

Electromagnetic Interference (EMI) in Power Supplies

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Abstract -- Increasing power density, faster switching and higher currents forces designers to spend more time both considering the effects of electromagnetic interference (EMI) and debugging a design that has EMI problems but is otherwise complete. This paper explains the different types of EMI and their coupling mechanisms and the existing EMI regulations. The most frequent noise sources, transmission paths and receiver sensitivity are examined. Based on real designs and measurements, specific procedures are recommended for use throughout the design cycle, to make the power supply work reliably and pass EMI testing.

I. INTRODUCTION

In power supplies, the two prominent types of EMI are conducted EMI and radiated EMI. Comprehensive regulations provide limitations to radiated and conducted EMI generated when the power supply is connected to the mains.

Comparing the modern power switches used in power supplies with those from older generations, the new switches have significantly reduced switching times, leading to faster and faster rise and fall times for the voltage and current waveforms. These fast edges produce significant energy at surprisingly high frequencies, and are the root cause of all EMI problems in switched-mode power supplies. This high frequency energy causes ringing in all the resonant tanks, small or large, that exist within the power supply. In general, this ringing does not cause problems; however, in some cases, this may stop the power supply from working properly or passing tests.

Faster switching also means that losses can be reduced, improving the efficiency of the power supply. But faster switching should also enable higher switching frequencies, ultimately leading to smaller passive components and better transient behavior – a promise that has not been realized.

The main reasons for this are the cost of transformers for use at these frequencies and the disproportional complexity of solving high frequency EMI problems.

Resonant and quasi-resonant topologies offer an elegant way out of this dilemma. They have been around for a long time, but due to limitations, they have not

been widely accepted. The sensitivity to load and line regulations can limit their usage and parameter variations of passive components can make series production difficult and expensive. Further, for some stages of the power supply (e.g. secondary side post-regulation) a resonant version does not really exist. It is only with today's modern control ICs that quasi-resonant power supplies show their potential while maintaining good EMI performance. So it is not surprising that more and more designs are using this topology.

Given these new developments, it is clear that EMI performance can no longer be considered only after the main power supply design is finished. It needs to be designed into the power supply right from the start at specification level, just like reliability and safety, influencing topology and component selection.

The goal is to meet EMI regulations while not disturbing other applications nearby. The power supply should also be self-compliant and tolerate a certain amount of EMI from the outside. This paper will show how to “embed” EMI considerations throughout the entire design cycle. The intent is to give the power supply designer a good understanding of the problem and an overview of the measures that can be taken while designing and testing the power supply, to improve time to market and to come up with a robust design. It is not a comprehensive overview on the topic, as a large amount of good literature exists already.^{[1]-[4]}

II. DIFFERENT TYPES OF EMI AND THEIR CHARACTERISTICS

Three things can cause an EMI problem: A signal source creates some kind of noise, there is a transmission path for the noise, and/or there is a receiver sensitive enough to be distorted by the noise, as shown in Figure 1.

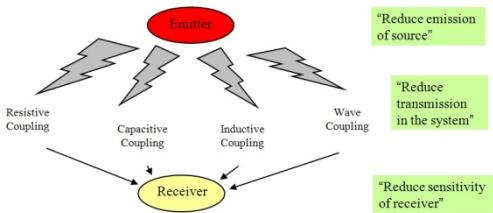


Fig. 1. EMI sources.

The noise source can be inside or outside the power supply. Tackling the noise problem at the source means reducing the emission levels — for example, by lowering noise amplitudes. Different coupling mechanisms exist for noise, and many EMI countermeasures focus on these; however, they overlook what can be done at the emitter or receiver. A receiver susceptible to noise injection must exist in the system if there is an EMI problem. Here, the obvious solution is reducing its sensitivity.

At this point, a fundamental distinction must be made between the two types of EMI problems:

- Improving EMI so that the design meets regulations and will pass EMI testing (also called EMC or electromagnetic compliance)
- Improving EMI so that the design works reliably in all modes of operation, with good efficiency, and does so without being disturbed by other (EMC-compliant) equipment nearby

For the first type, test methods and certified labs exist. For the second type, it is important to take the design through all design stages, carefully checking to see if poor EMI design may be the cause of the problem. Here, it is important to consider component variations. Maybe the components in the prototype are such that no problem is visible, but the components used in production may cause problems.

The four coupling mechanisms are:

Resistive (or galvanic) coupling: The noise signal is transferred via electrical connections. This works at all frequencies, and is usually fixed by good layout (particularly the ground layout) and filtering with capacitors and inductors or lower signal levels with RC elements. “Common impedance” coupling can be classified as galvanic coupling.

Capacitive coupling: Electrical fields are the main transmission path. Capacitance levels are mostly small so this affects small signals and/or high frequencies.

Shielding the source using thin conductive layers is most effective.

Inductive coupling: This transmission path is quite common in switched-mode power supplies since high-frequency currents in the inductors can cause strong magnetic fields at higher frequencies, where the coupling factors can be higher. Magnetic shielding is less effective than electric shielding since the absorption depth is smaller, requiring thicker materials. Inductive coupling is best addressed at the source.

Wave coupling: Here, the noise typically has a high frequency, and is transmitted via an electromagnetic wave. It does not play a major role in power supplies, since frequencies are not high enough, and can be damped very effectively with shielding.

This paper will focus on capacitive, resistive, and inductive coupling; as they are the most important sources of EMI issues in power electronics applications. It is generally accepted industry practice to consider conducted EMI below 30MHz, radiated EMI above 30MHz, and in most cases up to 1GHz – exceptions do exist, however.

Coupling modes cannot be treated in isolation since ideal elements exist only in simulators, not in real life. Parasitic elements are always present. The parasitic capacitors and inductors contribute to the problem, as parts of tank circuits that will resonate when stimulated by a voltage or current edge. The parasitic tanks help to convert one coupling mode into another, and that is why coupling modes cannot be analyzed and fixed in isolation. The third parasitic element, resistance, actually helps to ease the problem by damping the resonant oscillation. Using the amplitude change from peak to peak can help to calculate the parasitic resistance, identify it in the circuit, and optimize the circuit accordingly.

III. REGULATIONS AND STANDARDS FOR EMI

As electrical consumers moved from simple light bulbs to large motors and particularly to switched-mode power supplies with rectifiers and capacitors at the inputs, the quality of the grid voltage and service worsened. This led to the emergence of worldwide

standards to mitigate these problems. Two considerations of these standards are:

- Limit the amount of emission (radiated/conducted) which a given application generates
- Define the minimum immunity levels (radiated/conducted) a given application must tolerate without malfunction

The list of standards is very long. The common theme is that certain standards define the limit values and their measurement methods and conventions, and additional documents define the regulations for classes of applications in more detail.

