

AN-2162 Simple Success With Conducted EMI From DC-DC Converters

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ABSTRACT

Electromagnetic Interference (EMI) is an unwanted effect between two electrical systems as a result of either electromagnetic radiation or electromagnetic conduction. EMI is the major adverse effect caused by the application of switch-mode power supplies (SMPS). In switching power supplies, EMI noise is unavoidable due to the switching actions of the semiconductor devices and resulting discontinuous currents. EMI control is one of the more difficult challenges in SMPS design, beyond functional issues, robustness, cost, thermal and space constraints.

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1 Overview

Electromagnetic Interference (EMI) is an unwanted effect between two electrical systems as a result of either electromagnetic radiation or electromagnetic conduction. EMI is the major adverse effect caused by the application of switch-mode power supplies (SMPS). In switching power supplies, EMI noise is unavoidable due to the switching actions of the semiconductor devices and resulting discontinuous currents. EMI control is one of the more difficult challenges in SMPS design, beyond functional issues, robustness, cost, thermal and space constraints.

To prevent electronics from interfering with the operation of other devices, EMI is regulated by the government where the electronic device is being sold. In Europe, there are the European norms, (EN55022 etc.) and in the USA there is FCC part 15. EMI in SMPS is classified in two forms: conducted EMI and radiated EMI. They are differentiated by the manner in which the EM field propagates between circuits. For conducted EMI, noise is coupled via conductors or through parasitic impedances, or power and ground connections. While for radiated EMI, unwanted noise is coupled via radio transmission. This brief focuses on the theory and mitigation techniques of the conducted portion of EMI, specifically as generated by a step-down switcher.

2 Conducted EMI

Conducted EMI arises from the normal operation of switching circuits. The ON and OFF actions of the power switches generate large discontinuous currents. The discontinuous currents are present at the input side of buck converters, the output side of boost converters and at both input and output ports of flyback and buck-boost topologies. Voltage ripple generated by discontinuous currents can be conducted to other systems via physical contact of the conductors. Without control, excessive input and/or output voltage ripple can compromise operation of the source, load or adjacent system. The discontinuous currents at the input port of a converter need to be filtered by an input filter to smooth out the voltage perturbations leading to the source. Meanwhile, the output side is usually well filtered by the existing output filter of the converter. Proper application of filtering leads to meeting regulatory requirements that allow the end product to be sellable in the marketplace.

Conducted EMI is sub-divided into differential-mode and common-mode categories as the two modes are similarly measured but controlled through different methods. The following schematic is a representation of a SMPS system showing common mode and differential mode signal locations. This configuration is generally found with the AC-DC type SMPS as well as galvanically isolated DC-DC converters, as shown in Figure 1.

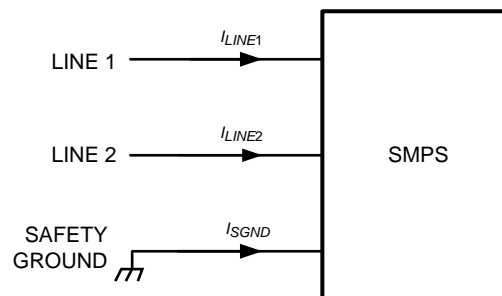


Figure 1. Three-Line SMPS Input Port

The common mode noise V_{COMM} and differential mode noise V_{DIFF} are described by

$$V_{\text{COMM}} = (V_{\text{LINE1}} + V_{\text{LINE2}}) / 2 \text{ and } V_{\text{DIFF}} = (V_{\text{LINE1}} - V_{\text{LINE2}}) / 2, \quad (1)$$

where V_{LINE1} and V_{LINE2} are the noise voltages on line and return terminals, respectively. Common mode conducted noise is a signal which is found in-phase on both the line and return conductors with respect to safety ground. Common mode noise also typically has equal amplitude on both line and return conductors with respect to neutral. In contrast, differential mode interference is a noise signal which exists between the line and return conductors. (Line 1 and Line 2)

In a typical IC based non-isolated DC-DC SMPS, only two lines connect to the input port. So any current going in through one terminal has to go out through the other. In this configuration, the common mode noise V_{COMM} will always be zero.

