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Increase of Tape Wound Core Losses Due to Interlamination Short Circuits and Orthogonal Flux Components

B. Cougo
A. Tüysüz
J. Mühlethaler
J. W. Kolar

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B. Cougo, A. Tüysüz, J. Mühlethaler and J. W. Kolar
Power Electronic Systems Laboratory, ETH Zurich
ETL I14, Physikstrasse 3
CH-8092 Zurich, Switzerland
cougo@lem.ee.ethz.ch

Abstract – **High performance laminated core materials are nowadays used in several different applications, from some Watts to some Megawatts and from some tens of Hertz to some hundreds of Kilohertz. Cutting laminated or tape wound cores in order to obtain a desired geometry results in higher core losses mainly due to the introduction of short circuits between layers of magnetic material and also due to the flux which is perpendicular to the layer plane as given for the fringing field of inductors or the stray field of transformers. This paper verifies the influence of some machining methods on the increase of core losses and shows an approach to keep the effect minimized. Furthermore, the importance of considering core losses due to perpendicular flux is verified for a cut core inductor and a transformer arrangement.**

I. INTRODUCTION

Amorphous and nanocrystalline iron materials are used in a very wide application area covering different types of inductors, transformers and electrical machines, because of their high saturation flux density and lower losses compared to other soft magnetic materials, including conventional silicon-steel. In [1], an improved amorphous iron is presented to increase the energy efficiency of distribution transformers. In [2], a transformer for a 30 kW, 200 kHz resonant converter is designed using a nanocrystalline core. An efficiency increase of 6% has been reported using amorphous iron instead of low-loss silicon steel in a 2.4 kW, 8500 rpm switched reluctance machine in [3]. Amorphous iron has also been used to build a world-record 1 000 000 rpm, 100 W electrical machine prototype in [4]. Moreover, amorphous and nanocrystalline iron materials are used as key components in cutting edge research such as beam-dump kickers of the large hadron collider in CERN [5], ultra-thin magnetic components with PCB integrated transformers [6] and novel electrical drive topologies [7].

Both amorphous and nanocrystalline materials are conventionally produced as insulated layers of around 20-25 μm thickness, wound on a round or U-shaped frame form. In many applications these forms are cut in the middle to form two C-shaped or U-shaped cores which can be more easily assembled together with windings when building transformers and inductors. In applications where those cores are used to build an electrical machine like in [3], the laminated cores are further cut by wire erosion to the final shape of the related electrical machine part.

In [2], an average of 100% loss increase is reported comparing the non-cut and the cut cores in the case of nanocrystalline cores. In this paper, we show several measurement results related to additional core losses due to different machining methods, for both amorphous and nanocrystalline materials. Furthermore, the possible sources of those losses as well as possible procedures to reduce them are discussed.

II. SURFACE SHORT CIRCUITS INTRODUCED BY MACHINING

A. Description of problem

In [2], the authors state that possible reasons for additional losses in cut cores compared to the roll of raw nanocrystalline ribbon are mechanical and thermal stresses during the core preparation and the introduction of short circuits between the laminations during the cutting process. Another cause of additional core losses in cut cores is shown to be the eddy currents caused by the flux component orthogonal to the lamination direction in [8].

In this section, the effects of the surface short circuits are investigated on both amorphous and nanocrystalline cores. In the case of amorphous iron, two identical hollow cylindrical cores are cut out of a non-commercial laminated block made of HB1 and a commercial C-core made of SA1 material. Both SA1 and HB1 are amorphous iron materials having layer thickness of about 25 μm and developed by Metglas. The hollow cylindrical cores were cut using electric discharge machining (EDM). The HB1 block after the EDM as well as the hollow cylindrical cores can be seen in Fig. 1.

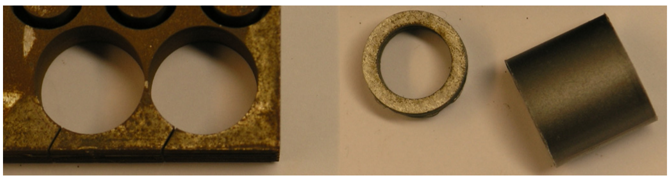

Fig. 1. Picture of a laminated block of HB1 amorphous iron and the cylindrical cores cut out using EDM.

