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Strategies to Reduce Copper Losses in Connections of Medium-Frequency High-Current Converters

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Abstract- **In medium-frequency high-current converters, semiconductors are usually connected to passive components by means of copper plates or PCBs which generally have their thickness defined by the current frequency and their width defined by the maximum allowed copper losses. In this paper we will show some strategies to reduce copper losses in these connections by either interleaving parallel copper plates having currents in opposite directions or interchanging plates having currents in the same direction. Analysis is performed using 2D Finite Element Method (FEM) simulation and experimental results demonstrate the validity of the study.**

I. INTRODUCTION

In a world with growing interest for energy savings, DC-DC converters operating at medium frequencies are a promising option for weight and loss reduction of systems where DC transmission is considered. In order to decrease the size of these converters, switching at higher frequencies is an interesting option to reduce passive components and isolation transformers.

High-power medium-frequency converters are nowadays developed for applications mainly related to traction [1-3] and renewable energy [4,5] systems. In these applications, currents at the range of hundreds to thousands of amps at some tens of kilohertz are found and can only be handled by the use of either litz wires or foil wires and copper plates.

In these converters, power semiconductor modules normally have screwed terminals which impose the use of copper plates to interconnect them to other components such as transformers, inductors and capacitors. For the frequency and magnitude of currents involved in these systems, large copper plates with reduced thickness are necessary, which decrease the power density of the converter.

This paper proposes some compact arrangements of copper plates to reduce high frequency copper losses in the connection of semiconductors and passive components of medium frequency converters handling high currents.

II. CONNECTIONS IN BIDIRECTIONAL CONVERTERS

In order to illustrate the problem of high frequency copper losses in the connections, a widely used converter for bidirectional isolated DC-DC applications will be used: the Dual Active Bridge (DAB) converter. It is used in several applications having different modulation strategies, where the most common allows Zero Voltage Switching (ZVS) [6] and/or Zero Current Switching (ZCS) [7]. Fig. 1 shows a typical configuration of this converter where the connections between active and passive components are highlighted.

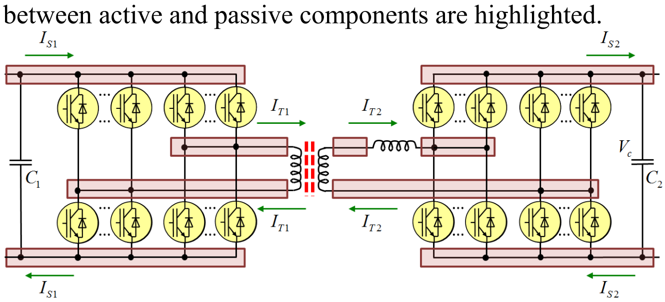


Fig. 1. Dual Active Bridge converter with paralleled switches.

If the current in the low voltage side of the DAB converter is high, several switches in parallel may be used, which makes necessary the use of copper plates or PCB to interconnect them. Flat conductors are also used in the terminals of the foil windings of medium-frequency high-current transformers, as the one shown in Fig. 2 [8].

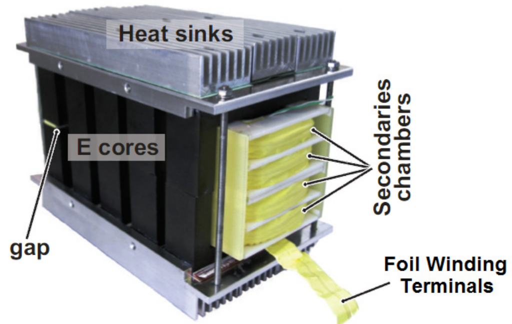


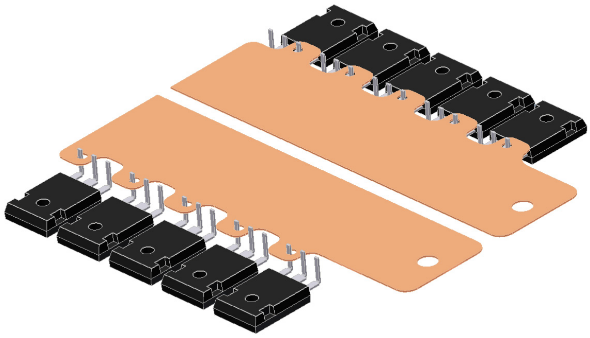
Fig. 2. Medium-frequency high-current transformer used in a 3.5kV/11kW/30kHz DC-DC converter for charging capacitor banks of power modulators [8].

