



Summary:

This application note will give an overview of electromagnetic interference (EMI), the appropriate standards and regulations, how these standards and regulations relate to dc/dc power modules, suggestions for external filtering solutions, and suggested layout and grounding practices.

1.0 Introduction

Designing for electromagnetic compatibility (EMC) is one of the most difficult challenges for electronic system designers. Almost all-electronic equipment is required to meet one or more EMC standards at the system or product level. One of the most challenging subsystems when speaking about EMC is the power supply or in this case the dc/dc power module. All modern dc/dc converters are composed of one or more switching stages containing both pulsed voltages and currents, which generate a broad noise spectrum resulting in electromagnetic interference (EMI).

This application note will give an overview of electromagnetic interference (EMI), the different standards and regulations, how these standards and regulations relate to dc/dc power modules, suggestions for external filtering solutions, and suggested layout and grounding practices.

The first step in designing systems for EMI compliance is to understand that the different standards and regulations do not directly apply to the dc/dc power module but to the overall system. Regardless, understanding and minimizing the emissions emanating from the power module is a good beginning to EMI system compliance.

2.0 General Overview

Electromagnetic interference (more commonly known as EMI) refers to how different sets of electronic equipment interact with each other, usually in a negative manner. The recent advances in semiconductor devices and large-scale integration has dramatically reduced the size of electronic equipment while increasing the probability for electromagnetic interference between the different systems and subsystems. Today's electronic designers must make sure their solutions work in an environment of high EMI. It is not practical to ask new product designers to test their equipment under all conditions and possible end-user configurations, therefore strict emissions regulations have been established. In the United States the Federal Communications Commission (FCC) regulates the use of radio and wire communications. Part of its responsibility concerns the control of electromagnetic interference. The standards for the allowed levels of electromagnetic emissions are outlined in part 15 of the FCC rules and regulations. These rules apply to almost all-electronic equipment. Under these rules, limits are placed on the maximum allowable radiated emissions in the frequency range between 30 to 1000 MHz and on the maximum allowable conducted emissions on the AC power line in the frequency range of 0.450 to 30 MHz.

Radiated Emissions

Radiated emissions refer to interference that is coupled through the air. It is the belief of the FCC that at frequencies below 30 MHz the primary cause of EMI occurs by allowing RF to flow through the AC power lines where it subsequently radiates into neighboring equipment (conducted emissions).

All electronic equipment that generates pulses of any kind in excess of 10,000 pulses per second (> 10 kHz) is subjected to these regulations. Electronic equipment is divided into two classes according to the FCC:

- Class A: Electronic equipment that is marked for use in a commercial, industrial, or business environment [2].
- Class B: Electronic equipment that is marketed for use in a residential environment, notwithstanding its use in a commercial, industrial, or business environment [2].

Class B equipment is more likely to be located in close proximity to radio and television receivers, therefore, the emissions limits for these devices is more restrictive relative to Class A. As it was stated before, compliance is the responsibility of the end-product manufacturer.

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Tables 1 and 2 show the different radiated emissions limits for both Class A and Class B. A true comparison of these limits cannot be made unless they are compared at the same distance. The Class A limits can be extrapolated to a distance of 3-m by using a $1/r$ extrapolation where r is the distance between the source and the receiving equipment. In general, Class B limits are more restrictive by a factor of 3 (~ 10 dB) as shown in Figure 1.

Frequency (MHz)	Measuring Distance (m)	Field Strength ($\mu\text{V}/\text{m}$)
30 - 88	30	30
88 - 216	30	50
216 - 1000	30	70

Table 1: FCC Class A Radiated Emissions Limits [2].

Frequency (MHz)	Measuring Distance (m)	Field Strength ($\mu\text{V}/\text{m}$)
30 - 88	3	100
88 - 216	3	150
216 - 1000	3	200

Table 2: FCC Class B Radiated Emissions Limits [2].

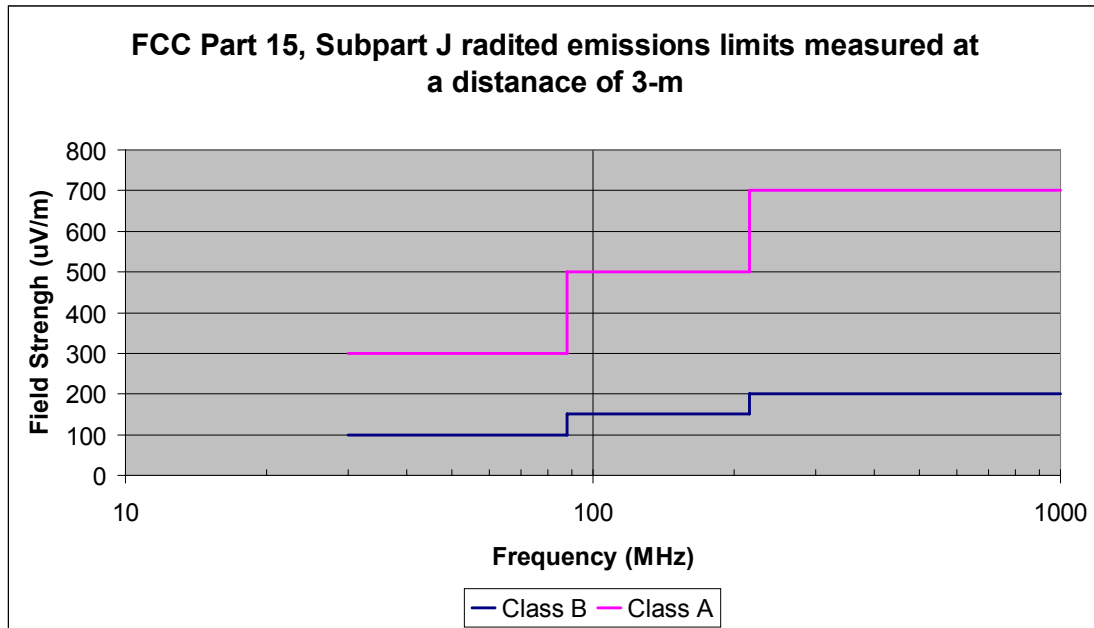


Figure 1: Radiated emissions limits measured at a distance of 3.0m [1].

