Paper ID 292

Effect of Size and Position of Pinholes on Transformer Core Loss

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Abstract: This paper presents the investigation of the variation of core loss due to the effect of pin holes in the transformer core which are used to stack the core sheets in a step lap pattern. A three-phase distribution transformer with a rating of 160 kVA, 11 kV/ 415 V has been selected for the investigation. The transformer model was developed using SolidWorks software and examined for the no-load loss using finite element analysis software ANSYS Maxwell. Simulation results were obtained for different pin hole sizes and positions. The flux variations in the core, with and without pin holes are analyzed. Based on the core loss, the optimum pin hole diameter and positions are determined. Analysis shows that the hysteresis loss is not significantly affected by the pin holes while the eddy current loss has an effect from pin hole diameters. Analyzing the results, the optimum pin hole diameter is determined as 6 mm corresponding to an increased loss of under 1% of the loss. Results further show that placing the pin holes where the flux distribution is a minimum, reduces the core loss. The results of the analysis are planned to be implemented in an actual distribution transformer.

Keywords: transformer core, core loss, core stacking, step lap, pin hole

Introduction

Power system reliability mainly depends on the efficient working of the power transformers which are key components in the power system. Estimation of the core losses in the transformer is a vital issue, and has to be implemented in the design stage of the transformer. Accurate prediction of these losses is becoming more important in the design and also in the economic aspect [1].

In the transformer, a combination of hysteresis loss and eddy current loss is the main contributor to the core loss [2]. It is initiated by the magnetizing current required to energize the core of the transformer. The magnitude of the eddy current is reduced by using laminated sheets insulated from each other. Laminations are lapped to avoid air gaps developing in the magnetic core. Of the two methods of lapping commonly used in distribution transformer cores, the step lap joints are considered superior to the butt-lap joints when considering the magnetic characteristics such as magnetizing current, core losses and noise level [3]. The material used in the manufacturing of the core is grain oriented electric sheet steel with Silicon around 3% by weight [3]. The grain oriented laminations have to be precisely aligned to get the maximum benefit. Thus pin holes are made in the laminations to aid aligning. These pin holes increase the core loss. If the pin holes are made very small the aligning pins would bend, so that they need to be of a minimum size. The position of the pin holes will aid the alignment when placed in the middle, but shifting it away from the main magnetic path would reduce the losses.

Thus the present study examines the practice of the currently used sizes of pin holes and their positions with regard to the magnetic field and the corresponding core loss.

Arrangement of the Transformer Core

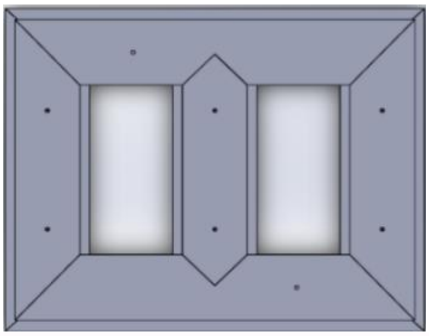

Fig. 1. Surface view of 3-phase Transformer with solid stacks

Initially, a three-phase transformer, with three solid stacks, shown in Fig. 1, was designed to actual dimension (used in LTL Transformers) of 160 kVA, 11 kV/ 415 V transformer using SolidWorks software with the actual positions of the pin-holes shown in Fig. 2.

The cross-section of the core with three stacks of different widths are shown in Fig. 3 and the holes and slots used as guides during assembly of the core are shown in Fig. 4.

