Modeling of Transformer Core Joints via a Subproblem FEM and a Homogenization Technique

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***Abstract*—A subproblem finite element method is developed for modeling the transformer core joints. It applies magnetostatic and magnetodynamic models on progressive geometries and different components of the solution, supported by different meshes. It allows an efficient and robust analysis of magnetic circuits in any frequency range, with an accurate calculation of flux density, losses, reluctance and impedance in transformer core joint zone. The models of the study properly account for the effects of core design parameters such as length of air gaps and overlap length stacked-lamination cores. The proposed models, which include saturation, are applied to grain-oriented silicon steel and two types of step-lap joints are considered: single-step-lap joints and multi-step-lap joints.**

***Index Terms*—Transformer core joints, magnetic reluctance, impedance, subproblem finite element method, homogenization technique.**

I. INTRODUCTION

Joints play an important role in the performance of transformers cores. Step-lap transformer lamination core design leads to low no-load losses and a low noise level. The lateral step-lap enables a favorable assembly for the upper yoke. Fig. 1 shows the stacking of transformer core plates in step-lap. The details of the step-lap joints are presented in Fig. 2. Fig. 3 shows the localization of step-lap joints in a transformer core.


Fig. 1. Stacking of transformer core plates in step-lap.

Computing the magnetic field distribution inside the core, and particularly at the joints, is essential to estimate the core losses. Several papers have analyzed the magnetic field distribution in the joint zone [1 - 5]. The joint zone contains the air gaps and overlaps that cause the jump of magnetic field lines to adjacent laminations. This deviation of the magnetic field lines with respect to the rolling direction creates localized regions of higher magnetic flux density and therefore increased losses [1].

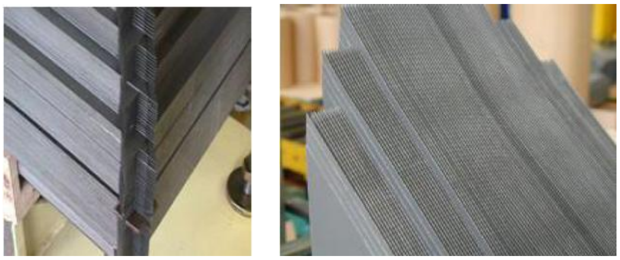
Fig. 2. Details of the step-lap joints.

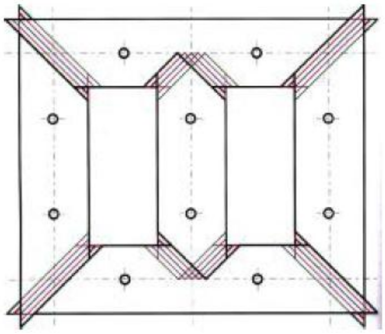
Fig. 3. Localization of step-lap joints in a transformer core.

Two types of step-lap joints are considered: single-step-lap joints (SSL) and multi-step-lap joints (MSL) as shown in Fig. 4. The performance of transformer cores is directly related to the joints.

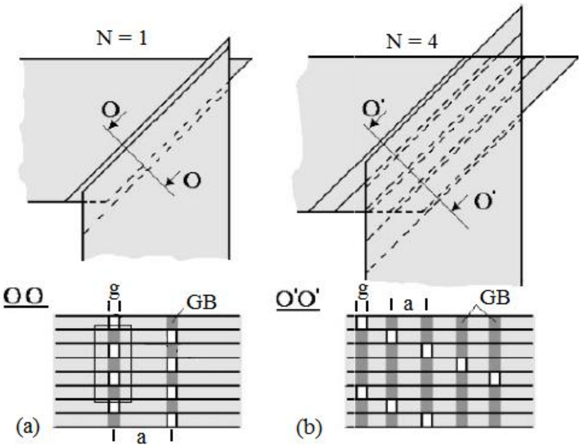

Fig. 4. Arrangement of laminations for two different joint designs: (a) SSL joint (N = 1) and (b) MSL joint (N = 4) [2].

There are many factors that affect their flux distribution such as: inevitable air gaps of length g, number of overlap steps N, etc (Fig. 4). The parameter g increases the magnetic reluctance of the joint. To avoid the high reluctance path of the gap, the flux escapes to the neighboring laminations which act as “gap bridge” (GB; Fig. 4) and become strongly overloaded. Critical induction B_c marks the induction for which GBs (which bridge air gap regions) reach saturation. For $B > B_c$ flux lines arise also in the gap, as indicated by dotted lines in Fig. 1. B_c increases with increasing N (e.g., $B_c \approx 1$ T for N = 1 and 1.7 T for N = 6) [2].

