A. Arruti, J. Anzola, I. Aizpuru and M. Mazuela, "Single Core and Modular Transformer Solutions: a Trade-Off Analysis of Volume, Losses and Temperature Rise," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, 2022, pp. 1-6.

DOI: https://doi.org/10.1109/IECON49645.2022.9968603

Single Core and Modular Transformer Solutions: a Trade-Off Analysis of Volume, Losses and Temperature Rise

Asier Arruti
Electronics and Computing Department
Mondragon Unibertsitatea
Hernani, Spain
aarruti@mondragon.edu

Jon Anzola
Electronics and Computing Department
Mondragon Unibertsitatea
Hernani, Spain
janzola@mondragon.edu

Iosu Aizpuru
Electronics and Computing Department
Mondragon Unibertsitatea
Hernani, Spain
iaizpuru@mondragon.edu

Mikel Mazuela
Electronics and Computing Department
Mondragon Unibertsitatea
Hernani, Spain
mmazuela@mondragon.edu

***Abstract*—In this paper, a comparison between single core and modular transformer solutions is made. Basic dimensional relations between volumes, areas and lengths are used to obtain mathematical expression of the power losses and temperature rise of the modular solution. Two design methodologies are tested: modular transformers with equivalent magnetizing inductance to the single core solution and minimum loss optimized modular transformer. The analytical expressions obtained are validated using a numeric transformer design algorithm. Other potential advantages attainable with the use of modular transformer configurations, such as the reduction in high frequency losses and improvement in cooling capabilities are further discussed.**

Keywords—transformer, modular converter, design, optimization

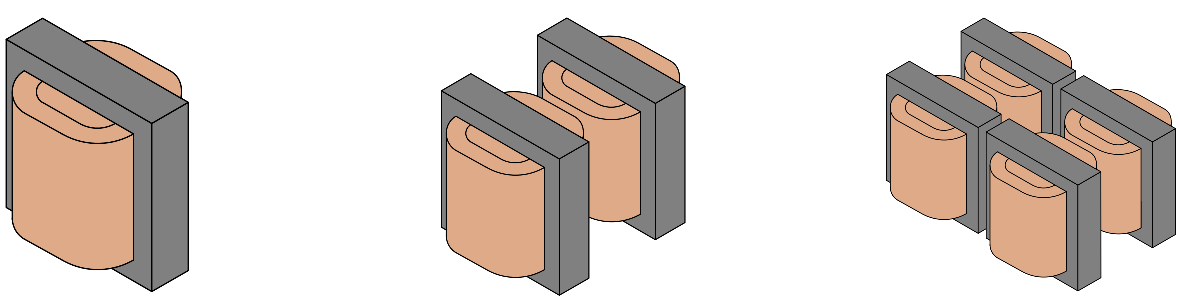
I. Introduction

With the introduction of fast switching devices to the market, such as transistors based on Wide Band Gap (WBG) materials, an improvement in the performance of power converters can be expected. By exploiting the advantages of these devices, designing converters at much higher frequencies is possible, although one should beware of the limitations imposed by the rest of the components, such as the design of high frequency passive components and the thermal limitations [1], [2].

Adding to this is the ever-growing importance of power density and/or efficiency of the converters in the modern market. Both of these can be closely related together; a more compact design generally entails a lower cooling capacity, which will result in a higher temperature rise unless the power losses are diminished [3], [4]. Examples of these requirements can be found in the electric vehicle; an owner might have an adequate charger installed at home, but due to the nowadays limited charging infrastructure, the electric vehicle will usually contain an on-board charger to use with the main utility grid in emergency situations. In such case, a high power density converter is desirable, since it reduces the volume 'wasted' by the on-board charger.