Figure 2 represents a typical SMPS system that has differential mode noise only. This configuration is found with non-isolated DC-DC type SMPS. The balance of this application note focuses on the reduction of this type of differential mode conducted EMI.

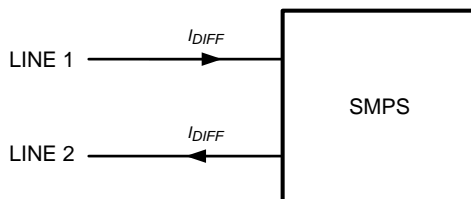


Figure 2. Two-Line SMPS Input Port With Differential Mode Noise Only

3 Conducted EMI Characteristics And Mitigation Technique

Conducted EMI involves the normal operation of DC-DC converters. It does not involve circuit parasitics except input or output capacitor ESR and ESL. PCB layout itself is not going to help reduce conducted EMI. Further, conducted EMI is only related to the current level, not the voltage level at input or output ports. In another words, with the same power level buck converter, lower input voltage means higher input current, thus worse input conducted EMI.

Compliance with conducted EMI standards usually requires the addition of a low pass filter between a switching-mode power converter and the input power source. Typically this is a passive LC filter with the inductor placed on the “hot” input lead of the SMPS (LINE1 in Figure 2).

The input port EMI noise comes from voltage ripple generated by the discontinuous current on the input capacitors. The fundamental frequency of the voltage ripple is the switching frequency of the converter. Higher order harmonics of the fundamental frequency also exist in the noise spectrum. Figure 3 represents a typical conducted differential-mode EMI plot of a DC-DC buck SMPS prior to the addition of the EMI filter. Note that the fundamental switching frequency and several harmonics extend above the regulatory limits. The height of the fundamental above the target limit line establishes the required additional filter attenuation needed in order to comply with the desired limit. Also note that from the standpoint of regulatory test requirements, the measurement frequency span extends from 10 kHz up to 30 MHz. However, there may be system requirements above the frequency range of the regulatory spec that fall into the scope of the SMPS input filter. These system requirements should also be considered and evaluated. It has been observed that keeping the conducted differential EMI performance in check above 30 MHz will assist in meeting the separately tested radiated EMI requirements. See AN-2155 for a discussion of radiated EMI mitigation.

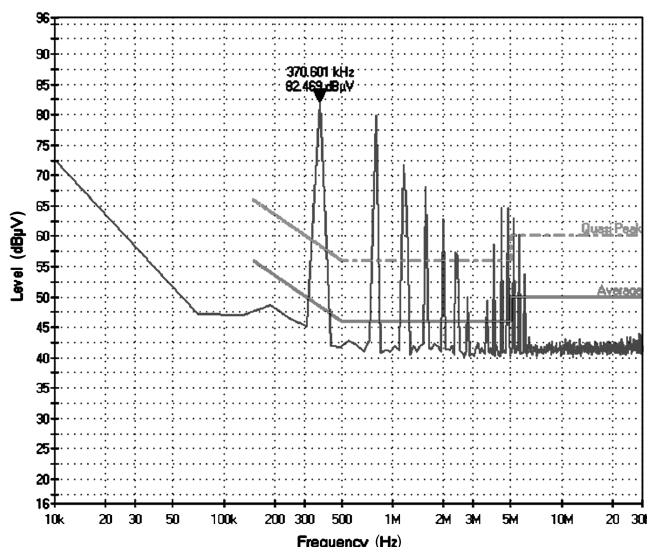


Figure 3. Conducted EMI Measurement Without Filter
Switching Frequency = 370 kHz

Figure 4 shows the conventional circuit configuration with a DC power source, the LC EMI filter and the target SMPS. Note the EMI filter configuration is actually from the right to the left. In other words the filter “ac input” is V_B and the filter “ac output” is V_A . Filter design is accomplished by choosing the inductor L_f and the capacitor C_f .