A. *Connecting the transformer to the semiconductors*

When connecting all switches in parallel, a good option is using PCB or copper plates, depending on the number of switches, their shape, the current value and the available space for connections.

Two options on arranging these switches may be considered: side by side using one layer or distributed with superimposed layers. This is shown in Fig. 3a and Fig. 3b, respectively, where no connection to the DC bus is shown.

If we take, for example, sinusoidal currents of 100A at 20kHz flowing in conductors which are 50mm wide and 1mm thick, we note copper losses of 6.4W/m for superimposed layers (Fig. 3b) and 11.7W/m for both conductors in one layer (Fig. 3a).



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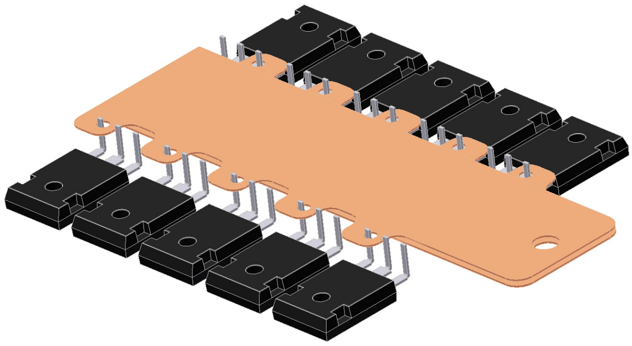
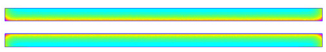


b)

Fig. 3. Different arrangements of copper plates connecting paralleled switches in full bridge converters. a) side-by-side in one layer; b) distributed in superimposed layers. Connections to the DC bus are not shown.

a)



b)

Fig. 4. Current distribution at high frequency in different arrangements of copper plates connecting paralleled switches in full bridge converters. a) side-by-side in one layer; b) distributed in superimposed layers. Darker colors indicate higher current densities.

Analyzing the Finite Element Method (FEM) simulation shown in Fig. 4 we note that when conductors are side-by-side, the high concentration of the flux in the region in between causes high current densities in this small part of the conductor and, as a consequence, high copper losses. Superimposed layers distribute the current in the whole width of the conductor, although skin and proximity effect is also observed.

B. Optimal thickness of superimposed copper plates

When using superimposed layers having currents in opposite directions, proximity effect imposes an optimal thickness of the conductors in order to reduce high frequency copper losses.

In high frequency transformer, optimal thickness of layers is usually calculated based on Dowell's formulas [9]. Initially this optimal thickness was found for sinusoidal current. Later, using Fourier coefficients, optimal thickness of layers were found for different current waveforms [10]. For sinusoidal currents, the optimal thickness depends basically on the number of layers. In this paper, all the analysis and measurements will be done for sinusoidal currents. For non-sinusoidal currents, one may use the same approach shown in this paper taking into account all the current harmonics.

Copper plates used for the connection of switches to the transformer are not surrounded by magnetic material and so Dowell's formula cannot be directly used to estimate high frequency copper losses in this case. Flux lines at the vertical direction (regarding Fig. 4b) induce higher copper losses in the extremities of the plates, which is not usually the case of conductors inside a core window.

However, since the conductors we study are copper plates which have the width much higher than the thickness, and also superimposed plates are very close to each other, then Dowell's equations estimates the AC resistance with a relatively high accuracy. This can be seen in Fig. 5 where we plot the equivalent AC resistance per meter of superimposed copper plates which are 50mm wide and 1mm thick, for 3 different frequencies and three different cases. Note that Dowell's formula is very accurate for conductors in a transformer window but less accurate for conductors in the air, although the behavior is about the same.

