Reduction stray loss on transformer tank wall with optimized widthwise electromagnetic shunts

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Abstract

This paper presents an optimized widthwise electromagnetic shunt as a cost-effective way to reduce the stray losses in transformer tank walls. A 1000 KVA, 10/0.4 kV oil immersed distribution transformer is used. 3-D finite element method (FEM) has been used to analysis and study the impact of proposed magnetic shunt on the reduction of tank losses. In this paper different combinations of optimized magnetic shunt have been studied. The paper compares the performance of proposed optimized magnetic shunt with the available conventional shunts. Considerable reductions in stray losses on the transformer tank wall are obtained by using the combinations of electromagnetic shunt with optimal thickness. Compared with aluminum shields and conventional electromagnetic shunt, the proposed optimized widthwise magnetic shunt reduces stray losses by 13.96%.

1. Introduction

Stray losses in the distribution transformers tank wall, due to high eddy currents near the low voltage bushes have received relatively little attention. Nowadays, we have seen those contributions and suggested the use of small inserts in the transformer to reduce the stray losses in tank walls [1]. In that paper, two-dimensional (2D) finite-element have been used to estimate the reduction of stray losses in transformer tank wall with low-cost plate inserts. In order to reduce the overheating of the flange–bolt region the copper links have been used to ensure the connection of both the cover and tank body in [2]. The failures that caused by the hot spot in transformer tank wall are included in the 13% of the total failures that happens in power transformers due to other causes [3]. Accordingly, it is important to analyze the growth of leakage flux and stray losses in the tank walls. To reduce the stray losses in the region of the tertiary voltage bushings (TVBS) of the transformer an L-shape non-magnetic stainless steel insert (SSI) has been proposed in the literature [4]. A T-shaped stainless steel plate was used in [5] for the elimination of hot spots and reduction of eddy current losses in the cover plates of distribution transformer. Based on results of that paper, T-shaped plate significantly reduces the load loss. C-shape electromagnetic shield has been proposed in [6] to protect a clamping frame of stray fluxes produced by high current leads (HCLs) of low voltage bushings. In [7], the influence of magnetic shunt geometry on the transformer leakage field is examined. The shape optimization of power transformer magnetic shunts, causes the significantly reduction in stray losses in the tank wall. Suitable magnetic shunts placed on the walls of the transformer tank, causes the increase of magnetic leakage field and also can increase the winding leakage inductance [8,9]. The stochastic-deterministic approach is used in [10], to optimal placement of a wall-tank magnetic shunt.

In our previous article [11], leakage losses and leakage currents in the structural component of the transformer based on the surface impedance method have been carefully investigated. So, this paper presents the optimized magnetic shunt to reduce the stray losses in transformer tank wall, with taking into account the results of previous article.

This paper is organized as follows. Section II briefly presents the estimation of stray losses on transformer tank wall. In the Section III, conventional magnetic shunt has been used in order to reduce the stray losses on transformer tank wall. Section IV introduced an optimized widthwise magnetic shunt to reduction of stray loss on transformer tank wall. Section v concludes this paper.

2. Calculation of stray losses in tank wall based on finite element method without magnetic shunts

FEM is a numerical technique to solve the differential and integral equations such as electromagnetic, magneto static, thermal conductivity, solid and structural mechanics and fluid dynamics. The basic idea of FEM is sub dividing physical problems with complicated differential equations into a number of sub-problems and dissolving these equations in the linear systems [7]. In order to calculate the stray loss in the transformer tank wall, using of vector potentials methods need to a great deal of elements (mesh) whereas the skin depth of the tank wall is small when compared with their geometry dimensions. Because of this, the magnetic field does not penetrate deep into the conductor. In this paper for accurate calculation of stray loss, the surface impedance boundary condition with the following relation between the tangential component of the electric and magnetic fields is applied [11].

$$Z_s = \frac{E_s}{H_s} = \frac{1+j}{\sigma\delta} = (1+j)\sqrt{\frac{\pi f \mu}{\sigma}} \qquad (1)$$

In this equation, E_s is the electric field and Hs is the peak value of the tangential magnetic field. Based on surface impedances method the stray loss can be calculated as below:

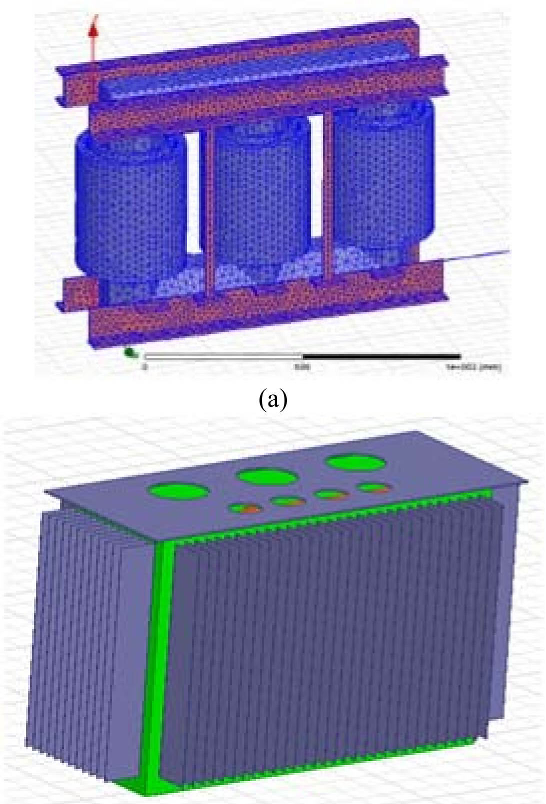
$$P_{sur} = \frac{1}{2}\iint \mathrm{Re}(Z_s) H_s^2 dA \qquad (2)$$

$$\mathrm{Re}(Z_s) = \sqrt{\frac{w\mu}{2\sigma}} \qquad (3)$$

$$P_{sur} = \iint \sqrt{\frac{w\mu}{2\sigma}} \frac{H_s^2}{2} d_s \qquad (4)$$

where P_{sur} is in W/m^2.

Fig. 1 demonstrated the three dimensional modeling of the core and tank under mesh operation. The tank wall made of stainless steel with 1.5 mm thickness.



(a)

(b)

Fig. 1. a) 3D mesh operation, b) tank wall of studied transformer

Based on 3D finite element method and the result of previous literature [11] the stray loss on transformer tank wall under unbalanced voltage shown in Fig. 4a. It can be seen in this fig that when a phase voltage is higher than of nominal value, because the increase of leakage flux, especially near this phase, the stray loss will increase considerably in comparison with normal case. More detailed description about the calculation of stray losses based on finite element method can be found in [11]. It can be seen in this paper that with increase the amount of VUF% stray losses and eddy current density on tank wall increases.

3. Reduction of stray loss at transformer tank wall using conventional vertical magnetic shunts

Hot spots and eddy current losses reduction in the structural components of distribution transformer such as core clamps and tank wall are the critical factors to improve transformer designs. The aim of this section is to reduce the leakage losses in the tank walls of transformer with the conventional magnetic shunts. In this study, electromagnetic shunts built using laminated steel. Accordingly, it must be modeled with non-linear anisotropic permeability. In order to modeling the nonlinearities of electromagnetic shunt, M5 type steel have been used. The B-H cure of M5 is shown in Fig.2.

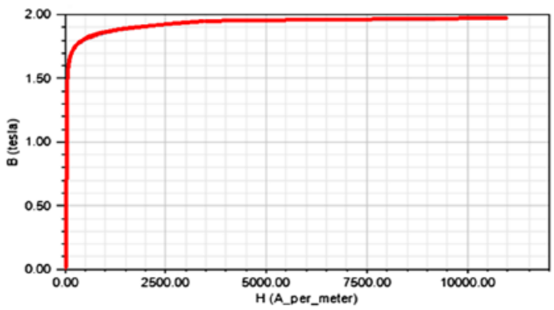


Fig. 2. B-H curve of laminating type of M5 material

Fig. 3 shows the conventional widthwise shunts that placed on the tank wall. Table 1 shows the magnetization characteristic and dimension of conventional vertical magnetic shunts that used in this paper to reduce the stray losses on transformer tank wall. The magnetic shunts with creating a low reluctance path carry most of the leakage flux. Series expansion of eddy-current loss has been used in [12] to calculate the stray losses in magnetic shunts. If magnetic shunts are of adequate thickness with lower watts'/kg characteristics, the losses in them are almost negligible. The altitude of magnetic shunt should be higher than of windings. If non-magnetic conductor such as Aluminum shields used instead of magnetic shield, the leakage flux repelled by them may find a path through nearby structural components. That is the disadvantages of non-magnetic shields.