With this increasing demand of high power density converters, the adequate design of elements such as transformers becomes a critical task [5], [6]. This is due to the high volume of the passive devices, since the energy storage elements and filtering requirements can make more than half of the converter. Fortunately, more and more methodologies for optimized high power density transformer designs can be found in the literature [5]. Still, in many cases, the power density might not be the only concern; there might be some other constraints for the maximum allowable converter length, width and height. Due to the standard sizes of magnetic cores, the optimum design obtained from those methods might not always comply with those constraints, making it necessary to resort to non-standard or custom magnetic core shapes.

This can be problematic, since not only the cost of these magnetic cores might be higher than their standard counterparts, in many cases the transformer design methodologies make many



(a) (b) (c)

Fig. 1. Examples of (a) a transformer and modular transformers made from (b) two cores of half the volume and (c) four cores of a quarter of the volume. All of them have the same total magnetic core volume.

important assumptions based on the geometry of standard cores [7]. As an alternative, there is the possibility to divide the transformer into various smaller cores, thus creating a multi core modular transformer. A depiction of a conventional transformer and two and four cores modular transformers is shown in Fig. 1.

The main contribution of this paper is an analytical closed form comparison of the conventional and modular transformers, to better understand the trade-offs between them and more adequately select the best solution for each application. Note that the use of a modular transformer can have some other indirect advantages, not only the new core sizes might be cheaper and more readily available, but also the shipping and manufacturing lead times and costs might be lower.

II. Scalability of Modular Transformers

Although the principle of transforming a conventional transformer into a modular transformer seems easy at first, some differences between the modular and conventional design exist. A starting point for the design would be to divide the conventional core into various elements with the equivalent total magnetic material volume, thus creating an equivalent core volume modular transformer shown in Fig. 1.

When dividing a conventional transformer into various magnetic cores, as long as the aspect ratios of the different cores are the same, some geometrical laws are obtained. In fact, by defining the amount of modular elements as n, the volumes of the conventional transformer core (v) and each of the modular configuration transformer cores (v_n) are related by (1). Furthermore, assuming the same aspect ratios between different core sizes, since the volume, a three dimensional space, follows (1), expressions (2) and (3) define the relations of the areas (a and a_n) and the lengths (l and l_n) of the cores. These dimensional relations serve as basis to analyse and compare both configurations.

$$v_n = n^{-1} \cdot v \tag{1}$$

$$l_n = n^{-1/3} \cdot l \tag{2}$$

$$a_n = n^{-2/3} \cdot a \tag{3}$$

Then, assuming that the efficiency and power loss distribution of the conventional and modular configurations are similar (this hypothesis will be further discussed later), to retain the same total magnetic losses at the same frequency, the magnetic flux densities (B) of both cases must be equal. The voltage on the windings of a transformer is defined as (4), and relating the magnetic areas (a_m) using (3), we can obtain the relation between the number of turns of the conventional (N) and modular (N_n) designs.

$$V = N \cdot a_\mathrm{m} \cdot \frac{dB}{dt} \tag{4}$$

$$N_{n,\mathrm{s}} = n^{-1/3} \cdot N \tag{5}$$

$$N_{n,\mathrm{p}} = n^{2/3} \cdot N \tag{6}$$

Note that, depending on the type of connection used between the different elements of the modular transformer, two configurations can be distinguished: the series connected modular transformer, and the parallel connected modular transformer (Fig. 2). Considering the voltage applied to each module, the number of turns on the windings relative to the turns of the conventional transformer are then (5) and (6) for the series and parallel modular transformers respectively.

