Determined the Positions and Dimensions of Horizontal Magnetic Shunts in Transformer Tank Walls Using Parametric Analyses Based on the Finite Element Method

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Abstract: Magnetic shunts efficiently mitigate losses caused by leakage currents in the tank walls of power transformers. Transformer manufacturers frequently utilize vertical magnetic shunts positioned on the inside surfaces of the transformer tank walls. This study investigated the optimum use of horizontal shunts in a power transformer. A 50 MVA power transformer, manufactured on a commercial scale and featuring optimized vertical magnetic shunts integrated into the wall structure, was analyzed using the 3D finite element method for 100 ms at full load. Simulations for analyses were performed using a commercial ANSYS Electronics Desktop 2021 R1 FEM software program. The model’s validity was demonstrated by verifying the analysis results with experimental tank loss values. Tank loss samples were obtained by analyzing the transformer tank for two milliseconds with vertical magnetic shunts only on the long front wall and the short side wall. Using these loss samples as a reference, parametric analyses were performed for two milliseconds with horizontal magnetic shunts only on the short side wall and only on the long front wall of the tank. A tank model with horizontal magnetic shunts of an appropriate location and size was obtained via the parametric analyses. This model was analyzed for 100 milliseconds at full load and compared with the experimental results of the transformer manufacturer’s vertical magnetic shunt transformer. According to the results, a saving of 25.83% was achieved in the horizontal magnetic shunt volume compared with the vertical magnetic shunt volume. The maximum magnetic flux density was lower in the horizontal magnetic shunts, and the maximum current density was lower in the transformer tank with horizontal magnetic shunts.

Keywords: magnetic shunt; transformer tank loss; finite element method; stray losses

1. Introduction

Energy transition is an important process for all countries due to the global climate crisis. Important elements in this process are the energy supply from renewable sources, energy efficiency, and the transition to microgrids where power systems can be managed. Increasing efficiency, controllability, and enhancing power systems’ reliability in electrical energy infrastructures is crucial in this respect [1]. The equipment used in power grids and consumption must be highly efficient. Studies on reducing the losses of large power transformers, increasing their efficiency, and ensuring operational continuity can be carried out in this context.

The power losses occurring during transformer operation are expressed as the sum of no-load losses and load losses. Load losses are the sum of copper losses in the phase windings of the transformer, losses caused by eddy currents in the windings, and losses...
caused by eddy currents in the metal structural components of the transformer. The eddy losses occurring in the metal structural components of the transformer, particularly the tank walls, comprise 20–50% of the load operating loss [2]. A significant proportion of these losses are power losses due to leakage flux in the windings on the tank walls, also known as tank losses. Stray losses caused by stray flux in a transformer’s tanks and structural components significantly impact its overall performance. Minimizing these losses is crucial for producers. Magnetic shunts are employed to minimize the dissipation of stray magnetic flux on the tank walls. Designing large power transformers presents a significant issue in determining the size and placement of magnetic shunts. Magnetic shunts consist of laminated steel packages used to minimize losses on the shunt surface caused by the normal component of the magnetic field [3]. Power losses in tank walls depend on physical and electrical parameters such as the winding currents, the winding structure, the distance between the windings and the tank walls, the distance from the magnetic shunts to the tank walls, the location and size of the magnetic shunts, and the tank’s electromagnetic properties.

The calculation, reduction, and analysis of transformer tank losses using various numerical methods have been intensively studied. Accurate calculations of transformer losses are crucial for analysis and design. In one study in the literature, an analytical method was developed to calculate the leakage losses in a three-phase transformer tank by considering the tank shape, three-phase excitation, hysteresis, and non-linearity [4]. In another study, the vertical magnetic flux density was obtained at discrete points on the tank surface to calculate the eddy current losses in the tank walls of a large power transformer, and a double-Fourier series was adopted to analytically express the obtained magnetic flux density [5]. Another study proposed the application of an impedance boundary condition to reduce the calculation time of the leakage loss in the transformer tank, and the calculation time was reduced by applying an impedance boundary condition to the outer surface of the transformer tank without considering the skin effect [6]. The losses in the transformer tank were shown for different distances of the outer winding from the tank for finite element method/surface impedance widths [7]. Transformer losses can be calculated using the finite element method, which is the most widely used, and other methods [8].

Various methods have been tried to reduce transformer losses. A study quantitatively analyzed the effects of different shielding configurations on loss reduction [9]. Another study found that placing a stainless-steel plate around the low-voltage conductors in the simulation of a 2000 kVA transformer reduced the magnetic field strength and the ohmic loss in the transformer tank wall [10]. Aluminum screens significantly reduce the overheating of the tank wall caused by the high-current-carrying low-voltage junctions [11]. The effects of different materials used in the manufacture of transformers on losses have also been investigated. The optimization of load losses was achieved by using different magnetic materials in the transformer tank wall [12]. The magnetic flux in the oil tank and windings was significantly reduced by using a shielding device made of different materials [13]. The total loss was reduced by 43.57% when a tank model made of a stainless-steel material instead of a low-carbon-steel material was used [14]. Stray losses in transformer tank walls can be significantly reduced by using aluminum magnetic screens [15].