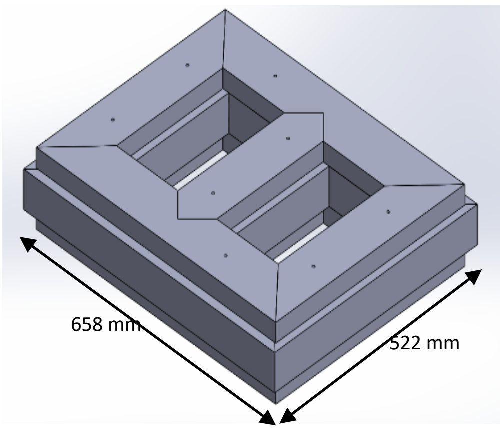

Fig. 2. Actual positions of pin holes

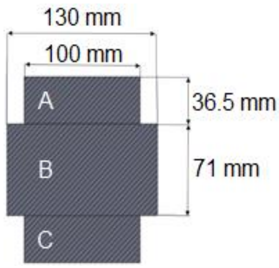

Fig. 3. Cross sectional view of a limb of the experimental core

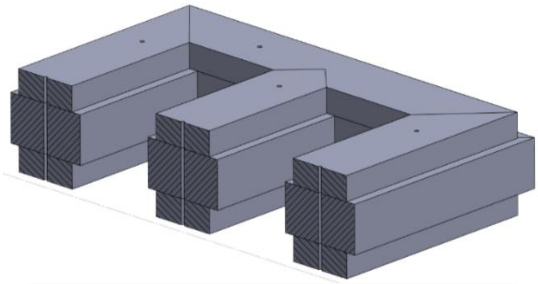

Fig. 4. Cross sectional view of the core with three stacks of solid

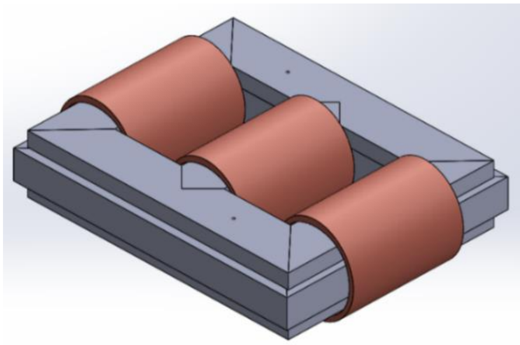

Fig. 5. Transformer core with windings

Since the purpose of the study is to determine precisely the flux paths and the corresponding losses in the core, only a single energized winding per phase was considered in calculating the core loss as the other winding would normally be kept open during the test. The low voltage winding of copper foil was accordingly designed using SolidWorks and the Transformer core with windings shown in Fig. 5.

A. Different pin hole diameters

The transformer core was designed for no pin hole and for varying pin hole sizes of 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 14 mm, 16 mm and 60 mm diameters to observe the core loss variation and flux distribution of the transformer with the pin hole sizes.

B. Different pin hole positions

For the calculation of transformer core loss for different pin hole positions, models were developed with varying pin hole positions from the original transformer model. Fig. 6 shows the designed models for the varied positions for 6 mm diameter pin holes and Fig. 7 shows the varied positions for 10 mm diameter pin holes.