The magnetic behavior of the cylindrical cores is measured using a simple measurement setup which is described in Fig. 2. The primary winding is excited with sinusoidal current and the open circuit voltage on the secondary winding is measured. The BH curve and the core losses are calculated according to (1-2),

$$H = \frac{N_1 \cdot i_1}{l_m} \tag{1}$$

$$B = \frac{\int u_2 \cdot dt}{N_2 A_c}, \tag{2}$$

where N_1 and N_2 are respectively the number of turns of the primary and secondary windings, i_1 is the measured primary current, l_m is the mean magnetic path length, u_2 is the measured secondary open circuit voltage and A_c is the cross sectional area of the cylindrical core.

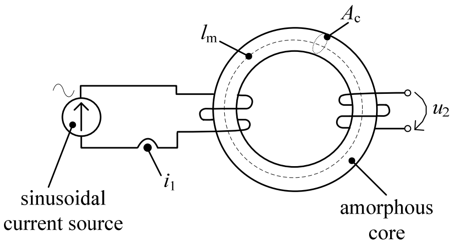

Fig. 2. Basic test setup.

B. Removal of surface short circuits

After the initial measurements, the cylindrical cores were put in a 40% ferric chloride ($FeCl_3$) solution, which is generally used for production of PCBs. This action was taken in order to remove any possible short circuits on the inner and outer surfaces of the cylindrical cores introduced by the EDM process. The cores have been rinsed with water and dried using a hot air blower and tested again immediately. The results are depicted in the following figures.

Fig. 3 shows the core losses of the HB1 core before and after etching the core with ferric chloride. A significant decrease in core losses can be seen after the etching process. The authors conclude that this is due to the removal of the surface short circuits introduced by EDM. Another result supporting this conclusion is the higher induction in the etched core for the same excitation, i.e., increased effective permeability after etching. Considering that the cores were excited with the same primary current before and after etching, the fact that curves in Fig. 3 associated to after the etching are shifted to the right shows that the cores have higher permeability after etching. This effect can be seen clearly in Fig. 4a, in which individual BH curves are depicted for the same HB1 core before and after etching. In Fig. 4b, the same effect is shown for SA1 material cut from a commercial C-core. Although not as strong as in the HB1, a permeability increase is visible. This difference is caused possibly by non-identical production procedure for the material and difference in material composition.

As mentioned above, after the acid bath, the cores are rinsed with water and dried using a hot air blower, and tested immediately. However, later measurements showed that the rinsing is not sufficient for stopping the etching process. Measurements were taken 2 days, 4 days and 2 weeks after etching. In those measurements, the core cross sectional area, A_c, is assumed to be constant, and the calculated BH curves are plotted in Fig. 5. The results can be interpreted as a changing stacking factor over the two weeks after the etching. This shows that although rinsed and dried, the cores are still losing magnetic material. As a result, a new step has to be introduced to stop the etching at a defined point in time. Neutralizing the acid with a basic solution before rinsing may be a solution, and is considered as part of the future work.

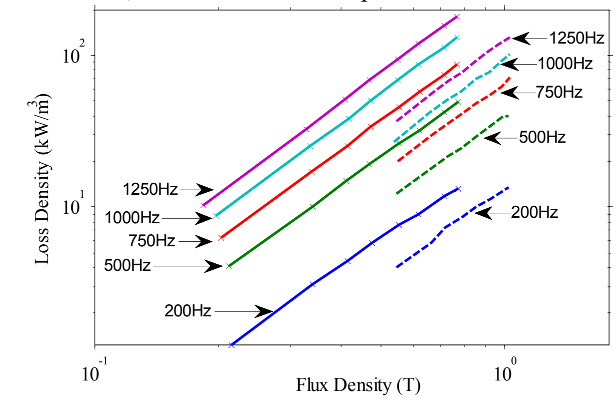

Fig. 3. Core losses of HB1 amorphous core before etching (solid lines) and after etching (dashed lines), at different frequencies.

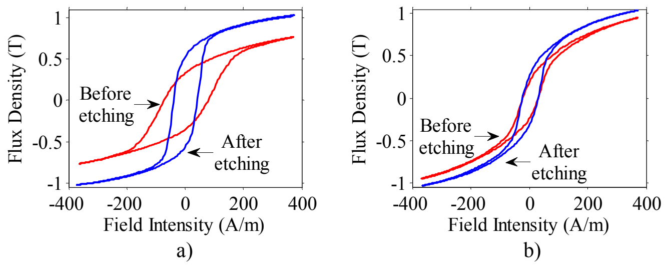

Fig. 4. BH curve of amorphous cores before and after etching, at 1.25kHz. a) HB1 material. b) SA1 material.

