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Using Ruggedized EMI Filters To Pass The CS101 Requirement Of MIL-STD-461D-F

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Power systems designed for military applications that require compliance to MIL-STD-461D-F must use an input EMI filter that contains adequate damping to meet the conducted susceptibility requirements of CS101. The risk of failing the CS101 test is often highest in the mid-frequency range, which includes the EMI filter cutoff frequency (typically 1 kHz to 10 kHz) where some filters exhibit peaking in their responses.

In this article, the CS101 requirements are examined and its implications for the design of the power system—the combination of input EMI filter plus power converter (i.e. a dc-dc converter)—are discussed at length. Finally, a discussion of the CS101 test methods is presented, including a number of testing precautions that designers should observe.

Impact Of EMI Filters On Bus Ripple

Most engineers buy EMI filters for the purpose of reducing high-frequency noise currents generated by a power converter in order to pass conducted and radiated emissions. But the filter also serves the very important role of attenuating any ripple voltage that exists on the input power bus.

Fortunately, a filter designed to meet the conducted emissions requirements will naturally attenuate bus ripple voltages at frequencies above the filter cutoff frequency with no additional effort by the filter designer (Reciprocity Theorem.) However, a filter designed only for conducted and radiated emissions may have a very high Q in order to save board space and reduce component count. This situation can be a problem when trying to meet CS101.

Fig. 1 curve “a” shows a filter response designed solely for emissions. Such filters may pass the emission requirements, but will often cause amplification of the input bus ripple at the filter cutoff frequency. Such amplification may result in a failure of the conducted susceptibility requirements in MIL-STD-461F, especially the CS101 requirement. A failure of MIL-STD-461F may be caused by excessive output ripple of the power converter (i.e. performance degradation of the load), internal large-signal interrupts (i.e. unexpected undervoltage interrupts) or damage to the power converter due to excessive ripple-induced component dissipation.

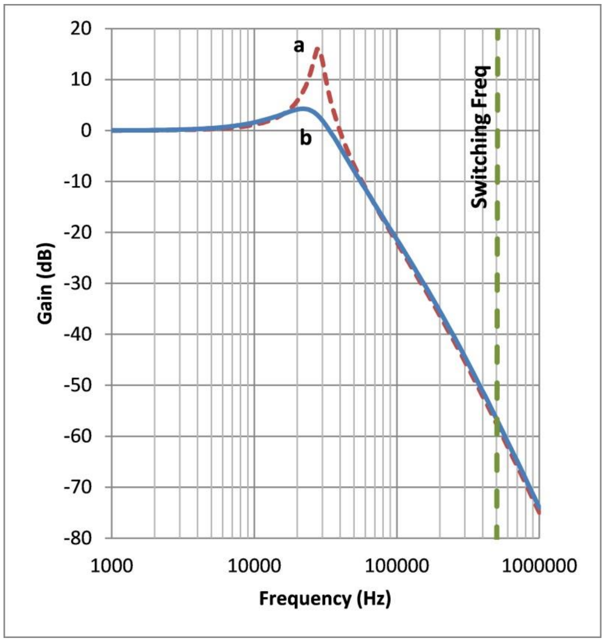

Fig. 1. EMI filter gain for an (a) underdamped and (b) damped design.

The CS101 Test Requirement

The CS101 requirement in MIL-STD-461F mandates that the equipment under test (EUT) continue to meet the specified performance according to the individual equipment or subsystem specification when subjected to an applied continuous sinewave signal that is injected onto the input power leads. The signal is injected differentially onto the power leads through the use a power amplifier and an injection transformer.

The magnitude of the injected signal is set according to either the voltage limit curve (measured at the EUT input) or the power limit curve (measured at the excitation generator terminals) (Fig. 2), whichever is the lesser. The test can be performed with a linear sweep over the full frequency range (30 Hz to 150 kHz), or with more sophisticated equipment, the full spectrum can be tested using discrete frequency steps with minimum dwell times.

