Optimizing Three-Phase Planar Transformer Construction

Production costs are reduced as well as transformer efficiency is increased

A three-phase transformer with flat conductor layers is proposed in this article. This arrangement is used for high current density transformers. Cost effectiveness in planar magnetic are related with the optimization in the number of layers in each winding. This fact takes more relevance for the medium and high power three-phase transformers where the number of parallels to achieve the required DCR is increased. The proposed method allows the use of off-the-shell core shapes that are used for single phase transformers. Cost impact is significant and design implications become more flexible. The proposed solution has been validated and compared using the conventional and the proposed methodologies to design a high power (20 kW) transformer.

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Planar transformers for three-phase applications are mainly used to handle medium to high current levels. If current value is high then a number of parallel windings must be added to reduce resistance, consequently losses and temperature rise in windings are minimized. Planar transformers have been conceived as a ordered stacking of copper frames. Sometimes these frames are embedded in a fiber glass laminate that provides mechanical stability and allows through the printed circuit technology to connect them. Sometimes these frames are separated by a polyimide layer and connection is done by adding a solder alloy material. Manufacturing process might become not feasible due the board size and conductor copper thickness. Not feasible in terms of prices or due to metallurgical issues that avoid a reliable joint in the connections. This feasibility is conditioned to the number of conductor layers. The problem to be solved is related to the manufacturing process of three-phase planar transformers. In particular, it is oriented to reduce the number of conductor layers in this kind of transformers. Additionally proposed alternative improve the electrical performance of the final component. This work presents an alternative method to design the three-phase planar transformer with the same electrical features than the conventional ones but reducing the number of conductor layers for each block.

Figure 0: Planar Transformer

Method is explained in two sections described as follows:

- Section II includes the description of a conventional winding layout. A particular transformer is designed in order to be used as reference for comparison.
- Section III describes the proposed alternative. The transformer included in Section II is modified in order to obtain a design with lower number of conductor layers for each block.

Conventional Winding Setup

A conventional approach to build a three-phase transformer is based on the placement of each of the single-phase windings at each core leg. The same idea can be followed to build a planar component. The only difference is that conductor layers are used instead of rounded wires.

A simplified representation of a conventional three-phase transformer is shown in Figure 1. Each white box (A-A', B-B', C-C') is a single-phase transformer and therefore includes a primary and a secondary winding. Using this configuration, each column of the transformer behaves as a single-phase transformer.

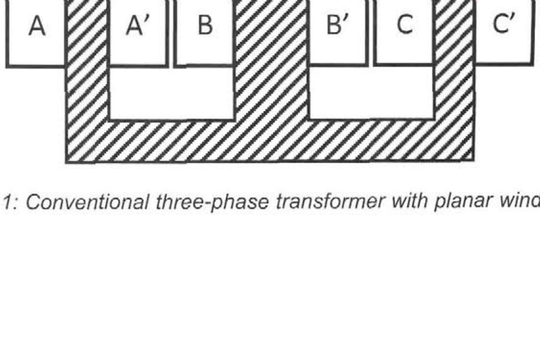

Figure 1: Conventional three-phase transformer with planar windings

The configuration shown in Figure 1 allows the use of low-profile cores. If a conventional core is used instead of a planar core due to low-profile version availability or to the required power drive then it is appreciated that transformer windings do not fill the whole window height since the high number of layers needed might make difficult, expensive, and even not feasible the fabrication of that conductor layers stacking.

Since each winding is placed at each leg of the core, one of the limitations of this configuration is that the maximum track width (see Figure 1) is approximately half the window width. As this fact fixes the maximum conductor section for each winding number of parallel windings must be increased to achieve the required resistance value.

Printed Wiring Boards (PWB) manufacturers provide technical limitations of their capabilities for manufacturing the multi-layer stacks. Additionally, PWB blocks cost increases drastically with the number of the layers and the copper thickness. It is a common practice to create stacks of multi-layer PWB blocks in order to reduce the cost and make cost-efficient and feasible the manufacturing process. But even applying this practice, there is a limit of layers that make feasible the manufacturing process for each specification.

For a 20kW, 820V/300V 40kHz transformer with planar windings a PWB structure of 96 layers was necessary to achieve the electrical constraints and considering that copper conductor thickness were 70µm. In terms of dimensions this implies that a 17mm thickness multi-layer PWB might be processed one per each single-phase.

The designed transformer was simulated using a Finite Element (FEA) tool in order to obtain the loss and the temperature values. The goal of the simulation is to have available parameters for comparison between the conventional winding setup and the proposed one in terms of electrical performance. Table 1 shows the conductor loss of the central (C) and lateral (L) windings (PC, PL) and their temperatures rise (TC, TL), obtained with FEA tool. Total losses Ptotal are calculated as 2 PL + PC.

P_C (W)	T_C (°C)	P_L (W)	T_L (°C)	P_{total} (W)
64	64	73	70	210

Table 1: Results for the conventional solution

Proposed Winding Setup

An alternative for the winding setup is shown in Figure 2, where each winding occupies the whole window width. This makes possible to increase of the track section, reducing the resistance, the power loss and the temperature using the same limitation for the maximum number of layers of each single-phase transformer.

The whole window height is filled because the central leg single-phase transformer is placed above the lateral ones. It is assumed that the maximum number of layers for each single-phase transformer is the same than in the conventional case (96 for this particular example).