Additionally, standards can be grouped into local/regional standards, MIL standards, automotive standards, standards for the aircraft industry, for physically large equipment, and for more specialized equipment (e.g. smart meters).

The two most important standards for power supplies are EN550xx and EN61000. Applications connected to the grid must comply with both. The first covers EMI limits for various applications, defining the measurement methods in more detail for both conducted and radiated EMI, defining limit values, and mostly considering the high frequency content the application generates. The following list gives an overview:

CISPR11, EN55011 for industrial, medical, scientific applications

CISPR13, EN55013 for consumer applications

CISPR14, EN55014 for home appliances, power tools, involving motion control

CISPR15, EN55015 for lighting equipment

CISPR22, EN55022 for computing applications

The standard CISPR16 / EN55016 defines the measurement method for the applications listed above and is central to all of them.

The standard EN61000 (or “61k”) is the “PFC” standard and considers the line frequency harmonics a given application generates, up to the 40th harmonic frequency or 2kHz and below. Extension of the standard to consider interharmonics up to 9kHz is in discussion. No defined impedance is used with the standard but the harmonic current content generated by the application is

measured and appropriate limits defined. Using a defined impedance to measure the harmonic current is not required today, but is also under discussion.

The standard 61k-3-2 defines the limits for applications <16A, and 61k-3-12 for 16A...75A current consumption. The standard 61k-4-7 defines the measurement and evaluation method. Additional 61k standards define the behavior for voltage and frequency variations, immunity to conducted and radiated radio frequency signals, fast voltage transients, surges, voltage dips / drops, short interruptions and flicker, and magnetic fields.

For the standard 61k, the equipment typically is grouped into different classes, with professional equipment above 1000W power consumption still being excluded. Different limit levels exist for the different classes. An overview is given below.

In most cases, a good PFC circuit is sufficient to meet the 61k regulations. Circuits that have just an input rectifier and capacitor connected directly to the mains may not be able to meet the requirements without a PFC. It is also important to note that 61k requires repeatability of the test results, within 5%.

Class	Equipment	Power	Comment
A	3-phase equipment, household appliances, tools, dimmers for incandescent lamps, audio equipment, everything not B, C or D	> 75W	Limit values are defined as absolute values
B	Portable tools, Arc welding equipment	> 75W	Limit values are defined as absolute values
C	Lighting	> 25W	Limit values defined as relative values to first harmonic
C	Lighting	< 25W	Limit values defined only for 3rd and 5th harmonic, relative to first harmonic
D	Personal Computer, Monitor, Television	75W - 600W	Limit values relative per input power

IV. MEASUREMENT AND SOURCES OF EMI

Conducted EMI

The impedance of an AC power line varies widely. The impedance at the end of a long cable in some remote area can be quite different from the impedance of a cable in an industrial park, located right next to a transformer station. When a power supply generating noise is connected to this impedance, the noise measurement

results will vary widely. For this reason, a standardized impedance is used. The noise current generates a voltage across this standardized impedance, so the results for noise levels can be compared.

The standardized setup, as defined in CISPR16 / EN55016 for measuring conducted EMI is shown below:

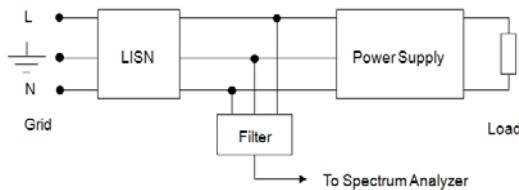


Fig. 2. Connection of a LISN to a power supply under test.

On the left side, the block called LISN (“Line Impedance Stabilizer Network” also known as AMN, for “Artificial Mains Network”) represents the standardized impedance. The noise signal is taken from this impedance with a high-pass filter, amplified, and connected to a spectrum analyzer. This analyzer is used to measure the harmonic energy content of the noise signal across a wide frequency range.

Fig. 3 contains a line impedance stabilizer network to connect the line, load, and the spectrum analyzer. Note that the connections are “live.” The LISN is directly connected to the mains, in contrast to the usual measurement practice where an isolation transformer is used for safety reasons. The ground connections can also carry significant leakage current. It is important to realize this difference, as it has significant safety implications when operating the equipment in test.

One important differentiation to make is the one between common and differential mode noise. Common mode noise is caused by a capacitive coupling of the switching stage into ground, and appears with the same phase and amplitude at both lines.

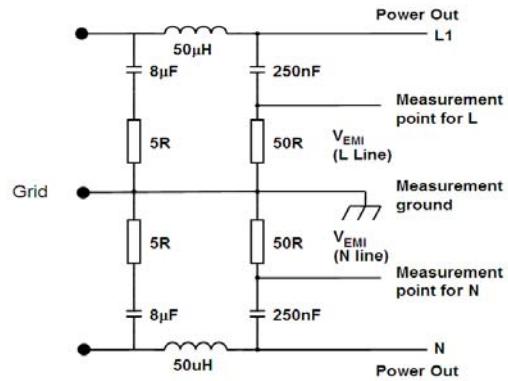


Fig. 3. Equivalent circuit of a LISN.

Differential mode noise is caused by the time-varying current demands of the switching stage, conductively coupled via the bus cap into the lines, and appears as an out-of-phase voltage at the lines. The measurement points showing where to connect the analyzer are indicated in Figure 3. In reality, the two voltages will be quite different, depending on the impedance of the line but can be “decomposed” into their differential and common mode equivalents.

An EMI analyzer is shown in Figure 4. Typical specifications include a bandwidth of at least up to 1GHz, and a selectable bandwidth to perform the measurements in line with the standards. A large dynamic range is important. If the analyzer starts clipping high-level peaks, the measurement is unreliable due to noise spill-over.



Fig. 4. Example Spectrum Analyzer used for EMI testing.

Two measurement methods exist, called “Average” and “Quasi-Peak”, and they have different limit values as shown in Figure 5 below (QP = upper line in red, AV = lower line in blue):

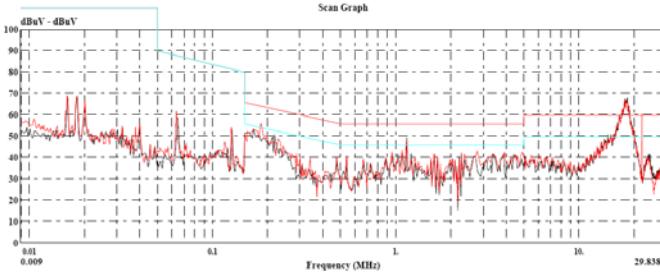


Fig. 5. EMI Frequency Spectrum showing average (AV) and quasi-peak (QP) plots.

