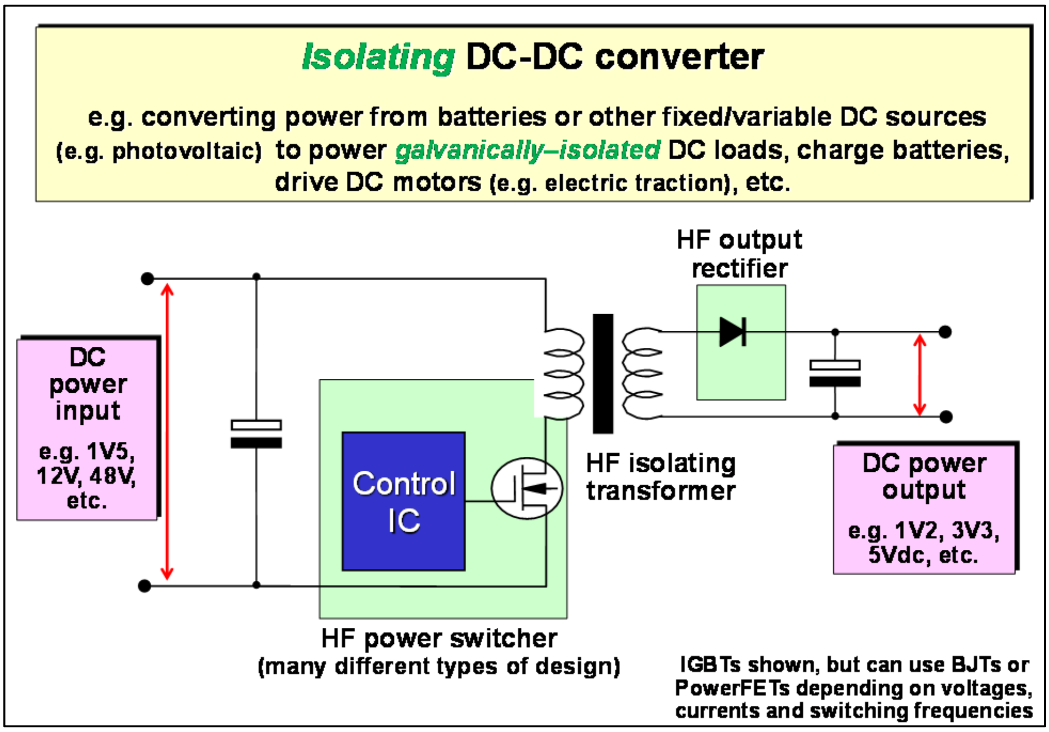

Figure 14 Isolating DC-DC converter

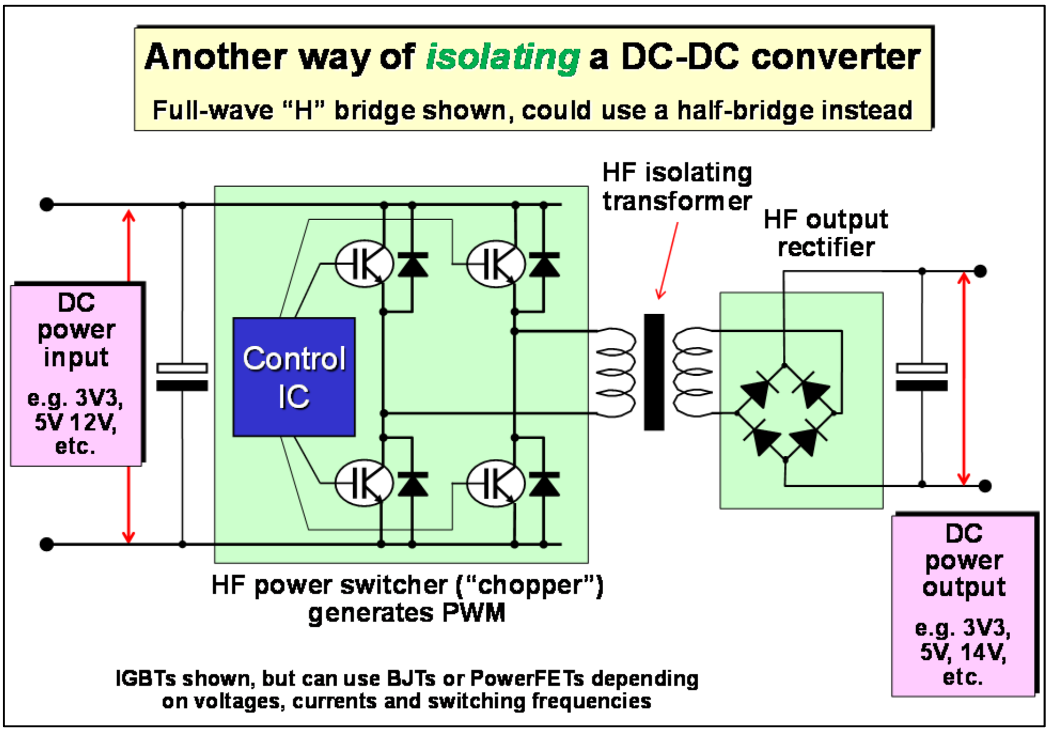

