

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 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.

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Keywords: Power transformer; Short-circuit impedance; Finite element method; Electric shielding; Optimization methods

1. Introduction

The process of electric utilities restructuring, privatization and deregulation has created a competitive, global marketplace for energy. In this new and challenging environment, there is an urgent need for a transformer manufacturing industry to improve transformer efficiency and reliability and to reduce cost, since high-quality low-cost products have become the key to survival [1,2]. Transformer reliability is improved by the accurate evaluation of the leakage field, the short-circuit impedance and the resulting forces on transformer windings under short-circuit, since these enable to avoid mechanical damages and failures during short-circuit tests and power system faults. The technical and economical optimization of transformer design contributes significantly in transformer cost reduction.

Numerical field analysis techniques used in conjunction with optimization algorithms for the design optimization of magnetostatic devices are widely encountered in the technical literature. In Ref. [3], direct differentiation of finite element (FE) matrices is used for the sensitivity analysis of three-dimensional (3D) magnetostatic problems, while in Ref. [4] the FE formulation

is used for calculation of global quantities for the derivation of the best search direction of deterministic optimization methods. In Refs. [5,6] the authors use the finite element method (FEM) for the shape optimization of a BLDC motor and a linear actuator, respectively. The boundary element method (BEM) is employed in Refs. [7,8], where the authors carry out the design optimization of magnetostatic devices through boundary integration formulas.

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, [9], 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.

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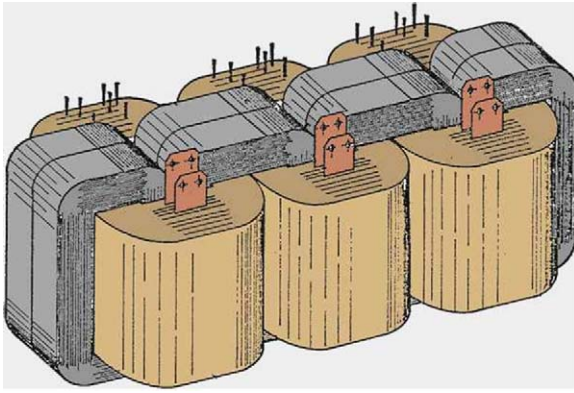


Fig. 1. Real geometry of a three-phase, wound core, distribution transformer.

The impact of magnetic shielding on the transformer electric shield has been examined with the use of hybrid three-dimensional finite element-boundary element method (FEM-BEM) in Ref. [10]. Experimental study of this kind of shielding is also carried out in Ref. [11], while in Refs. [12,13], the transformer tank shield geometry is optimized with the use of 2D FEM in conjunction with deterministic optimization methods. In the present paper, two-dimensional finite element method is applied to cases involving the shape optimization of power transformer electric shielding. The 2D FEM is suitable for use with optimization algorithms, as it reduces the total time needed for the magnetic field calculation during each iteration (due to the reduced number of mesh nodes involved in 2D modeling). The shape optimization is combined with the shielding power loss minimization, resulting to total cost reduction of the electric shielding.

2. Transformer modeling with 2D finite element method

The considered transformer is 1250 kVA, rated primary voltage 20 kV and rated secondary voltage 400 V, three-phase, wound core, distribution transformer (Fig. 1). 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.

Fig. 2 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).

For the transformer magnetic field simulation, the active part is represented by a triangular finite element mesh, illustrated in Fig. 3.

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.

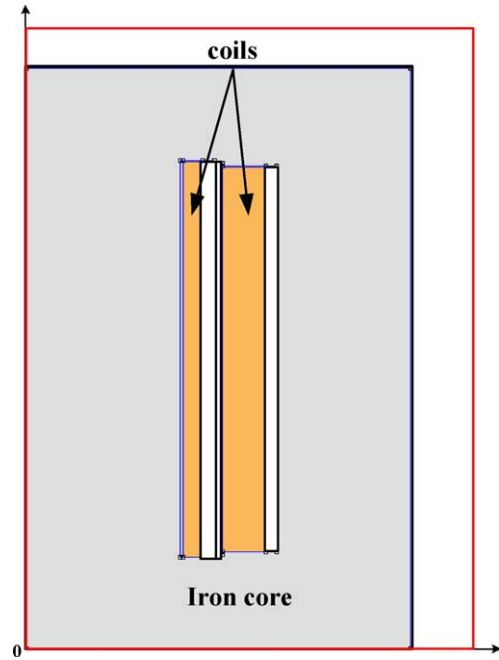


Fig. 2. 2D FEM model of transformer one-phase part (modified geometry).