Magnetic shunts are an effective method to reduce losses in transformer tanks. Studies have investigated the effect of the magnetic shunts used [16]. In one such study, width-optimized electromagnetic shunts were compared with conventional electromagnetic shunts and aluminum shielding, finding that the width-optimized electromagnetic shunts were more effective in preventing leakage currents than the others [17]. Another study stated that the magnetic flux density was mainly concentrated in the magnetic core, the magnetic flux leakage on the tank wall was small, the magnetic fields between the LV and HV windings were stronger than the other parts, the tank losses occurred mainly in the parts near the windings, and the tank losses could be reduced by placing magnetic shunts near the tank [18].
The most important problem in using a magnetic shunt is determining its size, shape, and location. One study examined the effective parameters affecting the design of magnetic shunts to control the leakage flux to reduce the losses and noise generated in transformers with different power and short circuit voltages [19]. Some research on the shapes of magnetic shunts determined that using a U-shaped magnetic shunt on the clamp is a more effective shunting method than using L- and inverted-L-shaped magnetic shunts [20]. By using L- and C-type magnetic shielding on the yoke clamps, a study determined that the effect of L-type magnetic shielding on the eddy current loss reduction in the yoke clamps was greater than when using C-type magnetic shielding [21]. A study in this field expressed the optimum shunt element dimensions in a 1000 kVA transformer depending on the design dimensions of the transformer windings and core [22]. It has been shown that if the shunts are very close to the tank wall, the shunt edges may create strong leakage areas on the tank surface due to their end effects; therefore, these areas can be reduced by flattening the shunt edges [23]. In a study using machine learning methods for the location of magnetic shunts, feed-forward neural networks (FFNNs) and the finite element method (FEM) were used to determine the magnetic shunt location on the tank wall of a transformer and to reduce leakage losses. The study found that using an FFNN model-based approach to determine the shunt location is simpler than using only FEM models [24].

Additionally, studies have investigated the effects of different materials used in magnetic shunts. A comparative study on the use of granular electrical steels (GOESs) and non-granular electrical steels (NGOESs) in magnetic shunts of power transformers showed that NGOES shunts were as effective as conventional GOES shunts in reducing leakage losses, temperature, and cost [25]. Parametric methods have also been used to analyze magnetic shunts. The effect of magnetic shunts on the electromagnetic (EM) force of a 10 kVA power transformer was investigated parametrically for different sizes and shapes. It was determined that the magnetic shunts increased the radial EM force and decreased the axial EM force [26]. The literature also includes studies on horizontal magnetic shunts. Moghaddami et al. proposed a new hybrid numerical/analytical method based on double-Fourier series expansions of the magnetic field distribution on the shunt surface to calculate leakage losses in magnetic shunts in a 200 MVA power transformer. The horizontal magnetic shunt arrangement was as effective as conventional vertical shunts in reducing stray losses while reducing the shunt weight [3]. In another study, a distribution transformer with a power of 1250 kVA was examined according to the parametric finite element method. It was shown that choosing the height of the horizontal shunt package to be placed on the surfaces corresponding to the upper and lower edges of the windings on the inner surface of the tank wall to be equal to 30% of the winding height can effectively reduce tank losses [27]. Another study on horizontal shunts found that horizontal wall shunts were more effective than vertical wall shunts in reducing leakage losses in a 315 MVA converter transformer (CT) and that leakage losses decreased with increasing shunt thickness [28]. A parametric analysis was conducted to investigate the potential for reducing leakage losses applied to the converter transformer tank by optimizing the thickness of the horizontal and vertical wall shunts. It has been demonstrated that the magnitude of stray losses is inversely proportional to the thickness of the wall shunt. Furthermore, it has been demonstrated that the horizontal wall shunt is more effective than the vertical wall shunt in reducing stray losses [29].

Additionally, there are studies in the literature examining the stray losses of transformers and their effects. The impact of asymmetric coils on the formation of stray losses within the core clamps and transformer tank walls was also investigated. Strategies to reduce stray losses have been investigated, including the installation of magnetic shunts as protective shields for tank walls. In particular, the incorporation of magnetic shunts has been identified as a promising approach to reducing additional losses by up to 40% [30]. Stainless steel (SSI) was mounted in the location of the bushing insulators in the transformer tank, which was constructed from low-carbon steel, in order to prevent stray losses and therefore overheating [31]. The particle swarm optimization (PSO) algorithm, in con-
junction with electromagnetic and thermal finite element (FE) models, was employed to ascertain the dimensions and locations of three tank wall magnetic shunts in a power transformer. A multithreaded algorithm was devised to address this numerical issue. It was determined that while the calculation time is considerable, the presented approach offers an effective solution.

