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Yüksek verimli transformatörlerde buşing bağlantı noktalarında meydana gelen eddy akımı kayıplarının azaltılması

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ÖZ

Alçak gerilim sargılarının bağlantı uçları sebebiyle transformatörlerin kazan kapağı üzerinde önemli ölçüde eddy alımı kayıpları meydana gelmektedir. Bu çalışmada, bu kayıpların azaltılması amacıyla kapak tasarımı manyetik özellikli olmayan paslanmaz çelik malzeme kullanılarak iyileştirilmektedir. İyileştirme çalışmalarında kayıplardaki azalmanın yanı sıra imalat koşulları ve maliyet göz önünde tutulmaktadır. Farklı kapak tasarımları için manyetik akı dağılımları ve eddy akımı kayıpları üç boyutlu sonlu elemanlar analizi ile incelenmiş ve sonuçlar deneysel çalışmalarla doğrulanmıştır. Alçak gerilim buşing bağlantı bölgelerinin paslanmaz çelikten imal edilen I-biçimli tek parça levha kullanılarak üretilmesi ile kapak üzerinde meydana gelen güç kayıplarının tamamına yakını ortadan kaldırılmıştır. Yeni kapak tasarımı ile transformatör kazanında oluşan toplam kayıplar %18.22 oranında azaltılmıştır.

Anahtar Kelimeler: eddy akımı kayıpları, sonlu elemanlar analizi, kayıp azaltılması, transformatör

Reduction of eddy current losses around bushing holes on the top-plate of a high efficient transformer

ABSTRACT

Low voltage winding leads cause local eddy current losses in top-plate of the transformer tank. In this paper, this loss component which also causes local hot spots is investigated. Top-plate design is modified using stainless steel non-magnetic material, around the low voltage bushing holes. Manufacturing issues and cost as well as power losses are considered as main criteria during modification study. Magnetic flux distributions and eddy current losses are analysed and compared for different designs. Comparisons are based on 3D finite element simulations and experimental studies. Results show that, insertion of single I-shaped stainless steel plate around low voltage bushing holes reduces eddy current losses to nearly zero. Using modified top-plate design, total stray losses on whole transformer tank is reduced by 18.22%.

Keywords: eddy current losses, finite element analysis, loss reduction, transformer

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1. INTRODUCTION

Transformers are very important components of a power system. Even if they operate with very high efficiencies, due to reached high power level and numbers of the transformers installed in grid, loss minimization studies continue their importance. Total power loss of a transformer is expressed as the sum of no-load and load losses. Unlike no-load losses, which are constant, load losses depend on the load current and include I2R losses in the windings, stray losses due to leakage fluxes in the windings and other parts and loss due to circulating currents in parallel windings and parallel winding strands [1].

Distribution transformers are the second largest loss making components of distribution grid. Currently, total installed power capacity of distribution transformers is estimated as 15000 GVA on the World and the global stock of distribution transformers is about 118 million units [2]. Dry and oil type distribution transformers had been regulated by CEI EN 50541-1 in 2007 and CEI EN 50464 in 2011, respectively. However, since 1st July, 2015, these regulations were replaced by the new and stricter European Standard EN 50588-1 [3] according to EU Regulation 548/2014. To obtain the strict necessities of this standard, all loss making parameters of the transformers should be carefully considered and total loss should be reduced. Stray losses on structural parts are one of these losses. Occurred stray losses are directly related to the parameters such as leakage field, winding geometry, distance between tank and windings, electromagnetic parameters of metal parts, etc. These losses cause local hot-spots and overheating on the tank walls, top and bottom plates and other structural parts, sometimes resulting overheating failures of transformers. The electromagnetic parameters of materials such as electrical conductivity and magnetic permeability strongly affect the stray losses. To overcome of the difficulties to calculate, finite element method has been extensively used for the definition of leakage flux and stray losses [4-9].

In literature, many studies had been presented to define and reduce stray losses and overheating problems. Most of these studies were focusing on stray losses on tank walls. However, high current leads near tank walls and top-plates cause additional local losses and hot-spots. Only a number of studies specifically realized to reduce these local losses.