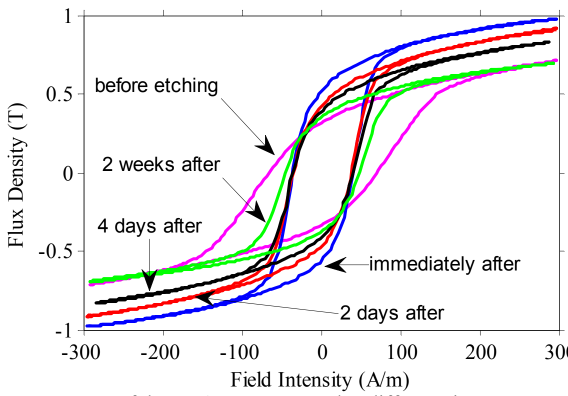

Fig. 5. BH curves of the HB1 core measured at different times.

C. Short circuits in nanocrystalline toroidal cut cores

To study the effect of short circuits when cutting nanocrystalline cores, two toroidal cores T60004-L2100-W342 from VacuumSchmelze [9] were taken as reference.

From now on we denote "Core A" the nanocrystalline core which was cut in the middle using a thin metal saw. "Core B" is the one which was cut using EDM, the same processes used to cut the cylindrical core described before. A picture of the cross section of these two cores is shown in Fig. 6.

Core B, cut by EDM, has a much more regular and smoother cut although physical aspects give the impression it has more short circuits between layers than the core cut with a saw.

Before continuing, it should be noted that short circuits in the cylindrical cores tested in the last sub-section and in the toroidal cores tested here create different paths for the eddy currents. Extra eddy currents generated by short circuits in the cylindrical core will flow through these short circuits but also through the top-most and bottom-most layers, as shown in Fig. 7a. In toroidal cores, extra eddy currents will flow mainly in the short circuits, as shown in Fig. 7b. This difference in the eddy current paths and also the fact that the short circuit surface is much greater in the cylindrical core than in the toroidal core may cause different core loss increase in these two types of cores.

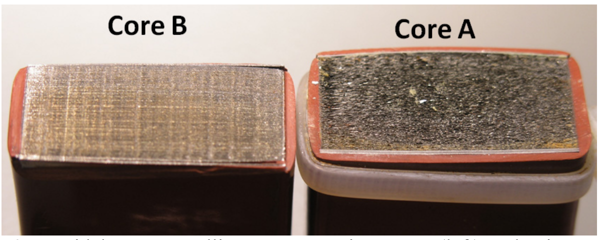

Fig. 6. Toroidal nanocrystalline core cut using EDM (left) and using a thin metal saw (right).

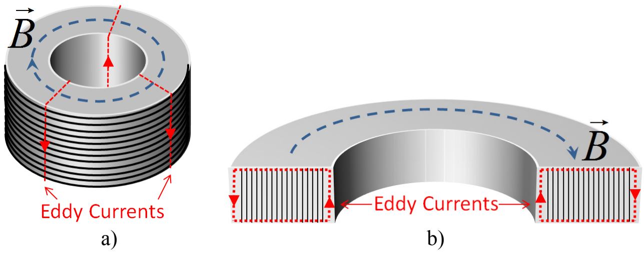

Fig. 7. Eddy currents in the presence of short circuits in the a) cylindrical core; b) toroidal cut core.

Using imposed square wave voltages at 20kHz and the experimental setup described in [10], core losses were measured in the toroidal cores before and after cutting them. Also the losses of another commercial nanocrystalline cut core from Vacuumschmelze were measured. It is a U-core which is about three times bigger than the toroidal ones and has the reference number T60102-L2198-W171. It will be referenced here as “Core W171”. All measured core loss densities cited above are plotted in Fig. 8, where also theoretical core losses of this nanocrystalline material, calculated using the manufacture’s datasheet [9] are included.

Note that the two non-cut toroidal cores have lower losses than the calculated one. After these cores were cut, their losses increased significantly. The one cut using EDM had the losses increased about 4.3 times while the losses of the core cut with a saw increased about 1.9 times. Cut Core W171 has higher losses than cut Core A.

