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Design of EMI Improved Isolated DC/DC Converter for Space-based Applications

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***Abstract*—For space exploration, for instance by use of CubeSats, there is need for small converters which can both operate isolated and non-isolated with a low EMI profile. Incorporating Electromagnetic Compatibility (EMC) within the design stage is therefore crucial, and can be achieved by applying different EMI mitigation techniques from the very start of the design. This paper investigates inherent reduction of EMI via interleaving, balancing, and symmetrically designing a DC/DC converter. Mass and volume restraints are considered as well during the design. It will be shown that these relatively advanced (but matured) design techniques, already well known and utilized on Earth, can be utilized for a novel design for space based applications with beneficial charateristics.**

I. INTRODUCTION

In order to keep pushing forward in current space exploration there are 58 countries around the world making use of a new type of satellites, the so called CubeSats. These are small lightweight satellites build up from different modules with a standardized size. These CubeSats are meant for enabling cheaper space exploration for more parties, by use of Commercial Of The Shelf (COTS) components. The origin of these CubeSats lies in being an enabling technology for education [1].

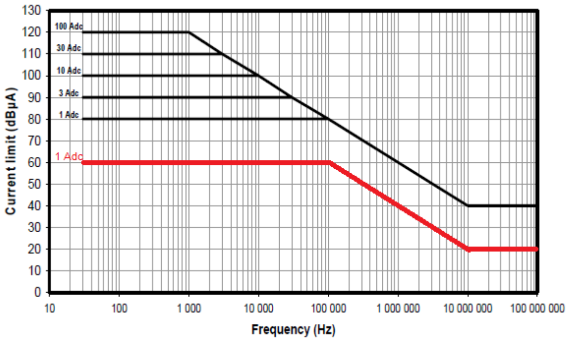
Within the aerospace industry there are strict requirements for converters. Mainly due to the fact that volume and weight are limited. From an electromagnetic environment point of view, the small spaces require everything to be integrated as much as possible, which can be troublesome with the many different sensors and sensitive observation equipment onboard as a payload. This is why there is need for an innovative design which takes EMI from the first step into account, instead of a secondary optimization objective. Advanced methods and techniques of inherently reducing EMI generated by power electronics have been employed in several domains, like automotive, commercial and maritime. These mitigation technologies are reaching maturity, and are becoming interesting for usage in the (aero)space industry.

There is need for a converter which has a focus on the following points: modularity, redundancy, reduction in output ripple and achievable efficiency while leaving a small footprint. As expected the main focus during the design of the converter lies on the reduction of the EMI from the converter by implementing several options for inherently mitigating the emissions, without the need for bulky and heavy filters. The options vary greatly in complexity and in the additional components required and an overview can be found in [2].

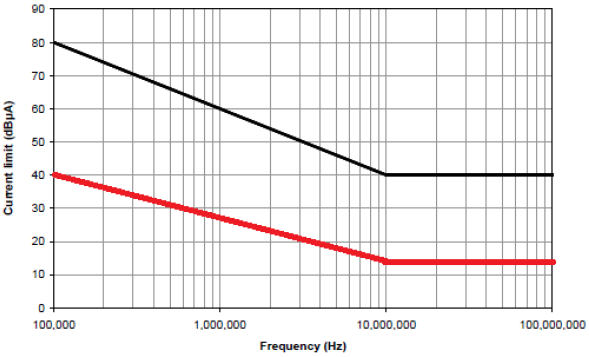
Besides the reduction of emissions from the converter a focus on keeping the mass as low as possible and having a high reliability for the system is crucial, due to its space based application. A weight reduction can for instance be achieved by increasing the operational frequency of the system, as the required passive components will shrink in size, but at the penalty of increasing the losses [3], [4].

In order to limit EMI problems there has been done a range of different approach. These approaches have been tested in practice for different fields. The EMI mitigation techniques range from different design topology towards physical layout of the system building build. [2] Interleaving is used in higher power application with strict EMI requirements [5], [6]. There are also different ways of mitigating Common Mode (CM) emissions, by use of balancing or split transformer. [5] Next to these EMI reduction techniques there might still be need for filtering in order to achieve the targeted limits. and a passive EMI filter will therefore be designed as well. The highest priority will be given to mass. As was discussed, a higher switching frequency reduces the mass of the converter, as smaller magnetic components and capacitors can be used, however this train of thought does not only hold for the functional components but can be extended for the filter design. However, it has also been shown that CM filter weight increases due to larger CM emissions at higher frequencies [7]. The attenuation of an EMI filter will degrade at higher frequencies due to parasitics, therefore components must be selected carefully to reduce higher frequency Conducted Emission (CE) [8], [9]. As a possible solution tuning the switching operation, one can optimally generate the noise with respect the filter's performance [10].