In this study, transformer and tank models were created using a commercial FEM software program, and analyses were carried out. The tanks of existing power transformers have been predominantly manufactured using conventional vertical magnetic shunts. There are few studies in the literature on the use of horizontal magnetic shunts as it is a new method. The contributions of this study to the literature and important highlights are as follows:

- Unlike other studies, this study obtained loss samples from conventional vertical magnetic shunts optimized and manufactured by the transformer manufacturer.
- Based on these loss samples, the appropriate location and size of the horizontal magnetic shunts were determined using the size–loss relationship via a parametric finite element analysis.
- A parametric analysis was carried out separately for the long front walls and the short side wall of the tank.
- In addition, this study determined the tank losses according to the size and position of the horizontal magnetic shunts using a parametric analysis and presented the transformer manufacturer’s preferences.

It can be observed that the reference loss examples presented in existing methodologies are all tank walls, and the number of magnetic shunts is represented in the form of multiple packages [3,27,32]. In existing methodologies, the number of parametric variables appears to be a variable such as Δh [27]. Furthermore, no determination based on a size–loss relationship is evident in the existing methods. The loss examples referenced in the proposed method pertain to short, long, and entire tank walls. In the proposed method, a reduced shunt package is employed. In the proposed method, the size–loss relationship is determined by defining five parametric variables, namely Δx, Δy, Δz, Δw, and Δd. To emphasize the innovative nature and contributions of our study, the method we propose and a comparison of existing methods are given in Table 1.

Table 1. A comparison of existing methods and the proposed method.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Existing Methods</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Referenced loss example</td>
<td>Entire tank wall [3,27,32]</td>
<td>Short, long, and entire tank walls</td>
</tr>
<tr>
<td>Size–loss relationship</td>
<td>Not achieved</td>
<td>Achieved</td>
</tr>
<tr>
<td>Number of magnetic shunts</td>
<td>Multiple shunt packages [3,27,32]</td>
<td>Reduces shunt packages</td>
</tr>
<tr>
<td>Number of parametric variables</td>
<td>1 [27]</td>
<td>5</td>
</tr>
</tbody>
</table>

The rest of this paper is structured as follows: Section 2 presents the theoretical background. Section 3 covers the materials and methods, including the transformer simulation model and the parametric analysis. Section 4 presents the results of the parametric and full-load analyses. Finally, Section 5 presents the conclusions.

2. Theoretical Background

2.1. Skin Effect

The “skin effect” refers to the phenomenon that occurs when a high-frequency current flows through the surface of a conductor and reduces in strength as it moves toward the center of the conductor. This surface impact must be considered to facilitate the precise computation of the eddy currents occurring in the transformer tank. It is important to generate a mesh that considers the surface depth to incorporate the surface effect into
the finite element approach. According to the expression, the skin thickness at which the leakage flux acts on the metal component is written as

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \sqrt{\frac{2}{\omega \mu \sigma}}$$  \hspace{1cm} (1)

where

- $\delta$ = the skin depth (m);
- $f$ = the frequency (Hz);
- $\mu$ = the permeability of the material (H/m);
- $\sigma$ = the electrical conductivity of the material (S/m).

There is a significant relationship between the material’s electromagnetic characteristics and the skin thickness. With a frequency of fifty hertz for the mains, this thickness falls in the millimeter region. Considering that the skin thickness is relatively insignificant compared with the dimensions of the transformer’s structural components, applying the finite element method necessitates utilizing a dense mesh structure in addition to a substantial quantity of finite elements. As a result, it necessitates a high processing capacity and extends the amount of time needed to solve the problem. The surface impedance approach is utilized to model the tank wall to overcome this disadvantage. Consequently, the solution time and the number of finite elements formed in the tank construction are both greatly reduced. The surface impedance boundary condition is used to accurately calculate the stray losses, along with the relationship between the tangential component of the electric and magnetic fields [33].

$$Z_S = \frac{E_S}{H_S} = \frac{1 + j}{\sigma \delta} = (1 + j)\sqrt{\frac{\pi f \mu}{\sigma}}$$  \hspace{1cm} (2)

In this equation, the electric field is denoted as $E_S$, and the peak value of the tangential magnetic field is denoted as $H_S$.

2.2. Stray Losses

Stray loss at tank walls accounts for approximately 70–80% of the total stray loss in large power transformers. Eddy currents cause power loss in the transformer tank and are caused by leakage flux in the winding. The power loss in the transformer tank is known as stray loss and can be calculated using the Poynting vector. Stray loss is calculated using Maxwell’s equations [34,35].

$$\nabla \times E = -\frac{\partial B}{\partial t}$$  \hspace{1cm} (3)

$$\nabla \times H = J$$  \hspace{1cm} (4)

$$\nabla \cdot B = 0$$  \hspace{1cm} (5)

The two fundamental relationships between the magnetic flux density and the magnetic field strength and between the current density and the electric field are

$$B = \mu H$$  \hspace{1cm} (6)

$$J = \sigma E$$  \hspace{1cm} (7)

where $H$ represents the strength of the magnetic field in joules per meter, $E$ represents the strength of the electric field in volts per meter, $B$ represents the magnetic flux density in watts per square meter, and $J$ represents the current density in amps per square meter.

