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EMC design of Switching Power Converters Part 6 - Design Techniques for HF output rectifiers

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EMC design of Switching Power Converters

Part 6 —
Design Techniques for high frequency (HF) output rectifiers

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Issues 93 – 96 of The EMC Journal carried earlier parts of this “Stand Alone” series, which is 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; whether they are used in modules, products, systems or installations.

I also aim to cover hybrid & electric automobiles, electric propulsion/traction; “green power” (e.g. LED lighting); and power converters for solar (PV), wind, deep-ocean thermal, tidal, etc.

If you read the earlier parts of this series in previous issues of the EMC Journal, you will notice that the numbering of figures has changed, and the numbering of the sections does not correspond to the number of the published part of the series (e.g. this is the fifth part and it covers Section 6). I hope you can forgive me for this lack of consistency.

I will generally not repeat stuff I have already published, instead providing appropriate references to material published in the EMC Journal [14] and my recently-published books based on those articles [15].

6 EMC design of HF output rectifiers

6.1 *Schottky, “soft-switching”, or synchronous rectifiers*

All PN-junction rectifiers and diodes generate switching noise. They create brief bursts of noisy reverse current every cycle, while their minority carriers decay in reverse voltage mode.

(Minority carriers are often called “holes”, but according to my Physics of Semiconductors lecturer in 1970 they are really electrons orbiting atomic nuclei in forbidden energy bands, i.e. negative-mass electrons – anti-matter!)

While a rectifier is reverse-biased but its minority carriers have not yet decayed completely, it is effectively “shorting-out” the power supply, and it is hardly surprising that this causes EMI.

So the best rectifiers are Schottky types, because they have no minority carriers and so are much quieter than PN junction “silicon” rectifiers. Schottky rectifiers made of silicon-carbide (SiC) are now available up to 1.2kV, and when used in existing designs to replace PN junction silicon rectifiers have been found to need fewer snubbing and filtering components.

SiC Schottky rectifiers cost more than PN junction silicon types, but this is another example of where focussing on the BOM cost alone can lead to more costly products, see [12]. The real cost of the EMI suppression components that are required is usually only found towards the end of a project, when a pre-production prototype is put in an EMC test lab.

(Leaving EMC to the end of the project is very bad project-risk and financial-risk management, but it is what most companies, whose managers mistakenly think lowest-BOM cost is important, actually do.)

At such a late stage in a project it is often considered too risky to make changes to the design, so all that can be done is to throw EMI suppression at the prototype until it passes the test (risking the possibility that the suppression components can't actually be fitted inside the enclosure).

In this situation, the usual result of trying to keep the BOM cost low by using silicon rectifiers rather than SiC shottkies, is that the components that have to be added to suppress the rectifier noise cost more than the additional cost of using SiC shottkies in the first place/earlier in the design.

But not all silicon rectifiers are equal. When using silicon rather than Schottky, we will generally get lower emissions by using the so-called "soft switching" types of fast rectifiers, as shown by Figure 6.1-1.