Conducted Emissions

Table 3 shows the conducted emission limits for both Class A and Class B type equipment. Conducted emissions are measured as the voltage measured common-mode (+Vin to ground and -Vin to ground) on the power line using a 50-ohm/50-μH line impedance stabilization network (LISN).

Frequency (MHz)	Class A (μV)	Class B (μV)
0.45 - 1.6	1000	250
1.6 - 30	3000	250

Table 3: FCC Conducted Emmission Limits [2].

Standards

The International Special Committee on Radio Interference (CISPR) regulates the international community. CISPR has no regulator authority, but its standards have been adopted by most European nations. Figure 2 shows a comparison between the CISPR recommended radiated emission standard and the FCC limits. The FCC limits have been scaled to a 10 m measuring distance for this comparison [1]. Figure 3 shows a similar comparison for the conducted emission standards. The limits in Figures 2 and 3 are displayed in decibels relative to 1 μV. The emission levels in decibels can be easily calculated using the following expression: emissions in decibels = 20 log (noise level voltage/1μV).

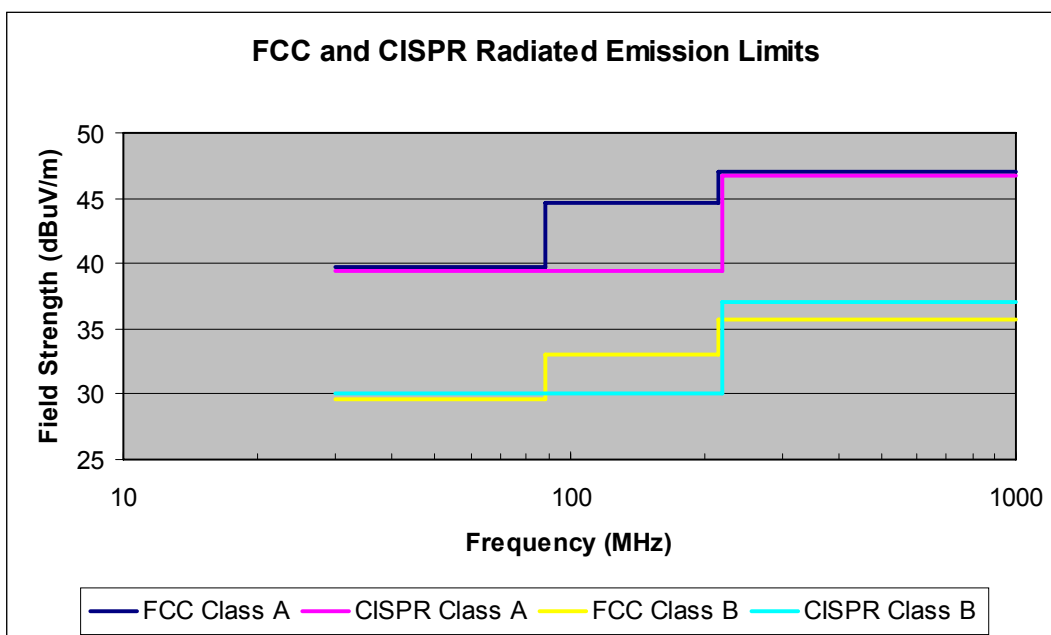


Figure 2: Radiated emission limits measured at a distance of 10 m [1].

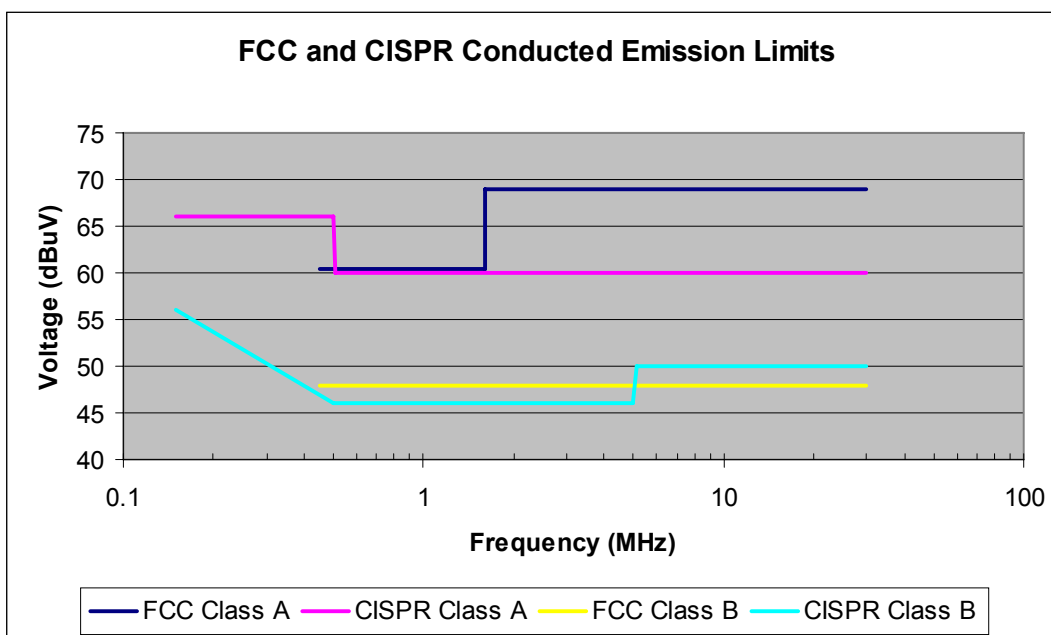


Figure 3: Conducted emission limits [1].