Equation (4) can be simplified with vector algebra by taking the curl of both sides.

$$\nabla (\nabla \cdot H) - \nabla^2 H = \nabla \times J$$  \hspace{1cm} (8)
Using Equations (3) and (5)–(7), Equation (8) is expressed as follows:

$$\nabla^2 H - \mu \sigma \frac{\partial H}{\partial t} = 0 \quad (9)$$

A structural component is assumed as shown in Figure 1. The magnetic field strength $H_y$ and current density $J_x$ are considered as functions of $z$. The complex permeability can be written as Equation (9) for this problem.

$$\frac{d^2 H_y}{dz^2} = j \omega \sigma \mu H_y \quad (10)$$

$$H_y = H_a \text{ for } z = 0 \quad H_y = 0 \text{ for } z = \infty \quad (11)$$

By simplifying Equation (10) from the above conditions,

$$H_y = H_a e^{-(1+j)z} \quad (12)$$

where $H_a$ is a complex number, and $m$ is the complex propagation constant that represents propagation.

By solving Equations (10) and (11),

$$H_y = H_a e^{-(1+j)z} \quad (14)$$

Equation (14) is substituted into Equation (4) and simplified using vector algebra.

$$J_x = \frac{1 + j}{\delta} e^{-(1+j)z} \quad (15)$$

The time-averaged intensity of stray loss in the transformer tank can be obtained by calculating the real part of the complex Poynting vector on the surface.

$$P = \frac{1}{2} \text{Re}(E \times H^*) \quad (16)$$

On the surface ($z = 0$), Equations (14) and (15) are substituted into Equation (16). The stray loss per unit surface area is

$$P = \text{Re} \left( \frac{H_a}{\delta} (1+j) H_a z \right) = \frac{1}{2} \text{Re} \left( Z_0 H_a^2 \right) \delta \quad (17)$$

$$P = \frac{1}{2} \frac{H_a^2}{\delta} = \sqrt{\frac{\omega \mu}{2 \sigma}} \quad (18)$$
Therefore, the transformer tank’s total power loss is

$$P = \sqrt{\frac{\mu \mu_0}{8\sigma}} \int_{\text{surface}} H_x^2 \, ds$$  \hspace{1cm} (19)

3. Materials and Methods

In this study, a parametric analysis method for the best horizontal shunt size and location for a power transformer was developed. The results were analyzed via simulations. The real parameters of a commercially manufactured power transformer were used in the application. Firstly, a simulation of the considered power transformer was carried out using the finite element method. Then, the simulation results were compared with the test results of the same transformer at the production site, and the simulation was verified. After verifying the validity and reliability of the simulation model, the optimum size and location of the horizontal shunts to be used in the tank walls were determined using the parametric method developed. Parametric analyses were carried out by defining the variables for both the short side wall and the long front wall of the transformer.

3.1. Transformer Simulation Model

The power transformer’s parameters, analyzed using the finite element method, are presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>50 MVA</td>
</tr>
<tr>
<td>Input voltage</td>
<td>170 kV</td>
</tr>
<tr>
<td>Output voltage</td>
<td>36 kV</td>
</tr>
<tr>
<td>LV winding current</td>
<td>874.8 A</td>
</tr>
<tr>
<td>HV winding current</td>
<td>163 A</td>
</tr>
<tr>
<td>TAP winding current</td>
<td>163 A</td>
</tr>
<tr>
<td>Number of LV windings</td>
<td>190</td>
</tr>
<tr>
<td>Number of HV windings</td>
<td>755</td>
</tr>
<tr>
<td>Number of TAP windings</td>
<td>264</td>
</tr>
<tr>
<td>LV winding resistance</td>
<td>0.0307 ohm</td>
</tr>
<tr>
<td>HV winding resistance</td>
<td>0.7269 ohm</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Connection type</td>
<td>YNyn</td>
</tr>
<tr>
<td>Core material</td>
<td>M-5 steel</td>
</tr>
<tr>
<td>Magnetic shunt material</td>
<td>M-5 steel</td>
</tr>
<tr>
<td>Tank material</td>
<td>ST-52 steel</td>
</tr>
<tr>
<td>Winding material</td>
<td>Copper</td>
</tr>
<tr>
<td>Dimensions of the tank</td>
<td>4840 × 1720 × 2745</td>
</tr>
<tr>
<td>Thickness of magnetic shunt</td>
<td>15 mm</td>
</tr>
<tr>
<td>Idle loss</td>
<td>26.195 kW</td>
</tr>
<tr>
<td>Load loss</td>
<td>196.40 kW</td>
</tr>
<tr>
<td>Tank loss</td>
<td>11.00 kW</td>
</tr>
<tr>
<td>Magnetic shunt loss</td>
<td>0.28 kW</td>
</tr>
</tbody>
</table>

An external electrical circuit was established to analyze the 3D model of the power transformer at full load. A load resistance of 20.50 ohms was selected for the full-load analysis. The electrical excitation circuit model is depicted in Figure 2.
A parametric analysis flow chart is shown in Figure 3. This study was carried out using a parametric analysis built into ANSYS. After defining the dimensions of the magnetic shunts, a parametric analysis was set up by defining the change intervals of the dimensions of the magnetic shunts as parametric variables in the Optimetrics tab in the Project Manager. The tank loss was obtained graphically depending on the parametric change in the magnetic shunt dimensions.

