AeroQor Single-Phase EMI Design

Application Note

Summary

This application note addresses DO-160G compliant solutions using SynQor's Isolated Power Factor Correction modules and reviews electromagnetic interference design practices to meet the required standards.

Introduction

Designing DO-160G electromagnetic compatible solutions is typically a difficult challenge. Meeting electromagnetic interference emission (EMI) performance specifications is ultimately a system problem and will depend on more than just the parameters of a specific filter and/or converter's elements. EMI system performance is also affected by how the interconnect cables are routed, grounding practices, the characteristics of the load, the use of EMI shielding, and enclosures, to name a few.

As with any power conversion device, SynQor's Isolated Power Factor Correction modules (PFIC) generate a broad spectrum of differential and common-mode noise. This application note is a guide to help designers use SynQor's Isolated PFIC products to meet DO-160G conducted and radiated emissions requirements.

Throughout this application note, the single-phase PFIC evaluation board, EVAL-1000042, will be used as a test vehicle to illustrate the concepts needed to design an EMI-compliant system. However, we would like to mention that the EVAL-1000042 PCBA (Printed Circuit Board Assembly) has not been designed to meet any specific requirements and it is for general test purposes only. The evaluation board serves as a convenient demonstration and testing platform, and no compliance guarantees are made that it will meet any particular standards.

Contents

Safety Warning!

Shock Warning: There are areas of this evaluation board that have access to exposed hazardous high-voltage levels. Exercise caution and avoid contacting such voltages. Also note that the evaluation PCBA may retain dangerous high voltages (temporarily) after the removal of the input source. Exercise caution at all times when handling.

Thermal Considerations: When testing converters using the EVAL-1000042 PCBA, ensure adequate cooling. It is recommended to attach a heat sink to the baseplate of the module and apply forced air cooling using a fan. Monitor the converter temperature to ensure it does not exceed the maximum temperature rated per the datasheet specification.

Sockets: Please note that the evaluation board uses sockets for ease of testing. For long-term testing, thermal evaluation, and/or permanent installations, use soldered connections.

Terminology:

AeroQor – Product Line of high efficiency AC-DC Power Factor Correction modules and filters designed to be used as a COTS component in airborne applications.

ACF-U-230-QT - AeroQor AC Line Filter (quarter-brick package size).

APFIC-U-24R-HT - AeroQor Isolated Power Factor Correction module. (24V output Regulated, half brick package size).

DO-160G - Environmental Conditions and Test Procedures for Airborne Equipment (Rev-G; Dec-8-2010)

EMC - Electromagnetic Compatibility.

EMI - Electromagnetic interference**,** undesirable electromagnetic emissions.

EVAL-1000042 – Evaluation Board for the AeroQor series contains the AeroQor AC line filter and Isolated Power Factor Correction module.

LISN – Line Impedance Stabilization Network.

Noise - AC component, the residual variation of the DC signal derived due to the switching action of a converter or random signal variations emitted from an external source.

CM noise - Common-mode asymmetrical (in phase) noise, measured between input and output to Ground.

DM noise - Differential-mode is symmetrical (out of phase) noise, measured across input and output terminals.

PFIC - Isolated Power Factor Correction module.

PF- The ratio of real power (kW) to apparent power (VA).

PCB – Printed Circuit Board.

PCBA – Printed Circuit Board Assembly.

Ripple - AC component, the residual periodic variation of the DC signal.

RFI - Radio Frequency Interference, any undesirable electrical energy with content within the frequency range dedicated to radio frequency transmission.

Y-Capacitor – AC line-to-ground safety rated capacitor used for CM noise filtering.

Section 1 – DO-160G EMI standards are system level design requirements.

Understanding the specific standards and how they relate to system compliance is critical when addressing EMI design. It is essential to comprehend that conducted and/or radiated emissions do not apply to PFIC modules as stand-alone products. The PFIC modules are just one element of the many components inside today's avionic systems. DO-160G EMI standards apply to the system as a whole and not to the individual elements that make up the system. Electronic equipment inside an aircraft must meet specific conducted and radiated emission levels. Requirements vary depending on the application, the location of the system inside the aircraft, and the type of aircraft.

Table 1. DO-160G Conducted and Radiated Emissions Category Descriptions [1].

Types of Testing	Category	Description
Power Lines and Bundle	B	This category is intended primarily for equipment where interference should be controlled to tolerable levels.[6]
Power Lines and Bundle	L	This category is defined for equipment and interconnected wiring located in areas far from apertures of the aircraft (such as windows) and far from radio receiver's antenna. This category may be suitable for equipment and associated interconnecting wiring located in the electronic bay of an aircraft.[6]
Power Lines and Bundle	M	This category is defined for equipment and interconnected wiring located in areas where apertures are electro-magnetically significant and not directly in view of radio receiver's antenna. This category may be suitable for equipment and associated interconnecting wiring located in the passenger cabin or in the cockpit of a transport aircraft.[6]
Power Lines and Bundle	H	This category is defined for equipment located in areas which are in direct view of a radio receiver's antenna. This category is typically applicable for equipment located outside of the aircraft.[6]
Bundle	P	This category is defined for equipment and associated wiring located in areas close to HF, VHF, or Global Positioning System (GPS) radio receiver antennas, or where the aircraft structure provides little shielding.[6]
Power Lines and Bundle	Q	This category is defined for equipment and associated wiring located in areas close to VHF, or GPS radio receiver antennas, or where the aircraft structure provides little shielding.[6]

Table 1 lists the different emissions categories related to airborne systems. There are six distinct categories as it relates to conducted emissions in DO-160G. Emissions can be measured on each power line or as an interconnecting cable bundle. Power line type requirements have four distinct sets of limits. Categories B, P, and Q all have a specific limit, while categories L, M, and H, all share the same limit (Figures 1 and 2). The P limit is the harsher of all the six limits associated with power lines or cable bundles.

For the purpose of this document, the conducted emissions were measured at each input power line (L1 and L2/N) using the setup and procedures outlined in DO-160G. We will refer to category M limits when discussing compliance throughout this application note. Category M is the typical conducted emissions limit for in-cabin applications. AeroQor products were mainly designed for in-cabin type applications. This application note will also discuss how the APFIC-U-XX-HT family of products can meet the more stringent limits if required.

The test setup includes 5uH Line Impedance Stabilization Networks (LISN), a current probe, an EMI bench, and a spectrum analyzer. Power lines tied to the ground plane locally are not tested. Conducted emissions from the Equipment Under Test (EUT) are measured between 150kHz and 152MHz. Figure 3 shows the typical setup used to measure conducted emissions from a EUT according to DO-160G. We have chosen not to ground either of the two input lines in the test setup used.

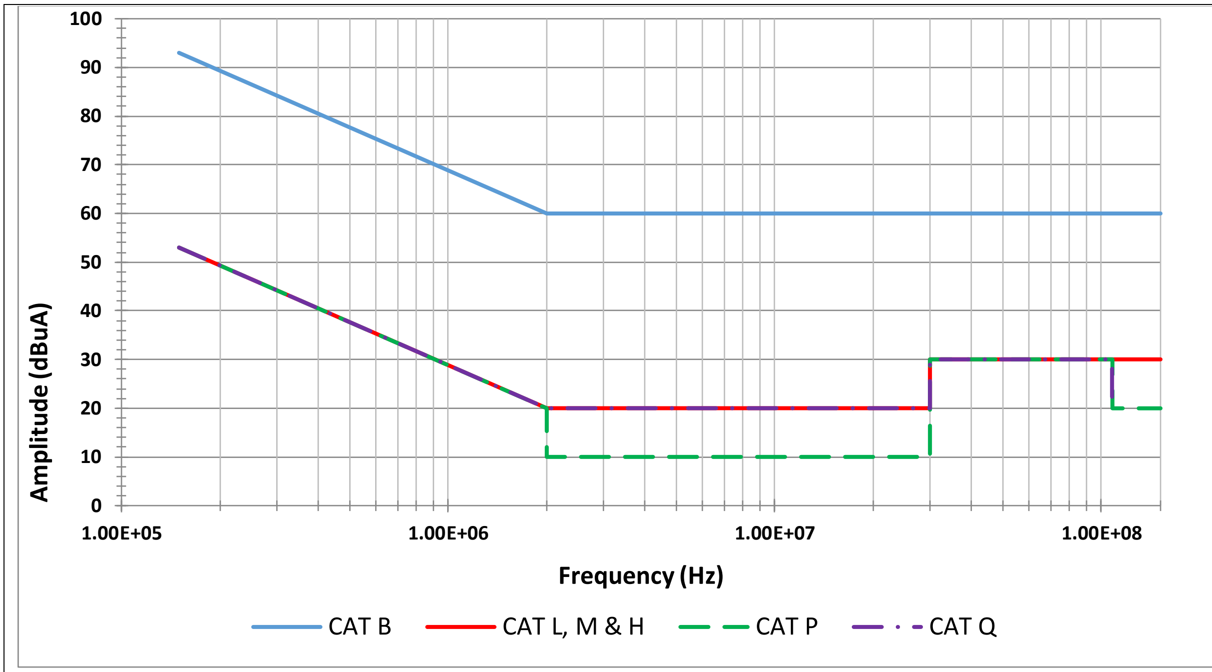


Figure 1. DO-160 Conducted Emissions Limits for Power Lines [1].

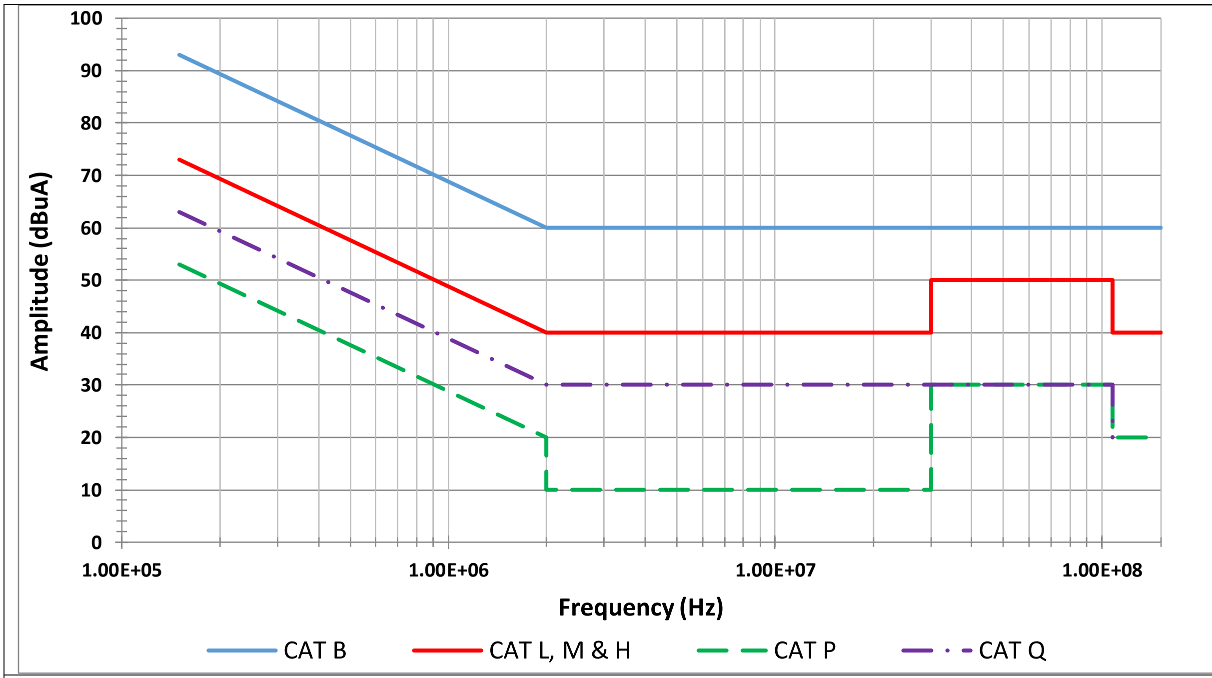


Figure 2. DO-160 Conducted Emissions Limits for Cable Bundles [1].

