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Daniel Roger, Mathieu Rossi, Krzysztof Komez, Ewa Napieralska-Juszczak, Jérôme Cambier. Design of coils for high-power medium-frequency transformers using Grain-Oriented hot cores. International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF), Sep 2023, Pavia (IT), Italy. <hal-04288954>

HAL Id: hal-04288954

<https://hal.science/hal-04288954v1>

Submitted on 16 Nov 2023

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Design of coils for high-power medium-frequency transformers using Grain-Oriented hot cores

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Abstract— This article proposes a design of windings for medium-frequency transformers (MFTs) at the heart of high-power Solid-State Transformers (SSTs). With aluminum interleaved foils of the correct thicknesses, it is possible to obtain low winding losses and a very low leakage inductance well adapted to SSTs. The magnetic phenomena are analyzed by a 2D FEM model obtained connecting in series 4 sub-models describing specific parts of foil coils. The proposed winding avoids Litz windings, which are significantly more expensive. On the other hand, the high capacitance between foils yields a good distribution of the electric field inside a winding fed by fast fronts voltage pulses.

Keywords— Solid-State Transformer (SST), medium frequency transformer (MFT), foil coils, grain oriented electrical steel (GOES), wound core.

I. INTRODUCTION

With more and more renewable intermittent sources, the grid stability becomes more challenging because the large adjustable power stations take a decreasing part. The meshed distribution grid stability can be improved by smart nodes controlling the bidirectional energy flows at the grid's critical nodes in real time. High-power Solid-State Transformers (SSTs) can perform this function. The central elements of such SSTs are medium or high frequency transformers. The standard solution consists in designing such transformers around ferrite or nanocrystalline cores with Litz-wire coils [1]. High-power SSTs are often made of many elementary cells. It is also possible to design high-power MFT (several MVA) with wound cores made of grain-oriented electrical steel (GOES) thin strips. This material can withstand high temperatures; this property is used for reducing core losses [2,3]. High-power SST applications often operate at high voltages; a specific conception of windings, able to withstand high-voltage fast-fronted pulses is necessary. The paper proposes a winding design that offers the low leakage inductance and the high-voltage capability required for high-power SSTs.

II. HOT-CORE TRANSFORMER STRUCTURE

The schematic structure of the hot-core transformer is presented in Fig. 1. There is no contact between the core and the coils, which are fixed between the upper and lower supports that are not shown in this schematic structure. Fresh airflows (green arrows), provided by small fans, allows the cohabitation of a hot core inside coils at usual temperatures. Accepting reasonably high core temperatures, this transformer can operate at high flux densities up to 4 kHz. In these

conditions, specific power is high and the efficiency in the same range than standard SSTs.

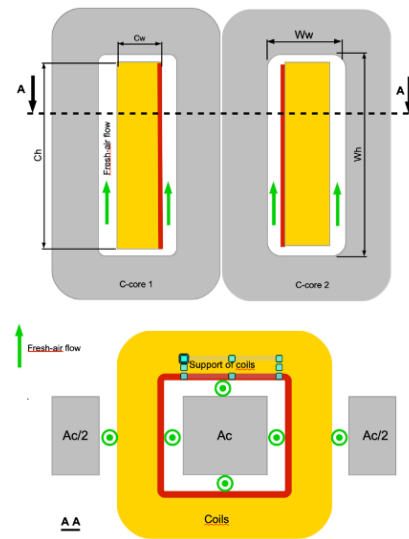


Fig. 1. Hot-core transformer structure.

III. WINDING DESCRIPTION

The primary and the secondary coils are made with two interleaved aluminium foils whose thicknesses are 1 mm. The aluminium foils are insulated by a 200 μm thick polymer. In Fig. 2, the 14-turn secondary coil is drawn in blue and the 10-turn primary coil in red, between turns 2 and 12 of the secondary coil.

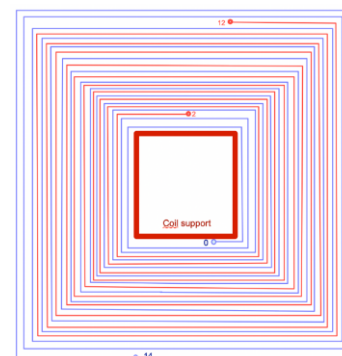


Fig. 2 Interleave foil coils providing a low leakage inductance.

With large aluminium foils and a thin polymer layer, the capacitances between turns are higher than for standard coils made with Litz wires. The over-voltages due to the high slew rate rectangular pulses are limited. With this winding technology such MFTs can be associated to high-voltage

IGBT bridges able to reach powers in the 10 MW range. This structure can also operate up to the thermal class of the polymer sheet that separates the foils (200°C for a class C polymer), which is higher than for Litz wires.

IV. DETERMINATION OF THE LEAKAGE INDUCTANCE

Figure 3 presents a high-power SST that connects two DC smart grids. The MFT is placed between two active bridges.