With the number of turns of the windings defined, the magnetizing inductances (L_m) of both transformers can be compared. Since the reluctance of a core relates to its magnetic length and magnetic area, using (2) and (3) to relate the reluctances ($\mathcal{R}$) of the different cores, the expression (7) is defined. Using the relation between the number of turns and the reluctance, the inductances for each element of the modular configuration are (8) and (9) for the series and parallel connected cases. As expected for an equivalent core volume and magnetic flux density design, the total magnetizing inductance of the series and parallel modular transformers is equal to the conventional design.

$$\mathcal{R}_n = n^{1/3} \cdot \mathcal{R} \tag{7}$$

$$L_{\mathrm{m},n,\mathrm{s}} = n^{-1} \cdot L_\mathrm{m} \tag{8}$$

$$L_{\mathrm{m},n,\mathrm{p}} = n \cdot L_\mathrm{m} \tag{9}$$

To estimate the core losses of the modular and conventional configurations, some other assumptions are necessary. In this case, considering that a similar winding technique and configuration is used for both designs, both configurations have the same winding area filling factor. Similarly, if half of the winding area is assigned to each winding, the total copper losses will be double the copper losses of the primary or secondary windings.

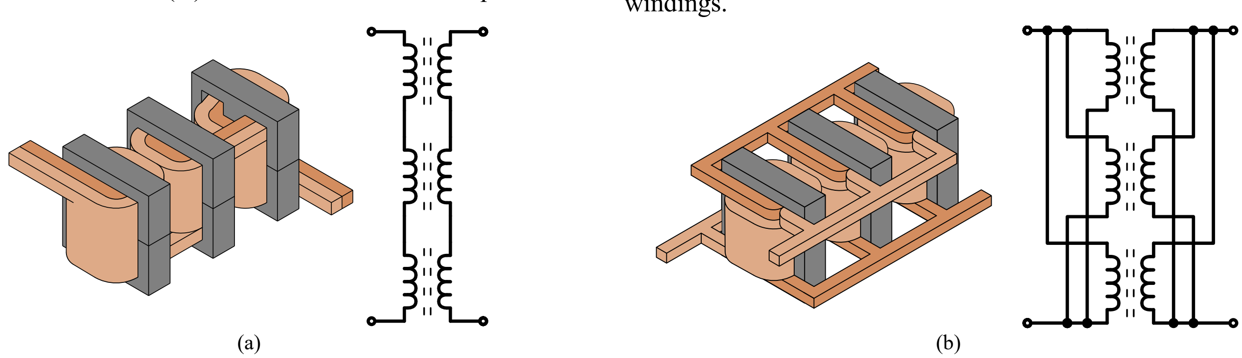


Fig. 2. Examples of (a) series connected and (b) parallel connected modular transformers (n = 3).

Using (3) once again, we can relate the effective area occupied by the conductors of each configuration, and dividing this by the number of turns obtained from (5) and (6), we achieve expressions (10) and (11) to define the copper area of each conductor (a_{c}) for the series and parallel configurations respectively. By combining the number of turns (5), (6), the copper areas (10), (11), and relating the mean lengths per turn of the conventional and modular configurations using (2), a definition to relate the winding resistances (R) of the conventional and modular configurations can be formed, and expressions (12) and (13) are obtained for the series and parallel configurations respectively.

$$a_{\mathrm{c},n,\mathrm{s}} = n^{-1/3} \cdot a_{\mathrm{c}} \tag{10}$$

$$a_{\mathrm{c},n,\mathrm{p}} = n^{-4/3} \cdot a_{\mathrm{c}} \tag{11}$$

$$R_{n,\mathrm{s}} = n^{-1/3} \cdot R_{\mathrm{c}} \tag{12}$$

$$R_{n,\mathrm{p}} = n^{5/3} \cdot R_{\mathrm{c}} \tag{13}$$

Although the resistances for the series and parallel cases are different, due to the current distribution of each configurations, the copper losses on each module are the same for both cases, and using Joule's law, they can be related to the conventional configuration by (14). It is important to note that in this analysis the high frequency losses are neglected. By adding together the losses of all the modules, (15) represents the relation between the total copper losses of the modular and conventional configurations, concluding that the modular configuration is worse than the conventional transformer. In fact, one can estimate the increment of the total power losses considering that for the optimal number of turns (assuming the conventional transformer design fulfils this condition), the optimal core losses (P_{m}) to copper losses (P_{c}) distribution is (16) [5], where β is the Steinmetz coefficient for the flux density, obtaining the expression (17).

