EMI Comparison of Hard Switched, Edge-Resonant, and Load Resonant DC/DC Converters Using a Common Power Stage

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Abstract: This paper compares conducted EMI of hard switched, edge-resonant, and series resonant power converters. All of the DC/DC converters use a common power stage, output filter, transformer, and gate drive electronics, with minimal modifications to support the different topologies and control approaches. The edge-resonant converter has the lowest conducted EMI emissions at light load conditions, and the lowest differential mode EMI for heavy load conditions. The paper also discusses the importance of maintaining balance and symmetry when decoupling the common mode and differential mode noise components from the LISN voltages.

I. INTRODUCTION

This paper provides a comparison of conducted EMI between hard switched and soft switched DC/DC power converters. The same converter power stage, transformer, and output stage are used for all approaches, providing a common platform for measuring EMI differences due to hard switching or soft switching. Using the same power stage layout ensures that each approach has the same parasitic circuit elements. Measured EMI differences are due to circuit operation and topology. Several approaches are compared: hard switched, edge-resonant [1,2] (or zero voltage transition), and series resonant [3]. All of the topologies use the same basic full bridge converter power stage, shown in Fig. 1. The common power stage has minimal modifications to support the different topologies, for example a hard switched implementation has a short circuit between the terminals, as shown in Fig 1. An edge-resonant converter has an inductor between the terminals. A series resonant circuit has a series inductor-capacitor combination between the terminals, and the output filter inductor is removed.

All of the topologies are operated with the same input voltage, output voltage, and two load conditions: light load (10%) and full load. The switching frequency of the hard switched and edge-resonant topology is maintained at 250 kHz. The series resonant converter operates at 250 kHz for full load. At light load the series resonant converter operates with two control approaches: 900 kHz full square wave, and 250 kHz with phase shift control.

The control board for each of the different topologies uses the preferred control approach. The hard switched implementation uses duty cycle control. The edge-resonant converter uses phase shift control. The series resonant converter operates above resonance, using frequency control (at heavy load), and frequency/phase control (at light load).

Conducted EMI is measured across the 50 Ω resistors in the line impedance stabilization network (LISN). The measured conducted EMI frequency range is 0.1 to 50 MHz. A differential mode (DM), common mode (CM) noise isolator [4,5] is used for all of the conducted EMI measurements. This separates the DM and CM noise components from the LISN voltages.

II. MODULAR CONVERTER CIRCUIT

A common power stage provides a comparison framework for hard switched, edge-resonant, and series resonant power converters. The EMI spectrum for each of the topologies was measured using a conducted EMI test setup, which includes the DC/DC converter, input power, LISN, DM/CM isolator, and spectrum analyzer (HP 8546A). All of the topologies operate with an input voltage of 270 VDC, and an output of 10 VDC. Results are measured for 5 A (light load) and 50 A (full load) conditions. The spectrum analyzer is set to "peak" mode, to provide a worst case measurement. The spectrum analyzer used settings of 9 kHz for the resolution bandwidth (RBW) and video bandwidth (VBW). A DM/CM isolator separates the differential mode and common mode conducted EMI, this isolated DM (or CM) signal goes to the spectrum analyzer.

The DM current is defined to be current flowing through one of the 270 VDC input power wires, and returning through the other. The CM current is common to both 270 VDC power wires, and returns by the ground wire. The ground wire is

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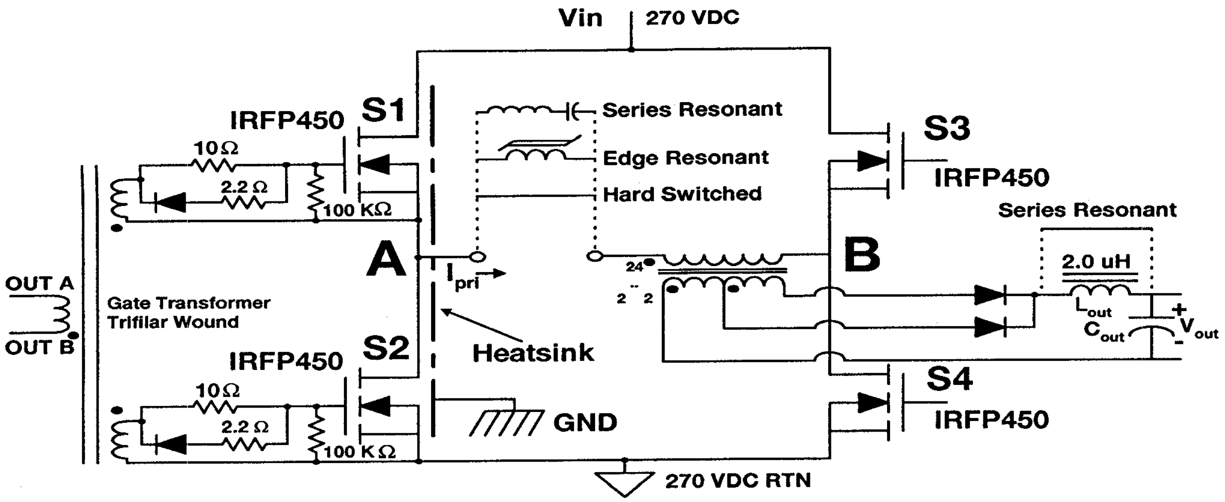


