Technical Article

Simulating the Conducted EMI of Switching Power Converters

October 14, 2016 by Mike Walters

This article describes a method for simulating conducted EMI in switching power converters highlighting LISN model development and EMI signature extraction.

Simulation of electromagnetic interference (EMI) eliminates the ‘black magic’ of EMI design, enables increased power density with filter optimization, and reduces the risk of product delays. This article shares a methodology for model development and simulation of common mode and differential mode conducted EMI. An example simulation of a 1MHz switching power converter illustrates model development and compares the results with measurements.

All power converter products must meet EMI certification before release to production. EMI verification is typically one of the last product certification tests due in part to the high cost of an EMI certification lab and the need to evaluate the production version. Failing EMI compliance delays product introduction. One way to avoid an introduction delay is to overdesign the EMI filter to insure EMI compliance. However, this option increases the size of the filter, which lowers the converter's power density. An optimized filter maximizes the power density, and EMI simulation helps reduce the risk of product delay.

EMI Filter

The EMI filter is only one piece of the high-density power converter puzzle. Recent promotion of wide-bandgap power devices, including SiC and GaN, promise increased power density with higher switching frequencies. However, when the switching frequency is within the conducted EMI frequency band, the size of the EMI filter is often larger than expected [1]. The faster switching edges of the wide-bandgap semiconductors generate a rich spectrum of high-frequency noise requiring use of unfamiliar EMI components. Design engineers must comprehend each component's details on EMI performance to take advantage of higher switching frequencies.

Compounding the issue, an EMI filter may not be effective at the high switching frequencies due to the parasitic characteristics of the components. The impedance characteristics of the components change across the frequency band required for EMI certification. At the upper frequencies, inductors tend to behave as capacitors and capacitors tend to behave as inductors. It is not surprising that design engineers refer to EMI design as 'black magic'.

Optimization of the EMI filter

Optimization of the EMI filter increases the risk of delay for product introduction. Consider the traditional trial-and-error development process where the design engineer methodically evaluates the first prototype and insures the product meets the efficiency and thermal goals before evaluating EMI at a certified lab. If the product fails to meet the EMI limits, the engineer modifies the power converter and reevaluates the efficiency and thermal properties before scheduling another test secession at the EMI facility. The development cycle, including design, fabrication, and evaluation, repeats until the product meets the EMI limits. Each iteration adds development cost and delays the product's introduction.

This article advocates using a simulation model to optimize and evaluate the EMI filter during the design phase of the power converter's development. A simulation model helps the designer understand the conducted noise sources and coupling and can help quantify limits for each of the filter's parameters. Design iterations with simulation are much faster and less expensive than trial-and-error hardware iterations. Simulation helps the designer quickly evaluate their filter optimization ideas and reduces the risk of product delay.

The next section briefly describes the noise sources in switching power converters and the EMI standards for conductive emissions. This section also describes a generic simulation model that adds elements of the test setup given in the standards. The article further describes the method to extract the EMI signature. An example illustrates the construction of a simulation model for an active clamp flyback converter operating at 1MHz and compares the simulation results with published results. The final sections describe the method to estimate some of the missing model parameters and offers concluding remarks.

EMI noise sources and standards

Conducted EMI of switching power converters contain both common-mode (CM) and differential-mode (DM) components as illustrated in Figure 1. The high slew rate of the switching node generates CM noise in a switching power converter and couples the noise through the transformer's inter-winding capacitance, Cps to earth ground. The impedance from the power return to earth ground completes the CM noise path. The input current of a switching converter is the DM noise source. DM noise current flows in both power leads.