Figure 15 Another way of isolating a DC-DC converter

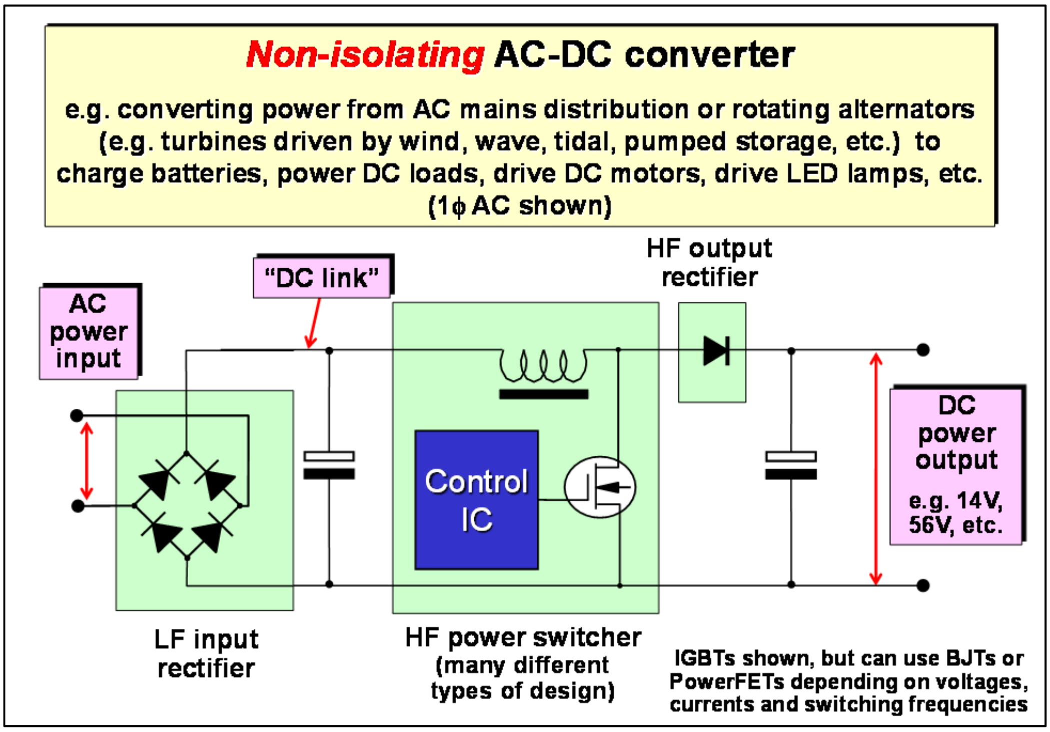

Figure 16 Non-isolating AC-DC converter