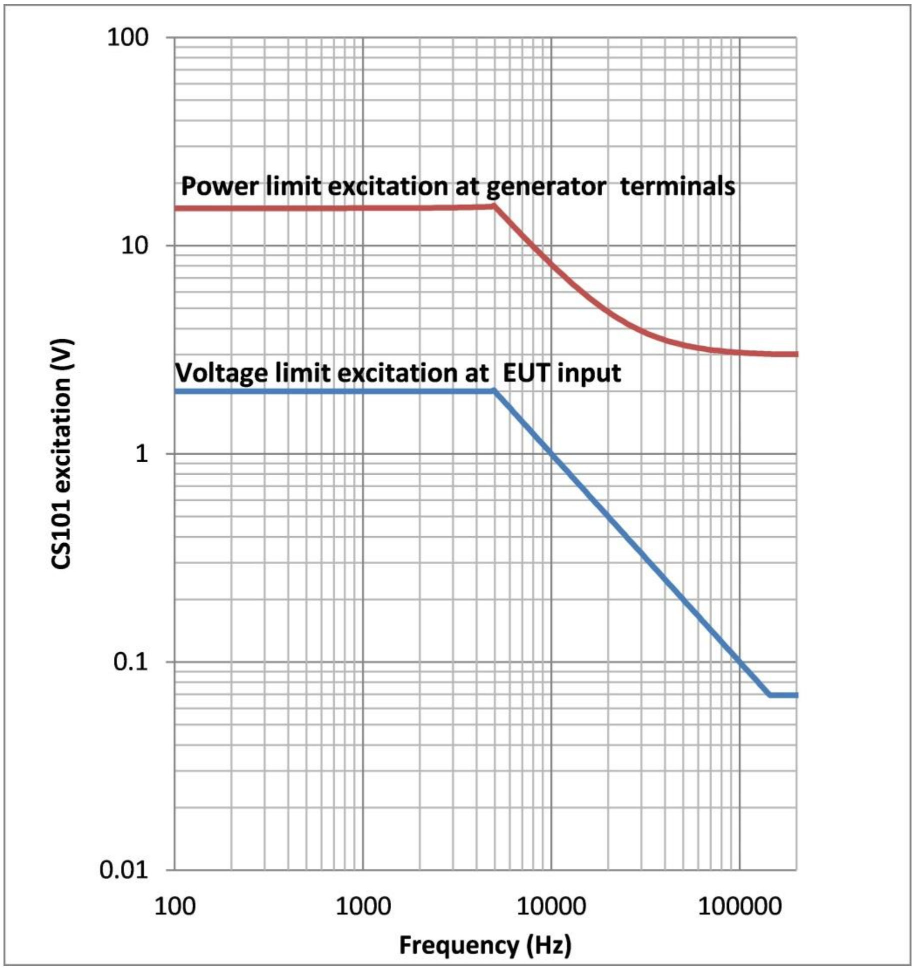

Fig. 2. CS101 excitation limit curves.

When developing a power system that can meet CS101, there are two primary design criteria. The first criterion is simply to make sure that the internal components within the power system don't get over-stressed (especially damping elements.) The second criterion is to provide enough attenuation of the injected signal to maintain a very low ripple voltage on the converter output. How much signal attenuation is required will depend upon the equipment performance specification and the sensitivity of the equipment to output ripple voltage at different frequencies.

When designing a power system, the designer typically does not know the equipment sensitivity to output ripple. As a result, it is a common practice to design for as much attenuation as is practical given the cost and space constraints of the power system, and then perform the CS101 test with the powered equipment attached to determine pass/fail.

Power System Gain

For a simple power system architecture that includes an EMI filter followed by a power converter, both stages must work together to attenuate the injected input signal. For the converter, current-mode control provides better audio rejection than voltage-mode control due to the current-loop cancellation of the output L-C filter resonance as well as the feed-forward effect of the current loop.