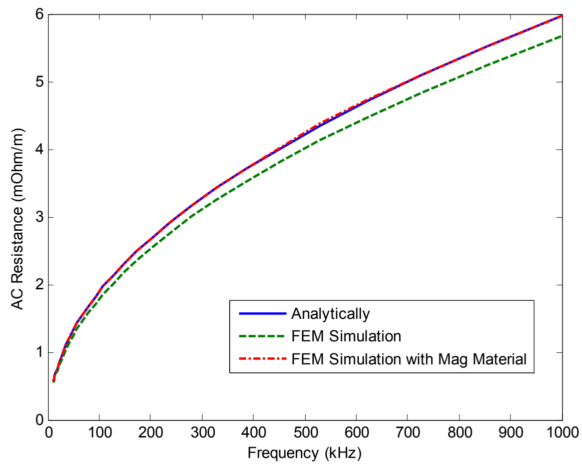


Fig. 5. AC resistance behavior of superimposed copper plates, for different frequencies and different cases: 1-Using Dowell's formula, 2-Performing a FEM simulation, 3- Performing a FEM simulation having the conductors surrounded by magnetic material (as in a core window).

C. Finding the optimal thickness

Equations in [10], which are based on Dowell's formulas, could be used to obtain an estimation of the optimal thickness of superimposed copper plates. However, a more precise evaluation of the optimal thickness could be done by 2D FEM simulations, which are very fast, even when the skin depth is small and a great number of nodes is necessary.

The optimal thickness of superimposed copper plates may change with two parameters which are not considered when using Dowell's formula: the conductor width (Z) and distance between the conductors (X). We show in Fig. 6 and Fig. 7 the influence of these parameters in the AC resistance per unit length and the optimal thickness. Geometrical parameters are normalized by the skin depth (δ), which may be calculated for a given frequency (f) by the equation below:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \qquad (1)$$

where ρ is the conductor's resistivity and μ is the conductor's permeability, which is usually equal to the air's permeability.

In Fig. 6 and Fig. 7, since geometrical parameters are normalized by the skin depth, the AC resistance per unit length (R_{ACn}) is normalized by the square of the skin depth. It means that one could calculate the AC resistance of a plate (R_{AC}), for a given width Z and thickness X and length ℓ, by taking the corresponding point in the curve in these figures and using the following formula:

$$R_{AC} = R_{ACn}.\delta^2.\ell \qquad (2)$$

Fig. 6 shows that increasing the width of the plate reduces the AC resistance. However, the decrease in the AC resistance is not inversely proportional to the increase in the width because of the concentration of current in the extremities if the plates, due to the 2D characteristic of the field in the region close the conductors. Note also that the optimal thickness of the plates decreases with the increase in the conductor width and that it approaches the theoretical value for conductors inside a transformer, which is close to *1.6δ* [11].

Fig. 7 shows that increasing the distance between plates reduces the AC resistance and also increases the optimal thickness of the plates. This is because the field intensity is decreased when conductors are separated.

D. Reducing copper losses in superimposed plates

Analysis presented in last sub-section shows that high frequency copper losses may be reduced by either increasing the plate width or increasing the distance between plates. The last option is not so practical since the gain on the loss reduction is small. Obviously, for reducing copper losses the designer should choose a plate having thickness close to the optimal.

If a high current application has a relatively high frequency, either the designer develops a way to efficiently extract the copper losses generated in the plates or very wide plates must be used. For example, if an application where 600A at 20kHz flow through copper plates, the optimal thickness of a copper plate at 100°C is 0.53mm and the width of the plate must be equal to approximately 205mm in order to have an equivalent current density of 5A/mm^2. This plate width may be too high for certain applications where space is an important constraint. Also large plates may not efficiently reduce losses since the current flowing from the switches to the transformer or inductor must be concentrated in the connection terminals and so high current densities close to the terminals may induce high losses.

Two different techniques may be used to efficiently reduce copper losses without increasing the plate width and consequently decreasing the converter's power density: 1 - Interchanging the position of parallel plates having the current at the same direction; 2 - Interleaving parallel plates having the current at the opposite direction.

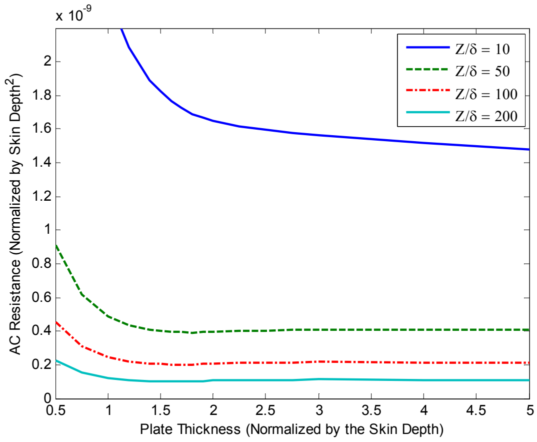


Fig. 6. Variation of AC resistance per unit length of superimposed copper plates with the plate width and thickness (the distance between plates is equal to 1 skin depth).