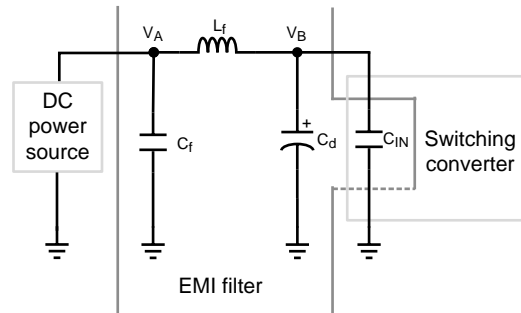


Figure 4. Simplified Schematic For EMI Filter Design

The typical procedure for designing an input filter for a Buck or Buck-Boost converter is summarized below:

1. Identify noise level at the switching frequency. Figure 3 shows the most significant noise magnitude appearing at the switching frequency. The required attenuation is the difference between the non-filtered noise level and the governing EMI standard requirement at the switching frequency. The low pass filter provides even greater attenuation for the higher order harmonics of the switching frequency. The switching frequency attenuation is the worst case condition and is the focus of the filter design. The typical procedure is to measure the EMI peak level without added filters under worst case operation. (Highest input current.) The repeatable measurement of conducted EMI performance requires the inclusion of a Line Impedance Stabilization Network (LISN) between the power source and the EMI filter. Details on noise measurement by a LISN is provided in a later session of the document Section 6. (This brief also provides two methods to quantify the noise magnitude without a LISN.)
2. Calculate the required attenuation. The difference between the noise level at the fundamental switching frequency and the required level defined in the appropriate standard for the target market place.
3. Select filter inductance L_f .
4. Calculate filter capacitance C_f .
5. Calculate damping capacitance C_d . Another aspect of the design of the LC stage is that large values of L_f and small values of C_{IN} can lead to input instability on the SMPS with accompanying adverse effects on the normal operation of the supply. The damping capacitance C_d can be used to provide extra damping such that the input filter is not affecting the stability of the converter.

4 EMI Filter Design

This brief provides simple equations to predict the required attenuation and L_f , C_f selection.

4.1 Required attenuation

Two easy-to-use methods introduced here can be used to estimate the required EMI filter attenuation previous to making a certified measurement using a LISN and spectrum analyzer.

METHOD 1

It has been observed that the time domain amplitude of input ripple can lend to an estimate of the required attenuation needed and can be done using a wide bandwidth oscilloscope. Observing the voltage ripple on the input of the SMPS with an oscilloscope and applying the following equation allows us to estimate the fundamental EMI amplitude. This method allows a first pass design of the filter components previous to certified measurements.

$$|Att|_{dB} = 20 \log (V_{in-ripple-p2p} / 1\mu V) - V_{max} \quad (2)$$

where $|Att|_{dB}$ is the required attenuation for the input filter design in dB; the $V_{in-ripple-p2p}$ is the measured peak-to-peak voltage ripple at the switching frequency in volts; and V_{max} is the target maximum allowable value at the switching frequency in dB. V_{max} is a noise level requirement found in the appropriate EMI standard at the switching frequency.

METHOD 2

The current at the input can be modeled as a square wave (by assuming small ripple approximation), as shown in Figure 5.

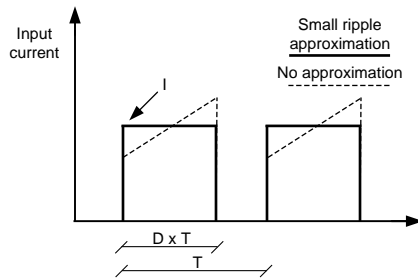


Figure 5. Small Ripple Approximation

By simply extracting the first harmonic of current from the Fourier Series of the input current waveform and multiplying that value by the impedance at the input port (the impedance is defined by the existing input capacitor C_{IN}), an analytical formula can be derived to obtain the required attenuation:

$$|Att|_{dB} = 20 \log \left(\frac{\frac{I}{\pi^2 f_s C_{IN}} \sin(\pi D)}{1 \mu V} \right) - V_{max} \quad (3)$$

Where D is the duty cycle, I is the DC inductor current (which corresponds to the output current in case of a buck converter), f_s is the switching frequency, and C_{IN} is the existing input capacitor of the converter which is assumed to be a low ESR ceramic type.

4.2 Inductor Selection: L_f

The inductor defines the resonant frequency of the EMI filter hence its value (L_f) is usually in the range of 1 μH to 10 μH for low and medium power applications. Choose the highest value in compliance with amperage and physical size requirements.