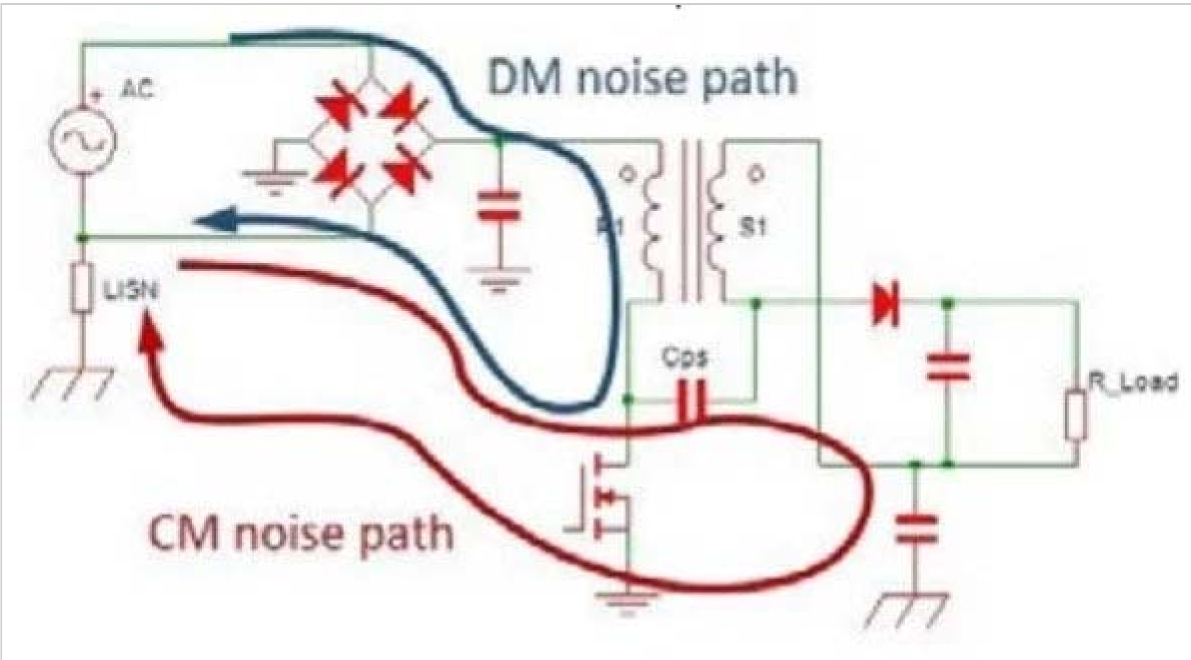

Figure 1: Conducted noise paths

International communities have established EMI limits and testing standards. In the US, the FCC specifies limits for conducted emissions over the frequency range from 450 kHz to 30 MHz. In Europe, the International Special Committee on Radio Interference (CISPR) specifies limits for conducted emissions over the frequency range from 150 kHz to 30 MHz. Engineers design the EMI filter to attenuate the converter's switching noise to below the limits of the frequency band specified by the standards.

The conductive EMI testing standards specify a test set up that includes a line impedance stabilization network (LISN) between the input source and the power converter to isolate the noise of the power converter. Figure 2 shows the LISN schematic added to a generic switching converter. The standards specify a LISN with 50µH inductors in series with both the power and return lines. The 0.1µF capacitors couples the noise to the EMI receiver reference to earth ground. The 50Ω resistors model the input impedance of the EMI receiver.