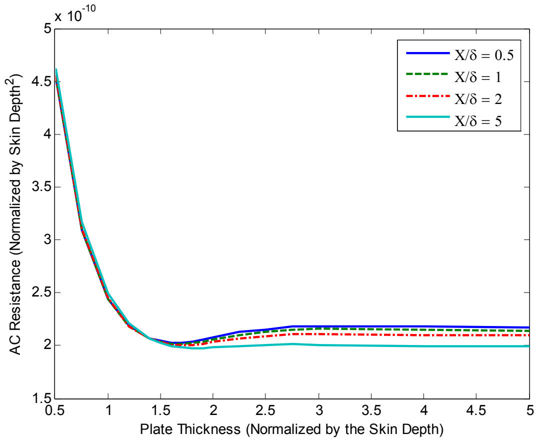


Fig. 7. Variation of AC resistance per unit length of superimposed copper plates with the plate thickness and the distance between plates (the plate width is equal to 100 skin depths).

III. INTERCHANGED PLATES

Simple paralleling copper plates does not help on reducing copper losses since each individual plate occupies a different position in the field created by all conductors. Since the plates are connected in parallel in the ends, eddy current circulate by the inner and the outermost plates the same way as if there was a single plate with the thickness equal to the sum of the each plate's thickness.

Effective paralleling may only occur if conductors experience the same field, averaged along their length [12-14]. This is the case of litz wires [15] and Roebel bars [16].

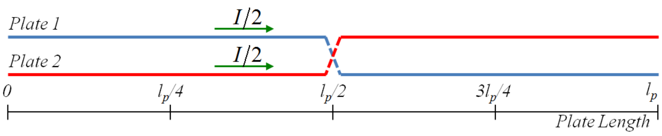
In the case of planar wires (foil wires, copper plates, PCB), interchanging layers in order to equalize the fields can also be done. In [12], authors construct a planar litz conductor by dividing the wide planar conductor lengthwise into multiple strands and weaving these strands in much the same manner as one would use to construct a conventional round litz wire conductor. About the same idea was used in [13] in order to build a flat litz ribbon cable.

Foil wires are interchanged in different layers and at different positions of a multi-layer winding used in high frequency transformer by authors in [14]. They give details on the calculation of the position where the layers must be interchanged, depending on the number of layers, the number of turns. Since the conductors are inside a core window, Dowell's equations can be used to estimate copper losses.

For the case studied in this paper, copper plates are not surrounded by magnetic material and as a consequence, Dowell's equations can not be directly used. Instead, copper loss reduction using interchanged layers will be evaluated by assuming that interchanging can perfectly balance the fields in the paralleled copper plates and thus the current is equally distributed among them, allowing the use of 2D FEM simulation.

Example of how layers must be interchanged so each copper plate experience the same field is shown schematically in Fig. 8, for the cases of 2 and 4 interchanged plates. Note that the total length of the plates is l_p and interchanges occur at multiples of l_p/n_p where n_p is the number of interchanged plates.

The same analysis as the one made in last section could be done for interchanged layers of copper plates which are superimposed. The conductor width (Z) and distance between the conductors (X) change the AC resistance. However we fix here $Z = 100\delta$ and $X = \delta$, and we verify the influence of interchanging layers in the AC resistance (per meter) and the optimal thickness. Results are shown in Fig. 9, for 1, 2 and 4 interchanged copper plates, using Dowell's equations and also simulated using FEM software. Note that curves using analytical calculation (Dowell's equations) and FEM simulation have the same shape although Dowell's equations produce a non negligible error because 2D effects are not taken into account. Also note that effective reduction of AC losses only occur up to a certain ratio between the plate thickness and the skin depth (or up to a certain frequency, if the plate thickness is fixed), and beyond this point the proximity effect between interchanged plates is so high that copper losses are even higher than in a configuration with a single plate. The optimal thickness of each plate decreases with the number of interchanged plates.



