EMI Filter design for DC/DC converters for all electric aircrafts

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Abstract - To design a input filter of an DC to DC converter for all-electric aircraft (AEA), a base knowledge is needed over electromagnetic interference (EMI). The cause of EMI and the consequences of not filtering the EMI have been studied. Furthermore, the influence of changing the duty cycle and frequency of the PWM input signal of the converters related to EMI have been observed. And the changes of connecting multiple converters to the one power supply in parallel. Furthermore, different filters has been studied and simulated to reduce the EMI. Finally, a filter was made and tested if it hold up to DO160-G standards. Unfortunately, the designed filter did not meet standards when tested, due primarily to parasitic elements and the filter's manufacturing process.

keywords - EMI, EMC, EMI filter, Common mode, Differential mode

I. Introduction

In recent years, the development of all-electric aircrafts (AEA) has expanded. This is mostly due to the worldwide technological initiative to use more electric transportation. Electric transportation is also getting more attention due to the rising concern of global climate change. The aviation industry is currently responsible for around 2.1% of the total CO_2 emissions worldwide[1]. The shift to an all electrical airplane will aid in reducing the emissions.

However, this shift to electric propulsion instead of many traditional aircraft systems will bring engineering challenges with it. One of the main challenges with the implementation of AEA are the electromagnetic compatibility (EMC) issues. By changing to AEA, many systems of the traditional aircraft will become electrical. This will also lead to an increase of electric switching devices which are a main source of electromagnetic interference (EMI) [2][3]. An increase of EMI can cause multiple problems, like malfunctioning of essential avionics, or other EMI sensitive equipment.

Due to the high voltage battery of AEA many buck converter are needed to reduce the voltage to a preferred level. Most of the aircraft converter will be needed in the secondary distribution system, also know as the non-propulsion system. Currently the standard DC voltages used in traditional aircraft are 28, 270, and 540Vdc, which due to legacy equipment will also be used in AEA [4]. A standard outlined in the DO160-G is required to attenuate the EMI produced by secondary levels [5]. This will make it possible for AEA to comply with EMC regulations.

There are many ways of reducing the EMI. One of the most common way is by placing a EMI filter. However, the filter can represent up to 30% of the total system weight [6]. This can be problematic because weight is a scarcity on an airplane and space needs to be used as efficiently as possible. This means that a better understanding of the system is needed to provide an optimized EMI filter design.

This paper will investigate the resulting EMI from the operation of a DC/DC buck converter. This will be done by connecting three equal buck converters parallel to a single DC source. Afterwards, the duty cycle and switching frequency of the PWM signals has been changed to observe the changes on EMI levels. By doing this, the operation modes that promote the highest emissions can be found. This will help in deciding the filter topology and component specifications. Also, the positioning of the filter will be looked at. A filter can be connected to multiple devices, or connected to single device.

The goal of this research is to identify the characteristic of a EMI filters that can comply with the DO-160G specification. The analysis will also help us comprehend the mechanisms that lead to EMI in a DC/DC converter when three converters are linked to a single power source.

In section II, a more in dept analysis of the system as a whole will be provided. After that, in section III will be discussed how to measure EMI in the circuit and the filter structure. In section IV, the measuring setup will be described. Afterwards, the results will then be presented and debated in section V. Finally, in section VII a conclusion is offered in light of the aforementioned findings.

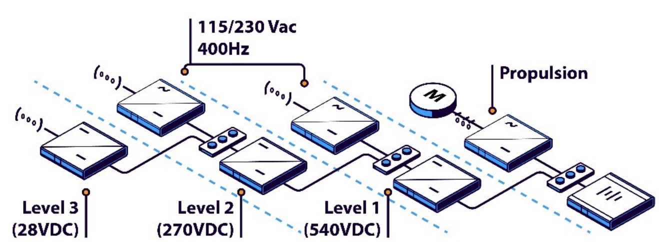

Fig. 1: Schematic of the different voltage levels of a AEA[7]

II. General overview

The electric systems of the AEA can be divided into two different main parts: primary and secondary system [2]. The primary systems consist of the powertrain. This system demands high power. For example, the AC motors that drive the propellers. Secondary system is a non-propulsion system. The secondary system is commonly divided into three separate voltage levels: 28, 270, and 540 Vdc. Each of those

levels has crucial avionics that must function properly. These include devices like altimeters, which operate at 28Vdc, electro mechanical actuators, which operate at 270Vdc, and the landing gears, which operate at 540Vdc [4].
To reduce the voltage level of the aircrafts power supply to the mentioned voltage levels, a buck converter is needed. However, the fast switching of the converter causes voltage and current transients. This transient causes EMI to propagate through the circuit, i.e., conducted interference [8] [3].
To understand the EMI that a circuit experiences, EMI needs to be divided into differential mode (DM) signal and common mode (CM) signal. DM can be seen as the signal of interest. It loops through the closed loop of the circuit as shown in figure 2 [8]. The CM can be seen as the noise signal, that is created by parasitic elements in the circuit or radiated emissions. CM goes through the whole circuit and loops back to the source via the return path (protective earth, the ground). The path that CM and DM current take can be seen in figure 2