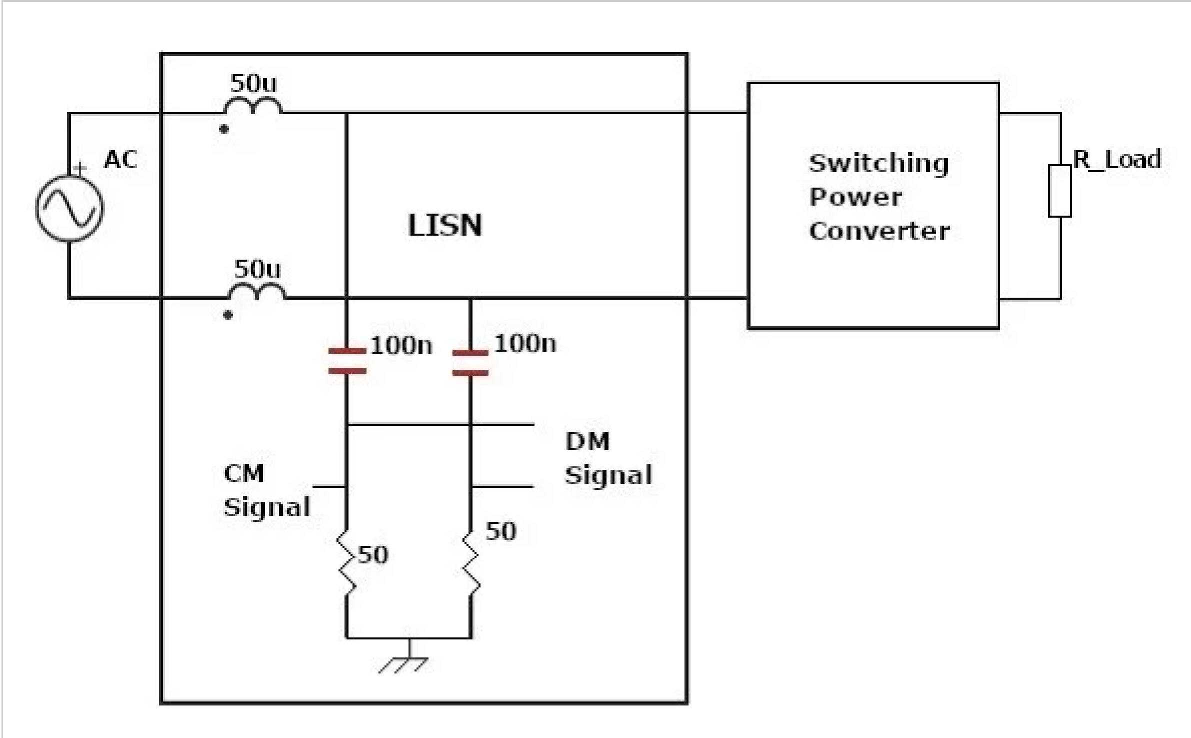

Figure 2: Conducted EMI testing with a LISN

Model and simulation approach

The EMI receiver measures the noise by sweeping an intermediate frequency (IF) filter over the specified frequency band and captures the noise amplitude with a quasi-peak detector [2]. The IF filter is a band-pass filter with a 9 kHz bandwidth at -6dB. Conceptually, a quasi-peak detector works like a peak detector followed by a lossy integrator, where the integration charge time constant is 1ms and the discharge time constant is 160ms. Quasi-peak detector readings are always less than or equal to the peak detection.

An EMI simulation runs a transient analysis of the power converter and collects time-domain data. After the simulation run, Fourier methods transform the time domain data into frequency domain components. The Fourier data reports the peaks at each frequency. Rather than add complexity of a quasi-peak detector model to the simulation, you can choose to scale the peak frequency data to the RMS value [3].

Simulating EMI in a switching power converter can be challenging. Large data files result from simulating the switching converter over several AC line cycles while resolving the edges of the switching waveforms. Furthermore, a simulation schematic rich in parasitic elements and the desire to monitor numerous signals both increase the size of the data collected. Nyquist criteria requires time-domain data resolved to at least 16ns to transform the data to 30MHz. However, an even smaller time increment maybe need to preserve the fidelity of the switching edges. Nanosecond resolution for each waveform over tens of milliseconds of line input leads to large data files and can challenge the simulator's memory limitations and slow down the simulation time.

How do you decide which parameters of the switching converter to include in the model? Which parasitic elements do you place in your model? Do you use the manufacture's models for their semiconductors? You will need to use your engineering judgment to answer these questions.

Be careful using a supplier's model for their semiconductors. Manufacturers rarely state the limitations, validation criteria, or purpose of the model. This places the burden of understanding the model on the user. The design engineer can examine the Spice deck of the model and decipher the cryptic code or run a set of test simulations to assess the model's performance. I find both of these efforts tedious and usually end up building my own model. Below I describe the switch model development for a soft-switching converter.

EMI simulation example

The following example uses the SIMPLIS simulation tool to evaluate EMI. SIMPLIS is specifically developed for switching power converters and uses piecewise linear (PWL) modeling and simulation techniques [4]. SIMPLIS is much faster than SPICE for switching converter simulations and does not suffer with convergence issues. SIMPLIS data points are not equally spaced in time due to the PWL techniques. However, discrete Fourier analysis requires equally spaced time-domain data points. SIMPLIS provides the spectrum function to simplify frequency content extraction from the time domain data. The spectrum function first interpolates the data to equally spaced data in time, then performs a discrete Fourier analysis with the Hanning window function, and returns the magnitude of the frequency components. The result is both fast and accurate.

