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Five-Limbed Transformer Cores

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There are many five limbed core configurations. In all the existing configurations specific loss (loss per kg at a given flux density) is higher than the three phase three legged core. The reasons are yoke areas not matching with the amount of the flux flowing and the mitered joints also not matching with the quantity of the flux flowing. Compared to the non-split cores, the split cores are posing manufacturing problems and higher losses. Model core of a new configuration and two model cores of existing configurations were built and tested. Relative merits of the new core configuration and reduction in losses are tabulated. This new core configuration can be adopted easily for both non-split and split cores. Relative advantages and disadvantages of different core configurations are discussed.

Tests conducted on model cores described in this paper are limited to five-limbed core type transformer cores. Iron losses were measured at different flux densities on model five-limbed cores with different core configurations. The first model (Type 1) is the typical configuration being used by transformer manufacturers around the world. An attempt is made to build another model five-limbed core (Type 2) by modifying the position of mitered joints of main end limbs laminations. This modification was done so that the flux from the main end limbs can flow from limbs to yokes without overcrowding at mitered joints. Often, the diameter of the main limbs is greater than the maximum widest width lamination normally available (1000 mm). For this reason, five-limbed cores often have split limbs. A third model (Type 3) representing the split core was also built to get a loss comparison with non-split cores.

Keywords: *Five limb cores, Flux distribution and Split cores.*

1.0 INTRODUCTION

The prices of the transformers and the cost of their losses play a vital role in a power system on capital and operational costs. Iron loss (no-load loss) being constant at all loads, has a higher loss capitalization cost ($/kW) than the load loss. Large MVA 3-phase transformers reduce the cost per MVA and also losses per MVA. With large MVA transformers fewer transformers are needed to cover the total system MVA and therefore fewer spares are required.

Nowadays, the design of large MVA transformers is not the limiting factor. Transformer MVA rating is often limited by transportation restrictions. Transportation weight restriction is not that much of a problem. Regular rail cars up to 400 tonnes capacity are available. Schnabel cars up to 450 tonnes capacity are also available. Often transportation height poses the restriction. This is mainly due to bridges and tunnels in the rail route. Special transportation methods like 'Schnabel' have overcome the limitation of the transportation height to some extent. To design a transformer tank for Schnabel transportation is costly compared to that by normal rail car. In almost all the countries a special train (dedicated train) is employed for Schnabel transportation, this increases the cost further.

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Five-limb cores have made their way into the design of large transformers by offering reduction in transportation height. Based on the type of five-limbed core construction (yoke height of 50%to 60% of core diameter) up to one yoke height reduction is achieved compared to the equivalent 3-phase, three-limb design.

Cold-rolled grain-oriented (CRGO) steel with low specific loss in the rolling direction (grains oriented direction) gave advantage over earlier (non-oriented) steels for reduction in size and weight of the transformer for the same losses and same parameters (impedance, noise level, BIL etc.). At the same time, CRGO steel has posed the problem to transformer design engineers to construct cores such that the flux path is mostly in the rolling direction. Specific loss when the flux flows at 90º to the rolling direction is 2½–3 times higher than the specific loss when the flux flows in the rolling direction.

2.0 FIVE LIMBED CORE CONFIGURATIONS

Most five limbed cores are with configuration shown in Figure 1. In this configuration, area of the yokes between the main limbs (bcd and ihg) is 57% of the main limbs (A, B and C) area. Area of the end yokes (ab, de, ji and gh) and area of the end limbs (aj and ef) are 43% of the main limbs (A, B and C) area.

The reason for most of the five limbed cores construction is as in Figure 1 is as follows. To the left of the end limb A, there is only one magnetic circuit (baji), whereas to the right of the end limb A, there are three magnetic circuits in parallel (bchi, cdgh and defg). Also the area of main yokes and main limbs B and C is much larger than the area of end yokes and end limbs. Due to these reasons reluctance of the magnetic path to the right of limb A is lower than the reluctance of the magnetic path left of limb A. Thus about 57% of the total flux flows to the right of limb A and 43% of the total flux flows to the left of limb A. The same analysis is applicable to limb C. To obtain the measured loss same as calculated loss and to obtain savings in core weight, main yokes area is 57% of main limbs area. End limbs and end yokes area is 43% of main limbs area.

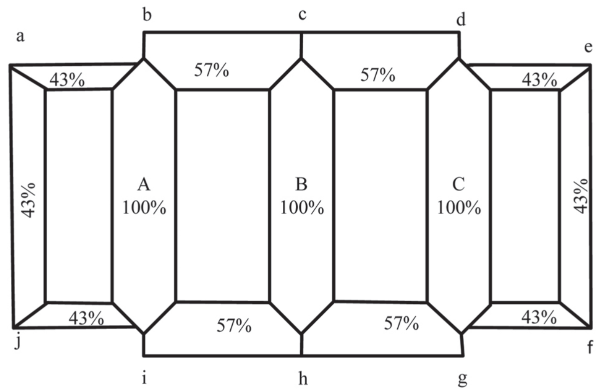

FIG. 1 TYPE 1: CORE CONFIGURATION PRESENTLY BEING USED BY MOST OF THE MANUFACTURERS.