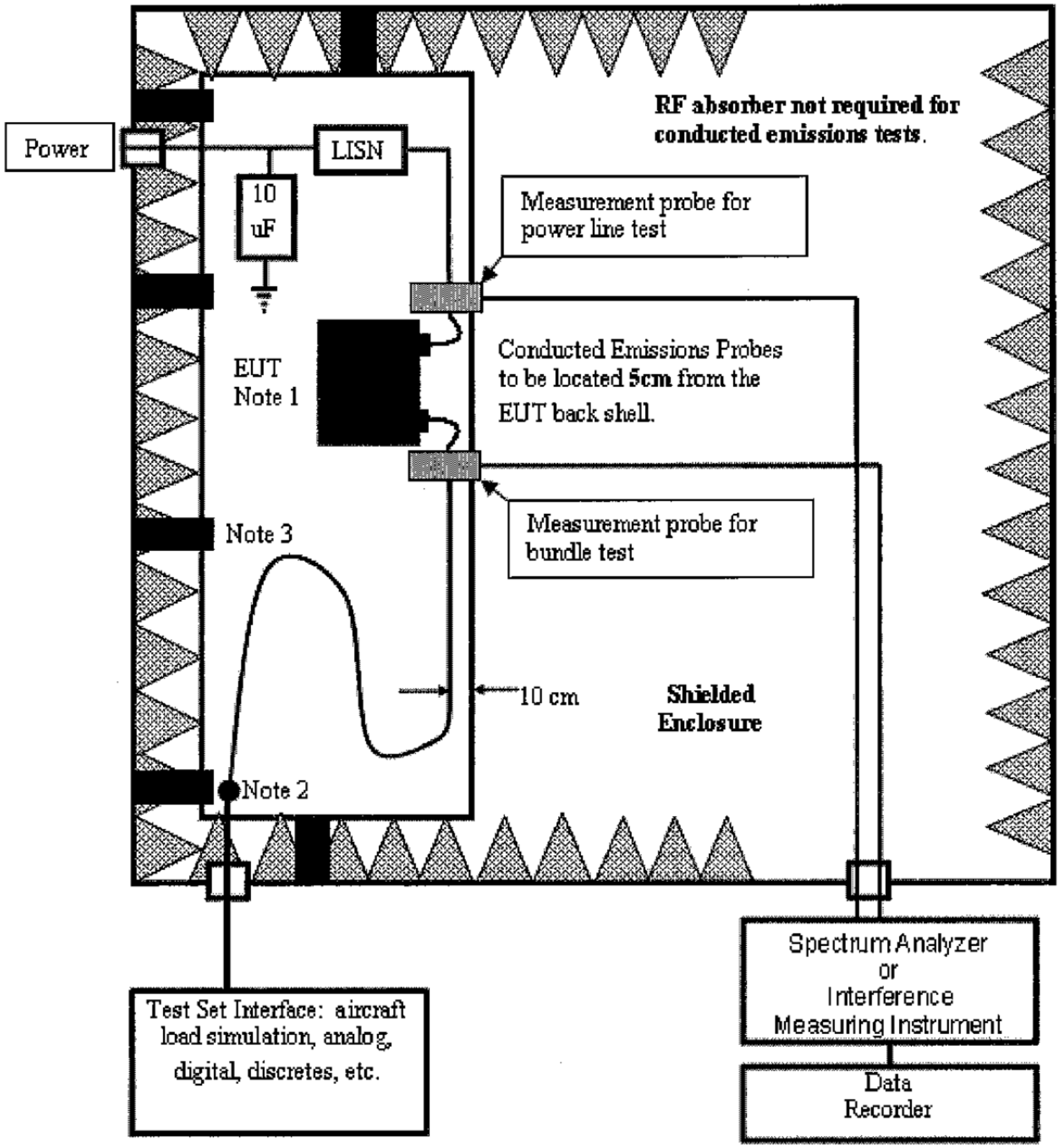


Figure 3. DO-160G conducted emissions setup [1].

Stand-alone AeroQor PFIC products will not meet the EMI standards required for aircraft applications (DO-160G). An EMI AC Line filter is needed, along with a few additional external components to meet the different requirements. This application note will show how SynQor's AeroQor PFIC modules, in conjunction with a properly rated SynQor line filter solution, can be configured to meet conducted emissions category M limits specified in DO-160G. SynQor's AeroQor AC filters have been designed to work in conjunction with the PFIC modules to simplify the overall system design and help customers meet conducted emissions requirements. However, meeting EMI performance specifications is ultimately a systems requirement and will depend on more than just the selected filter elements and converters. For example, EMI performance will be affected by how the interconnect cables are routed, grounding strategies, load characteristics, and EMI shielding and enclosures. A modularized design approach using the PFIC and AC line filters allows for faster implementation and creates overall cost savings for system designers and manufacturers.

AC-DC converters, by nature, generate significant levels of both conducted and radiated noise. It is good practice to suppress emissions as close as possible to their source. Such an approach will prevent noise from propagating through the system, thereby decreasing the complexity of how to resolve the noise emission question. It is good practice to have some level of local EMI suppression for every power stage. For example, placing the ACF-U-230-QT line filter in front of the single-phase PFIC module prevents significant EMI from propagating through its input terminals onto other aircraft areas. The AeroQor products were specifically designed to help system integrators meet the different requirements specified by DO-160G.

Section 2 – Understanding electromagnetic emissions

First, it is essential to understand the nature of noise emissions before diving into developing solutions that can help us meet DO-160G and/or other EMI standards. Electromagnetic emissions can affect neighboring electronic circuits through interconnecting conductor wires (conducted emissions) and/or radiated emissions (through the air). Conducted emissions propagate through the power distribution networks affecting neighboring systems. On the other hand, radiated emissions propagate through space without conductors and can be just as disruptive to adjacent equipment.

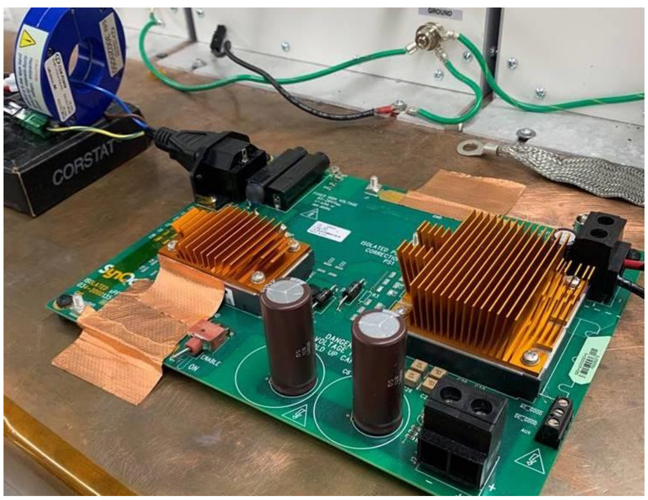


Figure 4. Conducted Emissions Setup

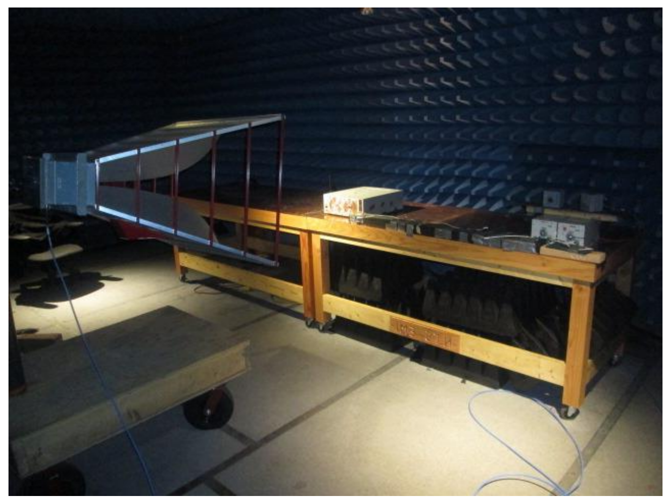


Figure 5. Radiated Emissions Setup.

Current probes clamped around the input cables of the system under test or LISNs are used to test DO-160G conducted emissions, Figure 4. The current probes directly measure the current ripple in the input lines, while LISNs measure the voltage ripple resulting from the input current ripple (indirect measurement). Different antenna set-ups at a specific distance from the device under test measure radiated emissions, Figure 5. It is always helpful to understand the testing methodology and be familiar with the test setup before trying to resolve test outages.

Conducted and radiated emissions can be further sub-categorized into two different types of noise: differential and common-mode. Identifying whether noise emissions are differential-mode or common-mode will help in determining the best manner in which to address the problem. Differential-mode symmetrical (out-of-phase) noise is measured between the power feed and its return path. Common-mode asymmetrical (in-phase) noise is measured between each of the power lines and ground. The definition of common-mode (CM) and differential-mode (DM) voltages and currents is illustrated in Figure 6.

Differential-mode and common-mode noise emissions are inherent to the basic operation of switching power converters. The basic operation of any AC-DC PFIC module will result in the generation of ripple currents and voltages, which translate into DM and CM emissions. These unwanted voltages and currents are created by the high voltage switching action in the boost and the isolation stage required to perform the desired power/voltage conversion. It is important to recognize that the load can also be a source of emissions. Emissions from the load can negatively affect the EMI performance of the overall system. Filters can be used to mitigate the high-frequency noise produced by the converter and the load. On the other hand, low-frequency noise (emissions) is typically addressed by the hardware implementation of the power converter and the module's control strategy for practical reasons.

Vd = V1 - V2 = DM voltage component
Id = (I1 - I2) / 2 = DM current component
Vc = (V1 + V2) / 2 = CM voltage component
Ic = I1 + I2 = CM current component
Cs = effective parasitic capacitance between the module components and the chassis ground.

Note: Cs is the combination of many capacitors in parallel; each component in the module has capacitance to chassis ground. Typically, only switching nodes (high dv/dt) are sources of CM noise.

