Effect of Artificial Burrs on Local Power Loss in a Three-Phase Transformer Core

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The increase in losses due to burrs occurring on cut edges of electrical steel laminations in transformer cores is difficult to quantify. Artificial burrs were applied to a 350 kVA, three-phase, five packet, transformer core. Total core loss, flux density distribution and local loss near the burrs were measured. Burrs applied to a portion of a packet of laminations in one limb caused the flux distribution to become more non-uniform than normal throughout the whole core. Local losses increased significantly outside the burr region. The loss increased to over 1000 W/kg in the severely burred region at 1.8 T, 50 Hz. Measured flux distribution data was used in simplified eddy current calculations to predict the total and localized losses. The predicted and measured localised losses in the burred regions followed similar trends but did not agree well in magnitude probably due to the errors caused by the simplifications and assumptions which were necessary in the eddy current analysis.

***Index Terms*—Lamination edge burrs, power transformer core losses, electrical steel, eddy currents.**

I. Introduction

Edge burrs, when located in unfavorable positions in a stacked transformer core, create electrical short circuits between adjacent laminations and the resulting eddy currents increase the core losses [1], [2]. The effect occurs when burrs on opposite sides of a stack of laminations form a closed path allowing additional eddy currents to circulate [1]. In extreme cases, localised losses may be high enough to trigger an avalanche effect resulting in catastrophic local core melt and transformer failure. Localized loss in electrical steel laminations, averaged over a region of around 10 mm diameter, is proportional to the linear rate of rise of temperature which occurs in the region immediately after energizing a core [3], [4]. This small temperature rise, normally less than 0.5 C and only linear for a few seconds, can be measured using small temperature sensors coupled to sensitive, low noise measurement equipment [5].

Eddy currents which are induced within the core enclosed by edge burrs, produce a magnetic field opposing the exciting field thus reducing the flux density within the burred region. If burrs are present in one packet of laminations, the flux density in that limb will be reduced so the overall core flux in the other packets must rise resulting in increased losses throughout the whole core and increased magnetizing current [6]. Hence, even if burrs are not serious enough to cause core damage they can reduce the efficiency of a transformer, particularly operating at high flux density.

Although burrs which do occur in a transformer core are probably randomly distributed in small regions, the artificial burrs in this investigation have been set up in a controlled manner over much larger regions than would be expected in practice. Hence, although the localised loss reported here is generally far higher than would be expected in well produced cores, it is easier to measure and therefore interpret the burr effect. The effect of randomly occurring burrs in a transformer will follow similar trends so they can be estimated by scaling down the exaggerated values presented here.

Measured losses have been compared with values calculated from a simple theoretical estimation of the eddy current losses in the burred region and taking into account the change in overall core flux distribution caused by the burrs.

II. Core Model, Measuring Method and Loss Estimation Method

A 388 kg, 3 phase, 3 limb, 350 kVA, 7 multi step-lap, power transformer core was assembled from 0.3 mm thick laminations of high permeability grain oriented 3% SiFe (HGO) with nominal loss of 0.97 W/kg at 1.7 T, 50 Hz. The core was energized at 1.5 T to 1.8 T, 50 Hz under sinusoidal overall flux density.

Fig. 1 shows the experimental core layout.

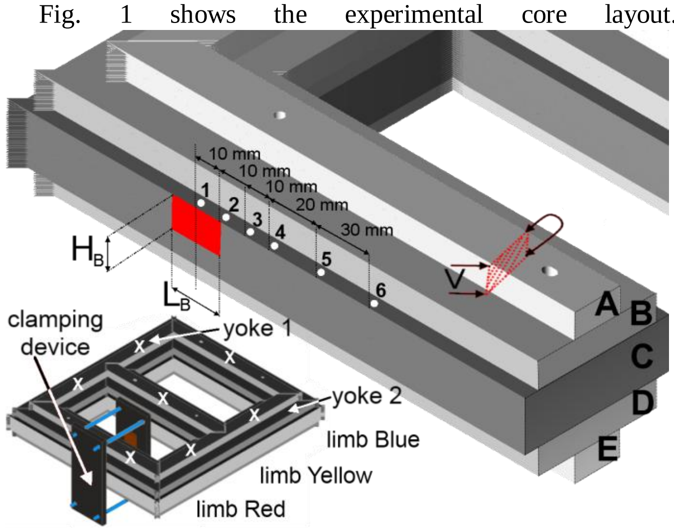

Fig. 1. Experimental core showing clamping rig for applying artificial burrs and thermocouples and needle probe measurement positions.

