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# Design of a Medium Frequency High Power Transformer built with thin Grain Oriented Electrical Steel Core

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**Abstract** - The paper addresses the problematic of a medium frequency transformer prototype design using grain oriented electrical steel (GOES) core with the future aim to build a solid-state transformer (SST) for DC grids. SSTs are electronic components using static converters connected at the primary and the secondary sides of a medium or high frequency transformer. This technology enables smart nodes for an active control of power flow within DC grids. In most of the reported cases, SSTs combine amorphous or nanocrystalline magnetic materials for the core and wide-bandgap semiconductor technologies with complex control strategies. This makes those SSTs expensive. The paper suggests another approach for designing low-cost SSTs taking advantage of widespread GOES associated to well-known silicon-based semiconductor converters working with very simple command strategies. The study focuses on a prototype dedicated to answer questions raised by the optimal design of a MFGO transformer

**Keywords** - Solid-State Transformer. Medium frequency power transformer. Thermal modelling. Grain oriented electrical steel.

## I. MOTIVATION OF THE WORK

Solid-State transformers are promising technologies for future electrical grids [1]. The basic concept of the SST is made of two power electronic converters connected via a medium to high frequency transformer (figure 1). This structure is adapted to smart grids and clean technologies [2,3]. Several topologies of SSTs are available for various applications [4].

The transformer is one main component in the SST; it provides the energy transfer as well as the voltage change and a galvanic separation between the input and output stages. Because of high operating frequencies, the volume of the transformer is reduced when compared to traditional power transformers at 50 Hz.

The big challenge for the SST design is the high efficiency at low cost. A compromise has to be reached considering the selection of the magnetic materials, the power electronic components and their driver [6]. In most of the reported cases, SSTs combine amorphous or nanocrystalline magnetic materials for the core and wide-bandgap semiconductor technologies with complex control strategies. This association is meant to be used at frequencies higher than 10 kHz for high power densities and efficiencies, but at high costs. Low cost wide-spread thin GOES and well known silicon-based IGBT converters, offer alternative solution for designing economically wise high power low-cost SSTs.

This paper shows the design process steps of a SST prototype. It is used for extensive measurements to get useful data for defining SSTs at maximum rated power in a reduced volume. The frequency and maximum flux density applied to the GOES core are the main parameters to play with for

reaching maximum efficiency. Internal temperature of the winding is taken as the limiting parameter.

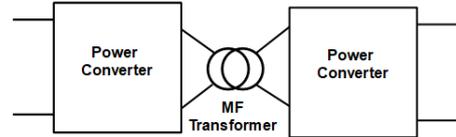


Fig. 1. Elementary topology of the SST

## II. TRANSFORMER DESIGN

With regards to transformer performance, the windings configuration is critical. Figure 2 shows the chosen structure for the transformer core. The benefit of this arrangement is a magnetic flux parallel to the easy magnetisation axis of the GOES strip. It enables low loss and the geometry, easier cooling. The windings are made of Litz wires to reduce skin and neighbouring effects.

Respective configurations of primary and secondary windings in separate layers provide an ability to adjust the leakage inductance value. This inductance is meant to protect the power electronics against strong variations of the voltage (high dv/dt). The adjustment is easily made by controlling the distance between primary and secondary windings.

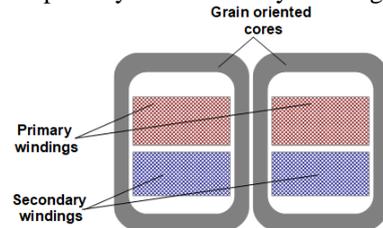


Fig. 2. Transformer structure

The area product formula [7], valid with sine or square waves, has been used to help at transformer core design:

$$A_p = \frac{S \times 10^4}{K \times B_{max} \times f \times J \times k_f \times k_u} \quad (1)$$

$$A_p = A_c \times W_a \quad (2)$$

With:

$A_p$ : Area product (cm<sup>4</sup>);

$A_c$ : Core area (cm<sup>2</sup>);

$W_a$ : Core window area (cm<sup>2</sup>);

$B_{max}$ : Maximum flux density (T);

$S$ : Transformer power rate (VA);

$f$ : Operating frequency (Hz);

$J$ : Current density in the windings (A/cm<sup>2</sup>);

$K_f$ : Stacking factor of the GOES;

$k_u$ : Window utilization factor;

K: Waveform coefficient. K=4 for square wave and 4.44 for a sine wave;

The winding turns are calculated by:

$$N = \frac{U}{4 \times B_{max} \times f \times k_f \times A_c} \quad (3)$$

For the sake of simplicity, the same number of turns for the primary and the secondary windings is considered.