$$P_{\mathrm{c},n} = n^{-1/3} \cdot P_{\mathrm{c}} \tag{14}$$

$$\sum P_{\mathrm{c},n} = n \cdot P_{\mathrm{c},n} = n^{2/3} \cdot P_{\mathrm{c}} \tag{15}$$

$$\frac{P_{\mathrm{m}}}{P_{\mathrm{c}}} = \frac{2}{\beta} \tag{16}$$

$$\sum P_{\mathrm{loss},n} = \frac{2+\beta \cdot n^{2/3}}{2+\beta} \cdot P_{\mathrm{loss}} \tag{17}$$

It is clear that for an equivalent magnetic flux density design, the modular transformer is less efficient than the conventional transformer, for a two module transformer the power losses increase by +31.45%, while for a 5 module transformer the power losses are +102.95% (using ferrite N87, β = 2.3). In certain cases, the increase in power losses might be admissible, since the transformer power losses might only represent a small fraction of the total converter power losses.

Still, for high power density applications, the conventional transformer might be working close to its thermal limits, and the increased power losses of the modular transformer might push the temperature above the design limitation. To evaluate the impact of the increased power losses in the temperature, the 'level 1' empirical thermal equation (18) from [8] is used, being A the surface area of the transformer. Considering the relations defined in (3) and (17), the temperature increase of a modular transformer is then (19). For a two module transformer, the temperature increases by +3.92%, while for a five module transformer the temperature increases by +16.86%.

$$P_{\mathrm{loss}} = (\Delta T)^{1.1} A \tag{18}$$

$$\Delta T_n = \sqrt[1.1]{\frac{2 \cdot n^{-1/3} + \beta \cdot n^{1/3}}{2+\beta}} \cdot \Delta T \tag{19}$$

Equations (17) and (19) present a compact way to evaluate the trade-off of employing a modular configuration instead of a conventional one. Although not as efficient as the conventional configuration, the modular transformer might prove useful in certain applications. For example, considering the core geometry from Fig. 3, the conventional transformer from Table I requires a core with a height of 80 mm, which will not easily fit in a 2U rack, while the lower height of the modular configurations could easily fit at the expense of a slight increment in power losses and surface temperature.

Returning to the hypothesis made at the beginning of this analysis, assuming that the efficiency and power loss

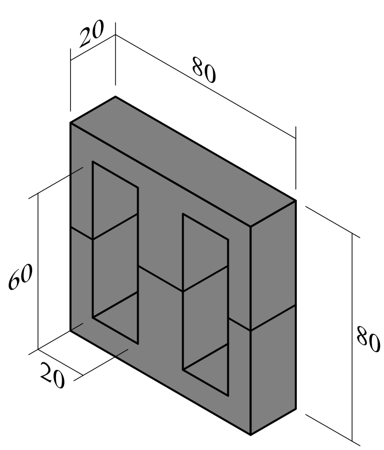


Fig. 3. EE core aspect ratios.

Table I: Comparison of conventional and modular transformers.

Parameter	Conventional $n = 1$	Modular $n = 2$	Modular $n = 3$
P (kW)	6.3	6.3	6.3
f (kHz)	100	100	100
P_{loss} (W)	8.1	10.6	12.8
ΔT (ºC)	30	31.18	32.6
Height (mm)	80	63.5	55.5

distribution of the conventional and modular solution were similar, it is clear that (17) disproves this statement, and a more optimal design is achievable if the condition (16) is ensured. To do so, the power losses can be defined as a function of the number of turns of the transformer windings (20). For the series and parallel modular transformer, this becomes (21) and (22). By equalling the derivative of these expressions to zero, the optimal number of turns (N_{opt}) for each case can be obtained, and expressions (23) and (24) relate the number of turns of the modular and conventional configurations.