In [10], local stray losses on tank wall near the low voltage cable leads of a power transformer were studied. Local hot-spots and the effects of aluminium shields placed between tank wall and low voltage leads were investigated. In [11], eddy current losses in bushing mounting plates of a 225kVA pad-mounted transformer were analysed. Eddy current losses were calculated using both analytical and FEA as well as measured from temperature rise. In [12], stray losses in the metallic ducts of a 2000kVA distribution transformer were studied. FEM was used to calculate these losses. Using stainless steel ducts instead carbon steel, throat losses were decreased. However, selection of plastic material was also proposed by authors. In [13], a numerical analysis of the eddy current loss due to current carrying primary conductor of a current transformer was presented. Three different types of insert material and shape were analysed and compared. Obtained results show that, by means of stainless steel inserts, total losses in the current transformer were considerably reduces.

In this study, eddy current losses on the tank top-plate around bushing mounting holes, which are generated by low voltage winding leads, are investigated. Leakage field around the phase windings also cause additional stray losses on the top-plate of tank. This stray loss component was neglected here, because of these losses are very little part of total stray losses. At first, stray losses on the transformer top-plate made by low carbon steel, were calculated. Then, top-plate was modified using stainless steel material around the bushing mounting holes and flux distribution and power losses are re-analysed. Manufacturing issues as well as total cost were also considered during modification study of top-plate. Obtained simulation results are also verified by experimental studies.

2. STUDIED TRANSFORMER

Studied transformer in this paper is a three phase, 1500kVA, 34.5/0.9kV, two winding, specially designed transformer with Dy11 connected windings. Cooling system was designed as ONAN and extra coolant radiators have been placed onto the tank walls, to provide efficient heat transfer and optimal cooling.

As a result of electrical and mechanical design procedures, transformer top-plate dimensions are calculated as 820x1870x8mm and made by low carbon steel material. Bushing holes with the diameter of 57mm and 76mm are placed on top-plate for the connection of low voltage and high voltage bushings, respectively.

A photograph of the studied transformer, including oil conservator, cooling radiators, bushings and other accessories on the top-plate, is shown in Figure 1.

Figure 1. Photograph of studied transformer

3. LOSS ANALYSES AND OPTIMIZATION OF THE TOP-PLATE

Low carbon steel is widely preferred material in the manufacturing of transformer tank walls and top-plate by manufacturers. However, considering the electromagnetic nature of low carbon steel material, calculation of stray losses using analytical methods is not easy. Therefore, electromagnetic analyses using finite element method (FEM) provides great advantage and easiness for eddy loss calculations. Simulation studies were performed by ANSYS Maxwell v16.0 electromagnetic analysis software. To simulate the rated operation of transformer, the leakage field and resulting losses have been calculated for a short circuit condition with a rated current.

Solution of the described three-dimensional analysis of the transformer model is performed in time domain with the following equations.

$$\vec{B} = \nabla \times \vec{A} \tag{1}$$

$$\nabla \times \vec{H} = \vec{J} \tag{2}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{3}$$

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = \vec{J} - \sigma \frac{\partial \vec{A}}{\partial t} \tag{4}$$

In these equations; $\vec{H}$ is the intensity of magnetic field, $\vec{J}$ is the current density μ is the permeability, σ is the conductivity, $\vec{E}$ is the intensity of electric field, $\vec{B}$ is the magnetic flux density and $\vec{A}$ is the magnetic vector potential.

The field equations which are solved by Maxwell3D are derived from the differential form of Maxwell's equations. In three dimensional electromagnetic problems, the quantities solved are the magnetic field and the current density while magnetic flux density is automatically calculated from the H field. Boundary conditions are automatically used by the software to reduce the complexity of the model. The skin depth which the induced currents penetrate of the tank, is expressed as,

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}} \tag{5}$$

where; ω is the angular frequency, μ_0 is the permeability of the free space, μ_r is the relative permeability of the tank material and σ is the electric conductivity. Tank top-plate are made of low carbon steel, which has and electrical conductivity $\sigma = 5000000\, S/m$ and a relative permeability $\mu_r = 500$. Due to the necessity of very small and high number of finite elements on the top-plate, solution process takes too many times and need very high computer capacity. Therefore, surface impedance method was applied to the top-plate model. With this method, total number of finite elements was decreased and solution time was shortened. The quantity of stray loss considering skin depth is calculated by the surface impedance as [7],

$$P = \iint_S \sqrt{\frac{\omega\mu}{2\sigma}} \frac{\mu_0^2}{2} dS \tag{6}$$

To improve the solution, finite element mesh on top-plate was optimized. Total number of finite elements on whole top-plate is 132400 and 110000 of them are described around the low voltage bushing mounting holes. Due to the flux distribution could be neglected, a specific mesh description was not needed around high voltage bushing holes. Resultant finite element mesh is given in Figure 2.