Figure 1 : Common Converter Power Stage Used for EMI Comparison

connected to the heatsink. The MOSFETs, transformer, output rectifiers, and output inductor are mounted on the heatsink.

The power converter consists of a modular power stage, with a replaceable control board, as shown in Fig. 2. The same full bridge power stage, output filter, transformer, and gate drive electronics are used for all approaches. This allows a direct comparison of the different topologies, with identical electrical circuit parasitics and layout. The only power stage modification between the different approaches is the replaceable resonant components in series with the transformer primary, and the presence or absence of the output inductor, as shown in Fig. 1. The series resonant components used are 36 uH and .018 uF. This gives a resonant frequency of 200 kHz. Using this resonant tank, the series resonant converter operates at 250 kHz, full square wave at an output of 10 V, 50 A, allowing a direct comparison with the other approaches.

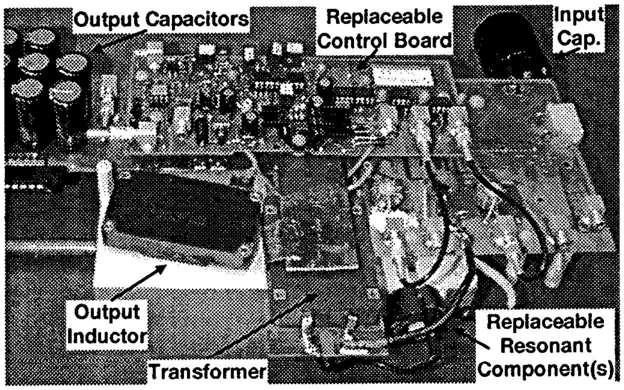


Figure 2 : Photograph of Modular Power Converter

The hard switched topology operates at a constant 250 kHz switching frequency, with controllable on time μ, as shown in Fig. 3. The edge-resonant approach operates at 250 kHz, with regulation occurring due to the phase shift (ϕ) between the bridge legs, depicted in Fig. 4. The edge-resonant approach operates in a zero voltage switching (ZVS) condition, with the 25 uH series saturable inductor, and transformer magnetizing inductance (140 uH) storing the necessary reactive energy for ZVS from no load to full load [6]. The series resonant converter operates at 250 kHz, full square wave at 50 A (i.e. $\phi = 0$ in Fig. 4). There are two operating conditions for the series resonant converter at 5 A, full square wave 900 kHz, and 250 kHz with phase shift (i.e. $\phi \neq 0$ in Fig. 4).

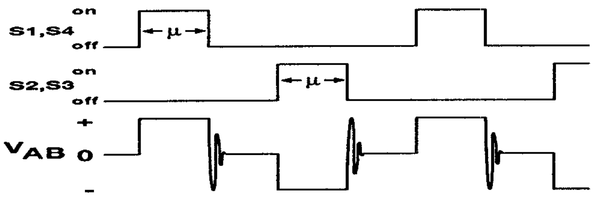


Figure 3 : Hard Switched Gate Drive and Bridge Voltages

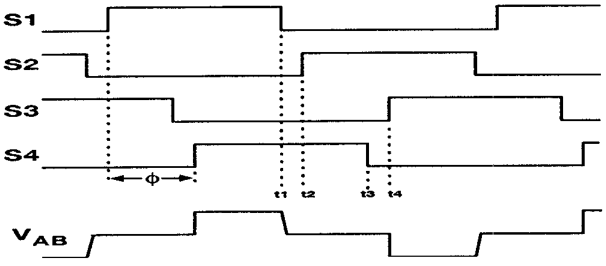


Figure 4 : Edge-Resonant and Series Resonant Gate Drive and Bridge Voltages

III. EMI MEASUREMENT RESULTS

Figure 5 displays the time domain bridge voltage (V_{AB}) and current (I_{PRI}) for each of the approaches at light load (5 A). The bridge voltage for the hard switched condition has a fast rising edge, as seen by the pronounced ringing during the transitions. The edge-resonant converter has well controlled switching transitions, with rise and fall times of approximately 150 ns. The series resonant phase shift approach displays a loss of ZVS operation, as shown by the fast transitions. For the series resonant approach using full square wave (900 kHz) control, all the edge transitions are soft switched.

