UNIVERSITY OF CANTERBURY

A Radially Laminated Core for Partial Core Transformers

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1 INTRODUCTION

There are a number of areas of research for transformers at present which are focussed on reducing the losses in transformer cores as well as the steel weight. One way to reduce core losses is to remove the core altogether making an air-core transformer which have been primarily used in pulse transformers [1] and superconducting transformers [2] [3] [4]. However these designs have issues with large magnetising currents. Alternatively, the use of partial-core transformers (PCT), which have been developed as resonant test transformers [5] [6], power transformers [7], and superconducting transformers [8] [9] [10], can be seen as a compromise between the transformer performance and a reduction in the use of materials.

In a PCT there is a steel core down the centre of the windings, however the steel limbs and yoke of a traditional core have been removed as shown in Figure 1. As the remainder of the magnetic flux path is now through air instead of steel, there is a much higher reluctance path in a PCT than a full core transformer [5]. The University of Canterbury (UoC) has developed a number of partial-core transformers (PCTs) in an attempt to reduce the electrical losses of the PCTs.

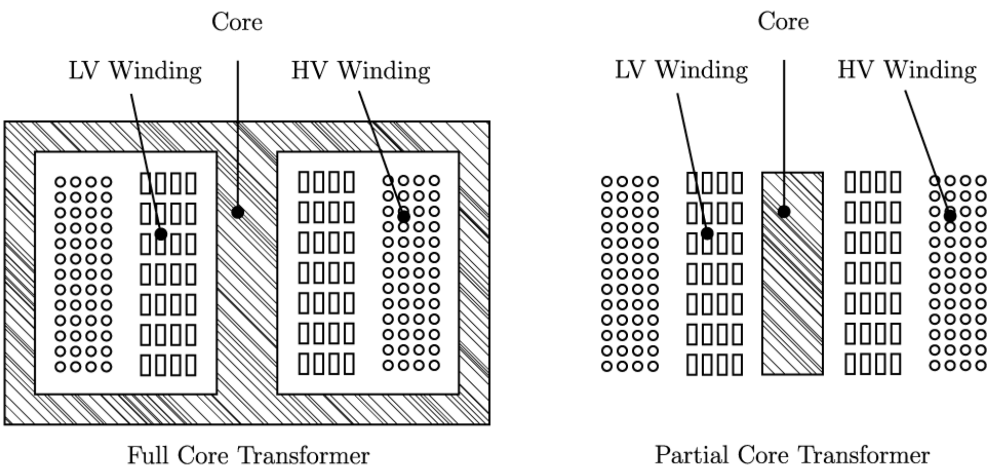

FIGURE 1: A CROSS SECTIONAL VIEW OF THE DIFFERENCES BETWEEN FULL CORE AND PARTIAL-CORE TRANSFORMERS.

Towards the ends of the core in a PCT, the magnetic flux tends to spread outwards radially within the core. This increases the eddy current losses in the core compared to that seen in traditional full core design [11] [12]. Thus, PCT designs tend to have significantly higher eddy current losses per unit weight in the core compared with full core counterparts.

This paper starts by providing a background into partial core transformers and their applications as well as a look into the performance of transformer steel. A radially laminated core is then designed and constructed to be compared with a traditional parallel stacked core for use in PCT. The two cores have been tested under open circuit conditions and their core losses computed from measured results. The core losses have also been compared to the modelled core loss as a test of the model accuracy.

2 BACKGROUND

2.1 PARTIAL CORE TRANSFORMERS

A partial core transformer (PCT) is different from a full core transformer in that the outer limbs and connecting yokes are absent from the PCT as shown in Figure 1 above. This enables a smaller, lighter, and easier to manufacture transformer with some caveats around the transformer's performance. It also means that the magnetic circuit for a PCT will consist of the core and the surrounding air. This results in a high magnetic reluctance when compared with similar rated full core transformer. Despite this, it is possible to design a PCT that performs comparably to a full core transformer under full load conditions while making significant savings on core material and transformer weight.

There are resonant PCTs being used in industry for high voltage testing of machine stators [5]and cables [6]. The efficiency of the transformer is not as important for these testing transformers but rather the low magnetising reactance of the transformer[1]. The reactance of the transformer is matched to the capacitive load of the insulation under test reducing the reactive power drawn from the supply to almost zero. The resonant transformer developed in [11] was much smaller than previously used equipment and could be supplied off the local 400V supply due to the low reactive power requirement.

To produce a viable power PCT the losses must be reduced to be comparable with those of a full core transformer. A high magnetizing current increases the winding losses for the PCT. The winding losses could be reduced by using larger conductors for the windings to reduce the resistance of the windings,

$$R = \frac{\rho \ell}{A} \tag{1}$$

Increasing the area would also result in a larger transformer size and a greater quantity of conductor material. Reduction in material and size were two benefits of the PCT over the full core transformer so increasing conductor size is not an ideal solution.

