How to Design MIL-STD-461C/D/E EMI Filters for 12V/24V/28V Input GAIA Converter DC/DC Modules

- To comply with MIL-STD-461C power leads :
  - CE 03 : Emission requirement over 15KHz to 50MHz
  - CS 01 : Susceptibility requirement over 30Hz to 50KHz
  - CS 02 : Susceptibility requirement over 15KHz to 400MHz
  - CS 06 : Susceptibility requirement for spikes

- To comply with MIL-STD-461D/E power leads :
  - CE 102 : Emission requirement over 10KHz to 10MHz
  - CS 101 : Susceptibility requirement over 30Hz to 150KHz
  - CS 114 : Susceptibility requirement over 10KHz to 400MHz
  - CS 115 : Susceptibility requirement for spikes

1- Introduction to EMI

1-1 General

Electromagnetic interference compatibility is of primarly importance in avionics/military applications and are divided in 4 main classifications :
- conducted emission (CE)
- radiated emission (RE)
- conducted susceptibility (CS)
- radiated susceptibility (RS)

EMI emissions (conducted and radiated) address noise generated by the device under test whereas EMI susceptibility describe the noise environments that the device under test must tolerate without malfunction.
Conducted noise is transmitted along the electrical cables that connect the input power bus to the device under test while radiated noise occurs through the unintended transmission or reception of noise signals.

From a design perspective, conducted emission are further divided into common-mode and differential-mode noise. Differential-mode conducted noise results from current flowing in one terminal of the converter and out the other. Common-mode noise, on the other hand, flows through the ground and returns in the same direction in both the power and return lines. Differential-mode noise is generally associated with switching currents whereas common-mode noise are primarily a result of pulsating voltages in the circuit.

1-2 Requirements

One of the main functions of the various electromagnetic interference (EMI) standards is to establish a common technique for the measurement and characterization of EMI performance reproductable from one test laboratory to another. The requirements are governed by different standards whereas the most popular are as follow :

• The US MIL-STD-461C standard : “Electromagnetic Interferance Characteristics, Requirements for Equipment”. Revision C

• The US MIL-STD-461D standard : «Requirements for the control of electromagnetic Interference Emissions and Susceptibility». Revision D

• The US MIL-STD-461E standard : «Requirements for the control of electromagnetic Interference Emissions and Susceptibility». Revision E

• The DO-160D standard : ”Environmental Conditions and Test Procedures for Airborne Equipment”.

• The French GAM-EG 13B standard : “Essais Généraux et Environnement des Matériels”.

• The UK Def-Stan 59-41 standard : “Electromagnetic compatibility Part 1 - 7“

2- Electromagnetic Interference Requirements

2-1 Conducted Emission (CE)

GAÏA Converter modules use soft-switching topologies to minimize switching noise. This noise is defined in terms of input ripple current and consists of relatively high fundamental component (switchning frequency above 500 KHz for majority of GAÏA Converters products) and its harmonic. As a result :

- GAÏA Converter modules comply with «low frequency» conducted emission stand alone.
- GAÏA Converter modules comply with «high frequency» conducted emission with simple additionnal external filter.

2-2 Conducted Susceptibility (CS)

Conducted susceptibility requirements definie various noise sources which when conducted on the power lines should not cause malfunction of the converter.

- GAÏA Converter modules integrate an input filter that provides in most cases input attenuation of approximatly 30 dB
- GAÏA Converter modules comply in most cases with «low frequency» conducted susceptibility stand alone with the output voltage maintained within it's total regulation limits, nevertheless a simple additionnal filter can be used.
- GAÏA Converter modules comply with «high frequency» conducted susceptibility with a simple additional external filter with the output voltage within it's total regulation limits
- GAÏA Converter modules comply with «Spikes» conducted susceptibility with additionnal external transient supressor with the output voltage within it's total regulation limits.