4.3 Capacitor Selection: C_f

Pick the higher value determined by the following two formulas:

$$C_{fa} = \frac{C_{IN}}{C_{IN} L_f (2\pi f_s / 10)^2 - 1} \quad (4)$$

$$C_{fb} = \frac{1}{L_f} \left(\frac{10^{|Att|_{dB}/40}}{2\pi f_s} \right)^2 \quad (5)$$

Where f_s is the switching frequency of the converter.

The first formula ensures that the resonance frequency of the EMI input filter is at least one decade below the switching frequency. The second formula is derived from an approximation that ensures proper attenuation of the EMI filter. Select the higher value of C_{fa} and C_{fb} because both conditions must be met.

4.4 Damping capacitor: C_d

Addition of an input filter to a switching regulator leads to a modified control-to-output transfer function. The output impedance of the filter must be sufficiently small at point VB so that input filter does not significantly affect the loop gain of the SMPS. The peak of the impedance at the filter's resonance corner frequency is largely dependent on the filter LC parasitics. Added damping is needed when the output impedance is very high at the resonant frequency. (i.e. Q of filter formed by C_{IN} and L_f is too high.)

An electrolytic cap C_d can be used as damping device, with value

$$C_d \geq 4 \times C_{IN} \quad (6)$$

And ESR value:

$$ESR_d \approx \sqrt{L_f / C_{IN}} \quad (7)$$

The purpose of ESR_d is to reduce the peak output impedance of the filter at the cutoff frequency. The capacitor C_d blocks the dc component of the input voltage, and avoids excessive power dissipation on ESR_d . The capacitor C_d should have lower impedance than ESR_d at the resonant frequency, with a value greater than the filter capacitor C_{IN} , in order to not affect the cutoff point of the main filter. Figure 6 shows transfer functions of an undamped (solid line) and a damped (dotted line) filter as an example. This represents the source impedance of the EMI filter output at point VB, looking toward the dc source. The impedance peak of the filter is greatly reduced with the addition of the damping capacitor. The dc voltage rating of the electrolytic should be at least 25% larger than the worst case maximum source voltage.

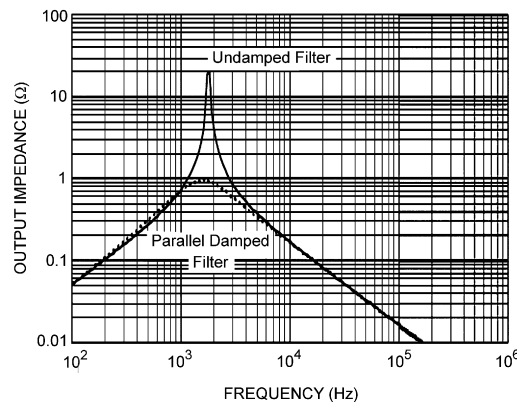


Figure 6. Example Of Undamped And Damped Filter

5 Design Example

5.1 Example 1: LMZ23605

The first design example is based on LMZ23605 Evaluation Board. Please refer to AN-2085 for the details about the board.

The operation condition of the experiment is summarized below:

V_{IN} (min)	30 V
V_{OUT}	3.3 V
I_{OUT} (max)	3 A
C_{IN}	$2 \times 10 \mu F$
f_S	800 kHz

The input filter component values used in the experiment is listed below:

Est. Noise Level	$\approx 80 \text{ dB}\mu V$
Required Noise Level V_{max}	$\approx 40 \text{ dB}\mu V$
Required Attenuation	40 dB
Selected L_f	1 μH
Calculated C_{fa}	4.9 μF
Calculated C_{fb}	2.5 μF
Selected C_f	4.7 μF
C_d	150 μF^*

NOTE: * C_d here is part of the input capacitors on the LMZ23605 evaluation board.

Figure 7 shows the additional attenuation provided by the addition of L_f and C_f . Figure 8 shows the conducted differential-mode EMI plot of the LMZ23605 Evaluation Board before and after the addition of LC filter.