As an example, let us consider the EMI characteristics of an off-line active clamp flyback converter. CPES (Center for Power Electronics Systems) published the EMI results of their investigation into the development of a 65W active clamp flyback converter with a switching frequency of 1 MHz [5]. Their investigation showed the addition of a shield winding to the main transformer reduces both the CM and DM noise. Another CPES publication details a single-stage EMI filter design used to meet the EMI standards [6]. Figure 3 shows the schematic of the active clamp flyback converter and EMI filter.

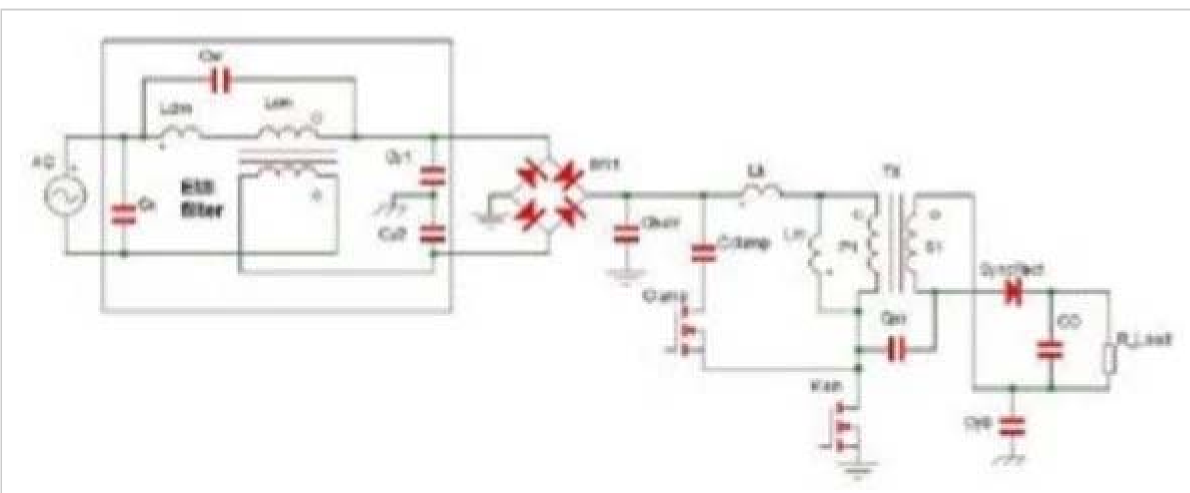

Figure 3: Off-line active clamp flyback converter with EMI filter

Figure 3 also shows several parasitic components. In addition to the primary and secondary windings, the main transformer includes the magnetizing inductance Lm, the leakage inductance Lk, and the primary to secondary capacitance, Cps. The single magnetic component of the EMI filter includes the common mode inductance, Lcm, the differential mode inductance, Ldm, and winding capacitance, Cw.

The goal of this simulation example is to reproduce the findings of the CPES researchers with a simple simulation model. The active clamp flyback converter operates with zero voltage switching. This simplifies the model of the MOSFETs and synchronous rectifier as explained below. The simulation uses CPES component values were disclosed and reasonable estimates for the remaining components. Table 1 lists the component values disclosed in the CPES publications.

Component	Value	Notes
Cclamp	100nF	
Turns ratio	P1:S1 = 10:2	
R_{DS}(on)	0.29	transphorm TPH3202LS
Co(er)	36pF	transphorm TPH3202LS
Cbulk	94uF	Rubycon BXW 2x 47uF
Cx	130nF	muRata GA3 2x 56pF
Lcm	1.4mH	
Ldm	30uH	
Cw	15pF	
Cy1 = Cy2	1nF	

Table 1: CPES active clamp flyback components

Figure 4 shows the resulting simulation schematic. The earth ground (green wire) is the Earth port connection in the schematic. Ideal voltage-controlled voltage-sources with unity gain (E1 and E2) monitor the CM and DM mode noise. The bridge rectifier, BR includes nonlinear junction capacitance. An ideal diode models the synchronous rectifier. The simulation operates open loop to help manage data file size by eliminating the large time constant associated with a feedback loop. The pulse generator sets the 1MHz switching frequency and the pulse width sets the output voltage. Asymmetrical delays and logic functions drive the switches and allow for dead time adjustment.