FCC and CISPR also specify susceptibility emission limits of home electronics equipment and systems. To date, the FCC does not regulate the susceptibility of electronic equipment; the FCC relies on self-regulation by the industry. European nations are governed by the standards suggested by CISPR. Any product sold in Europe must meet these requirements. All SynQor power modules are tested and meet IEC PUBL. 1000-4-3 limits. IEC 1000-4-3 test at field strengths of 3 V/m (normal performance) and 10 V/m (reduced performance). It has been shown that field strength greater than 2 V/m occurs for approximately 1 % of the time [1].

Another standard that is sometimes relevant is the EN300 386-2. This standard is relevant only for telecommunications equipment and it applies to equipment with either AC or DC power mains. For systems with DC input mains the EN300 386-2 standard specifies levels identical to the one specified by CISPR Class A limits. However, the EN300 386-2 standard extends to lower frequencies (20 kHz - 150 kHz). All of the SynQor power modules operate with switching frequencies in excess of 150 kHz. Therefore, typical power modules do not affect the low frequency emission levels of the system.

3.0 EMC For Power Modules

The first step in tackling the EMI problem is a thorough understanding of the requirements and how it relates to your system. Remember, there are no conducted or radiated emission restrictions that apply to power modules as a stand-alone product. Power modules are considered one of many components of modern telecom or computer equipment. The requirements apply to the system. The end product must meet a set of conducted and radiated emission levels that depends on the equipment usage and country into which it is being sold. Due to the fact that EMI is a system level requirement, it is not practical nor economical for high-power modules to meet either the conducted and radiated limits as a stand-alone component. Most high-power modules supplied by SynQor or any other manufacturer will probably not comply with the conducted and radiated limits specified by the different standards without some effort in the design of the system to limit noise.

3.1 Conducted EMI

Most electronic equipment has only one interface with the power source. It is at this interface that the conducted emission standards apply. In most applications, power modules are usually isolated from the main power source by EMI filters, circuit breakers, fuses, transient protection devices, DC/DC converters, and/or AC/DC power converters. Therefore, in most applications the conducted emissions radiating from the power-module do not appear directly at the power mains. It is very possible that the system will meet the conducted EMI limits without any of the power modules meeting the EMC standard as a stand-alone component. Many systems will meet all EMI standards by simply using a single EMI filter at the input of the power mains.

AC/DC and DC/DC converters by nature generate significant levels of both conducted and radiated noise. Furthermore, if these noises are not suppressed close to the source, they can very easily couple to other areas of the system, greatly increasing the complexity of the problem. Therefore, it is recommended to have some level of EMI suppression local to each power module.

$$\begin{aligned} V_d &= V_1 - V_2 = \text{differential mode voltage component} \\ I_d &= (I_1 - I_2) / 2 = \text{differential mode current component} \\ V_c &= (V_1 + V_2) / 2 = \text{common mode voltage component} \\ I_c &= I_1 + I_2 = \text{common mode current component} \\ C_s &= \text{effective parasitic capacitance between the dc/dc/ module} \\ &\quad \text{and the chassis ground} \end{aligned}$$

In order to better understand the source of conducted emissions, emissions are generally classified as differential (symmetrical) or common (asymmetrical) mode noise. The definition of common mode (CM) and differential mode (DM) voltages and currents is illustrated in Figure 3.

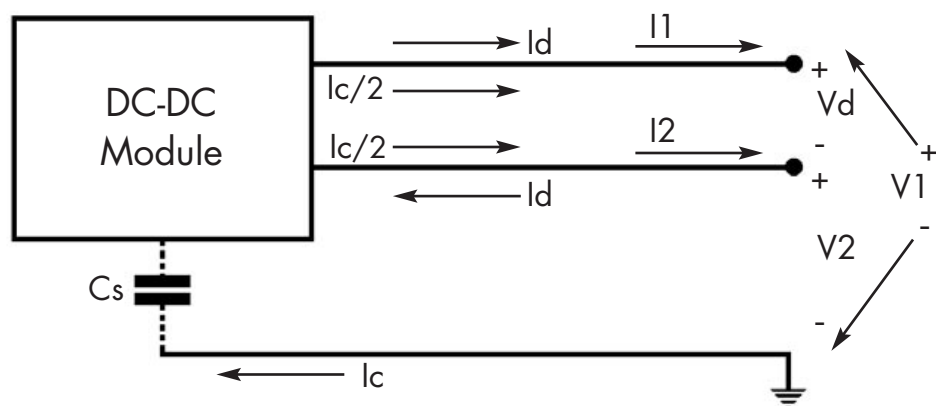


Figure 3: Definition of differential and common mode currents and voltages.

The natural operation of dc/dc converters results in differential mode type currents and voltages. SynQor has added an input filter to all of its power modules to decrease the DM noise emitted by the converter. The common mode noise emitted by the module cannot be directly determined since there is no direct coupling mechanism. The common mode current level is directly related to the effective parasitic capacitance between the power module and chassis ground. SynQor's power modules utilize an open frame design with no baseplate and no chassis ground connection. Not having a baseplate greatly reduces the effective capacitance between the module and chassis ground. Therefore, common mode currents are greatly reduced relative to typical power modules.

