Calculation of Eddy Current Field in the Ascending Flange for the Bushings and Tank Wall of a Large Power Transformer

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The 3-D open boundary eddy current field induced by heavy current flowing in the coils and winding leads in large power transformers is calculated. The eddy current loss and local overheating problem in the tank wall and in the ascending flange of bushings are analyzed and reported in this paper. The effectiveness of a magnetic bypass plate near the coil ends for reducing the eddy current loss and local overheating in the clamp plates is discussed.

***Index Terms*—Eddy current field, loss, power transformer.**

I. Introduction

DUE TO transportation constraints, the physical size of large power transformer is very compact, and hence its electromagnetic (EM) load density is very high [1], [2]. The strong fields will induce heavy eddy current loss in some metallic parts of the transformer, such as the clamp plates, tank wall, and the ascending flange of the bushings. There could be local overheating problems and detrimental transient forces [3]–[5] if these strong EM fields are not mitigated carefully in the design stage.

To obtain an accurate distribution of the leakage magnetic field in the transformer being studied, tests are carried out and the EM fields on the up clamp and on the inside surface of the tank walls of the transformer are measured. It is found that in the vicinity of the clamp plate corresponding to the center lines of the C-phase coils, the maximum flux density $\mathbf{B}_z$ is higher than the critical overheating limit stipulated by the designer. In a one-phase model of the transformer which is constructed to validate the simulation studies, the overheating problem in the clamp plates and ascending flange of the bushings are also measured using infrared radiation thermometer.

Even the clamp plates in the transformer being studied are made of steel with low magnetic permeability and a shield is installed on the inside surface of the ascending flange of the bushings to alleviate the overheating problem, they are not very effective in reducing the losses [6], [7]. In this paper a 3-D open boundary eddy current field induced by the heavy winding and terminal lead current of the transformer being studied is computed and reported. Eddy current loss and local overheating in the tank wall and the ascending flange of the bushings are also studied. Proposed means to alleviate overheating and excessive losses in power transformers are also analyzed and reported.

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II. Formulations

To analyze the eddy current and losses in transformers, the 3-D open boundary eddy current fields satisfying the following equations are evaluated [8]–[10]:

$$\left.\begin{array}{l}\nabla \times (\nu\nabla \times \dot{\mathbf{A}}) - \nabla(\nu\nabla\cdot\dot{\mathbf{A}}) \\ \quad +\sigma\nabla\dot{\phi} + j\omega\sigma\dot{\mathbf{A}} = 0 \\ \nabla\cdot(-\sigma\nabla\dot{\phi} - j\omega\sigma\dot{\mathbf{A}}) = 0\end{array}\right\} \text{ in } V_1 \tag{1}$$

$$\nabla \times (\nu\nabla \times \dot{\mathbf{A}}) - \nabla(\nu\nabla\cdot\dot{\mathbf{A}}) = \dot{\mathbf{J}}_s \text{ in } V_2 \tag{2}$$

where V_2 is the source current area; V_1 is the other area without source current. The Coulomb gauge condition is introduced.

The boundary conditions are

$$\left.\begin{array}{l}\mathbf{n}\times\dot{\mathbf{A}} = 0 \\ \nu\nabla\cdot\dot{\mathbf{A}} = 0\end{array}\right\} \text{ in } S_1 \tag{3}$$

$$\left.\begin{array}{l}(\nu\nabla\times\dot{\mathbf{A}})\times\mathbf{n} = 0 \\ \mathbf{n}\cdot\dot{\mathbf{A}} = 0\end{array}\right\} \text{ in } S_2 \tag{4}$$

$$\left.\begin{array}{l}\dot{\mathbf{A}}_1 = \dot{\mathbf{A}}_2 \\ \nu_1\nabla\cdot\dot{\mathbf{A}}_1 = \nu_2\nabla\cdot\dot{\mathbf{A}}_2 \\ \nu_1\nabla\times\dot{\mathbf{A}}_1\times\mathbf{n}_{12} = \nu_2\nabla\times\dot{\mathbf{A}}_2\times\mathbf{n}_{12} \\ \mathbf{n}\cdot(-j\omega\sigma\dot{\mathbf{A}} - \sigma\nabla\dot{\phi}) = 0\end{array}\right\} \text{ in } S_{12}. \tag{5}$$

