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Comparison of Power Loss and Magnetic Flux Distribution in Octagonal Wound Transformer Core Configurations

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Abstract – In this paper, various configurations of octagonal wound transformer core topology, which has previously proved advantages on conventional wound cores, are studied. Each configuration has different joint types and different placement of joint zones on the core. Magnetic flux distributions and power losses of each configuration are analyzed and compared. Comparisons are based on both 2D&3D finite element simulations and experimental studies. The results show that, joint types and their placements on the core cause local flux accumulations and dramatically affect power loss of the core.

Keywords: Transformer, Octagonal wound core, Joint gap, Flux distribution, Core loss

1. Introduction

Transformers are widely used electrical machines to step up and down voltage level in transmission and distribution systems. Even if they operate with very high efficiencies, due to reached high VA values and numbers of the transformers installed in a power system, loss minimization studies gain great importance. Among the losses, iron losses are particularly important, considering the fact that the transformer is continuously energized, and therefore, considerable energy is consumed in the core, while load losses occur only when the transformer is on load.

Different methods of stacking core steel have been used in transformer production. The butt lap method, using rectangular core section, was applied to core design and given best results with non-oriented steels. With the development of grain-oriented steel, due to the permeability is higher in the direction of the grain, the lamination sections are mitered at a 45° angle at the corners and T-joints, where the flux changes direction by 90° [1]. By improving the quality of the steel and using better building and design techniques, iron losses can be reduced [2, 3]. The modern multistep-lap method uses various numbers of layers of differently shaped sections. With this method, each layer is cut into slightly different lengths and their corners have slightly different shapes. However, the joint zones keep containing air gaps, which are occupied by low permeability air or oil, and overlaps that cause the magnetic field lines to jump to adjacent laminations. This deviation of the magnetic field lines with respect to the rolling direction creates localized regions of higher magnetic flux density and therefore increased losses. In [4-9] it was proved that core losses in joint regions are closely dependent on the magnetic field in the laminations, physical properties of the core material and construction parameters of the joint region such as the number of steps, the number of lamination per step, size of gaps and lamination thickness.

With such core construction, flux path is interrupted by joints at least four times in a single phase core type and eight times in a three phase shell type transformer cores. In addition to the air gaps, cutting or slitting can introduce localized stresses which degrade the magnetic properties. Wound cores are important alternatives for these problems. In one type of wound core construction, the core is wound into a continuous coil, and is cut so that it can be inserted around the coils. The cut laminations are then shifted relative to each other and reassembled to form a staggered or stepped type joint. With this construction, flux path is interrupted by joints only two times. In addition, a wound core without any joints could also be constructed by wounding steel strips around the coils, or the coils would need to be wound around the core. Techniques for doing this are available but are somewhat costly [10]. As a result, in larger power transformers, stacked cores are more common, whereas in small and medium distribution transformers, wound cores predominate. Wound cores show better performance and increased efficiency compared to the stacked cores.

A novel wound core design, which has octagonal shape and also called Unicore, was introduced in 1990s by AEM Cores Ltd. This construction emerged from conventional wound structure with the purpose of reducing losses and manufacturing cost while preserving all the advantages of conventional wound core. Manufacturing process and comparison of these two constructions by means of the size, weight, excitation current and eddy-current losses are expressed in [11]. Today, with the capability of processing