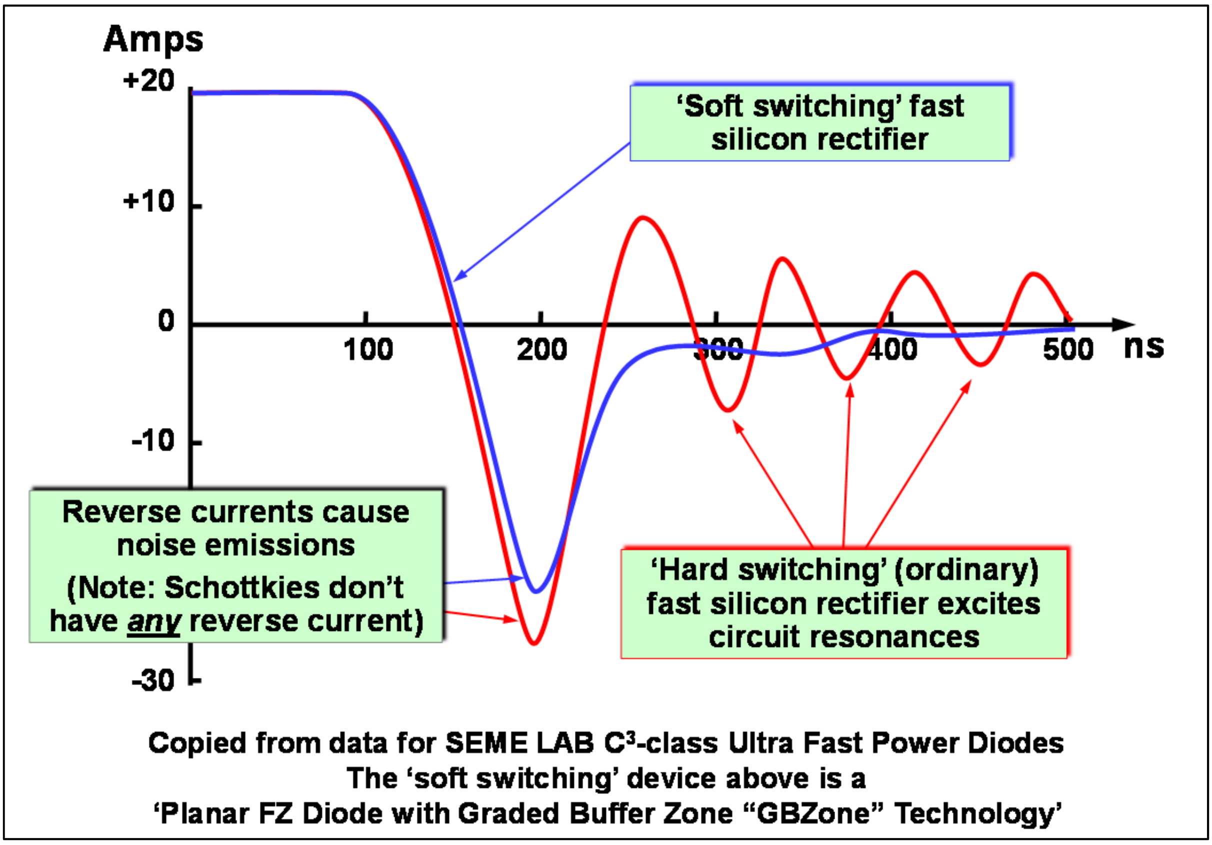

Figure 6.1-1 Comparing reverse currents of ordinary and soft-switching fast rectifiers

Synchronous rectifiers use PowerFETs instead of silicon rectifiers. But they create similar emissions problems to silicon PN diodes, in this case caused by the "shoot-through" currents caused by crossover conduction – when they short the power rails out momentarily, rather like the reverse recover current in a PN junction – causing noise and exciting resonances.

Schottky rectifiers are generally much quieter, but probably not as thermally efficient as synchronous rectification.

6.2 Using snubbers

The purpose and general design of snubbers was covered in Section 2.4 and its Figure 2C, published in Issue 94 of the EMC Journal [42]. It did not suggest any values for the snubber components, because they are best predicted by using computer-aided circuit simulators working with detailed component parameters (not generic library devices) that also take the impedances of the PCB's copper traces and any wiring into account.

Lacking such sophisticated simulators – as most of us do despite the fact that it is easy to make a very good financial case for purchasing such simulators and being trained to use them effectively – we are left with experimenting to find the best combinations of R and C for suppressing emissions without causing too much heat loss.

We don't need to tie up an EMC test lab while we optimize snubber values, because we can get very close indeed by experimenting at our own test bench using true high-voltage-rated galvanically-isolated ("floating") differential oscilloscope probes or a close-field probe with an oscilloscope or spectrum analyser, to monitor overshoots and ringing, in a similar manner to the discussion on this in Section 2.6 of [42].

HF output rectifiers that use SiC Schottky devices will probably not need snubbing at all – saving the cost of those components and also improving the thermal efficiency of the power converter.

Figure 6.2.1 shows various resistor-capacitor (RC) snubber designs for use with different types of HF output rectifier circuits. Synchronous rectifier technologies are not shown, but will generally need snubbing in a similar manner.