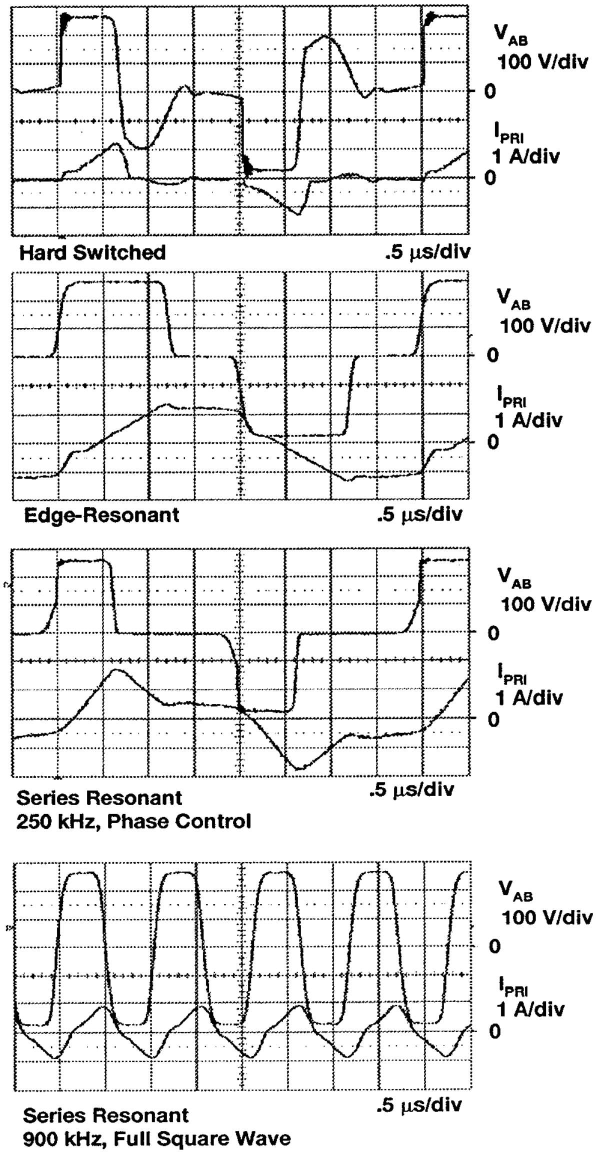


Figure 5 : 50 Watt Bridge Waveforms

The high frequency EMI spectrum, is dominated by the rise and fall times of the bridge voltage (V_{AB}). Slower edges correspond to reduced high frequency emissions. The relationship between the rise and fall times of a trapezoidal waveform and its high frequency spectrum is illustrated in Fig. 6. If the rise and fall times are very fast, the spectral envelope rolls off at a maximum rate of 20 dB/decade. The slow edges allow the envelope to fall at a 40 dB/decade rate, starting at a frequency of $1/(\pi t_r)$, where t_r is the rise and fall times [7].