In Sec. II there will be a short description of the functional requirements for the converter in question. Sec. III will take an overview at possible converter designs. In Sec. IV there has been taken a look at Differential Mode (DM) noise reduction due to interleaving. Sec. V will go over advantages of interleaving besides the reduction in DM noise. Within Sec. VI there are noise reduction techniques discussed for CM noise. Sec.VII there are filters designs given in order to be in line with the requirements.



(a) DM



(b) CM

Fig. 1. conducted emission limit lines for power leads, adopted from ECSS-E-ST-20-07C. Where the targets are given in red

II. System requirements

In this paper a converter is designed intended for application within CubeSats, but of course not limited to. The design shall consider the following baseline converter parameters: nominal input voltage 28 V, nominal output voltage 5 V, average output power 30 W, peak power 36 W, and stand-by power up to 1.5 W. The system should both be able to operate with an isolated secondary side and connected secondary side. Next to the baseline parameters there is a focus on targeting CM and DM conducted emissions. These are compared to limits set by annex A.2 of the European Cooperation for Space Standardization- Electrical- Standard -20-07C (ECSS-E-ST-20-07C) [11]. These limits can be achieved by using several EMI mitigation techniques in conjunction with an optimal filter design. Targets that were set for DM conducted emissions (Fig. I):

- $f = 30\,\mathrm{Hz}$ to $100\,\mathrm{kHz}$:$60\,\mathrm{dB}\mu\mathrm{A}$
- $f = 100\,\mathrm{kHz}$ to $10\,\mathrm{MHz}$:starting at $40\,\mathrm{dB}\mu\mathrm{A}$ and subtracting $20\,\mathrm{dB}\mu\mathrm{A}/\mathrm{dec}$ after.
- $f = 10\,\mathrm{MHz}$ to $100\,\mathrm{MHz}$: $20\,\mathrm{dB}\mu\mathrm{A}$

for CM conducted emissions (Fig. I):

- $f = 100\,\mathrm{kHz}$ to $10\,\mathrm{MHz}$: starting at $40\,\mathrm{dB}\mu\mathrm{A}$ and subtracting $12.5\,\mathrm{dB}\mu\mathrm{A}/\mathrm{dec}$ after.
- $f = 10\,\mathrm{MHz}$ to $100\,\mathrm{MHz}$: $15\,\mathrm{dB}\mu\mathrm{A}$

Tab I shows the settings for use of the FFT in accordance with ECSS-E-ST-20-07C.

TABLE I
FFT settings for ECSS-E-ST-20-07C.

Frequency range	RBW	Min. Dwell time
1 kHz to 10 kHz	100 Hz	15 ms
10 kHz to 150 kHz	1 kHz	15 ms
150 kHz to 30 MHz	10 kHz	15 ms
30 MHz to 1 GHz	100 kHz	15 ms
Above 1 GHz	1 MHz	15 ms

With respect to power quality design the following targets are set:

- secondary output voltage ripple $25\,\mathrm{mV_{pp}}$ 0.5 %, when measured with at least 1 MHz bandwidth;
- secondary output voltage spikes $100\,\mathrm{mV_{pp}}$, when measured with at least 50 MHz bandwidth;

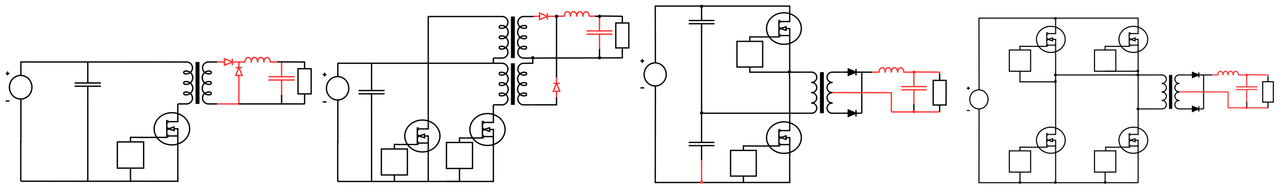
As the design is intended for aerospace and aeronautics applications, it should be optimized towards low mass as well as high power efficiency, while simultaneously increasing power quality and reducing conducted emission parameters.