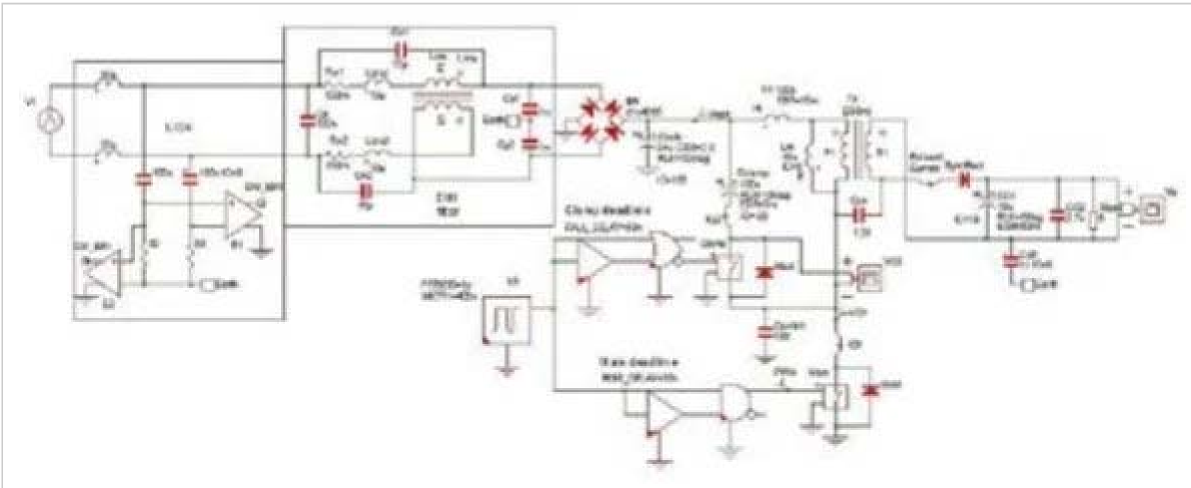

Figure 4: Example simulation schematic

The model for the main and clamp MOSFETs in this example use a simple voltage-controlled switch, ideal diode, and a single switch node capacitor. Justification for this simple model comes from the zero-voltage switching (ZVS) operation. Prior to MOSFET turn-on, current flows in the body diode and the voltage is near zero. At turnoff of either MOSFET, the transformer primary current flows in the non-linear output capacitance of both MOSFETs. During the turn-off transition, the voltage increases across one MOSFET while decreasing across the other MOSFET. Likewise, the non-linear capacitance increases during the transition across one of the MOSFETs and decreases across the other MOSFET. You can think of the non-linear capacitors in anti-parallel that, in effect, reduces the non-linear behavior. This simulation uses a single switch node capacitor, Cswitch with a value of twice the CO(er) stated on the MOSFET datasheet. The transformer current at turn-off and Cswitch sets the slew rate of the switch node and is the CM noise source. This simple model results in faster simulation when compared to a vendor’s MOSFET model with non-linear output capacitance.

The SIMPLIS spectrum function operates on CM and DM transient simulation noise data from 13.34ms to 30ms. This allows the transient simulation to reach steady-state and captures the noise over a full AC cycle. Each simulation adjusts the pulse width of the pulse generator to realize 19.5V at the output. Additionally, the MOSFET voltage and current probes allow confirmation of ZVS operation for each switching cycle over the line cycle.

The CPES researchers first explored the impact of a transformer shield without the EMI filter. To compare their results with simulation, the schematic of figure 4 removed the EMI filter (Cx, Cy1, Cy2, Cw1, Cw2, Lcm, Ldm1, and Ldm2) and directly connected the LISN to the bridge rectifier, BR.

Simulation Results

Figures 5 and 6 shows the measurement and simulation results of the transformer shield without the EMI filter. The measured results are from the CPES publications (see references 5 and 6). The simulation assumed a value of 400pF for Cps to model the capacitance without a shield and effectively removed Cps with a value of 1.5fF to model the effect of adding a transformer shield.