The frequency range on the x axis is from 9kHz to 30MHz. The noise level on the y axis is scaled from 0 to 100dB μ V, with $V_{dB\mu V} = 20\log(V_{rms}/106)$. The straight red line represents the limit values for the quasi-peak measurement, and the blue line the limit values for the average measurements (both correspond to the standard EN55011/22-ClassB).

This power supply clearly exceeds the limits at around 18MHz. Note that the limits are independent of the rated output power of the power supply, explaining why more effort needs to be made to meet the limits for larger power supplies. The table below shows the limits according to EN55022, class B:

Frequency	Limit (dB μ V)	Limit (V)	Comment
9kHz ... 50kHz	110	316mV	Quasi-peak
50kHz...150kHz	90 ... 80	32mV ... 10mV	Quasi-peak
150kHz ... 500kHz	66 ... 56	2mV ... 0.63mV	Quasi-peak; linearly falling with log (frequency)
	56 ... 46	0.63mV ... 0.2mV	Average; linearly falling with log (frequency)
0.5MHz ... 5MHz	56	630 μ V	Quasi-peak
	46	200 μ V	Average
5MHz ... 30MHz	60	1mV	Quasi-peak
	50	316 μ V	Average

Note also that there is an increase in the limits at 150kHz, accompanied by a change in measurement bandwidth from 200Hz to 9kHz – this is the main reason (albeit not the only one) why switched-mode power supplies usually operate at main switching frequencies below 150kHz. In fact, a switching frequency of less than 50kHz can be desirable, since this would place the second and third harmonic in the frequency space where higher levels are tolerated. The measurement bandwidth

definitions are shown in Figure 6 and defined in standard CISPR-16.

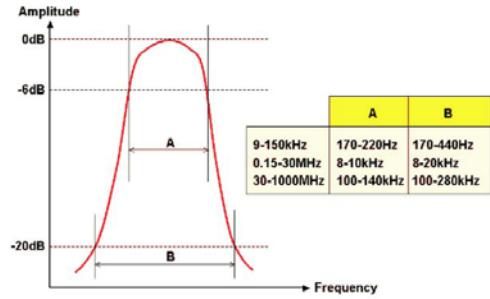


Fig. 6. Bandwidth definitions for EMI measurement.

In switched-mode power applications, conducted EMI is primarily caused by fast voltage changes. Unfortunately, this is how all switched-mode power supplies work. The fast edges contain many harmonics and these harmonics are coupled into both inputs and outputs with different damping. The rise and fall times also influence the high frequency content of the noise. Reducing the switching speed improves EMI behavior but reduces efficiency, especially in hard-switched topologies. In terms of the emitter-coupling-receiver model discussed earlier, nothing can be done at the receiver since this is the defined impedance of the LISN. However the switching and coupling can be influenced.

First, the noise signal coming from the switching action has to pass through the DC blocking capacitor. This capacitor is a non-ideal element – if it were ideal, it would have a very low impedance, approaching zero at very high frequencies and effectively eliminating all of the noise. Its parasitic characteristics contribute to reduced damping at higher frequencies, being the main source of conducted EMI in a switched-mode power supply.

A capacitor like the (typically electrolytic) bulk capacitor in the SMPS has a parasitic resistance (ESR) and a parasitic inductance (ESL). These are typically modeled in series with the main capacitor, as shown in Figure 7 (the leakage resistor is of lesser importance here).

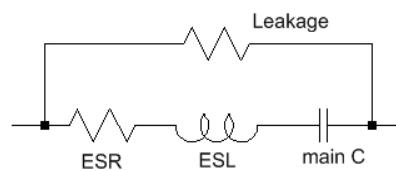


Fig. 7. Equivalent circuit model of an electrolytic capacitor.

Typical values for an industrial grade $100\mu\text{F}/450\text{V}$ capacitor, like the B43601 from EPCOS, are $\text{ESR}_{\max} = 1900\text{m}\Omega$ and $\text{ESL} = 20\text{nH}$. At lower frequencies, especially the main switching frequency, a current is being forced in and out of the capacitor, causing a voltage drop across the ESR. This pulse current and ESR value can be used to assess the voltage at these frequencies, and comparing it with the allowed levels under EN550xx, yields the required attenuation the EMI filter must provide. At higher frequencies, the ESL impedance is higher than the ESR, and the capacitor behaves like an inductor.

For conducted EMI, the basic filter topologies are the pi filter, the T filter, and the L filter. The circuits shown in Figure 8 are for both balanced and unbalanced versions. The left side is always the line side; the right side is the load side.

Depending on the required attenuation, the filter needs to have one, two, or even three stages (it is rare to see more than two stages). It is important to consider the power and signal flow when laying out the filter. The best form factor is usually achieved with a balanced implementation: making the filter long and thin, reducing the coupling capacitance, and increasing the impedance between input and output. The components should be large enough to cope with the required peak currents and provide sufficient damping (with a margin). They should not be too large, since all capacitors and inductors have a self-resonant frequency (“SRF”), which depends on the parasitic inductance and capacitance, and this frequency will be lower with larger components. Above the SRF, the attenuation function is basically gone. This explains why sometimes using two smaller components instead of one large may be better.

It is important to note that the EMI filter will work most of the time in an unmatched setup, with the line and load impedances different from the design impedance of the filter, which is therefore reflecting most of the energy. However, the energy must be absorbed somewhere, underlining the need for lossy components in the circuit. As a general rule, it is better to offer a dissipation path for the unwanted energy, rather than letting it find its own path.

A pi filter is used in most applications. The pi filter has an advantage in coupling with the LISN, effectively

increasing the order of the filter, and works well in most SMPSs where a large bus cap is connected to the output of the filter. The T filter has an inductive input and output, where the input makes life easier for the over-voltage protection at the input (the voltage can rise faster compared to the pi filter where the input capacitor would have to be charged first). For “difficult” lines, this may be a better choice. The output, however, is facing the bus cap and may starve the SMPS if not designed properly. In many cases, the L filter provides a good compromise but offers only 12dB loss per octave since it has only two elements (a double-L may be required in some cases). Here, the bus cap cannot replace the output cap of the filter, since its SRF is too low.