Core configuration in Figure 2 is a modification to the configuration in Figure 1. In Figure 2 area of end limbs, end yokes and main yokes are same as that in Figure 1, 43% and 57% of main limbs area respectively. In the configuration of Figure 2, location of miter on end limbs (A and C) is modified. In Figure 1, miter location is at 50% of the main limb lamination width. Miter location in Figure 2 is at 57% and 43% of the main limb lamination width. Core construction per Figure 2 is easier compared to that of Figure 1. This is because in Figure 2 all bottom yokes are at the same level. In Figure 2 the top yokes are also at the same level. Core per Figure 2 will weigh slightly more than that of Figure 1.

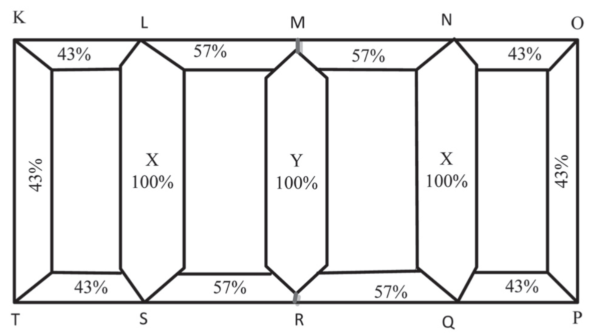

FIG. 2 TYPE 2: NEW CORE CONFIGURATION WITH LOWEST TESTED LOSSES

Core configuration in Figure 3 (Type 3) represents that of a split core. Model core built is with no split in main limb laminations. Yoke laminations were shaped same as in split cores. When the maximum core lamination width is more than the maximum width of available steel then split core has to be used. Some manufacturers split all the core laminations. Width of the split is normally 5 mm. Some manufacturers split only needed core laminations, whose width is more than maximum steel width available. In such an arrangement to maintain the oil flow to cool the laminations, the split ends at normal cooling duct parallel to the width of the laminations. Laminations or steel rolls up to 1000 mm width are available easily. Laminations or steel rolls up to 1170 mm width are supplied by some steel companies as a special order. Delivery time for 1170 mm width rolls are longer compared to the standard maximum width rolls of 1000 mm.

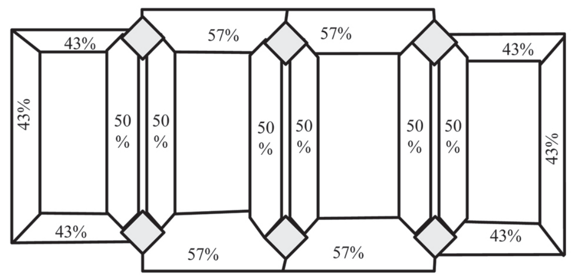

FIG. 3 SPLIT CORE WITH THE SQUARE PIECES FOR 57% AND 43% YOKES.

Some manufacturers had built split cores without any gap at the split. To build such cores is very difficult because of two reasons. The first reason is to cut the long laminations to have the same width along the whole length. The second reason is to assemble the laminations perfectly with no gap along the whole length of the lamination and also to assemble the laminations without overlapping one over the other.

Core configuration in Figure 4 is same as that of Figure 5 except the yoke laminations shape. To cut the yoke laminations as in Figure 4 is costly and time consuming. To cut the yoke laminations per Figure 3 takes less time but laminations of square shape are also to be cut. But construction of the core per Figure 4 is easy and takes less time than the Figure 3. Also in Figure 3 special care is required to maintain the position of the square piece in the yokes correctly. In Figure 3 there is one extra air gap in yokes compared that of Figure 4.

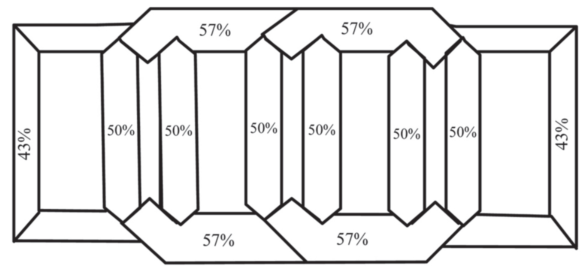

FIG. 4 SPLIT CORE WITHOUT THE SQUARE PIECES FOR 57% AND 43% YOKES.