Figures 4 and 5 show a comparison of how the SynQor power modules differ from the traditional dc/dc module relative to their coupling mechanism for common mode emissions. Both of these figures present a simplified version of the common mode emissions problem in dc/dc modules. It is well known that there are many different coupling mechanisms between the power module and chassis ground. But at the same time as power supply designers, we recognize that the semiconductor devices in conjunction with the power transformer represent the major sources of common mode voltages and currents. Figure 4 shows the traditional implementation of high-power dc/dc modules. Capacitance C_{s1} represents the effective parasitic capacitance between the baseplate and chassis ground. Capacitance C_{s1} is usually very small, its value is directly related to the size of the baseplate, the proximity of the baseplate to chassis ground, and the size and shape of the chassis ground. In many high-power modules the baseplate is directly connected to chassis ground shorting capacitance C_{s1} . Capacitance C_{s2} is the parasitic capacitance between the semiconductor devices and the baseplate. In order to maximize the thermal performance of the module, in the traditional solution, a very thin thermal pad separates the "tab" of the semiconductor devices and the baseplate. This type of construction results in significant parasitic capacitance between the semiconductors and the baseplate. Capacitance C_{s2} provides an easy coupling mechanism for common mode currents to flow into the chassis ground, especially when the baseplate is connected to chassis ground.

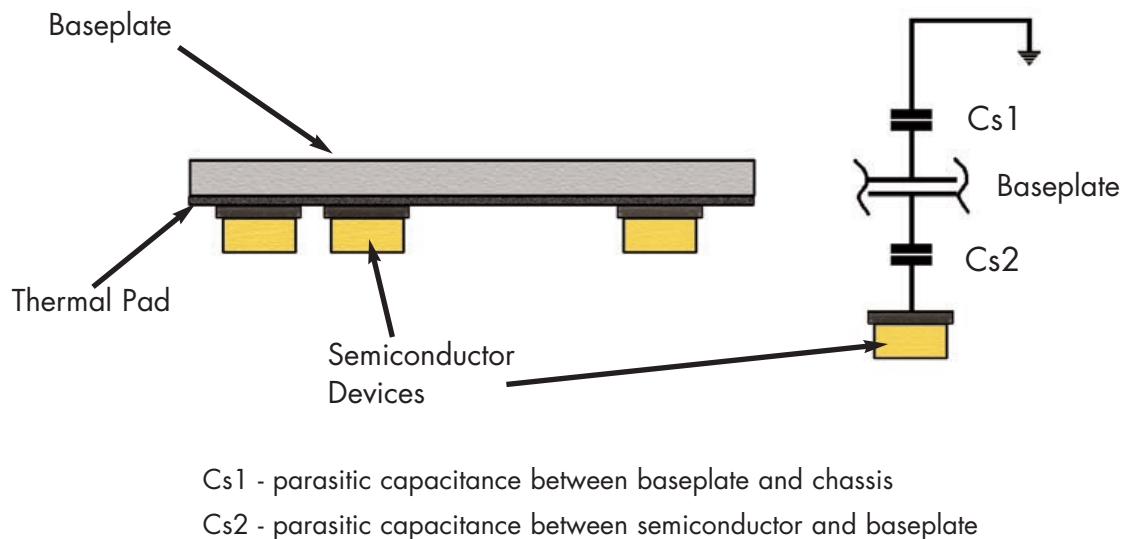
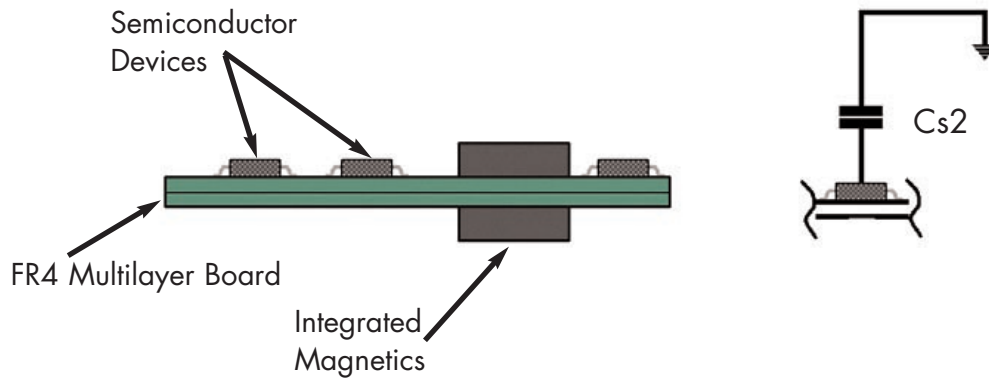


Figure 4: Traditional physical design for high power dc/dc modules.

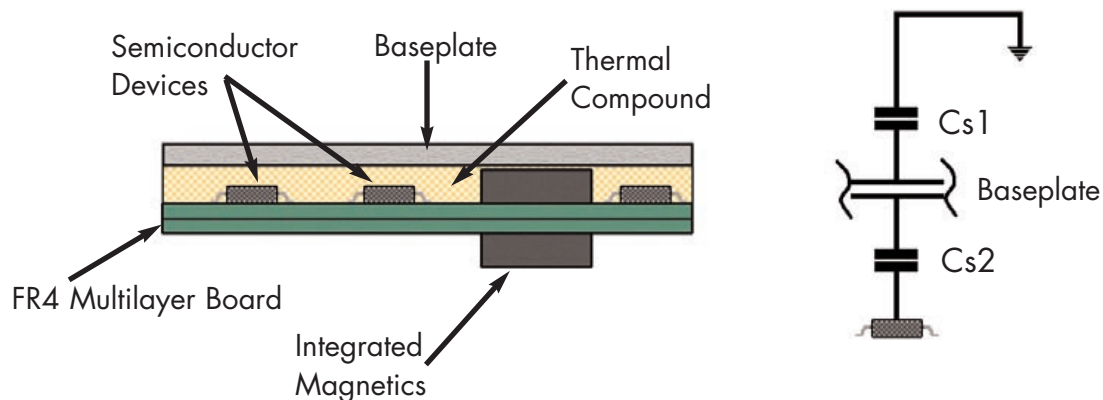
Figure 5 shows the physical solution of the SynQor power module. The preferred solution does not have a baseplate ($Cs1 = 0$). Capacitance $Cs2$ is the effective parasitic capacitance between the semiconductors and chassis ground. This capacitance is small relative to the traditional physical implementation, resulting in reduced common mode emissions.