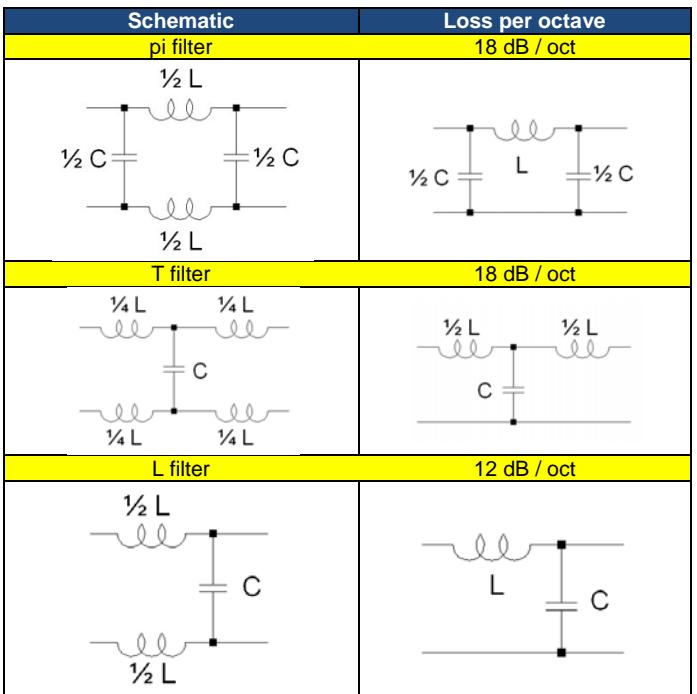


Fig. 8. Types of input filter.

These filter topologies address differential mode noise but not common mode noise. For this, an additional element needs to be introduced to increase damping on the lines and provide a return path for the noise. The common mode noise is primarily caused by capacitive coupling of the switching stage into the ground line, and the current loop for this noise is then completed via the LISN and the differential mode EMI filter. The coupling capacitance is typically small, so for the filter to be effective, large inductance values are required. The line-to-line caps in the differential mode EMI filter do not help here, and the inductors in this filter are too small to

provide useful damping. An effective solution to the problem is the so-called “common mode choke”, where two inductors are wound on a common core, and connected so that the two inductors look like a transformer with the winding starts connected in phase for common mode noise (see Figure 9):

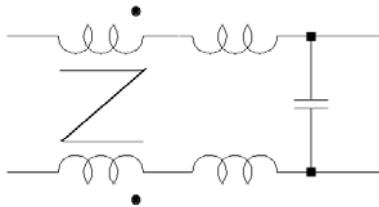


Fig. 9. Common mode and differential mode choke.

This inductor is also called the “zorro” inductor. It is designed to have the required inductance value for common mode (the left inductors) but wound in a way that maximizes leakage inductance, providing the required inductance level for differential mode (the right inductors) – an elegant and compact solution to the problem.

Figure 10 shows a practical EMI filter implementation. The black area in the upper middle part is the input connector. Next to the input connector is the fuse, and the metal box is the main switch. The first choke is below the main switch, followed by the first capacitor (gray square), the second choke and the second capacitor.

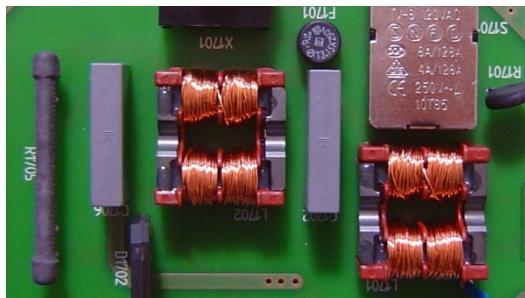


Fig. 10. Practical EMI filter implementation.

The purpose of the dark gray resistor is to limit inrush current. Part of the bridge rectifier is visible. This filter is a two-stage L filter using two chokes. No capacitor is connected across the lines at the input side.

It is important to connect a capacitor from the lines to ground to provide a return path for the common mode noise current. These capacitors have three requirements. They must be small enough to not cause too high leakage, tripping the ground fault interrupters; they must be large enough to provide low impedance for the

common mode noise current; and they must comply with the safety requirements as the ground connection may break, and a user might touch the midpoint. These capacitors are also called Y-caps, since in most cases two are connected from the two lines to ground.

The calculation of the filter components requires the following data:

Line frequency	f_{Line}
Minimal RMS voltage	V_{\min}
Maximum RMS load current	I_{\max}
Lowest switching frequency	f_{swmin}

First, the design impedance is calculated as:

$$Z_d = \frac{V_{\min}}{I_{\max}} \quad (1)$$

Next, the filter topology is chosen based on the characteristics described above. The number of stages is determined later.

Finally, the required attenuation at the lowest problem frequency f_{swmin} is determined. This is either by simulation or by measurement of the power supply without the EMI filter and using the final layout for the rest of the power supply.

The filter cutoff frequency f_{cut} is determined from the attenuation needed at the problem frequency (plus a margin of 6 ... 10dB), while at the same time providing minimal attenuation at the line frequency. This is an iterative process, ultimately determining how many stages are needed in the filter. The cutoff frequency should be at least 10 times the line frequency.

Calculate the L and C values of the filter as follows:

$$L = \frac{Z_d}{2\pi f_{\text{cut}}} , \quad C = \frac{1}{2\pi f_{\text{cut}} Z_d} \quad (2)$$

Using these component values, the individual values are calculated and the filter is constructed. For the differential mode filters, these values are the same as the components in the above filter circuits. For the common mode filter, it is important to note that L is the inductance of the common-mode choke windings in parallel and C is the capacitance from the lines to ground.

Further optimization can be done. Here are some suggestions that are further discussed in the references^{[1][4]}:

- Insert series-resonant tanks fine-tuned to the problem frequency. This will work only for fixed-frequency SMPS or fixed-frequency noise peaks and the impact will depend on component variations which can be large with passive components, so bandwidth must be increased at the expense of damping at the design frequency.
- Insert RC shunts across the lines, to attenuate certain frequencies and also introduce some damping
- Add resistive impedance into the filter to make the filter more lossy.
- Reduce the quality factor (by optimizing the inductors) of the stages in the EMI filter to reduce ringing. The ringing frequencies should be far away from the problem frequencies, the main switching frequency and its third harmonic frequency. Capacitors usually have a much higher Q factor than inductors, and not much can be done about it.
- A differential mode choke can help in difficult situations, but is a more complex component and rarely seen in SMPSs. Their current capabilities generally limit their use to lower powers.

Radiated EMI

Measuring radiated EMI is also defined in CISPR16 / EN55016 and requires a probe (antenna) for the magnetic field. This can be as simple as a small coil connected to a measurement amplifier and to an oscilloscope or spectrum analyzer. The magnetic probes used in EMI labs are calibrated probes, and require a fair amount of know-how and additional equipment to make accurate measurements. Performing the measurements according to the requirements of the standard is significantly more complex than performing the measurements for conducted EMI, since the field probes need to be calibrated and a measurement room needs to be used which is free from other magnetic fields.