Some manufacturers build the cores as in Figure 6. In this configuration, area of all the yokes and the end limbs are 50% of that of main limbs. Though no tests were done on the model cores of this configuration, it is author's experience that the core of Figure 5 will test more loss than that of Figure 1. This is because the flux density in the main yokes is more than that of the main limbs. Though the flux density in the end limbs is lower than the flux density of the main limbs, the total losses will be still more than that of Figure 1. Many different areas to main yokes and to end limbs are being adopted. A few are 55% of main limbs area to main yokes and 45% of main limbs area to end legs. Also 60% and 40% areas respectively are also being used. Selection of areas is based on shop facilities and experience of the manufacturer.

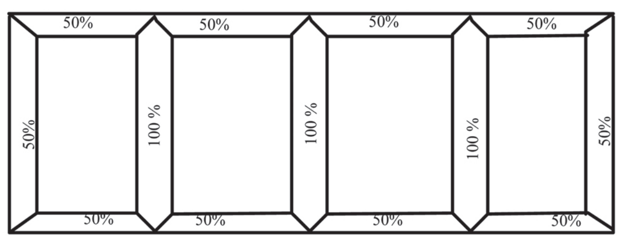

FIG. 6 CORE WITH 50% YOKES.

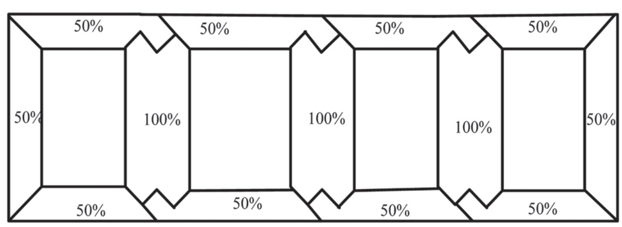

FIG. 6 TYPE 3: CORE WITH 50% YOKES EQUIVALENT TO THE SPLIT CORE.

3.0 FLUX DISTRIBUTION

Type 1 core

An enlarged section of top portion for limb A is shown in the Figure 7. Consider the instant when the sine wave flux is at the maximum value in limb A.

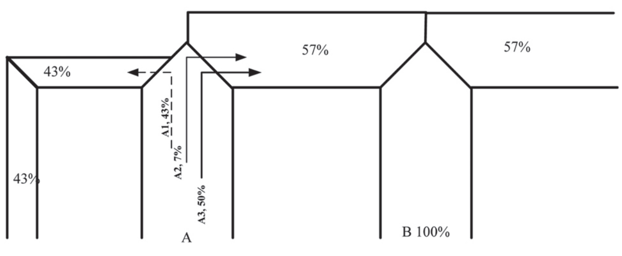

FIG. 7 FLUX DISTRIBUTION WITH MITER AT 50% OF THE WIDTH.

As discussed earlier, reluctance in the direction ‘bc’ is lower than that in the direction ‘ab’. So, 57% of the flux flows in the direction ‘bc’ and 43% of the flux flows in the direction ‘ab’. For the analysis, the main end limb is divided into three portions of 43%, 7% and 50% (a1, a2 and a3 respectively). 43% of the flux in a1 flows in to end yoke with no distortion. The problem is regarding the 57% of the flux flowing in to the main yokes. The miter in this direction covers only 50% of the limb lamination width. As shown in Figure 7 at the point of flux transfer from main limb to main yoke, 57% of the flux (flux in a2 and in a3 flows through the miter made for 50% of the flux). Flux in a2 converges in to the miter made for a3 which is made for 50% of the flux only. At this point the flux density is more than the designed flux density in the main limbs. After this point, the 57% of the flux distributes itself in to 57% of the main yoke area maintaining the same flux density as in the main limbs.

The phenomena explained above happen at the bottom on main limb A when the flux is passing from the main yoke to the limb A. When the sine wave flux in the main limb C is maximum, the same phenomena explained above for limb A happens for limb C also.

As explained above, due to the crowding of the flux during transfer from end main limbs to main yokes and also during the transfer of the flux from the main yokes to main end limbs, losses will be more than the calculated value assuming that the flux flows smoothly throughout the core without overcrowding at any point. At these over crowded places the core temperature will also be higher than the other parts of the core. This over crowding increases the sound level also.

The flux measured in the end limbs as a percentage of the flux in the main leg limbs is given in the Table 1.

Type 2 core

An enlarged section of top portion for limb X is shown in the Figure 8. Consider the instant when the sine wave flux is at the maximum value in limb X. For the analysis the main limb is divided in to two portions 43% and 57% (x1 and x2 respectively). 43% of the flux in x1 flows in to the end yoke with no distortion. 57% of the flux in x2

TABLE 1
FLUX MEASURED ON END LIMBS OF MODEL CORES

Sl. No.	Flux density (kL/cm^2)	Flux in end limbs % of main leg limb flux	
		Type 1 core	Type 2 core
1	14	42.9	37.7
2	15	44.9	37.8
3	16	46.2	38.5
4	17	46.7	38.1
5	18	46.4	38.5
6	19	44.9	37.5

also flows smoothly to the end yoke because the miter is made at 57% of the main limb width. At the bottom of the main limb X, 57% of the flux from the main yoke to the main limb also flows smoothly.