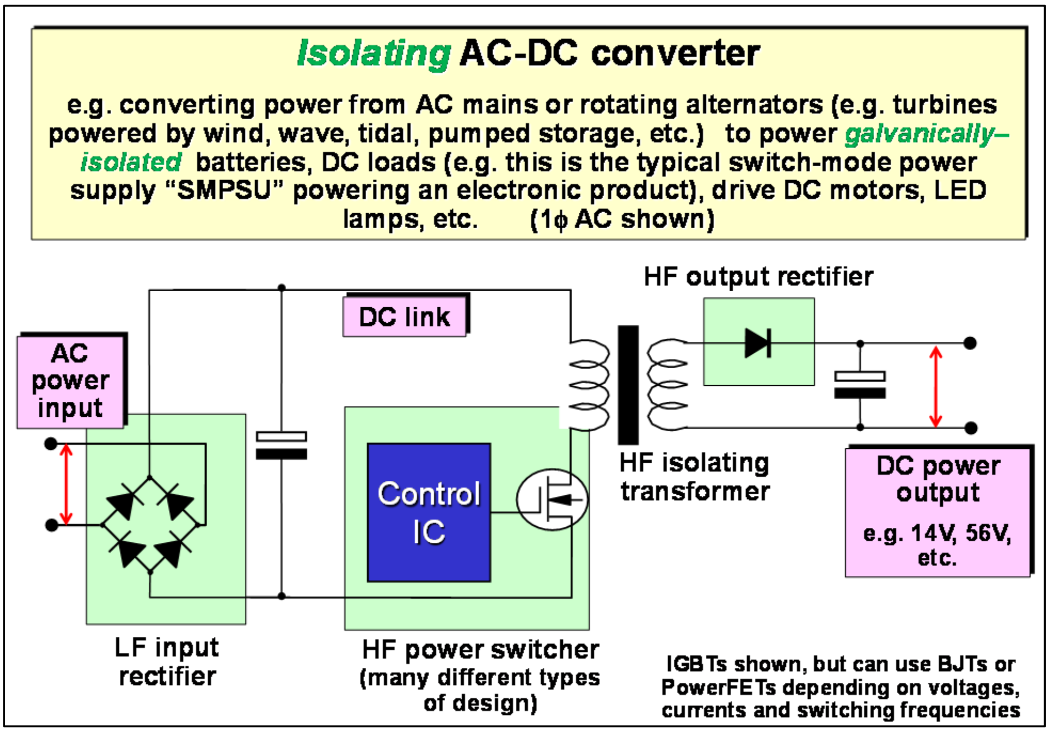

Figure 17 Isolating AC-DC converter

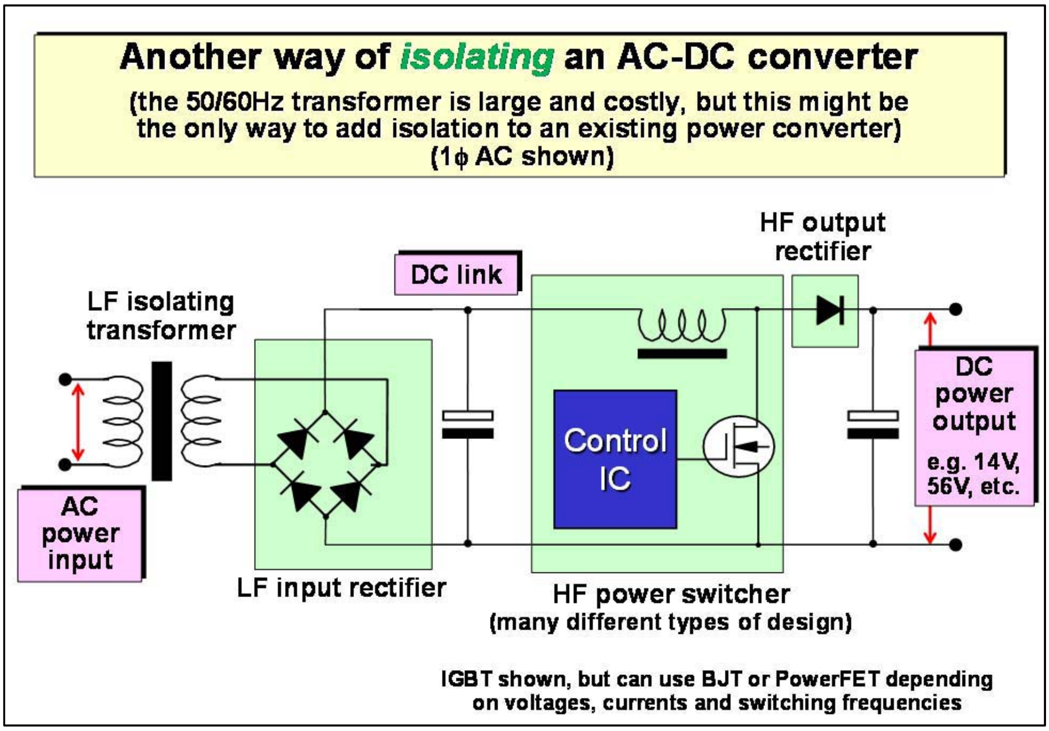