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

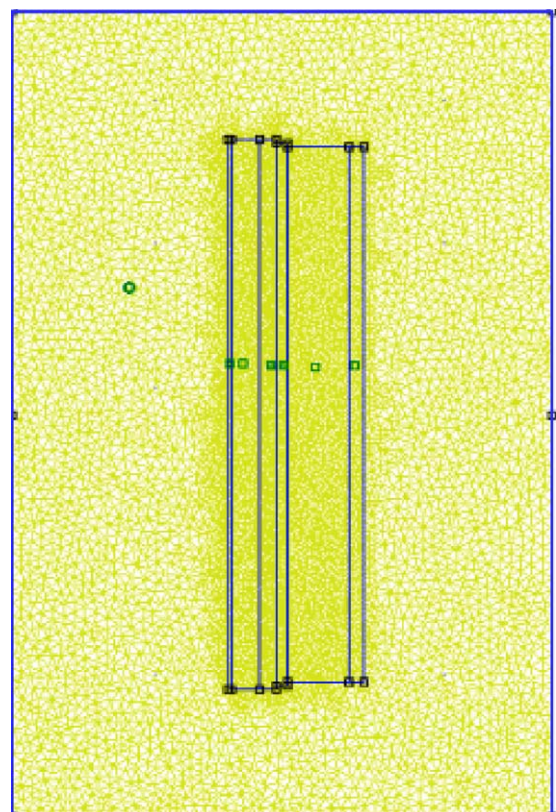


Fig. 3. 2D finite element mesh for the transformer 1250 kVA.

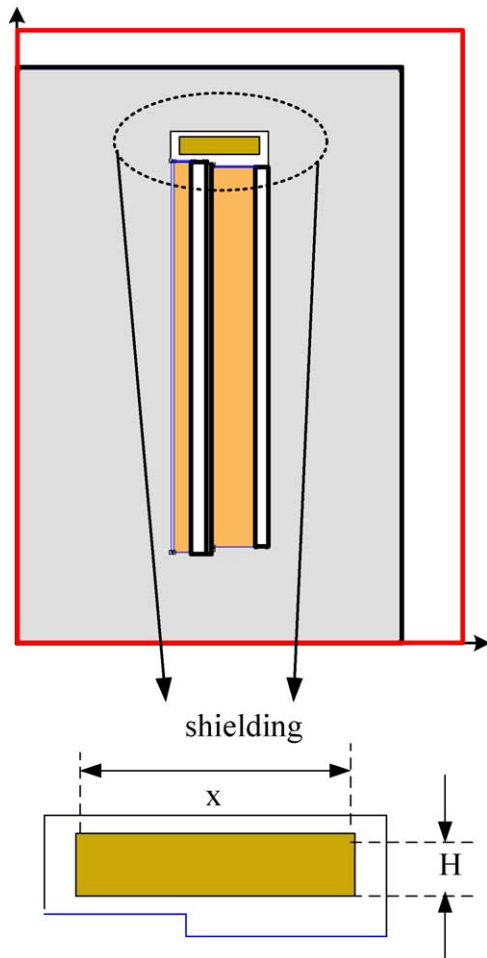


Fig. 4. Placement of electric shielding above the transformer windings and design variables (shielding width, x and height, H).

shielding resulted 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.

Fig. 4 illustrates the placement of electric shielding above the transformer windings. It consists of copper sheets of a given width and height, located in the gap between the upper part of the core and the windings. This location is chosen so that the copper attenuates the magnetic flux lines coming out of the windings, resulting to reduction of the transformer leakage field, which is mainly concentrated in the gap between the low and high voltage winding.

Figs. 5 and 6 demonstrate the impact of this kind of shielding, by comparison of the transformer magnetic field under short-circuit test, before and after the placement of the shielding. The attenuation of the flux lines above the windings is obvious in Fig. 6, compared to Fig. 5, corresponding to decrease of the leakage field and the short-circuit impedance.

