An Alternative for Reducing the Layers in the Construction of Three-Phase Planar Transformers

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Abstract—A modified winding layout for three-phase transformers with PCB windings is proposed in this paper. This modified layout can be used in high current transformers with many PCB layers to simplify the fabrication process. One of the key factors that might increase the cost and complexity in the construction of planar transformers is the number of layers of each PCB winding. This issue becomes even more important in medium-high power three-phase transformers, where the number of PCB layers is higher. In addition to that, the proposed method allows the use of commercial core shapes that are commonly used to design single-phase transformers. This fact makes possible the reduction of cost and flexibility of the design solutions.

The proposed solution has been validated and compared using the conventional and the proposed methodologies to design a high power (20 kW) transformer.

I. INTRODUCTION

Many high-power dc-dc converters have three-phase topologies with three-phase transformers. To implement the three-phase transformation, designers can choose between two possible alternatives:

- Three individual single-phase transformers.

- A single three-phase transformer with a three column core.

The first alternative provides an easy solution with an almost perfect balance between phases. The second alternative can present some unbalance in open- and short-circuit impedances, but the transformer volume is lower.

An implementation of the first alternative is presented in [1], where a dc-dc converter with active clamp with a three-phase topology is analyzed and built.

The second alternative is used in [2]. The authors customize a commercial EI-118 core to make the central leg of the same width as the outer legs, but differences among the open- and short-circuit inductances of the three columns are noticeable in the paper results. The present work presents an alternative solution where core is not customized and planar windings are used to reduce the transformer parasitics. If the system unbalance caused by the different column parasitics is acceptable, the proposed design is acceptable.

The first alternative was used in [3-4] for a three-phase photo-voltaic power system. Planar transformers, as in the present work, were used to implement the single-phase transformers.

Finally, an application example that includes a three-phase transformer is presented in [5]. The designs presented in this work were made thinking in this power converter.

The topic of this work is related to the design and manufacturing of planar transformers for three-phase applications. These applications commonly handle medium or high current levels. If the value of the current is high, it is necessary to add parallel windings in order to reduce the resistance and consequently losses and temperature at the windings. Since planar transformers are commonly made with Printed Circuit Boards (PCBs), the addition of several parallel windings yields to a high number of PCB layers.

Sometimes, the fabrication process might become very expensive or even not feasible because of the very high number of PCB layers required. The problem to be solved in this work is related to the fabrication process of three-phase planar transformers. In particular, it is oriented to reduce the number of PCB layers in this kind of transformers. Although the proposed alternative might also improve the electrical performance, the main problem to be solved is the reduction of cost and/or feasibility of the manufacturing process.

This work presents an alternative to design the three-phase planar transformer with the same electrical performance than the conventional ones but reducing the number of PCB layers for each block.

The way that has been followed to explain the method is 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 layers for each PCB block.

II. CONVENTIONAL WINDING SETUP

The conventional approach to build a three-phase transformer is based on the placement of each of the single-phase transformers at each core leg. The same approach can be followed to build a planar component. The only difference is that PCB layers should be used instead of round 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.
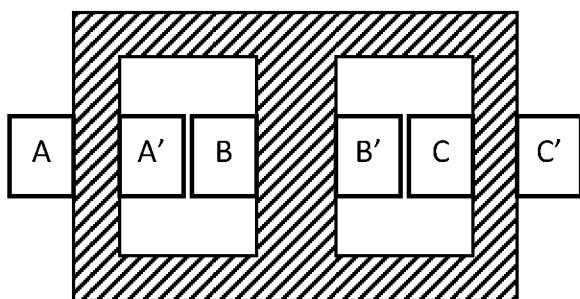

Figure 1: Conventional three-phase transformer with planar windings.

The configuration shown in Figure 1 makes possible the use of low-profile cores. However, if a conventional core is used because a low-profile version is not available for the common power levels of three-phase applications, it might be very likely that the windings of the transformer do not fill the whole window height because the high number of layers needed to fill the window might make difficult, expensive, and even not feasible the fabrication of that PCB stack.

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. This fixes the maximum conductor section for each winding. This limitation might be overcome adding more windings in parallel, but this solution increments the number of PCB layers.

The PCB manufacturers provide technical limitations of their capabilities for manufacturing the multi-layer PCB stacks. In addition to that, the cost of the PCB blocks increases drastically with the number of the layers for each multi-layer block. It is a common practice to create stacks of multi-layer PCB 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.

In order to illustrate this problem, a real example will be presented. A commercial PCB manufacturing company was contacted to design a specific transformer. According to that particular manufacturer, the maximum number of layers for each winding that made feasible the fabrication of a given design was 96. Therefore, that planar design was limited to a maximum of 96 layers. A 20 kW, 540 V/270 V transformer was designed using the conventional windings layout with 96 layers per winding. The details of the number of layers and geometrical parameters of the core and the PCB tracks will not be included in order to simplify the explanation and the benefits of the proposed solution.

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 (P_C, P_L) and their temperatures (T_C, T_L), obtained with FEA tool. Total losses P_{total} are calculated as $2\,P_L + P_C$.

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.

III. PROPOSED WINDING SETUP

The proposed 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).
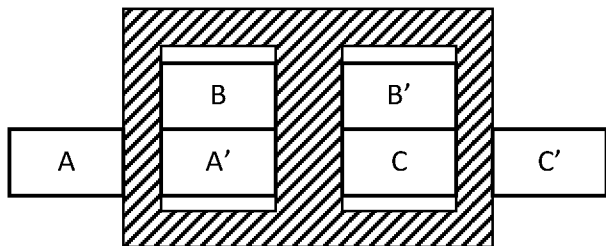

Figure 2: Proposed three-phase transformer with planar windings.

The advantage of this construction is that transformers with a very large number of layers, which could not be built using the conventional method, can be fabricated using this modified structure. This is a very interesting property that can avoid the limitations of the fabrication process using the conventional windings layout of the previous section.

Assuming that the maximum temperature and minimum efficiency are given specifications of a particular design, the maximum resistance of the windings can be calculated. Once the resistance is obtained, the minimum section for the conductor tracks can also be obtained. Finally, using the resistance and the number of turns, the number of parallel windings needed to obtain that resistance is also easy to be calculated. This number of parallel windings might be very high for many practical cases. The main difference between the proposed alternative and the conventional one is that the 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.

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 (P_C, P_L, and P_{total}) and temperatures (T_C, T_L) obtained for this configuration are shown in Table 2.

P_C (W)	T_C (ºC)	P_L (W)	T_L (ºC)	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 reduction of the loss (136W instead of 210W) and the temperatures is obtained. 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 layers. In other words, for the same power loss 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 "not 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 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 (ºC)	P_L (W)	T_L (ºC)	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 magnetics in two main technologies: Multilayer PCBs or, as currently used, PWBs (printed winding boards) 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 soldering in a wave solder machine process. 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.

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 selected 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 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 the tin 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 it is not.

IV. 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 that were not 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.

Therefore, the production costs of the transformers are reduced using the proposed alternative.

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