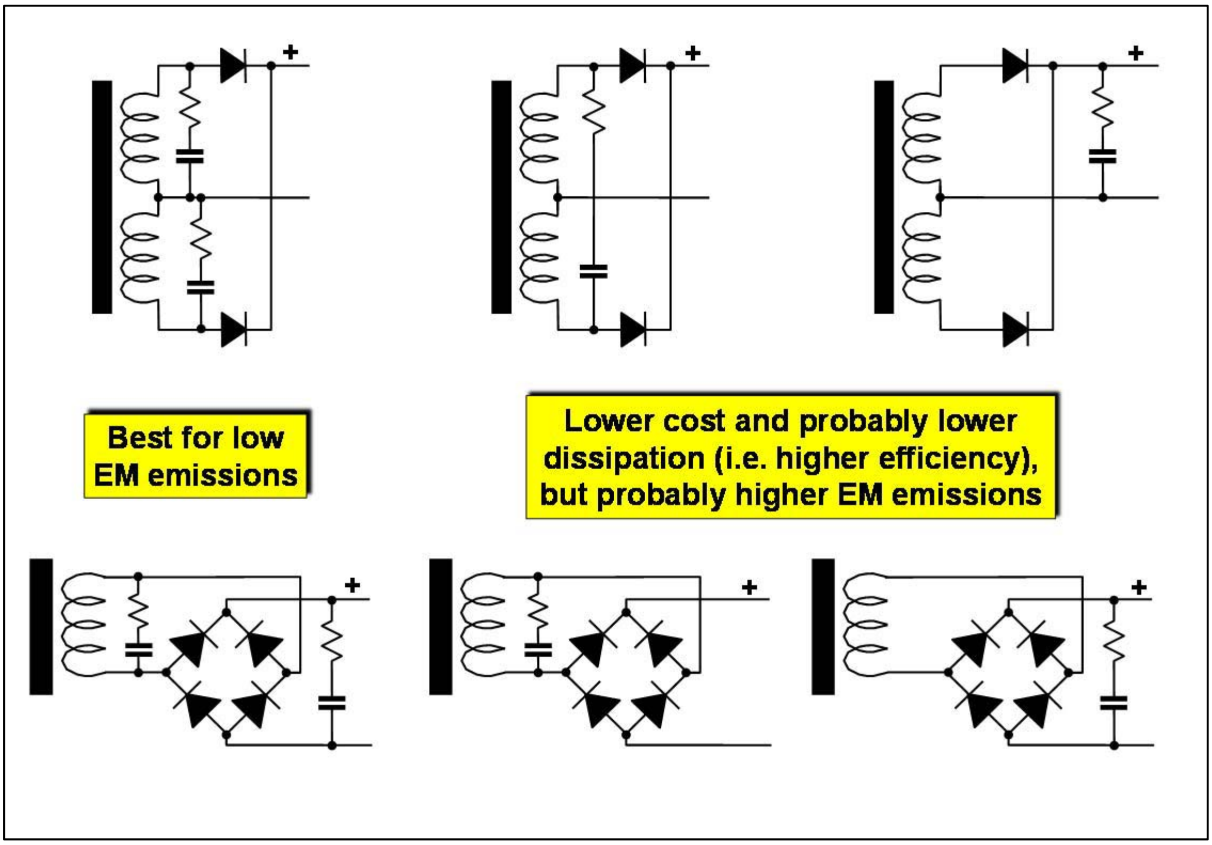

Figure 6.2-1 Snubber designs for different types of HF output rectifiers

If the circuits of Figure 6.2-1 don't work as well as hoped, it may be due to the circuit's strays or parasitic, and it could be worthwhile experimenting with other locations for snubbers to see if they work better, before redesigning the power converter's PCB layout to something that is better controlled (a subject that will be discussed in a later article).

Actual snubber performance at radio frequencies (RF) is limited by the types of components used, and by the way they are assembled and connected to the circuit they are snubbing.

Resistors suffer from heating and self-inductance problems, so we use low-inductance power resistors that are correctly rated for their peak and RMS voltages, peak and RMS currents, and peak and continuous RMS power dissipation in the highest ambient temperatures they will experience.