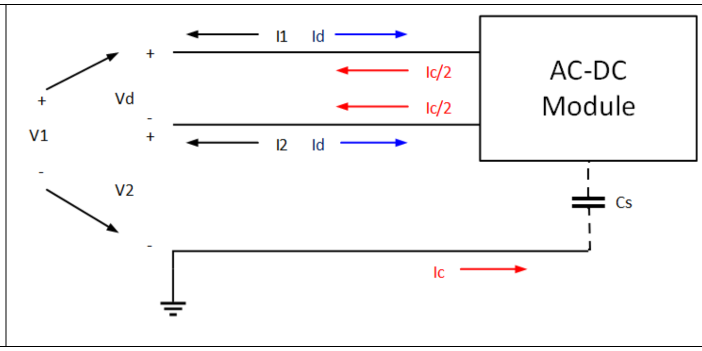


Figure 6. Definition of differential and common-mode currents and voltages [2].

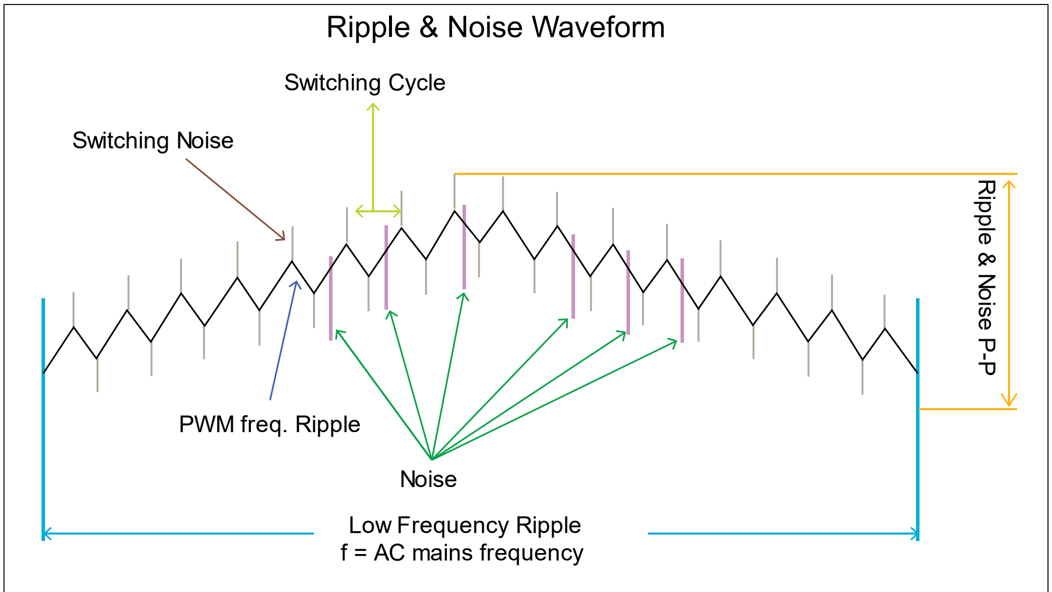


Figure 7. Input PFC ripple noise currents product of switching nodes [3].

Figure 7 represents the typical input current of a PFC stage. The PFC input current ripple has the following identifiable AC components:

- Low-frequency ripple associated with AC Line frequency, twice line frequency (example 120Hz for 60Hz line).
- High-frequency ripple due to pulse width modulation (PWM) of the main PFC switches (for example, 200 kHz).
- Switching noise that occurs at the switching transitions.
- Non-periodic random noise unrelated to any of the above may come from other circuits or the load.

Differential-mode noise present at the input terminals is a combination of the voltage ripple generated by the current running through the input capacitors and differential-mode noise introduced by power conversion components in the switch mode power converter. The fundamental frequency of this voltage ripple is the switching frequency of the PFIC converter. The generated differential ripple usually has a complex non-sinusoidal shape resulting in higher order harmonics of the fundamental switching frequency. In addition to switching noise, a low-frequency AC noise/ripple is present as a result of the power factor correction action.

Differential-mode noise exhibits a voltage variation (out of phase) across the input and output conductors. The action of the internal power switches (from the ON state to the OFF state) in the converter causes di/dt changes that generate differential currents that travel through the converter's input and output terminals (PFIC) as illustrated in Figure 8. Differential currents generate differential voltages. A shunt or differential capacitor across the input or output terminals will mitigate or reduce this type of noise. In-line inductors can also be added to provide additional filtering (LC filter).

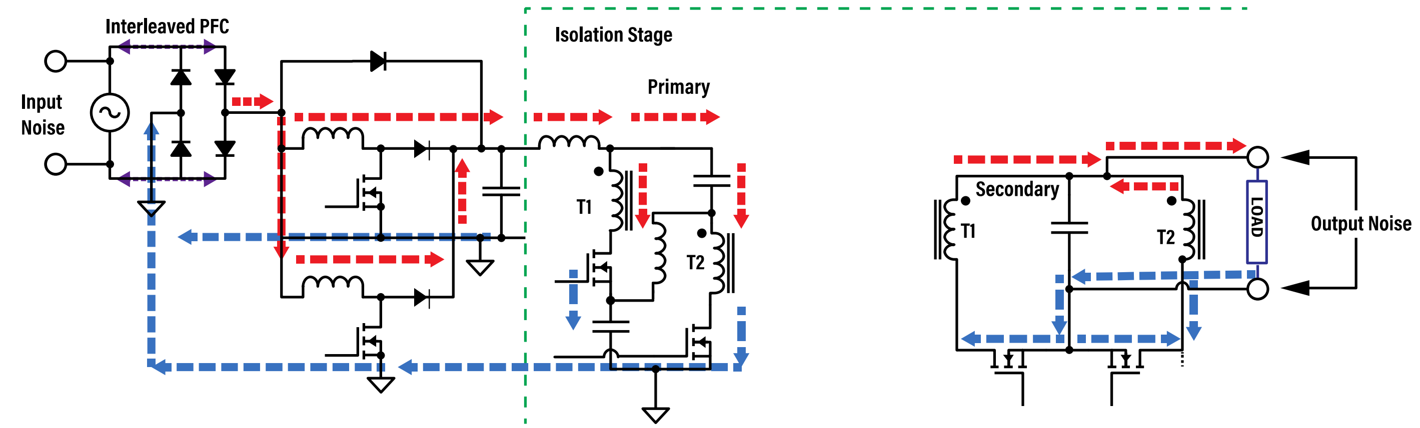


Figure 8. Differential-mode (DM) noise emitted when current flows in the input and the output of the converter (normal switching action), Purple AC current, Red forward current, Blue return current.

Furthermore, the switching action in power converters results in the charging and discharging of parasitic capacitances, present on all power converters, with respect to earth ground. The currents generated by charging and discharging of these capacitances result in common-mode noise/emissions. Some examples of the parasitic capacitances found in a switch-mode power converter are shown in Figure 9 (dashed lines capacitors). CM noise is usually present in all the converter's power rails and is measured with respect to ground. This noise is commonly associated with the parasitic capacitances between the different module components and chassis ground and the input to output power transformer parasitic capacitance on isolation stages. It is usually composed of high-frequency harmonics that do not necessarily match the harmonics of the switching frequency. It is challenging to accurately predict common-mode emissions because it is difficult to accurately model and identify the different parasitic components associated with common-mode noise.

CM signals are voltage / current waveforms common to both terminals, power, and return. These CM signals appear on both power lines (power and return) in phase and with equal amplitudes. If differentially measured across the power lines, these CM noise emissions would exhibit a near zero voltage variation. A differential capacitor is ineffective when trying to mitigate CM emissions. CM noise, however, does exhibit voltage variations between the input power and ground or between the output power and ground. The return path of CM noise currents is through chassis ground, as shown in Figure 9.

To mitigate common-mode emissions, capacitors can be placed between each power rail and chassis ground. Another effective option is to employ a common-mode inductor or choke in the input and/or output power lines. A common-mode inductor (with two opposing windings) takes advantage of the fact that the CM noise currents are equal and flow in the same direction. A common-mode inductor mostly attenuates CM currents while leaving differential currents relatively unaffected.

CM noise that is not offered a clear return path to its source will force itself back to its source, bypassing the input and/or output filters. This is what makes identifying and resolving CM EMI problems so difficult. The source of the problem could be far away from where it is found/measured. Therefore, providing a path for common-mode currents between input and output terminals is an effective technique to mitigate CM emissions. It is common, in isolated power converters, to place a high-frequency capacitor between input and output returns for this purpose. This capacitor provides a low impedance path to many CM currents back to its source. Because this capacitor breaches the safety boundary, it needs to meet regulatory safety requirements (Y1 type safety capacitor for an AC/DC type product).