2-3 Radiated Emission (RE)

Radiated emission govern the electric and magnetic fields emitted.
GAÏA Converter modules switch above 500 KHz such that there is no noise source in the range of RE01 (or RE101).
GAÏA Converter modules are 5 sides metal package and the 6th side could be designed by a PCB ground shield under the converter which limits high frequency emission from the converter it self in the range of RE02 (or RE102).
Most radiation usually emanates from the input cabling or load circuitry and that is were carefull system design is essential.
Compliance should be tested at the complete system level and is heavily dependant on the system design grounding, shielding and cabling.
GAÏA Converter modules comply in most cases with electric and magnetic radiated emission stand alone with a PCB ground plane.

2-4 Radiated Susceptibility (RS)

Radiated susceptibility requirements dictate electric and magnetic fields level which should not cause degradation or malfunction of a system. As with emission, potential problem areas are input cables and output circuitry.
GAÏA Converter modules comply with electric and magnetic radiated susceptibility stand alone.

2-5 Compliance Summary

The following table resumes GAÏA Converter products compliance with EMI requirements for the most popular MIL-STD-461C, MIL-STD-461E and DO-160D standards.

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Specifications	MIL-STD-461C	MIL-STD-461E	DO 160D	GAIA Converter module compliance
Conducted emission (CE)				
Low frequency	CE 01	CE 101	Section 21	module compliant stand alone (see product datasheet)
High frequency	CE 03	CE 102	Section 21	module compliant with additional EMI filter
Conducted susceptibility (CS)				
Low frequency	CS 01	CS 101	Section 20	module compliant with additional EMI filter
High frequency	CS 02	CS 114	Section 20	module compliant with additional EMI filter
Spikes (CS)	CS 06	CS 115/116	Section 22	module compliant with transient supressor
Radiated emission (RE)				
Magnetic field	RE 01	RE 101	Section 21	module compliant stand alone (see product datasheet)
Electrical field	RE 02	RE 102	Section 21	module compliant stand alone (see product datasheet)
Radiated susceptibility (RS)				
Magnetic field	RS 01	RS 101	Section 20	module compliant stand alone (see product datasheet)
Electrical field	RS 03	RS 103	Section 20	module compliant stand alone (see product datasheet)

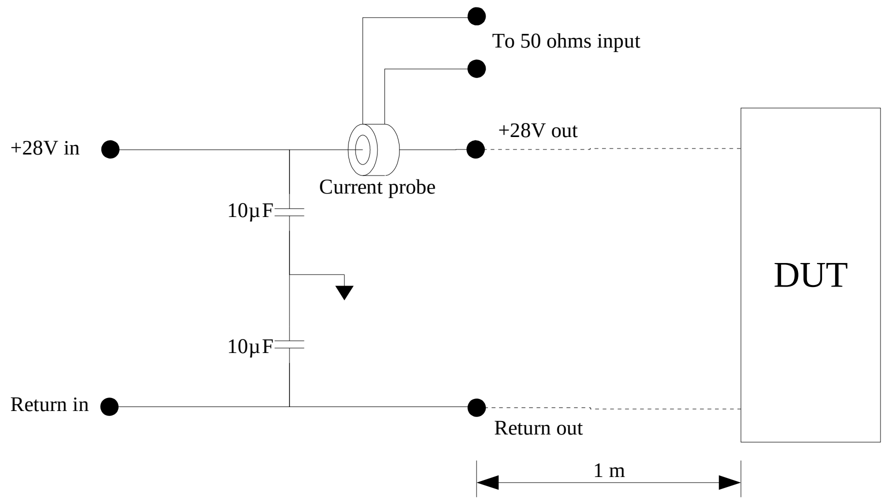
3- MIL-STD-461C/D/E Conducted Emission Tests Set-Up

The most popular revisions of MIL-STD-461 standard are the C and D/E revisions. The MIL-STD-461C and MIL-STD-461D/E do not measure the same characteristics in the same way. The MIL-STD-461C measures input conducted emission using a current probe and states the emission in terms of dBµA while the MIL-STD-461D/E uses an input line impedance stabilization network (LISN) and measures noise in terms of dBµV.