Figure 18 Another way of isolating an AC-DC converter

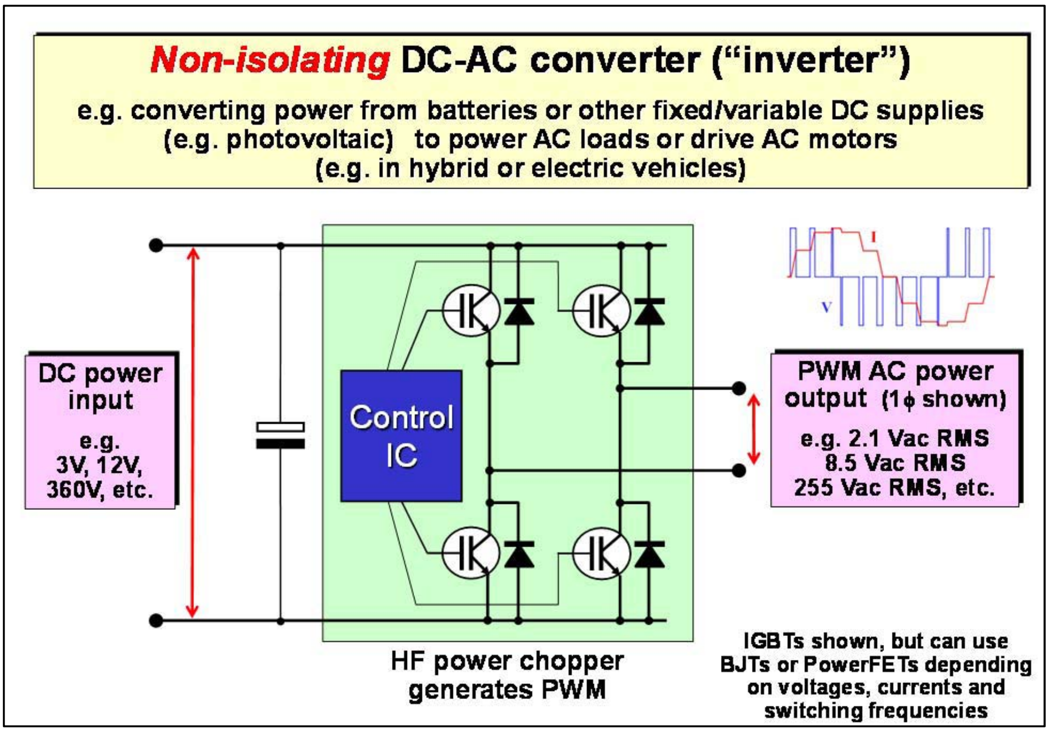

Figure 19 Non-isolating DC-AC converter ("inverter")