We generally avoid all wirewound types (even if their suppliers claim they have low-inductance), and for the best RF don't even use spirally-toleranced resistors, but prefer SMD chip resistors (not MELF, because they use spiral tolerancing) or large-area thick/thin film resistors printed on flat ceramic substrates.

I have seen metal-oxide film power resistors fail open-circuit due to RF energy at the point where they are cut spirally to bring their value within tolerance, so such types are best avoided for snubbers.

Capacitors suffer from self-inductance, self-resonance, and pulse handling capacity problems, and the best type of dielectric is ceramic, preferably the C0G or NP0 types. In plastic-dielectric capacitors Teflon® or polypropylene are the best types. For snubbers it is important that we only use capacitors with suitable dV/dt and dI/dt ratings, and good capacitor manufacturers will be able to provide appropriate tables to help us design reliable snubbers. Never assume that because components work well enough on a prototype, that they therefore be reliable in production.

An array of smaller capacitors in parallel generally works better at higher frequencies, and can cost less too.

Snubbers should be mounted directly to the terminals of the switching device concerned. Leads, traces, and wires all have inductance, so if using leaded components make sure their leads are short when they are assembled. For this reason, surface mounted parts are wonderful for snubbers.

When we have to use wires to connect a snubber to the circuit it is snubbing, we must always design so that we can use twisted pairs for the whole length of the cable (or at least as long a length as we can).

PCB traces used to connect snubber components to a circuit can have as much inductance as a wire, so we always take care to keep them as short and wide as is practical and route them at all times over a plane on an adjacent PCB layer plane that carries their return current. It may even help to use closer trace-plane spacing than we would normally.

Remember, $V = L\, dI/dt$, and any length of conductor – whether component lead, wire or PCB trace that is not in intimate proximity with the conductor carrying all of its return current – adds inductance at up to 1nH per millimetre of length. So, for example, if we had 10mm of such conductor carrying, say, 40A peak with a risetime of 20ns, the ability of our snubber components to control the overvoltages caused by circuit resonances would degrade by up to 20V.

Where snubbers would have to be too large or costly or dissipate too much power, using an appropriately-rated output inductor could be a big help, and this is discussed next.

6.3 *Output inductors*

An output inductor helps to smooth the output waveform and reduce emissions, and in this section we are only concerned with its use in reducing emissions caused by the HF output rectifier.

When the sized inductor has a large enough value its flux will never decrease to zero and the result will be that it will force half-sinewave (approximately) voltages to appear at the secondary winding that feeds the HF output rectifiers.

Half-sinewaves have much less harmonic content than the switching waveforms without any inductance, but the zero crossings of the half-sines are discontinuous and so will still generate some common-mode (CM) and differential-mode (DM) RF noise that can be emitted from the circuit.

However, using a *balanced* output inductor with a large enough value will force the AC voltages at the secondary winding that feeds the HF output rectifiers to become full sinusoids (approximately) at the switching frequency, with correspondingly low levels of harmonics, reducing output rectifier emissions much more as a result.

Figure 6.3-1 shows these two ways of using inductors in an HF output rectifier, with sketches of the corresponding waveforms at the AC input of the diode bridge assuming sufficiently large values of inductance. The inductance must be large enough that the flux does not go to zero even on the lowest value of load current, and it must not saturate even with the highest value of load current, even when the inductor is running at its highest temperature.