3-1 MIL-STD-461C Measurement Method

The conducted noise emission measurement method of MIL-STD-461C is described in MIL-STD-462C standard.
The «DUT» (Device under test) is powered thru a 1 meter lengh parallel wire.

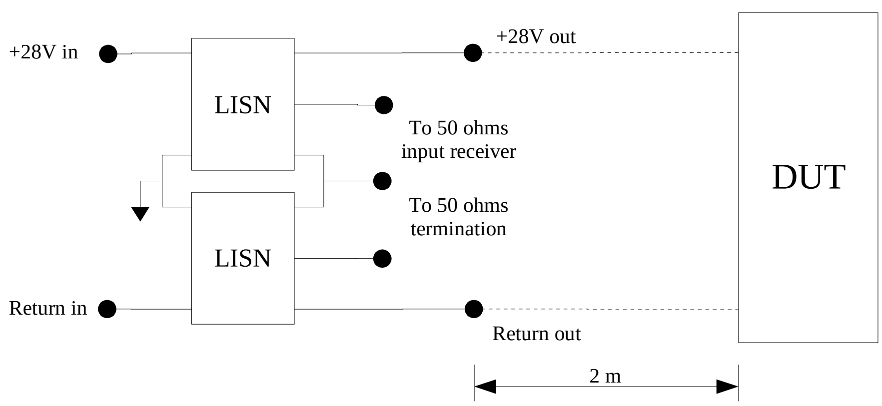
One end is terminated with the DUT and the other end is terminated with 10µF capacitors to ground plane. The measures are made with a current probe, the unit of measurement being dBµA.



3-2 MIL-STD-461D/E Measurement Method

The conducted noise emission measurement method is described in the MIL-STD-461D/E standards.
The «DUT» (Device under test) is powered thru a 2 meters length parallel wire.

One end is terminated with the DUT and the other end is terminated with LISN networks.
The measures are made with a measurement receiver, the unit being dBµV