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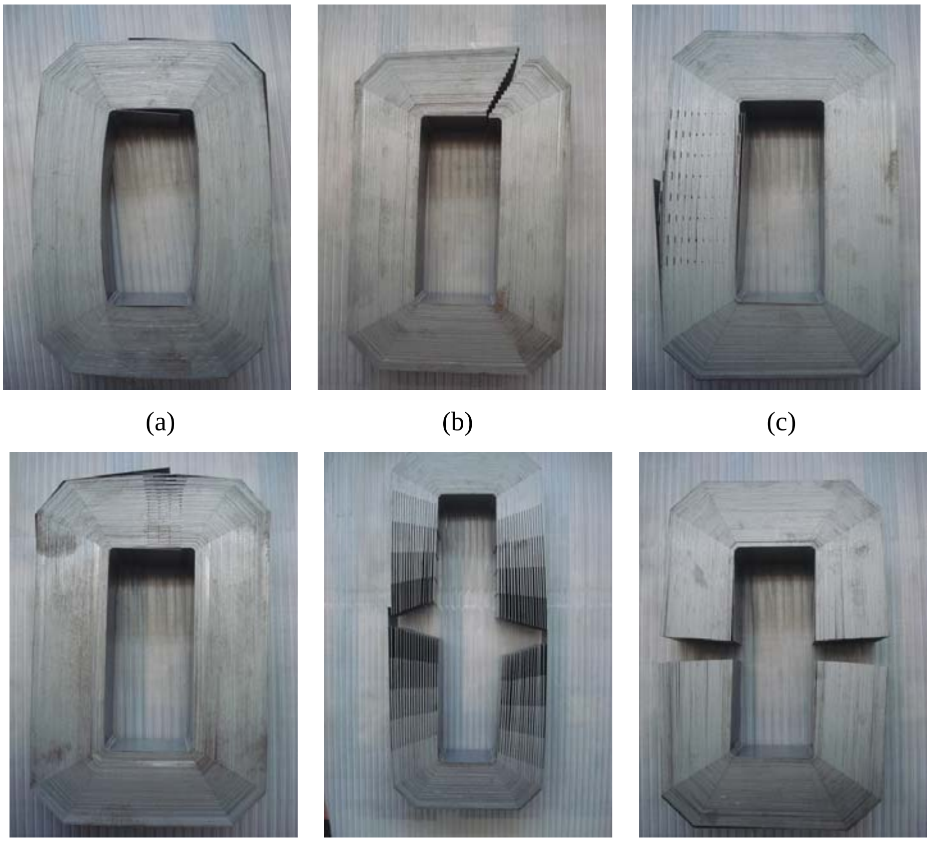


Fig. 1. Examined core configurations, (a) Core-1, (b) Core-2, (c) Core-3, (d) Core-4, (e) Core-5, (f) Core-6

steel strips up to 425mm wide, producing octagonal wound core distribution transformers up to 5MVA is possible.

This study is focused on octagonal wound core configurations. Six different octagonal wound core configurations are analyzed and compared. Each core has different joint types and different placement of joint zones on the core, from each other. Effects of these differences on the flux distribution and no-load power loss which is an important parameter for a transformer, are investigated, by means of simulations and experimental studies. Obtained results are also commented in terms of the effect on core manufacturing processes.

2. Studied Core Configurations

A series of finite element analyses and experimental studies were carried out using designed six different octagonal wound core transformer configurations, given in Fig. 1. Advantages of octagonal wound construction were previously explained in literature.

Core-1 is a basic octagonal wound core. There is no any joint zone or air gap on the flux path. So, circulating magnetic flux is not interrupted.

Core-2 has a concentrated joint region on the upper yoke of the core. This region was designed in multi-step lap construction as one book with fifteen steps and twelve plates per step.

Core-3 has the joint region on the left limb of the core. This joint was designed in multi-step lap construction with eight steps per book and two plates per step.

Core-4 has its joint regions on the upper yoke of the core. This region was assembled in multi-step lap construction with four steps per book and two plates per step.

Core-5, which is also called as duo-core, has joint regions on both limbs. Each region was assembled in multi-step lap construction with five steps per book and two plates per step.

Core-6 was assembled as a combination of two C-shaped core parts. Each part was built by cutting each lamination with required length, bending them at each of the four corners and arranging them to obtain a C-shaped core.

At test bench, given in Fig. 2, cores are supplied by a California Instruments 4500Lx programmable AC power source, in order to magnetize the cores from 0.6T to 1.5T with pure sinusoidal voltage waveform. For voltage, current, magnetic field and power measurements, a Tektronix