From our tests, cut cores which have a more regular and smoother cut surface have also higher losses. This is probably because they have more short circuits between layers of magnetic material. This is consistent with the measurement of short-circuit resistance with a multimeter. Core B has 2.42Ω between the inner- and outer-most layers while Core A has 7.84Ω and core W171 has 59Ω.

In order to reduce core losses, the same procedure as described before can be used. The two toroidal cores had their cut surfaces immersed in a 40% ferric chloride ($FeCl_3$) solution for 10 minutes, at room temperature. Core losses were measured after rinsing and drying. After measurement, Core B was put again in the solution, for 30 minutes more, and core losses were once again measured. These results are shown in Fig. 9.

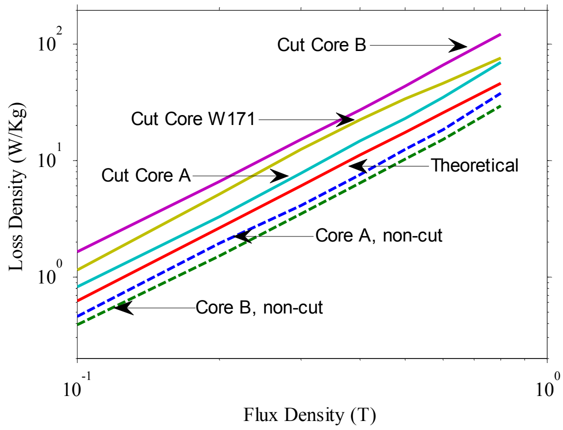

Fig. 8. Measured loss density of different nanocrystalline cores, before and after cutting, for triangular flux at 20kHz.

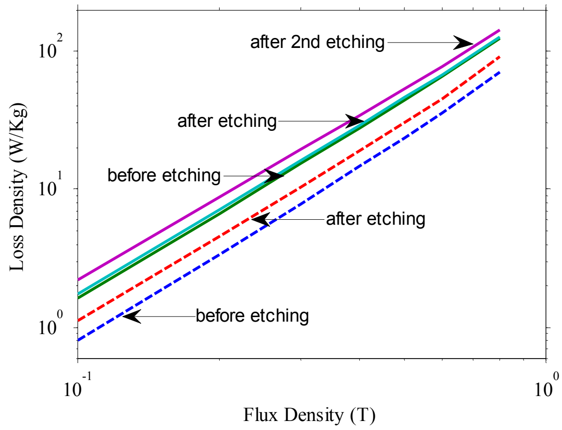

Fig. 9. Measured loss density of different nanocrystalline cores, before and after etching, for triangular flux at 20kHz. Dashed lines: Core A. Solid Lines: Core B.

For these toroidal nanocrystalline cores, etching did not decrease core losses. Actually, the losses even increased. Possible reasons for that are:

1 – Besides removing magnetic material, etching could have also destroyed part of the insulation between layers and, consequently short circuits were increased. This was not observed with the multimeter measuring the short circuit resistance.

2 – Some short circuits were removed but another phenomenon associated to the etching of magnetic material generated more losses.

This second option will be further investigated.

III. Orthogonal Flux Lines

Since only short circuits of layers cannot explain the increase of core losses after cutting and etching nanocrystalline toroidal cores, another possible reason is the presence of magnetic flux which does not flow parallel to the layers of tape wound cores.

As shown in Fig. 10a, when the time-variant magnetic flux flows in the direction of the layers, since the magnetic material is electrically conductive, eddy currents will appear in the cross section of each layer, creating a flux to oppose the main flux, which is explained by Lenz's law. According to [11], eddy current losses per unit volume (P_e) in these thin magnetic layers may be calculated as:

$$P_e = \frac{\pi^2 f^2 d^2}{6\rho} B_p{}^2 \quad (3)$$

where B_p is the peak flux density, f is the frequency of the magnetic flux, d is the thickness of a layer and ρ is the resistivity of the magnetic material. This formula is valid in cases where the skin effect is not relevant. This is the case for tape wound cores given that the thickness of each layer is very small, e.g., as for nanocrystalline cores around 20µm [12], and the operating frequency is not higher than some hundreds of kHz.