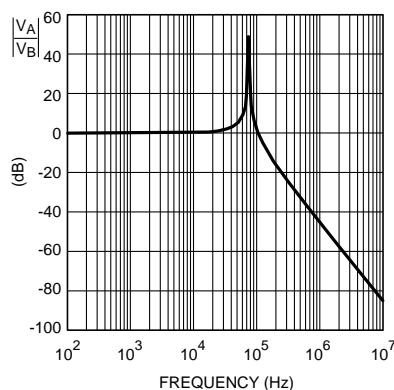


Figure 7. Bode Plot of the LMZ23605 additional (L_f, C_f) input filter

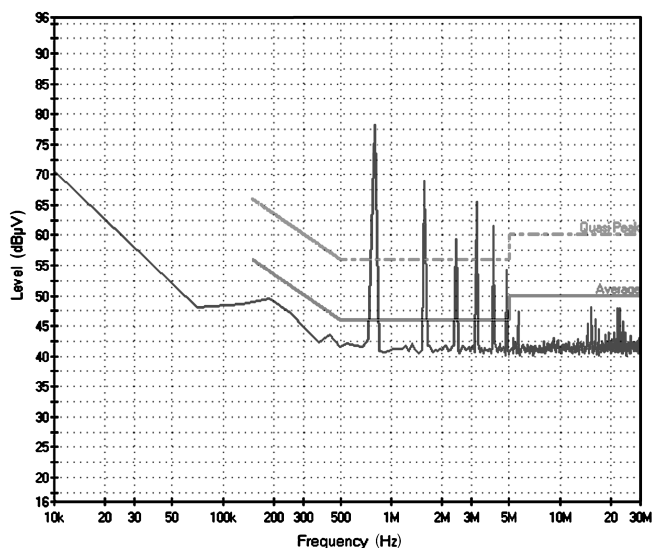


Figure 8. LMZ23605 Evaluation Board Conducted EMI Measurement Without Filter

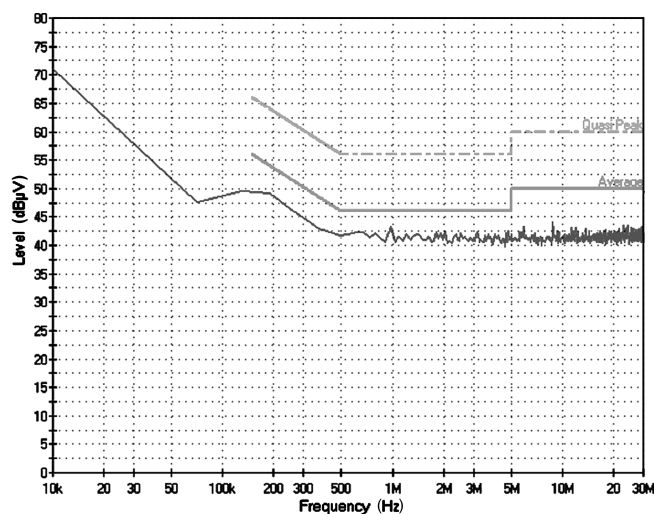


Figure 9. LMZ23605 Evaluation Board Conducted EMI Measurement With Filter

5.2 Example 2: LMZ14202

The second example is based on LMZ14202 Evaluation Board. Please refer to AN-2024 for more details.

The operation condition of the experiment is summarized below:

V_{IN} (min)	30 V
V_{OUT}	3.3 V
I_{OUT} (max)	1.6 A
C_{IN}	10 μ F + 1 μ F
f_S	370 kHz

The input filter component values used in the experiment is listed below:

Est. Noise Level	\approx 80 dB μ V
Required Noise Level V_{max}	\approx 40 dB μ V
Required Attenuation	40 dB
Selected L_f	3.9 μH
Calculated C_{fa}	8.3 μ F
Calculated C_{fb}	6.4 μ F
Selected C_f	10 μF
C_d	100 μF

Figure 10 shows the additional attenuation provided by the addition of L_f and C_f . Figure 11 shows the conducted differential-mode EMI plot of the LMZ23605 Evaluation Board before and after the addition of LC filter.

