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► **To cite this version:**

Pierre-Louis Bourlon, Arnaud Bréard, Christian Vollaire, Marc Meyer. Comparison between segregation and filtering using a black-box inverter model. 2023 International Symposium on Electromagnetic Compatibility – EMC Europe, Sep 2023, Cracovie, Poland. pp.1-5, 10.1109/EMCEurope57790.2023.10274370 . hal-04515501

HAL Id: hal-04515501

<https://hal.science/hal-04515501v1>

Submitted on 23 Dec 2024

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Comparison between segregation and filtering using a black-box inverter model

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Abstract— Electrification of aircraft propulsion increases embedded power electronics and leads to reconsider specification and integration logic of power electronics systems. At the same time, aeronautics constraints, such as weight and volume, requires to wisely define segregation rules and avoid additional filters. These two solutions are compared through a practical case. To do so, a power chain is modelled and experimentally validated over different network impedances. Segregation and filtering values are defined to comply with victim susceptibility limit. At the end, the solutions are compared over different criteria.

Keywords— EMC, segregation, cable, power electronic, avionic

I. INTRODUCTION

Urban Air Mobility (UAM) increases embedded power electronics on aircraft platforms. This increase comes with integration challenges, especially between high power systems and low power avionics. Indeed, high power systems based on Silicon Carbide (SiC) transistors use higher switching frequency and greater $\frac{dV}{dt}$ than previous technologies. Thus, electromagnetic interference (EMI) frequency spectrum is wider and level is higher.

Hence, the Aircraft Manufacturers (AM) have to reconsider specifications and integration logic. For that, they can redefine:

1. Emission and susceptibility limits
2. Installation rules (segregation rules between routes, shielding ...)

In this process, UAM platform specificities shall be taken into account. For example, conducted emissions from power electronics are significant up to 30 MHz. Therefore, radio navigation and communication systems operating up to this frequency are not installed. Thus, front door problematic is not present and this study is limited to crosstalk. The use of high voltage and current requires to separate power cables to limit partial discharges or Laplace force in case of a short-circuit. In these conditions, differential mode currents may not be negligible from crosstalk perspective.

On the standards side, ED-14G/DO-160G [1] specify required avionics performances (EMC, thermal ...). In Section 21, conducted emissions are measured in a standardized environments using Line Impedance Stabilization Network (LISN). Electrical Aircraft uses generally several inverters that can be in parallel and batteries. Consequently, DC power network impedance can differ from a LISN what can significantly influence the conducted emissions [2].

The AM have to develop tools to specify and integrate these power converters:

- Robust differential and common mode conducted emission model of a power system
- Reliable and simple crosstalk model
- Avionics susceptibility model (not treated in this paper)

The AM need a power system model that is fast, reliable and if possible respect Intellectual Propriety (IP). Extensive time or frequency domain models [2] [3] based on schematics, bill of materials and PCB layout are not compatible with these objectives. Terminated Behavioral Model (TBM) meets this need [5]. This model is reliable for cases close from its network extraction impedance. Recently, this model has shown good predictability, on an asymmetric (boost) converter, for cases far from its network extraction impedance [6]. Crosstalk between cables or within a cable bundle has been extensively studied [7][8]. To date, no study has compared segregation and filtering. To simplify the study, avionics susceptibility is the one demonstrated during standard tests. Indeed, AM reuse or buy Commercial-Off-The-Shelf (COTS) avionic systems and cannot modify or test them again without significant additional cost.

EMI from a power system couple to avionics systems that can be sensitive. One of these couplings is crosstalk between a power route and a signal route. Crosstalk depends on mode propagation (differential or common), loads condition at the ends of lines (inductive or capacitive coupling) and cables segregation. Conventional solutions (filtering, segregation, shielding) to reduce crosstalk are not compatible with

aeronautics constraints (weight and volume) and should be optimized.

In general, the power system manufacturer is responsible for filtering. Nevertheless, the AM influences filtering with its conducted emissions requirements. Thus, the AM needs to identify the trade-off between conducted emission constraint at power system level and integration efforts at platform level. In this paper, two solutions are compared: filtering (at power system level) and segregation (at platform level).

This paper consists of 3 parts. First, inverter and crosstalk models are experimentally validated over different DC network impedances. Then, the routing segregation and the inverter filtering are defined to meet susceptibility demonstrated on sensitive signals. Finally, segregation and filtering are compared.