In switched-mode power supplies, radiated EMI “hotspots” can serve as an indicator for potential problems; however, when fixed, the power supply usually passes EMI testing without any problems, as magnetic fields usually do not reach very far. Hence, a

simpler radiated EMI test can be used to spot potential problems, using a so-called “sniffer” probe.^[4]

This probe consists of a small coil which is shielded against electrical fields and isolated on the outside for safety reasons. Two examples are shown in Fig. 11:



Fig. 11. 3D and 1D EMI sniffer probes.

The first probe has a linear coil, causing it to be most sensitive across the length of the probe. The second probe has three coils, which are perpendicular to each other and electrically connected in series. Its sensitivity to H-fields is independent of the field orientation. It depends on the particular case to determine which probe is best, but in general, the 3D probe is used to “scan” the application for locations with high field intensity, and the 1D probe is used to get a more precise picture of the nature of the problem.

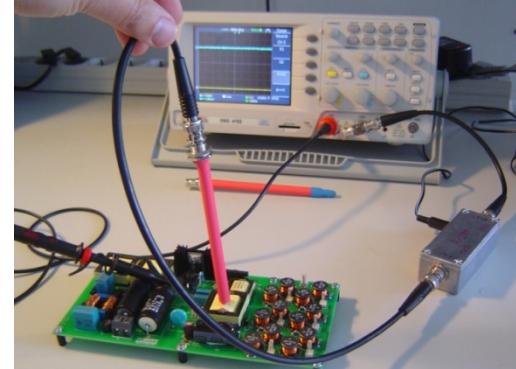


Fig. 12. Using an EMI sniffer probe.

The test setup with these probes is shown in Figure 12. The probe is connected to a probe amplifier and then to an oscilloscope. Both the probe and the amplifier output require a 50Ω termination. An additional HV probe is connected to the board under test.

Radiated EMI issues in switched-mode power supplies are generally related to currents being switched. This usually happens in sync with some clock frequency. This represents a very convenient way to get closer to the problem, simply by using this clock or switching signals to synchronize the oscilloscope, so that the image becomes stable. Switching a current can trigger resonant tanks in the application, and they then resonate with their characteristic frequency. This frequency is from the

oscilloscope screen and is used to calculate which of the parasitic elements in the circuit might be the source. The speed with which the ringing decays can give an insight into the Q-factor of that resonant tank.

As mentioned, this type of EMI comes from switched currents with high di/dt . The two most prominent sources are loops with fast current rise times and the leakage fields of inductors (other examples are given below). The coupling mechanism works like a transformer, and is shown in more detail in Figure 13.

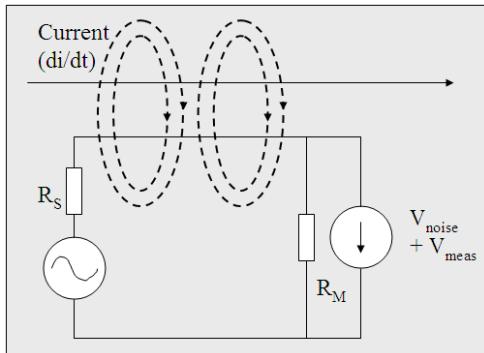


Fig. 13. di/dt induced EMI.

The current change induces a noise signal voltage:

$$V_{\text{noise}} = \frac{R_M}{R_S + R_M} \times M \times \frac{di}{dt} \quad (1)$$

The coupling factor M depends on distance, area and orientation of the magnetic loops, and magnetic absorption between the loops – just like in a transformer. In addition, noise voltage depends on the strength of the current change and on the impedance of the receiver. This correlation is straightforward and the necessary countermeasures can easily be derived.

Avoid high di/dt – move to softer (slower) switching or zero-current switching where possible.

Make the impedance as low as possible in the signal processing nodes – implement current-based signal transfer or add additional resistors to ground at sensitive inputs (if possible) to reduce the impedance of these nodes (easier when the signal is driven by a voltage source). Differential signaling should also be considered. The induced noise voltage should couple into both signals identically and is then factored out at the receiver, adding circuit complexity.

Reduce the coupling factor M between the magnetic loops. At system design and PCB level, the orientation of the current loops should be orthogonal, not parallel. The current loop areas should be made as small as possible, even if that means running the return path in parallel or on top / under the current path and increasing the resistance (we will see later that this might not be such a bad thing). Increasing the distance between the emitting current loop and the loop picking up the noise may help, but requires a redesign of the PCB if the problem is detected when the hardware is built. At this point, magnetic shielding can help, but this includes manufacturing complexity, adding to the system cost.

It is important to identify potential current loops with high di/dt in the circuit and take appropriate measures at the design level to reduce the impact. To do this, analyze the current flows at normal behavior of the circuit and check which elements only see current flow in one part of the cycle – these elements are very likely to be in a current loop with high di/dt .

Other more unusual sources of resonant ringing and EMI radiation exist, namely:

Diode reverse recovery. Once conduction stops, the space charge needs to be replenished, and in case of “snappy” diodes, the resulting di/dt can be high.

Transformer shield ringing. The shield is capacitively coupled to the primary winding that sees high dv/dt , and has parasitic inductance in the path to ground. This tank is excited by primary-side switching and can couple radiated EMI into the ground connection.

Ringing between parallel caps. Small differences (e.g. in the ESR) can lead to charge ringing back and forth, typically at very high frequencies.

Ringing between parallel rectifiers. Depending on small variations of the turn-off voltage, the reverse recovery charge (or parts of it) can flow back and forth between the two diodes, typically at high frequencies.

Noise pickup in secondary side chokes. Converters requiring a secondary side choke can pick up magnetic fields from the transformer and other primary side circuitry. This is best avoided by carefully arranging the magnetic orientation of the components.

V. EMI AS AN INTEGRAL PART OF THE DESIGN FLOW

Design step	Measure
Specification	Define required EMI levels the power supply must comply with
Select topology	Choose topology that creates low EMI (e.g. QR flyback for lower powers, LLC for higher powers)
Calculate the components	Implement enough headroom for the parasitic ESR of the EMI filter. Make sure the nodes, especially those inside the control loop, have the lowest possible impedances.
Simulate the design	Use a simulation model for the LISN to predict the EMI generated by the power supply, separately for common and differential mode noise. Choose the EMI filter topology based on the required attenuation levels. Calculate a first version and simulate this too.
Build a prototype	Try to be close to the final arrangement of components in the finished power supply, so the radiated EMI signature can be verified. Minimize high-current loop areas and parasitic capacitance of nodes with high dv/dt. Leave some space at the input to put in an EMI filter later.
Test the prototype	Once the power supply works well inside the specifications, perform pre-compliance testing of the power supply without an EMI filter, to measure the conducted noise (again, common and differential mode), and compare with the simulation results. Perform first radiated EMI test to identify potential "candidates" for radiated fields.
Add the EMI filter	Build the EMI filter into the prototype and perform another full function and EMI pre-compliance test. Note that the EMI filter adds impedance at the power input and may resonate, so the regular function of the power supply must be verified again.
Design the final version	The implementation of the final version in a PCB will change certain aspects of the conducted and radiated EMI . Make sure the specification for the components used in production comply with the requirements for being EMI compliant (particularly the bulk caps and inductors).
Test the final version	After verifying the full function of the power supply, perform pre-compliance testing to ensure that the noise levels are still acceptable. Perform pre-compliance testing at high and low line conditions, with low line being more critical (longer conduction angle on the input rectifiers). Examine the impact of different component sources on the noise. Build several power supplies and check if the noise levels are repeatable, or vary significantly from power supply to power supply.