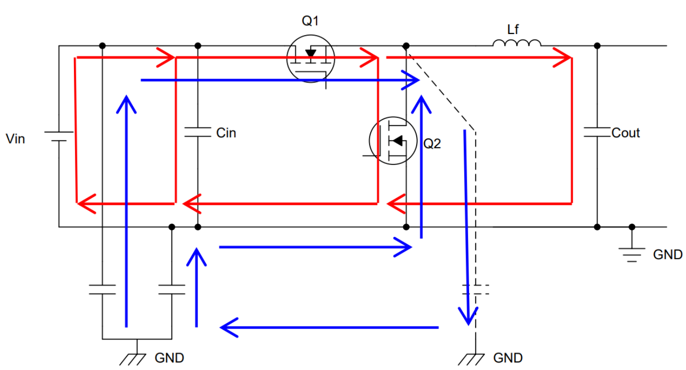

Fig. 2: DM and CM pathways through a standard buck converter[8]

Fortunately, there are many ways of reducing EMI in a circuit. The circuit can be shielded by using a Faraday cage, or by using isolated cables to decrease cross talk between cables. An other solution is the use of line filters. A filter is a circuit capable of passing or attenuating other frequencies [9]. The frequency of interests for AEA are between 150KHz and 152MHz as by D0-160G standard, section 21 [5]. The EMI current needs to be below the limits present in the DO-160G standard to make sure that in real application the system works properly and does not interfere with the aircraft equipment, or other EMI sensitive electronics.

III. Filter Design

A. Filter topology

Progress has been made in designing EMI filters for DC/DC converters with using standard filter typologies, like π and T [10]. For this assessment a (Γ, π) filter was the chosen filter topology as shown in figure 3. The selected filter topology aims at reducing both DM and CM. This filter design consist of a CM Γ filter and a DM π filter. The filter in figure 3 can be represented in a CM equivalent circuit and DM equivalent circuit as shown in figures 4 and 5.

The CM filter works by letting the CM current through the choke, which will cause an magnetic field to be created. Through the current going in on both sides in the same direction, an magnetic field is created that is being strengthen by both currents. This magnetic field will increase the inductance that the CM current will experience and will attenuate the CM current. However, the CM choke will not attenuate the DM current, because the electromagnetic field created by the DM current will cancel each other out, due to the direction of the current flow. The magnetic field will not be completely be cancelled out, the choke will cause a small leakage inductance that will effect the DM. This leakage inductance is around 0.5% to 1% of the real inductance [11]. Furthermore, a capacitor is connected to the ground to filter out the low frequency component of the CM current. To know at which frequency the filter starts to attenuate the signal, the cutoff frequency needs to be calculated. The cutoff frequency is the frequency at which the signal has been attenuated by 3dB. The cutoff frequency for the CM filter can be calculated by using equation 1 [12].

$$f_{cutoff} = \frac{1}{2\pi\sqrt{(L_{CM} + 0.5L_{DM})2C_y}} \tag{1}$$

A DM π filter needs to be placed to filter out the differential current. Equation 2 was being used to calculate the cutoff frequency of the π filter. As shown in figure 5[12], C_y would influence the cutoff frequency but if $C_x >> C_y$, the influences of C_y would be minimal. The CM choke leakage inductance, however, cannot be disregarded because it will affect the cut off frequency.

$$f_{cutoff} = \frac{1}{2\pi\sqrt{(2L_{DM} + L_{leak})(C_x + 0.5C_y)}} \tag{2}$$

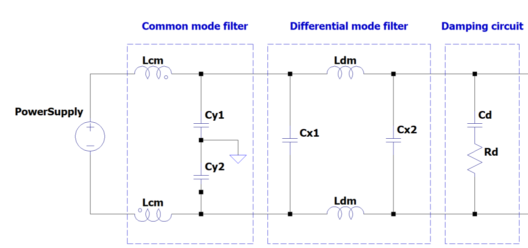

Fig. 3: The filter topology of the EMI filter with damping circuit. C_{x1} and C_{x2} have the same value. C_{y1} and C_{y2} have the same value

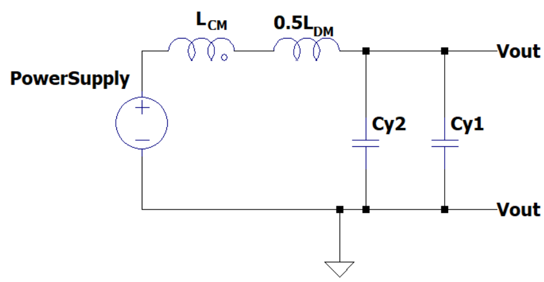

Fig. 4: Equivalent filter for CM current

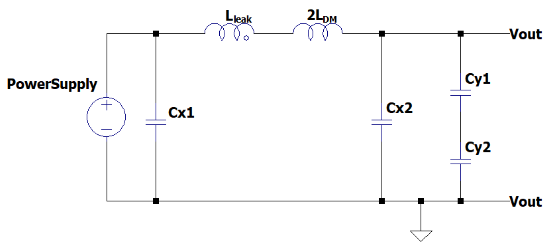

Fig. 5: Equivalent filter for DM current

B. Differential mode and Common mode

The EMI frequency spectrum of the CM and DM are needed to determine a suitable cutoff frequency for the filter. For this, the CM and DM current need to be measured. Separator devices are being used to measure the modes. However, those devices have high standards to meet, like flat frequency responses for frequencies of interest[13]. Besides this, when a mode is being measured, the other mode needs to be fully excluded from the measurement.
Due to superposition, each mode can be looked at separately. The DM and CM voltages can be defined in electric potentials of PE, line, and neutral, as shown in equation 3 to 7 [13].