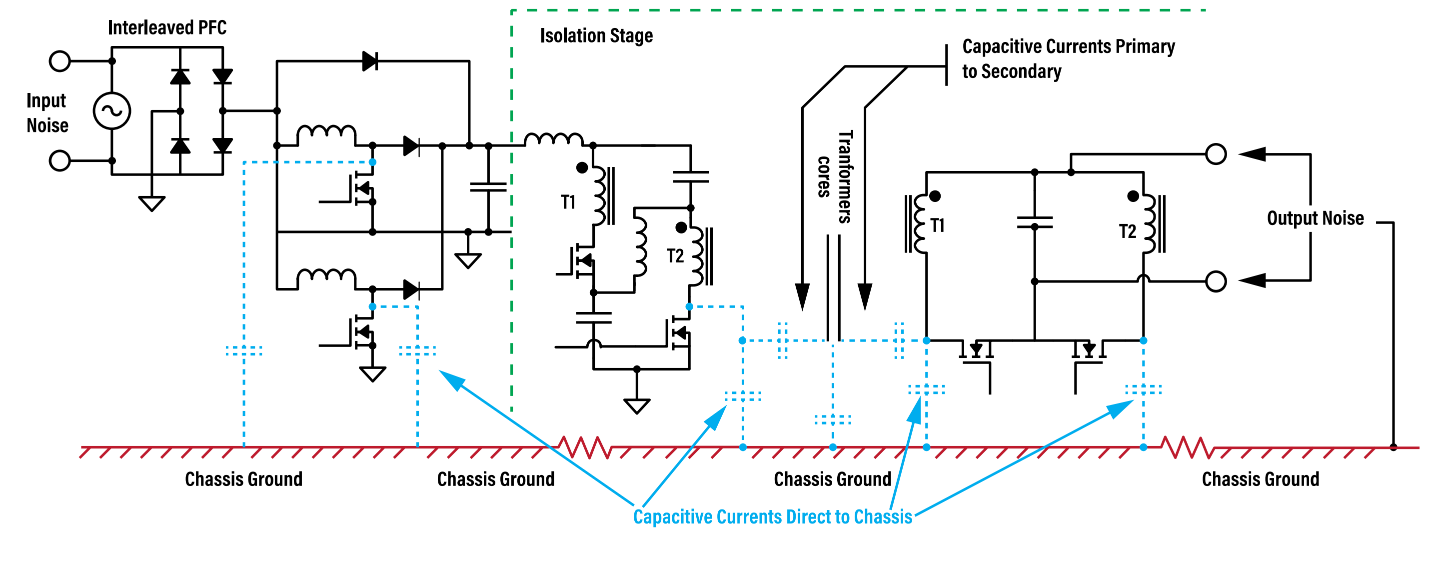


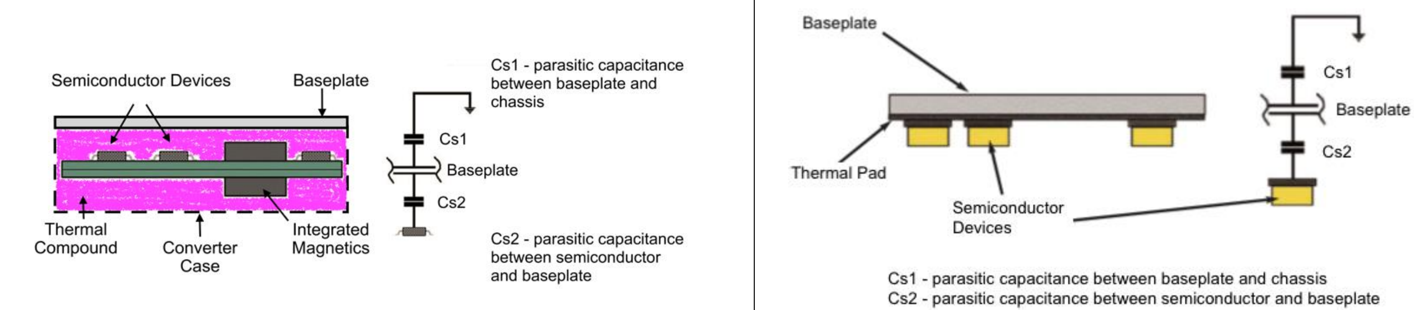
Figure 9. Common-mode (CM) noise emitted when transient from switching voltages are coupled to earth ground by parasitic capacitance from noisy (high dv/dt) nodes in the converter (PFC and isolated stage).

To address the noise on the input terminals, SynQor suggests using a two-stage input filter to attenuate both CM and DM noise emitted by the PFIC module and/or the load. A designer can choose to design a line filter composed of a discrete set of filtering components. This approach is a fairly complicated process since the filter does not only need to be specifically designed to attenuate the CM and DM noise signatures of the power converter, but it also has to meet various Civil Aviation standards like DO-160G, 787B3, and ABD0100.1.8. SynQor's ACF-U-230-QM and QT filters have been specifically designed to attenuate the noise emissions generated by the AeroQor products in order to comply with the required civil aviation limits.

Section 3 – AeroQor PFIC module baseplate design and EMI performance

SynQor's AeroQor PFIC modules have been designed to minimize common-mode emissions. SynQor utilizes a multilayer PCB construction where the power components are thermally coupled to the baseplate through a low dielectric thermal compound (Figure 10(A)). This type of construction results in small parasitic capacitances between the different switching elements of the power converter and the baseplate. Figure 10(A) shows the physical implementation of the AreoQor products as it concerns CM emissions, and Figure 10(B) shows the preferred physical implementation used by most of our competitors. In the physical construction of the AeroQor products, the distance between the switching components and the baseplate is relatively large (20 to 30 mils). On the other hand, in traditional designs like the one shown in Figure 10(B), the physical proximity of the switching devices to the baseplate is only a few mils. Therefore, the parasitic capacitance between the switching devices and the baseplate for this type of construction (Cs2) is several orders of magnitude larger when compared to the typical implementation used by SynQor. This clearly demonstrates how the SynQor construction minimizes the common-mode currents generated by the different switching components by minimizing the value of Cs2. It could be argued that the thermal performance of a product using the physical construction shown in Figure 10(A) should be inferior. SynQor's unique electrical design limits the power dissipation found in any single device resulting in power dissipation evenly distributed throughout the module surface, resulting in superior thermal performance. The thermal performance of the SynQor products is usually as good or better than that of our competitors.

SynQor recommends electrically grounding the baseplate (high-frequency short) to minimize/eliminate the effect of Cs1. This can be done by physically grounding the baseplate to input or output return or by connecting a capacitor between the baseplate and input or output return (high-frequency short). Remember, CM noise has to find a way back to its source. Therefore, a high-frequency capacitance between input and output returns is also recommended. By using a capacitor to effectively ground the baseplate, the baseplate can be at a different potential than either the input or output returns (remain isolated) if required by the system architecture.



(A) (B)

Figure 10(A & B). Physical design of a SynQor encased module (A), vs. the traditional physical design for PFC modules (B). Note the substantially lower capacitance (Cs1 & Cs2) in SynQor's design.

Section 4 – Correlating sources of noise emission in the PFIC module to conducted emissions:

Understanding the sources of the noise emissions at specific frequencies is critical when establishing a comprehensive noise mitigation strategy. It is sometimes easier to explain complex concepts by using a real-life example. Therefore, in the following discussions, we will refer to the EVAL-1000042 PCB evaluation board. The scans shown in this Application Note were taken from a system composed of an ACF-U-230-QT filter and an APFIC-U-24R-HT module assembled on the EVAL-1000042 evaluation board. This Application Note will comment on the effects of populating or not populating several capacitors in the board and the option of introducing an external common-mode inductor or choke. It is important to note that the EVAL-1000042 board was not designed to meet any specific EMI and/or civil aviation requirements. Even though this Application Note will show various configurations that can meet DO-160G CAT-M conducted emission standards, it is important to remember that the test setup used to perform the different scans is not a certified DO-160G test bench. The described setup will be used to test and illustrate various noise mitigation techniques.

The stand-alone APFIC-U-24R-HT product will not meet the emissions standards required by DO-160G. An input filter will be needed to reduce both the differential and common-mode noise generated by the PFIC. The ACF-U-230-QT filter was designed to work in conjunction with SynQor's AeroQor PFIC products. The filter targets both the differential and common-mode noise generated by the PFIC. Figure 11 shows a DO-160G conducted emissions scan of the EVAL-1000042 evaluation board with the ACF-U-230-QT filter and APFIC-U-24R-HT converter with only 10nF of common-mode Y-capacitors between VOUT- and hold-up return (C8 in Figure 17); please note that the datasheet recommends 20nF. The scans show that this simple configuration meets the DO-160G CAT-M requirements. It would be desirable to have increased margins at frequencies above 20 MHz, but this is a good start.

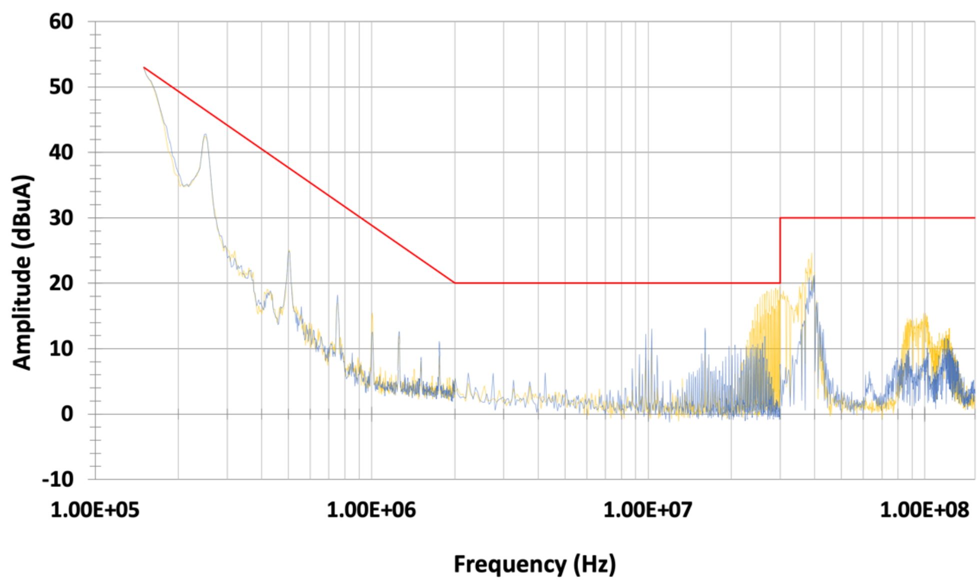


Figure 11. DO-160G CAT-M Grounded baseplates (filter and converter) conducted emissions.
Blue: Line conducted emissions; Yellow: Neutral conducted emissions

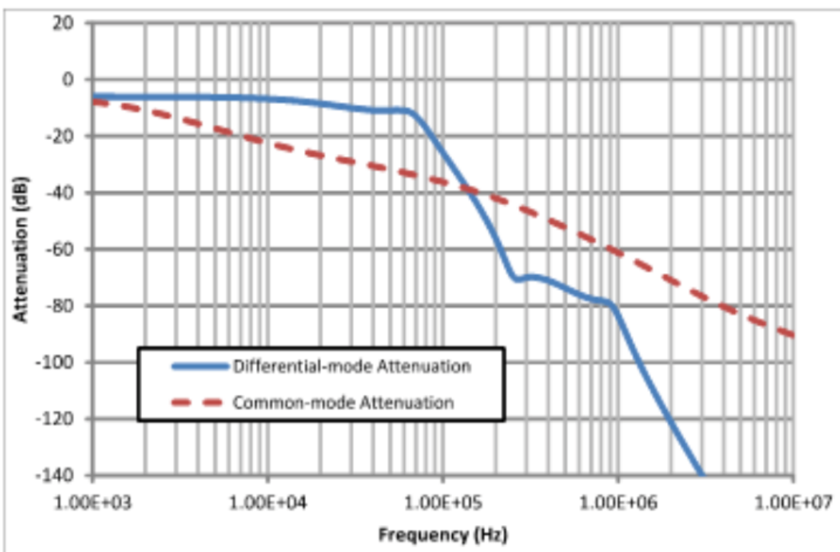


Figure 12. ACF-U-230-QT CM (Common-mode) and DM (Differential-mode) filter attenuation (simulated, source and load resistance are 50Ω).

Figure 12 shows the attenuation (from the datasheet) for the filter module as a function of frequency for both DM and CM noise. The filter provides effective attenuation at frequencies above 80-100kHz. The amount of attenuation increases significantly as the frequency increases. However, at frequencies below 80kHz, the filter offers marginal or no attenuation. At these frequencies, the system relies mainly on the good EMI performance of the isolated PFC module and less on the filter attenuation characteristics. Emissions at these low frequencies cannot be filtered by means of a reasonably sized filter. Therefore, performance in this region of the frequency spectrum relies on the proper design of the PFIC converter. At low frequencies, low emissions result from selecting the appropriate control strategy for the PFIC module while providing close to unity power factor. As shown in Figure 11, the PFIC module generates significant emissions at 250 kHz (switching frequency) and the subsequent switching frequencies harmonics (500 kHz, 750 kHz, …). At these low frequencies, the generated noise is primarily differential and is due to the inductor ripple current generated by the converter switching action. The inductor's sizes and values (filter and PFIC module) were selected to meet specific current ripple values with the product operating at heavy loads with consideration of the emissions requirements at these loads. Therefore, for applications that nominally operate at lighter loads (less than 50 % load), it might be necessary to add differential filtering to meet the specific EMI requirements at these reduced loads. The EMI requirements are determined as a function of the system load.