$$P_{\text{loss}} = k_1 N^2 I^2 + k_2 N^{-\beta} V^{\beta} \tag{20}$$

$$P_{\text{loss},n,\text{s}} = n^{1/3} k_1 N^2 I^2 + n^{(-\beta-3)/3} k_2 N^{-\beta} V^{\beta} \tag{21}$$

$$P_{\text{loss},n,\text{p}} = n^{-5/3} k_1 N^2 I^2 + n^{(2\beta-3)/3} k_2 N^{-\beta} V^{\beta} \tag{22}$$

$$\frac{dP_{\text{loss},n,\text{s}}}{dN} = 0,\ N_{\text{opt},n,\text{s}} = n^{-\frac{1}{3}\frac{\beta+4}{\beta+2}} \cdot N_{\text{opt}} \tag{23}$$

$$\frac{dP_{\text{loss},n,\text{p}}}{dN} = 0,\ N_{\text{opt},n,\text{p}} = n^{\frac{2}{3}\frac{\beta+1}{\beta+2}} \cdot N_{\text{opt}} \tag{24}$$

From (23) and (24), the rest of relations between the optimal conventional and modular transformers are obtainable. The total magnetizing inductance of the modular transformer is then (25), which decreases as the number of elements of the modular transformer increase. Similarly, the total power losses of the modular transformer are (26), which for two and five module transformers equals to an increase in power losses of +28.6% and +77.57% respectively (97.4% and 87.5% of the equivalent magnetizing flux design). By using (18), the expression for the temperature increase becomes (27), which is +1.49% and +3.49% for a two element and a five element modular transformer.

$$n \cdot L_{\text{m},n,\text{s}} = L_{\text{m},n,\text{p}}/n = n^{\frac{-4}{3\beta+6}} \cdot L_{\text{m}} \tag{25}$$

$$\sum P_{\text{loss},n} = n^{\frac{2\beta}{3\beta+6}} \cdot P_{\text{loss}} \tag{26}$$

$$\Delta T_n = n^{\frac{1}{3.3}\frac{\beta-2}{\beta+2}} \cdot \Delta T \tag{27}$$

III. Numerical Validation

To verify these mathematical expressions, a numerical approach is used. For a base geometry (fixed core volume) and frequency, the program will sweep the winding turns number, obtaining many different transformer designs. The same process is repeated for the modular transformers, but this time the amount of modules is also swept (and the core volume adjusted accordingly). The best single core transformer solution is selected and used as reference. Then, for each amount of modules, the modular configurations with the same magnetic flux density (equivalent magnetizing inductance) and the minimum losses are selected, and compared against the single core solution.

The series and parallel connected modular transformers are tested separately. Note that the same assumptions used for the mathematical analysis also apply to the numerical method: the high frequency copper losses are neglected, similar winding configurations are used for all cases, to estimate the core losses the general Steinmetz equation is used, and (18) is used to calculate the transformer temperature rise.

The comparison between the numerical and analytical methods is shown in Fig. 4. For the base transformer (n = 1), different combinations of core sizes, frequencies, input and output voltages and temperature rises are tested, and the same results are obtained in all cases.