The clamping device was used for applying artificial burrs of length L_B and height H_B on either side of packet C. L_B was fixed at 25 mm and three values of H_B were used, namely 10

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mm, 15 mm and 20 mm shorting out approximately the top 33, 50 and 66 laminations of packet C which itself comprised 182 laminations, 160 mm width. Copper tape, pressed against the sides of the stack of laminations by wooden blocks and uniformly clamped by steel plates was found to be an effective way of reproducing the effect of burrs [1]. The presence of the clamping device itself did not change the core losses.

The flux density in each packet was measured using needle probes [7] at locations marked X in Fig. 1. Conventional wound search coils were use to measure flux density in the burr region. In the worst case, the uncertainty of flux density measurements was less than 2% at 95% confidence.

Type K Thermocouples were fixed on the lamination at the top of packet C at the positions shown at set distances from the centre of the burr location to measure the initial rate of rise of temperature and hence localised losses with and without burrs. A six channel thermocouple amplifier circuit was connected to a NI 6259 data acquisition card, and the voltage signal was filtered and plotted to obtain the initial slope using the Excel curve fitting function. It was estimated that the localized loss could be measured with uncertainty of ± 6.2 % at 95% confidence.

Total loss was measured using a NORMA D6000 power analyzer with uncertainty of ±5.5% at 95% confidence.

The estimation of the effect of the burr on total and local losses was made based on a modified classical eddy current equation which assumes that thickness of the burred laminations is not negligible compared to material width [1], [8]. The total eddy current loss P_e, in the burred region was calculated as the sum of P_x, the classical thin sheet eddy current loss, and P_y, the loss due to eddy currents (due to the burrs) flowing perpendicular to the laminations surface given by

$$P_x = \frac{\pi^2 f^2 B_{max}^2 H_B{}^2}{6\rho D}, \quad (1)$$

$$P_y = \frac{4\pi^2 f^2 B_{max}^2}{\rho}\left(\frac{1}{3}\left(\left(\frac{b}{2}+d_b\right)^3 - \frac{b^3}{8}\right)\right), \quad (2)$$

where f is the magnetising frequency, B_{max} is the packet peak flux density, ρ is the material resistivity, D is its density, b is the lamination width and d_b is the copper tape thickness as shown in fig 2. The thickness of copper tape represents the thickness of a real burr occurring within the width of the stack.

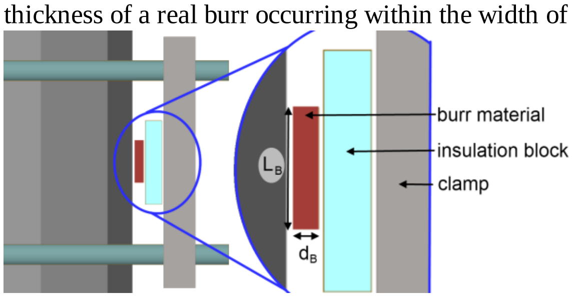

Fig. 2. Top view of the burr clamping showing the insulation block, burr (copper tape) length L_B and thickness d_B.

Because of the additional variation in packet to packet flux density caused by burrs, the values of B_{max} used in (1) and (2) were the values measured in each packet at each location shown in Fig. 1 and not the nominal or overall flux density measured using search coils wound around the full core cross sectional area.

Initially, (1) was used to calculate the sum of the eddy current losses occurring in all packets of the core with no burrs present taking account of the measured change in B_{max}. This was subtracted from the measured loss to obtain the corner joint losses and the sum of hysteresis and excess loss which were assumed to be unchanged by the presence of burrs. In a burred core the sum of (1) and (2) was used to calculate the additional loss in the burred region of packet C and added to the sum of the classical eddy current loss from (1) and the non-eddy losses occurring in the full core to obtain an estimate of the total loss in the burred core.

To obtain data necessary to carry out the above calculation of eddy current loss, the packet to packet flux density and local flux density in the burred region of packet C was initially measured together with the nominal loss versus flux density characteristics of the steel in an Epstein square.