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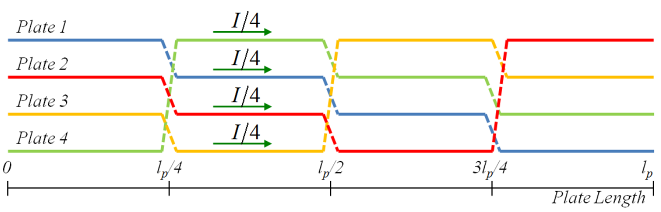


b)

Fig. 8. Interchanging of layers for flux balancing in parallel conductors. Optimal interchanging for a) n_p=2 (2 conductors); b) n_p=4 (4 conductors).

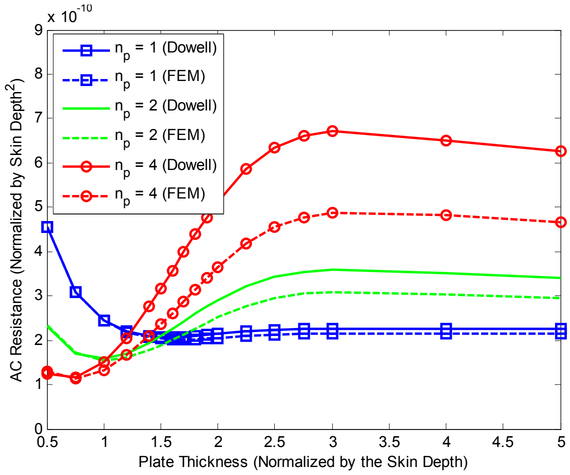


Fig. 9. Calculated and simulated variation of AC resistance of superimposed copper plates with the plate thickness for 1, 2 and 4 interchanged plates. Plate width is equal to 100 skin depths and distance between plates is equal to one skin depth.

IV. INTERLEAVED PLATES

Another way of reducing high frequency copper losses when copper plates are superimposed is paralleling these copper plates and interleaving them. Interleaving reduces the magnetic energy around the conductors and, as a consequence, the AC inductance and copper losses. There are many ways of interleaving parallel copper plates. We can classify them into symmetrical and asymmetrical interleaving. Example of these two types can be seen in Fig. 10, for 2 levels of interleaving.

Symmetrical types guarantee equal current distribution among all paralleled plates, as can be seen in Fig. 10. In asymmetrical configurations, copper losses in the outer conductors are lower than in the inner conductors but total energy is smaller than in the symmetrical case and so AC copper losses are lower. Current imbalance is not a particular problem for these paralleled plates, provided that total losses are lower.

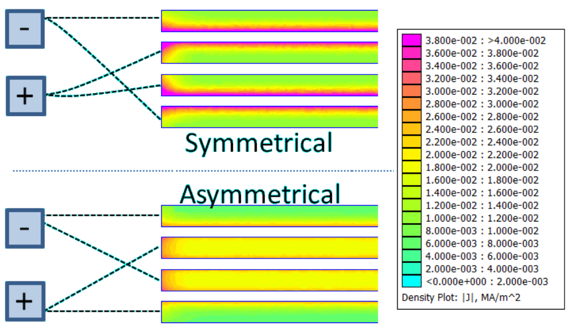
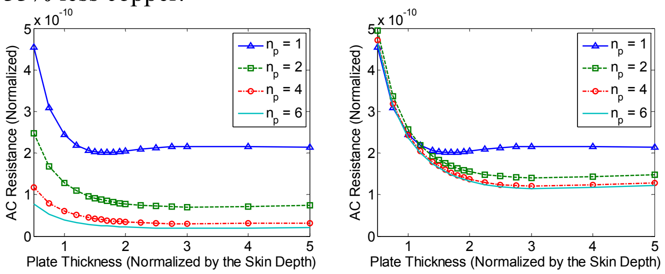


Fig. 10. Current density in part of the cross section of interleaved superimposed plates with two paralleled plates per conductor (n_p=2). Upper conductors: Symmetrical. Bottom conductors: Asymmetrical. Symbols "+" and "-" indicate the parallel connection of the plates and the current direction.