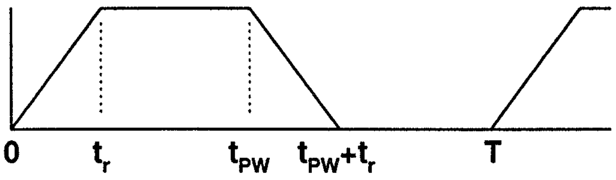


Figure 6a : Trapezoidal Waveform

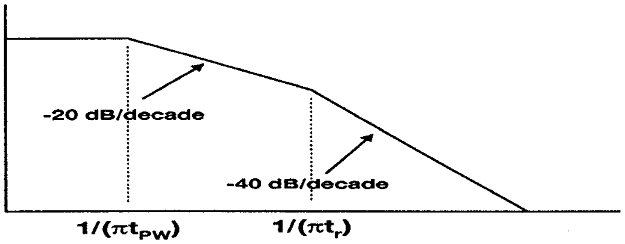
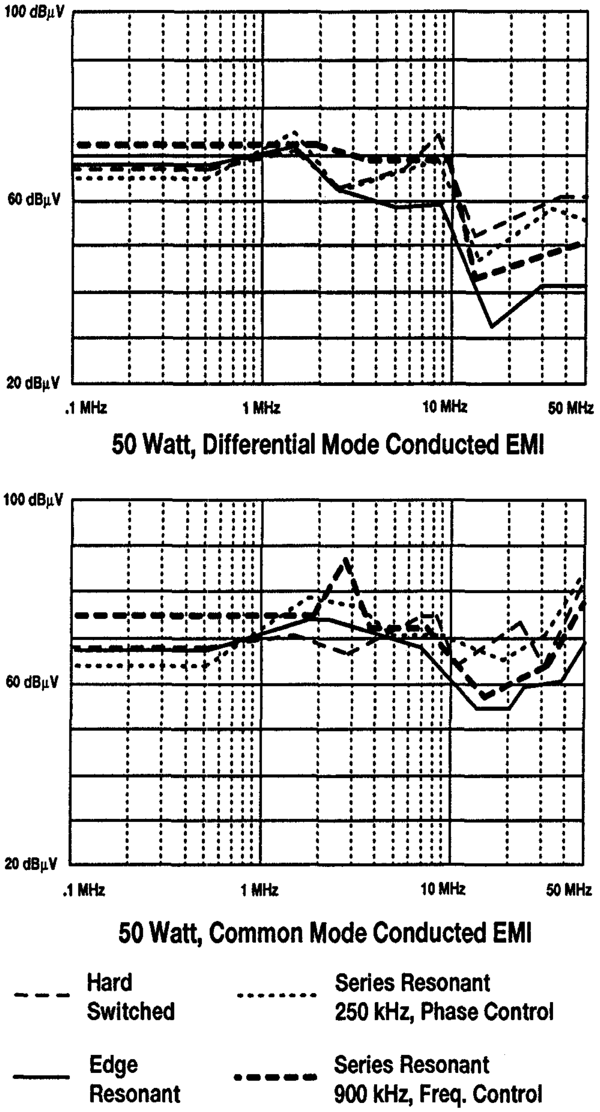


Figure 6b : Spectral Envelope of Trapezoidal Waveform

For easy visual comparison, Figs. 7 and 8 overlay the EMI envelopes for each of the converter topologies at light (5 A) and heavy (50 A) load conditions. These are the spectral envelopes from Figs. 11 and 12, shown at the end of the paper. Figure 11 shows the measured conducted DM and CM noise for each of the converter topologies operating at the light (5 A) load condition. The full (50 A) load EMI measurements are displayed in Fig. 12. Envelopes for each of the EMI measurements are superimposed upon each of the plots of Figs. 11 and 12. It is somewhat subjective to draw the exact shape of the EMI envelopes. The envelopes do not conform directly to the 250 kHz component, since it is consistently much smaller than the 500 kHz harmonic.

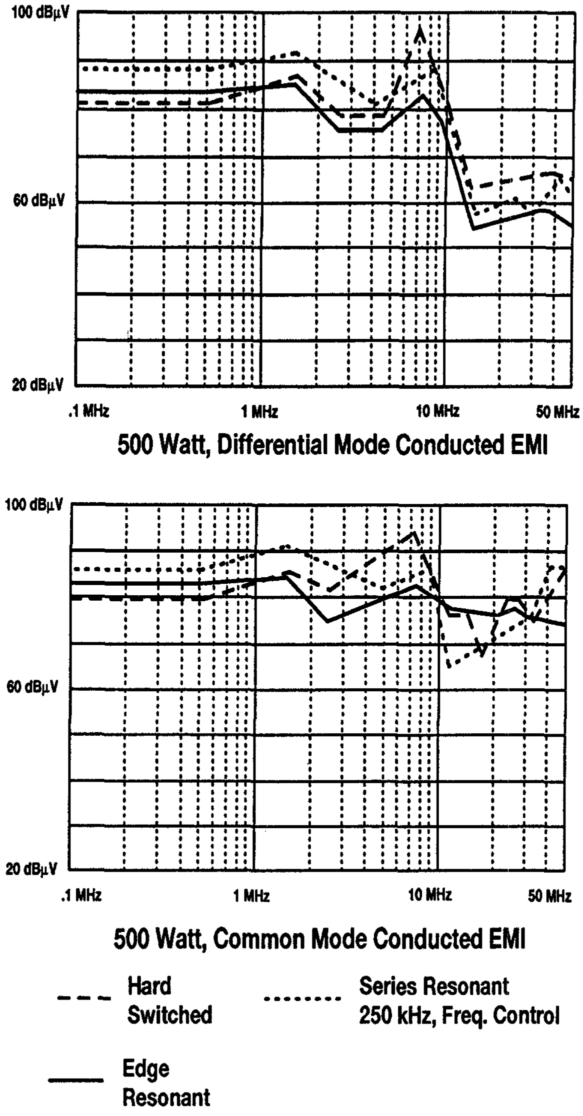
At the light load condition, a major difference between the hard switched and edge-resonant approaches is the bridge voltage (V_{AB}) transition times. The edge-resonant rise and fall times, of 150 ns (about 2 MHz), agree with the approximate divergence of the spectral envelopes. Starting at 2 MHz, the two spectra begin to diverge at approximately a 20 dB/decade