Typically, the converter provides good audio rejection over the entire frequency spectrum. This is usually true because at frequencies beyond the converter bandwidth, the input signal is attenuated by the output L-C filter. At frequencies below the converter bandwidth, the active feedback loop gain provides good attenuation. It is common for the output L-C filter resonance to be inside the bandwidth of the converter, thus maintaining high signal attenuation across the entire spectrum. A second-stage output L-C filter will create a peak in the audio gain plot if underdamped, but this peak is typically at a frequency much higher than the input EMI filter resonant frequency, so the combined audio rejection is often sufficient.

For the EMI filter, the attenuation at higher frequencies is usually dictated by the level of rejection that is required to meet the conducted emissions requirement. When designing for CS101, typically the design activity involves adding damping elements to a preliminary filter that was initially designed for meeting conducted emissions. Damping is important because it lowers the filter Q, which lowers the peak gain at the resonant frequency. The filter may have multiple resonant frequencies, but the lowest resonant frequency (cutoff frequency) is of primary concern for CS101 because it will result in a gain greater than 1.0, which magnifies the input signal.

If insufficient damping is used, the signal magnification at the lowest resonant frequency can be very high; which shifts the burden to the converter to adequately attenuate the amplified signal. Inadequate filter damping will also cause the filter to interact with the converter loop gain, which could cause degraded transient performance as well as instability.

Audio Rejection

When considering the audio rejection of an EMI filter/converter combination, it’s helpful to break up the frequency spectrum into three frequency bands: low frequency, mid frequency and high frequency.

At frequencies below the filter cutoff frequency, (Fig. 3a), 100% of the audio rejection is provided by the converter. However, the converter audio rejection at these low frequencies is usually very high due to the feedback loop gain. For this frequency band, it is advantageous to have very high loop gain at low frequency and high bandwidth. Current-mode control also provides additional benefits.