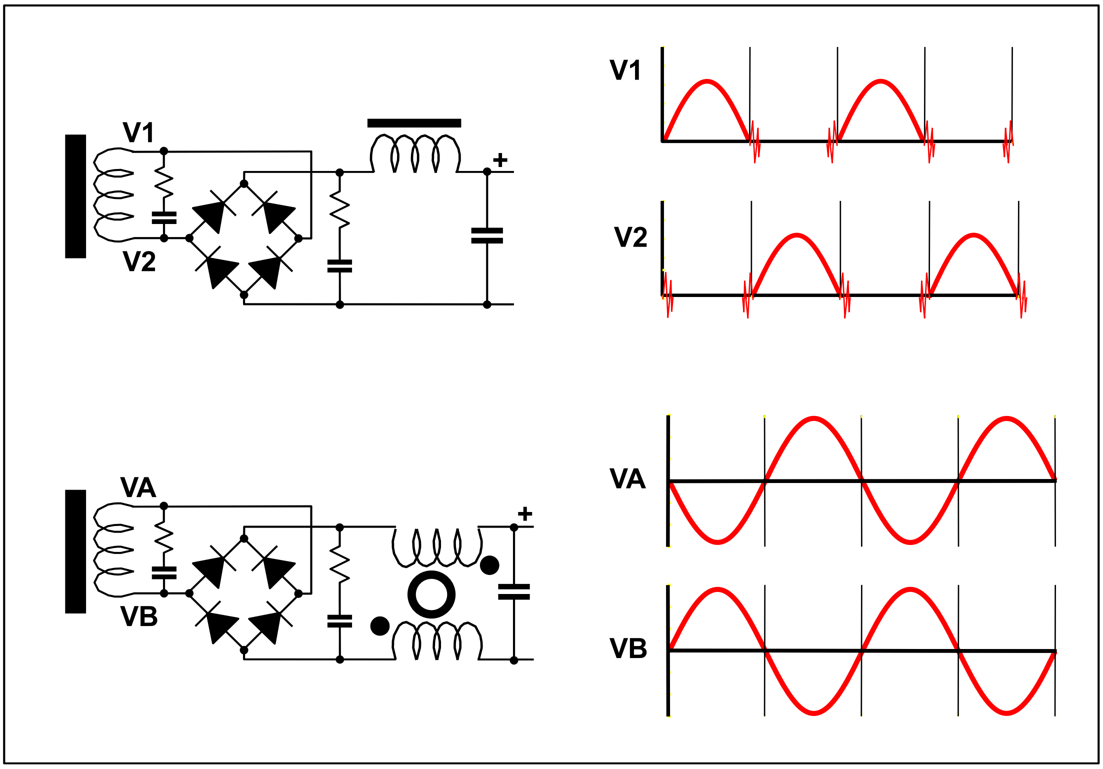

Figure 6.3-1 Examples of the use of unbalanced and balanced output inductors

Notice the directions of the windings on the balanced inductor design – the two inductor windings can be combined on a single magnetic core as a differential-mode choke to reduce PCB area and BOM cost. (It is not a common-mode choke.)

Unlike the isolating transformer, the magnetic flux in an adequately-dimensioned HF output inductor never goes to zero, so its magnetic core will need an airgap, the subject of the next section.

Obviously, output inductors are not small or low-cost, but their use might help solve problems that cannot be cost-effectively dealt with by other methods, and they also help provide a much less noisy unregulated DC output voltage.

6.4 Inductor core shapes

Inductors that need energy storage, such as the HF output inductor discussed above, traditionally store it in the air using gapped rod- or bobbin-style cores, but for low magnetic (H) field emissions they should ideally use closed magnetic circuits.

Unfortunately, magnetic energy cannot be stored in a high-permeability material, so for good EMI we need to use inductors with core types that have much less stray (leakage) flux when measured at a distance:

a) Toroids using iron powder (or similar materials) in a resin binder, which store their energy in the microscopic gaps distributed throughout their bodies.

b) E-cores or pot cores with air gaps in their central limbs, completely surrounded by their windings.

   The stray flux from gapped cores can be further reduced by creating an *external* shorted turn by wrapping a substantial copper tape around the whole transformer and soldering its ends together.

   The direction of wrapping the tape is important, so if adding the shorted-turn makes no difference, try it again with the direction of wrapping rotated by 90 degrees.

   Because ferrite cores are resistive, and so could radiate electric fields as a result of stray capacitance coupling to the dV/dt of the windings, emissions might be reduced further by connecting this tape to the output circuit's 0V reference.

c) Any type of core fitted with a suitable magnetic shield.

   Instead of a shorted *external* turn of copper tape, as much (or better) reduction of EMI can be achieved by fitting a shielding can over an output inductor or isolating transformer, bonded on all four sides to a continuous 0V reference plane underneath.