Introducing the boundary conditions, the weighted residue equation can be written as

$$\int_V (\nu\nabla\times\mathbf{N}_i\cdot\nabla\times\dot{\mathbf{A}} + \nu\nabla\cdot\mathbf{N}_i\nabla\cdot\dot{\mathbf{A}} + j\omega\sigma\mathbf{N}_i\cdot\dot{\mathbf{A}} + \sigma\mathbf{N}_i\cdot\nabla\dot{\phi} - \mathbf{N}_i\cdot\dot{\mathbf{J}}_s)dv = 0 \text{ in } V \tag{6}$$

$$\int_{V_1} \nabla N_i\cdot(j\omega\sigma\dot{\mathbf{A}} + \sigma\nabla\dot{\phi})dv = 0 \text{ in } V_1 \tag{7}$$

where N_i is the weighted function. In the model the uniqueness condition is satisfied. V is the complete solved area. By meshing triangular prism in the area and solving the equations, the magnetic flux, eddy current and losses can be calculated.

To validate the approach presented in this paper, a 17-MVA transformer is selected as the magnetic field test model. The corresponding calculated values of magnetic flux density on the

TABLE I
COMPARISON BETWEEN COMPUTED AND MEASURED MAXIMUM MAGNETIC FLUX DENSITY ON THE SURFACE OF THE TANK WALL (mT)

Height (mm)	0	70	140	210	280	330	355	380	450
Computed	0.43	2.7	5.4	9.4	15.0	16.9	16.8	15.9	10.8
Tested	0.50	2.5	5.5	9.7	14.0	15.8	15.7	14.6	10.0
Error (%)	-14	8.0	-1.8	-3.1	7.14	6.96	7.0	8.9	8.0

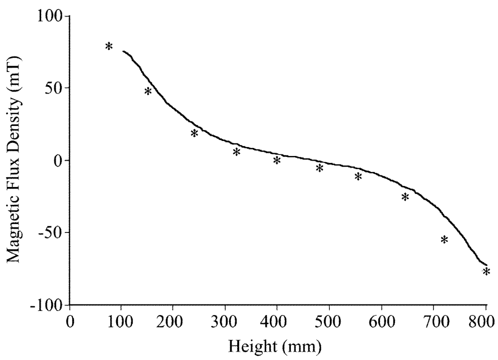

Fig. 1. Field distribution on the surface of the B-phase core (the height of the coil is from 100 to 800 mm).

surface of the tank wall and iron core and the test results are given, respectively, in Table I and in Fig. 1. It can be seen that the calculated results agree well with the measured ones, thus confirming the proposed approach is an accurate methodology in the study of eddy current field and losses in large transformers.

III. ANALYSIS AND CALCULATION

The method above is employed to compute the eddy current fields and eddy loss in a 720-MVA/500-kV transformer. In the numerical calculation of the eddy current field, the total elements and nodes are 53 768 and 42 106 and there are 136 732 unknown variables. The preconditioned complex biconjugate gradient (PCBCG) method is used to solve the equations. The computation time is 282 min using a Pentium IV personal computer (2.6 GHz and 1-GB memory). The source programs (FE method) such as mesh generation, stiffness matrix generation and the equation solver are written in Fortran by our research group.

The transformer is a newly developed high-power transformer with heavy leakage magnetic field. The field will induce eddy current losses in metallic parts such as the clamp plates, ascending flange of the bushings and tank walls. There are also local overheating in the aforementioned parts because the losses are concentrated in specific locations. These will induce pyrolysis in the oil and cause degradation in the insulation materials to result in reduced reliability. In order to study these problems, a one-phase transformer model having the same capacity of one core leg of the 720-MVA three-phase transformer being studied is calculated and tested. The hot spots are all measured in the model. It is found that there are indeed overheating in the ascending flange of the bushings which are made of A3 steel plates. The overheating mainly occurs in the edge parts near the heavy current leads. There are also overheating in the clamp plates as well. In the vicinity of the end windings there are heavy leakage fields that could induce eddy current in the clamp plates and pull plates. Though the clamp plates are made of steel with low magnetic permeability, there are still overheating problems