$Cs2$ - parasitic capacitance between semiconductor(s) and chassis ground

Figure 5: Physical design of a typical SynQor dc/dc module.

SynQor offers a baseplate option on all of their modules (Figure 6). In this implementation, capacitance $Cs2$, which represents the effective capacitance between the semiconductor devices and the baseplate, again, is significantly smaller when compared to the traditional design. It is the proximity of the metal "tab" of the semiconductor devices to the base plate that contributes to increased coupling (increased $Cs2$) and increased common mode currents in the traditional arrangement. Therefore, SynQor's dc/dc power modules generate reduced levels of common mode emissions.



$Cs1$ - parasitic capacitance between baseplate and chassis

$Cs2$ - parasitic capacitance between semiconductor and baseplate

Figure 6: Physical design of a SynQor module with the baseplate option.

Table 4 summarizes the EMC related characteristics of selected SynQor modules. Please consult the individual datasheet for specific data on each module. The switching frequency is listed to help understand the noise spectrum and help in the design of an external filter. It is important to note that the switching frequency of the modules has a tolerance of +/- 17 % over temperature. The table summarizes the characteristics of the input filter. Most modules have a Pi type filter at the input. C1 is the capacitance connected directly at the input pins. C2 is the second capacitor of the Pi filter. In all of the SynQor modules, the inductor is located in the +Vin lead.

Module Type	Nominal Operating Frequency (kHz)	Input Filter	Input Capacitance C1, C2 (μF)	Input Inductor (μH)
PQ48150QGA06NNS	270	2 nd order	0, 2.46	4.7
PQ48120QGA08NNS	215	2 nd order	0, 2.46	4.7
PQ48060QGA17NNS	215	2 nd order	0, 2.46	4.7
PQ48050QGA20NNS	300	2 nd order	0, 2.46	4.7
PQ48033QGA25NNS	240	2 nd order	0, 2.46	4.7
PQ48025QGA25NNS	200	2 nd order	0, 2.46	4.7
PQ48020QGA25NNS	270	2 nd order	0, 2.46	4.7
PQ48018QGA25NNS	240	2 nd order	0, 2.46	4.7
PQ48015QGA25NNS	200	2 nd order	0, 2.46	4.7
PQ48050HTA33NNS	200	Pi	1.64, 3.28	4.1
PQ48033HTA50NNS	260	Pi	1.64, 3.28	4.1
PQ48025HTA60NNS	200	Pi	1.64, 3.28	4.1
PQ48020HTA60NNS	200	Pi	1.64, 3.28	4.1
PQ48018HTA60NNS	200	Pi	1.64, 3.28	4.1
PQ48015HTA60NNS	260	Pi	1.64, 3.28	4.1

Table 4: EMC characteristics of the SynQor power modules. Refer to individual technical datasheets for information on specific modules.

Figures 7, and 8 show the conducted emissions of the 25A quarter-brick and the 50A half-brick 3.3V modules operating at full load with the aid of an external filter. The modules were tested in an independent Lab (KTL of Dallas) in accordance with the accepted CISPR standards. The modules were loaded with a passive resistive load to avoid any possible interaction between the "dynamic load" and the module. The units were mounted on a four layer test board where the bottom layer was used for a chassis ground plane. The results show peak measurements relative to the average Class B (CISPR) limits. The implementation of the two external filters used is summarized in Figure 9. The suggested filters allow for the modules to meet CISPR Class B conducted emissions limits. Capacitors CYS1 and CYS2 are added to minimize the electromagnetic interference emanating from the output cables in the 5 to 30 MHz frequency range. These capacitors could be omitted if the output distribution bus is relatively short in length.

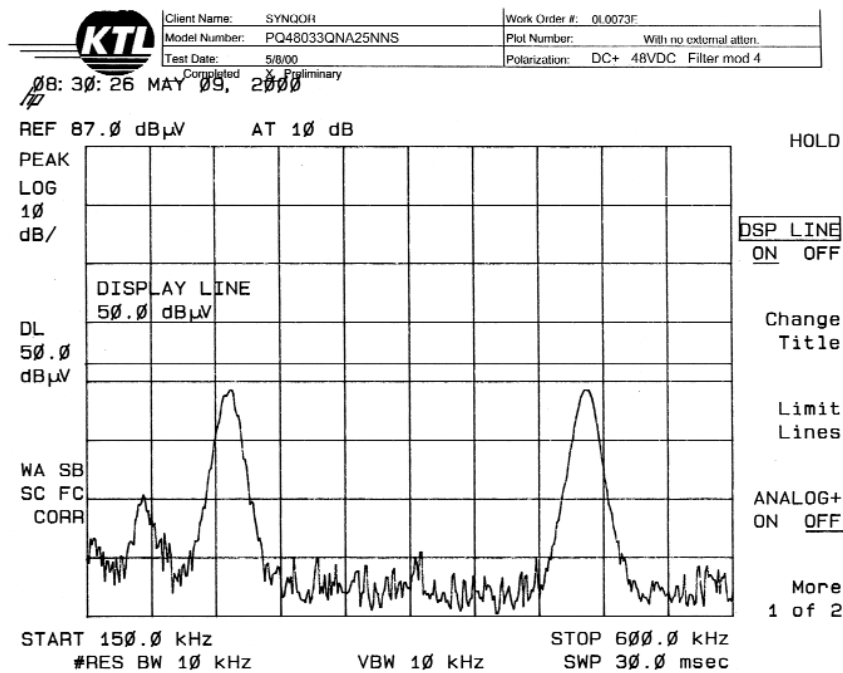


Figure 7a: Conducted emission from 150 kHz to 600 kHz for the 25A quarter-brick using the EMI filter shown in Figure 9a [6]. The data shown corresponds to the emission measured in the positive input lead. The 50-dB μ V level is shown as a reference.