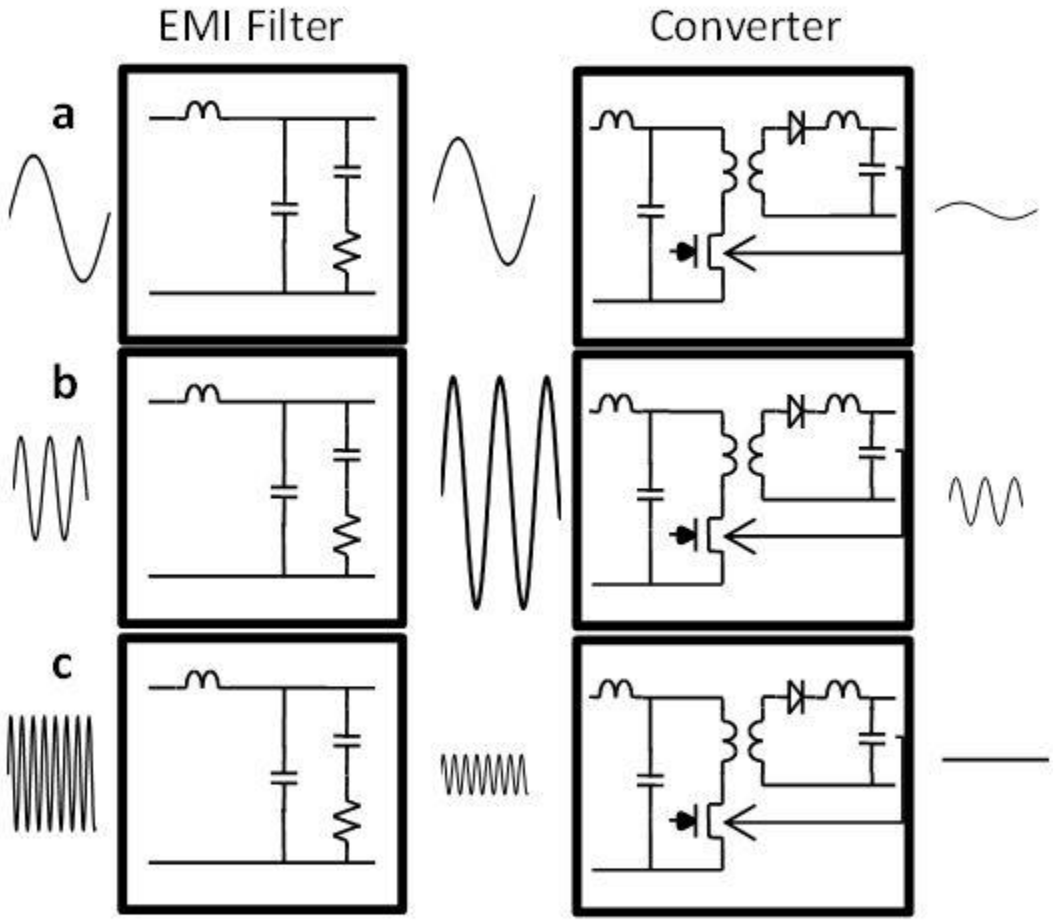

Fig. 3. Power system gains in different frequency regions.

At mid-level frequencies near the filter resonance (typically 1 kHz to 10 kHz), the audio rejection is dominated by the filter damping (Fig. 3b.) A good converter design will have adequate audio rejection in the mid-frequency band, but these benefits may be compromised by an inadequately-damped filter that causes excessive audio amplification of the input signal. Because a practical filter design (considering cost and space) will usually result in an underdamped input filter (Q > 0.5), it is usually necessary to add enough damping to limit the Q to less than 3.0. And if cost and space permit, it is usually helpful to reduce the Q even further.

However, as the filter Q is lowered below 3.0, the incremental growth in board space and component count starts to have diminishing returns. Attempting to lower the Q below 2.0 typically requires an unacceptably large circuit board area and component count. In general, lowering the filter Q will increase overall audio rejection at the resonant frequency and thus reduce the risk of failing CS101. Since it's uncommon to know in advance how much audio rejection is necessary to pass CS101, the design activity is often governed by design goals with the purpose of reducing risks. If the system fails the CS101 test, it is usually in this mid-level frequency band. This frequency band is where the designer should focus most of the design effort.

At higher frequencies above the EMI filter resonance, the audio rejection is typically very good where the EMI filter is providing the majority of the rejection. A good converter design will also provide a significant amount of rejection. The combined audio rejection of the filter and converter is typically very high in the higher frequencies (Fig. 3c.)

Test Method Considerations

When performing a CS101 test, the spectrum of highest risk is typically right at the resonant frequency of the EMI filter. When the injected signal is applied at that frequency, it is not uncommon for the power amplifier to limit the signal magnitude according to the power limit curve in MIL-STD-461F. If the filter cutoff frequency is 5 kHz or less, then the power limit is defined as the audio amplifier output voltage that results in 80 W of dissipation in a 0.5-Ω calibrated resistor load. Using a typical injection transformer with a 2:1 turn ratio, this equates to an amplifier output voltage of approximately 15 Vrms (≤5 kHz.)

If the amplifier reaches the pre-calibrated power limit at the resonant frequency of the filter, this does not mean that the EMI filter is dissipating 80 W! This is true because when examining the ac loop, which includes the signal injection transformer, the EMI filter input terminals are effectively in series with the 10-μF capacitor in the setup diagram of CS101 (Fig. 4.)