Typically, the combination of the AeroQor AC filter and PFIC module, along with a couple of external CM capacitors, is enough to meet the various conducted and radiated DO-160G standards (Figure 11). Proper layout and component placement (including power bricks) are necessary to prevent noise emissions from circumventing the filter components. For example, placing unfiltered conductors in close proximity to the input terminals of the filter module will result in noise bypassing (jumping around) the filter module. This will very likely result in poor system EMI performance.

Section 5 – Determining the nature of the noise emissions based on EMI scans

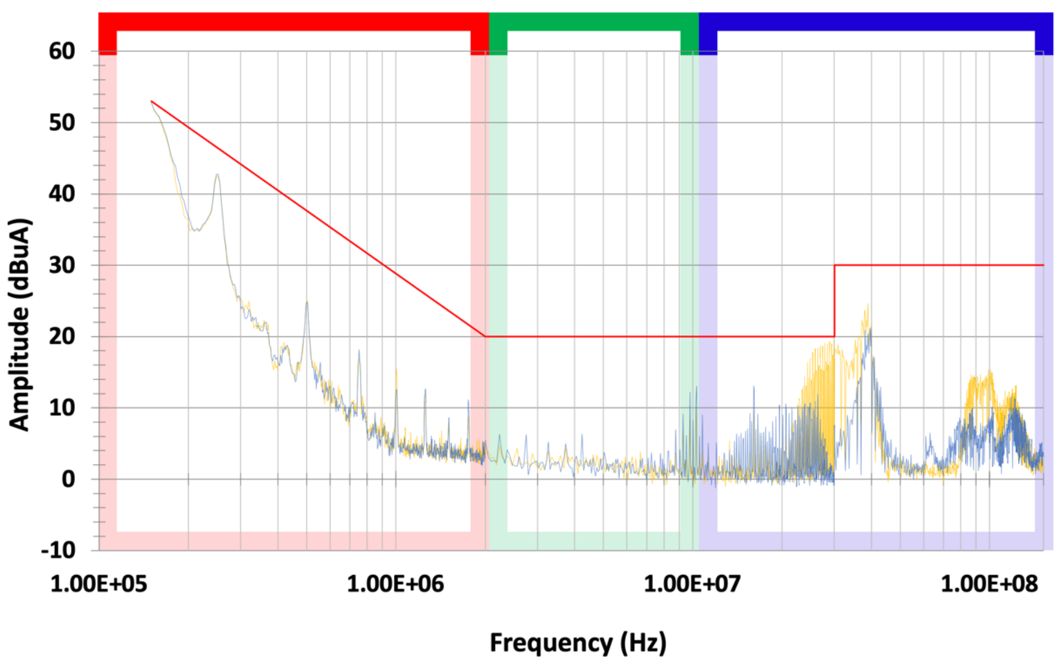


Figure 13. DO-160G CAT-M conducted emissions without the recommended Y-capacitors:
Red (150kHz – 2Mhz): Typically, noise is predominantly DM noise in nature.
Green (2Mhz – 10Mhz): Typically, noise is a mixture of DM and CM.
Blue (10Mhz – 200Mhz): Typically, noise is predominantly CM noise in nature.

Determining the nature of the noise emissions is a critical factor in establishing the best approach to contain such emissions. The frequency range of the emissions can offer some insight into the possible nature of the source. DM noise emissions usually show at the fundamental ripple frequency (twice the switching frequency for the PFIC) or harmonics of this ripple frequency. On the other hand, CM noise emissions mainly occur at higher frequencies since they are a result of fast switching transitions. However, it must be understood that noise emissions at any specific frequency can be composed of a mixture of both CM and DM noise (especially in mid-frequency range).

Figure 13 can help illustrate a rule of thumb that can be used to identify the nature of noise emissions based on the frequency at which they occur without directly measuring CM and DM noise. The chart has been split into three regions to highlight the areas where DM noise (red region) and CM noise (blue region) are most prevalent. DM noise mitigation techniques typically yield better results in the red highlighted frequency range (Figure 13). CM noise mitigation techniques will generally be more effective in the blue marked frequency range. Finally, the mid-region, highlighted in green, denotes an area where noise emissions would benefit from both increased differential-mode and common-mode filtering.

As discussed, the frequency of noise emission can offer some idea regarding the type of noise affecting the system. However, just relying on the frequency to determine the nature of the noise emission could be misleading. A current probe and a spectrum analyzer or oscilloscope with good FFT capabilities can be used to identify the nature of the measured noise more accurately. The test setups shown in Figure 14 can be used to identify CM and DM noise. The test setup takes advantage of the fact that the differential currents flow in opposite directions in the power lines. In contrast, common-mode currents have the same amplitude, frequency, and flow in the same direction on both the power and return lines (Figure 6). A current probe that can hold both power lines through its magnetic core can be used to differentiate between DM noise from CM noise by taking advantage of magnetic field current cancelation.

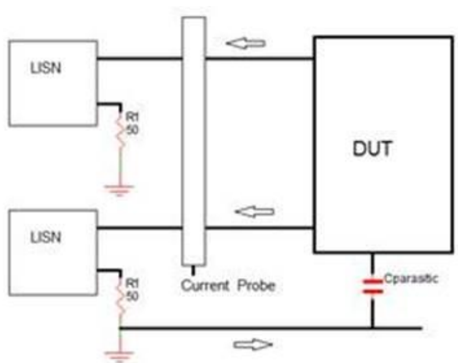
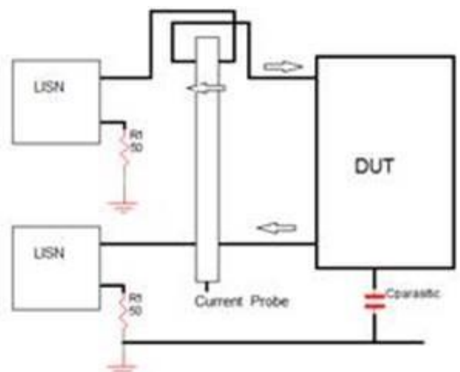
	
Measurement #1	Measurement #2

Figure 14. Measurement technique that can be used to differentiate DM from CM noise in a system using a current probe and a spectrum analyzer or scope with FFT capabilities.

If the noise emissions are mainly differential-mode in nature, the noise level when the input lines run straight through the probe (Figure 14, Measurement #1) will be significantly lower than when one of the lines is looped around the probe (the current in the looped line normally flows in inverse direction to the other line; Figure 14, Measurement #2) so that the current flow is reversed. For common-mode noise, the opposite is true. If the noise emissions are mainly common-mode in nature, the noise level when the input lines run straight through the probe (Figure 14, Measurement #1) will be significantly higher than when one of the lines is looped around the probe (Figure 14, Measurement #2). Designers and testers can use this simple and effective technique to identify the nature of noise emissions.

Section 6 – EMI considerations and PCB layout design

Before we continue with this section, we would like to introduce the concept of a network or net, which will help as we discuss PCB design concepts. A net is composed of all the interconnecting traces, copper planes, pads, component leads, vias, and pins that are connected together to represent a single potential.

The PCB layout can substantially affect the overall EMI performance of the system or subsystem positively or negatively. The filter and PFIC module may have outstanding EMI characteristics, but the system could exhibit high noise emissions if good EMI design practices are not followed. Good design practices should be used when determining how power will flow through the system, the location of components, and how the physical connection between different components is implemented. Often poor decisions in the PCB design can lead to high noise emissions, even after the addition of multiple external filtering components. Much care should be taken at the system level design to ensure that the PCB implementation, the routing of cables, the grounding scheme, and EMI shield solution will all work together to keep EMI emissions at bay.

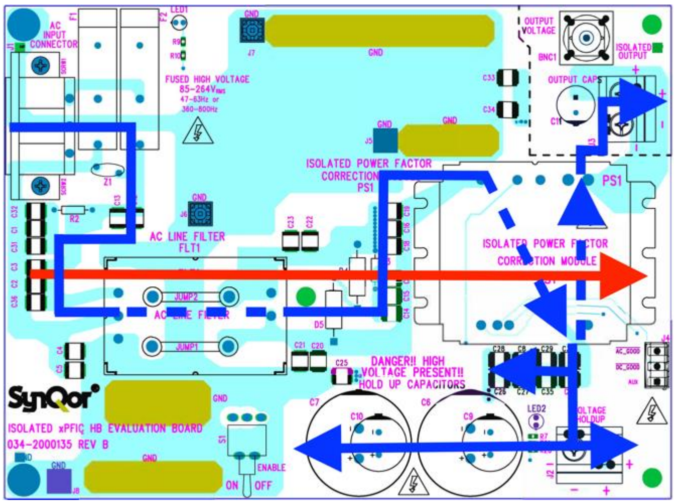


Figure 15. Power flow through EVAL-1000042 PCBA (Printed Circuit Board assembly).

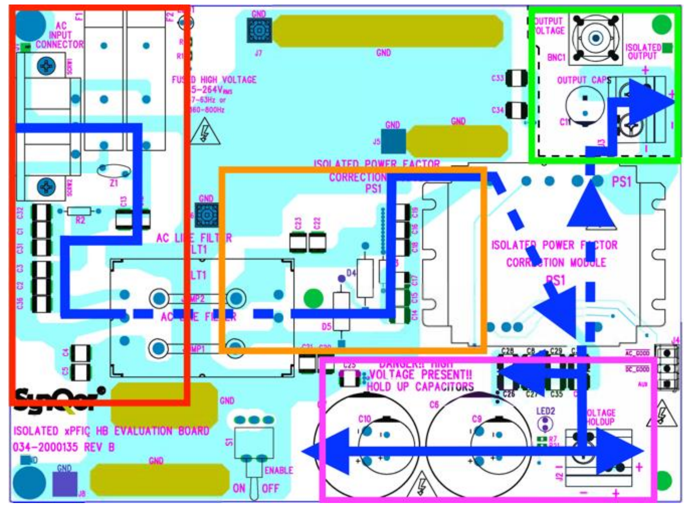


Figure 16. Location of various compartments operating in the EVAL-1000042 PCBA.

Component placement is of particular importance when designing a system that needs to meet stringent EMI requirements. Best PCB design practices typically keep noise emitting nets away from other nets. This practice reduces noise coupling between different networks. Noise coupling is the mechanism under which noise can jump from one section to another. It is also good practice to minimize current loops. Furthermore, keep nets with high dv/dt signals as isolated as possible. Following these design practices should keep noise compartmentalized and prevent it from propagating through the system. One of the simplest ways to implement these design guidelines is to design power flow to follow short, straight lines. This simple design concept helps keep noise emissions contained and minimizes coupling. For the purposes of this discussion, we will use the layout design of the current EVAL-1000042 evaluation board as an example. The evaluation board can help illustrate some of the concepts that should be considered during the EMI system level design phase.
As suggested, power should ideally run in a straight line, for instance, from left to right, as shown by the red arrow in Figure 15. A layout following a straight line will have much better EMI characteristics than a system having a “U” shape configuration. In a “U” shape design, the input nets and output nets are next to each other, allowing noise to easily couple from the output onto the input, possibly bypassing the filtering components. Unfortunately, it is not always possible to follow these design guidelines. Space limitations and/or other system constraints can sometimes dictate the final system configuration/layout. Regardless, follow these guidelines as best as possible.