High temperature superconductors have very low losses as well as a small cross sectional area which gives a better result than simply increasing the conductor size. Research has been done into the use of superconducting materials for the windings in order to reduce the winding losses resulting from the high magnetising current [13]. Superconducting materials have a high cost associated with them and require liquid nitrogen for cooling the windings so they are currently an expensive option.

2.2 TRANSFORMER STEEL

Transformer cores are normally made with grain-oriented electrical steel which is designed to have low magnetic hysteresis area, high permeability, and high resistivity resulting in low core losses. The material is usually manufactured in the form of cold-rolled strips less than $2\,mm$ thick. These strips are called laminations when stacked together to form a core. In a traditional full core transformer, the magnetic flux will tend to travel along the direction of the steel's grains minimising the energy dissipated in the core as seen in Figure 2.

[1] That said, current research is suggesting the core losses do play an important role in the maximum impedance of the tuned resonator. Thus a reduction in core losses can increase the performance of these devices.

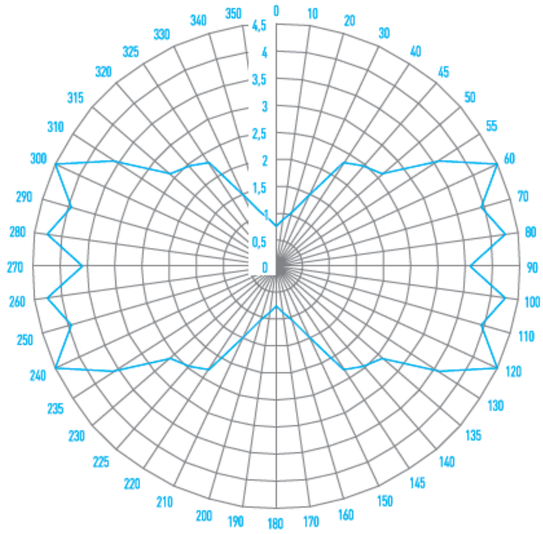

FIGURE 2: CORE LOSSES AT ANGLES TO THE GRAIN DIRECTION [14].

For a PCT the flux path through the air after it leaves the core can be seen in Figure 3. The flux does not leave the core directly through the top or bottom face of the core but instead it begins to spread radially out of the core before the ends.

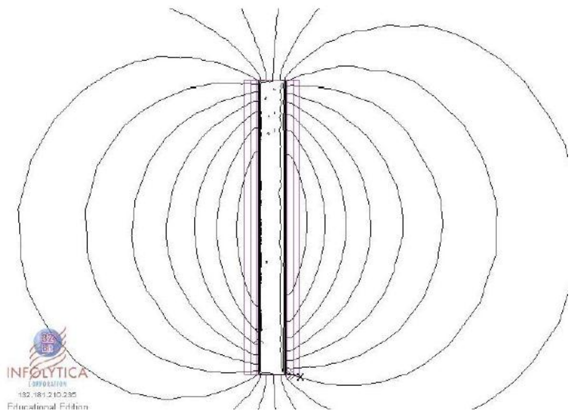

FIGURE 3 LEFT: FLUX PLOT FOR A PCT [4].

As the flux spreads radially outward, the flux travels through multiple laminations in one direction instead of being contained within a single lamination, as shown on the left in Figure 4. The flux paths which are contained within a single lamination correspond to a high eddy current resistance due to the lamination thickness being less than twice the skin depth [12]. When the flux is travelling across a lamination the eddy current path is the face of the lamination and therefore not restricted by the lamination thickness, thus the flux crossing multiple laminations is what causes the high eddy current losses [12]. This can be overcome by radially orienting the laminations of the core as in the right hand side of Figure 4. The flux no longer crosses multiple laminations which reduces the eddy current losses.

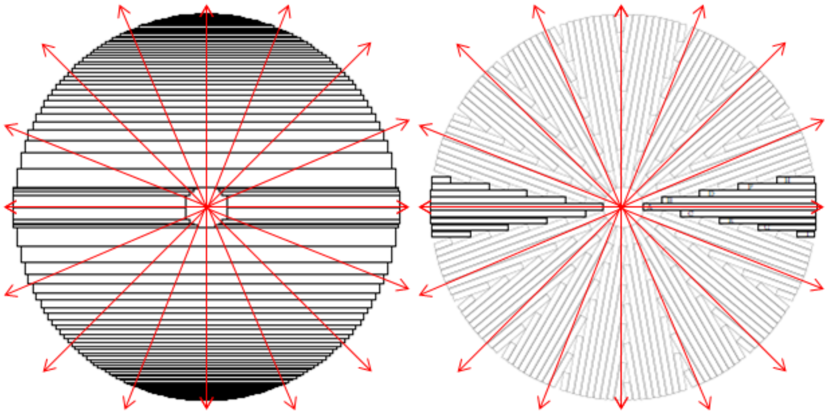

FIGURE 4: AN EXAMPLE OF PARALLEL STACKED LAMINATIONS AND RADIAL LAMINATIONS FOR A PCT WITH RED ARROWS REPRESENTING DIRECTIONS OF FLUX SPREAD.