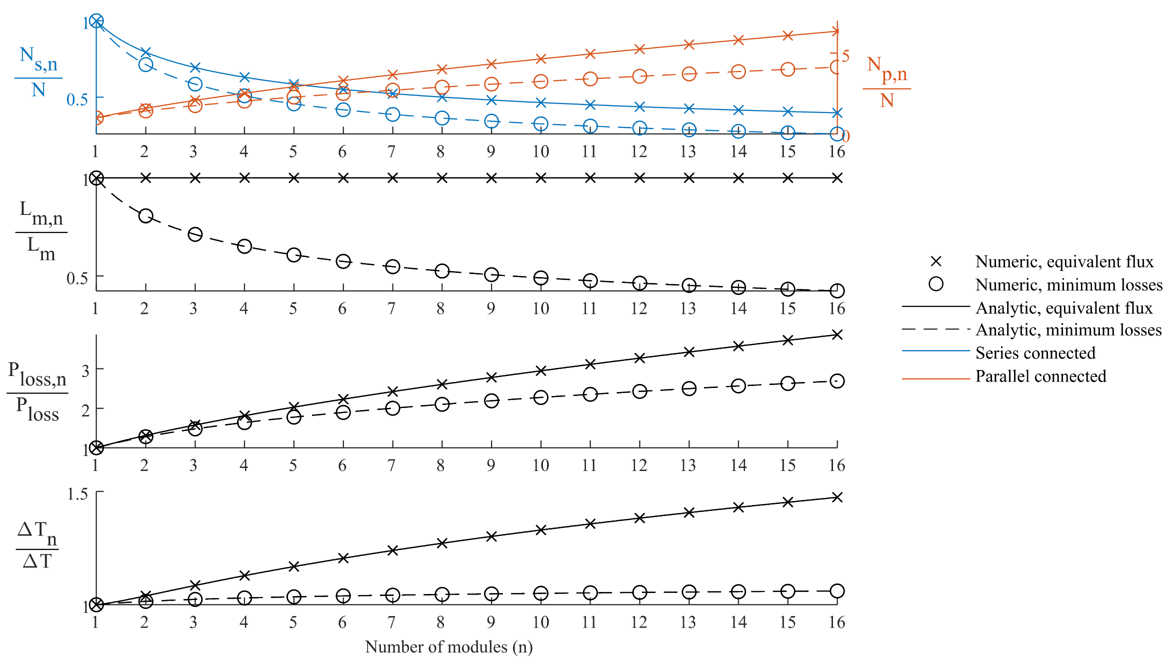
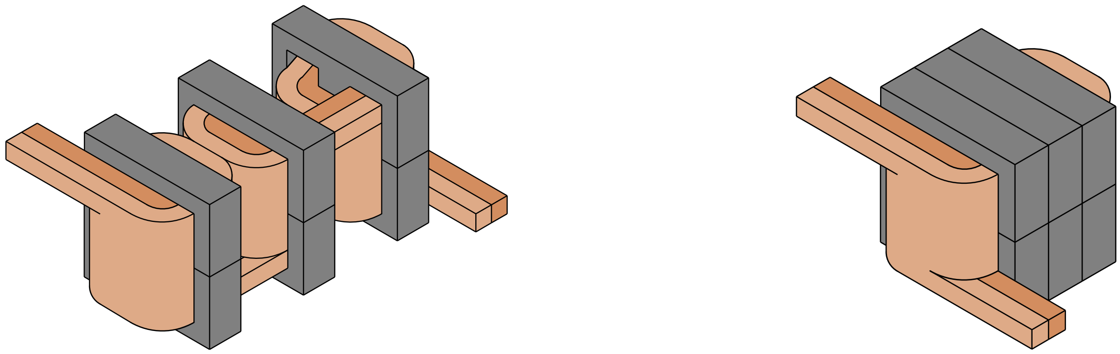


Fig. 4. Comparison between numeric and analytic results for the number of turns, equivalent total magnetizing inductance, total power losses, and temperature rise of the conventional and modular transformers.



(a) (b)

Fig. 5. Representation of (a) series connected modular transformer and (b) equivalent stacked core transformer (n = 3).

IV. Discussion

According to the results of this investigation, it appears that smaller cores are limited to lower power densities than bigger cores for the same temperature rise. On the contrary, many authors have demonstrated that a smaller core can achieve higher power densities at the same temperature. For example, the analysis made in [9] shows that for a constant power density, decreasing the power of the transformer (and the volume of the core accordingly) results in a decrease in temperature rise (albeit with a lower efficiency). One should note that this is only true if the frequency of the transformer is adapted accordingly; as the volume of the core is decreased, the frequency must be increased to reduce the core losses.