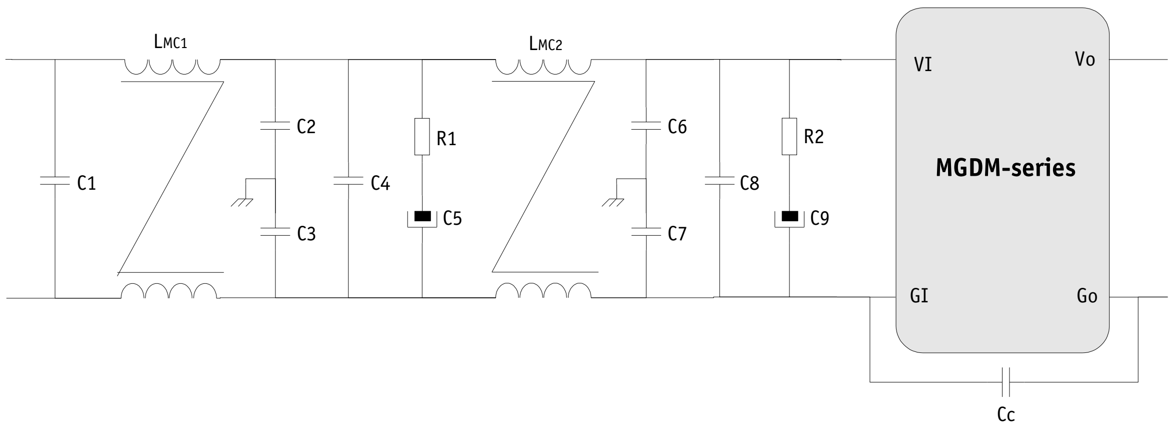


4- EMI Filter as Schematics of Discrete Components

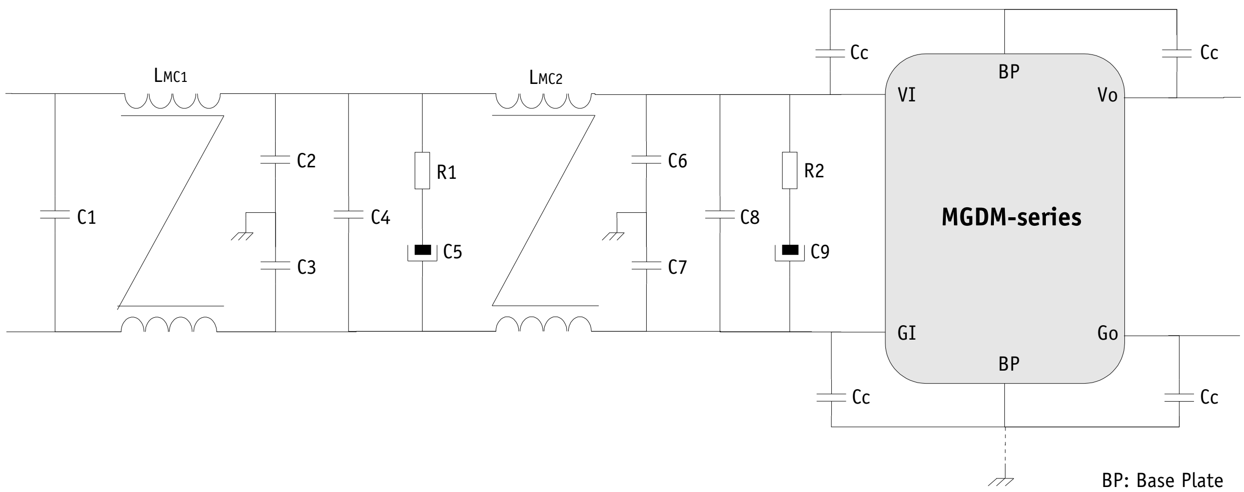
The GAIA Converter EMI filter solution is based on the following unique electrical schematics whatever the modules used or power required, just vary the common mode noise capacitor arrangements depending on the type of modules used :

- EMI filter schematics for module without baseplate
- EMI filter schematics for module with baseplate

4-1 EMI Filter Electrical Schematics for «Non Baseplate» Modules



4-2 EMI Filter Electrical Schematics for Modules with Baseplate



4- EMI Filter as Schematics of Discrete Components (continued)

4-3 General Discussion for Choice of Components

The components choice is driven by the following considerations :

L_{MC1}, L_{MC2} .... : The inductors are common mode choke. They provide common mode noise filtering and differential mode input ripple current filtering through their leakage inductance. The value is determined to meet EMI conducted emission requirements of the various standards.
It is recommended to use a component with a resonant frequency higher than 2MHz.
The DC resistance (*DCR*) of the inductor has to be minimized in order to reduce power losses and heating. Particular operating conditions could require an inductor heat sink or an efficient cooling solution (see examples hereunder).
In these conditions, the design of the layout has to be done to cool the inductor to avoid an over heat of the component.
The DC drop voltage (V_{DROP}) has to be analyzed too, particularly during low voltage operating conditions to ensure that the converter input voltage remains in its specified range and to avoid the module undervoltage lock-out (UVLO) activation.
These parameters are calculated as follow:

$Pd = DCR \times I_L^2$ $\quad$ $V_{DROP} = DCR \times I_L$ where I_L is the current inductor.

Example :
The application is using two MGDM150 converters with a 9 to 45V input range.
A MGDS-150-H-C delivers 100W and a MGDS-150-H-E delivers 120W. Considering an Efficiency of 80%, the input power is $P_{in}=P_{out}/0.8$ = 275W so with an input voltage V_{in}=18V, I_L=15.3A.
With a DCR=10mohms :
P_D=2,34W (dissipated in each common mode choke).V_{DROP}=150mV (for each common mode choke).

C1, C4, C8 .... : These capacitors are ceramic chip capacitors. They provide the input current ripple filtering.

C2, C3, C6, C7 .... : These capacitors provide common mode noise filtering. They have to be connected to the mechanical ground with a particular attention to reduce connection length. The capacitor should be good quality, low ESR and ESL ceramic capacitor to get an efficient filtering.