3 DESIGN AND CONSTRUCTION OF A RADIAL CORE

The radial core was designed and built to allow a direct comparison of the core losses between the existing parallel laminated core and the radial laminated core arrangement within an existing copper winding PCT. This required the physical dimensions of the two cores to be the same with the only difference being the orientation of the laminations.

The radial core uses 10 sizes of lamination with one lamination of each size included in each triangular wedge as shown in Figure 5. The width of each lamination is detailed in Table 1 where the lamination thickness is 0.23mm.

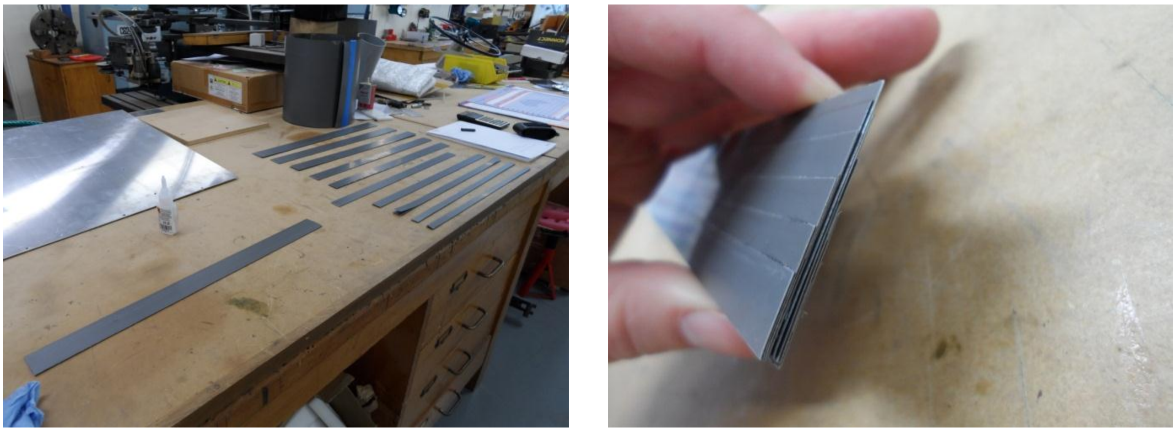

Figure 5 Left: Assembly process. Right: An assembled wedge of 10 laminations.

66 wedges were assembled to form the radial core in Figure 6. There are two additional 80mm laminations bent to 90˚ down the centre of the core. These two laminations form crosshairs for the core to provide stability in the construction stage. They also provide a point for the core to be suspended from when lowering it into the PCT winding arrangement. The wedges have been bound in the cylindrical shape using EPA heat shrink tape and then coated with a lacquer spray.

TABLE 1: WIDTH OF LAMINATIONS

Lamination No.	Width (mm)
1	36
2	34
3	31
4	28
5	25
6	22
7	19
8	16
9	13
10	10

TABLE 2 DIMENSIONS OF THE CORES

Dimension	Parallel Core	Radial Core
Length	474 mm	474 mm
Outer Diameter	(79.9±1)mm	(80.4±0.5)mm
Inner Diameter	~16 mm	-
Lamination Thickness	0.23 mm	0.23 mm
No. of Laminations	348	660
Stacking Factor	0.89	0.72
Total Steel Weight	15.37 kg	13.15 kg

The radial arrangement of laminations is less efficient than the parallel arrangement resulting in a lower stacking factor for the core of 0.72 as opposed to 0.89. This resulted in a lower steel weight for the radial core however the other dimensions are the same, see Table 2 and Figure 7. Both cores can therefore be used within the existing PCT winding arrangement however the losses must be compared using Watts/kg instead of Watts as the core weights are not directly comparable.