II. SITUATION PRESENTATION

The situation considered is represented on Figure 1. An inverter and its L-C loads are connected to LISNs through power cables. L-C loads and LISN simulate respectively the behavior of a motor and a battery. Filtering (C_X and C_Y) can be added to reduce conducted emissions. On Figure 2, a power route (P) is composed of power cables that are spaced by a distance of x_{23} . Similarly, a sensible route (S) includes weak signal cables. Between route P and S, a segregation distance x_{12} is defined. Route S plays victim role and is modelled as a simple conductor. Nevertheless, it can emulate a shielded pair with relevant correction factors applied (common mode rejection ratio and shielding effectiveness)

Power cables currents can be decomposed into two modes: Differential Mode (DM) and Common Mode (CM). These modes are defined by (1) (2) and Figure 1.

$$I_{DM} = \frac{I_1 - I_2}{2} \quad (1)$$

$$I_{CM} = I_1 + I_2 \quad (2)$$

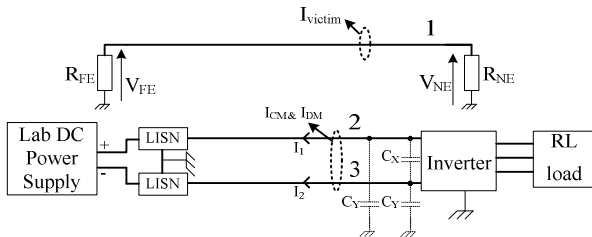


Figure 1 System schematic

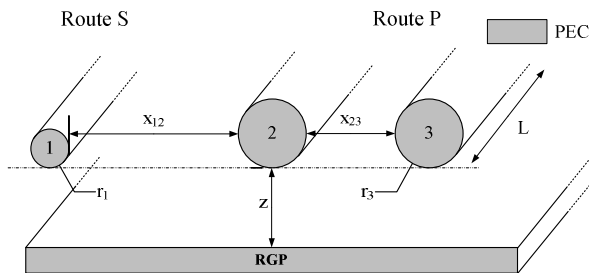


Figure 2 Routes and cable layout

III. MODEL PRESENTATION AND VALIDATION

A. Inverter black-box model

The model used is described in [5] (Figure 3). This type of model is valid only for one operating point (voltage and load). It can be extracted from simulation or experimental measurements. This model is built by measuring two currents and three known impedances. IP is protected since only the behavior of the inverter is provided. This model makes the assumption that the inverter is linear. It will be verified using impedance different from the one used during model extraction.

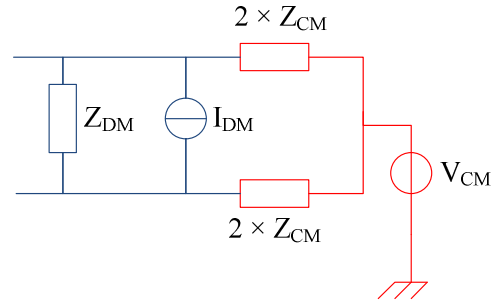


Figure 3 Terminated Behavioral Model circuit [5]

B. Crosstalk model

To compute crosstalk, a simulation tool called “ASERIS-NET” is used. This tool is based on Multi-conductor Transmission Lines method. An electrostatic Boundary Element Method is applied to the cross section of the line to compute the inductance and capacitance matrices [9]. This tool does not provide closed-form expressions and requires more computation time compared to analytical methods. Nevertheless, it can handle complex situation (dielectric layer, losses, unusual geometry ...) and has been widely validated. In this study, cables and the reference ground plane are considered as perfect and lossless.

C. Experimental validation

The test bench uses a three-phase inverter based on SiC transistors driving an L-C (Figure 4). The inverter is connected to DC lab supply through LISNs.

The validation of the model is a three-step process (not detailed here):

1. Extraction of the model with known system impedances
2. Computation of currents with final installation: 3m cables are added according to layout described in Figure 2. This step verifies crosstalk model and modelling process.
3. Add CM capacitors to verify robustness and predictability of the inverter model when system impedances are modified.



Figure 4 Setup picture

D. Results

The settings used for validation of the model are summarized in the TABLE 1. Cables height, radius are fixed.