Cc .... : These capacitors provide common mode noise filtering. They have to be connected either to the baseplate or either between Gi and Go pins, with a particular attention to reduce connection length. The capacitor should be good quality, low ESR and ESL ceramic capacitor to get an efficient filtering.

R1, C5 optional network ... : R1, C5 optional network is used for damping. It lowers the Q factor of the differential filter and so it can be useful to meet conducted susceptibility requirement specified by EMI standards. Typical value of R1 is in the range 0 Ohm up to 2.2 Ohms. the value of C5 is higher than 5 times the value of C4.

R2, C9 optional network ... : R2, C9 damping network is used for stability purposes in negative input impedance systems such as DC/DC converters.
C9 value should be in the range of 5 to 10 times C8 value.
R2 value should be in the range of 0 Ohm to 2.2 Ohms and might be C9’s ESR in some cases.
R2 and C9 is a network whose function is to lower the filter’s output impedance.
The value of C9 strongly depends on the application’s conditions (input voltage range and total power drawn from the source) as well as on the standard in which the module is being tested (MIL-STD-461C or D/E).

4- EMI Filter as Schematics of Discrete Components (continued)

4-3 General Discussion for Choice of Components

Note on optional damping network R1, C5 and R2, C9 :

DC/DC converters are Negative Input Impedance systems whereas a filter composed of passive elements displays a positive output impedance to the converter.
To ensure the stability of the whole system {LISN+Filter+DC/DC converter}, the impedance seen at the filter's output must be kept below the converter's input impedance, which is given by the following formula :

$$|Zin| = (Vi)^2/Pin = (Vi)^2 n/Pout$$

where Vi is the input voltage, Pout the power drawn from the converter by the load and n the efficiency of the converter.

As can be seen from the preceeding equation, the worst case for system's stability occurs at Vimin, hence why it is with this value of input impedance that you should design your filter.

As the filter is made of low ESR inductors and ceramic capacitors, it has an important Q which causes a sharp increase of the filter's ouput impedance at the resonnance frequency and leads to a violation of the stability criteria, causing the system to break into oscillations. Consequently, the values of C9 and R2 have to be adjusted to dampen sufficently the filter's resonnance and make its output impedance lower than the converter's input impedance(a 10dBOhm margin between both values is recommended).
The standard in which the module is tested has also to be considered since the LISN contributes to the filter's output impedance and this leads to higher values of C9 in MIL-STD-461E than in MIL-STD-461C.

4-4 List of Component Values

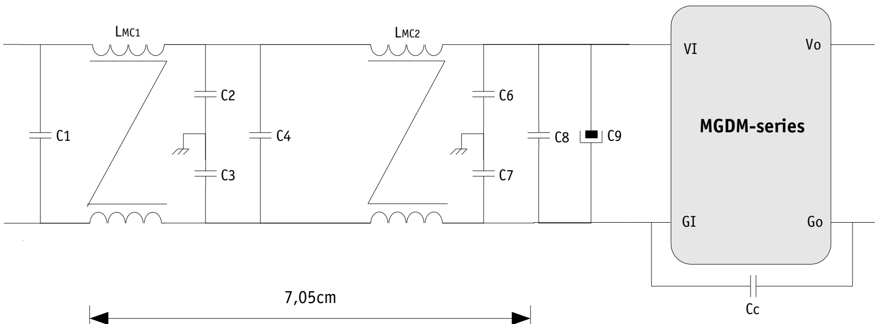
The following table gives a resume of suggested values for different input current requirements.