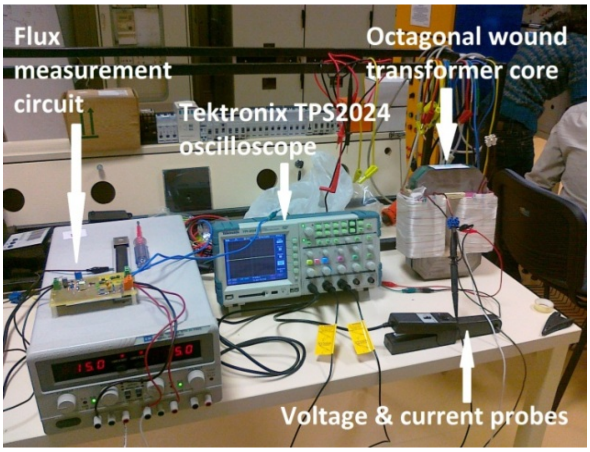


Fig. 2. Experimental setup

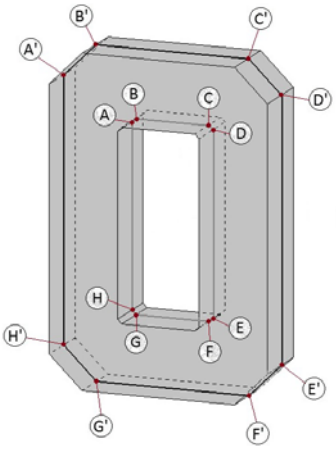


Fig. 3. Octagonal wound core with interior and exterior virtual flux paths

TPS2024 digital storage oscilloscope and a FLUKE 41B power analyzer are used.

3. Flux Distributions

2D and 3D finite element simulations are intensively carried out to define magnetic field distributions of cores. Magnetic flux densities and loss distributions of studied core configurations are analyzed and compared under equal excitation conditions. Extensive experimental analyses are also studied.

Magnetic flux distributions on the core regions are investigated to define the effects of joint areas. For this aim, two different virtual paths are defined along the laminations. First path is drawn into the middle of the interior lamination. Second path is similarly drawn into the middle of the exterior lamination of the core. These virtual flux paths begin from the points of A and A', respectively, and follow their way on the clockwise direction as shown in Fig. 3.

Magnetic flux density distributions along created virtual paths on interior and exterior laminations are given in Fig.4 for all studied octagonal wound cores. Due to the lengths of these two paths are different, these lengths are converted into unit length and measured flux values are placed onto the same axis. These results were obtained from finite element analyses for the average flux density of 1.5T in the core cross sections.

Effects of joint gaps are observed by means of obtained flux distribution waveforms of studied cores.

Without joint gaps, as given in Fig. 4(a) for Core-1, the flux density inside the sheets would be uniform. Due to the magnetic flux density is smallest and useless in the corners of the conventional circular wound cores, these corners are trimmed at octagonal construction. However, flux densities on the corners of all studied cores, labeled from A' to H' in Fig.3, are calculated around 0.6T as given in Fig.4 which are still smaller than average core flux density.

Magnetic flux lines turn into the sheet of the next step when approaching a gap. These gaps cause local disturbances of flux distribution which results a peak on flux waveform. Magnitude of these peaks are directly related to the factors such as gap width, number of plates per step and distance of two neighbor gaps on both vertical and horizontal direction.