When the flux is orthogonal to the layers (refer to Fig. 10b), the first observation is that the equivalent permeability is much smaller since the flux must flow though the air gaps in between layers. The second is the fact that eddy currents are created in the layer plane, which might generate much higher losses in the material since these currents will flow in a much larger area and also because skin effect in this direction is not negligible. According to [11], eddy current loss density P_{erec} generated in a rectangular conductor plate of height D_H and width D_W, can be calculated as

$$P_{erec} = \frac{8 f^{1/2} \rho^{1/2}}{\mu^{3/2} \pi^{3/2}} B_p{}^2 \left[D_W + D_H \right] \quad (4)$$

where μ is the permeability of the magnetic material.

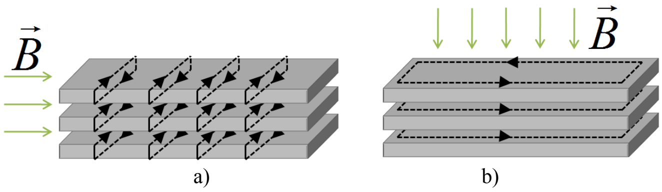

Fig. 10. Eddy currents in tape wound cores. a) Parallel flux density. b) Orthogonal flux density.

In order to verify the influence of orthogonal flux in cut cores, a thin paper sheet was inserted between the two halves of the three nanocrystalline cores tested before etching. Like this, an airgap of thickness equal to approximately 0.1mm was inserted in the magnetic circuit. The results of the losses before and after inserting this thin paper sheet are shown in Fig. 11.

Measurements show that "Core B" had the losses increased by the insertion of an airgap. For the other two cores, the losses have decreased. "Core B" is the one which has lower losses and also which physically appears to have less short circuits. Thus, one possible interpretation for this loss increase is that, with an airgap, since the fringing flux is increased, losses due to orthogonal flow in the layers close to the airgap result in additional losses.

Losses of the other two cores decreased with the insertion of the airgap. Also for these cores, the fringing flux increased, generating extra losses. However, less flux has to pass by core sections where short circuits are located, and thus the losses due to these short circuits are reduced. The reduction of losses due to short circuits is more important than the extra losses due to orthogonal flux.

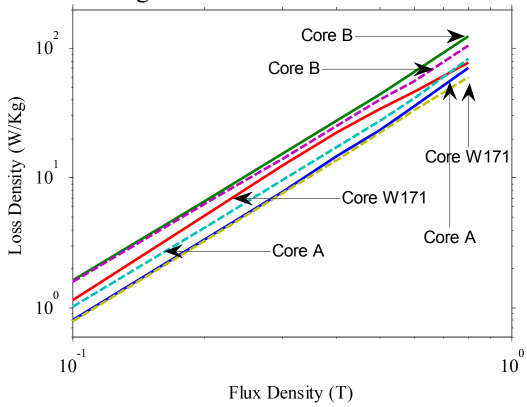

Fig. 11. Core losses in nanocrystalline cut cores, with and without air gap. Dashed lines: With air gap. Solid Lines: No air gap.

Another interesting test to verify the influence of orthogonal flow is to shift one half core, in the vertical or horizontal direction, as shown in Fig. 12. If an isotropic material was used, the flux in the core would be well distributed in most of its extent, but it would be concentrated in the contact between both half cores, as shown in the Finite Element Method (FEM) simulation result of Fig. 13.

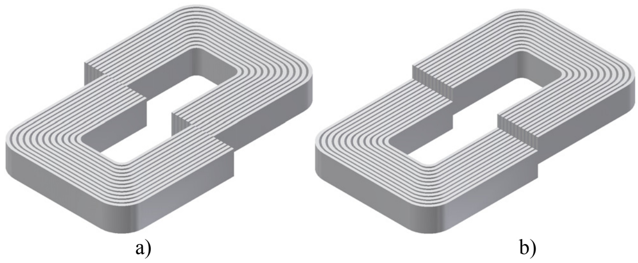

Fig. 12. Displacement of the core halves. a) Horizontal direction, b) vertical direction.

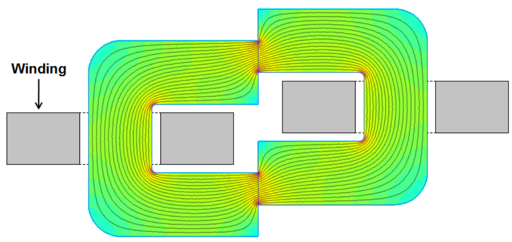

Fig. 13. Flux behavior for horizontal displacement of the cores halves. Colors represent the flux density inside the core.