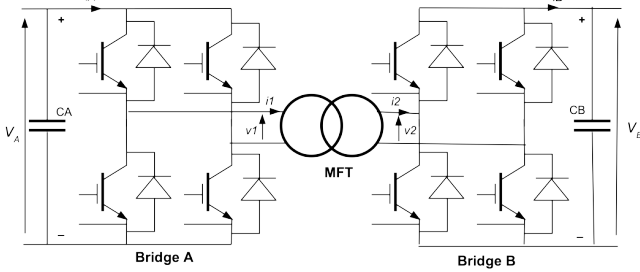


Fig. 3 Example of a high-power SST connecting two DC smart grids.

The power transferred between the input and output is controlled by the phase shift φ between the command of the two bridges [4]. In (1), V_A and V_B are voltages of the two smart grids, ω is the angular frequency, and L_L is the leakage inductance of the TMF referred to the primary side. This equation shows that the leakage inductance L_L must be as low as possible for transferring high powers.

$$P = \frac{V_A V_B}{\pi \omega L_L} \varphi(\pi - |\varphi|) \quad (1)$$

A transformer is a three-dimensional object; a significant part of the winding is outside the core windows; this observation must be considered in the FEM analysis. The 3D model of such an object requires too many nodes because the foil thickness must be split into several layers for modelling the skin and proximity effects. A specific 2D model, with a reasonable mesh is proposed. This model it is made of a series connection of 4 sub-models (Fig. 4). The first sub-model considers the two straight parts of the winding inside the core windows. The second one describes the straight part of the coil end with the primary connection bars. The third one represents the front part with the secondary connection bars that impose a different air-layer between several foils. The fourth part describes the 4 circular parts that connect the straights parts. Boundary conditions are defined on specific lines separate the sub-models. The foil thickness is split into 7 layers for obtaining at least 3 elements in the skin depth at 4 kHz.

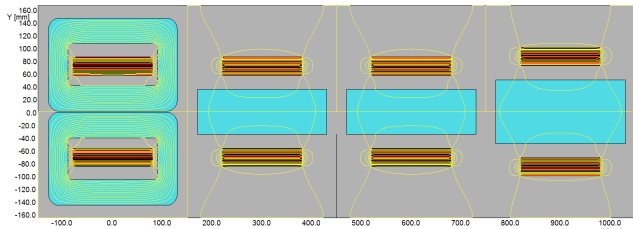


Fig. 4 Transformer 2D model that consists of a series connection of 4 sub-models representing specific parts of the foil coils of the transformer.

Figure 5 presents an example of the current density distribution inside a 1 mm thick aluminium foil. Because skin and proximity effects, the leakage inductance decrease with frequency. The change is about 5% between 1 kHz and

10 kHz. The leakage inductance measured at 4 kHz on the prototype defined in figure 1 and 2 is 0.77 μH . This measurement is in good agreement with the value computed by the FEM 2D model at the same frequency.

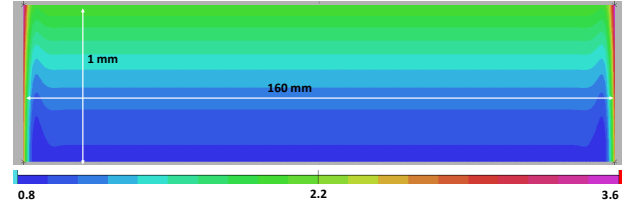


Fig. 5 Example distribution of the instantaneous value of the current density (A/mm^2) in the cross-section of the foil (deformed dimensions).

It should be emphasized that this low leakage inductance is obtained thanks to the full interlacing of the windings. For concentric classical windings, the leakage inductance is about 30 times higher (Fig. 6). This very good result is obtained with a slightly more complicated winding construction.

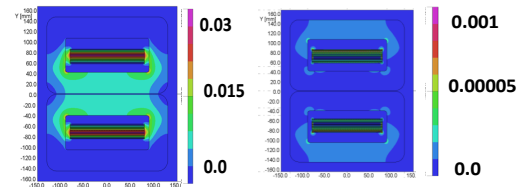


Fig. 6 Left: flux density magnitude for concentric coils. Right: Flux density magnitude for interlaced coils.

For the interlaced winding, the inductance value is very sensitive to the spacing between foils. For the considered model, an increase the spacing between foils by 0.2 mm (double insulation thickness) increases the inductance by 18%.

V. CONCLUSION

The article presents a high-power MFT operating at 4 kHz using a GOEs wound core and foil windings. The transformer design assumes that the core will operate at high temperatures for reducing eddy current losses. The design of the foil windings requires an analysis of the field phenomena that corresponds to skin et proximity effects. A construction with interlaced primary and secondary coils yields a very low leakage inductance at the operating frequency.

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