In order to examine the impact of the shielding dimensions on the short-circuit impedance variation, an investigation of the influence on the short-circuit impedance decrease (DU_k) of the shielding width has been conducted, for different values of the

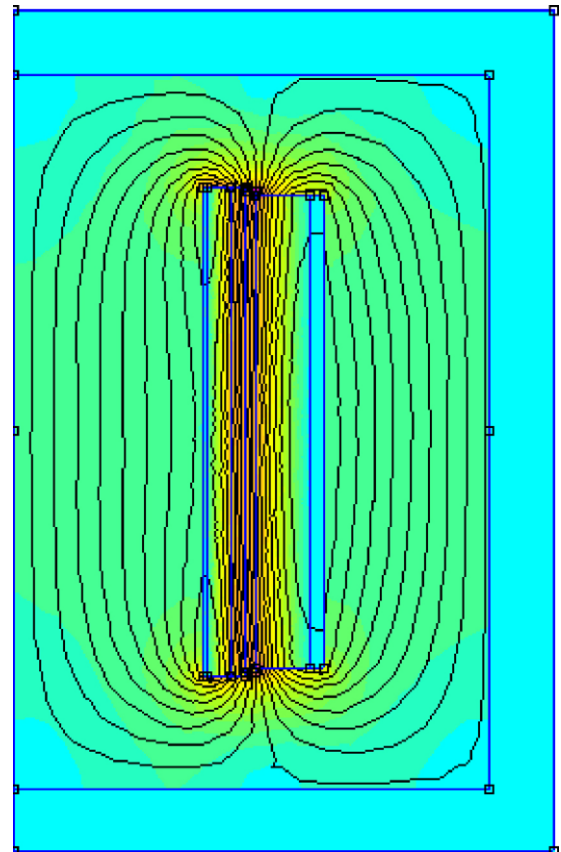


Fig. 5. Magnetic field distribution under short-circuit test before the placement of electric shielding.

shielding height and the respective results for a given height value, equal to 84 mm, are shown in Fig. 7. The same analysis has been performed for the impact of the shielding height, at various values of shielding width (resulting to DU_k curves as a function of the shielding height).

According to Fig. 7, a decrease from 0.5% up to 3.5% can be achieved by increasing accordingly the shielding width. However, in such a case, the increase in the shielding material cost and power loss must be considered, in order to find the optimum compromise between U_k reduction and loss increase. Fig. 8 illustrates the variation of the shielding power loss as a function of its width. The choice of the optimal shielding configuration should accordingly be based on combination of the results of Figs. 7 and 8, for different values of shielding height values. Therefore, the electric shielding shape optimization is a complex task, which must take into account the DU_k and loss variation with the shielding dimensions. This is solved as a non-linear, multi-criteria, constrained optimization problem.

The general mathematic form of the electric shielding geometry optimization consists in the minimization of an objective function $F(\mathbf{X}_i)$, where \mathbf{X}_i is the vector of the design variables of the problem. In case of the electric shielding, the design variables comprise the geometrical parameters of the shielding, while the objective function is governed by the desired change in the transformer leakage field. The vector \mathbf{X}_i is subject to constraints imposed by the transformer geometry (active part and

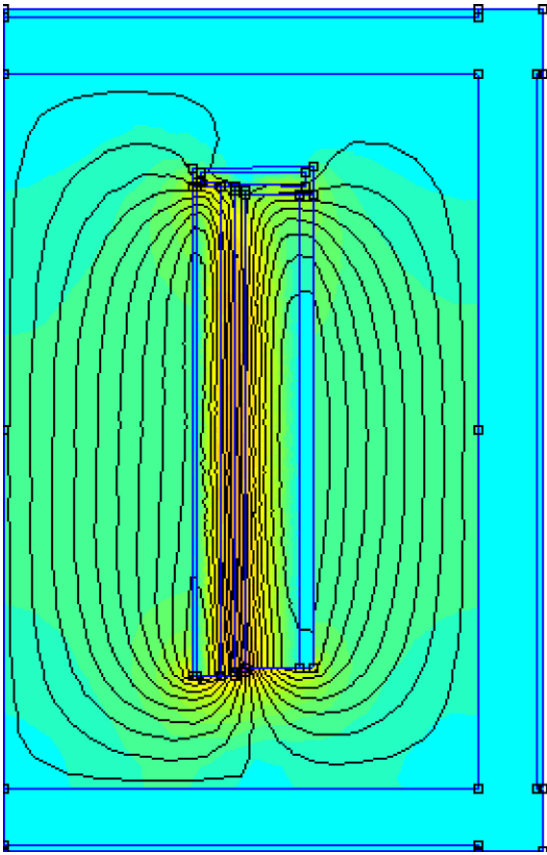


Fig. 6. Magnetic field distribution under short-circuit test after the placement of electric shielding.