The wire area is calculated by:

$$A_w = \frac{I_p}{J} \quad (4)$$

With  $I_p$  given by:

$$I_p = \frac{S}{U} \quad (5)$$

In first instance a toroidal transformer specified at table 1 has been designed and tested:

TABLE I PROTOTYPE SPECIFICATIONS

Parameter	Value	Unit
S	9	kVA
U	220	V
$B_{max}$	1.7	T
f	2	kHz
J	3	A/mm <sup>2</sup>
K	4	
$k_f$	0.916	
$k_u$	0.12	

The first tests show that in that prototype, operation is limited at 1 kHz and 1 T because of temperature limitation, and maximum transmissible power limited at almost 1.5 kW. However, the prototype in figure 2 is way better since most of its surface is in contact with the air, thus leading to better results.

TABLE II RESULTS OF TESTS AT 1 KHz & 1 T

		NO-LOAD TEST	SHORT-CIRCUIT TEST	
			PRIMARY CURRENT	
LOSSES		17 W	19.4 A	30 A
TEMPERATURE AT STEADY-STATE		110 °C	60.2 W	170.3 W
CORE	PRIM.	81.2 °C	71.8 °C	140 °C
	SEC.	56.2 °C	64.2 °C	120 °C

### III. THERMAL MODEL

The increase in frequency and flux density to reach optimum volume efficiency is limited by the temperature allowed by the insulating media, here around 180°C.

A thermal model is then mandatory to predict the temperature of the various transformer parts at steady-state for given losses to avoid the breakdown of the system. The model presented below is built on the following assumptions:

- uniformity of the temperature in the core and the windings.
- heat transfer mainly operated through conduction and convection mechanisms.
- The thermal conductivity is independent from the temperature.

The corresponding model is shown at figure 3.  $T_C$ ,  $T_{W1}$ ,  $T_{W2}$ ,  $T_R$ , refers respectively to core, primary windings, secondary windings, room temperature.  $P_C$ ,  $P_{W1}$ ,  $P_{W2}$  are respectively the losses of the core and the 1 and 2 windings.  $G_{W1}$ ,  $G_{CW1}$ ,

$G_{W1W2}$ ,  $G_{CR}$ ,  $G_{W1R}$ ,  $G_{W2R}$  stand for the respective thermal conductances.

The model can be described by the following matrix equations:

$$[P] = [A][T] - [B]T_R \quad (6)$$

Where:

[P] is a vector representing the core and windings losses; [A] is a 3\*3 matrix representing thermal conductances; [B] is another vector representing thermal conductances; [T] is a vector of temperatures in the core and the windings predicted by the model;  $T_R$  is the room temperature supposed to be constant.

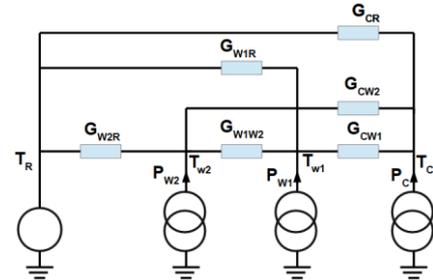


Fig.3. Thermal model of the MFGO transformer

The first step is to find the thermal conductances, and build the matrix [A] and [B], so the temperatures can be obtained by this formula:

$$[T] = [A]^{-1}([P] + [B]T_R) \quad (7)$$

We thus suggest an experimental method based on a number of different and sufficient tests led on the transformer. For each the temperatures shown in the model are measured using thermocouples.

### IV. CONCLUSION

A design of a high power, low cost medium frequency transformer for SST applications is presented. The approach uses thin grain oriented electrical steel sheets, and silicon based IGBT converters with a simple control strategy. A compromise shall be achieved between the operating frequency and the maximum flux density level, the key factor being the maximum temperature allowed inside the transformer. Therefore a thermal model is set up which will be detailed together with the related results in the full paper.

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