Although in this analysis the effect of the high frequency copper losses has been neglected, there is reason to believe that the modular transformer should be less prone to high frequency copper losses. In fact, using the asymptotic approximation of the high frequency copper losses (28) from [10], being the width of the core window (w_{w}) thinner for a smaller core, using the same strand diameter (d_{r}) in both designs the impact of the frequency is lessened. Note that the high frequency effects in the windings are a complex phenomenon, and depend heavily in the winding structure, thus, this statement only applies to conventional and modular designs with the same winding structure.

$$\frac{R_{\mathrm{ac}}}{R_{\mathrm{dc}}} \approx \begin{cases} 1+\frac{1}{9}\left(\pi f \sigma \mu k_{\mathrm{cu}} w_{\mathrm{w}} t_{\mathrm{f}}\right)^2 \\ 1+\frac{1}{12}\left(\pi f \sigma \mu k_{\mathrm{cu}} w_{\mathrm{w}} d_{\mathrm{r}}\right)^2 \end{cases} \tag{28}$$

It is possible to stack the cores of the modular design together to reduce the total length of the windings and achieve a higher efficiency (Fig. 5), although with a significant impact in the temperature rise due to the reduction in cooling area. For example, using the numeric method, the total losses of an optimally designed stacked cores for n = 2 and n = 5 are 77.75% and 61.24% of their modular counterparts, although their temperature rise is +15.02% and +28.03 higher. Both configurations can be mixed together, making a modular transformer composed of modules made with stacked cores, achieving a solution with smaller power losses than a purely modular solution but with a lesser temperature rise than a stacked core transformer.

Lastly, although in the analysis series connected and parallel connected modular transformers are treated individually, both configurations can be used simultaneously by connecting a winding in series and the other in parallel (Fig. 6). This kind of connection is known as matrix transformer, and was explored more deeply in [11]. One advantage of this configuration is that it allows to design high voltage gain transformers using lower voltage gain modules. For example, an 8:1 transformer can be made from four 2:1 smaller transformers, connecting all the primary windings in series and the secondary windings in parallel. This technique is used in [12] for the design of a high power density 1 kW 390/12 V converter.

It is evident that this analysis should be expanded to consider more factors, which can positively or negatively affect the modular configuration. For example, the impact of the modular configuration on the parasitic inductances and capacitances has not been explored. Also, the improved cooling capabilities of planar transformers combined with the modular configuration

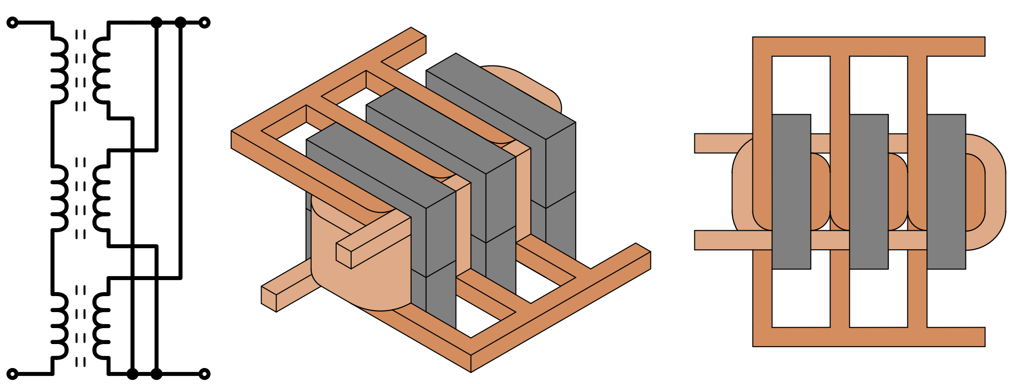


Fig. 6. Example of a matrix transformer with the primary windings (light brown colour) in series and the secondary windings (dark brown colour) in parallel.

could potentially achieve much higher cooling performances than conventional configurations. It is imperative to analyse these topics before reliable assessing which configuration is superior for a given application.