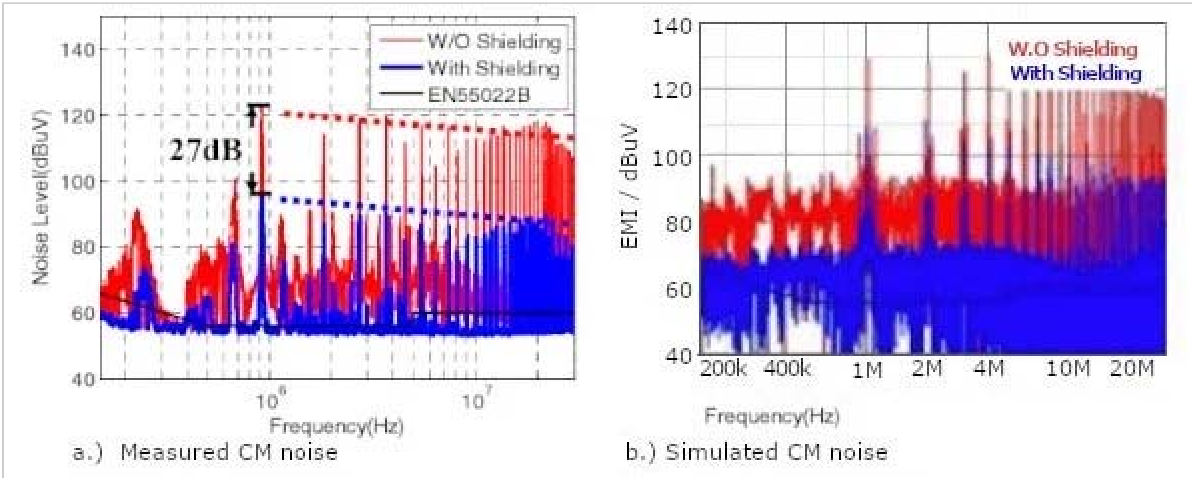

Figure 5: Common mode noise with and without shield winding and no EMI filter

Comparing measured and simulation results, figure 5 shows similar reductions of the switching frequency noise with a transformer shield. Adding a shield reduces the simulation CM noise by 21dBuV compared with 27dBuV measured by the CPES researchers.

Figure 6 shows the transformer shield reduces the simulation DM noise by 6dBuV compared with 21dBuV measurement at the switching frequency. At higher multiples of the switching frequency, the simulation results show reductions of 10dBuV and 18dBuV (2MHz and 4MHz respectively). The CPES researchers attribute the DM noise reduction to CM/DM noise transformation due to the non-linear junction capacitance of the bridge rectifier.

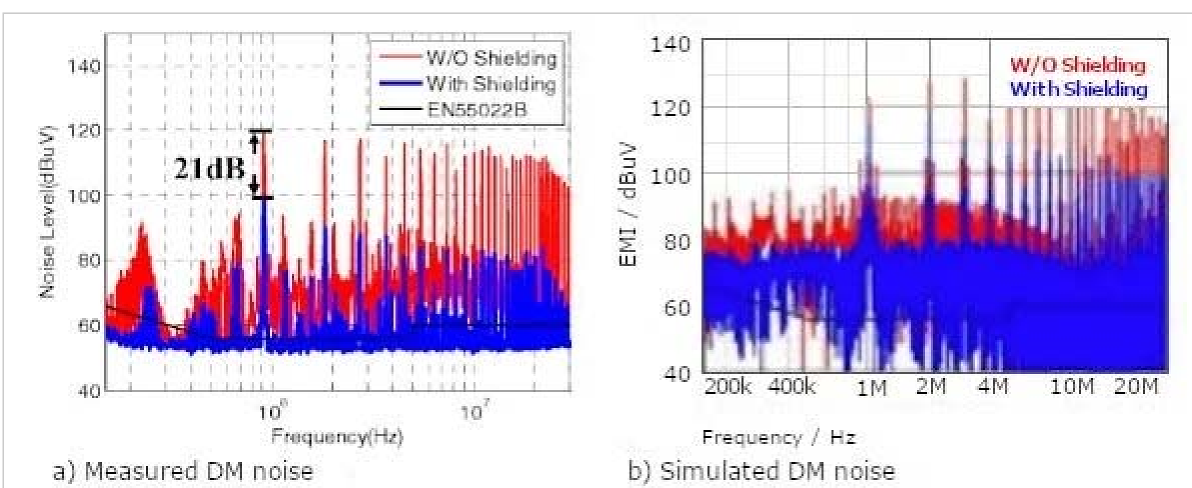

Figure 6: Differential noise with and without shield winding and no EMI filter

Given the measured noise with a shield winding, the CPES researchers chose a single-stage EMI filter design. Their results compared the resulting noise with and without the EMI filter. The single-stage filter uses a single magnetic choke for both Lcm and Ldm. The simulation model for the choke (shown in figure 4) includes 1.4mH for Lcm, and splits Lcm into two, one for each winding (Ldm1 and Ldm2). Splitting Ldm maintains impedance symmetry in the power and return lines. Finally, the model includes the winding capacitance, Cw1 and Cw2 across the choke's power and return terminals.