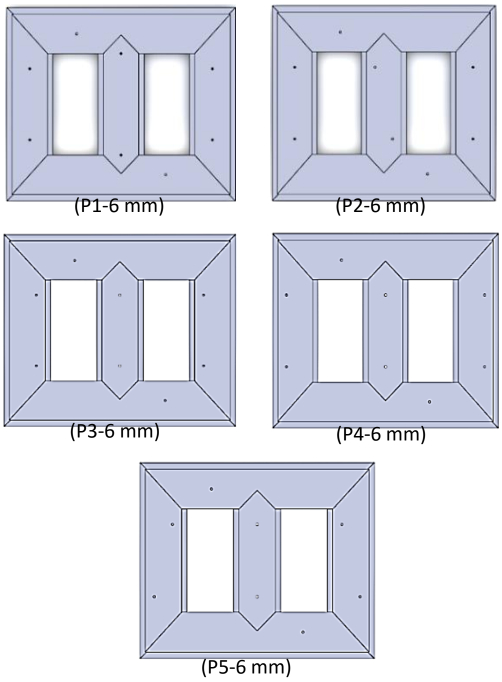

Fig. 6. Proposed positions for 6mm diameter pin holes

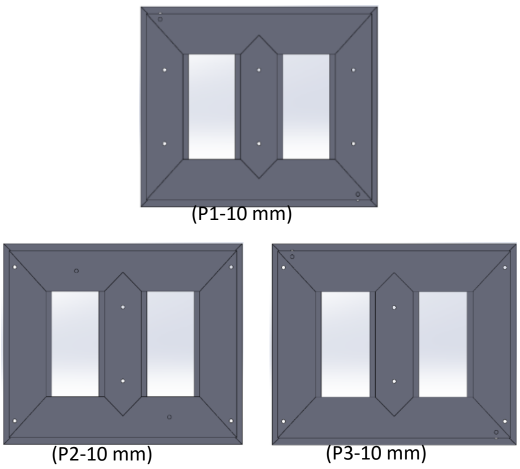

Fig. 7. Proposed positions for 10mm diameter pin holes

Methodology

ANSYS Maxwell, a field simulation software based on finite elements was used to study the time varying electromagnetic fields in the transformer core. The automatic adaptive mesh generation available in the software removed the complexity from the analysis process [4] and presented in the Fig. 8.

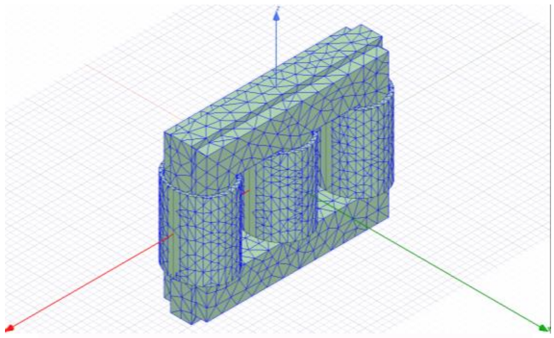

Fig. 8. Mesh plot in inside selection/ Length based operation

A higher mesh resolution has been used in regions where accuracy is important and to obtain reliable computed results. As adaptive mesh refinement is possible in Maxwell static solvers, the required level of accuracy has been achieved. For core loss analysis, only a low voltage winding is considered in each limb as no load test is done by open circuiting the high voltage side of the transformer. Actual voltages, and winding resistance values were assigned for all three windings and results were obtained for a defined time period for the transient simulations.

The material used for the core is 27ZH100 silicon steel and by assigning a lamination factor, the same effect of the laminated core can be obtained for the solid stacked core. Fig. 9 and Fig. 10 show the B-H (Flux density - Magnetic force) curve and B-P (Flux density - Specific core loss) curves respectively for this material.

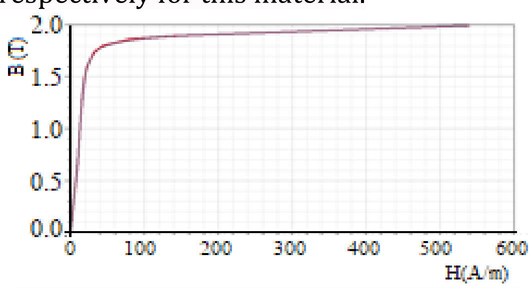

Fig. 9. Flux density (B) vs Magnetic force (H) curve

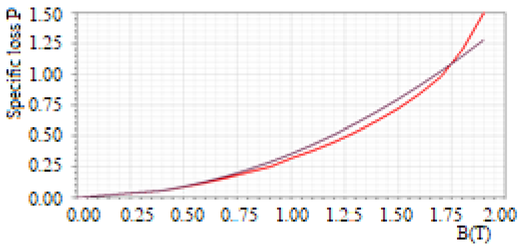

Fig. 10. Specific core loss (P) vs Flux density (B) curve

Results Analysis

Flux distribution of the transformer core with, without pin holes and different positions of pin holes were analyzed using the results of the simulations using the ANSYS Maxwell Software. Time variations of input voltage, induced voltage and current curves for low voltage winding were obtained. The obtained time variation of core loss graph includes hysteresis loss and eddy current loss and the obtained core loss was averaged over 100 ms to 120 ms.