As an example, at 1.7 T, 50 Hz, with 66 laminations burred in stack C in the Red limb the measured flux density within the burred region was 1.18 T. The nominal loss at 1.18 T interpolated from the Epstein data was 0.44 W/kg. To obtain the sum of hysteresis and excess loss the eddy current loss for non-burred stack at 1.18 T, calculated to be 0.14 W/kg from (1) was subtracted from the nominal loss at the same flux density. The eddy current loss in the burred region calculated from (2) was 622 W/kg. (In each case, $\rho = 48 \times 10^{-6}$ Ωm, $D = 7650$ kg/m^3, $d_b = 8 \times 10^{-5}$ m where d_b was assessed by microscope observation of the thickness of the Cu tape used as the artificial burr. The thickness of the Cu tape was chosen to be comparable with actual burr dimensions [9]).

The specific total loss in the non-burred region at the nominal flux density of 1.7 T was calculated in stacks A-E. As an example, at the marked location in stack B in the Red limb the flux density was 1.86 T. The high value of flux density in stack B is due to the presence of the burrs in stack C in the same cross section of the limb. The average flux density within this cross section remains 1.7 T. However, flux is redistributed from part of stack C into all other stacks. The nominal loss at 1.86 T interpolated from Epstein square data was 1.47 W/kg. Similar calculations were made for all regions not directly affected by burrs to obtain total values of specific total loss for the whole core.

III. Results and Discussion

Fig. 3 shows the variation of measured specific total loss with nominal core flux density of the core with the three different burr regions in packet C compared with the variation in the non-burred core and the localised loss at one point in centre of the Blue limb of packet C of the non-burred core.

The local loss in the centre of the outer lamination of packet C in the Blue limb of the non-burred core is lower than the total per unit core loss but higher than the Epstein loss due to the building factor of the core which in this case is around 1.25 at 1.7 T. The local loss result is shown here to verify that it is consistent with the known building factor and to give confidence to the validity of the local losses measured in burred regions.

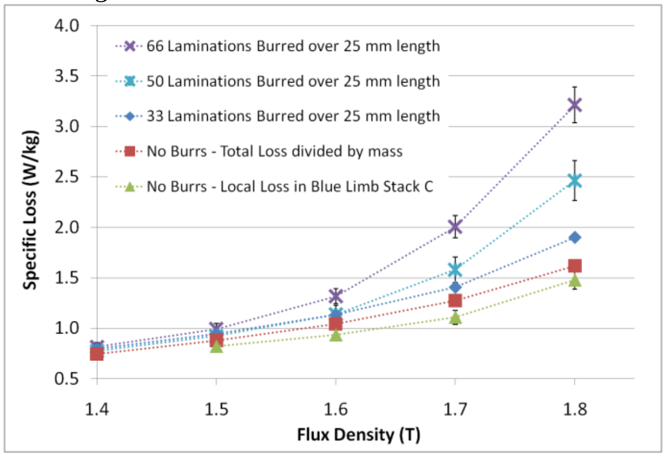

Fig. 3. Variation of specific loss with overall flux density of the core for 25 mm long burrs of different heights compared with the non-burred core and the localised loss in the Blue limb, stack C on the top lamination

According to the modified classical eddy current equations (1) and (2), the loss increase should be proportional to the square of the peak flux density and the number of burred laminations. However, in the core with the largest burr region covering 66 laminations, the specific total loss increases by 13% at 1.5 T and by 100% at 1.8 T. Likewise, the additional eddy current loss should be proportional to H_B^n where n should be constant but it ranges from 2 to 8 depending on flux density suggesting that other factors are involved. Obviously the assumptions that no leakage flux is caused by the burrs, hysteresis and other losses are constant and the model is only valid for constant permeability and sinusoidal flux all contribute to the difference between measured and theoretical variation of eddy current loss with flux density and burr area.

The relationship between the overall flux density of the core and the peak flux density in the cross sectional area occupied by 66 burred laminations is shown in Fig 4. The values are similar at low and high flux density but between 1.0.T and 1.5 T the flux density in the burred region is significantly reduced by the eddy currents.