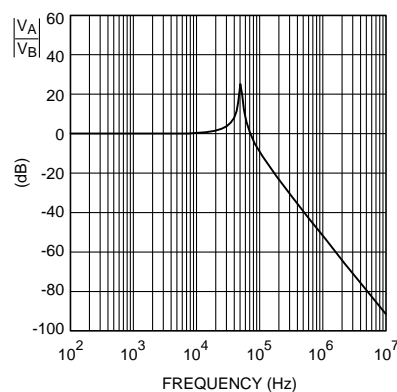


Figure 10. Bode Plot of the LMZ14202 additional (L_f , C_f) input filter

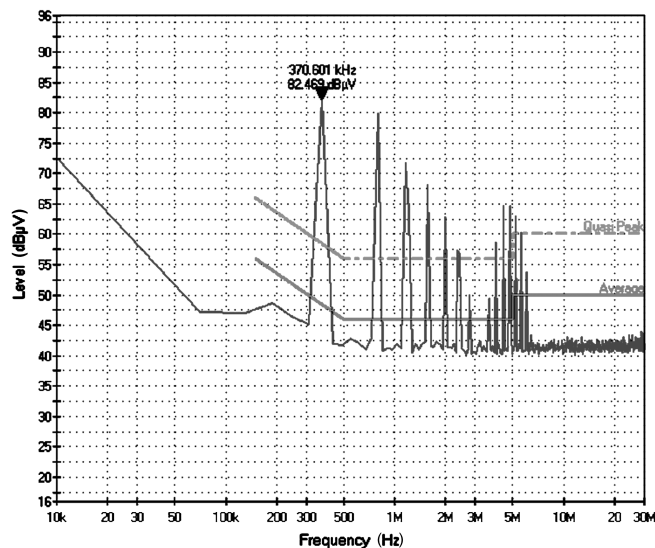


Figure 11. LMZ14202 Evaluation Board Conducted EMI Measurement Without Filter

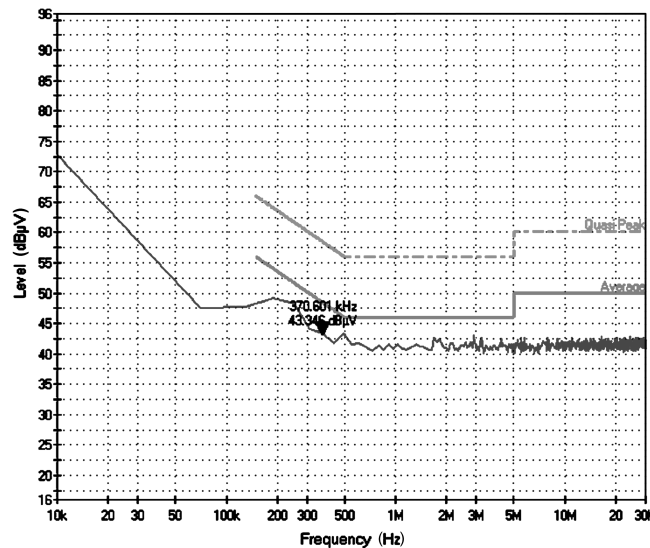


Figure 12. LMZ14202 Evaluation Board Conducted EMI Measurement With Filter

In most cases LC design will benefit from iteration. In these examples, the SMPS system now passes required conducted compliance levels.

The EMI measurements shown in this document are obtained using a Line Impedance Stabilization Network (LISN). The details of a LISN are discussed in the next section.

6 Line Impedance Stabilization Network

For consistent results, conducted EMI tests are performed using a temporarily installed passive device called a LISN. The LISN is connected in series with the power input lines to the SMPS under test. The LISN establishes consistent source and measurement impedance allowing for repeatability of test results. Conducted emissions are measured using a spectrum analyzer via an RF connection to a port on the LISN. The LISN is employed for both common mode and differential mode tests.

The schematic of a three-line SMPS test system with the LISN included is shown in Figure 13. Figure 14 shows the LISN equivalent circuit in a two-line SMPS. Run EMI scans with the spectrum analyzer connected first to Line 1 and then to Line 2 and select the scan with the highest graphical results. Note that average and quasi-peak limit lines are illustrated on the EMI plots. Consult the spectrum analyzer equipment operating manual for proper interpretation.

Regulatory standards suggest the required bench arrangement for location of source, LISN, SMPS under test, and their locations relative to the measurement bench top. These locations must certainly be observed for certified tests. However, there is notable freedom to depart from these positions for trial readings provided the power cables aren't coiled up tightly. Tightly coiled power cords may contribute series cable inductance that may falsely lower the analyzer reading.