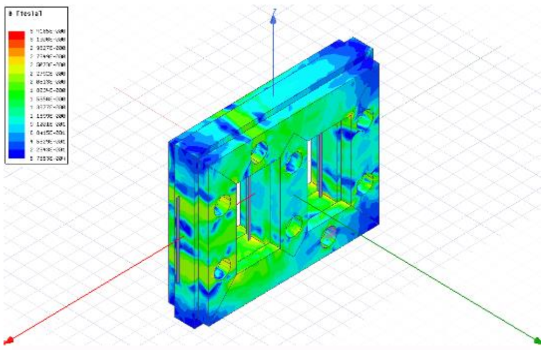

Fig. 11. Flux Distribution in Core with 60 mm diameter Pinholes

To understand how the pinhole diameter impacts on the core, and validate the analysis, loss, an exaggerated 60 mm diameter pinhole was designed, and the flux distribution seen in Fig.11. It can be observed that either sides of the pinholes have a dense flux which express that the pinholes have been considered correctly in the simulation. Fig. 12 shows the deviation of the arrows (showing the direction of the flux) near the pinholes showing the effect of pinholes for the flux distribution.

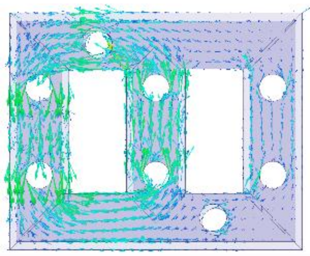

Fig. 12. Vector diagram of flux distribution of core with 60mm diameter pin holes

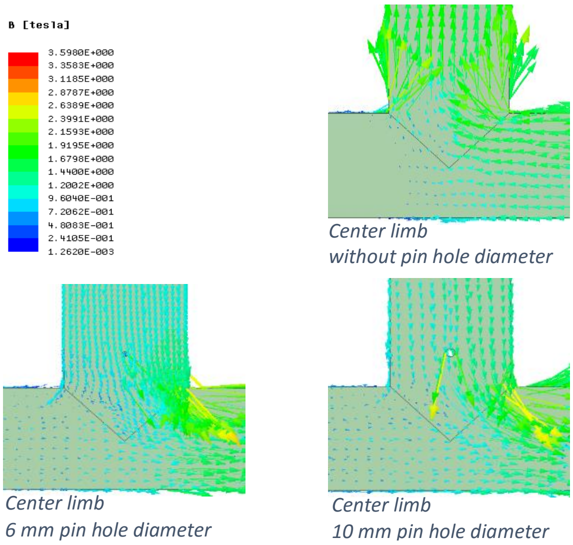

Fig. 13. Flux distribution in center limbs with out pin holes, with 6 mm and 10 mm diameter pin holes

Fig. 13 shows the flux distribution in the centre limb in the absence of pin holes, and in the presence of 6 mm and 10 mm diameter pin holes. It is seen that the flux distribution near the pin holes shows a slightly visible deviation. It is obvious that when the pin hole diameter increases, the deviation of the flux path is also high. Similarly, it can be seen that flux path is disturbed in the core limbs with pinholes than the core limb without pin holes. Colour of the flux lines can be read by using the colour bar and the flux density value that obtained was 1.76 wb/m^2.

Using the standard EMF equation of Transformer given in equation (1), the flux density is determined.

$$\mathbf{v = 4.44BAfT} \qquad (1)$$

where; v - Voltage (rms)

B - Magnetic flux density

A - Cross section area of a core limb
f – Frequency
T - Number of turns

$$B = \frac{415/\sqrt{3}}{4.44 \times (16530 \times 10^{-6} \times 0.95) \times 50 \times 39} \quad (2)$$

$$B = 1.76\ \mathrm{Wb/m^2}$$

(A has been multiplied by a factor of 0.95 to represent minute air gaps that may be present in between laminated sheets.)

The input voltage graph and induced voltage graph are shown in the Fig. 14 and Fig. 15 respectively.