Analysis will be made with asymmetrical configuration since it is the one that more efficiently reduces AC copper losses. In this analysis n_p is the number of copper plates having current at the same direction. For the same example of last section (Z = 100δ and X = δ), we increase the number of interleaved copper plates and we vary the plate thickness. Like this the influence of interleaving in the AC resistance (per meter) and the optimal thickness is evaluated. Simulated results are shown in Fig. 11a, for n_p equal to 1, 2, 4 and 6. In Fig. 11b, the AC resistance is multiplied by the number of paralleled plates. This shows that, in addition to the great reduction of total AC resistance, interleaving also reduces the average losses in each plate. Note that optimal thickness is increased when the number of paralleled plates is increased and for n_p equal to 2, 4 and 6, optimal thickness of each plate is close to 3δ. However, if we use a thickness equal to 2δ, there is a minor increase in the AC resistance although we use 33% less copper.



a) b)

Fig. 11. Simulated variation of AC resistance of superimposed copper plates with the plate thickness, for 1, 2, 4 and 6 interleaved plates. Plate width is equal to 100 skin depths and distance between plates is equal to one skin depth. a) Normalized AC resistance. b) Normalized AC resistance of each plate.

V. Comparing the Techniques

We showed that we can reduce high frequency copper losses by interchanging plates having current at the same direction or interleaving plates with current at opposite direction. Now, we compare both solutions for the same example. Instead of showing simulation results normalized by the skin depth, a fixed geometry will be used. This geometry is not composed by thick copper plates but by long foil conductors having a very small thickness. This was chosen so the related resistances are not so small and experimental results can be later obtained using an impedance analyzer. Experimental results will be shown in the next section.

Conductors will be foil wires 17mm wide and 0.1mm thick, at 25°C. Like this, DC resistance is approximately 10.1mΩ per meter, per foil. The number of conductors (n_p) will be 1, 2 and 4, and the frequency of the current flowing through the conductors is varied from 10kHz to 1MHz. Besides the “interchanged” and “interleaved” configurations, also one configuration having a simple paralleling of 2 or 4 conductors will be used in the comparison. Distance between conductors is equal to 0.2mm.

AC resistance per meter of all these configurations was simulated in FEM software and the results are shown in Fig. 12. Note that both interchanging and interleaving solutions are better than simply paralleling copper plates. However, interchanged plates have higher losses than interleaved plates, especially at higher frequencies where proximity effect is much more pronounced in the first configuration.

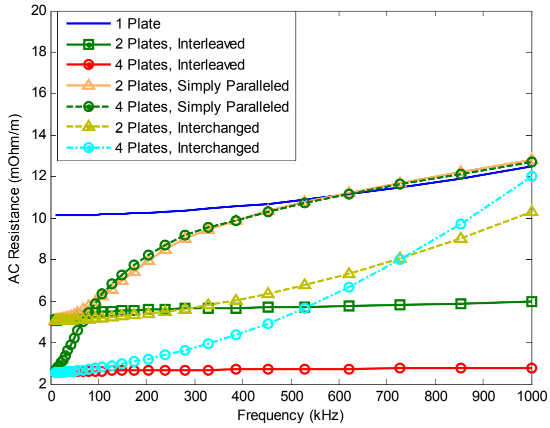


Fig. 12. Simulated AC resistance of superimposed copper plates versus frequency. 1, 2 or 4 plates are used in different configurations: simple paralleling; interchanging plates; interleaving plates.

VI. Experimental Results

The same example used in the last section was measured using an Agilent 4294A impedance analyzer. Four copper foils of 1m each were used and the AC resistance was measured for different configurations. Foils conductors were isolated by a 0.06mm thick tape and the distance between conductors was reduced to the minimum possible by pressing conductor together.

All conductors were folded in the middle in order to reproduce the currents in opposite directions flowing through the connections of commutation cells of DAB converters. Fig. 13 shows schematically all the configurations which were experimentally tested. Signs “+” and “-” are used to indicate which terminals of the impedance analyzer the conductors are connected to. A photo of the configuration with 4 interchanged conductors is shown in Fig. 14.

Since measured resistances are low, non negligible errors in the measurements are expected and resistance of the connection between the conductors and the impedance analyzer may influence the measurement, although short circuit calibration is done before each measurement. More precise measurements may be obtained inserting a transformer between the measuring device and the copper foils in order to increase the impedance measured by the impedance analyzer. This transformer must have a very low leakage inductance and very low resistance for the hole measuring frequency range.