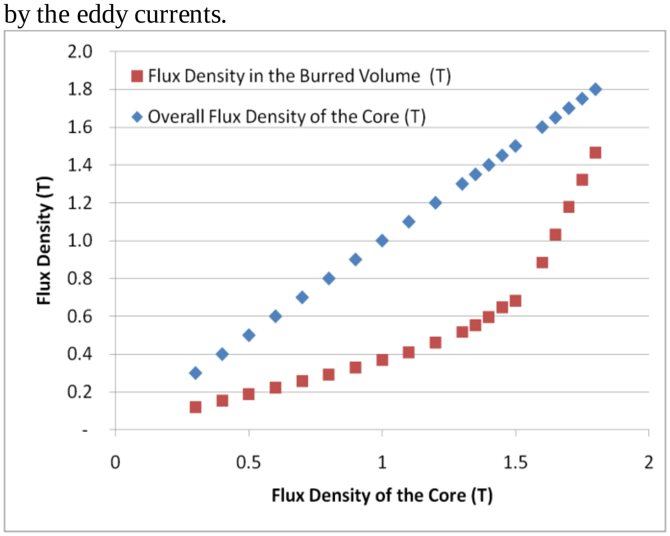

Fig. 4. Variation of flux density within 66 lamination burred region with overall core flux density.

At low core flux densities, the flux flows along the low reluctance path around the burred volume which results in a close to linear relationship between the applied field and effective flux density up to about 1.3 T. At average core flux densities approaching the knee of the magnetization curve, the permeability drops in the regions not affected by the burrs and the reluctance becomes higher than within the burred volume hence the flux density increases more rapidly.

Fig. 5 shows the effect of increasing the number of burred laminations on the local loss in the centre of the burred region at core flux densities from 1.5 T to 1.8 T. Between 1.5 T and 1.7 T a square relationship exists between the loss and the number of laminations but this breaks down at higher flux density. It is well known that even when the overall flux density is sinusoidal, harmonics do occurs in individual packets and even laminations in a packet [10]. In the burred cores it is suspected that these harmonics will increase particularly at high flux densities so the estimations, which are based on sinusoidal B, become less accurate.

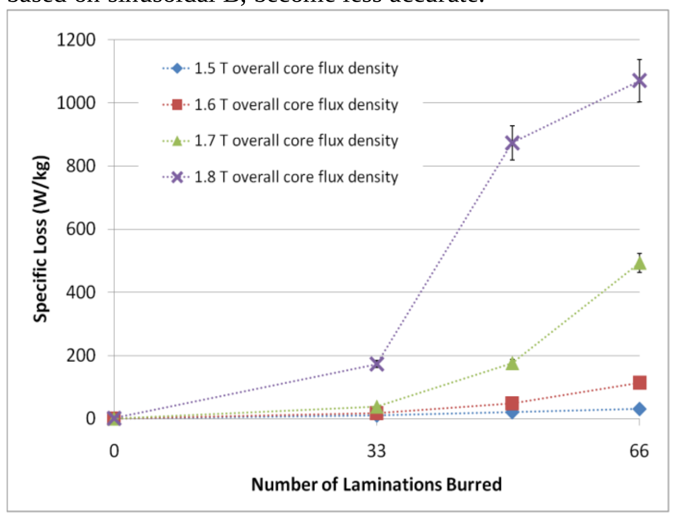

Fig. 5. Variation of specific loss measured by initial rate of rise of temperature method with number of laminations burred at point 1 (centre of the burred region)

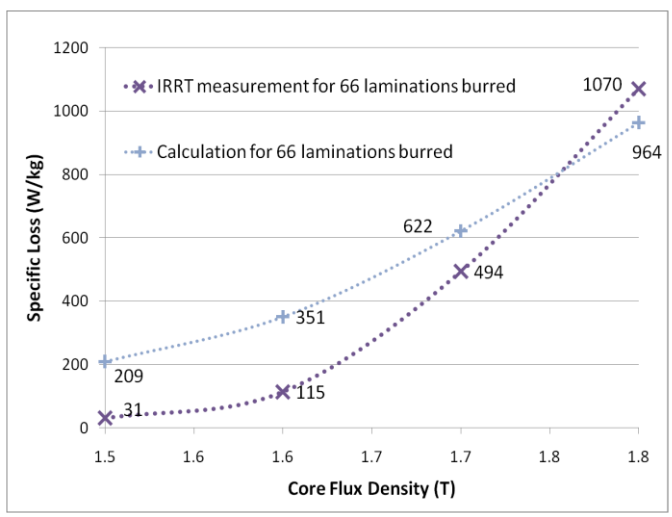

Fig. 6. Comparison of Specific Loss measurements by initial rate of rise of temperature method and the estimation made taking into account the flux distribution measurement within the core affected by burrs.