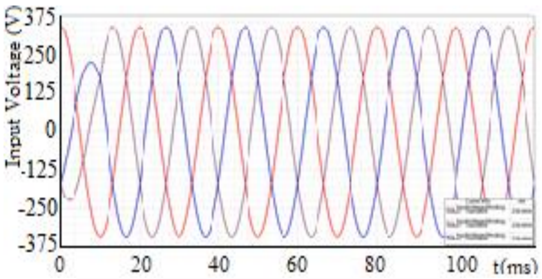

Fig. 14. Input voltage versus Time

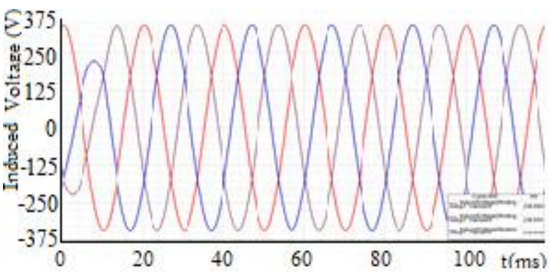

Fig. 15. Induced voltage versus Time

E. *Pin hole Diameter*

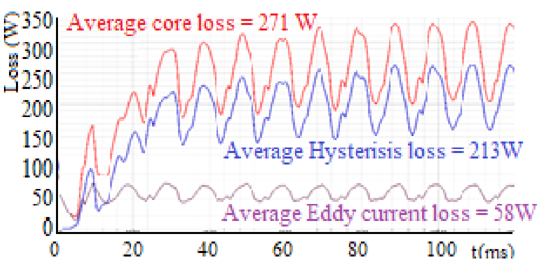

Fig. 16. Eddy current loss, Hysteresis loss and Core loss versus Time for no pin holes

The Fig. 16 presents the time variation of core loss obtained for the core with no pin holes. The core loss is the summation of both eddy current loss and hysteresis loss, and it is observed that the eddy current loss is less than the obtained hysteresis loss. As per the results, a nonlinear increasing core loss was obtained.

Table 1 shows the percentage values of core losses with respect to the core without and with pin holes. Accordingly, quite a large difference can be observed between 6 mm diameter pin hole and the 8 mm diameter pinhole and, a smaller difference between the 8 mm diameter pin hole and the 10 mm diameter pin hole. The effect of the pin hole diameter on the transformer core loss can be clearly identified. It proves that the core loss has been greatly affected by the pin hole diameter.

Table 9. Percentage change Core Loss Variation for Pinhole Diameter

Pin hole diameter (mm)	Total Core Loss (W)	Percentage change (%)
0	271.2384	0
4	271.4972	0.095
6	273.7431	0.923
8	288.5775	6.392
10	300.0218	10.611
12	301.0507	10.991
14	302.2046	11.416
16	305.5936	12.666

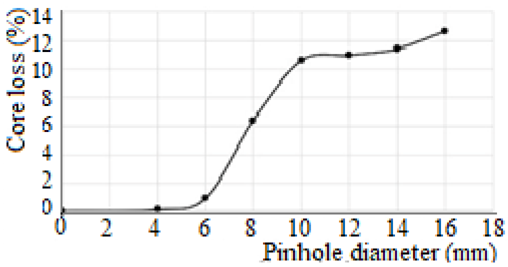

Fig. 17. Core loss variation for different pin hole diameters

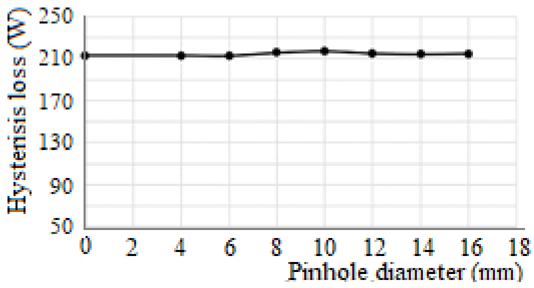

Fig. 18. Hysteresis loss variation for different pin hole diameters

Fig. 18 shows that there is hardly any effect on the hysteresis loss with the increase of pin hole diameters.