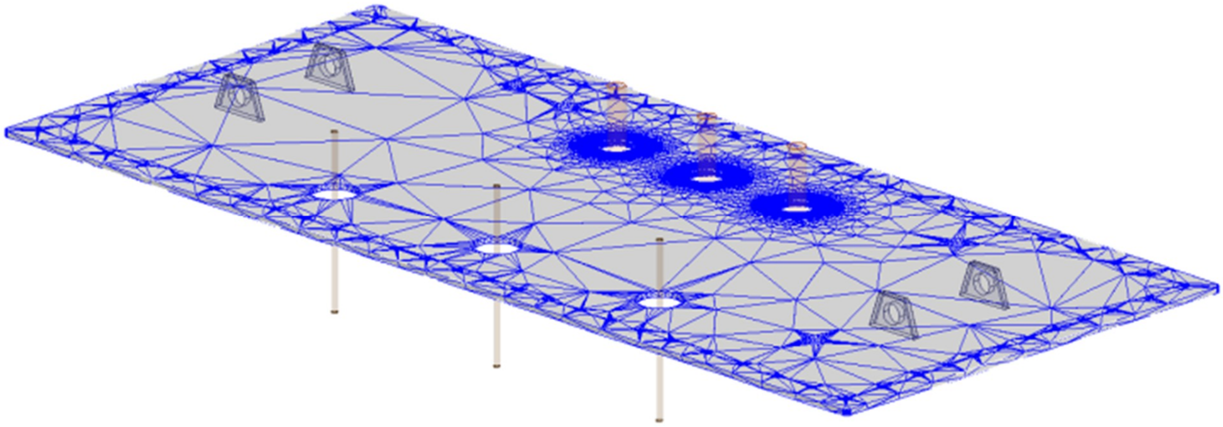

Figure 2. Finite element mesh for original low carbon steel top-plate

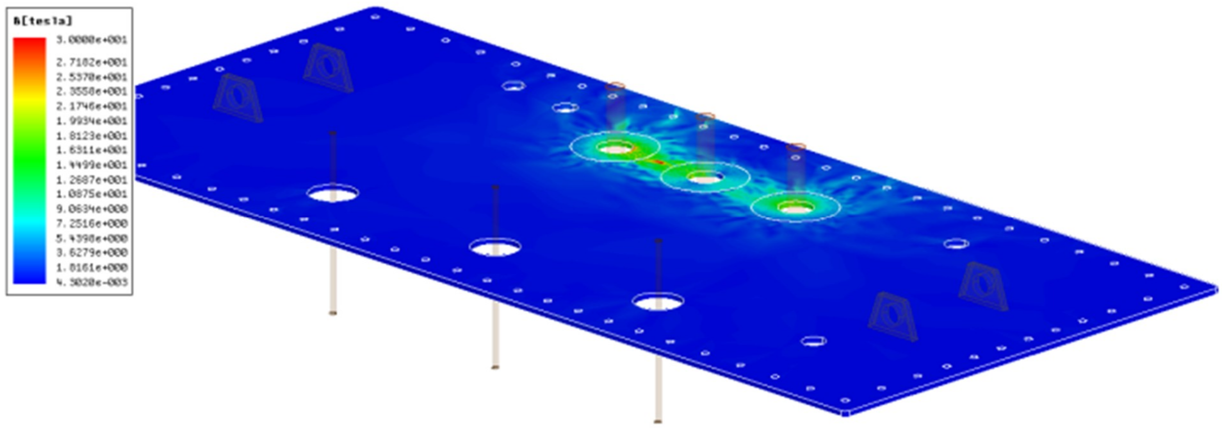

Figure 3. Flux distribution on original low carbon steel top-plate

To simulate the rated operation of transformer, pure sinusoidal rated current was applied to low and high current leads. Harmonic contents of phase currents were neglected. Obtained initial flux distribution on top-plate at rated current is given in Figure 3. Considering these flux distributions, it is clearly observed that the stray fluxes are mainly located around the low voltage bushing holes on top-plate. These fluxes cause high power losses and create local overheating problems. As a result of this simulation study, total power loss on tank top-plate was calculated as 230,73W.