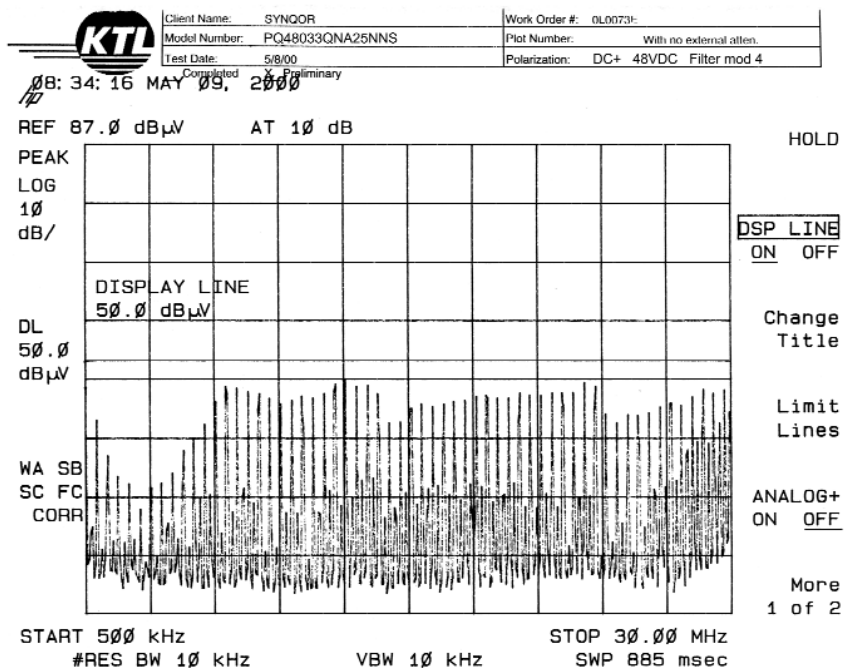


Figure 7b: Conducted emission from 500 kHz to 30 MHz for the 25A quarter-brick using the EMI filter shown in Figure 9a [6]. The data shown corresponds to the emission measured in the positive input lead. The 50-dB μ V level is shown as a reference.

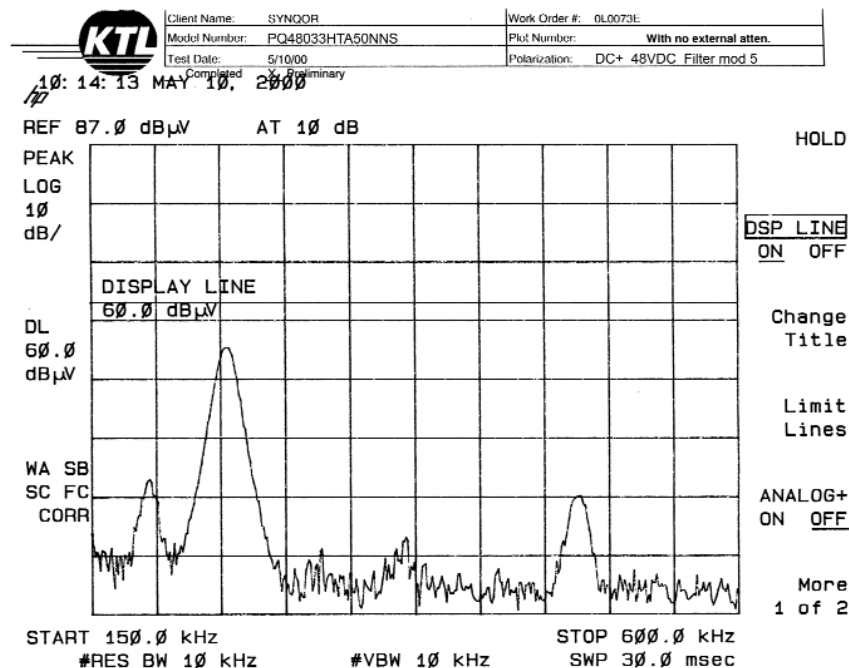


Figure 8a: Conducted emission from 150 kHz to 600 kHz for the 50A half-brick using the EMI filter shown in Figure 9b [6]. The data shown corresponds to the emission measured in the positive input lead. The 60-dBμV level is shown as a reference.