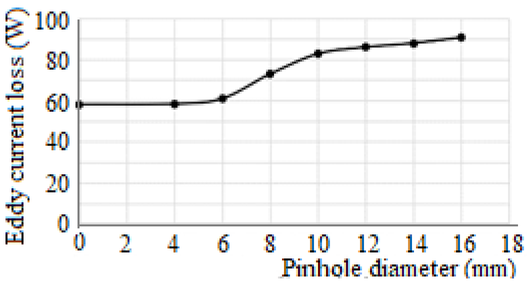

Fig. 19. Eddy current loss variation for different pin hole diameters

Fig. 19 depicts a significant effect on the eddy current loss with the variation of the pin hole diameter. In particular, it is noticed that there is no significant effect of the core loss (less than 1% of the loss) with pin holes of diameter upto 6 mm, and a significant increase thereafter.

Practically, the core loss for core with 6 mm diameter pin holes is obtained from the core loss curve for 27ZH100 material as,

Specific core loss = 1.1 W/kg
Weight of the core = 265.3 kg

Therefore, Core loss $= 1.1 \times 265.3 =$ 291.83 W

In the present simulation, only the core loss has been taken into consideration neglecting dielectric loss and copper loss.

Fig. 20 shows the induced current on the low voltage side in each winding for no pin holes.

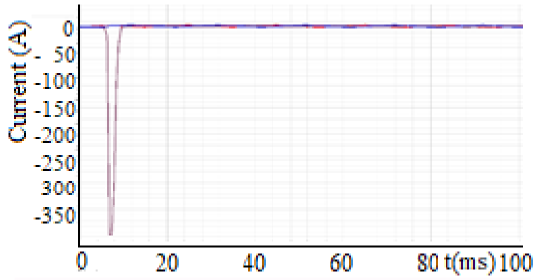

Fig. 20 Induced current in each winding with time for no pin hole

Table 10. Winding Current for different Pin hole sizes for single phase

Pin hole diameter (mm)	Current (A)
0	1.4228
4	1.456
6	1.6955
8	4.0834
10	8.5386
12	17.6709
14	26.4944
16	37.5703

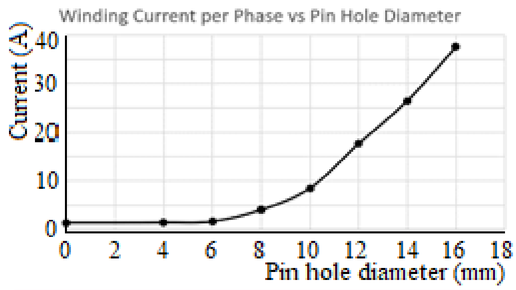

Fig. 21. Magnetizing current Variation for Different Pinhole diameters

Fig. 21 represents the variation of magnetizing current for pin hole diameters. As per the graph, only a slight increase in the magnetizing current is visible with pin holes of diameter upto 6 mm and a gradual increase thereafter. The fact is that the increase in magnetizing current means the increase in core loss which in here implies that the loss increases with the pin hole diameter as the magnetizing current increases. Thus, increasing pin hole diameter unnecessarily will leads to increase of core loss. Accordingly, the pin hole diameter of 6 mm can be considered as the optimum pin hole size for the particular transformer core.

B. *Pin hole Position*

The positions of the pin holes were decided by considering the flux distribution in the core. As in the Fig 6, five different pin hole positions were selected for the core with 6 mm diameter pin holes. Fig 22 shows the variation of the core loss with the pinhole positions. It is noticed that there is no significant change of the core loss with the different positions compared to the existing position.

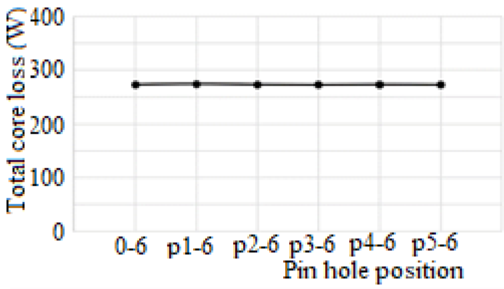

Fig. 22. Total Core loss variation for different pin hole positions of 6 mm diameter

For further analysis of the effect of the pin hole positions, a core with a greater pin hole diameter was selected and decided on various pin hole positions as in Fig. 7 where there is low flux concentration. The selection was done with the sole purpose of determining the effect of the pin hole position to the core loss without considering the mechanical strength of the core.