V. Conclusions

This paper analyses the effect of transforming a single core conventional transformer into a multiple core modular transformer. Both series and parallel connected modular transformers are analysed, and it is proved that the choice of connection does not affect the behaviour of the complete transformer. Two possible designs are tested, one with an equivalent magnetic flux density, and thus equivalent magnetizing inductances, and another where the number of turns is adjusted to minimize the power losses.

In the case of the equivalent inductance design, it is shown that the number of modules has a huge impact in the total losses (+102.95% with 5 modules), while the impact in the temperature rise is notably lower (+16.86%). By adjusting the number of turns, a better balancing between the core and copper losses is achievable, obtaining a better efficiency than the equivalent inductance design (+77.57% with 5 modules) and a much lower increase in temperature (+3.49%). The high frequency copper losses are not taken into account during the analysis, but there is reason to believe that their impact on modular transformers is lower than for a single core transformer.

When compared to stacked core transformers, it is shown that even with the increased length of the windings, due to the much higher cooling area, the modular transformer is capable of maintaining its temperature close to the single core design, while the stacked core solutions trades a better efficiency for a higher temperature rise.

Future work will be focused on the comparative analysis of high frequency effects in single core and modular transformers, the analysis of thermal dissipation in modular transformers and the validation of the different parameter sensitivities via experimental results.

Acknowledgment

The work of Asier Arruti is funded in part by the Non Doctoral Research Staff Training Program of the Department of Education of the Basque Government.

References

[1] J. W. Kolar, D. Bortis, and D. Neumayr, "The ideal switch is not enough," 2016.

[2] J. W. Kolar *et al.*, "PWM Converter Power Density Barriers," 2007.

[3] W.-J. Gu and R. Liu, "A Study of Volume and Weight vs. Frequency for High-Frequency Transformers," 1993.

[4] J. Biela and J. W. Kolar, "Cooling Concepts for High Power Density Magnetic Devices," 2007.

[5] W. G. Hurley, W. H. Wölfle, and J. G. Breslin, "Optimized Transformer Design: Inclusive of High-Frequency Effects," *IEEE Transactions on Power Electronics*, vol. 13, no. 4, pp. 651–659, 1998.

[6] M. Mogorovic and D. Dujic, "Sensitivity Analysis of Medium Frequency Transformer Designs for Solid State Transformers," *IEEE Transactions on Power Electronics*, vol. 34, no. 9, 2019.

[7] X. Yu, J. Su, J. Lai, and S. Guo, "Analytical Optimization of Nonsaturated Thermally Limited High-Frequency Transformer/Inductor Design Considering Discreteness of Design Variables," *IEEE Transactions on Power Electronics*, vol. 35, no. 6, pp. 6231–6250, 2020.

[8] V. C. Valchev and A. Van den Bossche, *Inductors and Transformers for Power Electronics*. Ablington: Taylor & Francis, 2005.

[9] T. Guillod and J. W. Kolar, "Medium-Frequency Transformer Scaling Laws: Derivation, Verification, and Critical Analysis," *CPSS Transactions on Power Electronics and Applications*, vol. 5, no. 1, pp. 18–33, 2020.

[10] M. Leibl, G. Ortiz, and J. W. Kolar, "Design and Experimental Analysis of a Medium-Frequency Transformer for Solid-State Transformer Applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 1, pp. 110–123, 2017.

[11] E. Herbert, "Design and Application of Matrix Transformers and Symmetrical Converters," *seminar presented at the Fifth International High Frequency Power Conversion Converence '90*, 1990.

[12] D. Huang, S. Ji, and F. C. Lee, "LLC Resonant Converter With Matrix Transformer," *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4339–4347, 2014.