$$V_L = \varphi_L - \varphi_{PE} \tag{3}$$

$$V_N = \varphi_N - \varphi_{PE} \tag{4}$$

$$V_{CM} = \varphi_L + \varphi_N - 2\varphi_{PE}, \tag{5}$$

$$V_{CM} = V_L + V_N, \text{ if } \varphi_{PE} = 0 \tag{6}$$

$$V_{DM} = V_L - V_N \tag{7}$$

By doing this equation, 8 and 9 can be derived. By measuring the line current I_L (Forward current) and neutral current I_N (Reversed current) of the circuit simultaneously, the DM and CM current can be measured in a time saving and reliable way. There are now two ways of measuring the CM and DM currents. The first approach is to measure the neutral current and the line current separately and then calculating the DM and CM current by using equation 8 and 9. The other way is to "directly" measure the currents. This is done by taking the line and neutral cables and probing them at the same time as shown in figure 6. By having both cables go through the same probe, the DM current can be measured by twisting the neutral cable when probing.

$$I_{DM} = \frac{I_L - I_N}{2} \tag{8}$$

$$I_{CM} = \frac{I_L + I_N}{2} \tag{9}$$

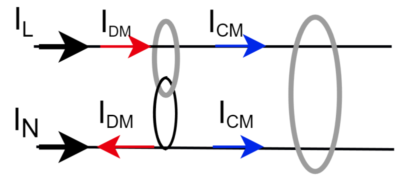

Fig. 6: Using a electromagnetic current probe (grey circles) to measure the DM (left probe) and CM (right probe) directly from the line and neutral cables.

C. Damping circuit

By using π filter to reduce the DM signal, a resonance effect is created. This resonance effect will amplify a certain range of frequencies instead of attenuating the signal. This ripple effect can be reduced by adding a damping circuit to the filter. The damping circuit consist out of a damping capacitor that is at least 5x higher than the $C_{x1} + C_{x2}$ [14], and a resistor. The resistor is used to remove the overshoot at the resonant frequency. Equation 10 can be used to get the resistor's value by setting the Q factor to 1.

$$Q = \frac{1}{R}\sqrt{\frac{L_{Leak} + L_{DM}}{C_x}} \tag{10}$$

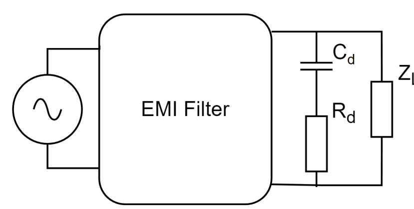

Fig. 7: Where Cd is the damping capacitor, Rd is the damping Resistor, and Zl is the load impedance.

D. Parasitic elements

The parasitcs elements should be taken into account when designing a filter. This is due to the fact that the parasitics will influence the attenuation and cutoff frequency of the filter.
The parasitic elements are more influential to the filter at higher frequencies. This is due to the self-resonating frequency that components have. The self-resonating frequency is the frequency at which, the parasitic elements will cause capacitive behavior in inductors and inductive behavior in capacitors. . Noticeable, equation 11 is that higher competent

values have a smaller resonant frequency. This means that smaller value components are preferred for designing EMI filters.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{11}$$

E. Layout

The layout of the circuit is also important for EMC. This is due to possible inductive or capacitive coupling as crosstalk. Crosstalk is observed when the electromagnetic waves created by a current through a trace or wire interferes with a signal of an adjusted trace or wire. This can be reduced by implementing proper design and layout techniques, by having enough between traces, in a way that it doesn't increase current loops, and avoid traces parallel to each other to minimize inductive coupling [10]. Furthermore, The coils used in the filter need to be perpendicular to each other to avoid that the magnetic fields of both coils couple, creating a noticeable magnetic field in the circuit represented by a mutual inductance.

F. Insertion Loss

The performance of filters are currently defined by the insertion loss (IL).The insertion loss shows how much power is being loss with the use of a filter with a certain input and output impedance i.e. gain. The IL is calculated by using equation 12 with $P_{L,wo}$ and $P_{L,w}$ being the power over the load with and without filter inserted [15].

$$IL_{dB} = 10\log_{10}\frac{P_{L,wo}}{P_{L.w}} = 20\log_{10}\frac{V_{L,wo}}{V_{L,w}} \tag{12}$$

IV. Measurement setup

To design an optimal EMI filter, the worse case scenario needs to be found. By knowing the worse case scenario a filter can be made that works for every situation.