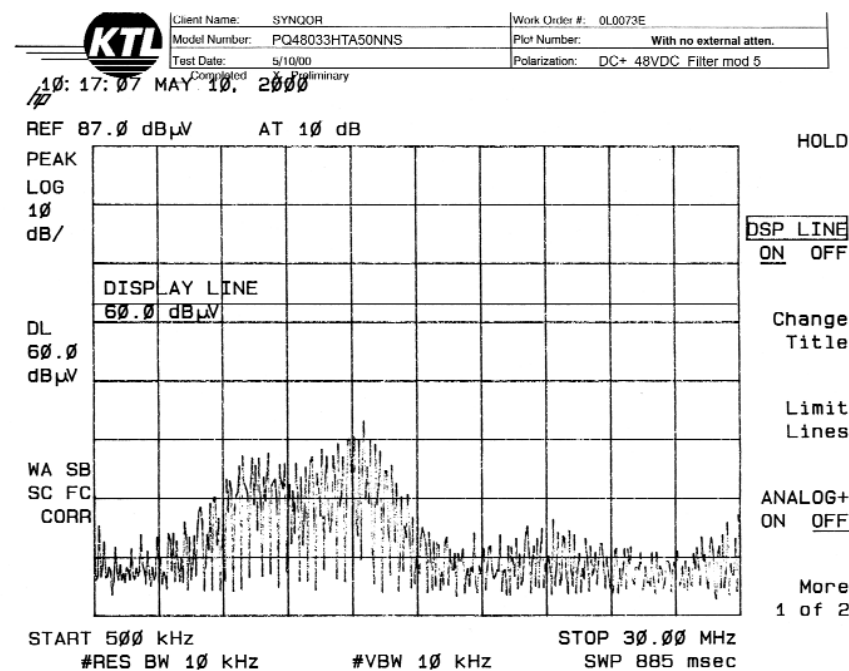
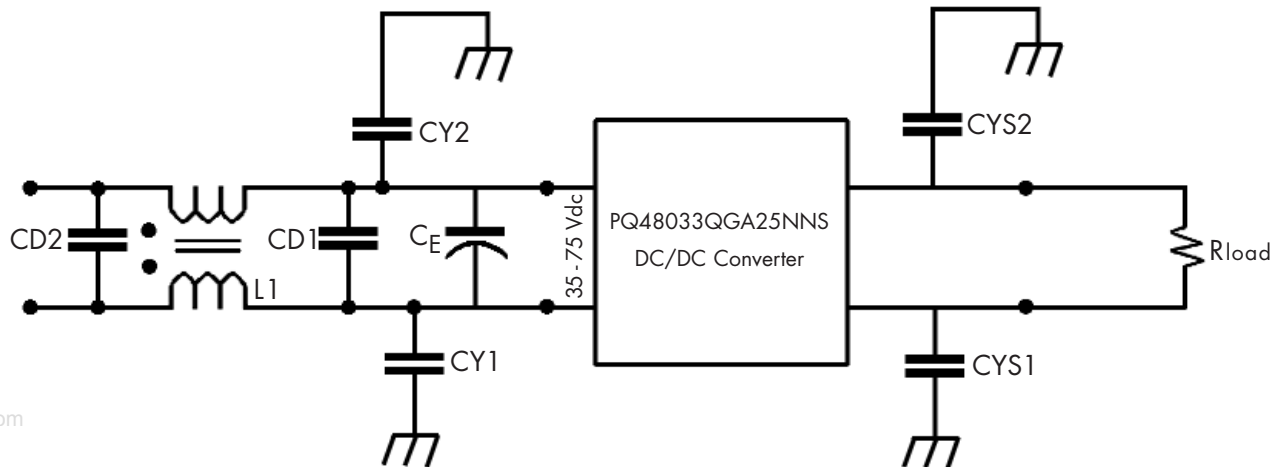


Figure 8b: Conducted emission from 500 kHz to 30 MHz for the 50A half-brick using the EMI filter shown in Figure 9b [6]. The data shown corresponds to the emission measured in the positive input lead. The 60-dBμV level is shown as a reference.

Filter Mod. # 4

CY1 = CY2 = CYS1 = CYS2 = 2700 pF / 2000V ceramic capacitor from AVX

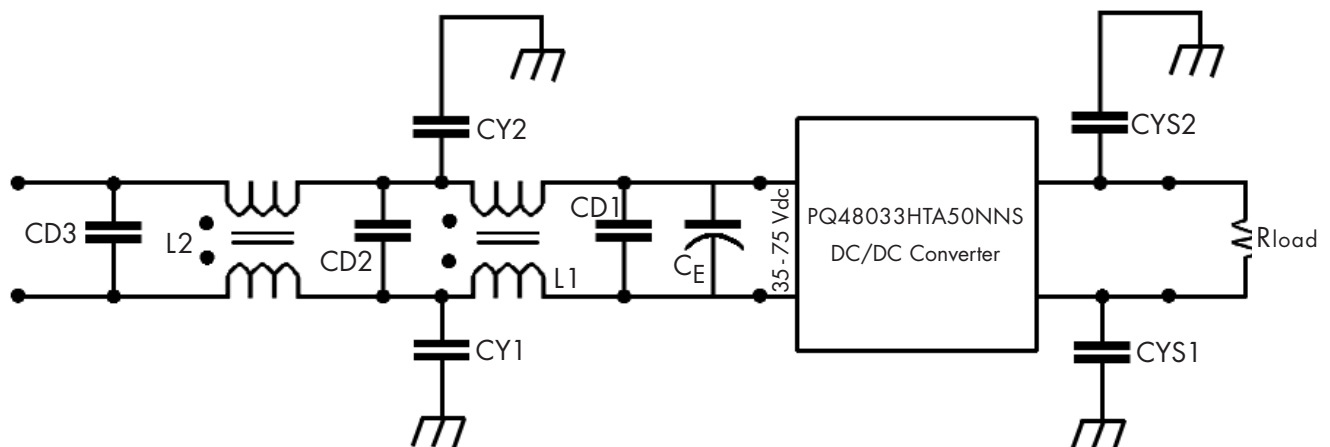
CD1 = CD2 = 3 x 1 μ F / 100V ceramic capacitor from AVX

L1 = inductor (Pulse part# P0422)

C_E = 33 μ F / 100V electrolytic capacitor, Refer to "Input System Instability" application note for details.

I_{out} = 25 Amps

Figure 9a: External filter used with the PQ48033QGA25NNS (quarter-brick 25A/3.3V) power module.

Filter Mod. # 5

CY1 = CY2 = CYS1 = CYS2 = 2700 pF / 2000V ceramic capacitor from AVX

CD1 = CD2 = CD3 = 2 x 1 μ F / 100V ceramic capacitor from AVX

L1 = inductor (Pulse part# P0353)

C_E = 33 μ F / 100V electrolytic capacitor

I_{out} = 50 Amps

Figure 9b: External filter used with the PQ48033HTA50NNS (half-brick 50A/3.3V) power module.