Shielding and shunting methods are applied to the transformers to reduce the stray losses in tank walls. Both of these methods were well explained in literature. These methods could be easily applicable in manufacturing stage and very efficient against the leakage field and resulting stray losses, especially on tank walls and the other structural parts. In addition, these methods also prevent the stray field losses, caused by parallel placed winding leads to the tank walls of the transformer. However, to reduce the stray losses on the top-plate, which are caused by vertically passing conductors through the bushing holes, the most efficient but cost-making way is to use non-magnetic materials to manufacture the top-plate of transformer tank. Aluminium and stainless steel are the most used materials for this goal. As a solution to the stray losses, whole top-plate could be manufactured by such materials. However, material cost of a stainless steel top-plate is higher about 3.5 times, compared to carbon steel top-plate. Therefore, partial use of non-magnetic material on top-plate was preferred.

Due to the explained issues above, only bushing mounting regions of the top-plate are modified and re-designed, instead of whole top-plate. Considering the flux distribution of low carbon steel plate, given in Figure 3, design of circular area of three low voltage bushing mounting holes with the diameter of 140mm are optimized. These regions were produced by using three O-shaped non-magnetic stainless steel materials. Aluminium material is not preferred due to the welding problems to carbon steel top-plate. For O-shaped stainless steel material, stray losses on top-plate were calculated as 41.89W with finite element analysis. Resulting flux distribution for this condition is given in Figure 4.

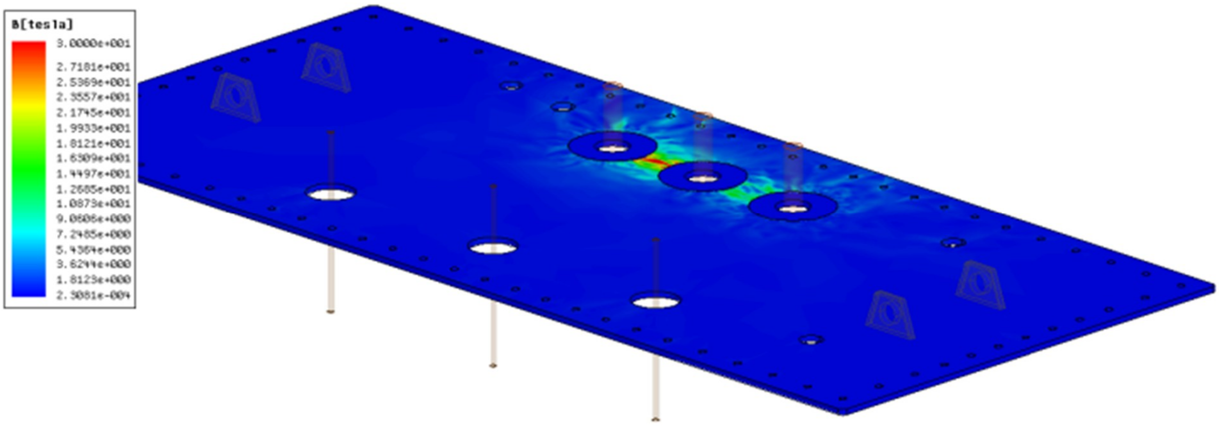

Figure 4. Flux distribution for inserted three O-shaped stainless steel plate

Obtained results show that, the stray loss on the modified top-plate is decreased by 81.8%, compared to the original iron top-plate. However, flux densities on the low carbon steel regions between stainless steel disc plates are still high and cause losses. With such a construction, material cost of top-plate could be reduced. However, due to the high manufacturing costs and long manufacturing time as well as mechanical issues, such a construction is not efficient and not preferable by transformer manufacturers.

Considering these issues, top-plate of the tank was re-designed once more. The region, which is 110mm wide and 550mm long, defined from Figure 3, was designed using single I-shaped plate. This plate was made by stainless steel material and placed onto the cut 100x540mm wide hole on the iron top-plate. Flux distribution and power loss of the re-optimized top-plate was simulated again and calculated as 242.54mW. Developed finite element mesh and flux distribution of re-optimized top-plate are given in Figure 5-6, respectively.