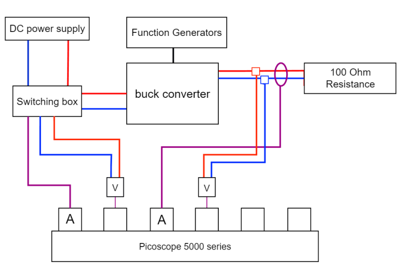

Fig. 8: A block diagram of the measurement setup

This is the reason why a setup has been made for emulating secondary distribution system as shown in figure 8. This setup consist out of a high voltage DC power supply that represents the power supply represents the DC power supply of the plane, provided by the battery pack [4]. The power supply is connected to a self designed switching box as shown in figure 21 in appendix VIII-B. The function of the switching box is to connect the different buck converters parallel to the power supply and to measure the input currents and voltages going to the buck converters.

A function generator is connected to the buck converter to send a PWM signal to control the output voltage of the converters. As PWM, a 5V trapezoidal pulse signal with a rising edge of 15ns was used. In addition, the function generator was set to 50Ω load. During the measurements, the duty cycle and frequencies of the PWM were changed to simulate various scenarios. The different scenarios can be found in appendix VIII-A.

At the output of the buck converter 100Ω resistor is connected as load which can hold up to 1500W.

Building block	Equipment used
Osciliscope	Picoscope 5000 Series (200 MHz)
DC Power supply	Chroma model 62024P-600-8
Voltage meter probe	TA043 differential probe (100MHz)
power supply of the current probe	N2779A power supply
function generator	T3AFG120 (120MHz)
buck converter	EVAL_1EDF_G1_HB_AN
Current probes	Picoscoop N2783B current probe (128MHz)

TABLE I: Measurement equipement setup

The PWM logical input of the converter is powered by a 5 volt power supply. Furthermore, a fan is being used to cool down the heat-sinks of the converters. To further simulate the secondary distribution, the electromagnetic environment (EME) of the laboratory is not EMI friendly, which causes an increased EMI level to be perceived than the expected. It happens due to the operation of multiple equipment, generating interference coupled into the setup.

The CM current and DM currents were measured in the setup. The input current has been measured at the inputs of each buck converter. The DM and CM current have been measured "directly"(III) and have been calculated by measuring the line and neutral currents. When measuring the currents, I also measured the input and output voltage of each level and output current for precaution. So, it would not be needed to redo the measurements, if those variables turns out to be a factor for designing a EMI filter.

The buck converters have been measured in different conditions. I have done measurements while using different frequencies and duty cycles. Also, checking what will happen when multiple converter are connected to the power supply. In total 1008 measurements have been taken in 69 different setups configurations. The different configurations can be found in appendix VIII-A.

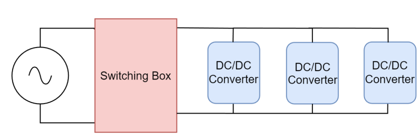

Fig. 9: A block diagram of the measurement setup

V. Results

To determine the average weight and volume of a EMI filter, a software called ODEF was used [16]. ODEF is a EMI filter design software that gives out a filter design for a given CM and DM current. The figure 11 and 10 were made. Centralized means that one big filter was connected to three converters. And localized is when each converter has his own filter connected to it and the total weight of all three filters.

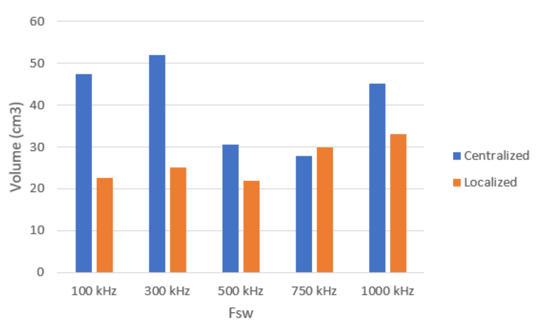

Fig. 10: The average volume of a centralized and localized EMI filter calculated by ODEF at different switching frequencies.

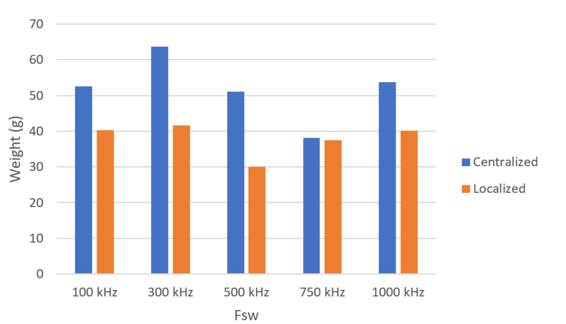

Fig. 11: The average weight of a centralized and localized EMI filter calculated by ODEF at different switching frequencies.

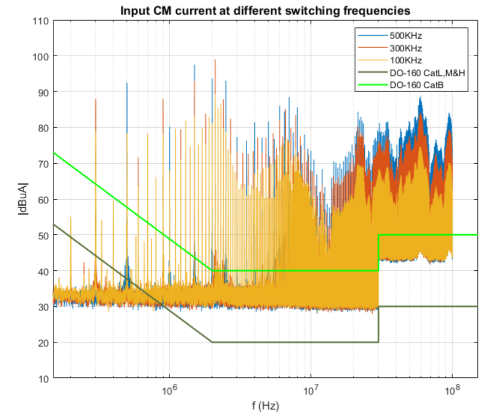

Fig. 12: CM current measured at the input of the buck converter at different switching frequencies. Only one converter was connected to the DC power supply.