III. Comparison between converter types

There is a range of type of converters which are applicable for the requirements set by the application. Based on the requirements set in Sec. II, it follows that the only feasible option will be an isolated buck converter. Based on this there are four options possible [12]. By studying the different topologies shown in Fig. 2, it is possible to draw a conclusion on the feasibility of these converters within space application. Each are centred around the use of a transformer, with their own advantages and disadvantages. The mass of the converter is an important limitation for the converter. By limiting the extra components needed the weight can be limited, based on this the forward converter is advantageous due to the fact that there are less switches needed compared to the other options. Besides the weight, the reliability is needs to be considered as maintenance in space is difficult and costly. Reliability can be increased, by utilizing redundancy i.e. not having a single point of potential failure. By considering Fig. 2 it can be concluded that the Push pull-, Half bridge- and Full bridge-converters do not obtain increased reliability by increasing the number of switches. The additional switches can be considered as part of the single point of failure [12]. Based on the points considered above the typical forward converter can be considered to be the most feasible solution within the scope of this paper. The added benefit in the control flexibility does not outweigh the lack in redundancy.

IV. Identification of Noise

The proposed converter have been simulated for the cases of having 1, 2 and 3 legs to investigate the beneficial effect of having multiple power legs. In Fig. 3 the block diagram of an interleaved forward converter is shown. Additionally, there



(a) Forward (b) Push Pull (c) Half bridge (d) Full bridge

Fig. 2. Different converter topologies that were considered

is a Line Impedance Stabilization Network (LISN) placed in accordance to ECSS-E-ST-20-07C. Based on the requirements presented in Sec. II the circuit was designed. The simulated output voltage ripple is shown in Fig. 4. The simulated circuit for a 3 legged interleaved converter is shown in Fig. 5. By use of interleaving there can be a significant reduction in components values whilst still maintaining the same output characteristics. Similar levels of output ripple is achieved although there has been a significant reduction in component values, and thus in component size as well. The changing component values are shown in red within Fig. III. Values used:

- 1 Leg: $L = 128.5\,\mu\text{H}; C = 100\,\mu\text{F}$
- 2 Legs: $L = 17.3\,\mu\text{H}; C = 56.6\,\mu\text{F}$
- 3 Legs: $L = 27.2\,\mu\text{H}; C = 25\,\mu\text{F}$

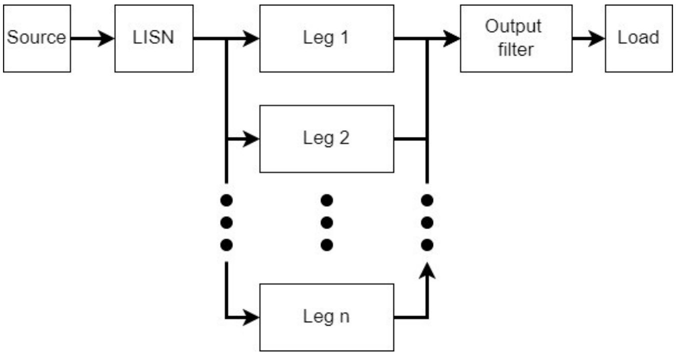


Fig. 3. Block diagram of a standard interleaved forward converter, with LISN present

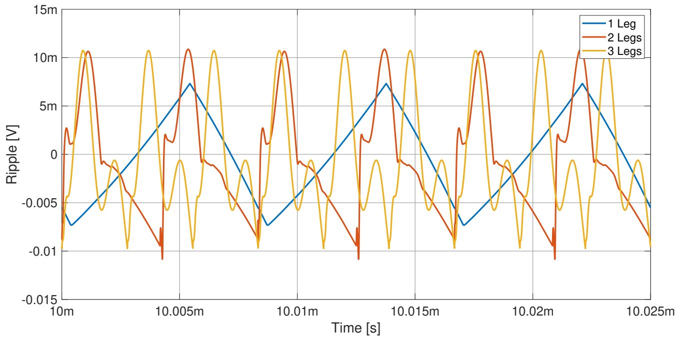


Fig. 4. Output ripple from interleaved converter. From the different waveforms it is clear that the frequency is increased and depended on the amount of legs. The peak to peak ripple stays with in the requirements

