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Geometry Optimization of Electric Shielding in Power Transformers Based on Finite Element Method

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Abstract. In this article, a finite element model, suitable for power transformer representation, is used for the evaluation of transformer characteristics and their modification due to the introduction of electric and magnetic shielding, focusing on the short-circuit impedance calculation. The use of deterministic optimization methods, in conjunction with the finite element model enables the optimization of the transformer shielding geometrical configuration, with respect to its cost and efficiency.

1. Introduction

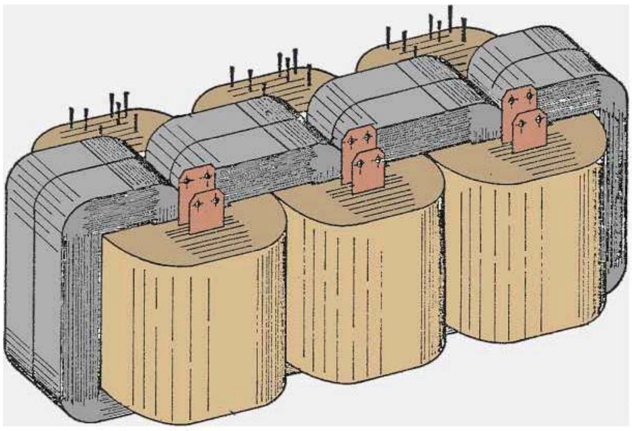
Transformer manufacturers are obliged to comply with the short-circuit impedance values specified by transformer users. In cases where the difference between the actual (measured) and specified values does not satisfy the limitations imposed by international standards, [1], design modifications should be implemented in order to meet the specifications. Reduction of the short-circuit impedance value can be achieved through electric shielding, which attenuates the stray flux from the transformer windings, resulting to decrease of the total leakage inductance. On the other hand, magnetic shielding increases the magnetic stray field and the winding leakage inductance. The finite element method is a reliable tool for the prediction of the leakage field variations due to the introduction of shielding and it can be used in conjunction with optimization methods for the design optimization of power transformer electric shielding, taking into account the shielding power loss minimization and the cost reduction through shielding material minimization.

2. Transformer modeling with 2D finite element method

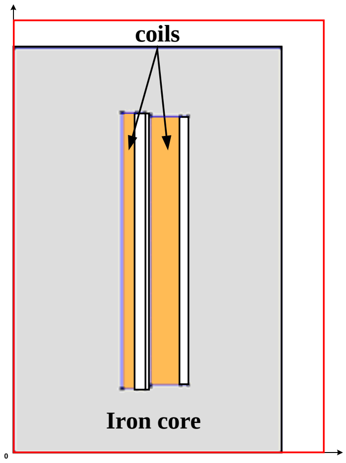
The considered transformer is a three-phase, wound core, distribution transformer (Fig. 1(a)). Its magnetic circuit is of shell type and is assembled from two small and two large wound iron cores. The Low Voltage (LV) winding (secondary winding) comprises layers of copper sheet, while the High Voltage (HV) winding (primary winding) consists of copper wire. Figure 1(b) shows the 2D FEM model of the transformer one phase part, based on cylindrical symmetry. In order to take into account the contribution of the winding parts outside the core window to the transformer leakage field, appropriate modifications of the winding height are implemented, based on the Rogowski coefficients (modified transformer geometry).

3. Geometry optimization of electric shielding

The 2D finite element model presented above has been used for the evaluation of the transformer short-circuit impedance (U_k) after the introduction of magnetic and electric shielding. Particularly, the short-circuit impedance has been calculated before and after the placement of electric shielding above the windings and magnetic shielding along the transformer tank walls. Comparison between the variations of the magnetic leakage field and the winding leakage inductance for each kind of shielding results to the conclusion that the electric shielding is the most efficient one, in terms of U_k variation, for the considered transformer. The optimization of the electric shielding dimensions is realized with the use of the 2D FEM model, in conjunction with deterministic optimization methods.



(a)



(b)

Fig. 1 (a) Real geometry of a three-phase, wound core, distribution transformer,
(b) 2D FEM model of transformer one phase part (modified geometry).

The general mathematic form of the electric shielding geometry optimization consists in the minimization of an objective function which must take into account three factors: desired increase in short-circuit impedance, restrain of the increase in the shielding power loss and minimization of the shielding material. The analytical expression of the objective function is given by (1):

$$F = w_1 \frac{|\Delta U_k^{spec} - \Delta U_k^{calc}|}{\Delta U_k^{spec}} + w_2 \left| \frac{P_{shunt}^{calc}}{P_{shunt}^{min}} \right| + w_3 \frac{S_{shunt}^{calc}}{S_{shunt}^{max}} \quad (1)$$

where, ΔU_k^{calc} is the calculated variation in the short-circuit impedance, ΔU_k^{spec} is the specified (desired) variation in the short-circuit impedance, P_{shunt}^{calc} is the calculated shielding power loss, P_{shunt}^{min} is the minimum permissible value of the shielding power loss, S_{shunt}^{calc} is the shielding surface used during the current iteration, $S_{shunt}^{calc} = x \cdot H$, where x the width and H the height of the electric shielding and S_{shunt}^{max} is the maximum shielding surface. The selection of the multiobjective function weights, w_1, w_2, w_3, aimed to a maximum accuracy in the variation of the short-circuit impedance, considering the minimization of the power losses and the shielding material as less important. Thus, more emphasis has been given to the configuration of the transformer characteristics than to the criterion of cost.

4. Results and discussion

Different optimization methods were used to minimize the objective function (1) in case of $\Delta U_k^{spec} = 3{,}5\%$. Table I summarizes the respective results for the optimal shielding geometry, the calculated variation in the short-circuit impedance and the shielding power loss and the number of iterations needed for the convergence of each method. Based on Table 1, the CG-FR method is the most appropriate in terms of convergence rate and optimal solution quality.

Table I: Results of different optimization methods (specified ΔU_k=3,5%, $P_{shunt}^{min} = 100W$, and $S_{shunt}^{max} = 2.000mm^2$)

Method	*Width x (mm)*	*Height H(mm)*	S_{shunt}^{calc} *(mm²)*	ΔU_k^{calc} *(%)*	P_{shunt}^{calc} *(W)*	*Number of Iterations*
Broydon-Fletcher-Goldfarb-Shanno (BFGS)	76,0	17,1	1.299,60	3,5	203,2	26
Davidon-Fletcher-Powell (DFP)	77,6	19,1	1.482,16	3,5	200,0	3
Conjugate Gradient-Fletcher Reeves (CG-FR)	76,6	14,4	1.103,04	3,5	214,4	4
Steepest Descent	79,2	19,8	1.568,16	3,5	204,6	5
Pattern search	79,6	20,0	1.592,00	3,5	206,4	5

References

[1] IEC 60076-1, "Power transformers – Part 1: General," 2000.