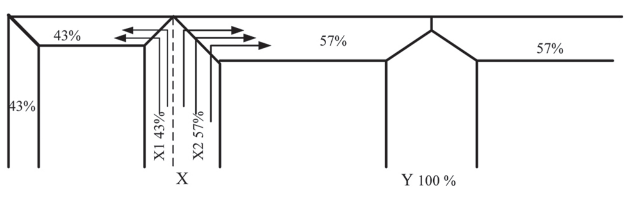

FIG. 8 FLUX DISTRIBUTION WITH MITER AT 43% AND 57% OF THE WIDTH.

In main end limb Z the miter is a mirror image to that in the end limb X. So, in the end limb Z when the flux is maximum, the flux transfer from main limb to main yoke and main yoke to main limb flows smoothly without any distortion.

Miter in the center limb Y in Type 1 core and in Type 2 core is same. By this the symmetry is maintained on both sides of the center limb Y.

The flux measured in the end limbs as a percentage of the flux in the main leg limbs is given in the Table 1.

Type 3 core

In this core also overcrowding of the flux described in Type 1 core happens. This can be avoided by having the split on the end limbs at 57% and 43% of the width rather at 50% and 50% of the width (middle of the lamination width).

Tests on model cores

Model cores of Type 1, 2 and 3 as per the details given in the Annexure I were built and iron losses were measured at various flux densities. Details of the three model cores built and tested details are given in Table 2. The results are tabulated in Table 3.

Conclusions

1. For Type 2 core the measured losses are lower compared to those in Type 1 core. The percentage reduction in loss at flux density 17 kL/cm^2 is about 6.4%. The lowest percentage reduction in loss is about 2.4% at flux density 15 kL/cm^2. Many transformers are designed around 17 kL/cm^2. It is encouraging that the loss reduction is maximum around this flux density.

TABLE 2

DETAILS OF THE THREE MODEL CORES BUILT AND TESTED

Description	**Type 1 core**	**Type 2 Core**	**Type 3 core**
Core height (mm)	504	504	490
Core length (mm)	1078	1078	1092
Core weight (kg)	98.24	100.2	99.98
Number of lamination sizes	4	5	5

TABLE 3

LOSSES MEASURED ON THE THREE MODEL CORES

Sl. No.	**Flux density (kL/cm^2)**	**Loss (W)**		
		Type 1 core	**Type 2 core**	**Type 3 core**
1	14	107	103	114
2	15	128	125	138
3	16	158	154	171
4	17	200	188	215
5	18	252	242	296
6	19	356	344	425

2. For Type 3 core the measured loss is more compared to that of Type 2 core. For Type 3 core the measured losses are higher by about 10.5% to 23.5% at different flux densities.
3. Core configuration and area of yokes and end legs play a vital role in the losses.
4. Harmonics are not measured during loss measurement on the model cores. In similar measurements, measuring harmonics at different flux densities is recommended. This is because the losses are dependent on harmonics also.
5. For Type 3 core, core height is less by 14% of yoke depth than that of Type 1 and Type 2 cores. Whereas for Type 3 core, the length is more by 14% of yoke depth than that of Type 1 and Type 2 cores.
6. In Type 3 core for each step two widths (100% and 50%) of laminations are required. For Type 1 and Type 2 cores for each step three widths (100%, 57% and 43%) on laminations are required.
7. Comparing to Type 1 core, in Type 2 core one 90° cut is eliminated.
8. Though a core with 50% area for yokes and end legs has some production advantages the losses are higher compared to Type 1 and Type 2 cores.
9. Though the model cores are with no laser etched steel, the measured results are applicable to cores with laser etched steel also.

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ANNEXURE I

Details of the model cores

1. Net area of cross section = 48.768 cm^2
2. Grade of steel = M4 (Annealed)
3. Number of layers of laminations = 92 (2 by 2 stacked)
4. Mitering overlap = 6 mm
5. Width of main limbs laminations = 100 mm
6. Main window height = 390 mm
7. Main window width = 208 mm
8. Number of turns on each main limb = 60 (Uniformly distributed throughout the limbs heights)
9. Turns on the three limbs are connected in star.
10. Power for measurement of losses is from a sine wave generator.
11. Supply frequency is 50 Hz.
12. The losses are measured by three watt meter method.

Calculated core weights

Type 1 core = 98.24 kg

Type 2 core = 100.2 kg

Type 3 core = 99.98 kg