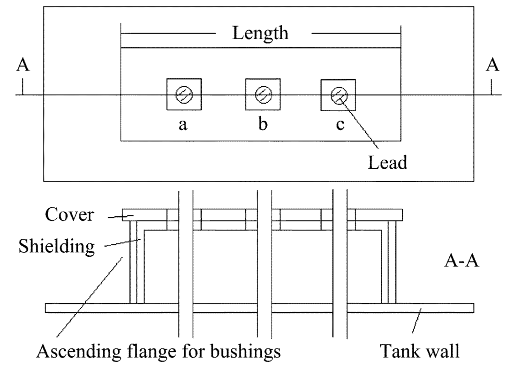

Fig. 2. Sketch of the ascending flange of the bushings of the transformer.

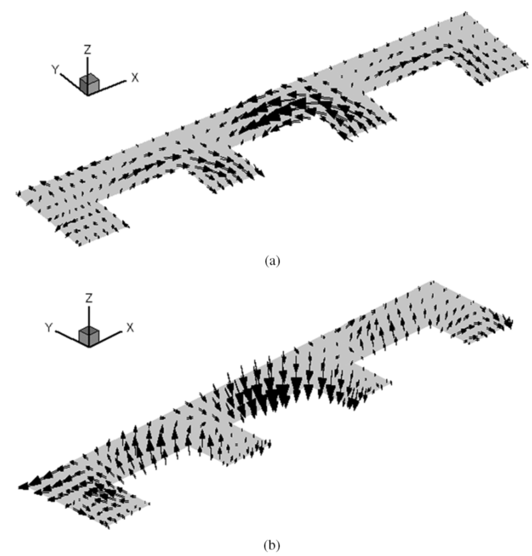

Fig. 3. Distributions of the magnetic flux density and the eddy current density in the cover plate of the ascending flange for bushing. (a) The magnetic flux density and (b) the eddy current density.

in these plates. Hence it is most likely that the 720-MVA transformer might also suffer overheating unless effective measures are implemented. In order to solve these problems, the 3-D eddy current field arising from both the heavy current leads and the windings are calculated and analyzed. It is found that the total loss is 1799 kW, which is the sum of the constant loss of 320.4 kW and the load loss of 1478.6 kW.

A. Eddy Current Field Calculation in the Ascending Flange of the Bushings

The heavy current leads are connected to the phase buses through the ascending flange of the bushings. The line current is 1.732 times of that of the windings in the delta connected transformer.

Current in the leads induces eddy current losses in the ascending flange of the bushings, especially in its cover. The equations derived above are used to compute the 3-D eddy current fields and the losses in the ascending flange of the bushings. Fig. 2 shows a sketch of the flange. Due to structural symmetry, only half of the model is needed as the computational area. The current flowing in the three phase leads is 20 kA. Fig. 3 gives the magnetic field and eddy current density distribution in the A3 steel cover. Its conductivity is 5.857×10^6 S/m (20 °C) and its B-H curve is shown in Table II. It can be seen that the eddy current density in the edge of the cover near the

TABLE II
B-H CURVE OF A3 STEEL

H (A/m)	16	80	160	240	400	800	1.2k	1.6k	2.0k	2.4k
B (T)	0.007	0.049	0.201	0.390	0.645	0.995	1.175	1.279	1.356	1.408
H (kA/m)	2.8	3.2	3.6	4.0	4.8	5.2	6.4	8.0	12.0	16.0
B (T)	1.444	1.478	1.506	1.529	1.571	1.584	1.626	1.660	1.723	1.800

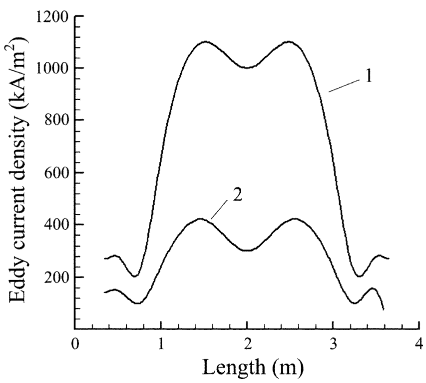

Fig. 4. Eddy current density in the cover plate of the ascending flange for the bushing. 1—A3 steel 2—the steel with low magnetic permeability.