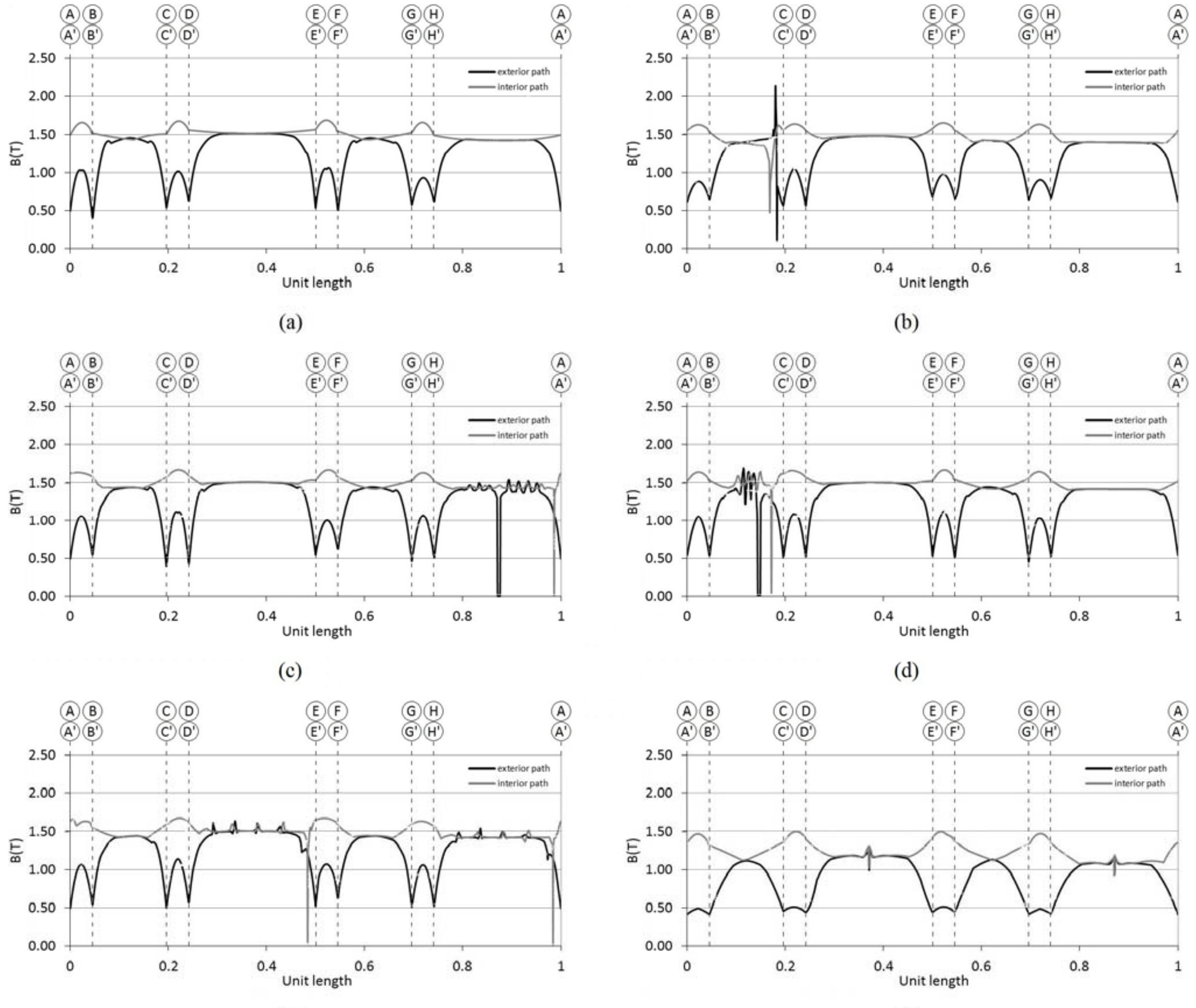
For an operating flux density of 1.5T, the flux density in Core-2, which has a concentrated joint region on the upper yoke, is calculated as 2.2T at joint region on exterior lamination. However, the flux density decreases about 0.1T and 0.5T in the gap, along exterior and interior paths, respectively.

Core-3, which has its joint region on the left limb, air gaps are on the same virtual line on horizontal direction. In other words, gap arrangements of each step in a book are different, but symmetric for all books of the core. As a result, magnitudes of flux peaks are reached up to 1.7T on exterior path.

For Core-4, due to the multi-step lap construction with four steps per book and distance of adjacent gaps are smaller than the construction of Core-3, maximum values of flux density peaks are greater as 1.75T.

However, for Core-5 which has joint region on both limbs, gap arrangement on horizontal direction is not on the same virtual line. In other words, gap arrangements are different for all steps and all books. As a result, magnitude of peaks reaches up to 1.65T on exterior flux path. These results also prove that the gap arrangement is an important factor affecting magnetic flux distribution.

Although all cores are excited by same voltage level, it is clear that, reached magnetic flux densities of all cores are very close, except Core-6. Unlike other tested core samples, average flux density is calculated about 1.2T for Core-6. Cause of this difference is easily obtained by comparing the core constructions of Core-1 and Core-6. Wide air gap surface of the two C-shaped core parts at joint



(a) (b) (c) (d) (e) (f)

Fig. 4. Magnetic flux distributions through interior and exterior virtual paths of; (a) Core-1, (b) Core-2, (c) Core-3, (d) Core-4, (e) Core-5, (f) Core-6

region is the only difference of Core-1 and Core-6. So, it is proven that, this large and concentrated joint region is the unique reason of this difference in average magnetic flux densities.

For all cores, far from the gaps the flux density level is identical in all sheets and equal to the value of the core induction. Similarly, flux densities reach their maximum values at the interior corners which is 15-20% greater than average values for all cores.

4. Core Loss Comparison

General specific core loss expression is given as;

$$P_C = k_h f B^n + k_e f^2 B^2 + k_{ex} f^{1.5} B^{1.5} \qquad (1)$$

under sinusoidal excitation. The three terms on the right-hand side are hysteresis loss, classical eddy current loss and excess loss components, respectively.