The blue line in Figure 15 denotes the actual path that power takes as it travels through the evaluation board. Power does not necessarily flow in a straight line through the PFIC evaluation board. In this case, the true path of the power flow is a compromise between EMI performance, component placement, and space constraints, as shown in the diagram.

Figures 16 and 17 highlight the four major sections that compromise the evaluation board. The input section is encircled by the red square (input filter). Note that the input section is only adjacent to the orange net, which interconnects the output of the filter to the input terminals of the PFIC. The AC line filter separates the red network from the orange network. The AC line filter provides a permeable frequency-dependent barrier that attenuates noise emissions inherent in the orange net as these emissions travel back to the input terminals. As discussed in section 5 (Figures 11 and 12), the filter attenuates noise emissions at frequencies above 100kHz, provided that the noise currents flow through the filter and not around it. The filter prevents high-frequency ripple/noise produced by the PFIC from propagating, in a significant manner, into the input conductors. It is important to keep noise coupling onto the input terminals as low as possible since it is the input terminals that directly connect to the noise measuring equipment when performing conducted EMI testing.

The PFIC module's control algorithm handles most noise emissions below 80kHz. For example, suppose the input voltage waveform is a clean sinusoidal signal. In that case, the input current drawn by the PFC module will try to match the voltage waveform characteristics. Therefore, noise currents at frequencies other than the fundamental frequency should be minimal. On the other hand, if the input voltage waveform is distorted, the input current drawn by the unit will also be distorted as the unit tries to maintain a unity power factor. Therefore, during EMI testing is essential to have a good clean source. Before starting testing, it is recommended to run a scan with the test source loaded with a passive resistive network at the system-required power level in the EMI test chamber to verify that the source does not generate any unwanted emissions (ensure you have a good test set-up).

When attempting to design a solution that can meet conducted emissions standards, it is important to point out that any noise emission present at the input traces will have a high probability of appearing in a conductive or radiated emission scan. Examining Figure 17, there are only a few filtering components between the input filter pins (red net in Figures 16 and 17) and the location where the input connector interfaces with the input conductors supplying power to the evaluation board. Consequently, it is vital to ensure that no additional noise can be coupled from any of the other PCB regions onto the input network. The traces or copper planes that interconnect the filter, the protection devices, the input connector, and any supplemental filtering components need to be kept as short as possible. Any potential current loops need to be made as small as possible. When possible, route power traces and their returns on adjacent PCB layers (one on top of the other) to minimize radiated noise coupling and reduce trace inductance. Any loop between two paths is an opportunity for radiated noise to become electromagnetically coupled to the conductors. Wide traces reduce trace self-inductance but should be kept away from radiated fields.

The orange network in Figures 16 and 17 interconnect the output pins of the filter to the input pins of the PFIC module. The orange nets have significantly more noise than the red (input) nets. The noise is a result of the switching action in the PFIC module. Keep a decent amount of spacing between the red and orange networks to minimize inductive and capacitive coupling. Reducing the length of the traces helps reduce noise coupling.

After the AC filter power flows from the orange network to the pink network (Figures 16 and 17) through the internal PFC circuitry, a full-wave rectifier, and the interleaved boost converters. The HU+ and HU- hold-up terminals in the PFIC module are essentially the output terminals of the interleaved boost converters and the input to the isolation stage in the PFIC module. The hold-up capacitor, C10 in Figure 17, placed across the HU+ and HU- terminals, helps handle the cyclic imbalance between the flow of energy drawn from the AC source and the continuous flow of energy delivered to the load. The primary function of C10 is to provide energy storage. The voltage across the hold-up capacitor typically has a ripple at a frequency twice that of the AC source (e.g., 120 Hz for a 60 Hz input). The larger the hold-up capacitor, or the higher the frequency of the AC source, the smaller this ripple will be. Smaller ripple translates into lower noise emissions. The amount of attenuation provided by the hold-up capacitor is proportional to the capacitance and frequency of the ripple.

Inside the PFIC module, the interleaved boost stages are followed by a high-efficiency, fixed-duty cycle isolation stage. This stage isolates the output from the AC mains (safety isolation) and steps down the voltage to the required output voltage level. The isolation stage in the PFIC products is effectively a high-efficiency DC transformer. The isolation stage runs at the same switching frequency as the boost converter. The noise emissions at the output will have contributions from both the hold-up capacitor net and the switching action in the isolation stage (green region Figure 16 and 17). A ceramic or film-type capacitor bank is usually placed between the output terminals to reduce the output's differential noise emissions (output ripple). These capacitors should have low internal resistance and inductance characteristics to maximize their efficacy. Please consult the product datasheet regarding maximum external capacitance and its effect on stability. Increasing the hold-up capacitor will also reduce the output voltage ripple. If needed, emissions can be further reduced by placing a low pass filter between the output terminals and the load (again, consult datasheet – FAE support for stability criteria).

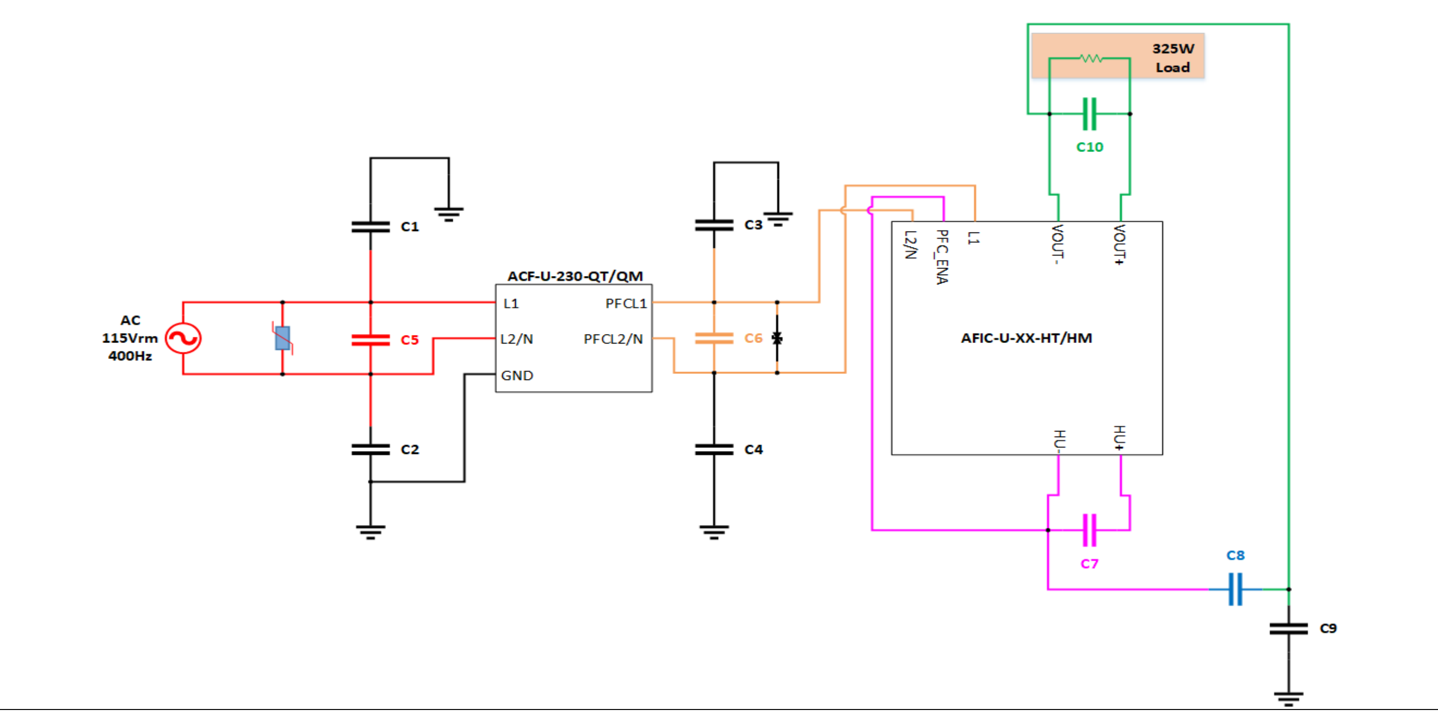


Figure 17. Eval-1000042 evaluation board compartmental diagram (follows Figure 16 color scheme). Note: C1-C4 capacitors should be Y2 rated. C8 should be Y1 rated.

Emissions on the output network (green region Figure 16 and 17) depend not only on the noise characteristics of the PFIC module but also on the noise characteristics of the load. Loads can be a significant source of EMI. Close proximity of this net to the input network (red net in Figures 16 and 17) can cause noise from the output circuit network to couple into the input terminals, bypassing the input filtering. Avoid "U" shape configurations that allow close proximity between the input and output networks.
The location of different components in the EVAL-1000042 board has been designed to keep each of the various circuit regions isolated from each other in an effort to reduce noise coupling. The design also attempts to ensure that noise emissions emanating from the different networks have a clear deterministic path back to the input or output terminals through the implemented filter networks. In the case of the input terminals, the design channels the majority of emissions from the PFIC module (particularly the high-frequency noise) through the AC filter, resulting in significant EMI attenuation. The ACF-U-230-QT filter (Figure 18.) and the APFIC-U-24R-HT PFIC module are designed to complement each other. The converter handles the low frequencies (line frequency harmonics) and the filter handles the high-frequency emissions.

Section 7 – Mitigation of Common-mode noise

Common-mode noise is typically created by the high-frequency switching elements inside the PFIC. The main components responsible for these emissions are the boost converter and isolation stage semiconductor switches, and the isolation power transformer. CM noise can appear on both the input and output conductors, even though only the input conductors are directly tested. During each switching action, as the solid-state switches open and close, high dv/dt transitions occur on all nodes connected to the semiconductor devices. These dv/dt transitions induce CM currents via the parasitic capacitances between the semiconductor devices and the baseplate and the input-to-output parasitic capacitance of the power transformer. Mitigating these CM currents usually requires the designer to provide a deterministic, low impendence path at the correct frequencies, for these currents to return to the source. Containing these currents can also be achieved by placing CM inductors on the input and/or output terminals. CM inductors provide a high impedance path to CM currents, channeling these currents away from the input and/or output terminals.

Grounding the converter and filter baseplates through a low impedance path to chassis ground helps return CM currents to the source before they can propagate onto the input/output terminals. These currents couple into the converter baseplate through the parasitic capacitances created between the baseplates and the various switching components inside the PFIC module. Grounding the converter and filter baseplates is an effective common-mode noise mitigation technique.