In tape wound cores, the displacement of the core halves in the horizontal direction (refer to Fig. 12a) creates orthogonal flux close to the region of contact of both core halves, as can be seen in Fig. 13. However, if there is a vertical displacement of half cores (refer to Fig. 12b), the flux is again concentrated in the region close to the contact between both core halves, but the flux flowing in each layer remains in the same layer and therefore no orthogonal flux is observed. Consequently, higher losses might be observed for a horizontal displacement. For verification, Core W171 was used, where a winding with 6 turns was used to apply a 20kHz square voltage. A second winding was used to measure the flux flowing and like this the losses could be measured. Some displacements were applied to the core halves in both directions and the losses were obtained. These results are depicted in Fig. 14.

Note that losses are greatly increased when the cores halves were displaced in the horizontal direction and only a minor loss increase is observed for vertical displacement, as predicted. If the displacement is such that only half of the cross section is in contact in both core halves (i.e. displacement equal to 50% in Fig. 14), core losses increased by a factor of 18 when the displacement is horizontal and only by a factor of 1.2 when it is vertical. Measurements were also made with ferrite and loss increase is around 30% for a misalignment of 50%, in both directions.

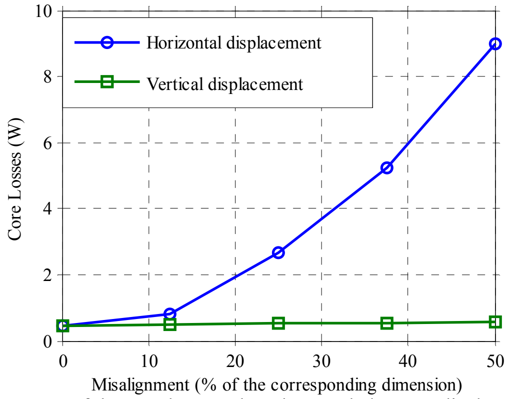

Fig. 14. Increase of the core losses when the core halves are displaced.

These results clearly show that orthogonal flux in nanocrystalline cores greatly decreases the performance of these types of cores. Actually, these conclusions can be extended to any type of tape wound cores. Accordingly, inductor and transformer manufacturers must be very careful with misalignments when assembling C-cores made of wound tape amorphous or nanocrystalline materials.

A. Increase of core losses in transformers

It was shown that orthogonal flux may greatly increase losses in tape wound cores. Like so, an interesting and important verification is the effect of this kind of flux in transformers.

Transformers are usually designed by considering the maximum magnetizing flux and taking this value as reference when calculating core losses. Core losses are frequently calculated using Steinmetz parameters provided by manufactures. However, for certain designs the leakage inductance is not negligible. Leakage flux flows through the magnetic material and also through the air and, consequently, orthogonal flux could possibly become important and generate significant core losses.

In order to confirm this thought, a simple transformer was built using Core W171. Two identical windings were wound in the core, one in each leg, as shown in Fig. 15. Each winding has 22 turns, made of two parallel litz wires having 1200 strands of 0.2mm diameter each, used in order to present much lower copper losses than losses generated in the core. Also a third winding having 4 turns was placed in the middle of the bottom leg with the intention of sensing the flux in this specific position and confirming the changing in the magnetizing and leakage fluxes for different loads.

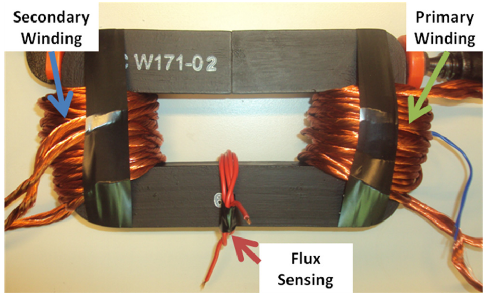

Fig. 15. Transformer built for testing extra losses due to orthogonal flux.

Square voltage was applied to the primary winding and the secondary was connected to a variable resistance. Total losses in the primary and in the secondary were measured using the Yokogawa WT 300 Precision Power Analyzer. Losses in the transformer were calculated by subtracting these two measured losses. Core losses are estimated by subtracting estimated copper losses from the transformer total losses. Analytical calculation using [13] and FEM simulations were performed to predict losses in the litz wire used in both windings. It was found that the AC resistance per unit length of the winding (at 20kHz) in the transformer is equal to approximately 2.58mΩ/m. Also, copper loss measurements were performed in the windings without being wound around the core and the AC resistance calculated from these measurements was close to 2.58mΩ/m. Measured values are 16% higher than calculated ones but are both much lower than core losses. Accordingly, core losses can be precisely determined by measurements.