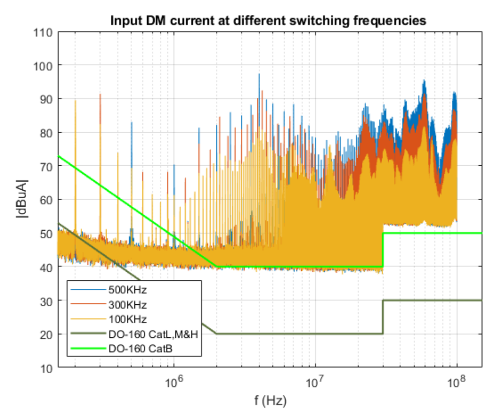

Fig. 13: DM current measured at the input of the buck converter at different switching frequencies. Only one converter was connected to the DC power supply.

Afterwards the different frequency was used to see how the converters react to different switching frequencies and a constant duty cycle of 50%. The frequencies used were 100, 300, 500KHz. The common mode and the differential mode current were measured and are shown in figure 12 and13.

Afterwards, measured with different duty cycle were taken to see how this would affect the CM and DM current. The duty cycle 25, 50 ,and 75% were measured at the constant swithcing frequency of 500KHz. The measurements are plotted in figure 14 and 15.

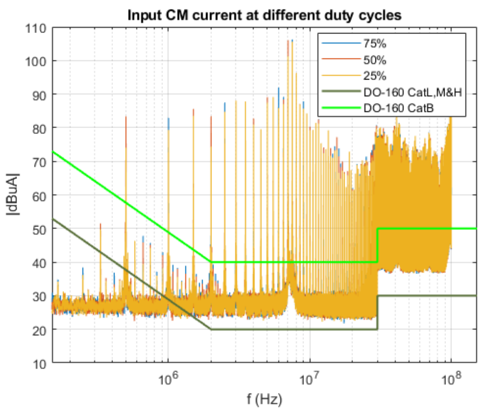

Fig. 14: CM current at various duty cycles with a switching frequency of 500KHz. Three loads were connected to the dc power supply. Two loads had a steady 50% duty cycle and one load had variety of duty cycles

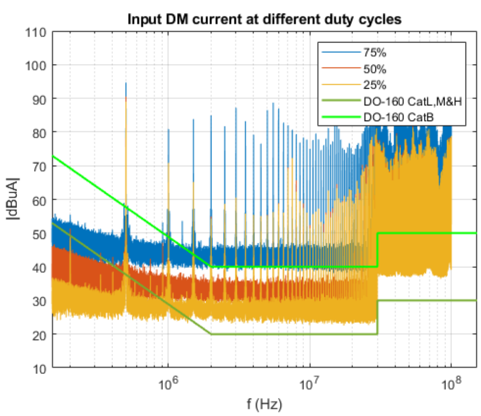

Fig. 15: DM current at various duty cycles with a switching frequency of 500KHz. Three loads were connected to the dc power supply. Two loads had a steady 50% duty cycle and one load had variety of duty cycles

Afterwards, a filter was designed using the equation in III-A to calculate the values with a cut off frequency of 10KHz. The circuit was then simulated in LTspice. The circuit was made and the bodeplot was measured and compared to the simulated bode plot.

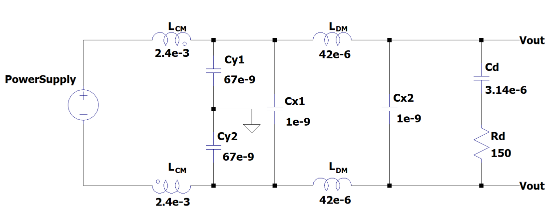

Fig. 16: Final filter design with component values

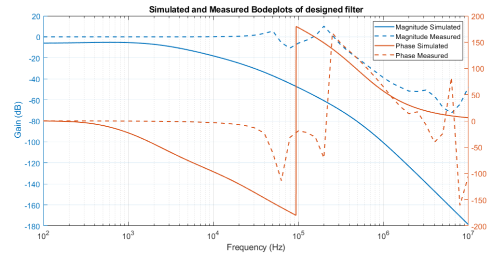

Fig. 17: Measured and simulated bode plot of designed filter.

The filter was then implemented and the CM and DM current where measured at the input of the converter as shown in figure 18 and 18.