Next to the significant reduction in the output stage component size, the input noise spectrum will be reduced significantly. The reduction of noise is inherited from the interleaving process. The switching become less severe and are balanced throughout the different cycles. In Fig. V the spectrum is shown, which is obtained from processing the data in accordance to the ECSS-E-ST-20-07C. A reduction of DM noise can be seen, from 10 kHz to approx. 200 kHz, as well as the frequency range above 1 MHz, with reductions around 10 dB. Next to the higher frequency reduction the main switching frequency of 120 kHz has been significantly suppressed, as for 2 legs the most dominant frequency becomes 240 kHz and 3 legs 360 kHz. This benefits small footprint filter design in the later stage, as higher frequency components require lower valued (and thus less bulky) passive components. The overall spectrum has been reduced by the interleaving.

By adding an input capacitance of $10\,\mu\text{F}$ to the system there can be a significant reduction of the DM noise spectrum, as it will greatly reduce fluctuations of the input DC voltage. Based on the data presented in Fig. V it is clear that due to the interleaving there can be a significant reduction in the DM noise produced by converter

There are multiple observation to be made from the spectrum. Interleaving the converters significantly reduces the frequency content in the lower part of the noise spectrum, as the total perceived system switching frequency increases with the number of legs, thus pushing it into the higher frequency range. By interleaving the overall amplitude is reduced significantly. Above 10 MHz resonances are appearing for the 3 legged converter, most likely due to the interaction of the capacitances and inductances between the converter legs. A more in-depth study should be performed to also include the parasitic behavior of each these as the simulation has been done by use of idealized components. Based on the parasitics there can be a significant change in the amplitude of the Fast Fourier Transform (FFT) in the higher frequency range. However the trends of shifting the EMI towards higher frequencies and more scarcely spaced should still hold by interleaving several legs. Additionally different loading circumstances were simulated, and it can be observed that the 3 legged interleaved converter is more resilient against the changing of the output conditions as it has been shown in Fig. V.

V. INTERLEAVING TRADE-OFFS

Beside the advantages of interleaving discussed in Sec. IV there are other advantages. Based on the construction of the

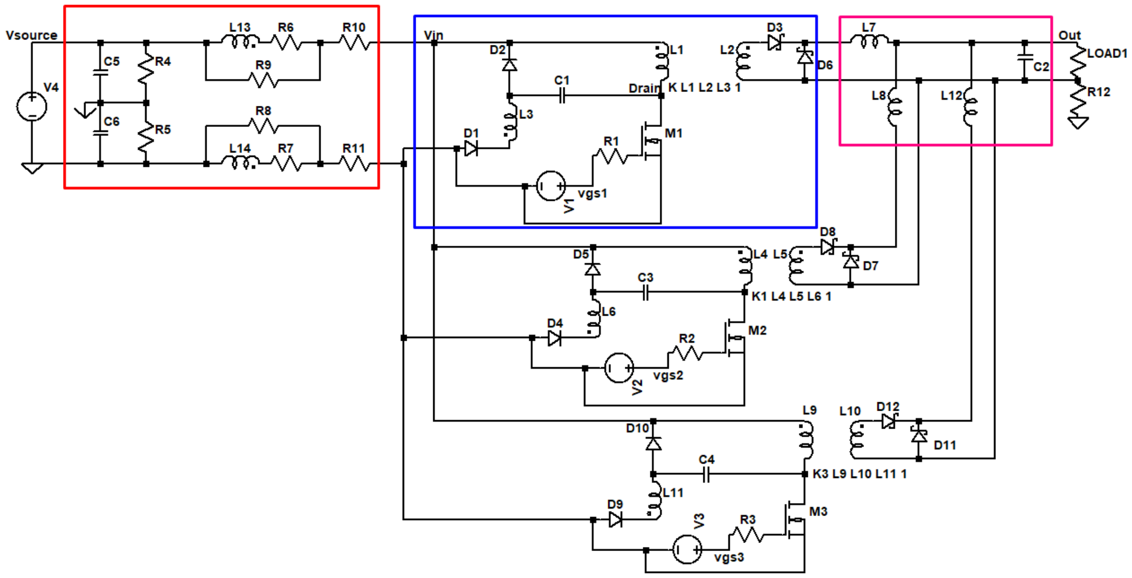


Fig. 5. Simulated circuit, with LISN marked in red, Blue marking one of the three converter legs, and in purple the output filter