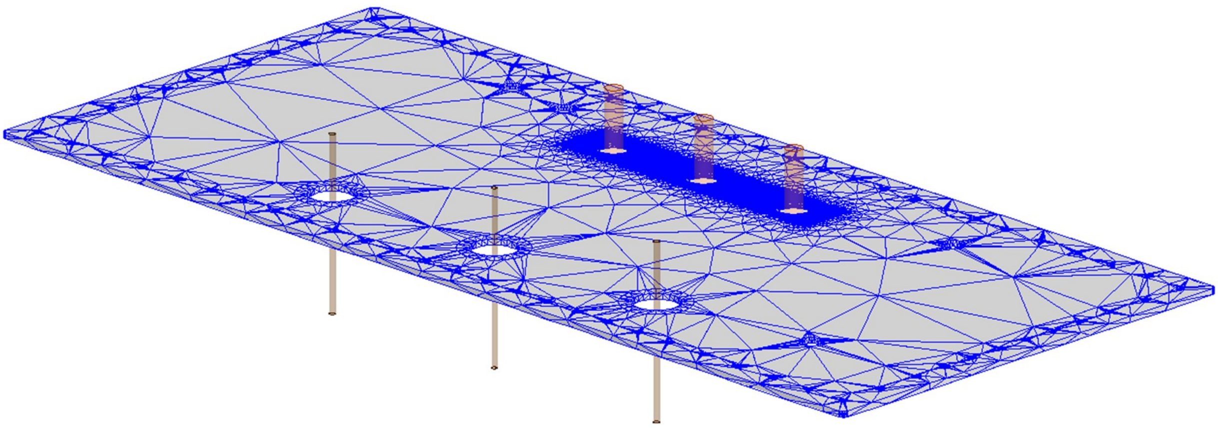

Figure 5. Finite element mesh for inserted single I-shaped stainless steel plate

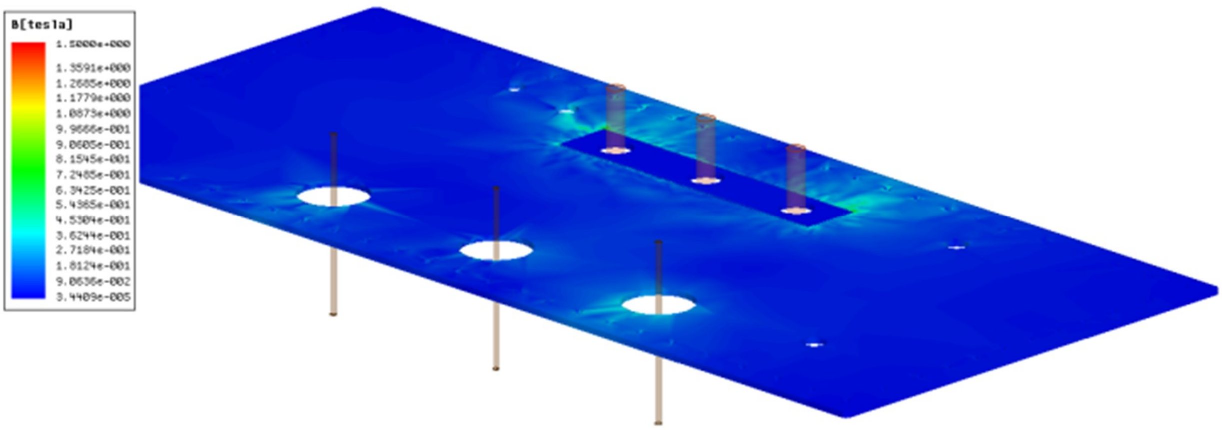

Figure 6. Flux distribution for single I-shaped stainless steel plate

4. EXPERIMENTAL STUDIES

Simulation results, presented in previous section, were also verified by experimental studies. Experiments were only realized for two conditions: fully iron top-plate and optimized top-plate using single I-shaped stainless steel plate. Considering the economic issues, top-plate optimized by three O-shaped stainless steel plates condition was not experimented. Tests and measurements were performed according to EN60076-1 necessities. For power measurements, an A-eberle PQ-Box 150 Mobile Power Analyzer was used.