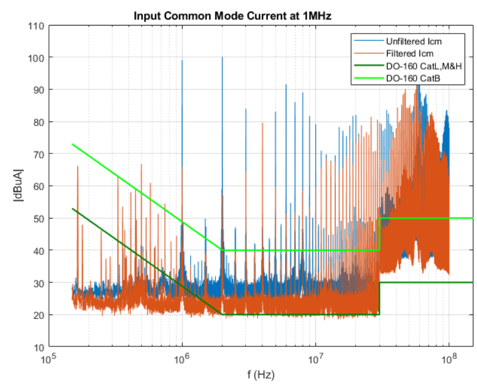

Fig. 18: Measured CM current before and after implementation the designed filter. The switching frequencies is 1MHz and duty cycle is 50%

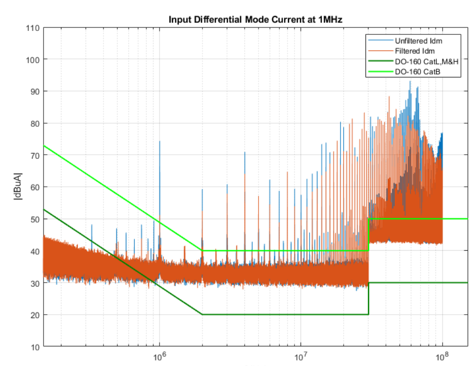

Fig. 19: Measured DM current before and after implementation the designed filter. The switching frequencies is 1MHz and duty cycle is 50%

VI. Discussion

By using ODEF an estimation has been made to the weight and volume of the filter. ODEF is a Matlab library that can design EMI filter with a given CM and DM current, which will also give an estimated weight and volume of the filter. This estimate was used to determine whether localized or centralized was preferable. It was discovered that using a localized filter reduced volume and weight on average. In addition, using centralized filters will lead to long transmission distances from filter to converter. This will leave the signal vulnerable to interference from radiated emissions. That is why, a localized filter has been chosen.

Afterwards, the worse case scenario was found by looking at the trend that CM and DM mode current followed. When the frequency increased, the voltage and current transient increased which create more CM current going through the system as shown in figure 12. However, using a higher frequency decreases the DM current. This is due to the fact, that the mosfets of the buck converter as shown in figure 2, are acting as a source for DM current. This is due to the PWM signal which will leak into the system through the mosfets. When using higher frequencies the PWM signal will deteriorate at the corners which will reduce the DM current. Furthermore, by increasing the duty cycle of the PWM signal, DM current will increase as shown in figure 15. However the increase in duty cycle does not affect the CM current as shown in figure14. The worse case scenario found was at 500KHz switching frequency with a duty cycle of 75%.

The cutoff frequency has been chosen to be 10KHz to be able to have enough attenuation to filter out the EMI assuming that the filter has a slope of -40dB/decade. By using the equation mentioned in section III-A, the following circuit was designed as shown in figure 16. Some component values were slightly changed, because of logistic difficulties in requiring components.

Afterwards, the filter was manually made as shown in figure 22 in appendix VIII-C. Then, the IL of the filter was measured and compared to the simulated plot in LT spice as shown in figure 17. The simulated and measured bode plots differ from each other. The cutoff frequency is around 100KHz instead of the measured 10KHz. Furthermore, a gain, instead of a attenuation, can be seen at 50KHz, which is probably caused by the resonance frequency due to the parasitics. This can be due to many different factors. Examples are, the prototyping boards poor soldering which create coupling behaviour between the traces as shown in figure 23 in appendix VIII-C, and parasitcs of the components.

The application of the filter can be seen in figure18 and 19. This correlated to what is seen in figure 17 that the filter does not attenuate the CM and DM current to D0-160 standards.

VII. Conclusion

For designing an EMI filter multiple factors need to be taken into account. The CM and DM need to be measured precisely to determine the required attenuation, and selecting the most suitable topology for the application. For the design of the filter, the size, weight are factors that need to be considered for secondary systems. Here out follows that using a localized filter is more preferable.

Also, in this paper, it was observed the influence that the duty cycles and switching frequencies have on a buck converter to the CM and DM currents. A filter has been made according to the worse case scenario that has been found. The component values of the filter have been calculated and simulated in LT spice. The filter was then developed, but it did not perform as expected. This was possible due to high parasitics values in the circuits. This could have been reduced by using a smaller inductance value and increasing the capacitor value to have a cutoff frequency of 10KHz. Furthermore, the manufacturing process could have been improved. I was inexperience in soldering which leaded to magnetic coupling between trace loops. More experience is required in the design and manufacture of EMI filters.