3.2 Radiated EMI

Again it is important to remember that only the system needs to meet the required standards. Radiated emissions are of importance in the 30 MHz to 1000 MHz range. Metal enclosures in addition to power and ground planes provide significant attenuation to electromagnetic emissions in the frequency range in question. Therefore, most physical system solutions will provide enough attenuation and allow the system to meet radiated emission standards with relative ease. It is neither practical nor economical to demand the typical dc/dc module to meet radiated EMC standards as a stand-alone product.

A one-piece metal "box" with no opening or cracks would be the ideal shield to radiated noise, but this is not a practical solution. When designing for radiated emissions it is important to minimize the size of any opening in the chassis box. The size of any opening in addition to its location relative to the source of radiated EMI is of great importance as it concerns radiated EMI. Furthermore, any location where two or more metal pieces of the chassis box meet needs to make electrical contact to maintain the integrity of the shield.

Again, radiated emissions are classified into differential and common mode depending on the source. Differential-mode noise radiates from small loop antennas. Loop antennas can be defined as the area enclosed by a current carrying loop. The magnitude of the field is proportional to the magnitude of the current, the enclosed area, and the square of the oscillating frequency. Reducing the area enclosed by any current loop can easily minimize differential-mode noise. Great care has been taken in the layout of all SynQor power modules to reduce differential mode radiation.

On the other hand, common-mode radiation is harder to control and usually determines the overall radiated emission performance of the product. Common-mode radiation usually emanates from the input and output cables. Due to their relatively long length, input and output mains are good transmitters of EMI noise. Input and output cables behave as monopole antennas driven by a voltage. Decoupling both input and output mains with ceramic capacitors to chassis ground close to the power module suppresses the excitation voltage. Great care has to be taken not to exceed the leakage current requirement (this is a safety requirement) when adding capacitors from any point to chassis ground in systems powered by an AC distribution.

For reference, Table 5 shows radiated emissions levels for a 25A quarter-brick 3.3Vout module operating at full load. The module was tested with the external filter suggested in Figure 9a in place. Again, a resistive load bank was used to obtain these results. The tables show peak measurements of the radiated emissions levels relative to the average Class B limits as suggested by CISPR. The data shows that the module and filter combination fails CISPR Class B emissions standards by only a few dBs. The module was tested in an outdoor independent test facility at KTL of Dallas.

The conducted and radiated emissions levels reported for the different modules should be used as a reference only. The emissions levels are very dependent on the physical configuration and grounding practices of the system under test.

Frequency (MHz)	Antenna Polarization	Reading (dB μ V/m)	Class B limit (dB μ V/m)	Diff. (dB)	Type of Measurement
30.17	H	30.9	30.0	0.9	Peak
30.66	H	1.929.7	30.0	-0.3	Peak
36.20	H	1.637.1	30.0	7.1	Peak
37.71	H	37.8	30.0	7.8	Peak
48.76	H	28.7	30.0	-1.3	Peak
52.03	H	31.2	30.0	1.2	Peak
86.46	H	23.4	30.0	-6.6	Peak
108.80	H	27.5	30.0	-2.5	Peak
141.28	H	43.5	30.0	13.5	Peak
142.80	H	43.5	30.0	13.5	Peak
160.38	H	32.8	30.0	2.8	Peak
165.13	H	32.5	30.0	2.5	Peak
208.90	H	29.2	30.0	-0.8	Peak
221.90	H	27.4	30.0	-2.6	Peak
228.48	H	28.1	30.0	-1.9	Peak
36.20	V	48.2	30.0	18.2	Peak
36.20	V	32.4	30.0	2.4	Quasi-Peak
37.75	V	48.0	30.0	18.0	Peak
37.75	V	32.4	30.0	2.4	Quasi-Peak
50.30	V	40.5	30.0	10.5	Peak
50.30	V	25.5	30.0	-4.4	Quasi-Peak
52.03	V	36.3	30.0	6.3	Peak
62.84	V	33.8	30.0	3.8	Peak
74.60	V	28.2	30.0	-1.8	Peak
85.96	V	31.1	30.0	1.1	Peak
119.13	V	35.5	30.0	5.5	Peak
125.40	V	36.1	30.0	6.1	Peak
142.50	V	41.8	30.0	11.8	Peak
142.50	V	32.3	30.0	2.3	Quasi-Peak
144.00	V	42.4	30.0	12.4	Peak
144.00	V	32.4	30.0	2.4	Quasi-Peak
165.10	V	30.1	30.0	0.1	Peak
208.80	V	28.1	30.0	-1.9	Peak
224.90	V	26.3	30.0	-3.7	Peak
302.57	H	26.0	37.0	-11.0	Peak
343.57	H	27.8	37.0	-9.2	Peak
377.50	H	25.1	37.0	-11.9	Peak
301.87	V	23.0	37.0	-14.0	Peak
334.08	V	19.9	37.0	-17.1	Peak
438.00	V	22.6	37.0	-14.4	Peak

Table 5: Radiated emissions of a 25A Quarter-brick 3.3V module with the external filter shown in Figure 9a.

4.0 Layout and Grounding Practices

Great care should be taken in the layout and grounding practices used for the module and system in general. A list of suggestions that will minimize conducted and radiated emissions include:

1. Add both, low frequency tantalum and high frequency ceramic capacitors to the dc/dc module output bus. Place at least one of each as close as possible to the output terminals of the module.
2. Add both, low frequency electrolytic and high frequency ceramic capacitor to the dc input distribution bus. Place at least one of each as close as possible to the input terminals of the module.
3. Use short leads on all filter and decoupling components. Minimize all circuit loops that carry significant current.
4. Minimize parasitic inductances by using wide distribution traces over ground planes.
5. Place a Y-capacitor between input and output ground planes. Return all common mode noise to the input ground.

Additional details about all of these topics can be found in [1,4].

5.0 References

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