50 Watt, Differential Mode Conducted EMI

50 Watt, Common Mode Conducted EMI

Figure 7 : 50 Watt Converter EMI Envelopes



500 Watt, Differential Mode Conducted EMI

500 Watt, Common Mode Conducted EMI

Figure 8 : 500 Watt Converter EMI Envelopes

rate, in good agreement with the expected result due to their rise and fall times. This result is more pronounced for the DM noise. The series resonant, phase shift control approach, loses soft switching and its DM and CM EMI spectra tend to fall between the hard switched and edge-resonant results.

At heavy load, the edge-resonant converter has faster rise and fall times than for light load. While the edge-resonant approach has lower DM noise than hard switched or series resonant, it is not as substantial an improvement as at light load. Above 10 MHz the edge-resonant DM emissions tend to be approximately 10 dB lower than the hard switched emissions. The series resonant converter tends to be slightly worse for its low frequency DM spectra, this could be due to the larger RMS primary currents. At higher frequencies, the EMI content of the series resonant approach is between the hard switched and edge-resonant spectral envelopes.

There are additional sources of EMI noise in the converters. The output rectifier diodes contribute significantly to common mode EMI. Additionally, there are topological differences between these approaches. The hard switched and edge-resonant approach are voltage fed (to the transformer secondary), while the series resonant converter is current fed. The output rectifier current for the series resonant approach is nearly sinusoidal. This limits the output rectifier dv/dt, leading to reduced common mode EMI at high frequencies (>10 MHz).

IV. TEST SETUP MEASUREMENT PRECAUTIONS

The test setup for conducted EMI measurements is shown in Fig. 9. The outputs of the LISN, when expressed by their constituent CM and DM components are:

$$\begin{aligned} V_{L,LISN} &= V_{CM} + V_{DM} \qquad (1) \\ V_{N,LISN} &= V_{CM} - V_{DM} \end{aligned}$$

where V_{CM} is due to common mode currents, and V_{DM} is due to differential mode currents [4].

The DM/CM isolator box generates a sum and difference of the LISN output voltages, to separate the common mode signal from the differential mode signal. This can be expressed as:

$$\begin{aligned} V_{CM} &= (V_{L,LISN} + V_{N,LISN})/2 \qquad (2) \\ V_{DM} &= (V_{L,LISN} - V_{N,LISN})/2 \end{aligned}$$

The DM/CM isolator is constructed using high quality, wideband RF transformers to appropriately add or subtract the LISN output voltages. The DM/CM isolator box connects to the LISN using two coaxial cables. The output of the isolator box provides a DM or CM signal to the input of the spectrum analyzer.

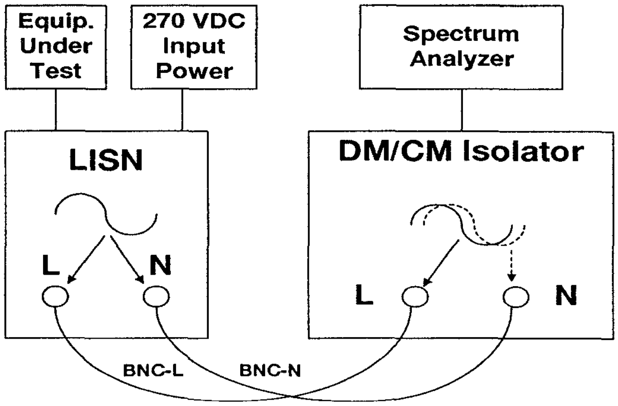


Figure 9 : Noise Separator Setup

It is extremely important to maintain electrical balance and symmetry for noise isolation when using a DM/CM isolator. Minimal imbalances can provide an unexpectedly rapid degradation in measurement capability. Any imbalances due to asymmetry in construction of the DM/CM isolator, LISN wiring, or coaxial interconnecting cables degrades the ability of the isolator to accurately determine the magnitude of a small component of noise (either DM or CM) when the other component is dominant.

As an example, consider a conducted EMI measurement where one of its frequencies consists exclusively of a CM component (no DM component). The LISN outputs, due to this CM component, are identical in magnitude and phase:

$$V_{L,LISN} = V_{N,LISN} = Z\sin(wt - \psi) \qquad (3)$$

where ψ is the phase angle, and Z is the magnitude. The sinusoidal waveform on the LISN of Fig. 9 denotes that the signal at both the line (L) and neutral (N) outputs are exactly the same magnitude, and in phase.