   Some suppliers offer shielded inductors for power converters, but some use ferrite instead of metal – which means that additional work might be required to reduce their electric-field emissions.

Figure 6.4-1 shows our example power converter's PCB assembly (see Figures 3B, 3C and 3D in [64]) fitted with a toroidal iron-powder output inductor, and an E-core isolating transformer with an air gap in the middle of its central limb

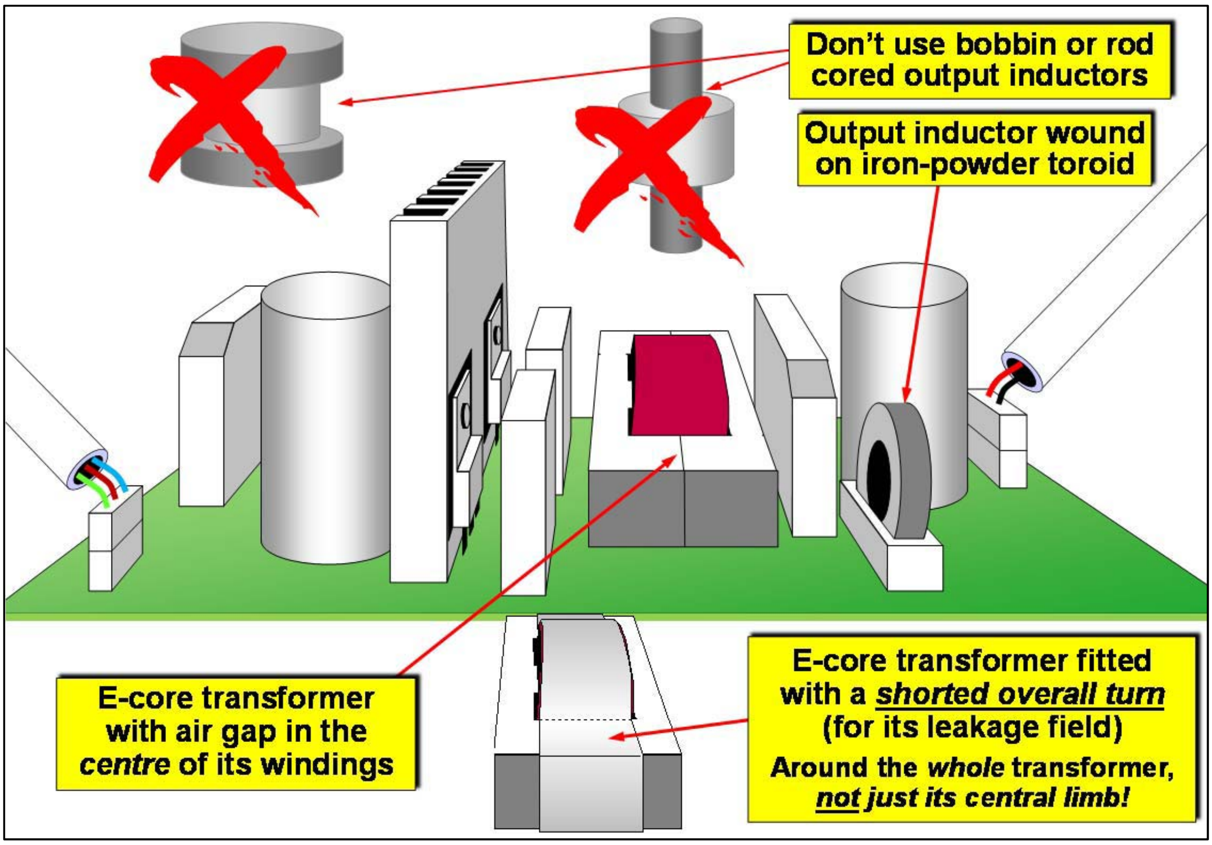

Figure 6.4-1 Example PCB assembly using E-core transformer with central air-gap, plus an added output inductor

That's it for this issue of the EMC Journal.

The next topic in this "stand-alone" series will deal with filtering the inputs and outputs.

References (only for this article)

[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

[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

[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

[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