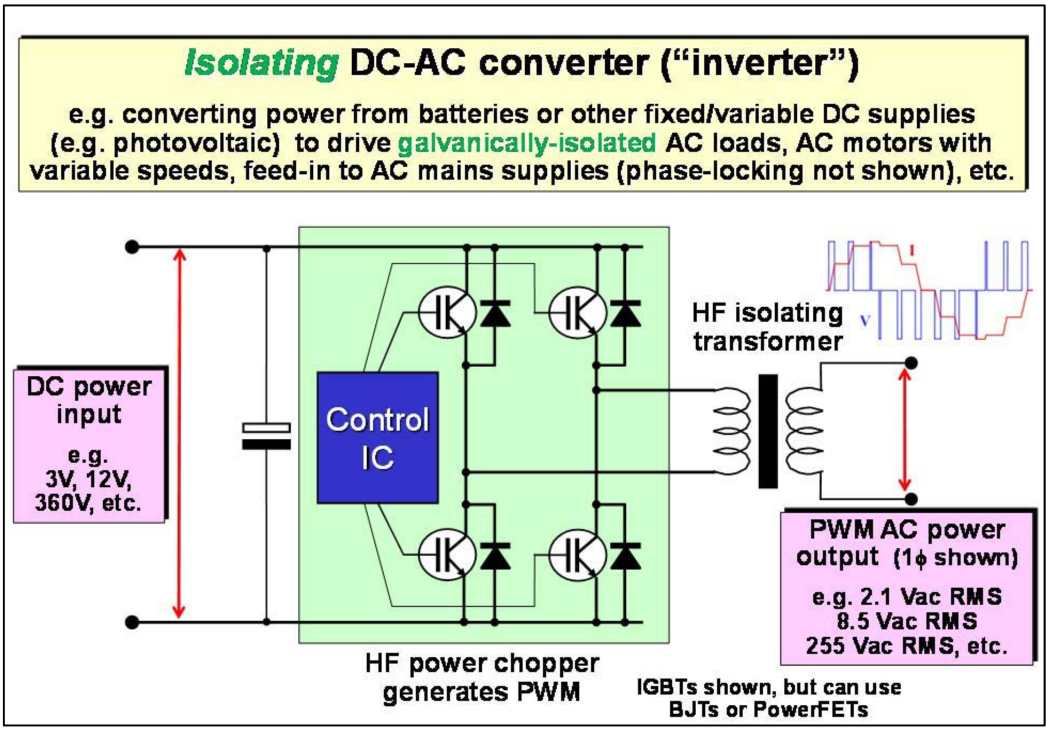

Figure 20 Isolating DC-AC converter (inverter)