Type of Filter Proposed	Components Recommended Value
5 A Filter	LMC1, LMC2 > 250 µH C1 = 4.7 µF / 50 V C2, C3, C6, C7 = 10 nF / 500 V C4, C8 = 22 µF / 50 V Cc = 10 nF / 500 V C9 =100 µF / 100 V
10 A Filter	LMC1, LMC2 = 470 µH C1 = 4.7 µF / 50 V C2, C3, C6, C7 = 10 nF / 500 V C4, C8 = 22 µF / 50 V Cc = 10 nF / 500 V C5 = 47 µF / 100 V C9 =220 µF / 100 V
15 A Filter	LMC1, LMC2 = 500 µH C1 = 4.7 µF / 50 V C2, C3, C6, C7 = 10 nF / 500 F C4, C8 = 22 µF / 50 V Cc = 10 nF / 500 V C5 = 47 µF / 100 V R1 = 1 Ohm C9 = 220 µF / 100 V

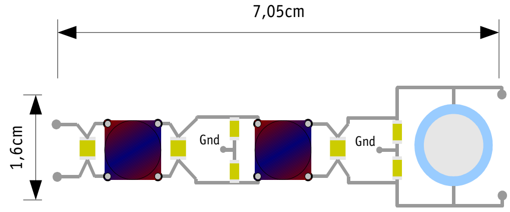
5- Suggested EMI Filter 5A

This filter configuration is recommended for GAIA Converter modules with permanent input current lower than 5A.

5-1 Electrical Schematics



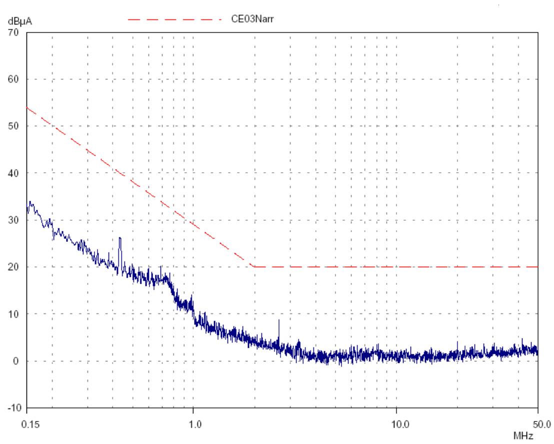
5-2 Lay-out

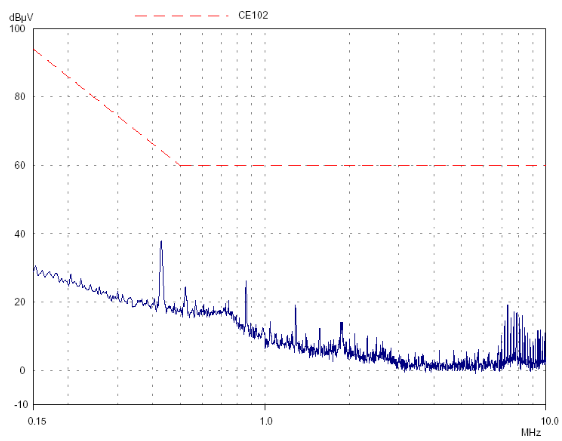


5-3 Bill of Material

Component	Value	Voltage	Current	Reference
Lmc1, Lmc2	590 µH	/	5.6 A	Pulse : P0353 or other common mode choke with a value higher than 250µH and rated to max. input current.
C2, C3, C6, C7	10 nF	500 V	/	AVX : 1206 7 C 103 M capacitor.
C1	4.7 µF	50 V	/	Murata : GRM32ER71H475KA88 or other chip capacitors connected in parallel with equivalent total value.
C4, C8	5 x 4.7 µF	50 V		Murata : GRM32ER71H475KA88 or other chip capacitors connected in parallel with equivalent total value.
Cc	10 nF	500 V	/	AVX : 1206 7 C 103 M capacitor.
Optional network				
C9	100 µF	100 V	/	Vishay : RVI136 serie 2222 136 5910 capacitor.