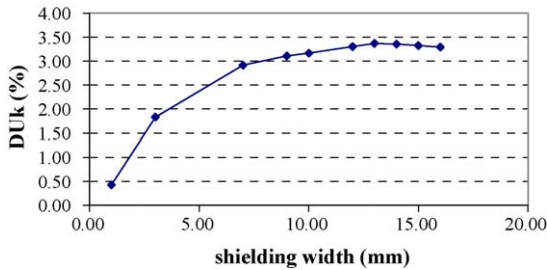


Fig. 7. Variation of short-circuit impedance decrease with the width of the shielding (for a given shield height, equal to 84 mm).

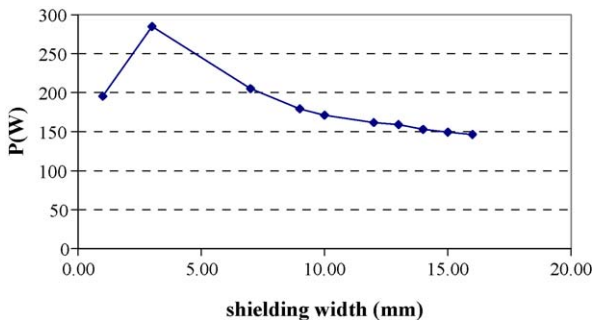


Fig. 8. Shielding power loss variation with the width of the shielding (for a given shield height, equal to 84 mm).

tank dimensions).

$$\text{Minimize } F(\mathbf{X}_i) \quad (1)$$

$$\text{under } \mathbf{X}_i^{\text{low}} \leq \mathbf{X}_i \leq \mathbf{X}_i^{\text{up}}$$

where $F(\mathbf{X}_i)$ is the difference between the specified and calculated DU_k , \mathbf{X}_i the vector of the design variables of the problem (width and height of the shielding) and $\mathbf{X}_i^{\text{low}}$ and \mathbf{X}_i^{up} are the constraints imposed by the transformer geometry.

4. Results and discussion

4.1. Formulation of the objective function

The objective function must take into account three factors: desired decrease 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 (2):

$$F = w_1 \frac{|\text{DU}_k^{\text{calc}} - \text{DU}_k^{\text{spec}}|}{\text{DU}_k^{\text{spec}}} + w_2 \left| \frac{P_{\text{shunt}}^{\text{calc}}}{P_{\text{shunt}}^{\text{min}}} \right| + w_3 \frac{S_{\text{shunt}}^{\text{calc}}}{S_{\text{shunt}}^{\text{max}}} \quad (2)$$

where $\text{DU}_k^{\text{calc}}$ is the calculated variation in the short-circuit impedance; $\text{DU}_k^{\text{spec}}$ is the specified (desired) variation in the short-circuit impedance; $P_{\text{shunt}}^{\text{calc}}$ is the calculated shielding power loss; $P_{\text{shunt}}^{\text{min}}$ is the minimum permissible value of the shielding power loss; $S_{\text{shunt}}^{\text{calc}}$ is the shielding surface used during the current iteration; $S_{\text{shunt}}^{\text{calc}} = xH$, where x is the width and H is the height of the electric shielding; $S_{\text{shunt}}^{\text{max}}$ is the maximum shielding surface and w_1, w_2, w_3 are the weight coefficients of the objective function components, with values $w_1 = 0.8, w_2 = 0.1$ and $w_3 = 0.1$.

The selection of the multiobjective function weights, w_1, w_2 and 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 the cost.

4.2. Comparison of different optimization methods

The following optimization algorithms, [10,14], have been tested in case of magnetic shunt optimization:

- (i) *Steepest Descent method*: It is a gradient-based method, where the search direction for the optimal solution is constructed using the gradient of the objective function.
- (ii) *Conjugate Gradient Fletcher-Reeves (CG-FR) method*: This method is a variation of the steepest descent method, with a modification in the search direction which attributes the property of quadratic convergence to the method.
- (iii) *Davidon-Fletcher-Powell (DFP) method*: The DFP is a quasi-Newton, variable metric (VM), gradient-based method, where the history from all previous iterations is used to establish the search vector for the optimal solution.
- (iv) *Broydon-Fletcher-Goldfarb-Shanno (BFGS) method*: The BFGS is another VM method and its difference compared to

Table 1

Results of different optimization methods (specified $DU_k = 3.5\%$, $P_{\text{shunt}}^{\min} = 100 \text{ W}$ and $S_{\text{shunt}}^{\max} = 2.000 \text{ mm}^2$)

Method	Optimal shielding geometry			$DU_k (\%)$	$P (\text{W})$	Number of iterations
	Width, $x (\text{mm})$	Height, $y (\text{mm})$	Area, $S (\text{mm}^2)$			
BFGS	76.0	17.1	1299.60	3.5	203.2	26
DFP	77.6	19.1	1482.16	3.5	200.0	3
CG-FR	76.6	14.4	1103.04	3.5	214.4	4
Steepest descent	79.2	19.8	1568.16	3.5	204.6	5
Pattern search	79.6	20.0	1592.00	3.5	206.4	5

the DFP lies in the way that the history of previous iterations is updated.