TABLE 1 PARAMETERS USED FOR VALIDATION MODEL

Parameter	Value
x_{12}	a
x_{23}	b
DC lab voltage	250 V
DC lab current	2.43 A
Switching frequency	20 kHz
C_Y	10 μ F

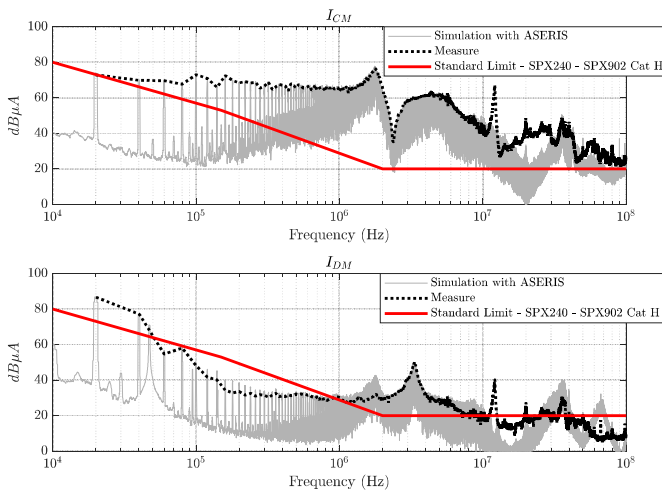


Figure 5 Common and differential mode current at the inverter level – Comparison between the simulation and the measurement

Regarding power line currents (Figure 5), a good correlation is observed between measurements and simulation up to 10 MHz. This is a known limit for this type of model. At low frequencies, DM current is 20 dB higher than CM current and standard limit. CM current becomes more predominant and excess standard limit as frequency increases.

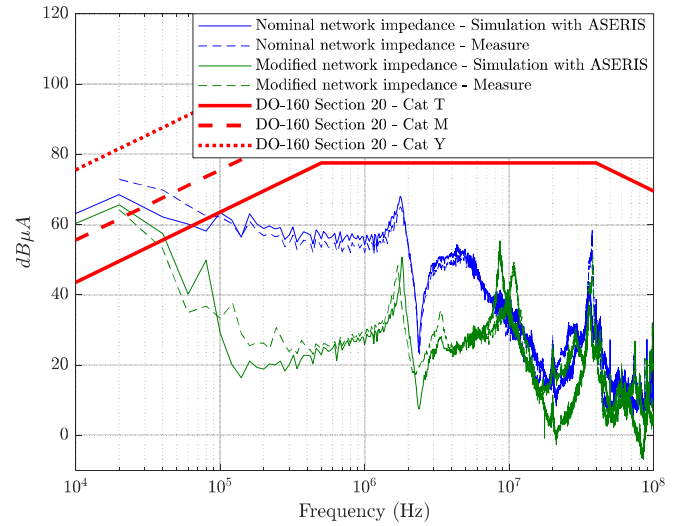


Figure 6 Victim coupled current without and with common mode filter - Comparison between the simulation and the measurement

Regarding victim line currents (Figure 6), a good correlation between measurements and simulation up to 10 MHz is observed. The model provides a good prediction when CM capacitance is added. The discrepancy around 100 kHz comes from a slight difference of resonance capacitor frequency between simulation and measurements. From these results, the inverter can be considered as linear at one operating point. Overall, model performances are satisfactory and can be used to calculate segregation and filtering.

The coupled current is 19.2 dB at 20 kHz above DO-160 Section 20 – Cat T limit. In the following section, segregation and filtering are compared to comply with this limit.

IV. COMPARISON BETWEEN SOLUTIONS

To evaluate effectiveness of solutions, attenuation is defined from a reference cable layout and without additional inverter filter. The reference cable layout is described in TABLE 1.

$$Attenuation = 20 \log_{10} \left(\frac{I_{victim-with\ solution}}{I_{victim-without\ solution}} \right) \quad (3)$$

A. Route segregation

Route S and route P cables are spaced to reduce the coupled current. Several geometric segregation are tested and summarized in TABLE 2.

TABLE 2 SEGREGATION PARAMETER USED

Parameter	Min	Max
x_{12}	a	$10a$
x_{23}	b	$4b$

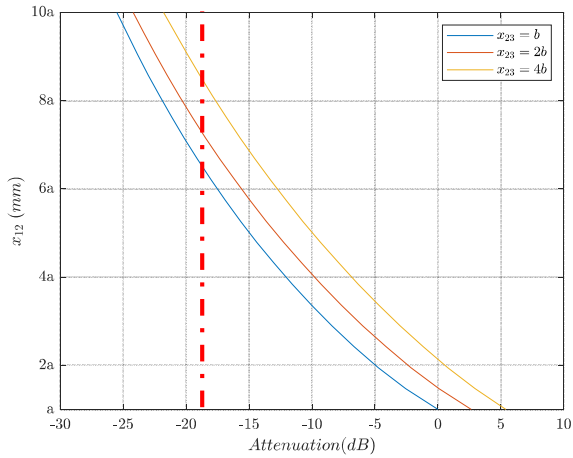


Figure 7 Segregation values in function of the attenuation required at 20 kHz

Figure 7 shows required segregation in function of the attenuation required at 20 kHz. Increasing distance x_{23} between cables located in route P leads to increase segregation distance between route P and S to keep attenuation constant. This means that differential mode is predominant at 20 kHz, which is consistent with power line current measurements on Figure 5. As x_{12} spacing increasing, common mode is more and more predominant.