As the significant change was observed, it was able to identify that the pin hole positions affect the flux distribution and the core loss.

The Fig. 23 shows the variation of core loss with the change of pin hole positions for 10 mm diameter. According to that P0-10 is the position kept as the reference and other positions were the proposed positions to determine the effect. It can be seen that there is a specific variation in the core loss and it is graphed in decreasing order of core loss values. Thus, the position P3-10 can be considered as the optimum pin hole position where there is a lesser core loss. The reduction of magnetizing current variation with the pin hole positions further implies the variation of core loss which is not mentioned here. But this result is valid only to determine the effect of pin hole positions to the core loss and it may be not practical in manufacturing.

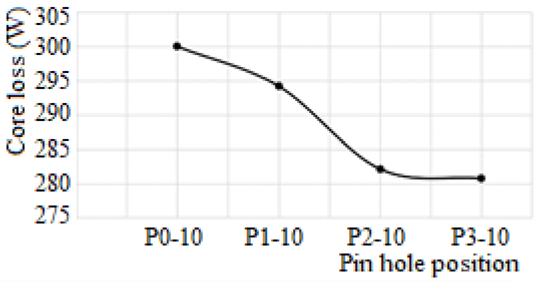

Fig. 23. Total Core loss variation for different pin hole positions of 10 mm diameter

Conclusion

The paper has presented an analysis of the variation of the core loss with the size and position of the pin holes in the stacking of step-lap transformer cores.

For a 160 kVA, 11 kV/ 415 V 3-phase distribution transformer, by analysing the range of pin holes 0 to 16 mm diameters, the study has shown that there is a visible increase in the core loss (from 0.92% to 6.39%) with the increase of the pin hole diameters from 6 mm to 10 mm. Further, the contribution of the pin hole diameter to the change of the hysteresis loss is negligibly small but has a significant effect on the eddy current loss.

When referring to the magnetizing current, it has been observed that the 6 mm diameter pin hole is also the optimum pin hole size, as up to that value gives a very low currents and rapidly increasing values as the current increases beyond 6 mm.

When different pin hole positions are considered, for small pin holes, the pin hole position has very little effect on the core loss compared to the normally used pin hole positions of the same diameter. But with 10 mm diameter pin holes, the changes in the pin hole positions show a significant variation in the total core loss compared to the existing pin hole positions of the same diameter pin holes. Hence it is clear that when the diameters of pin holes increase, the effect for the pinhole positions is greater and thereby it affects the total core loss. This further verifies the suitability of the core with 6 mm diameter pin hole size as optimum for the selected transformer.

In modelling a transformer, both practical and theoretical issues should be considered. For the 160 kVA transformer considered, the optimum pin hole diameter is 6 mm although the lesser diameters give a less core loss, smaller pin hole sizes will be difficult to handle. The increase in percentage core loss of the core with 6 mm diameter pin holes with respect to the core without pinholes is about 0.92%, which justifies the use of 6 mm diameter pin hole.

With regard to the position of the pinhole, with the 6 mm pin hole, position has very little effect. However positioning should preferably be in the low flux region for larger pinhole sizes than 6 mm. However in manufacturing a transformer as per the suggestions, the mechanical strength and the life expectancy should be assured atleast to the extent achieved in here.

Acknowledgement

Excellent completion of the project became a reality with the kind support and help of many individuals. We would like to extend our sincere thanks to all of them. Also, our gratitude goes to all academic and non-academic staff of the Electrical, Electronic and Telecommunication department of General John Kotelawala Defence University. We are very grateful to management of LTL Transformers (Pvt) Ltd for giving us immense support on providing test data and all the relevant details of distribution transformers.

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Professor Rohan Lucas, having received his BSc Eng degree in Electrical Engineering, completed his PhD from UMIST in 1974. He is a Senior Professor at the General Sir John Kotelawala Defence University in Ratmalana. He is the author of around 100 research articles on a variety of topics in electrical engineering and related areas. Prof. Lucas is the recipient of many awards including Engineering Excellence Award, Teaching Excellence Award, and many Outstanding Research Performances Awards.