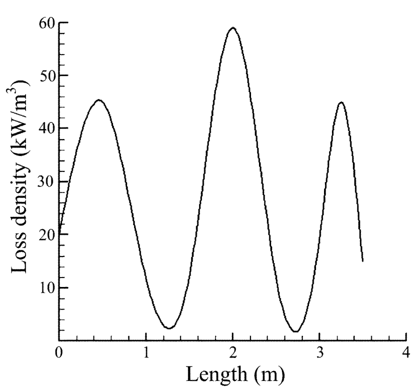

Fig. 5. Loss density in the cover plate of the ascending flange for the bushing.

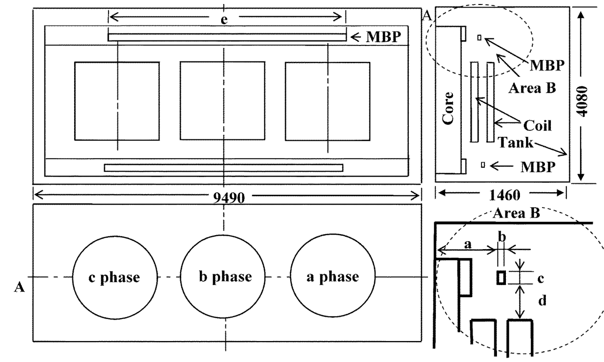

Fig. 6. Sketch of transformer with magnetic bypass plates.

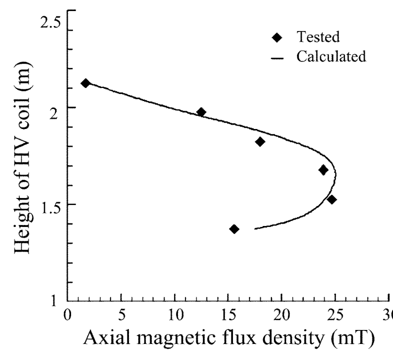

Fig. 7. Field distribution on the outside surface of the HV coil.

leads is lager than those in other areas. The distribution of the eddy current in the cover is not uniform. This may give rise to large local losses and overheating.

In order to alleviate the overheating problems, steel plates with low magnetic permeability (i.e., a relative permeability of unity) are used instead of A3 steel plates for the ascending flange of the transformer bushings. This makes the calculation of the 3-D eddy current field very complex because it is difficult to define the boundary of the solution area. By using steel with low magnetic permeability, the eddy current density in the cover is found to have decreased by about 40% as compared with those before. There is no local overheating in the cover even though the eddy current density at the edge of the cover is still larger than those in the other areas. Fig. 4 shows the eddy current density along the length direction in the cover of the ascending flange of the bushings. Fig. 5 shows the distributions of the losses density in the cover along the length direction.

B. Eddy Current Field Calculation in the Clamp Plates and the Tank Wall

The large leakage field near the winding ends will induce not only heavy eddy current losses in the clamp plates, it also gives rise to local overheating. In the transformer, all the clamp plates are made of steel with low magnetic permeability in order to alleviate the leakage flux problems. In order to obtain an accurate distribution of the leakage magnetic field in the transformer, tests have been carried out in which the electromagnetic fields on the outside surface of the C-phase of the HV coil, on the up clamp and on the inside surface of the tank walls have all been measured. In the region of the clamp plates corresponding to the center lines of the C-phase coils, the maximum B_z is 126 mT which is larger than the critical overheating limit of 26.7 mT. The maximum loss density is 46 kW/m^3 before installing the magnetic bypass plates (MBP) to be described later. In the one-phase transformer model of the 720-MVA transformer, the thermal profile in the clamp plates are measured using infrared thermometers to check whether there are potential overheating problems. Besides using low magnetic permeability steel clamp plates, the MBP scheme is designed to reduce the losses of the clamp plates to alleviate local overheating. The MBP plates, which are made of silicon sheets, are installed near the clamp plates so as to provide a path for the leakage magnetic field at the end of the three phase coils in the MBP plates. The leakage magnetic field in the clamp plates, pull plates and so on can be reduced with this arrangement. Fig. 6 gives the sketch of the windings, clamp plates, and the MBP.