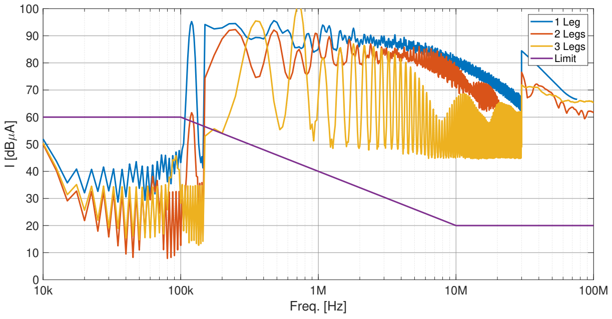
interleaved forward converter the reliability increases. If the system has been sized properly then one of the legs can fail whilst maintaining primary operation of the converter, although at the cost of an increase in EMI. Next to the increase in reliability it is possible to have a high degree of modularity, as the output power has a linear relationship with the number of legs. This allows the convert design to be scaled for different application, but at the cost of additional components. Which can be traded-off against reduced costs due to a "one design fits all" approach. Although there is a need for more components the passive components' size can be optimized . In case of an interleaving converter, it is possible to reduce the core size as the current is distributed over multiple cores. Based on the reduced current flowing through each switch the switching losses per device can be reduced. This can means that the per switching device the applied cooling can be reduced, e.g. smaller sized heatsinks. Next to the losses per switching device, the eddy current losses per core can be reduced. This can be advantageous for the amount of material needed in order to keep an optimal operating temperature in the core [13].

VI. CM NOISE REDUCTION TECHNIQUES

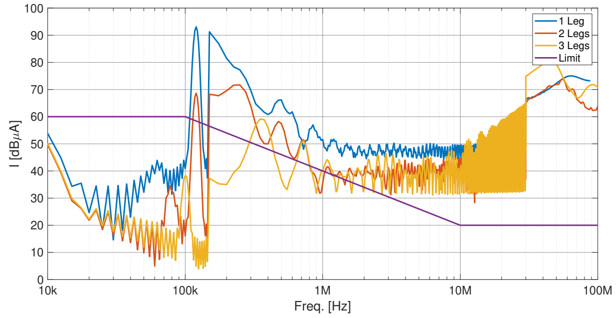
Next to the existence of DM noise there is also CM noise in power converters, which often cannot be seen in design schematics, as this noise follows propagational paths that originate from parasitic effects. In general one can investigate the trend in expected CM noise by adding capacitive coupling paths from several points in your simulation to Protective Earth (PE) and also by including the capacitive coupling between the primary and secondary side of the transformer. By adding rule of thumb sized parasitic coupling effects, the noise produced can be estimated, but this is subjective to change due the geometric design and eventual implementation techniques. In Fig. 7 the results can be seen after implementing similar parasitics as were described in [14]. In case of CM EMI, the trend in reducing EMI with increased number of legs is not as prominent. Most likely due to the increase of parasitic coupling paths, which would inherently increase the total capacitive coupling.

In order to reduce the common mode noise, usage of alternative transformer designs is possible. For instance a split transformer can be utilized to force a cancellation effect upon the CM EMI. In Fig. VI the basic circuit diagram can be seen. The windings are split over two separate inductors, distributing the total parasitic effect evenly, however with a phase-shift of 180 degrees, effectively cancelling the common mode current [15], [16]. By utilizing the split transformer the CM noise spectrum could be reduced significantly, as can be seen in Fig. VI . Note that the result shows the noise-floor of the simulation that was performed, which is not a realistic scenario. The effectiveness of this solution will be highly dependent on the possibility to produce highly balanced components, i.e. coupling factors of 1 and identical self-inductance values of each of the windings. As was the case in the DM EMI investigation, non-ideal simulation models for the components should be used to investigate their effectiveness.