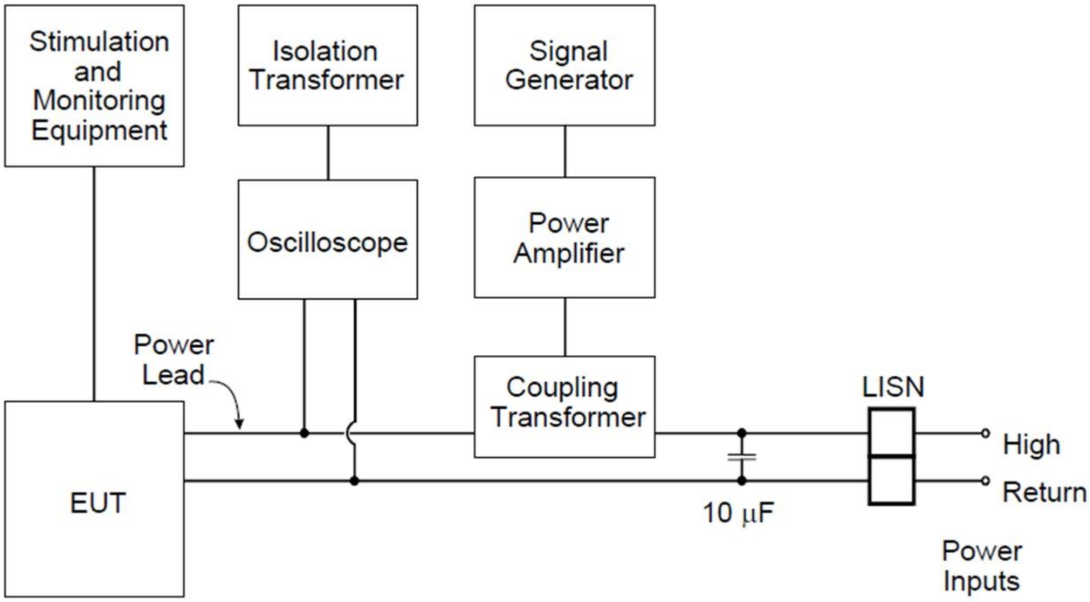

Fig. 4. CS101 test setup.

Consider an example power system with a filter resonant frequency of 3 kHz. If the power limit is reached during the test at 3 kHz, then the injection transformer secondary voltage is typically 7.0 ±0.5 Vrms (typical calibration terminal voltage that accounts for transformer parasitics.) At 3 kHz, the 10-μF capacitor has an impedance of –j5.3 Ω. This impedance is added to the complex input impedance of the filter.

In a practical system, the impedance of the 10-μF capacitor in series with the filter input impedance is typically greater than the 0.5-Ω calibration load. For this reason, the injection signal current is much smaller than the current generated during the calibration test that dissipated 80 W. Although the filter won't typically dissipate 80 W, damping elements within the filter can experience a significant increase in power dissipation at the resonant frequency, which the filter designer must consider when sizing the damping elements. From this analysis, it is clear that the external 10-μF capacitor plays a very important role in limiting the ac current into the filter and thus the dissipation of the damping elements.

The 10-μF external capacitor forms an underdamped L-C tank circuit with the 50-μH line impedance stabilization networks (LISNs) with a natural resonant frequency of 5 kHz. Another potential L-C resonant tank circuit is formed by the LISNs and the total bulk capacitance on the input stage of the power system (including EMI filter and input stage of the converter module.) If the resonant frequency of the LISNs and power system input capacitance is less than the resonant frequency of the LISNs and the 10-μF capacitor, then the power system will be resonant with the LISNs during the CS101 test. This resonance causes increased dissipation in the EMI filter damping elements.

Attempts have been made to increase the external 10-μF capacitor value to eliminate the resonance that the power system makes with the LISNs. This may be a violation of the CS101 requirements since no such allowances are made explicitly.

Furthermore, while it is tempting to increase the 10-µF capacitor value, as is often the case in electronics, this doesn't come without consequences. Increasing the 10-µF capacitor lowers its impedance at the cutoff frequency of the EMI filter. Since this capacitor is effectively in series with the EMI filter, increasing the capacitance results in overall lower load impedance to the injection transformer, which increases the injected ac current magnitude. The increase in current magnitude results in increased dissipation within the EMI filter.