In these components, B is maximum amplitude of the flux density; f is the frequency of exciting voltage; k_h, k_e and k_{ex} are hysteresis, classical eddy and excess loss coefficients, respectively. It is obvious that, these loss components are directly flux density dependent. However, loss coefficients k_h, k_e and k_{ex} are also dependent on B, as proved in [12, 13]. As a result of this dependence, each component of total core loss is directly affected by local flux concentrations, which are caused by joint regions through flux path. Losses of each core are investigated experimentally, using test bench given in Fig.2. Results are given in Table 1. Copper losses in excited windings are also measured for all cores. However, considering their

Table 1. Measured core losses and loss variations

	Core-1	Core-2		Core-3		Core-4		Core-5		Core-6	
B (T)	P_c (W)	P_c (W)	ΔP (%)	P_c (W)	ΔP (%)	P_c (W)	ΔP (%)	P_c (W)	ΔP (%)	P_c (W)	ΔP (%)
0.6	1.978	2.941	+48.68	2.104	+6.37	2.198	+11.12	2.288	+15.67	4.103	+107.43
0.9	4.362	6.469	+48.30	4.491	+2.96	4.600	+5.46	5.053	+15.84	9.130	+109.31
1.2	7.608	11.120	+46.16	7.991	+5.03	8.276	+8.78	9.138	+20.11	17.352	+128.07
1.5	13.786	17.929	+30.05	14.455	+4.86	15.326	+11.17	16.479	+19.53	31.114	+125.69

small value, they were neglected.

Core-1 shows best performance at no-load tests, as expected. Due to no joint region on flux path, there is no any additional local flux accumulation caused by air gaps at any part of core. So, measuring the minimum loss value would be possible. Core-1 considered as reference core during comparisons of other core configurations.

Depending on the number of air gaps and their displacement on the core, explained in previous section, measured core losses increase correspondingly. Comparing to Core-1, core losses of Core-3, which has totally 88 air gaps along flux path, and Core-4, which has totally 84 air gaps along flux path, are measured as higher as 4.86% and 11.17% respectively. In spite of the almost equal total number of air gaps, due to the distance of two neighbor gaps through flux path and number of steps per book are smaller, reached flux density value in joint area and measured loss of Core-4 are higher.

Compared to Core-1, Core-2 and Core-6 show the worst performances. Although its step lap construction, as a result of localized joint region, core loss of Core-2 is 30% higher, comparing to Core-1. Similarly, due to the large non-distributed air gaps on both limbs, loss of Core-6 is measured as 125% higher than Core-1. Comparison of measured loss results of Core-2 and Core-6 with the other cores proves the importance of distribution of air gaps, to minimize core losses.

5. Conclusion

Due to their advantages, octagonal wound core topology is becoming an important alternative on conventional transformer core structure, up to 5MVA.

In this paper, six different core constructions of this topology are studied. Differences of these core constructions are not only the placement of joint zones on flux path but also number of the air gaps and their distributions on each core. Effects of these differences on magnetic flux distribution and power loss of each core construction were investigated and presented.

Simulation results and experimental measurements prove that, octagonal wound core without joints shows best electromagnetic performance. The additional localized air gaps cause losing uniformity of flux distribution through flux path, resulting increased power loss.

However, especially for required higher power levels, manufacturing process is also an important stage, depending on increasing core and winding dimensions. Difficulty of wounding coils around the core is the disadvantage of jointless wound cores. Combining two C-shaped core parts to obtain whole core is the easiest core configuration investigated in this study. However, obtained results prove that, this configuration cause extremely high power losses. Therefore, duo-core construction which has joint regions on both limbs, seems as best choice among studied constructions, by means of its better magnetic performance and easier manufacturing process.

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Appendix

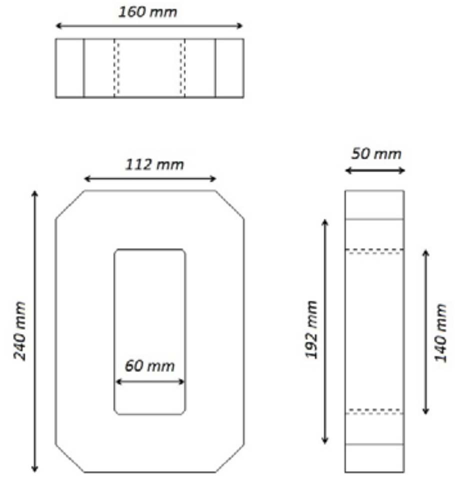

Fig. 5. Main dimensions of studied octagonal wound core constructions

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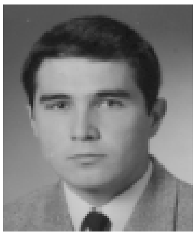

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