3.2. Parametric Analysis

To perform a parametric analysis, it is necessary to create a transformer model in a FEM software program, assign the material, determine the solver type, assign the mesh, determine the boundary conditions, create the excitation, and determine the analysis time. A parametric analysis flow chart is shown in Figure 3. This study was carried out using a parametric analysis built into ANSYS. After defining the dimensions of the magnetic shunts in the model setup section of the ANSYS Electronics Desktop 2021 R1 software program, a parametric analysis was set up by defining the change intervals of the dimensions of the magnetic shunts as parametric variables in the Optimetrics tab in the Project Manager. The tank loss was obtained graphically depending on the parametric change in the magnetic shunt dimensions.

Figure 2. Star–star-connected external excitation circuit.

Figure 3. Flowchart of parametric analysis.
In Figure 3, the input data for the flowchart are defined as follows:

- The transient regime is entered as the solution type.
- In the three-dimensional parametric model, M5 steel was designated as the transformer core and magnetic shunt material, copper as the winding material, and ST-52 steel as the tank material. Magnetic shunts are composed of a series of silicon steel laminations.
- In order to conduct a parametric analysis, the dimensions of the magnetic shunt are defined as variables, and the symbols $\Delta x$, $\Delta y$, $\Delta z$, $\Delta w$, and $\Delta d$ are defined as inputs.
- As this is a three-dimensional analysis, the boundary conditions have not been defined.
- In terms of excitation, the number of low-voltage windings is defined as 190, the number of high-voltage windings is 755, and the number of tap voltage windings is defined as 264 inputs.
- In the context of parametric analysis, the designated analysis time is defined as two milliseconds of input.
- The maximum mesh length is entered for each object. The maximum permissible length of the mesh for the transformer tank is 150 mm.

The ANSYS Electronics Desktop 2021 R1 FEM software was used to perform numerical simulations. Analyses were carried out in the transient solver. Three-dimensional tetrahedral FEM meshes were used to simulate the transformer. It was defined by assigning the winding number of low-voltage, high-voltage, and tap windings to the excitation section. The ANSYS program automatically meshes all objects in the model prior to the commencement of the analysis process. Modifications to the mesh process can be made within the program. The mesh size is contingent upon the geometry of the simulation. The utilization of mesh operations comprising an excess of requisite elements prolongs the analysis and, in certain instances, results in the analysis being terminated, contingent upon the computer’s processor and memory. The performance of the mesh process with a smaller number of elements than is necessary has an adverse impact on the sensitivity of the analysis. In light of these considerations, the maximum permissible mesh length was determined. For the horizontal magnetic shunt transformer tank, the maximum mesh length was 150 mm, and the total mesh number was 39,815. Since a 3D simulation was performed, defining boundaries was unnecessary. The largest object (region) boundary vector potential was considered zero. The results were convergent when the difference between the two iteration results was less than 1%. The circuit shown in Figure 2 was drawn in the SchematicEditor of the FEM software program and simulated by sending it as an external circuit to Excitations created in Project Manager. First, 2-millisecond tank loss samples were taken when the vertical magnetic shunt transformer tank had magnetic shunts only on the short side wall and only on the long front walls. Using these tank loss samples as a reference, the position and size of the horizontal magnetic shunts were determined via parametric analysis. In Figure 4, the green rectangles show the vertical magnetic shunts placed on the tank walls. Figure 4 illustrates the complete set of objects included in the model. These objects comprise a transformer core, windings, magnetic shunts, and a tank. Figure 5 shows the variation in tank loss with time during the 2-millisecond simulation period with vertical magnetic shunts only on the short side wall of the tank and only on the long front walls. The tank loss values obtained were utilized as the basis for comparison.

In the 2 ms analysis, the average tank loss values were 812.30 W and 699.70 W with vertical magnetic shunts only on the short side wall and only on the long front walls of the power transformer, respectively.

Figure 6 illustrates the variables defined for the dimensions of the horizontal magnetic shunts in the parametric analysis. These variables are defined separately for the short side wall and the long front walls of the transformer tank.

$\Delta x =$ the width of the magnetic shunt on the short side wall of the transformer tank (mm);
$\Delta y =$ the height of the magnetic shunt on the short side wall of the transformer tank (mm);
$\Delta z =$ the width of the magnetic shunts on the long front walls of the transformer tank (mm);
$\Delta w =$ the height of the magnetic shunts on the long front walls of the transformer tank (mm);
\( \Delta d \) = the distance between the magnetic shunts on the long front walls of the transformer tank (mm).

The vertical magnetic shunts employed by the transformer manufacturer on the tank wall have a thickness of 15 mm. In order to facilitate an accurate comparison between horizontal and vertical magnetic shunts, the thickness of the magnetic shunts was taken as 15 mm for the horizontal shunts.

![Figure 4](image_url)

**Figure 4.** Three-dimensional model of a transformer with (a) vertical magnetic shunts only on the short side wall and (b) vertical magnetic shunts only on the long front walls.

![Figure 5](image_url)

**Figure 5.** Time variation in transformer tank loss with (a) vertical magnetic shunts only on short side walls and (b) vertical magnetic shunts only on long front walls.