Table 1. Properties of electromagnetic shields

	A	B	C	D	E	F	G
Magnetic shunts	450	10	970	4,365	13,8	$1,1*10^6$	8055

Where A length (mm), B width (mm), C height (mm), D volume (m3)*10-4), E Thermal conductivity (W/m.c), F conductivities (siemens/m), and G mass density (kg/m3)

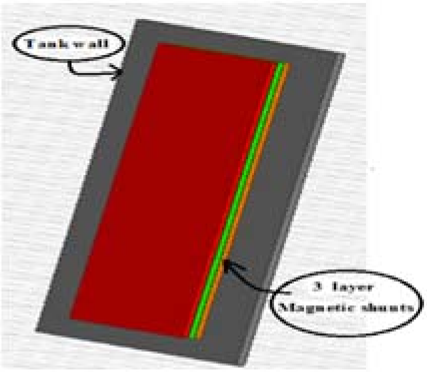


Fig. 3. Conventional widthwise electromagnetic shunt

The simulation results carried out on a 1000 kVA transformer, whose walls were internally lined with conventional electromagnetic shunts. Fig. 4a and 4b shows the distribution of eddy current density with and without placed magnetic shunts. As shown, conventional electromagnetic shields reduced the eddy current on transformer tank wall. But, this kind of magnetic shunt is not a cost-effective approach to reduce the leakage flux and stray losses on transformer tank wall.

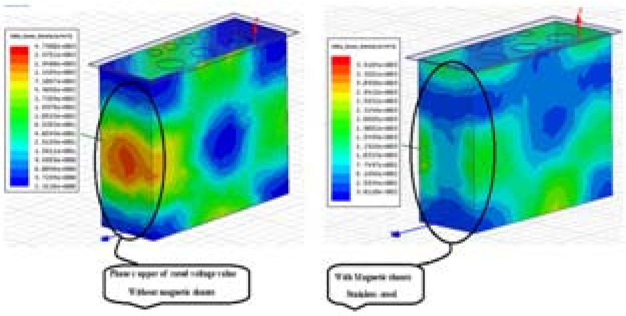
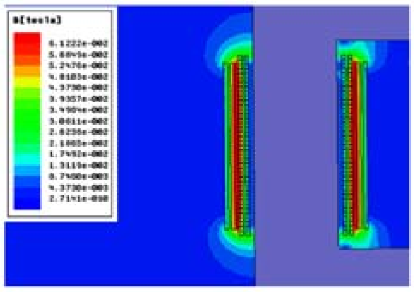
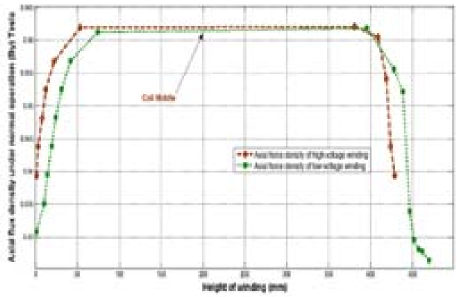


Fig. 4. Eddy current density on tank wall, a) without conventional magnetic shunt, b) with placed conventional magnetic shunt

As it shown in our previous work [13], the axial flux density at the middle part of the primary and secondary winding is higher than in comparison with the bottom and top of windings. Fig. 5a shows the resultants of the radial and axial components of the leakage flux density distribution in the primary and the secondary transformer windings. Fig. 5b shows the axial flux density versus high of winding under rated current of transformer in the primary and secondary winding. Therefore, leakage flux that flowing into the tank wall from the middle of the windings will be very high. Hence, in the next section optimized widthwise shunt based on geometry optimization has been presented in order to have an electromagnetic shunt as a cost-effective way to reduce the stray losses on transformer tank wall.