Fig. 15 shows the measured resistance of the configurations shown in Fig. 13 for frequencies from 10kHz to 1MHz. The measured resistance of 1 single conductor is also included.

Comparing experimental results (Fig. 15) with the simulated ones (Fig. 12), we observe relatively small differences. Some of these differences may come from the fact that the terminations of the foil conductors must be separated to connect to the impedance analyzer and in this small part the conductors are not superimposed, generating higher losses. However, in general, experimental curves have the same behavior of the simulated curves, which verifies the analysis developed in this study.

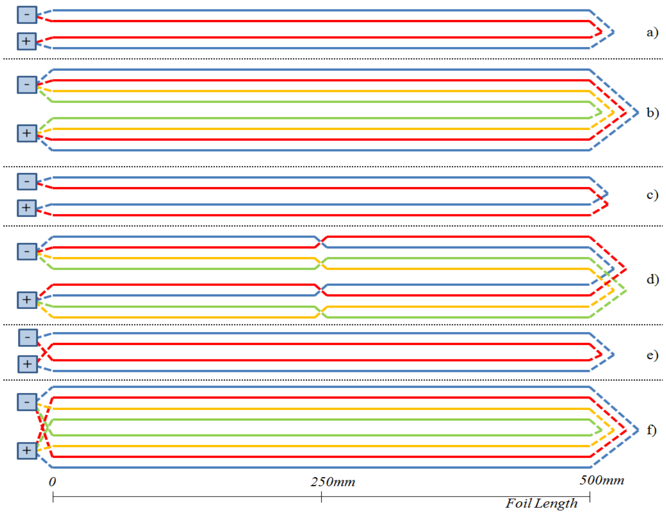


Fig. 13. Configuration of conductors experimentally tested. a) 2 conductors simply paralleled; b) 4 conductors simply paralleled; c) 2 interchanged conductors; d) 4 interchanged conductors; e) 2 interleaved conductors; f) 4 interleaved conductors; Symbols "+" and "-" indicate the connection of the plates to the terminals of the impedance analyzer.

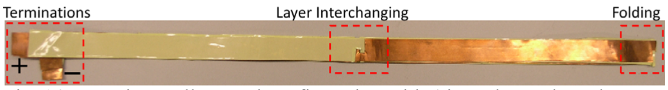


Fig. 14. Experimentally tested configuration with 4 interchanged conductors.

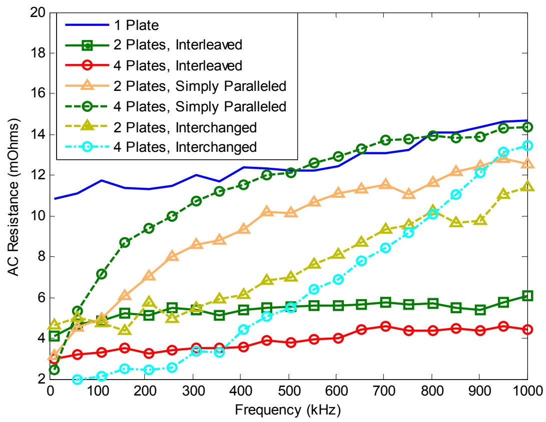


Fig. 15. Experimental measurement of AC resistance of superimposed copper plates versus frequency. 1, 2 or 4 plates are used in different configurations: simple paralleling; interchanging plates; interleaving plates.

VII. Conclusions

Superimposed copper plates or PCB layers are used in order to reduce high frequency copper losses in the connections between semiconductors and passive components when currents in these plates have opposite directions. Given that an optimal thickness of these copper plates exists for a given frequency, high-current medium-frequency applications have usually high copper losses in these connections. One option to reduce these losses is making copper plates wider, which may not be a good alternative for compact converters.

We have shown here two options to reduce high frequency copper losses without significantly increasing the space occupied by these connections. Both options rely on the parallelization of copper plates. In the first, plates are interchanged to equalize the flux experienced by them. In the second, plates are interleaved in order to decrease the magnetic energy around the conductor.

Analysis based on 2D FEM simulations showed the behavior of the AC resistance for each of the configurations, regarding the plate dimensions and the number of plates. Optimal thickness was investigated and experimental results confirmed the analysis presented in this paper.