Calculated and measured power losses are given in Table 1-2, respectively.

Table 1. Simulated eddy-current losses on top-plate

Low carbon steel top-plate	I-shaped stainless steel modified top-plate	reduction in power loss
230.73 W	242.54 mW	230.49 W

Table 2. Measured power losses of transformer

No-load test	Short circuit test		
	Low carbon steel top-plate	I-shaped stainless steel modified top-plate	reduction in power loss
2268 W	16608 W	16360 W	248 W

During the experimental studies, separation of measured stray losses on different parts of tank is not possible. Therefore, short circuit experiment was done for both conditions and measured total short circuit losses were compared to define the efficiency of top-plate optimization study. At first, original iron-made top-plate was placed on the transformer tank and total power loss was measured. Obtained power loss includes core loss, winding I^2R losses and stray losses of metallic structural parts of distribution transformer. No-load test was also performed to separate the core loss component. Then, top-plate was modified and single I-shaped stainless steel plate was placed onto the opened hole on top-plate. Short circuit experiment was repeated and power loss was also measured for this condition. Difference between the power losses of two experiments is accepted as the gain of the optimization study.

In Figure 7, final design of the top-plate of transformer tank with I-shaped stainless steel plate is shown.

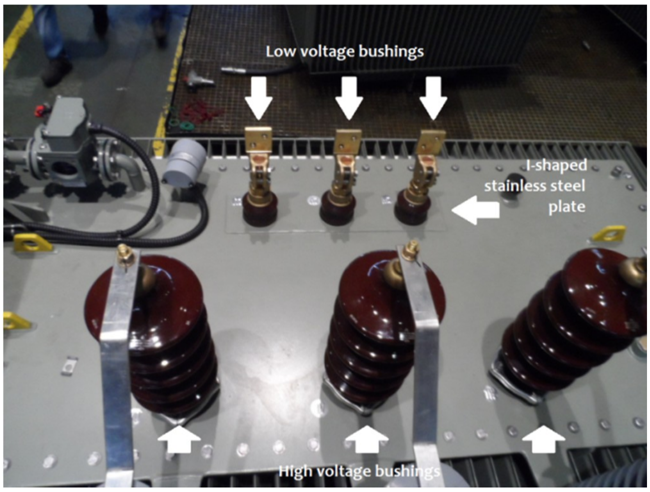

Figure 7. Top-plate of transformer tank with I-shaped stainless steel plate

With the original iron-made top-plate, transformer short circuit losses were measured as 16608W. Winding I^2R losses were also calculated as 15247W. According to these results, difference among these loss values mostly corresponds to the stray losses occured on whole transformer tank.

Using I-shaped stainless steel plate, short circuit losses were measured as 16360W, which are 248W less than original top-plate measurement results. Due to the all test conditions are identical, it is clear that the modification of the top-plate cause this loss reduction. This decrease corresponds to 18.22% of total stray loss value of whole transformer tank, which is calculated as 1361W. Considering the necessities of the loss classifications in EN 50588-1 regulation, this decrease provides an important advantage for high efficient transformer designs.

Measurement results were also compared to the finite element analysis results. Percentage error was calculated as about 7% which is in acceptable level.

5. RESULTS

Loss minimization studies have been gaining more importance since the publication of EN 50588-1 regulation. One of the loss components is stray loss occurred in the tank and other structural components of a transformer.

In this study, stray losses of a 1500kVA ONAN cooled distribution transformer was reduced by modifying the low voltage bushing hole region on the top-plate. Both the original and modified top-plate of the tank was analysed by finite element method and power losses were calculated. Stainless steel material was used in modification of the top-plate. Using single I-shaped stainless steel plate locally around the bushing holes, local eddy-current losses on top-plate were almost completely defeated. By means of a single I-shaped stainless steel plate, total stray losses were reduced about 18.22%. Simulation results were also verified by experimental studies. Obtained results show that the percentage error between simulation and experimental results is about 7% which is in acceptable level.

During this study, simplicity and easiness of manufacturing was also considered as well as total transformer cost. Using single I-shaped stainless steel plate, material cost, manufacturing cost and spent time in manufacturing stage would be minimum.

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