- (v) *Pattern Search method*: In this non-gradient optimization method, the search direction is cycled through the number of n variables in sequence and the $n + 1$ search direction is assembled as a linear combination of the previous n search directions.

The optimization methods mentioned above were used to minimize the objective function (2) in case of $DU_k^{\text{spec}} = 3.5\%$, $P_{\text{shunt}}^{\min} = 100 \text{ W}$, $S_{\text{shunt}}^{\max} = 2.000 \text{ mm}^2$.

Table 1 summarizes the respective results for the optimal shielding geometry, the calculated variation in the short-circuit impedance and the shielding power loss (corresponding to the optimal solution given by each method) and the number of iterations needed for the convergence of each method. Figs. 9 and 10 illustrate the variation of the difference between the specified and calculated variation in U_k and the shielding power loss, respectively, with the iterations of the methods of Table 1.

The observation of the results listed in Table 1 and the curves of Figs. 9 and 10 leads to the following conclusions:

- The DFP is the quickest converging method, providing the optimal solution in the smallest number of iterations. However, this solution is inferior to the ones provided by the CG and BFGS methods, as it corresponds to the greatest increase in the shunt power loss and area.
- Between the gradient-based methods, the CG and the DFP are the ones concluding to the optimal solution in the least number of iterations. The CG solution is more effective in

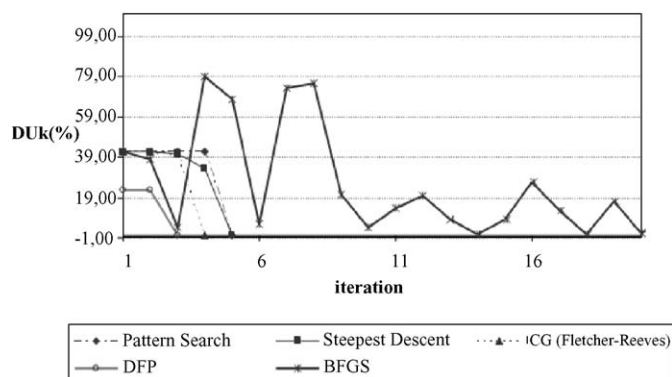


Fig. 9. Convergence to the target U_k value of the optimization methods illustrated in Table 1.

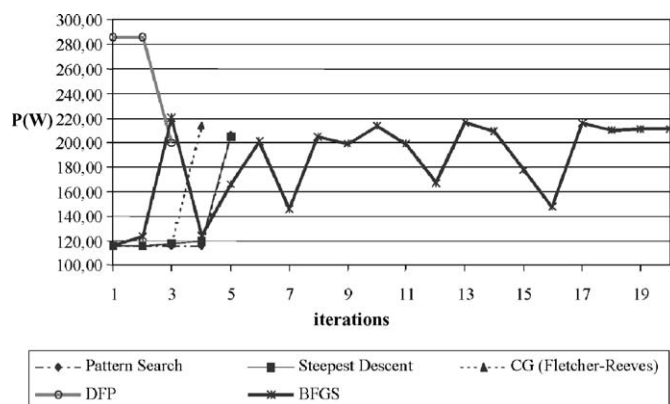


Fig. 10. Variation of shielding loss value of the optimization methods illustrated in Table 1.

terms of shunt loss and construction cost, as it corresponds to the minimum total area.

- The Steepest Descent and Pattern Search methods converge practically to the same minimum, with the same total number of iterations.

According to the above observations, the CG-FR method appears to be the most effective one for the solution of the electric shielding geometry optimization problem.

5. Conclusion

The application of a 2D FEM method has been introduced to the geometry optimization of electric shielding on power transformers. The problem was solved as a non-linear, multiobjective, constrained optimization problem and the proposed method was combined to several deterministic optimization algorithms. The CG-FR algorithm showed the best results in terms of convergence rate and optimal solution quality.

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