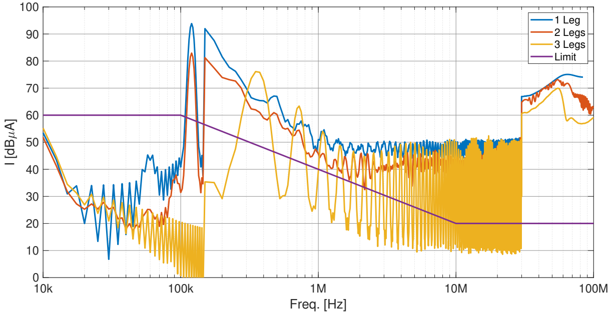
As is well known, the CM noise is greatly depended on the layout of the physical system. In Fig. 9 two different layout possibilities for the converter have been sketched. Parasitic capacitance will not only exist between the converter and PE (or chassis) but also between the different interleaved legs. The star layout configuration exemplified by Fig. VI forms a more uniform parasitic distribution than the stacked configuration shown in Fig. VI. From a modularity point of view the stack configuration might be more convenient.



(a)



(b) Addition of an input capacitor



(c) At peak output power

Fig. 6. DM Spectra of the input voltage per configuration and processed according to the ECSS-E-ST-20-07C.

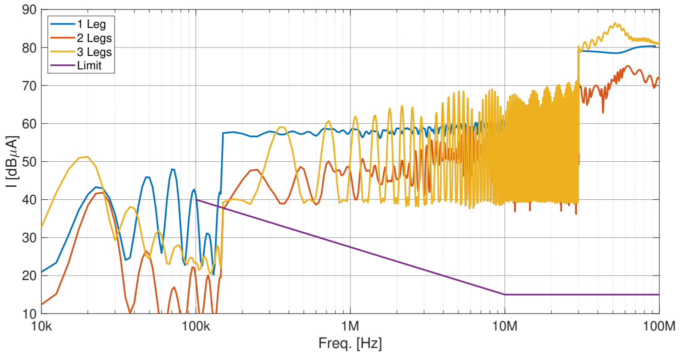
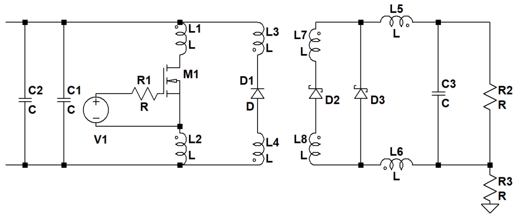
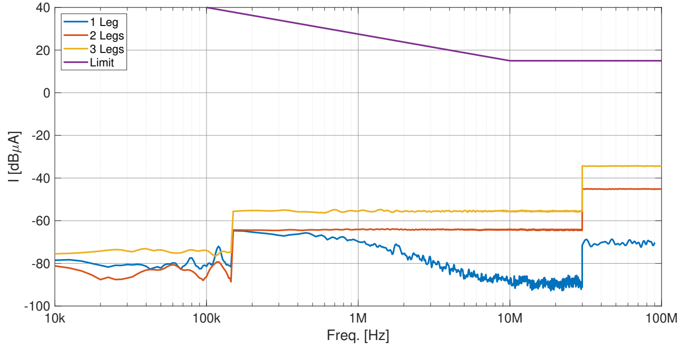