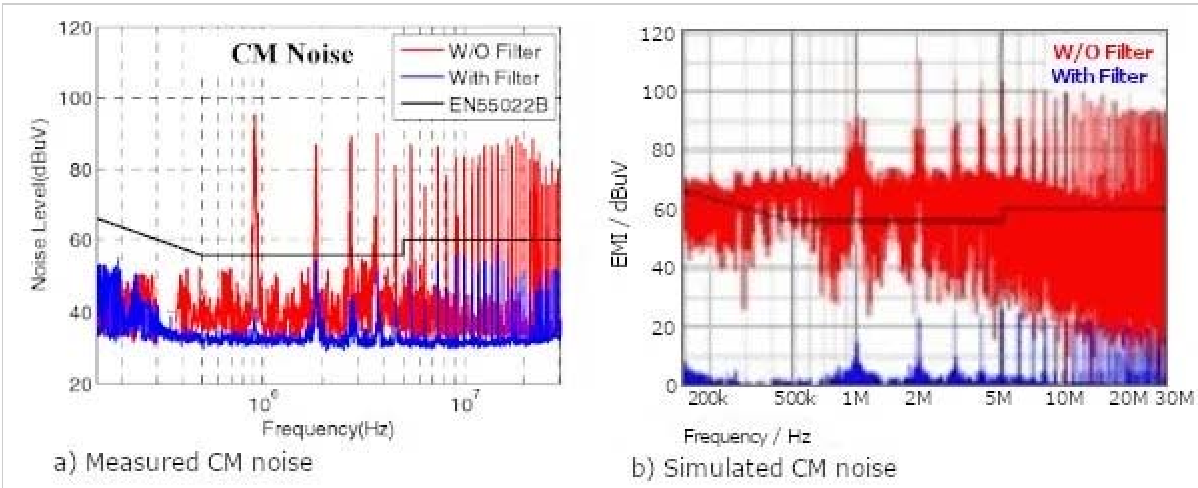

Figure 7: Common mode noise with and without an EMI filter

Figures 7 and 8 show the measurement and simulation results of adding the EMI filter to a transformer with a shield winding. The simulation compares data from the full simulation with EMI filter shown in Figure 4 with the simulation results without the EMI filter from above. Note the difference of range for the vertical axis for the simulation results.

Figure 7 shows the effectiveness of the EMI filter for CM noise for both the measured and simulation. Compared to the measured EMI filter attenuation of 55dBuV at the switching frequency, the simulation results show an attenuation of 73dBuV.

Figure 8 shows the effectiveness of the EMI filter for DM noise for both the measured and simulation. Comparing the measured EMI filter attenuation of 38dBuV at the switching frequency, the simulation results show an attenuation of 87dBuV. Figures 7 and 8 show the EMI filter attenuates both the CM and DM noise below the EN55022 Class B limits. However, the simulation results with EMI filtering are below the measured values.