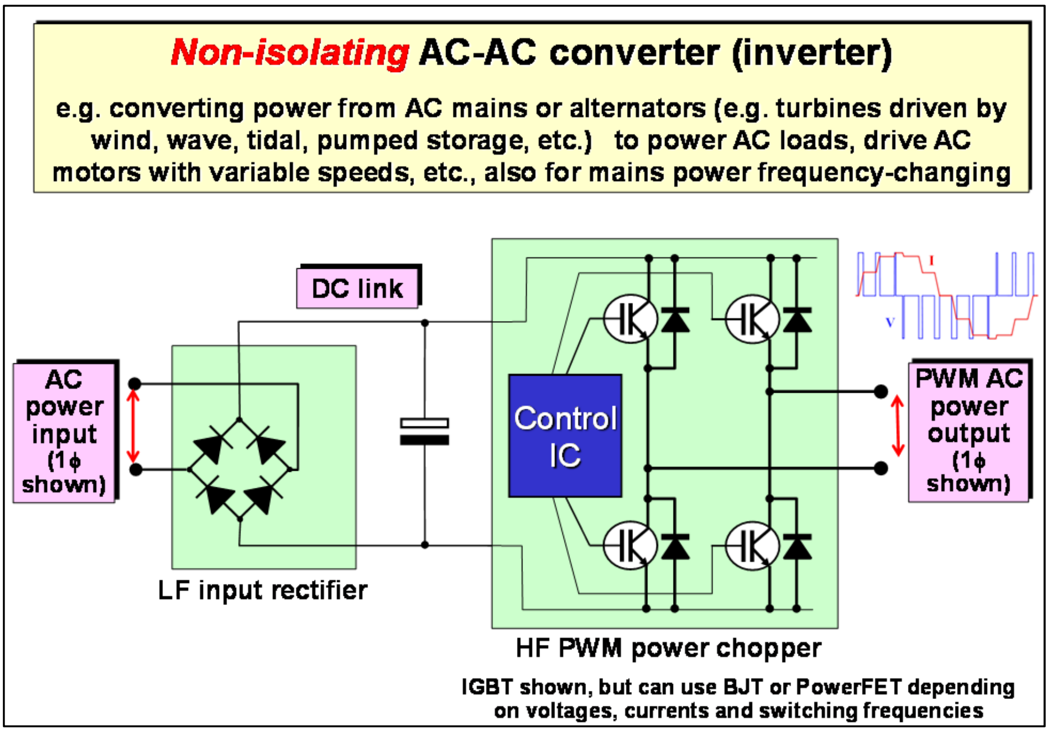

Figure 21 Non-isolating AC-AC converter (inverter)

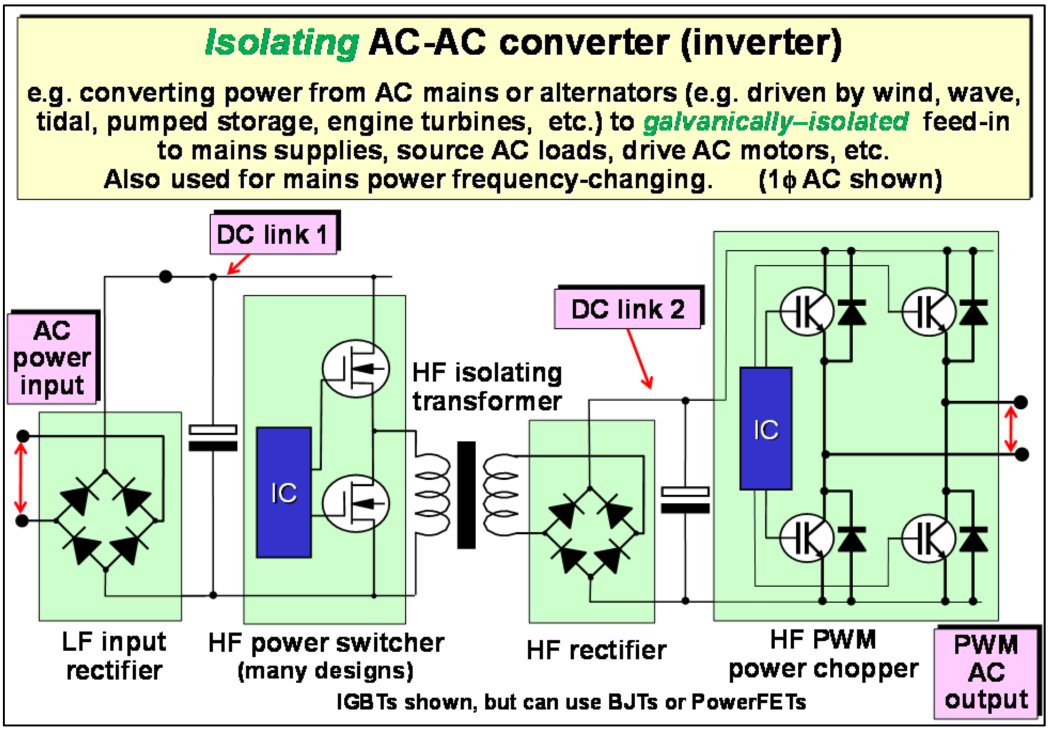

Figure 22 Isolating AC-AC converter (inverter)