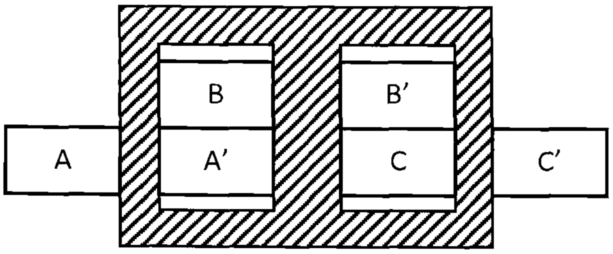

Figure 2: Proposed three-phase transformer with planar windings

The advantage of this construction is that transformers with a very large number of conductor layers, which could not be built using the conventional method, can be fabricated using this modified structure.

If electrical requirement are preserved then conductor layer section is obtained and as a result number of parallel windings might be reduced approximately two times because of the available section of the tracks in the proposed alternative is approximately twice the one of the conventional one.

Another characteristic of the proposed alternative is the possibility of using standard commercial cores that are commonly used for single-phase transformers. Since the input voltages are equal but shifted 1/3 of the period, the fluxes are also equal and shifted 1/3 of the period. As a consequence of that, the secondary voltages are equal and sifted 1/3 of the period. Since the central and lateral legs of standard EE and EI cores have different sections, flux densities differ. However, there is no need to use custom-made core shapes because the output voltages are balanced.

The high power transformer presented in Section II has also been designed using the proposed layout to illustrate the advantages of this solution. Again, it is assumed that the maximum number of layers is limited to 96 per single-phase transformer. The simulation with the FEA tool has also been performed for this configuration in order to compare the results with the conventional structure. The conductor power loss at each core leg (PC, PL, and Ptotal) and temperatures (TC, TL) obtained for this configuration are shown in Table 2.

P_C (W)	T_C (°C)	P_L (W)	T_L (°C)	P_{total} (W)
38	48	49	55	136

Table 2: Results for the proposed solution

Comparing tables 1 and 2, it can be seen that an important 35% loss reduction and associated temperature rise. This is a specific advantage of this particular case because the room availability of the conventional design.

However, the main benefit of the proposed alternative is the possibility of reducing the number of conductor layers. In other words, for same power loss model obtained in Table 1 (conventional design), the proposed alternative could be designed with approximately half of the layers for each winding.

In order to illustrate this advantage, a "non feasible" design using the conventional winding setup (presented in Section II) was calculated using a number of layers above the maximum feasible one, filling most of the window height. In particular, a design with two times the number of conductor layers per winding (192 layers) was considered. This design was calculated assuming that the non low-profile core was used and therefore there is room enough in the window to place this number of layers. Using the FEA tool, table 3 shows the results obtained in this case.

P_C (W)	T_C (°C)	P_L (W)	T_L (°C)	P_{total} (W)
33	45	43	52	119

Table 3: Results for the conventional solution with double number of layers "Non-feasible design"

It can be seen that the proposed solution presents power losses of 136W instead of 119W of this "non feasible" conventional design, but using half number of layers (96 instead of 192 layers). As mentioned before, this high number of layers makes not feasible the fabrication of the 192 layers solution because of interconnections between layers.

In an industrial perspective, PREMO, that has been developing planar transformers in two main technologies: Multilayer PWB and multi-stack of copper frames of different thickness according the constraints that frequency and proximity effects allow.

The first type is solved for the high frequency range using copper laminations from 2oz. to 6oz. and with a maximum PWB thickness of 3.7mm in order to allow automatic selective soldering in a wave solder machine process or a paste in pin technology. Depending on the copper thickness, number of layers is varying from ten to sixteen. If needed more layers a multilayer stack of two or more multilayer PWBs should be placed. This kind of stacking carries out a complex engineering process for automatic soldering that includes tin alloy selection (normally a lead free tin with some additives like Ni or Ge to allow a reliable soldering according IPC A-610 E standard) and a complex system of tooling and jigs for automatic connector insertion. An additional constraint for this part is size. A big part will need a high temperature exposure to ensure good thermal behavior during soldering and a thermal protection to the soldering heat while it is being mounted.

The second type is solved up to the limit of 125 kHz applications using copper frames from 0.25mm to 0.60mm separated by polyimide isolation frames and connected among them through a manual selective soldering process. There is a wide range of options that Premo has been using: selective soldering that uses a robot arm that dispenses the tin wire while pressing the copper stacking, ultrasonic soldering process that do a direct joint between two copper frames, step by step or induction soldering that heats tin balls in the joint to the melting temperature allowing a simultaneous soldering. Limit for this kind of structure is the number of turns per layer because it is a challenge to preserve the distance between tracks if they are reduced so much even that technique has been refined like a register process in PWB manufacturing.

Conclusions

This work presents an alternative to reduce the number of layers for each winding in planar three-phase transformers. An industrial partner that manufactures planar transformers has participated in the validation of this work, experiencing the benefits that the proposed solution provides. In particular, the cost reduction, simplicity of fabrication or even the possibility of manufacturing designs identifying those non feasible with conventional setups.

Comparing to conventional designs, the number of layers for each single-phase transformer can be divided by two, obtaining approximately the same conductor loss.

In addition, commercial single-phase EE or EI cores can be used in the designs, avoiding the need of a custom-made magnetic core.

As a future study it is required to analyze the impact of an interleaving phase windings to reduce leakage effect. Planar windings allow this arrangement.

At the end of the day, if production costs of three-phase transformers are reduced as well as transformer efficiency is also increased then it is possible to go through lower profile parts for higher powers.

References

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