After the variables were defined, parametric analyses were performed for three different situations involving magnetic shunts placed horizontally on the tank wall. Since finite element simulation is time-consuming, it was deemed sufficient to perform parametric analyses for only 2 milliseconds.

In Case 1: While there was no magnetic shunt on the long front walls of the tank, the loss values in the magnetic shunts of different sizes to be placed on the short side wall were investigated. Size-dependent tank loss values were obtained by changing the \( \Delta y \) size by 400 mm at each step from 400 mm to 2800 mm for three different shunts with \( \Delta x \) sizes of 500 mm, 600 mm, and 700 mm.

In Case 2: While there was no magnetic shunt on the short side wall of the tank and \( \Delta z \) was constant on the long front walls of the tank, the losses that occurred when magnetic shunts of different sizes were used were analyzed. The size-dependent tank loss values were obtained by keeping \( \Delta z = 3760 \text{ mm} \) constant and increasing the \( \Delta w \) parameter of the horizontal shunts by 100 mm in each step from \( \Delta d = 300 \text{ mm} \) to 900 mm for 300, 350, and 400.
In Case 3: While there was no magnetic shunt on the short side wall of the tank, the size-dependent tank loss values were obtained for the horizontal magnetic shunt with dimensions of $\Delta w = 400$ mm and $\Delta d = 600$ mm on the long front walls of the tank. The $\Delta z$ value was increased by 300 mm in each step from 2100 mm to 3900 mm.

In Case 4: Tank losses were obtained as a function of the magnetic shunt thickness by using the optimum horizontal magnetic shunt dimensions. The magnetic shunt thickness was increased by 5 mm in each step from 5 mm to 35 mm.

4. Results

This section presents the parametric analysis and full-load simulation results for the best size and location of the horizontal magnetic shunt transformer.

4.1. Results of Parametric Analyses

Figure 7 and Table 3 present the findings of Case 1 regarding the tank loss values obtained via parametric analysis on the short side wall of the tank. The resulting tank loss from the parametric alteration in $\Delta y$, with a fixed value of $\Delta x$, is demonstrated herein.

Table 3. Tank loss values (kW) according to magnetic shunt dimensions (mm) on the short side wall of the tank.

<table>
<thead>
<tr>
<th>$\Delta y$ (mm)</th>
<th>400</th>
<th>800</th>
<th>1200</th>
<th>1600</th>
<th>2000</th>
<th>2400</th>
<th>2800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$ (mm)</td>
<td>500</td>
<td>2.065</td>
<td>1.823</td>
<td>1.355</td>
<td>0.974</td>
<td>0.910</td>
<td>0.881</td>
</tr>
<tr>
<td>600</td>
<td>2.108</td>
<td>1.878</td>
<td>1.254</td>
<td>0.941</td>
<td>0.882</td>
<td>0.849</td>
<td>0.822</td>
</tr>
<tr>
<td>700</td>
<td>2.026</td>
<td>1.814</td>
<td>1.278</td>
<td>0.910</td>
<td>0.805</td>
<td>0.813</td>
<td>0.763</td>
</tr>
</tbody>
</table>

Since the tank loss was 812.30 W with a vertical magnetic shunt only on the short side wall of the tank, the optimum size for the horizontal magnetic shunt was $\Delta x = 700$ mm and $\Delta y = 2000$ mm. In this case, the tank loss was 805.10 W, as shown in Table 3.

Figure 8 and Table 4 present the findings of Case 2 regarding the tank loss values obtained via parametric analysis on the long front walls of the tank. The resulting tank loss, obtained from the parametric change in $\Delta d$ for a fixed value of $\Delta w$, is demonstrated.
4.1. Results of Parametric Analyses

Figure 7. Variations in tank losses for magnetic shunts of different sizes in the parametric analysis of the short side wall of the tank. (a) Tank loss resulting from parametric change in $\Delta y$ for $\Delta x = 500$ mm. (b) Tank loss resulting from parametric change in $\Delta y$ for $\Delta x = 600$ mm. (c) Tank loss resulting from parametric change in $\Delta y$ for $\Delta x = 700$ mm.

Figure 8. Tank losses for different sizes and positions on the long side walls of the tank in parametric analysis ($\Delta z = 3760$ mm constant). (a) Tank loss resulting from parametric change in $\Delta d$ for $\Delta w = 300$ mm. (b) Tank loss resulting from parametric change in $\Delta d$ for $\Delta w = 350$ mm. (c) Tank loss resulting from parametric change in $\Delta d$ for $\Delta w = 400$ mm.
Table 4. Tank loss values (kW) according to magnetic shunt dimensions (mm) and distance between magnetic shunts (mm) on the long front walls of the tank (∆z = 3760 mm constant).