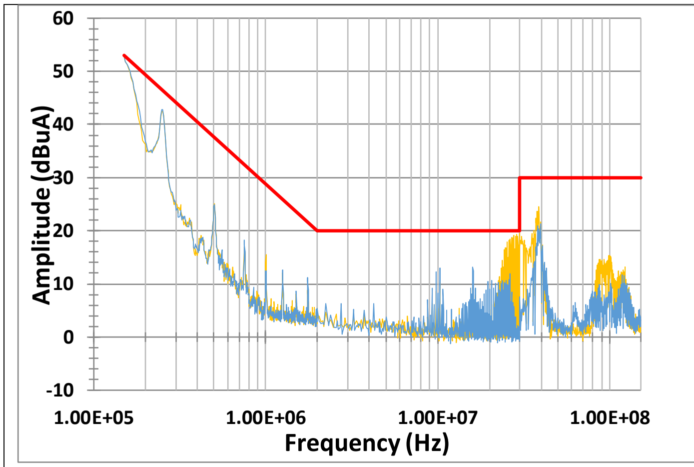


Figure 18. DO-160G CAT-M Grounded baseplates (filter and converter) conducted emissions (C8 capacitance 20nF). Same scan as shown in Figure 11.

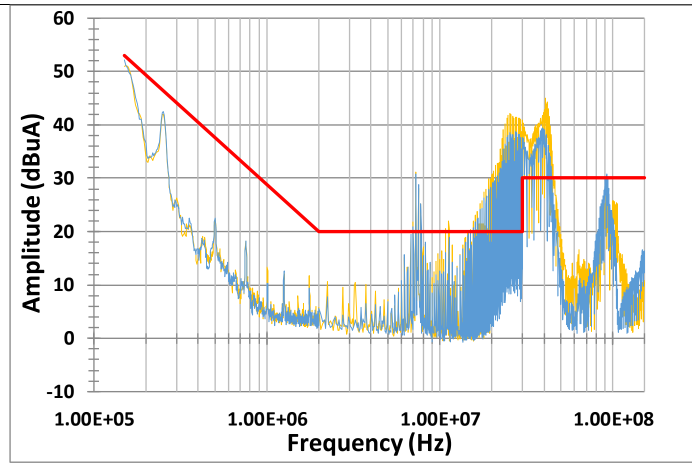


Figure 19. DO-160G CAT-M Ungrounded baseplates conducted emissions (C8 capacitance 20nF).

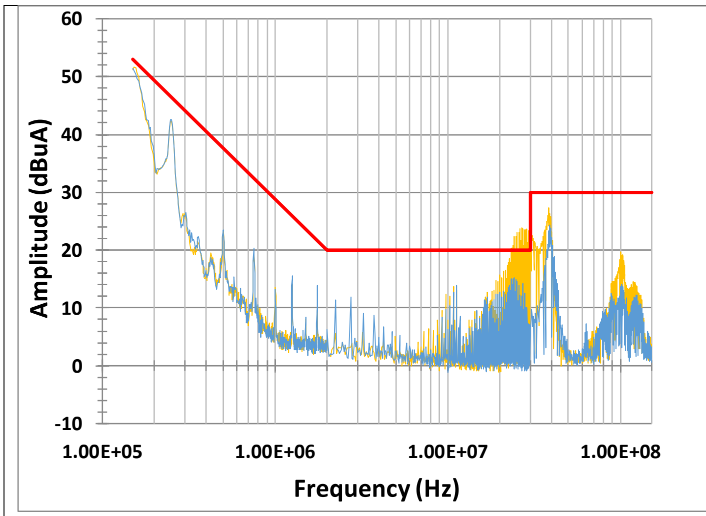


Figure 20. DO-160G CAT-M conducted emissions C8 set to 10nF (grounded baseplates).

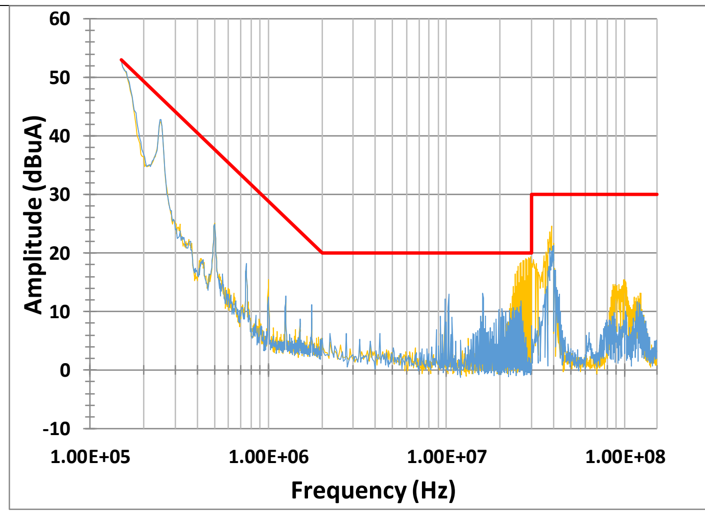


Figure 21. DO-160G CAT-M conducted emissions recommended C8 capacitance 20nF (grounded baseplates).

Note: Figure 21 is the same as figure 18.

Figures 18 and 19 illustrate how common-mode emissions can be significantly reduced by grounding the baseplates of the filter and PFIC. These figures show an improvement of 20dB or more in common-mode noise attenuation above 10MHz by simply grounding the baseplates. Further improvements can be achieved by adding a high-frequency capacitor between the output return and the hold-up return terminal (C8). For AC/DC systems, this capacitor needs to be Y1 safety approved capacitor. This capacitor allows for high-frequency noise generated in the power transformer or for input/output noise that migrated to the output/input to return to its source in a more deterministic manner.

The total capacitance value between the hold-up return and ground (output return and chassis ground) should not exceed 20nF (see product datasheet). Values of this capacitance above 20nF could disrupt the proper operation of the PFIC unit (increased harmonic content/distortion of AC input current). Furthermore, it could also increase leakage currents between the AC mains and ground, which can be a safety concern (consult system requirements). Figures 20 and 21 show the effect of increasing the value of C8 from 10nF to 20nF in the emission levels. Doubling the value of this capacitor results in significant noise attenuation at frequencies above 10MHz. For this capacitor to effectively manage the CM currents, it needs to have relatively low lead resistance and inductance at the frequencies of interest. Therefore, consider using multiple physical capacitors and/or a low inductance capacitor.

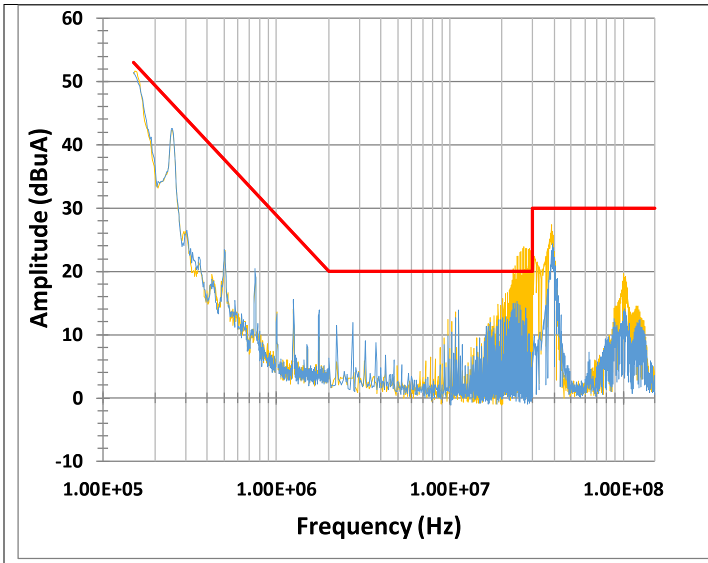


Figure 22. DO-160G CAT-M conducted emissions with C8 set to 10nF.

Note: Figure 22 is the same as figure 20.

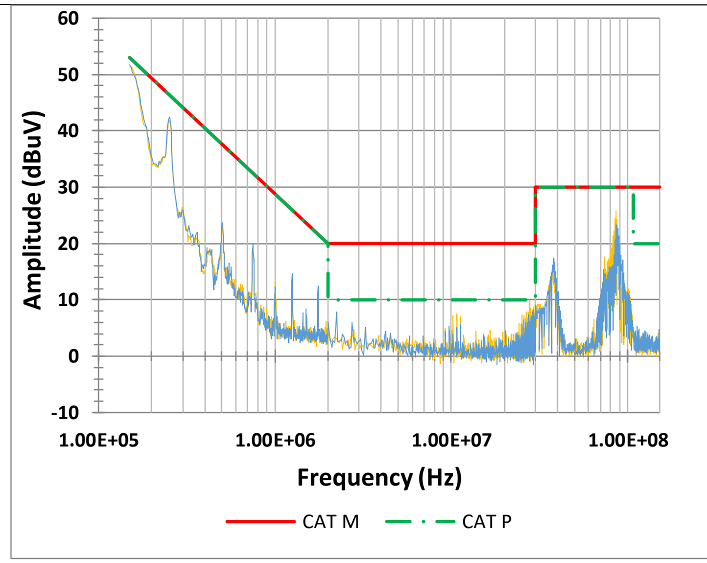


Figure 23. DO-160G CAT-M and CAT-P conducted emissions with C8 set to 10nF and an external common-mode choke.

Further reduction of noise emission at higher frequencies can be attained by adding a common-mode Y-capacitor between the output pins of the filter module and chassis ground (C3 and C4 Figure 17). These two capacitors help manage common-mode emissions generated by the primary references switching components in the PFIC module. Please remember that these Y-capacitors will affect the leakage current between AC mains and ground. In our set-up, the addition of these capacitors had an adverse effect (scans not shown). The SynQor filter modules were designed with well dampened Y-capacitor networks between the input/output pins to chassis ground. Adding an external Y-capacitor between the input/output filter pins and chassis ground is not necessary for this setup.

Further attenuation of emissions at frequencies above 10 MHz can be achieved by adding a common-mode inductor or choke between the input terminals and the filter module. Adding a CM choke will not adversely affect the “AC leakage” current. A CM choke with the appropriate core material (higher frequency, lower permeability ferrite) can yield close to a 10dB improvement at frequencies above 1MHz (see Figure 23). The 10dB improvement is sufficient to meet conducted emissions DO-160G category P requirements. The downside of this solution is that it requires additional board space. Figures 22 and 23 show the effects of the introduction of a CM choke across the input line of the EVAL-1000042 board on the EMI performance of the system.

Section 8 – Mitigation of Differential-mode noise

Up to this point, we have mainly discussed how to address common-mode emissions. Differential noise, as stated before, exhibits a differential voltage variation (out of phase) across the input and/or output conductors. Switch mode power converters generate ripple currents and voltages (differential noise) as a result of their basic operation. Differential noise generated by switch mode power converters will be observed at the converter ripple frequency and the subsequent harmonics of the ripple frequency. The PFIC product was designed using two interleaved boost converters. Therefore, the ripple frequency is twice that of the switching frequency. During low power operation, the PFIC turns off one of the boost converters to reduce power dissipation. Under these conditions, the current / voltage ripple fundamental frequency is the same as the switching frequency.