Core losses measured in the transformer described above are shown in Fig. 16a. Note that core losses considerably increase when the load current increases, due to the fact that orthogonal flux is increased. In Fig. 16b, the voltage sensed in the third winding confirms that the magnetizing flux decreases (in the position of the flux sensing winding) and the leakage flux increases when the current in the secondary winding increases.

Slightly higher core losses are observed for very low current in the secondary winding. This is due to two main reasons:

1 – For lower loads, the control system applying square voltage to the primary winding could not regulate the DC current and thus close to 2A DC was observed in the primary winding. This DC current increases core losses as described in [10].

2 – Voltage applied by the control system is fixed. When the current in the primary and secondary windings start to

increase, a small voltage drop is observed in the wiring from the source to the transformer, and, like this the flux generated in the primary side slightly reduces, reducing also core losses.

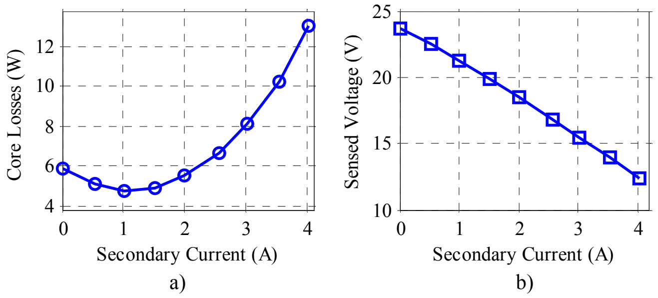

Fig. 16. a) Core loss increase in the tested transformer. b) Sensed voltage related to the flux flowing close to the middle of the bottom leg (Fig. 15).

B. Decreasing core losses in cut cores

It is very difficult to reduce losses in cut cores. However, a lower increase in core losses can be obtained if a proper cut is applied. This cut must assure:

- minimum number of short circuits between layers;
- minimum irregularity among different layers. Different layers having different sizes cause irregular airgaps in the contact between two half cores. Like this the flux flowing through one shorter layer tends to flow into another longer layer which is closer to the other half core. Consequently orthogonal flux is developed in the region close to the contact between two half cores and core losses are increased.

Authors in [14] affirm that inserting a ferrite plate in between halves of cores of amorphous material may decrease losses due to the reduction of fringing flux in the tape wound core, although it also reduces the maximum flux density attainable by the inductor since ferrite saturates close to 0.5T.

In order to reduce losses in transformers due to the leakage flux, one solution is to laminate the core in a direction where the leakage flux is not perpendicular to the layer plane. This is the case, for example, if a transformer were made with the cylindrical core used in this work (refer to Fig. 7a).

IV. Conclusion

Additional core losses are observed in cut cores. In this paper two different core geometries were analyzed: A cylindrical core where the layers are parallel to the cylinder height; and toroidal tape wound cores. Cylindrical cores were made with two different amorphous materials while toroidal cores were made of nanocrystalline material. Cylindrical cores were cut out of a massive amorphous block by using electric discharge machining (EDM). Toroidal cores were cut in half with EDM and also with a thin metal saw.

EDM introduces more short circuits between layers of magnetic material than a cut using thin saw. Thus, the increase of core losses by the cut is higher when using EDM.

Core losses in cut cores can be reduced by removing these short circuits. This may be done by exposing the cut surface to 40% ferric chloride ($FeCl_3$) solution. However, the etching has to be properly stopped after the short circuits are removed.

This technique was effective for a cylindrical core since short circuits were removed and no flux orthogonal to the magnetic layers was introduced due to the geometry of the core. However etching the cross section of toroidal nanocrystalline cores may remove some short circuits but may also introduce irregularities between layers and additional airgaps in the core. This increases fringing flux in the core and orthogonal flux in the magnetic layers, which significantly increases losses.

The increase of core losses due to orthogonal flux was verified by the increase of measured losses for core halves misaligned in the direction parallel to the layers. This was also experimentally verified by the increase of core losses in a transformer due to augmentation of leakage flux.

No technique is readily available for effectively decreasing losses in tape wound cut cores. Therefore, the best option is to have a careful machining technique such that a minimum amount of short circuits and irregularities between layers is generated.

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