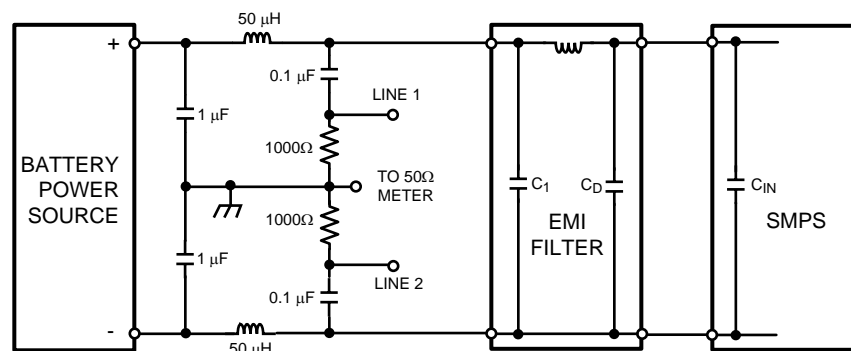


Figure 13. Schematic of Test Setup Showing Internal LISN Components

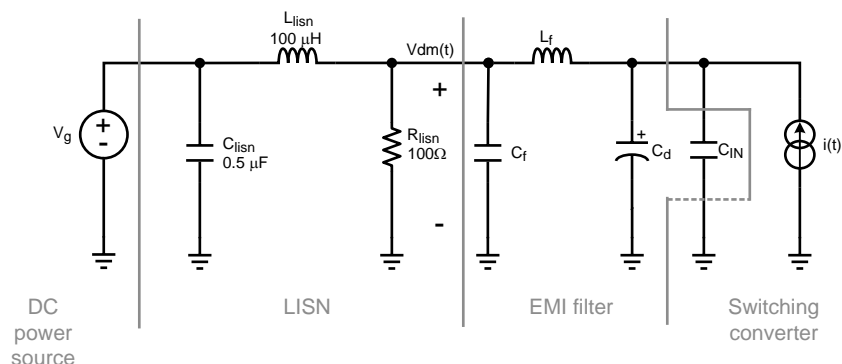


Figure 14. Schematic of Test Setup With LISN Equivalent Circuit in DC-DC Converters

CAUTION

The LISN is traditionally employed to test AC line operated products and usually has conventional US NEMA AC power connectors for I/O. These need to be adapted to appropriate DC connections for the power source and system under test. Caution - Be sure to securely stow these AC/DC cord adapters when not in use as the open wire terminations will present lethal voltages if inappropriately connected to mains wiring. It also can lead to disastrous results if AC mains voltage is applied to the DC-DC converter input.

The LISN has a selector switch to connect its monitoring output to either the hot or return supply leads labeled Line1 and Line2. A measurement scan is performed separately on each switch setting. Each spectrum analyzer scan takes approximately 10 minutes to complete.

It is highly recommended that a battery be used as the measurement system power source. A battery provides a quiet source of dc power that won't create or couple additional sources of EMI. Since batteries are a low impedance source, always include a series fuse for fire safety protection. Additionally an On-Off switch provides a convenient method of preserving battery run time between scans. LED indicators can provide quick operating status without added complexity.

An auxiliary function of the LISN is to protect the spectrum analyzer from the dc voltage present on the supply and return power conductors. This is accomplished by the 0.1 μF blocking capacitor(s) preceding the Line1-Line2 switch. The capacitor forms a high pass filter function that blocks the DC supply voltage from the sensitive 50 Ohm spectrum analyzer input. However, the high pass filter also faithfully couples the step voltage change that occurs when the Line1-Line2 or battery power switches are actuated. So it is advisable that the spectrum analyzer input be temporarily disconnected prior to any switching event. (As the measurement bandwidth is only 30 MHz, BNC interconnects can speed this step.) This will reduce the chance of damage to the spectrum analyzer input as the result of a switch induced transient. Damage to the input of the spectrum analyzer is both costly and time consuming to properly repair.

7 References

- [1] : Robert W. Erickson, "Optimal Single Resistor Damping for Input Filter"
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- [3] : M. Sclocchi, "Input filter design for switching power supplies"

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