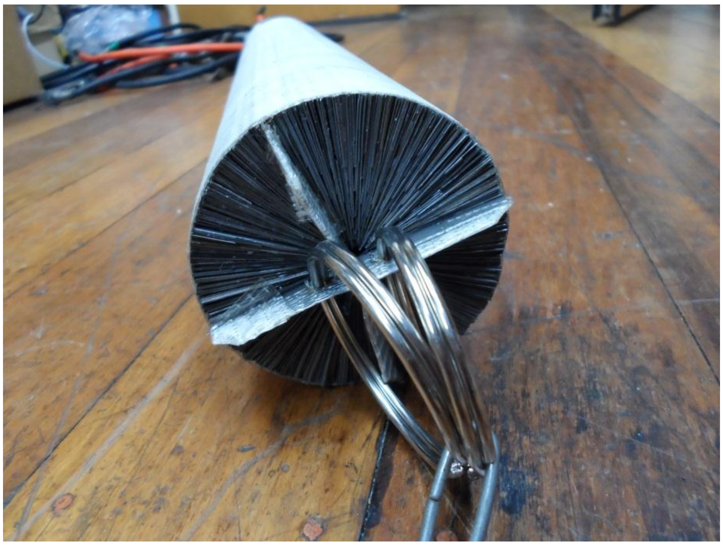

FIGURE 6 ASSEMBLED RADIAL CORE WITH RINGS THROUGH CROSSHAIR LAMINATIONS FOR SUSPENSION OF THE CORE.

FIGURE 7 TOP: RADIAL CORE. BOTTOM: PARALLEL CORE.

4 Testing and Results

The transformer testing was performed using a copper wound transformer with each core placed inside the windings at the same height. Figure 8 shows the winding and core arrangement used during testing.

Figure 8: Left: Copper winding Transformer. Right: Parallel core shown inside PCT

4.1 Open Circuit Testing

Open circuit testing was performed on the PCT with each of the cores in turn. This test was used to determine the core losses in the transformer while using an AVO Megger BM222 to measure the resistance of the windings so that the winding losses could be accounted for [13].

Figure 9 is a plot of the open circuit test result for applied voltage versus excitation current. There is a linear increase in the voltage with the excitation current which is expected for a PCT in which core saturation is not occurring. The voltage was increased to about 1.08pu to prove that the transformer would not go into core saturation at rated voltage.

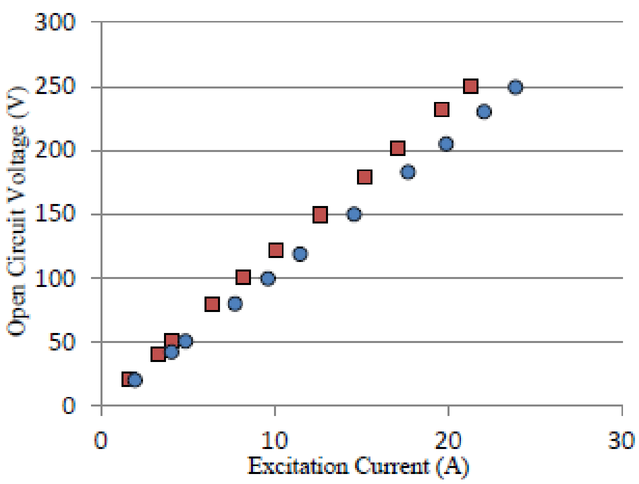

Figure 9: Open Circuit Test Results for the PCT. Red squares represent the radial core and blue circles are the parallel core.

The open circuit test results for the cores are presented in Table 3. Winding losses are calculated from the I^2R losses of the winding and account for between 45 and 55% of the open circuit losses. The core losses are calculated by subtracting the winding losses from the total measured losses. The results indicate that there has been a decrease in the total core losses for the PCT with the radial core com-pared with the parallel core. There is a total decrease in core losses of 4W/kg or about 37%.

TABLE 3: OPEN CIRCUIT TEST RESULTS FOR BOTH CORES AT RATED VOLTAGE

Parameter	Parallel Core	Radial Core
	Measured	
Primary Voltage (V)	230	230
Primary Current (I)	22.6	20.6
Real Power (W)	300	200
Apparent Power (VA)	5200	4700
power factor	0.06	0.05
Secondary Voltage (V)	228.8	228.6
Resistance Primary (Ω)	0.258	0.258
	Calculated	
P Winding (W)	132	109
P Core (W)	168	91
P Core (W/kg)	10.9	6.9

From Figure 9 and Table 3 it is also apparent that a reduction in excitation current has occurred between the parallel and radial core arrangements, despite the fact that there is less core steel present in the radial core[2]. This suggests that the radial core could have a lower reluctance than the parallel core. More experimentation is needed to verify this.

5 CONCLUSIONS

A radially stacked core was designed and constructed for use in a partial core transformer. The radial core was tested under open circuit conditions to obtain the no load losses and compared to a similar parallel stacked core. Results from the testing have demonstrated that a radial core can result in an improved efficiency for partial core transformers with a reduction in both excitation current (winding losses) and eddy currents (core losses).

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