5-4 Results MIL-STD-461C & E for Configuration : 1 x MGDS-35-O-C @ full load

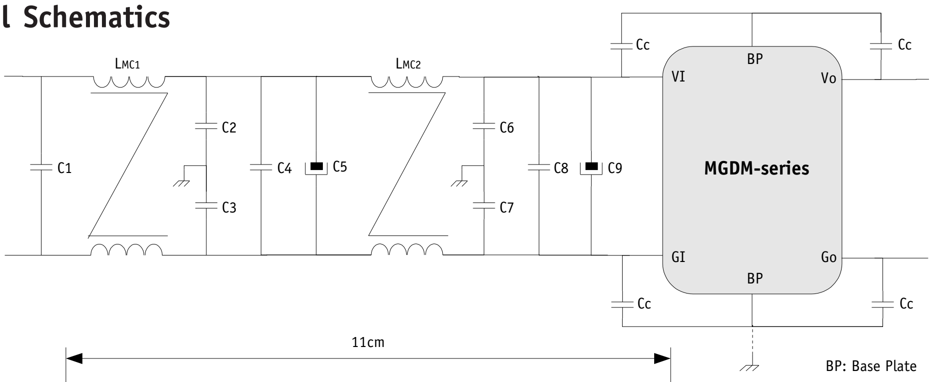




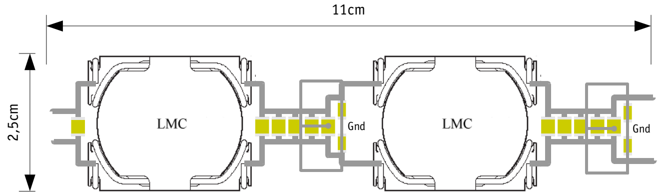
6- Suggested EMI Filter 10A

This filter configuration is recommended for GAIA Converter baseplate modules. it can be implemented as long as the permanent input current remains lower than 10A.

6-1 Electrical Schematics



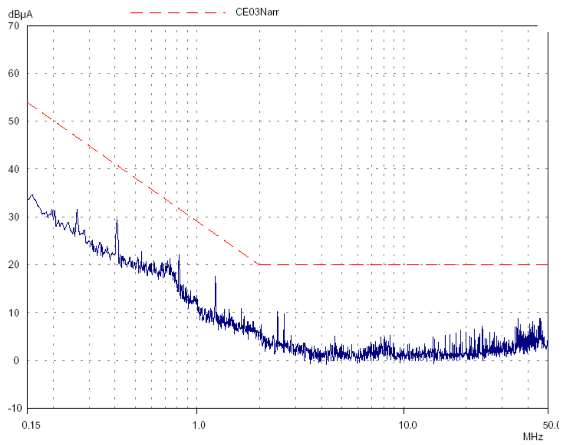
6-2 Lay-out



6-3 Bill of Material

Component	Value	Voltage	Current	Reference
Lmc1, Lmc2	470µH	/	14A	Pulse : P0502 or other common mode choke with value higher than 400µH and rated to max. input current.
C2, C3, C6, C7	10nF	500V	/	AVX : 1206 7 C 103 M capacitors.
C1	4.7µF	50V	/	Murata : GRM32ER71H475KA88 or other chip cpacitors connected in parallel with equivalent total value.
C4, C8	5 x 4.7µF	50V	/	Murata : GRM32ER71H475KA88 or other chip cpacitors connected in parallel with equivalent total value.
Cc	10nF	500V	/	AVX : 1206 7 C 103 M capacitor.
Optionnal Networks				
C5	47µF	100V	/	Vishay : RVI136 serie 2222 136 59101 capacitor.
C9	220µF	100V	/	