In this paper, the full problem is tackled iteratively starting from a reference problem with a finite element solution. The implementation is carried by implementing the following steps:

Step 1 (magnetostatic) - 2D plane model: a first 2D calculation allows to determine the field distribution in the transformer core (field in the plane of a sheet, the joins are not considered) with the whole environment taken into account (inductors and air).

Step 2 (magnetostatic) - laminated core: we consider that the field (step 1) is repeated in each sheet to take the stacking into account. (2a) Firstly, we neglect the thickness of the insulation between the core sheets, and (2b) next, we consider the insulation).

Step 3 (magnetodynamic) - eddy current: the currents induced in each sheet are determined either by calculation from sheet 3D or by a model of homogenization technique.

Step 4 (magnetodynamic) - correction due to 3D joints: for each joint configuration, a 3D local sub-problem for a joint subset is defined (we try to minimize the sub-problem exploring symmetries and periodicities) and solved. Thereby, we obtain the corrections of the flux density and the induced currents and thus the correction of reluctance (or impedance) for the core parts studied.

Step 5 - correction due non-linearity: the non-linearity is an additional step of correction that can be introduced at any time (either already in step 1, or in step 2, or in step 3 or like a correction of the step 4).

The main contribution of this paper is that the tools here developed allow to couple in a 2D classical model the 3D sub-problems taking into account accurately the effect of transformer core joints.

II. APPLICATION

The first examples considered for validation of the proposed approach are shown in Fig. 4(a) and Fig. 4(b). The problem is separated in three SPs: reference (section O′O′ using homogenization technique); SP 01 (section O′O′ using laminated iron core); and SP 02 (section O′O′ using laminated iron core and the MSL or section O′O′ using laminated iron core and the SSL).

The geometries of the arrangement of laminations for two different joint designs: (a) SSL joint and (b) MSL joint are presented in Fig. 5. Fig. 6 shows the field lines of the 3 SPs: (a) reference, (b) SP 01, (c) SP 02 with SSL joint and (d) SP 02 with MSL joint. The normalized magnetic flux densities on line AA´ (see Fig. 5(b)) for the MSL joint: reference, perturbation and corrected solutions are showed in Fig. 7 as an example of preliminary results. The base value is the maximum value of the corrected solution. The reference solution considers the core as a non-conducting region (magnetostatic formulation) and the perturbation solution takes into account the core as a conducting region (magnetodynamic formulation).

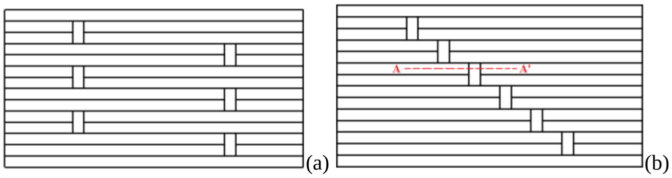

Fig. 5. Geometry of the (a) SSL joint and (b) MSL joint.

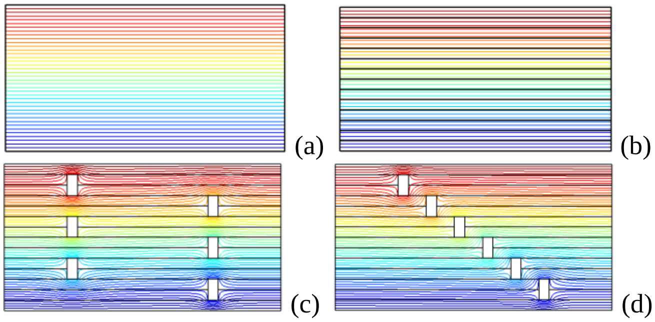

Fig. 6. Field lines of the 3 SPs: (a) reference, (b) SP 01, (c) SP 02 with SSL joint and (d) SP 02 with MSL joint.

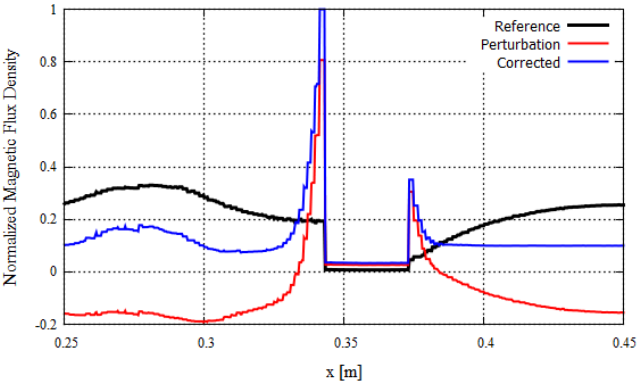

Fig. 7. Normalized magnetic flux densities on line AA´ (see Fig. 5(b)) for MSL joint.

The results of flux density, losses, reluctance and impedance considering the steps 1 until 5 to the arrangement of lamination for two different joint designs (SSL and MSL) will be detailed and presented in the extended paper.

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