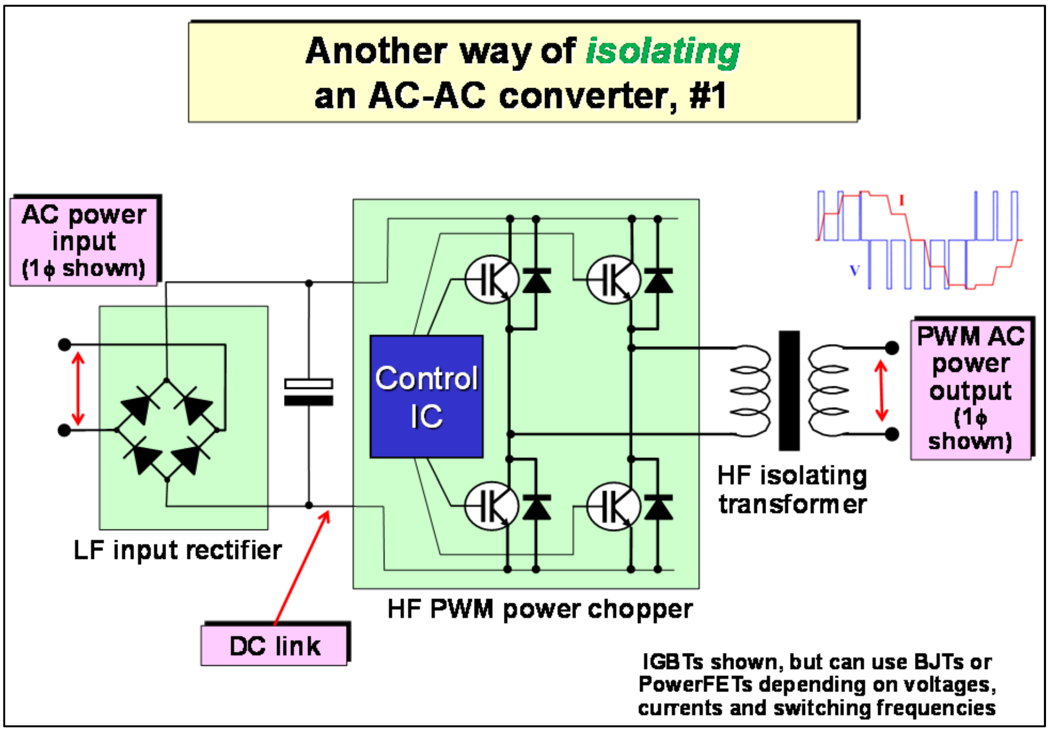

Figure 23 Another way of isolating an AC-AC converter, #1

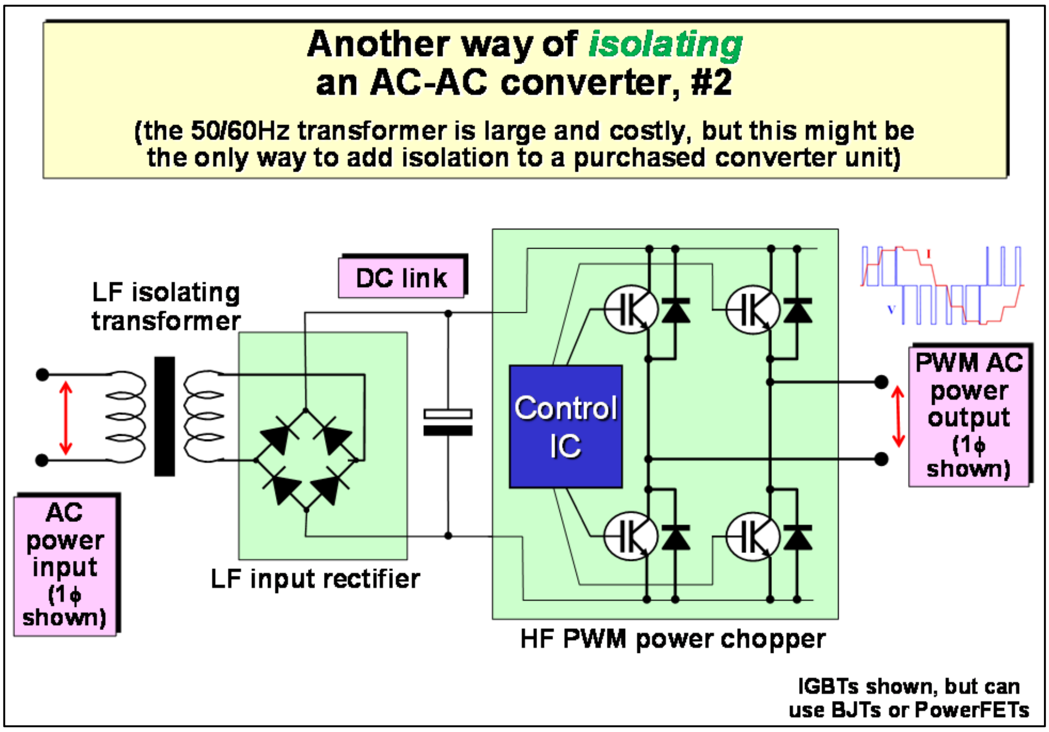

Figure 24 Another way of isolating an AC-AC converter, #2

On the inverters with PWM AC output, there is a little graph showing crude voltage (V) and current (B) waveforms (assuming an inductive load, such as a motor) to remind us that even though we might say that the output is 39.4Hz (for example) it is actually a switching waveform with a great deal of high-frequency energy in its spectrum.

1.6 What to expect in future articles

This series will deal with the EMC of each building block in turn, showing how they can be designed to reduce emissions, without going into other details of their devices and circuit design.

Then it will address other EMC issues such as mitigation (i.e. suppression of emissions using filtering, shielding, etc.), followed by the optimum EMC design of printed circuit boards (PCBs), cables and connectors.

10 References

[1] "AC-Link™ – 21st Century Technology for Marine Power Distribution, Electric Propulsion, Thruster and Ancillary Drives", Ian C Evans (Harmonic Solutions Co. UK, Scotland) and Rudy Limpaecher (Varentec LLC, USA), presented at the Marine Propulsion '08 Conference, Gothenburg, Sweden, 21 - 22 May 2008.