References

[1] Atag, “Emission airplanes.” [Online]. Available: https://www.atag.org/facts-figures.html
[2] N. M. L. Malburg and F. Leferink, “The changing electromagnetic environment onboard all-electric aircraft, an emc perspective.”
[3] S. K. Y. Z. Zhiming, L. Yitao, “Electromagnetic interference filter design.” [Online]. Available: https://www.researchgate.net/publication/280495787_Electromagnetic_Interference_Filter_Design
[4] A. T. I. Mirko Hornung and M. Cole, “Ce-liner - case study for emobility in air transportation.” [Online]. Available: https://www.researchgate.net/publication/268470882
[5] “Rtca do-160g.” [Online]. Available: https://do160.org/rtca-do-160g/
[6] A. AKSOZ and A. SAYGIN, “Emi filter volume and weight estimation for different frequency values.”
[7] T. Hartman and L. Malburg, “Input/output emi evaluation of a dc/dc converter.”
[8] T. Instrument, “Introduction to emi power supply design.” [Online]. Available: https://www.ti.com/lit/ml/slyp757/slyp757.pdf?ts=1656484798304&ref_url=https%253A%252F%252Fwww.google.com%252F
[9] A. about electronics, “Learn about various types of filters, including common terminology and important characteristics.” [Online]. Available: https://www.allaboutcircuits.com/technical-articles/an-introduction-to-filters/#:~:text=A%20filter%20is%20a%20circuit,many%20practical%20applications%20for%20filters.
[10] Schaffner, “The engineer’s guide to designing your emi filter.” [Online]. Available: https://www.mouser.com/pdfDocs/schaffner-engineers-guide-designing-emi-filters1-13-17.pdf
[11] S. G. W. J. H. R. S. Weber, M. Schinkel, “Calculating parasitic capacitance of three-phase common-mode chokes.” [Online]. Available: http://www.stefan-peter-weber.de/publikationen/pcim05.pdf
[12] D. Alexa, “Power line filter for switching power supplies.” [Online]. Available: http://www.ecoca.ro/papers/09_artim991.pdf
[13] N. M. Daria Nemashkalo and F. Leferink, “Mode decomposition in multichannel timedomain conducted emission measurements.”
[14] T. M. P. Por Richard, Lee Ozenbaugh, “Emi filter design.” [Online]. Available: https://books.google.nl/books?id=x_HRBQAAQBAJ&pg=SA19-PA17&lpg=SA19-PA17&dq=emi+filter+damping+capacitor+is+at+least+five+times+higher&source=bl&ots=Q-RGVKcM3K&sig=ACfU3U11WhqeEorUljPSe9W3kYS9JvVNYA&hl=pt-PT&sa=X&ved=2ahUKEwjw76OkmN_4AhV6m_0HHYsUCmYQ6AF6BAgnEAM#v=onepage&q&f=false
[15] J. K. Teuvo Suntio and K. Kostov, “Analysis and design of emi filters for dc-dc converters using chain parameters.”

[16] G. V. G. A. M. C. Di. Piazza, M. Luna and G. Giaconia, “Odef: An interactive tool for optimized design of emi filters.” [Online]. Available: https://ieeexplore.ieee.org/document/7793648

VIII. Appendix

A. Different measurement setups

Level 1	Level 2	level 3
25%	25%	25%
25%	25%	50%
25%	25%	75%
25%	50%	50%
25%	50%	75%
25%	75%	75%
50%	50%	50%
50%	50%	75%
50%	75%	75%
75%	75%	75%

TABLE II: Measurements were carried out at various duty cycles using three buck converters connected to a DC power supply. The switching frequency has been set to 100KHz, 300KHz, and 500KHz

Level1	Level 2
25%	25%
25%	50%
25%	75%
50%	50%
50%	75%
75%	75%

TABLE III: Measurements were carried out at various duty cycles using two buck converters connected to a DC power supply.. The switching frequency has been set to 100KHz, 300KHz, and 500KHz

Level 1	Level 2	Level 3
100	100	100
100	100	300
100	100	500
100	300	300
100	300	500
100	500	500
300	300	500
300	500	500
500	500	500
750	750	750
1000	1000	1000
100	100	1000
100	500	1000
100	1000	1000

TABLE IV: Measurements done with different switching frequencies and 50% duty cycle. Three buck converters were connected to the dc power supply

Level 1	Level 2
100	100
100	300
100	500
300	300
300	500
500	500
750	750
1000	1000

TABLE V: Measurements done with different switching frequencies and 50% duty cycle. Two buck converters were connected to the dc power supply

Level 1
100
300
500
750
1000

TABLE VI: Measurements done with different switching frequencies and 50% duty cycle. One buck converters were connected to the dc power supply