1. Write the Specification

At this point, the designer needs to determine the regulations governing the sale and use of the application. In most cases, this will be EN550xx and EN61k, as mentioned before. Here, it might be important to consider the project timing needed for compliance testing, and the space requirements for EMI filtering and shielding.

2. Select the Topology

Ongoing improvement in power switch technology and control IC functionality has led to a change in topologies, especially recently. The winners emerging in this topology race are the LLC converter for higher power levels, quasi-resonant flyback converters for lower power levels, and primary-side regulated converters for very low power levels. An overview of topologies versus typical power levels is shown in Figure 14.

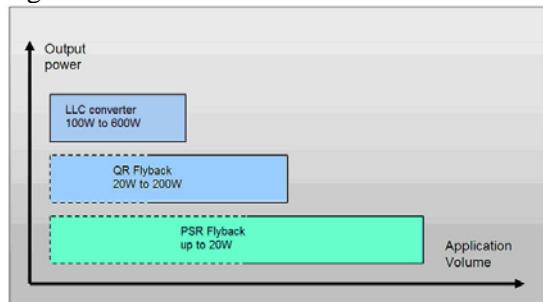


Fig. 14. Selecting low EMI topologies.

Both the quasi-resonant flyback and LLC converters have good EMI behavior, making them the topology of choice for many modern applications. Other topologies can be used but have some disadvantages. The regular flyback topology creates very high dv/dt and a high voltage peak. Here EMI compliance is not easy due to the high common mode noise components. In a flyback converter, the transformer is also the energy-storing component, resulting in high inductance values. The most effective way to achieve this is to use a gapped core. The magnetic fields emanating from the gapped core are also a source of radiated EMI.

Hard-switched topologies have a difficult EMI behavior as they generate high dv/dt and di/dt during switching. Since such topologies are used at higher power levels, the differential noise can be substantial, requiring large filters with low impedance at line frequency but high impedance at noise frequencies.

3. Calculate the Components

When calculating the components of the power supply, two factors should be considered. First, the estimated parasitic impedance of the EMI filter is part of the input impedance of the power supply. This is the case especially at low-line conditions, where the current is highest but the available voltage lowest. Realistic values must be assumed to ensure a working prototype close to the final design.

Second, to improve sensitivity against noise for proper functioning of the power supply, consider making the impedance of nodes as low as possible, particularly inside the feedback or protection circuitry. As a result, higher noise power is required to disturb the circuit. Additionally, certain signals can be moved from voltage to the current domain, or differential sensing can be used, routing the two signal wires as closely together as possible. Here, a differential-mode receiver will be able to detect the wanted signal even in the presence of noise. This method adds complexity, but can be a good solution in very dense environments.

4. Simulate the Design

Modern circuit simulators are fast and easy to use. Since the noise signature of a power supply depends on many factors, including final layout, size and material of the components, housing, and surrounding equipment, simulating the noise behavior is not very exact. However, it can give a good indication of what may need to be done later. Figure 15 shows an example of a test fixture used in a SPICE simulator:

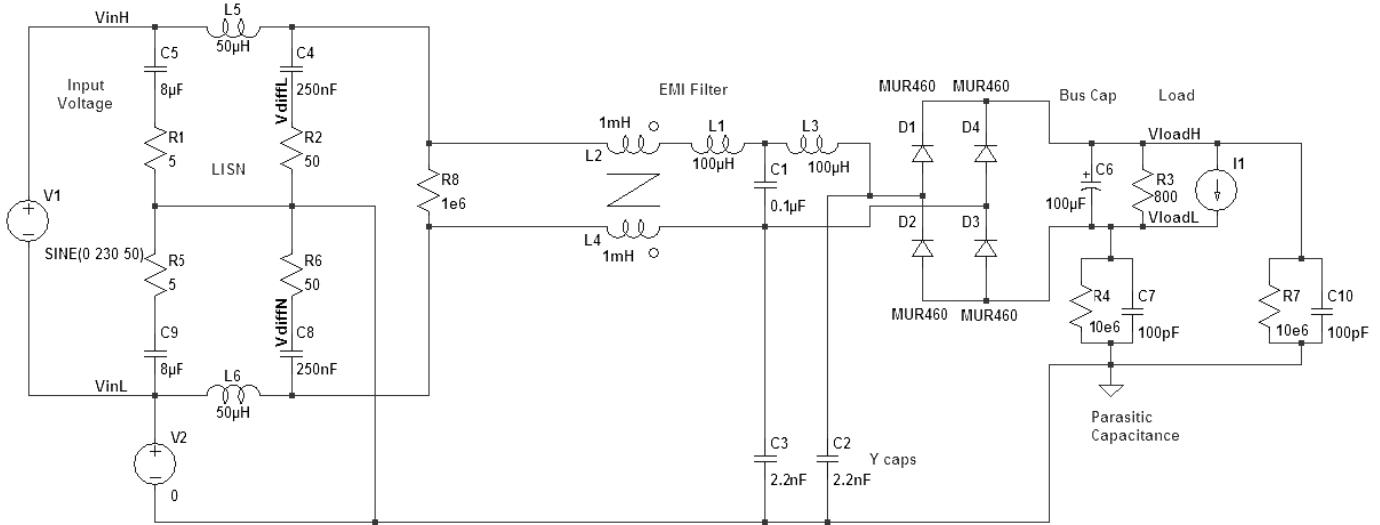


Fig. 15. Simulation schematic for EMI in switching regulator.

A sine wave voltage source V_1 models the line input voltage. The LISN is represented through its schematic, and the two measurement voltages are labeled V_{diffL} and V_{diffN} . At the center is a two-stage EMI filter in T-topology with a common mode choke and two Y-caps, followed by a bridge rectifier and bus capacitor, in parallel with a load resistor and a current source that will force a rectangular current into and out of the capacitor. The parasitic capacitors C_7 and C_{10} simulate the coupling of switching noise into the ground line.