[2] "G3 Electric Powertrains", in the "News" section of Automotive Design magazine, July 2010, page 10, www.automotivedesign.eu.com, also "Electric vehicles shift gear" in Eureka Magazine, August 2010, page 25, www.eureka.com.

[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, 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, Nutwood UK Nov. 2010, ISBN: 978-0-9555118-4-4, from www.emcacademy.org/books.asp.

[6] Booklets describing seventeen IEC/EN/CISPR EMC test standards, and the types of disturbances they address, by Keith Armstrong, published by REO (UK) Ltd and downloadable for free from: www.reo.co.uk/knowledgebase

[7] "Mains Harmonics", Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase

[8] "Mains Power Quality", Keith Armstrong, published by REO (UK) Ltd, free download from: www.reo.co.uk/knowledgebase

[9] "The First 500 Banana Skins" is a slim book containing 500 anecdotes or reports of instances where interference is proven or claimed to have occurred, indexed by application and also by type of interference. Buy it for about £10 from www.emcacademy.org/books.asp or read it online at www.theemcjournal.com (but you can't download the book from that site).

[10] "Guide to EMC for Functional Safety", The IET, 2008, ISBN: 978-0-9555118-2-0, printed full-colour book from www.emcacademy.org/books.asp, or download from www.theiet.org/factfiles/emc/emc-factfile.cfm

[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 wwww.theemcjournal.com.