If the coaxial connecting cables (BNC-L, BNC-N) are not perfectly balanced, there is a phase shift at the inputs to the DM/CM isolator box, given by the following equation.

$$\begin{aligned} V_L &= Z\sin(wt) \qquad (4) \\ V_N &= Z\sin(wt - \zeta) \end{aligned}$$

where ζ is the phase difference which may be due to cable length mismatch, different cable phase velocities, etc.

Even though there is no DM signal present at the LISN, the phase shift at the DM/CM isolator input creates an artifact DM component. The resultant artifact DM signal, as generated by a perfect DM/CM isolator box, is:

$$V_L - V_N = 2Z\sin(\zeta/2)\cos(wt - \zeta/2) \qquad (5)$$

Figure 10 illustrates the DM/CM isolator inputs of V_L and V_N, and its output signal V_L-V_N.

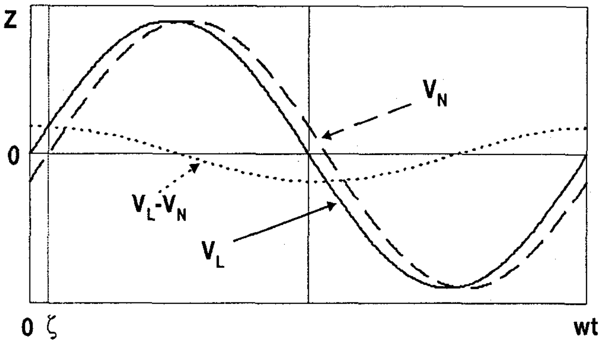


Figure 10 : DM/CM Isolator signals, illustrating response due to phase shift, ζ

For instance, assume that the LISN and DM/CM isolator are perfectly balanced. There is a common mode signal of amplitude Z, and no differential mode signal. The coaxial cables (BNC-L, BNC-N) are mismatched by 1 inch. The phase velocity of the coaxial cables is 2/3 the speed of light. At 30 MHz, this would correspond to a phase shift of 1.4 degrees. Even though there is no differential mode signal present at the LISN outputs, this coaxial cable 1 inch mismatch creates a DM signal artifact with a magnitude of 38 dB lower than the real CM signal. Thus this small cable length mismatch limits the DM/CM isolation capability to only 38 dB.

The DM/CM isolator generated common mode signal for this example would be affected very little. The 1.4 degree phase shift degrades the common mode amplitude by less than .01 dB from the correct value.

The same procedure applies for a dominant DM signal generating an artifact CM signal due to a coaxial cable length mismatch, or other asymmetries.

V. CONCLUSIONS

This paper provides a comparison of conducted EMI for three widely used DC/DC converter topologies: hard switched, edge-resonant (ZVS), and series resonant (ZVS). A common power stage is used for all of the approaches. The differences in the EMI emissions are due to topological and control characteristics. All testing is performed at the same input and output voltage conditions, for light (50 W) and heavy (500 W) load. In general, the edge-resonant approach has the lowest high frequency emissions.

It is important to maintain symmetry and balance when using an EMI setup to separate the DM and CM signals from the LISN voltages. For instance a 1 inch mismatch in coaxial cable length limits the setup to a maximum rejection capability of 38 dB at 30 MHz.

References:

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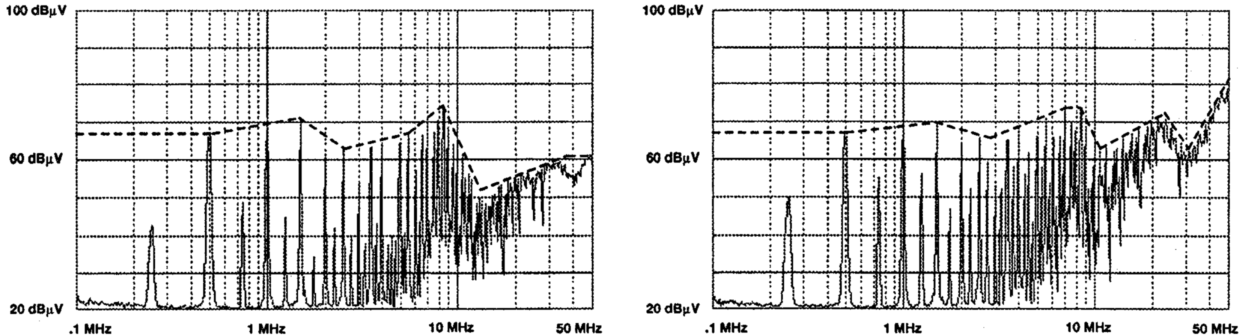
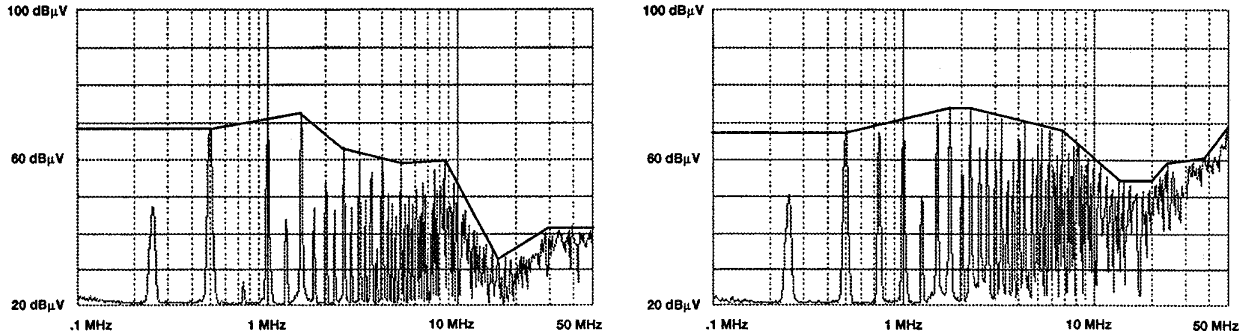


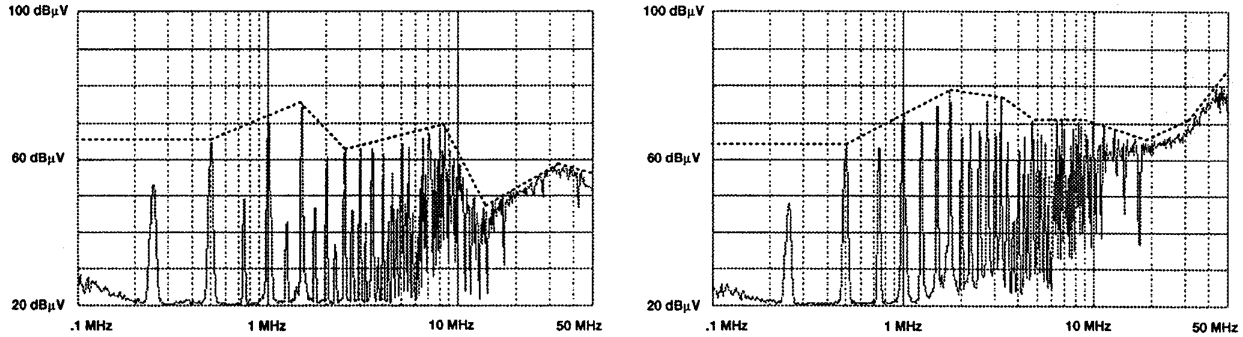
Hard Switched, Differential Mode, 50 Watts

Hard Switched, Common Mode, 50 Watts



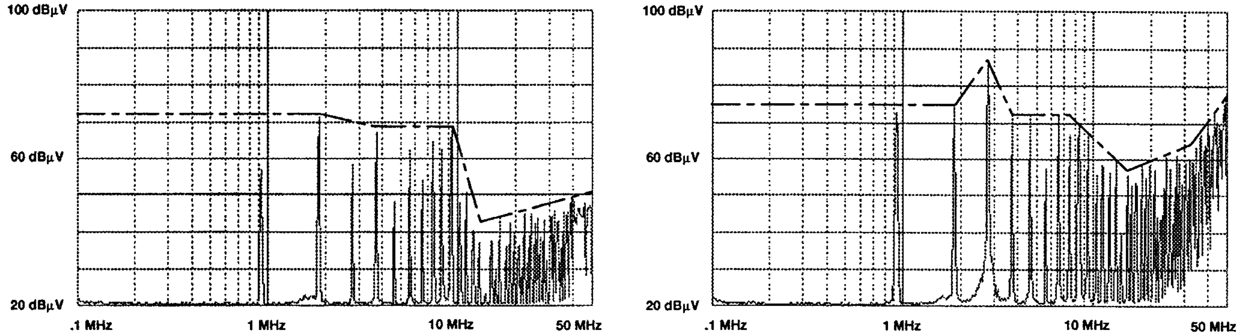
Edge-Resonant, Differential Mode, 50 Watts