Fig. 7. Spectra of the CM current produced by the converter

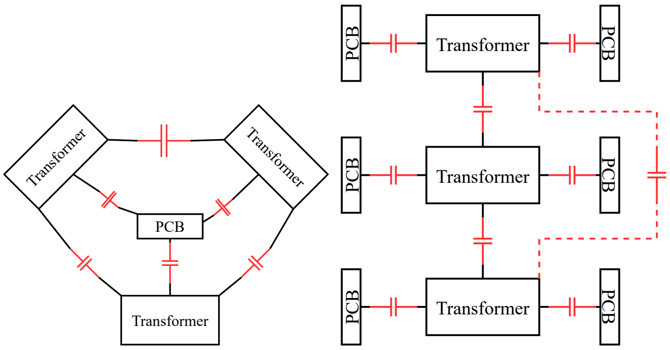


(a) Circuit diagram with split transformer



(b) Resulting spectra of ideal case

Fig. 8. Effect of ideal split transformer, with ideal coupling, and symmetry



(a) Star (b) Stack

Fig. 9. Layout configurations of multi-leg converters

VII. Filter design

In order to design a filter, a desired attenuation target has to be set. The desired attenuation can be extracted from the results in Sec. IV and Sec.VI, for DM and CM respectively. As was discussed, the expected CM emission is difficult to predict without a proper layout design, together with the effectiveness of the split transformer that requires substantial investigation, therefore the CM filter design is omitted in this analysis.

In case of DM EMI, Tab. II summarizes attenuation targets for several key frequencies. These do not include the customary EMC margin for compensating components values drift and/or tolerances. The point is not to have the correct filter design, but just to highlight the methodology in investing a power converter with a low/reduced EMI footprint.

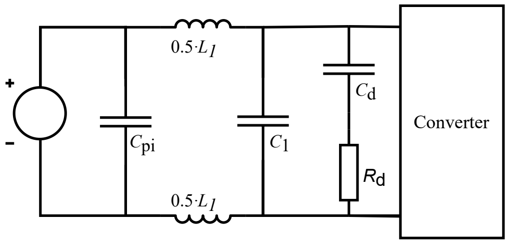


Fig. 10. Ideal Π-filter topology with damping

By following a similar design approach as was described in for instance [17] a different filter for each of the converters is designed. The designed filters are low-pass Π shaped filters Fig. 10. The resulting values of the filter components are shown in Tab. III. The filters are not optimized for the application but are still able to show the general trend. As can be seen from Fig. 11 these are able to attenuate the generated DM noise significantly. By increasing the interleaved legs the passive component values can be reduced. By decreasing the overall component value the size and weight can be reduced.

TABLE II
DM NOISE ATTENUATION TARGETS

N-Legs	120 kHz	150 kHz	360 kHz	10 MHz
1	55 dB	36 dB	15 dB	30 dB
2	23 dB	26 dB	11 dB	25 dB
3	0 dB	0 dB	26 dB	30 dB

TABLE III
COMPONENT VALUES OF DM INPUT FILTER FOR THE DIFFERENT CONVERTERS

N-Legs	C_1 (μF)	L_1 (μH)	C_d (mF)	R_d (Ω)	C_pi (nF)
1	300	10	3.0	0.1	300
2	60	1	0.6	0.2	500
3	10	0.6	0.05	0.2	300

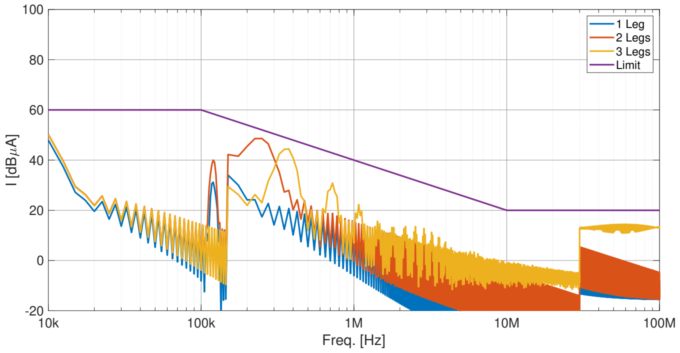


Fig. 11. DM noise after filtering

VIII. DISCUSSION AND CONCLUSION

The previous sections presented many simulation results which show the potential of interleaving converter legs, with and without implementing additional EMI reduction techniques. The DM noise is reduced inherently as it can be seen from Fig. V. This reduced DM noise will require a less stringent filtering performance. Next to the DM there are multiple techniques in order to limit the CM noise from the converters. Balancing the converters and forcing symmetry through transformer design show the largest potential reducing noise. This can be seen in Fig. VI, however this was an ideal simulation result and therefore requires practical validation work to investigate the potential effectiveness. Next to the possible advantages with respect to EMI, interleaving converter topologies also showed advantages in case of reliability and modularity. The results presented need to be analyzed carefully since there has only been paid limited attention towards the parasitic behaviour of the system. These can only be reliably determined when there has been made a physical prototype, or full-wave 3D simulations are performed.

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