Spacing configurations leading to 19.2 dB attenuation are identified (red dotted line) on Figure 7:

- $x_{12} = 6.5a$; $x_{23} = b$
- $x_{12} = 7.5a$; $x_{23} = 2b$
- $x_{12} = 8.5a$; $x_{23} = 4b$

B. Additional filtering

Common and differential filtering is added at DC input inverter level. Attenuation is computed for several combinations using ASERIS-NET. TABLE 3 summarizes the values used.

TABLE 3 FILTERING PARAMETER USED

Parameters	Min	Max
C_X	1 μF	300 μF
C_Y	4 μF	200 μF

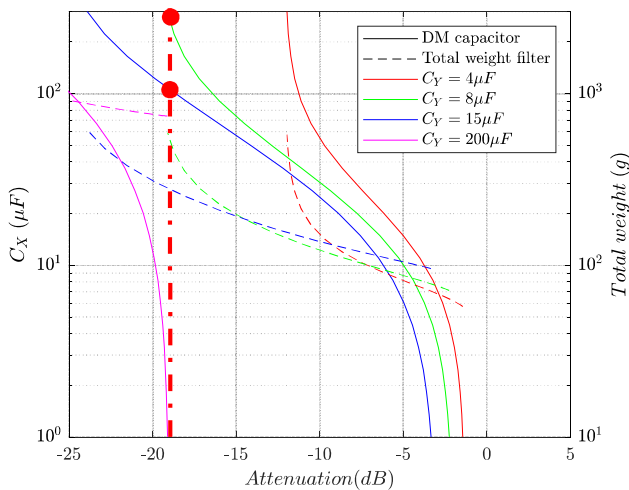


Figure 8 Filter values and filter weight in function of attenuation required at 20 kHz

Weight is an important constraint in aerospace. Capacitor weight is linearly interpolated from Vishay power electric portfolio [10].

Similarly to segregation, additional filtering needed is identified (red dots) on Figure 8:

- $C_X = 300 \mu F$; $C_Y = 8 \mu F$; Weight = 560 g
- $C_X = 100 \mu F$; $C_Y = 15 \mu F$; Weight = 290g

At one point, CM capacitance drives attenuation. With $C_Y = 4 \mu F$, it is impossible to get more than 12 dB attenuation. As C_X increasing, CM gets predominant at the inverter output level. A solution only based on CM filtering is not optimal in term of weight (pink curve).

V. DISCUSSION

Trade-off between solutions depend on constraints and the architecture of the platform. Route segregation limits bulky filtering. Unfortunately, allocated route space is not always wide enough to get required attenuation. In our case, additional shielding will have little effect since issues are located in low frequencies. In such case, the AM can ask additional filtering to the power system manufacturer. Filtering weight is estimated to 290 g per power system. Our approach can be seen as a worst-case scenario since single element topology filter is used. Final additional weight will depend on filter topology chosen by the manufacturer.

Route P segregation requirements (due to partial discharges, short-circuit protection ...) impacts integration. Increasing x_{23} spacing from b to 4b requires additional 5 dB segregation (for $x_{12} = a$). To keep victim current unchanged, x_{12} shall be set at 2a.

A pragmatic solution would be to modify susceptibility limits. For example, the Cat Y flat at 77.5 dB μA could be continued below 500 kHz. This part is related to High-Intensity Radiated Field (HIRF) and can be managed by additional tests if needed.

The model presented is compatible with generic current and voltage sources. Thus, actual conducted emissions limits and segregation rules could be modified using a worst-case scenario. Additional requirements may be needed on input CM and DM inverter impedances or DM power currents. These requirements imply to modify standards in the future.

CONCLUSION

Route segregation and filtering are compared as solution to integrate a power system. Terminated behavioral black-box inverter model is experimentally validated for different DC network impedances. It confirms the predominance of differential mode at low frequencies and linearity of the inverter model. Additional segregation and filtering are calculated using the ASERIS-NET tool. Finally, segregation and filtering are compared. Segregation offers several advantages (weight, reliability, safety) over filtering.

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