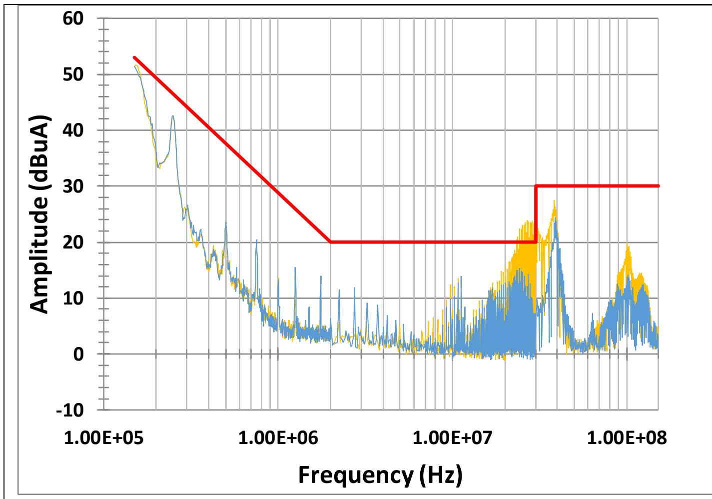


Figure 24. DO-160G CAT-M conducted emissions with C8 set to 10nF (Y-capacitor, input to output).

Note: Figure 22 is the same as Figure 24.

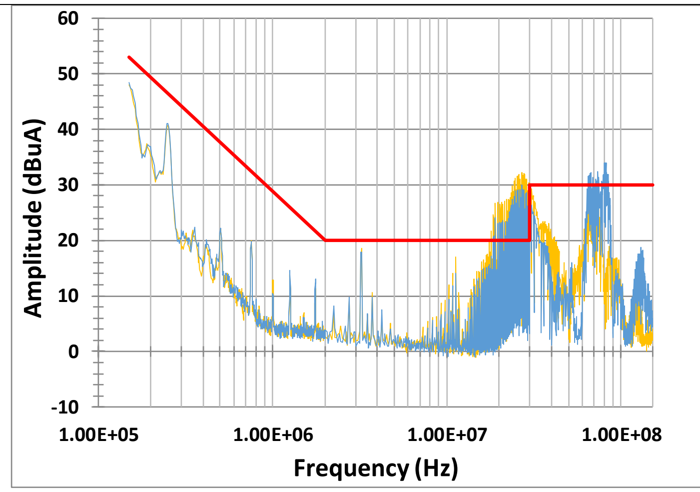


Figure 25.DO-160G CAT-M conducted emissions (same setup as Figure 24) with the addition of two 56nF differential capacitors placed across the input and output terminals of the filter.

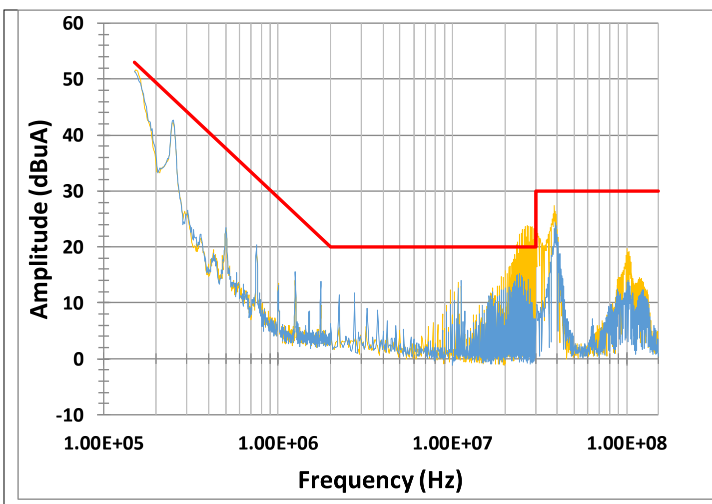


Figure 26. DO-160G CAT-M conducted emissions with C8 set to 10nF.

Note: Figure 22 is the same as Figure 26.

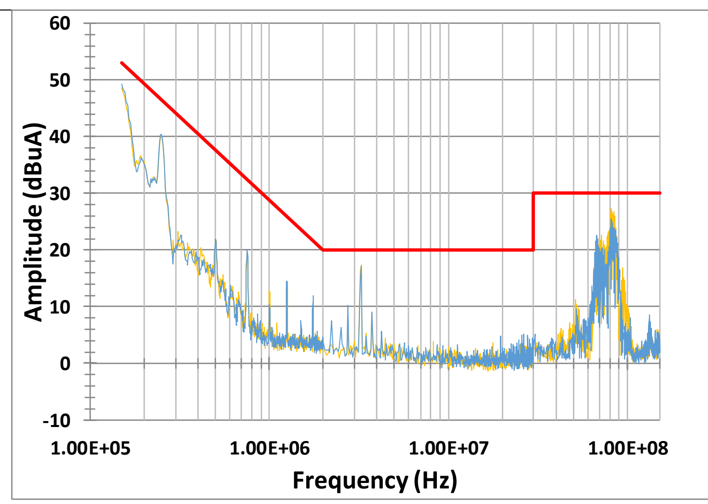


Figure 27. DO-160G CAT-M conducted emissions (same setup as Figure 25). CM choke added on the input, and three 56nF differential capacitors placed across the input and output terminals of the filter.

Even though differential noise is mostly due to the switching action of the power converter, differential noise can also be a result of electromagnetic field coupling. Current flow through any conductor can induce unwanted currents on neighboring conductors. The induction mechanism between neighboring conductors diminishes as the distance between the conductor's increases. In general, the induction level is inversely proportional to the distance between the conductors. It is important to keep noisy networks away from the input/output terminals to reduce this coupling effect. Unfortunately, this coupling mechanism cannot be eliminated. Therefore, it is recommended that input/output power and input/output return are routed one on top of the other in subsequent layers to reduce the coupling mechanism.

The differential input filter components should be selected so as to provide the required attenuation needed to suppress the input ripple currents generated by the PFIC. It is essential that the filter inductor-capacitor resonances are well-dampened. The SynQor filters are designed to provide the correct differential attenuation for the SynQor PFIC products utilizing well-dampened networks over the frequency of interest (DO-160G).

An interesting result was observed when two 56 nF capacitors (C6) were added differentially at the output of the input filter. These capacitors were added to provide additional differential filtering. Figure 25 shows the effect on the emission scans due to the addition of these two capacitors. Comparing Figures 24 and 25 suggests the measured conducted noise at the input terminals decreased at the fundamental ripple frequency (250kHz)and its subsequent harmonics. Unfortunately, adding these two capacitors increased the measured emissions at frequencies above 1 MHz. When dealing with EMI-related problems is not uncommon that additional filtering targeting a specific problem (frequency) results in increased emissions at other frequencies. For this particular test system, a better overall solution is to add an external common-mode choke before the input filter in addition to the two differential capacitors at the output pins of the filter module. The result for such a configuration is shown in Figure 27.

Section 9 – Radiated Emissions

All switch mode power supplies are sources of radiated emissions. Before attempting to meet radiated emissions requirements, it is recommended that the system first be tested for compliance with conducted emissions requirements. A system that is compliant with conducted emissions requirements is less likely to radiate significant noise through the input/output terminals. Long conductor terminals behave like antennas, allowing conductive emissions to radiate into the environment. Note that conducted emissions are usually only tested on the input conductors. A system that has significant conducted emissions in the input/output terminals will probably fail radiated emissions at frequencies above 10 – 20MHz. Low-measured conducted emissions above 10 MHz suggest low radiated noise from both input and output terminals.

An EMI shield is an effective technique to suppress radiated emissions generated from any component in the system. Every component lead or trace can behave as a transmitting antenna as frequencies increase. Conductors, leads, etc., can become effective antennas as their physical dimension is equal to or greater than the ½ wavelength of the radiating noise. An EMI shield (a Faraday's cage) can be placed around the noise-emitting components to suppress radiated emissions. The enclosure needs to be made from an electrically conductive material. It needs to be grounded. Ideally, it needs to be free of holes and crevices (small gaps and crevices will allow noise emissions at higher frequencies to escape/radiate into the ambient).

Any extended interfaces where two metal pieces meet can prevent the metal enclosure from suppressing radiated emissions. Generated noise with fields oriented parallel to the interface seam will easily circumvent the enclosure. To be an effective shield against radiated emissions, the two different enclosure sections have to effectively make electrically conductive contact along the entire length of the interface. The shield performance can be improved by adding an EMI gasket between two such metal pieces. It is also essential to ensure a good shielding solution is employed as it concerns any input/output connectors/cables.

Section 10 – Suggested Layout changes to EVAL-1000042 to improve EMI performance

The EVAL-1000042 evaluation board is meant to help customers familiarize themselves with the single-phase PFIC product line. The board was outfitted with placeholders for various external components to aid in this endeavor. The placeholders allow customers to test various configurations quickly and conveniently. To simplify testing, all components/placeholders (but one) in the EVAL-1000042 evaluation board are located on the top side of the board. This arrangement creates some layout limitations, especially as it concerns EMI. In this Application Note, it has been shown that the ACF-U-230-QT filter and APFIC-U-24R-HT module can meet the DO-160G CAT-M requirements in our internal test setup without having to populate many of these external components. If the unused placeholders were removed and some required components were placed on the opposite side of the PCB (on the current path), many of the long copper planes and traces could be replaced by shorter low inductance connections. Several copper planes that interconnect the input terminal to the filter and to the PFIC module could be rearranged so that the power traces and the return traces have a similar shape, allowing them to be placed one on top of another (for CM noise rejection). The same can be said for the hold-up and output traces. Having the forward and the return paths on top of each other can significantly reduce common-mode noise pick-up.

For example, the input fuses could be replaced with surface mount fuses and placed on the bottom side of the PCB. All the differential and common-mode capacitors between the input filter and the input connector can be removed (not needed). The same goes for the capacitors across the output of the filter. The capacitors that make up C8 and C9 should be relocated to the bottom layer of the PCB to reduce the length of the connecting traces. These few simple changes would allow the input connector to be placed near the input filter pins. The PFIC module could also be placed significantly closer to the filter, thereby reducing the length of the copper planes between the filter's output pins and the PFIC module's input pins. The hold-up capacitors and output electrolytic capacitors could also move to the bottom layer closer to the PFIC module pins, significantly reducing the length of the interconnecting traces. The hold-up and BNC output connectors are not needed. These changes could dramatically reduce the effective current loops in the evaluation board, decreasing noise coupling (and PCB size) and improving EMI performance.

Section 11 – Conclusions

Throughout this application note, we have shown the various techniques that can be used to reduce conducted and radiated emissions from a given set-up. Setting capacitor C8 to 10nF allows the test system to meet most DO-160G power line conducted emissions requirements except the most stringent category P. Category P can be met by adding an external choke in front of the evaluation board. A new PCB could benefit from additional noise reductions by removing the unused components' placeholders. Removing the placeholders allows for the possibility of reducing the distance between the input connector, the filter, the AeroQor PFIC module, and the output connector. Reduction of the length of these interconnects to about a ¼” will probably enhance the EMI performance of the test system.

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