(a)



(b)

Fig. 5. Simulated resultants of the a) radial and axial components of the flux density b) axial flux density under rated current

3. Reduction stray loss on transformer tank wall with optimized widthwise magnetic shunt

Utilizing the axial flux distribution that studied in the above sections as well as in [13], since the leakage flux density is the maximum at the centers of the electromagnetic shields, an optimized widthwise magnetic shunt in different lengths have been developed in this section, as shown in Fig.6. The characteristics of the shields that placed on the tank walls are the same as those of the shields that shown in Table 1. All electromagnetic shields are made up of rectangular plates of different sizes.

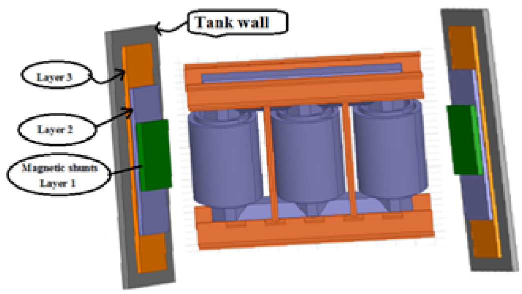


Fig. 6. Optimized widthwise electromagnetic shield

The dimensions of the plates that specified with L_1, L_2, L_3 must be determined in order to minimize the following objective function (W). To prevent the localized heating of transformer tank wall, the maximum value of eddy current density (J_{em}), must be less than of the specified eddy current density (J_{emo}).

$$W = V + P \qquad (5)$$

In this equation P expressed by the following Eq. (6) and V is the volume of shield plates.

$$V = 10(L_1 + L_2 + L_3)10^{-3} \tag{6}$$

$$P = \begin{Bmatrix} 0 & (J_{em} < J_{emo}) \\ J_{em} & (J_{em} \geq J_{emo}) \end{Bmatrix} \tag{7}$$

J_{em} is expressed by Eq. (8)

$$J_{em} = \sqrt{|J_{ex}|^2 + |J_{ey}|^2 + |J_{ez}|^2} \tag{8}$$

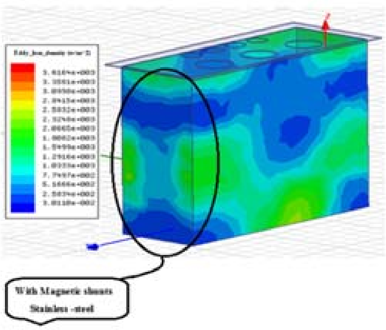
The restriction of the width of $L_1 - L_3$ is given below.

$$0 < (L_1, L_2, L_3) \leq 0.05 \tag{9}$$

The volume of L_1, L_2, L_3 shield plates related to the various combinations examined is shown in Table 2.

Table 2. Volume of shield plates related to different electromagnetic shield combinations

Magnetic Shunt	Length (mm)			Width (mm)			Height(mm)			Volume (m³)× 10⁻⁴
	Piece 1	Piece 2	Piece 3	Piece 1	Piece 2	Piece 3	Piece 1	Piece 2	Piece 3	
Case 1	450	450	450	5	4	1	290	630	970	2,223
Case 2				5	2	3				2,529
Case 3				5	1	4				2,682



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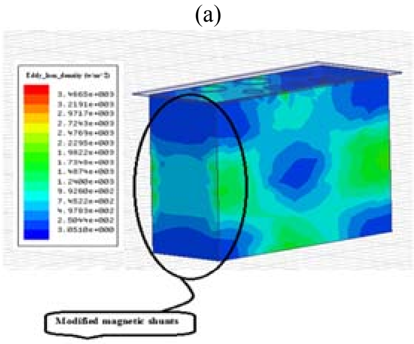
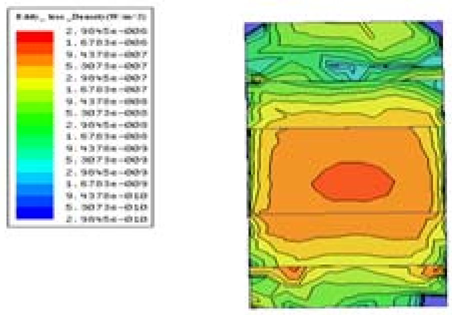


(b)