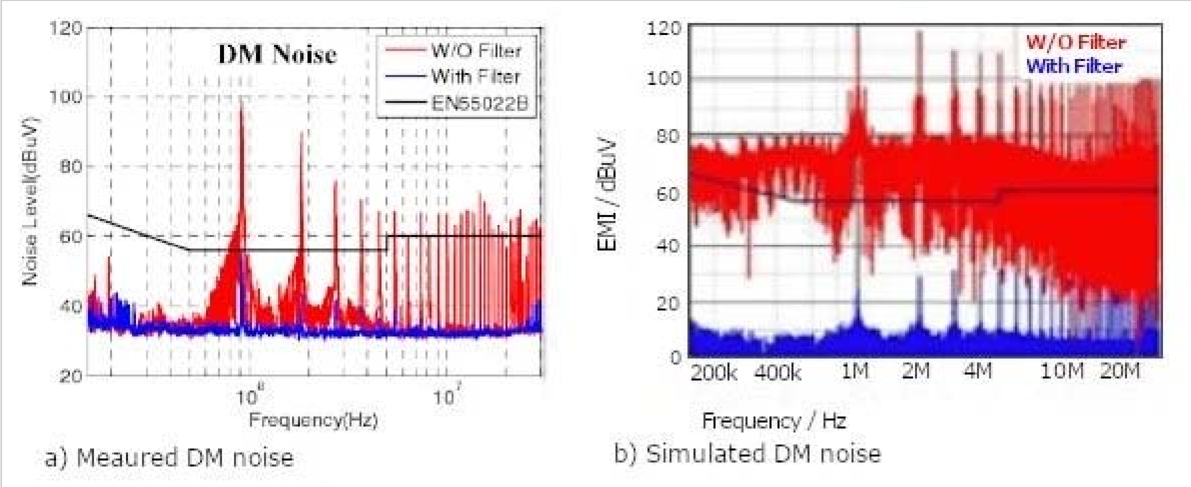

Figure 8: Differential mode noise with and without an EMI filter

Discussion

Although the simulation results support the CPES conclusions, the spectral amplitude does not exactly match the measured results. The difference is likely because the simulations used estimated parameters for a few of the critical components. CPES did not publish the values for Cps or Lm. The CPES researchers likely added a gap to the core; adjusting the magnetizing inductance to achieve ZVS. Additionally, the two CPES transformers, with and without shield winding, may have different core gaps and magnetizing inductance. I estimated values for Lm and Cps using the ZVS criteria. CPES disclosed the core structure and material for the main transformer. The calculated maximum Lm without a core gap and 10 primary turns is approximately 74uH. The worst-case for ZVS is a transformer without a shield because the magnetizing current flows in both Cswitch and Cps. CPES value for Cps is unknown, but a similar planar transformer reported Cps values ranging between 120pF and 550pF [7]. Assuming a Cps of 400pF without a shield winding, the simulation iterated the magnetizing inductance and monitored the voltage and current waveforms of the switches for ZVS. This process found a magnetizing inductance value of 10uH necessary to achieve ZVS. Simulations both with and without shield windings assumed the same magnetizing inductance, Lm of 10uH.

Other accuracy improvements of the simulation are possible, but with diminishing return for the effort. You could chose to add the PCB impedances, distributed winding capacitances, and permeability falloff with frequency to the model. You could estimate these parameters or use finite element electromagnetic analysis. Of course, finite element modeling requires the creation of a physical model and needs accurate material characteristics. Estimation of the parameters introduces uncertainty of the model's validity. At some point, the time and effort to improve the simulation accuracy exceeds the time and effort to simply build and measure the hardware.

Regardless of the absolute accuracy, the simple simulation model used in this article supports the findings of the CPES researchers. The simulation results show a reduction of EMI noise for a transformer with a shield winding and the CM/DM noise transformation due to the non-linear junction capacitance of the bridge rectifier. In addition, the simulation shows a single-stage EMI filter attenuates both the CM and DM noise below the EN55022 Class B limits.

Conclusion

This article describes a method for simulating conducted EMI in switching power converters. The method highlights model development with a LISN and a procedure for extracting the EMI signature from a transient time-domain simulation. It also identifies the critical noise sources and component parameters in the noise paths. The example simulation achieves reasonable results with a simple MOSFET model and avoids the complexity of non-linear output capacitance. Historically, power converters operated with a switching frequency below 150 kHz to avoid a large EMI filter. Wide band-gap devices operating at high switching frequency promise higher power density, but only with an optimized EMI filter. Simulating EMI enables quick filter optimization compared with hardware design iterations and multiple trips to a certified EMI facility. Engineers can use simulation to identify the boundaries of real and parasitic components on EMI performance. The identified boundaries help the designer optimize the EMI filter and select or design the proper components. Simulation enhances the design engineer's understanding of conducted EMI to help eliminate the 'black magic' of EMI design.

About the Author

Mike Walters has over 35 years of power electronics experience in the fields of LED lighting, computer power, and military aerospace. He has filed over 60 US patents with Cree, Intersil, International Rectifier, IBM, & GE. Mike is currently the proprietor of Walters Power Electronics, LLC specializing in power supply system architecture, system & product simulation, competitive analysis, integrated circuit definition as well as analog/digital control & circuit design.

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