Simulating the load is not very difficult. Here, a load current of $\pm 0.5\text{A}$ has been assumed, with a period of $10\mu\text{s}$ (or 100 kHz switching frequency), and an on-time of $4.9\mu\text{s}$. The rise and fall times are assumed to be 100ns . This is not far away from an LLC converter operating at 150W output power.

First, the simulation of the current at line frequency is shown in Figure 16.

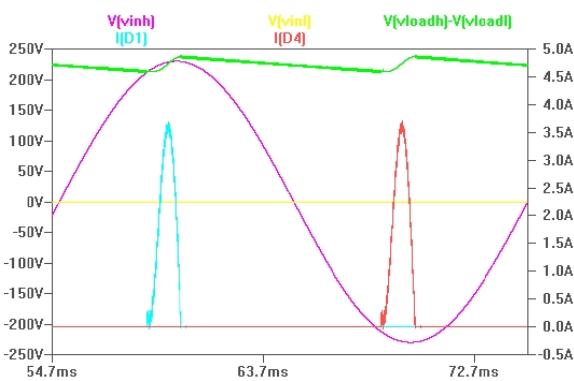


Fig. 16. Simulated input current and voltages.

As expected in a power supply without PFC, the input current spikes at line frequency are large (3.5A). It is obvious that they also contain high harmonic content at multiples of the line frequency, as shown in Figure 17.

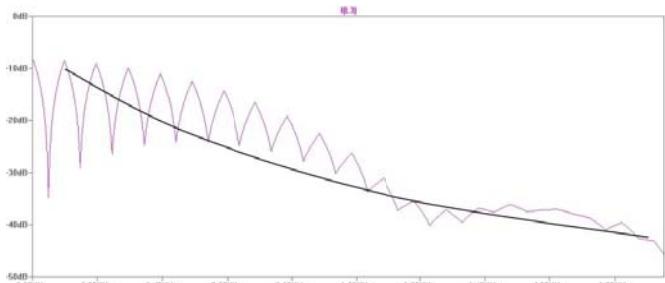


Fig. 17. Simulated EMI spectrum.

Here, the frequency range of 50Hz to 2kHz is shown as per the standard. Clearly, this design would not pass EN61k testing. The simulator would allow the insertion of low-frequency PFC filters to reduce the amplitude of the higher harmonics as needed but at this power level and the low frequencies involved, the filter would be very large. For this reason, an active PFC circuit should be considered.

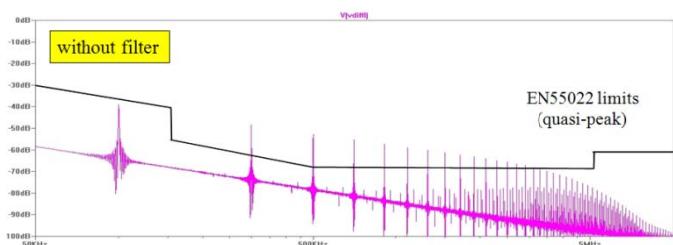


Fig. 18. Simulated spectrum without EMI filter.

Figure 18 shows the spectrum of V_{diffL} when no EMI filter is inserted in the circuit. The main switching frequency at 100kHz is clearly visible, and higher harmonics and the intermodulation results show up at higher frequencies. The amplitude is decreasing, which is caused by the decreasing impedance of the bus capacitance. In fact, playing with the ESR and ESL values of the bus cap show its impact on the amplitude of the noise peaks. From this picture, a first indication of the required attenuation levels can be derived and different filter choices can be made.

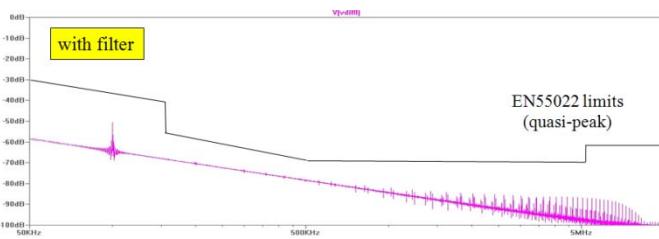


Fig. 19. Simulated spectrum with T-filter.

Fig. 19 shows the spectrum with the T-filter inserted. The main switching frequency is still visible, but the higher frequency content has been greatly attenuated. Simulating this design on a regular PC takes less than a minute, so testing alternative filter circuits and component values is relatively easy. The main advantage of using a behavioral representation of the main switching action of the power supply is the significant reduction in simulation time.

It is important to add realistic parasitics to the elements used in the EMI filter. If the simulation model uses only ideal inductors and capacitors, the simulation is pointless. In this example, the inductors have a parasitic C of 100pF and the capacitors have a parasitic inductance of 20nH. This may sound large but given the later arrangement of the components inside the filter, and the PCB traces to connect the parts, the values are of the right order of magnitude. Datasheets can provide a good indication of realistic parasitic elements. Alternatively, a good network analyzer can calculate the parasitic elements to be used in the models.

5. Build a Prototype

As explained, the noise signature of the power supply depends on many factors, including the layout and geometrical arrangement of the components. Therefore, it is desirable to build the prototype close to the final outline of the power supply, while still leaving space for the test points and the EMI filter. Try to be close to the final arrangement of components in the finished power supply so the radiated EMI "signature" can be verified.

Additional insight comes from measuring the inductors being inserted, like the transformers and chokes. This is done with a network analyzer, checking the behavior up to say 30MHz. With inductors, the parasitic capacitance and the inductance value at high frequencies is interesting and can help to spot radiated EMI issues. With transformers, the leakage inductance (also at higher frequencies) and the parasitic capacitances are at the primary, from primary to secondary, and to the shield may be helpful to know.

The routing on breadboard-type prototypes is usually done with hand-soldered metal wires that may have a lower resistance than the traces on the PCB of the final implementation. This may appear to have little relevance, but remember that the limits for noise voltages in question are very low as well. The higher PCB trace resistance leads to a higher noise voltage and trying to reduce it by widening the traces may result in higher common-mode noise. It can help to damp the ringing that may occur.

In the prototype, it is important to minimize high-current loop areas by putting the components close together, and routing the wires as close to each other as possible. This area is the "transmit" coil of the radiated field. If this area is minimized, then the field will be minimized and the parasitic inductance in this loop will slow down switching unnecessarily, leading to lower efficiency. If possible, the wires should be routed on top of each other. It is best to start the layout considerations with the high-current loops and arrange the rest around it. The control IC and its associated feedback and control circuitry should be arranged such that magnetic fields influence them as little as possible.

The power supply will have circuit nodes with a high dv/dt (the switching nodes). These nodes should be kept as small as possible, since any parasitic capacitance here will couple the switching noise capacitively to ground. To test this, mount the PCB on plastic spacers and place it on a metal surface connected to the ground of the input connector. This setup should be similar to the power supply mounting in the final product. The common mode noise will be much higher compared with testing the power supply on an isolated bench with a plastic surface, where the coupling will be much smaller.