<table>
<thead>
<tr>
<th>∆d (mm)</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆w (mm)</td>
<td>300</td>
<td>1.090</td>
<td>0.829</td>
<td>0.742</td>
<td>0.788</td>
<td>0.793</td>
<td>0.775</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>1.008</td>
<td>0.802</td>
<td>0.746</td>
<td>0.671</td>
<td>0.738</td>
<td>0.802</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.927</td>
<td>0.828</td>
<td>0.758</td>
<td>0.713</td>
<td>0.754</td>
<td>0.725</td>
</tr>
</tbody>
</table>

A power loss of 699.70 W occurred when a vertical magnetic shunt was placed on the long front walls of the tank. For the horizontal magnetic shunt, the loss closest to the vertical magnetic shunt occurred when ∆w = 400 mm and ∆d = 600 mm. In this case, the tank loss was 713.50 W, as shown in Table 4.

The findings of Case 3, which examined the impact of different lengths (∆z) of horizontal magnetic shunts installed on the long front walls, are presented in Figure 9 and Table 5. The effect of the parametric change in ∆z, with a fixed value of ∆w and ∆d, on the tank loss is illustrated.

Table 5. Variation in the power loss (kW) in the transformer tank depending on the length (∆z) of the horizontal magnetic shunt on the long front walls (∆w = 400 mm and ∆d = 600 mm).

<table>
<thead>
<tr>
<th>∆z (mm)</th>
<th>2100</th>
<th>2400</th>
<th>2700</th>
<th>3000</th>
<th>3300</th>
<th>3600</th>
<th>3900</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (kW)</td>
<td>1.579</td>
<td>1.222</td>
<td>1.031</td>
<td>0.853</td>
<td>0.809</td>
<td>0.728</td>
<td>0.693</td>
</tr>
</tbody>
</table>

The tank loss was 699.70 W with a vertical magnetic shunt only on the long front walls of the tank; as such, the most suitable shunt size and distance for the horizontal magnetic shunt were ∆w = 400 mm, ∆d = 600 mm, and ∆z = 3900 mm. In this case, the tank loss was 693.10 W, as shown in Table 5.

The optimum dimensions for the horizontal magnetic shunt and the distance between the magnetic shunts were determined with reference to the tank loss samples of the vertical magnetic shunts. In the analyses, it was determined that the optimum dimensions were ∆x = 700 mm and ∆y = 2000 mm for the short side wall and ∆w = 400 mm, ∆d = 600 mm, and ∆z = 3900 mm for the long front walls.

Once the optimum horizontal magnetic shunt dimensions had been determined, parametric analysis was used to find the optimum magnetic shunt thickness. The tank loss values as a function of the parametric change in magnetic shunt thickness using the optimum dimensions obtained for the horizontal magnetic shunt are shown in Figure 10 and Table 6.
It can be seen from Table 6 that the appropriate magnetic shunt thickness for the tank loss obtained by parametric variation in the magnetic shunt thickness using the optimum dimensions for the horizontal magnetic shunt is 15 mm. As can be seen in Table 6, there is no significant reduction in tank loss after 15 mm. Therefore, the optimum horizontal magnetic shunt thickness was selected as 15 mm.

### 4.2. Full-Load Analysis

The power transformer without magnetic shunts on the tank wall, with a vertical magnetic shunt manufactured and optimized by the transformer manufacturer and a horizontal magnetic shunt with the most suitable size and position obtained via parametric analysis, were analyzed for 100 ms at full load. Figure 11 shows the 3D transformer models representing the magnetic shunts on the transformer tank. The models illustrate three scenarios: the absence of a magnetic shunt within the transformer tank, the presence of vertical magnetic shunts within the transformer tank, and the presence of horizontal magnetic shunts within the transformer tank. Figure 12 displays the tank loss plots of the analysis results. The tank loss graphs presented here illustrate the performance of transformer models with varying magnetic shunt configurations. The models in question lack a magnetic shunt in the tank, possess a vertical magnetic shunt, and feature a horizontal magnetic shunt. Figure 13 provides an illustration of the current density distribution within the tank. The current densities depicted in Figure 13 correspond to transformer models that lack a magnetic shunt within the tank, possess a vertical magnetic shunt within the tank, and feature a horizontal magnetic shunt within the tank. Figure 14 illustrates the flux density distribution within the magnetic shunts. The aforementioned magnetic flux densities pertain to the vertical and horizontal magnetic shunt models. 

The simulation time was 13 h 31 min 49 s for the transformer model with a horizontal magnetic shunt in the tank; 13 h 5 min 10 s for the transformer model with a vertical magnetic shunt in the tank; and 12 h 21 min 37 s for the transformer model without a magnetic shunt in the tank. Table 7 compares the analysis and experimental results produced via the simulation for various scenarios. The modeling results for the vertical magnetic shunt closely match the experimental results obtained in the factory for the identical transformer. The simulation findings show a decrease of 2.27% in tank loss, 7.14% in shunt loss, and 2.39% in overall loss compared with the experimental results. These findings indicate that the experimental and simulation results agreed. The acquired results confirm the precision of the established model. Thus, the established model yields highly accurate findings in the context of horizontal magnetic shunts.