B. Setup

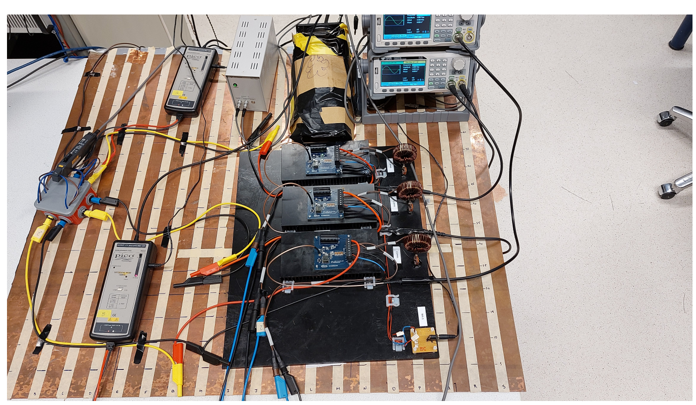

Fig. 20: Top view of the measurement setup

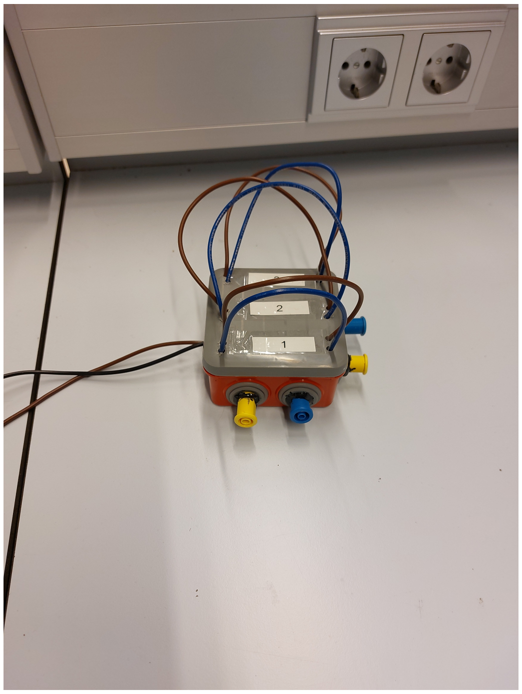

Fig. 21: Picture of the switch box

C. The designed EMI filter

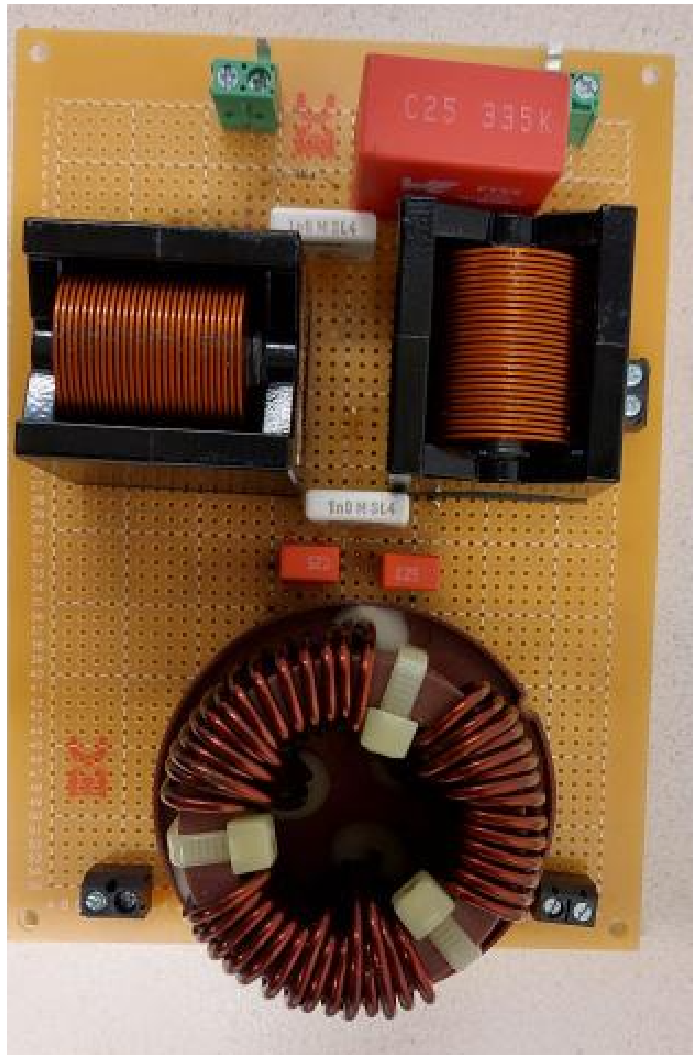

Fig. 22: Top view of the designed EMI filter

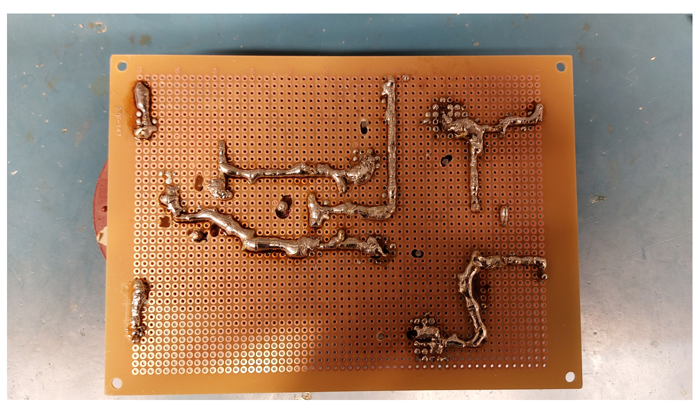

Fig. 23: The soldering layout of the EMI filter. Left being the input of the filter and right the output

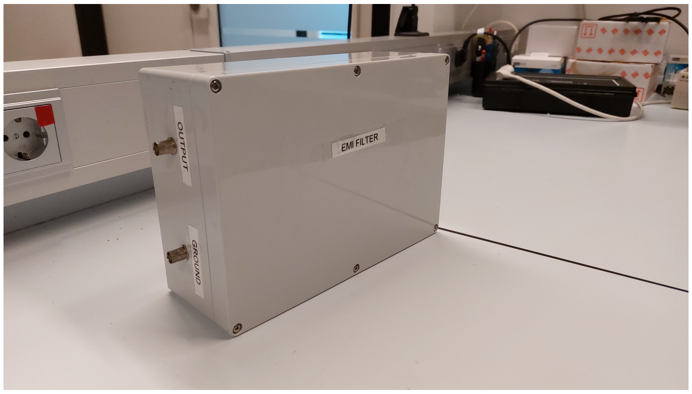

Fig. 24: The final design of the filter box