At higher frequencies, interleaved plates generate lower AC resistances than interchanging these plates. This is due to the fact that interleaving reduces the total energy of the system which significantly reduces the proximity effect between plates. This does not happen in interchanged plates. However, the interleaving technique increases parasitic capacitances between plates, which may be problematic when dealing with high voltages at higher frequencies. A good option to effectively reduce AC copper losses without excessively increasing parasitic capacitances is to develop a hybrid solution by interleaving interchanged copper plates.

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In a world with growing interest for energy savings, DC-DC converters operating at medium frequencies are a promising option for weight and loss reduction of systems where DC transmission is considered. In order to decrease the size of these converters, switching at higher frequencies is an interesting option to reduce passive components and isolation transformers.

High-power medium-frequency converters are nowadays developed for applications mainly related to traction [1-3] and renewable energy [4,5] systems. In these applications, currents at the range of hundreds to thousands of amps at some tens of kilohertz are found and can only be handled by the use of either litz wires or foil wires and copper plates.

In these converters, power semiconductor modules normally have screwed terminals which impose the use of copper plates to interconnect them to other components such as transformers, inductors and capacitors. For the frequency and magnitude of currents involved in these systems, large copper plates with reduced thickness are necessary, which decrease the power density of the converter.

This paper proposes some compact arrangements of copper plates to reduce high frequency copper losses in the connection of semiconductors and passive components of medium frequency converters handling high currents.

II. CONNECTIONS IN BIDIRECTIONAL CONVERTERS

In order to illustrate the problem of high frequency copper losses in the connections, a widely used converter for bidirectional isolated DC-DC applications will be used: the Dual Active Bridge (DAB) converter. It is used in several applications having different modulation strategies, where the most common allows Zero Voltage Switching (ZVS) [6] and/or Zero Current Switching (ZCS) [7]. Fig. 1 shows a typical configuration of this converter where the connections between active and passive components are highlighted.

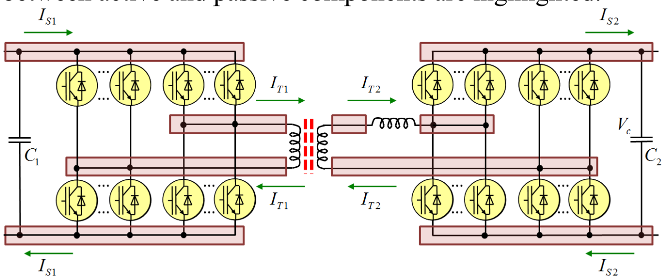

Fig. 1. Dual Active Bridge converter with paralleled switches.

If the current in the low voltage side of the DAB converter is high, several switches in parallel may be used, which makes necessary the use of copper plates or PCB to interconnect them. Flat conductors are also used in the terminals of the foil windings of medium-frequency high-current transformers, as the one shown in Fig. 2 [8].

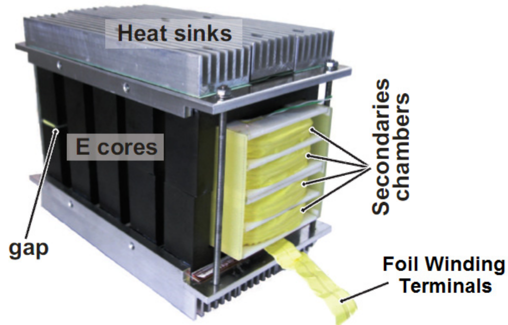

Fig. 2. Medium-frequency high-current transformer used in a 3.5kV/11kW/30kHz DC-DC converter for charging capacitor banks of power modulators [8].

A. *Connecting the transformer to the semiconductors*

When connecting all switches in parallel, a good option is using PCB or copper plates, depending on the number of switches, their shape, the current value and the available space for connections.

Two options on arranging these switches may be considered: side by side using one layer or distributed with superimposed layers. This is shown in Fig. 3a and Fig. 3b, respectively, where no connection to the DC bus is shown.

If we take, for example, sinusoidal currents of 100A at 20kHz flowing in conductors which are 50mm wide and 1mm thick, we note copper losses of 6.4W/m for superimposed layers (Fig. 3b) and 11.7W/m for both conductors in one layer (Fig. 3a).

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