A comparison between the measured and calculated localised loss in the presence of a 66 lamination burr at the centre of the burr location is shown in Fig 6. The correlation is poor over much of the flux density range. The difference between the measurement and the estimation is mainly due to the assumption that flux density is uniform throughout the whole volume affected by the burr. However, due to the fact that burrs effectively increase the thickness of the lamination from a single layer to 33, 50 and 66 layers respectively, flux density in the middle of the burred region is significantly lower than near the top and bottom laminations affected [8]. The assumption that excess and hysteresis losses remain unchanged after the burr is applied is unlikely to cause such differences. The most likely explanation is that the region affected by the burr is far greater that that enclosed by the two pieces of conductive tape used to create the short circuits on the sides of the burred packet so the simple eddy current analysis is flawed. The local loss was measured at positions 3–6 to determine the extent to which it changes in a longitudinal direction outside the 25 mm burred length.

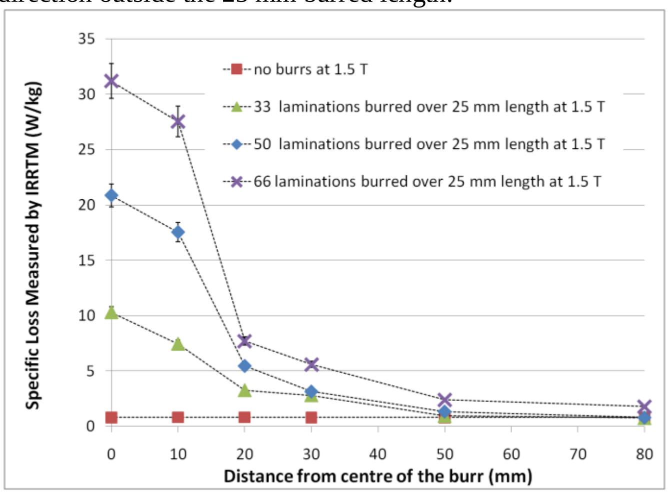

Fig. 7. Variation of specific loss measured using the initial rate of rise of temperature method with distance from the centre of the burred region.

Fig. 7 shows the result at 1.5 T overall core flux density. In all cases the local loss increases as far as 70 mm from the edge of the burred region.

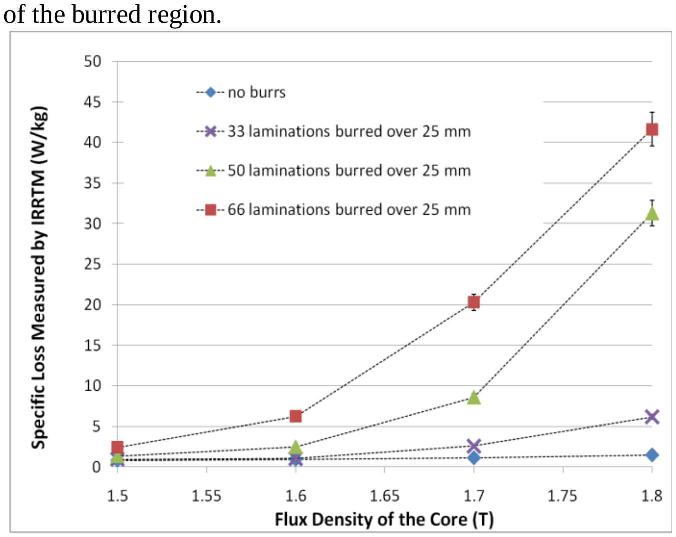

Fig. 8. Variation of specific loss with average flux density of the core 37.5 mm outside one edge of the 25 mm long burr.

Fig. 8 confirms the large increase of loss 50 mm from the centre of the burr over the full flux density range. This confirms the importance of including the effect of additional eddy currents in this volume outside the main burr region in the eddy current calculation. However it does not explain why the loss appears to be overestimated at low flux density and underestimated at high values. It is also possible that rapid heat transfer in the burr regions where rapid heating occurs may cause the initial rate of rise of temperature measurement method to become inaccurate and another source of error.

IV. Conclusion

This work has demonstrated that burrs can cause flux distortion in cruciform stacked cores as well as high localised heating within and outside the burred region. Flux density within regions affected by burrs is significantly lower than the average flux density within the experimental core limb and other regions correspondingly overfluxed.

Poor correlation was found between measured and calculated effects of burrs most probably due to the oversimplified eddy current model used but also perhaps due to breakdown of the thermal loss measurement technique due to rapid heat transfer near the burrs. Although the artificial burrs studied here have a far greater detrimental effect than expected from real burrs, the trends in the findings will still apply.

Acknowledgment

This work was supported by ThyssenKrupp Electrical Steel

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