Fig. 7 gives the field distribution on the outside surface of the HV coil. Fig. 8 shows the distribution of the z-direction magnetic flux density B_z along the length direction of the up clamp plate. The analyzed area is corresponding to a region of the C-phase coil. The maximum magnetic flux density is 16.6 mT which is less than the aforementioned criterion after installing the MBP plates. Hence there is no local overheating

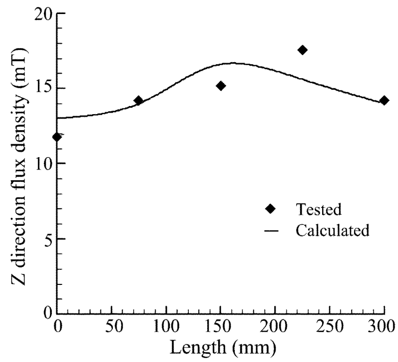

Fig. 8. Magnetic flux density B_z on the area of the up clamp plate.

TABLE III
LOSS DENSITY IN THE CLAMPING PLATE

Length of clamp	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Loss density 1	1.5	1.9	2.4	2.3	2.1	1.7	1.8	1.6	1.5
Loss density 2	38.5	33.1	21.2	13.3	21.1	32.0	36.5	28.2	19.5

Loss density 1 (kW/m^3)—with magnetic bypass plate,
Loss density 2 (kW/m^3)—with nonmagnetic bypass plate.
Length of clamp (meters) is the length from middle to the end of clamp plate

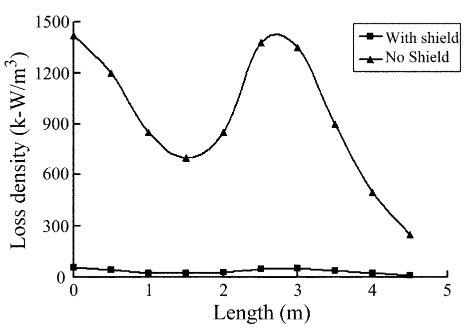

Fig. 9. Distribution of eddy current loss density along the length direction in the tank wall with and without shields (half the length of the tank).

in the clamp plates. Meanwhile, the maximum loss density is reduced to $2.2 kW/m^3$. The calculated results of the magnetic flux density in the up clamp plate are observed to agree well with the test results. By designing the parameters of the MBP plate, such as the parameters a, b, c, d, and e in Fig. 6, the maximum loss density in the plates can be reduced by 94%. In this scheme, $a = 947$ mm, $b = 50$ mm, $c = 80$ mm, $d = 205$ mm, and $e = 8800$ mm. Table III gives a comparison of the loss density in the clamp plate from the middle to the end along the axial direction. In other words, the MBP plate is effective in reducing the losses of these parts to avoiding local overheating.

In computing the electromagnetic field of the MBP plates, the maximum magnetic flux density is found to be 1.33 T which is less than the saturation flux density. Moreover, the measured value is 1.23 T and this compares well with the computed one. The eddy current loss in the MBP plate is small because they are made of silicon sheets. The design of the MBP plates is thus successful.

As the loss in the tank wall is high, a 4-mm-thick copper shield is used to alleviate the overheating problem in the tank wall. The total losses in the copper shield and tank wall are then reduced by 80% as compared to that with an unshielded tank wall. Meanwhile, the maximum loss density is reduced from 1400 to 60 kW/m^3 in the tank wall. Fig. 9 gives the distribution of the eddy current loss density in the tank wall along the length direction from the transformer center.

IV. CONCLUSION

This paper presents an accurate 3-D formulation to study the boundary eddy current field arising from the heavy winding and terminal lead currents in a compact power transformer. Eddy current loss and local overheating in the tank wall and the ascending flange of the bushings are also studied.

After identifying the hotspots, the designers propose to use steel plates with low magnetic permeability as the ascending flange for the bushings, and it is found that the eddy current density of the cover becomes lower than those in the A3 steel plates. With this arrangement overheating can be avoided in the 720-MVA transformer. Even though it is very costly to build a full-size model to validate the findings, a very comprehensive test has been carried out on a full-size one-phase model to validate the predictions. Proposed means to alleviate overheating and excessive losses in power transformers are also analyzed. The transformer losses are reduced significantly after the magnetic bypass plates are optimized and overheating in the clamping plates is avoided.

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