6-4 Results MIL-STD-461C for Configuration : 1 MGDS-75-0-C @ full load

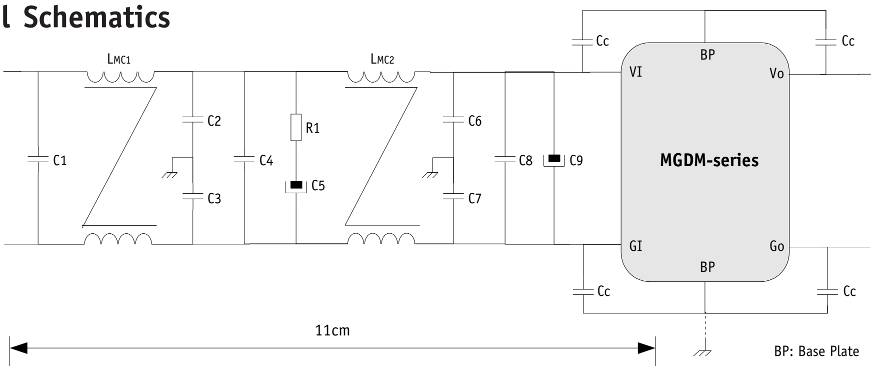


MHz

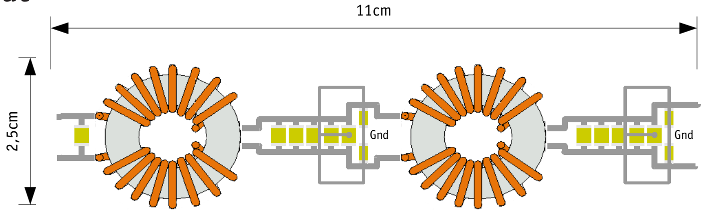
7- Suggested EMI Filter 15A

This filter configuration is recommended for GAIA Converter baseplate modules with permanent input current lower than 15A.

7-1 Electrical Schematics



7-2 Lay-out



7-3 Bill of Material

Component	Value	Voltage	Current	Reference
Lmc1, Lmc2	470µH	/	20A	CWS : C-36A37-00 or other common mode choke with value higher than 400µH and rated to max. input current.
C2, C3, C6, C7	10nF	500V	/	AVX : 1206 7 C 103 M capacitors.
C1	4.7µF	50V	/	Murata : GRM32ER71H475KA88 or other ceramic chip capacitors connected in parallel with equivalenet total value.
C4, C8	5 x 4.7µF	50V	/	Murata : GRM32ER71H475KA88 or other ceramic chip capacitors connected in parallel with equivalenet total value.
Cc	10nF	500V	/	AVX : 1206 7 C 103 M capacitor.
Optionnal Networks				
R1	1R	/	/	
C5	47µF	100V	/	Vishay : RVI136 serie 2222 136 59101 capacitor.
C9	220µF	100V	/	

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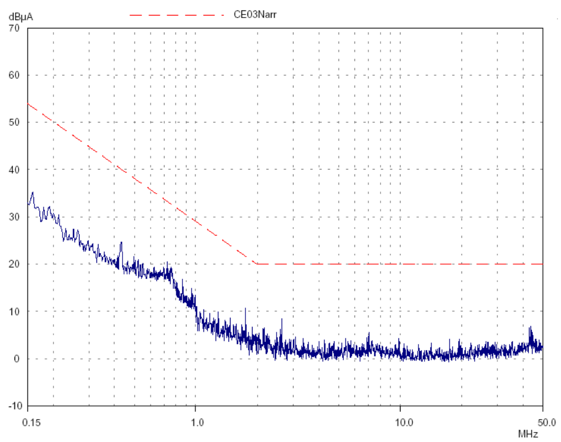
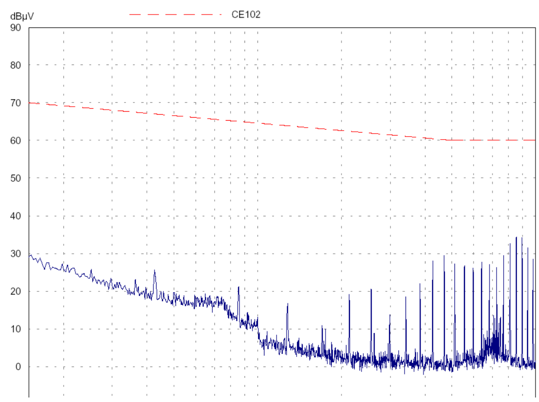
7-4 Results MIL-STD-461C & E for Configuration : 1 MGDS-150-O-C @ Full Load





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