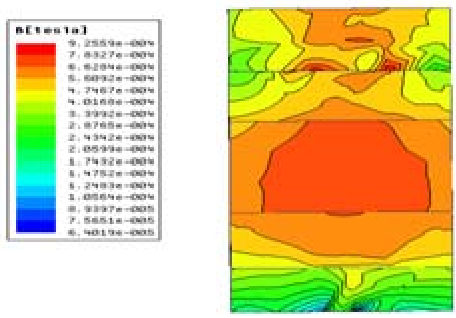
Fig.7. Eddy losses distribution of the transformer tank walls a) with conventional electromagnetic shielding b) with optimized electromagnetic shielding (combination 3)

Currents induced in the aluminum shields, produce a magnetic field. This magnetic field, partially eliminate the leakage flux, thereby causes the reduction of leakage losses in transformer tank wall. As given in Table 3, when electromagnetic shields are not used, based on finite element method the leakage loss under unbalanced voltage in the transformer tank wall obtained as 750.44 W [11]. When the optimized electromagnetic shields (combination 1) are used in the same unbalanced voltage condition, the leakage losses in the tank walls reduced by 645.65 W. Also, when aluminum shields are used in the same condition, the value of the leakage loss is 682.78 W. As a result, in the three-phase 1000 kVA distribution transformer under the same condition, the leakage losses of transformer tank wall using the optimized magnetic shunt decreased by 13.96% and also using the aluminum shields it decreased by 9%.

Fig. 8a shows the distribution of eddy losses on the surfaces of the electromagnetic shields (combination 1).As mentioned in the previous section, if the electromagnetic shields are made from CRGO laminations with sufficient thickness and low watts / kg, the electromagnetic shunts would have negligible losses. Fig. 8b shows the distribution of leakage flux at the surface of the optimized electromagnetic shields (combination 1). As seen in Fig. 8b, because of the axial leakage flux, the distribution of flux density in the middle of the electromagnetic shield is higher than of the other regions.



(a)



(b)

Fig. 8. a) Eddy loss density distribution, b) Leakage flux distribution on the used electromagnetic shield surfaces (Combination 1)

Table 3. Reduction of leakage losses in tank walls

The voltage of one phase is above a rated voltage is another phase is below of rated voltage (VUF= 4,8%)	Stray loss density (w/m^2)	Eddy current density on Tank wall A/m^2	Leakage Flux on Tank wall (T)	Stray loss on Tank wall (W)	reduced stray losses (%)
Balanced Voltage	4,3433*10^3	$5,6574*10^4$	$3,2723*10^{-3}$	695.53	-----
Unbalanced Voltage	$4,7950*10^3$	$5,8403*10^4$	$3,5927*10^{-3}$	750,44	---------
Using Aluminum shield in case of unbalanced voltage	$3,8214*10^3$	$4,9305*10^4$	$2,3488*10^{-3}$	682,78	9%
Using Conventional electromagnetic shunts in case of unbalanced voltage	$3,6164*10^3$	$4,7944*10^4$	$1,8573*10^{-3}$	662,56	11,71%
Using optimized electromagnetic shunts in case of unbalanced voltage (combination 1)	$3,3660*10^3$	$4,4839*10^4$	$1,7344*10^{-3}$	645,65	13,96%
Using optimized electromagnetic shunts in case of unbalanced voltage (combination 2)	$3,4196*10^3$	$4,5382*10^4$	$1,7557*10^{-3}$	651,60	13,17%
Using optimized electromagnetic shunts in case of unbalanced voltage (combination 3)	$3,4665*10^3$	$4,6812*10^4$	$1,7999*10^{-3}$	657,82	12,34%

4. Conclusions

An optimized widthwise electromagnetic shunt to reduce the leakage losses on the transformer tank walls has been proposed in this paper. Magnetic wall shunts are modeled with nonlinear high permeability and the corresponding losses are calculated using the 3-D finite element method. This method is called the "flux shunting" mechanism. In this way, the flux from the electromagnetic source is directed towards the magnetic material. Thus, these shields attracted the leakage flux and it causes a decrease in the eddy losses on transformer tank wall.

The proposed optimized electromagnetic shunt has been compared with conventional electromagnetic shunt and aluminum shielding using the finite element method. According to the results obtained, optimized electromagnetic shields were found to be more effective to prevent leakage currents than others.

5. References

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