### Table 6. Variation of power loss (kW) in the tank due to parametric variation of the magnetic shunt thickness.

<table>
<thead>
<tr>
<th>Magnetic Shunt Thickness (mm)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Loss (kW)</td>
<td>0.335</td>
<td>0.076</td>
<td>0.050</td>
<td>0.047</td>
<td>0.045</td>
<td>0.042</td>
<td>0.042</td>
</tr>
</tbody>
</table>

![Figure 10](image-url)  
**Figure 10.** Tank loss graph of parametric change in the magnetic shunt thickness.
The tank loss graphs presented here illustrate the performance of transformer models with varying magnetic shunt configurations. The models in question lack a magnetic shunt in the tank, possess a vertical magnetic shunt, and feature a horizontal magnetic shunt. Figure 13 provides an illustration of the current density distribution within the tank. The current densities depicted in Figure 13 correspond to transformer models that lack a magnetic shunt within the tank, possess a vertical magnetic shunt within the tank, and feature a horizontal magnetic shunt within the tank. Figure 14 illustrates the flux density distribution within the magnetic shunts. The aforementioned magnetic flux densities pertain to the vertical and horizontal magnetic shunt models.

Figure 11. Three-dimensional view of the analyzed power transformer and magnetic shunt models: (a) without magnetic shunt; (b) with vertical magnetic shunt; and (c) with horizontal magnetic shunt.

Figure 12. Tank loss changes at full load: (a) tank loss graph at full load without magnetic shunt in transformer tank; (b) tank loss graph at full load with vertical magnetic shunt in transformer tank; and (c) tank loss graph at full load with horizontal magnetic shunt in transformer tank.

Table 7. Comparison of analyses and experimental results for different types of magnetic shunts.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without Magnetic Shunt</th>
<th>Vertical Magnetic Shunts</th>
<th>Horizontal Magnetic Shunts</th>
<th>Experimental Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank loss (kw)</td>
<td>22.76</td>
<td>10.75</td>
<td>11.22</td>
<td>11.00</td>
</tr>
<tr>
<td>Shunt loss (kw)</td>
<td>---</td>
<td>0.26</td>
<td>0.38</td>
<td>0.28</td>
</tr>
<tr>
<td>Shunt volume (cm³)</td>
<td>---</td>
<td>154,518</td>
<td>114,600</td>
<td>154,518</td>
</tr>
</tbody>
</table>
walls had a width of 3900 mm and a height of 400 mm. The distance between the magnetic shunt; (Figure 14) in the context of horizontal magnetic shunts.

The analysis results were validated using the experimental data. Parametric analyses were carried out for the transformer with a horizontal magnetic shunt; (Figure 13) in its tank. The location and dimensions of suitable horizontal magnetic shunts were determined via parametric analysis. The parametric analyses revealed that the magnetic shunt on the short side wall of the transformer tank had a width of 700 mm and a height of 2000 mm. The magnetic shunt on the long front walls had a width of 3900 mm and a height of 400 mm. The distance between the magnetic shunts was 600 mm. The thickness of the magnetic shunt was 15 mm. The transformer was analyzed for 100 ms at full load based on the acquired magnetic shunt location and size. The analysis results were validated using the experimental data.

5. Conclusions

In this study, samples of the tank losses were taken from the short side and the long front walls of a vertical magnetic shunt transformer tank, which had been manufactured on a commercial scale and had been optimized. Taking these loss examples as a reference, parametric analyses were carried out for the transformer with a horizontal magnetic shunt in its tank, based on the finite element method. The location and dimensions of suitable horizontal magnetic shunts were determined via parametric analysis. The parametric analyses revealed that the magnetic shunt on the short side wall of the transformer tank had a width of 700 mm and a height of 2000 mm. The magnetic shunt on the long front walls had a width of 3900 mm and a height of 400 mm. The distance between the magnetic shunts was 600 mm. The thickness of the magnetic shunt was 15 mm. The transformer was analyzed for 100 ms at full load based on the acquired magnetic shunt location and size. The analysis results were validated using the experimental data.
Twenty-one and five magnetic shunts were used in the vertical and horizontal magnetic shunt transformer tanks, respectively. The number of magnetic shunts used was successfully reduced. Magnetic shunt volumes of 154,518 cm$^3$ and 114,600 cm$^3$ were used in the transformer tanks with vertical and horizontal magnetic shunts, respectively. A 25.83% reduction in the magnetic shunt volume was achieved. The total power loss for the vertical magnetic shunt, including the tank loss and the magnetic shunt loss, was 11.01 kW, and that for the horizontal magnetic shunt was 11.60 kW. The horizontal magnetic shunt demonstrated a 5.35% increase in loss. The power loss in the tank without a magnetic shunt was 22.76 kilowatts. Implementing a horizontal magnetic shunt decreased the tank loss by 49.03%. The maximum magnetic flux density in the horizontal magnetic shunts was lower than in the vertical magnetic shunts. The maximum current density in the horizontal magnetic shunt transformer tank was lower than that in the vertical magnetic shunt transformer tank. Additionally, the shunt size and tank loss relationship were determined via parametric analysis, and preferences were presented to the transformer manufacturer.

Author Contributions: M.Ç., Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing—original draft, Writing—review and editing. B.G. and ˙I.H., Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing—original draft, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author İrem Hazar was employed by Best Transformer Incorporated Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References


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