Edge-Resonant, Common Mode, 50 Watts



Series Resonant, Differential Mode, 50 Watts
Phase Control, 250 kHz

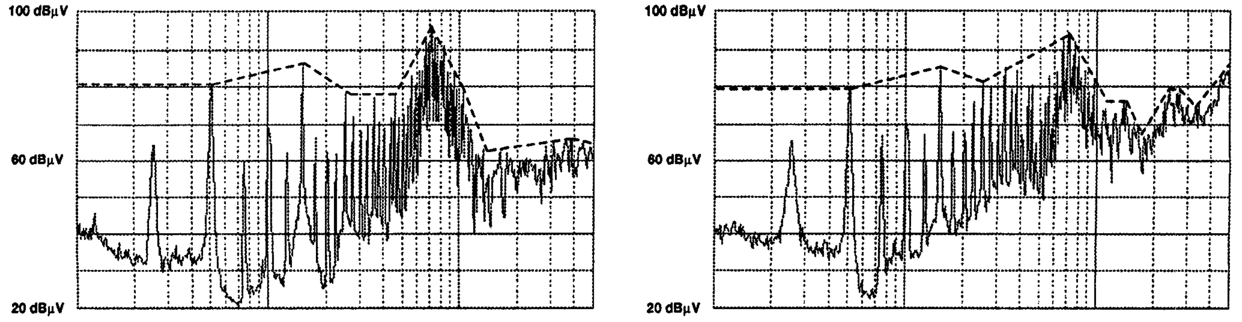
Series Resonant, Common Mode, 50 Watts
Phase Control, 250 kHz



Series Resonant, Differential Mode, 50 W
Frequency Control, 900 kHz

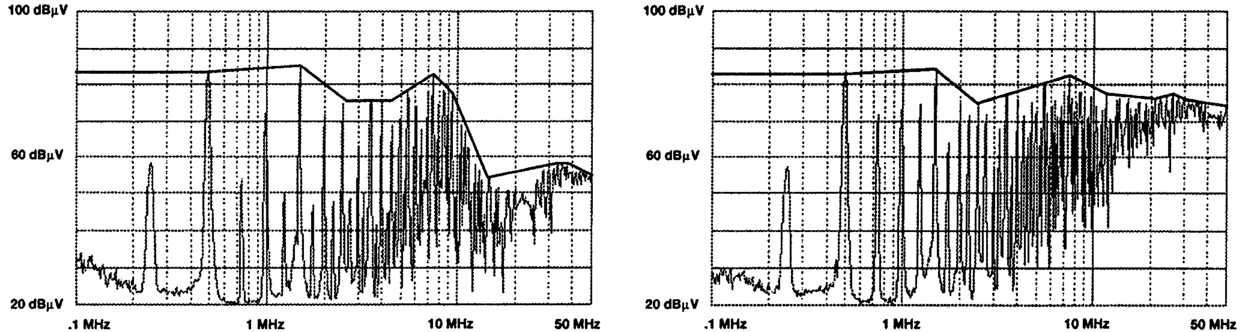
Series Resonant, Common Mode, 50 W
Frequency Control, 900 kHz

Figure 11 : EMI Comparison for a 50 Watt Load



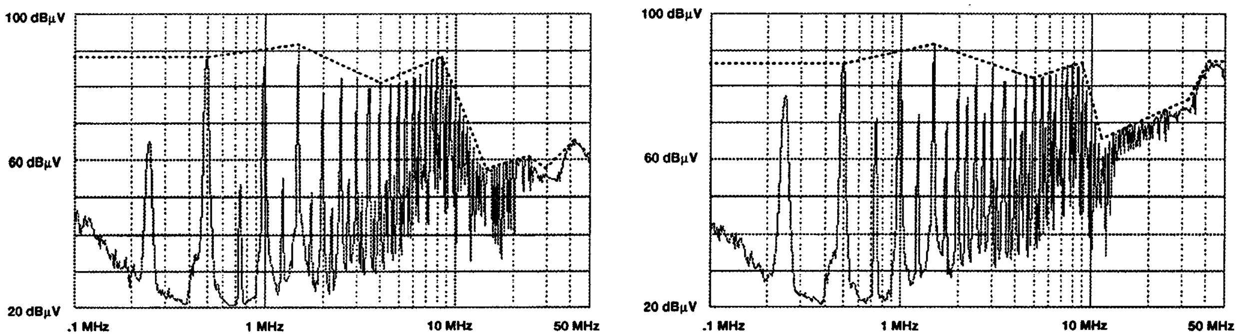
Hard Switched, Differential Mode, 500 Watts

Hard Switched, Common Mode, 500 Watts



Edge-Resonant, Differential Mode, 500 Watts

Edge-Resonant, Common Mode, 500 Watts



Series Resonant, Differential Mode, 500 Watts

Series Resonant, Common Mode, 500 Watts

Figure 12 : EMI Comparison for a 500 Watt Load