Finally, leave some space at the input of the prototype for placement of EMI components. In most cases, a common mode choke, two additional differential mode inductors and two capacitors across the lines should be a good start. The common mode capacitors should be included as well. Figure 20 shows this basic setup:

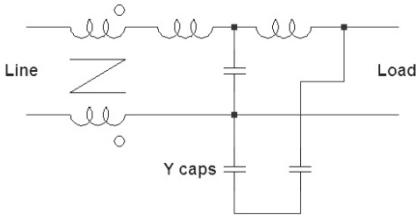


Fig. 20. Prototype EMI filter for 30W -200W Power Supplies

This should work for power supplies in the range of 30W to 200W. For smaller power supplies, fewer components may be required. For larger power supplies, a larger filter is needed, mostly driven by the higher peak currents. Remember that when the core of the inductor goes into saturation, the effective inductance value is greatly reduced, and all the noise will pass.

6. Test the Prototype

Once the power supply works well inside the specifications, it is worth performing pre-compliance testing of the power supply without an EMI filter, measuring the conducted noise (again, common and differential mode) and checking against simulation results. This will give a first indication of the required filter attenuation. It is quite useful to perform this test without an EMI filter, as this will show the unfiltered behavior. By adding the standard EMI structure, the potential problems may be harder to spot, since they may be smaller in amplitude.

In addition, check for frequencies that are not harmonics of the switching frequency – if you can spot them in the pre-compliance EMI spectrum, they may be a problem later. These frequencies come from resonant tanks in the circuit that are triggered by the switching action of the power supply, but resonate at their own natural frequency. Typical candidates for this are:

- Inductors resonating by themselves, at high frequencies where the parasitic capacitance and the inductor without core resonate (at these frequencies, the core may no longer contribute)
- Parasitic trace inductances (as a rough estimate, 1nH/mm) and parasitic capacitances of switching devices (e.g. MOSFET output capacitance or diode capacitance)
- Transformer leakage inductance and parasitic capacitances of the switching devices

First, perform radiated EMI tests to identify potential "candidates" for radiated fields. This procedure is explained in the section on radiated EMI. It is worthwhile spending half an hour on the working power supply, running at full power if possible (since this will cause the highest current spikes) and checking if particular hotspots can be found and explained. Next, compare the detected EMI frequencies with the lines in the conducted EMI spectrum to verify if they show up there as well. It is possible to get a "clean" voltage waveform on a node that shows strong radiated EMI, so looking at scope shots may not reveal the full picture. Redo the test at lower power, especially when the power supply changes its working modes across the power range, which many do (e.g. disabling parts of the power supply at lower power).

7. Add the EMI filter

Now it is time to add the pre-calculated EMI filter and test again. First, test the power supply across the full load range to see if the EMI filter has any negative impact on the proper function as it adds impedance in the input. If this is not done well, the added impedance at line frequency can starve the SMPS, and the output impedance of the EMI filter and its resonances may cause irregular behavior.

Next is another pre-compliance test on conducted EMI to see if the filter actually works as designed, and

provides enough attenuation, with a margin of 6dB–10dB. If not, check the spectrum and modify the component values. Another effective method, as explained above, is to add series-resonant tanks or RC shunts to help at certain problem frequencies.

If the damping is too high, it may be advisable to reduce the component values, e.g. by removing turns on the inductors, since the higher impedance may unnecessarily restrict dynamic behavior.

Remember to perform the test in a mechanical environment close to the final product, particularly for common mode noise, which is predominantly driven by capacitive coupling. This can be done with a metal sheet just below the PCB (with some isolation, of course).

8. Design the Final Version

The implementation of the final version into a PCB will change certain aspects of both the conducted and radiated EMI so care is needed when applying the modifications. Specifically, the grounding and the mechanical arrangement are important. The grounding will impact the common mode noise and the mechanical arrangement will impact radiated EMI and its impact within the power supply. Try arranging larger chokes at 90° angles to reduce the magnetic pickup of the noise. In a flyback converter, the transformer shield should be connected to the source of the switching element to shorten the capacitive return path of the switching noise. If a second shield is implemented, it should be connected to ground. Watch out for changes in the pinout of connectors or high-current components, as this may seem like a little change but can modify the high-current loops and their radiating area.

It is also time to think about manufacturing and the specifications of the components to be used in mass production. Their characteristics may vary (especially with the passive components), and so will their behavior regarding EMI.

It is quite common for capacitance values of electrolytic caps to change between -20% and +50%. Few manufacturers will specify variations on ESR and ESL, yet these values have a strong impact on EMI behavior, as seen before regarding the bulk capacitor and conducted EMI. Component variations are less of an issue with a (foil) capacitor used e.g. in the EMI filters,

since they tend to have less variation. It may be advisable for correct high frequency behavior to put a foil capacitor in parallel with the bus capacitor, since this will control its high frequency behavior much better. This is also the topology you usually end up with when combining an EMI filter in a pi topology with a “normal” SMPS.

Inductors may also vary significantly. Here, it is mostly the mechanical changes like proper mounting of the two halves of the transformer core that can make a big difference.

9. Test the Final Version

On the final version of the power supply, after verifying the full function of the power supply, perform pre-compliance testing again to check if the noise levels are still acceptable. You should have a good understanding on the areas of influence you still have when something is not as it should be.

Pre-compliance testing at high and low line conditions should be performed, with low line being more critical (longer conduction angle on the input rectifiers and higher currents in the power supply). This will be the worst case for radiated EMI.

Build several power supplies and check if the noise levels are repeatable, or vary significantly from power supply to power supply. If so, the real source for the noise signal(s) has not properly been identified and controlled. As most components cannot vary that much during operation, a prime candidate for this particular problem is the gate drive of the main switches. If there are layout issues, ringing, spikes, or capacitive feed-through, the rise and fall times may not be well-controlled, causing larger variations in the EMI spectrum. Again, you may not be able to see this from the voltage waveforms on the switching nodes, and this problem may also not be apparent from the efficiency curves.

It may also be advisable, especially when using passive components that are not fully specified and guaranteed in performance, to test a number of components of the different sources, to see if the power supply fully works and complies with EMI requirements at any combination.

VI. CONCLUSION

As long as voltages and currents are being switched, EMI will be generated and need to be addressed. This implies that there will never be a “silver bullet” — just improvements to the situation to arrive at an acceptable compromise. Once the basic mechanisms are understood, it is easier to analyze and re-engineer a given power supply to improve its behavior and really exploit all the performance advantages of modern power switches.

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