Another caution when performing the CS101 test concerns the impact that the power system inrush current may have on the power amplifier during a turn-on event. If the power amplifier and injection transformer are connected in-circuit when the EUT is turned on, the inrush current flowing through the injection transformer can force damaging levels of current into the output stage of the power amplifier. For this reason, it is advisable to disconnect the power amplifier output leads from the primary winding of the injection transformer until the EUT is up and running in steady state.

While disconnecting the power amplifier during a turn-on event is a good practice, it does cause another problem. The injection transformer secondary winding impedance becomes very high since it's equal to the transformer secondary magnetizing inductance when the primary winding is open-circuit. This high inductance in the input power wires can cause the converter to go unstable during a turn-on event. This problem can be solved by either turning on the power system under no load, or attaching a 5-Ω resistor across the primary winding. This 5-Ω resistor reflected through the 2:1 turns ratio results in only 1.25 Ω on the power input leads, which is usually small enough to not cause stability problems with low- to mid-power converters.

Make sure to have the 5-Ω resistor connected when running the calibration test to account for its effects. The impact during calibration is small because it is in parallel with the 2-Ω input impedance of the injection transformer. During the calibration test for 28-V systems, this 5-Ω resistor will dissipate 32 W, so the resistor must be sized accordingly.

While designing and properly sizing a damping circuit that will survive the stresses that are incurred during the test is a major part of passing the CS101 requirement, the signal attenuation of the power system must be demonstrated to be sufficient enough to prevent the powered equipment from failing to meet its own performance specification. When considering the power system alone, the goal is to attenuate the applied input signal and thus reduce the output ripple voltage at the load. Typically, the sensitivity that the load has to the output ripple at all frequencies is not known in advance, and so the adequacy of the power system attenuation must be tested according to CS101 while powering the load equipment.

During the CS101 test, it is not typically useful to monitor the power system output ripple voltage, but instead the performance of the load equipment should be monitored. The system is considered to have passed the CS101 test if stresses of the test do not cause permanent equipment damage, and the load equipment continues to meet the requirements according to its performance specification.

Conclusion

A power system that is designed to meet both the emissions and susceptibility requirements of MIL-STD-461 will necessarily have good audio rejection over the full test frequency spectrum of CS101. This requires additional damping in the filter circuit to reduce the amplification effect that will occur naturally at the filter cutoff frequency. The addition of the damping elements explains why filters designed for military applications are typically slightly larger than filters for commercial applications that don't have such susceptibility requirements.

Most filters and converters will provide good audio rejection at low and high frequencies without additional effort by the designer. However the mid-range frequencies around the filter cutoff frequency require the bulk of the design effort, which results in the addition of damping elements. A filter designed for conducted susceptibility will lower the filter Q to an acceptable level and be able to handle the additional dissipation during the CS101 test. The damping elements typically have no role in the low- and high-frequency performance of the filter. However in the mid-frequency range, where the risk of test failure is usually highest, these damping elements play a crucial role.

For a military application that specifies MIL-STD-461, it is important that the buyer choose a filter that was specifically designed for the conducted susceptibility requirements found in the standard. For example, VPT offers a wide selection of filters that were specifically designed for systems that require testing according to MIL-STD-461 (versions C-F.) These include products at different reliability levels from military COTs to hermetically sealed MIL-PRF-38534 Class K qualified hybrid filters that can be used in very high-reliability applications including space.

References

1. Department of Defense, MIL-STD-461F, CS101 Detailed Requirement & Appendix A, 2007.

2. R. D. Middlebrook, "Input Filter Considerations in Design and Application of Switching Regulators," IEEE Industry Applications Society Annual Meeting, 1976, pp. 91-107.

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For further reading on EMI filter design and operation, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category and select "EMI and EMC" in the Design area category.