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High power density medium frequency transformer built with thin GO electrical steel sheets

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Abstract- The paper presents the concept of a medium frequency transformer built with thin grain oriented electrical steel (GOES) sheets and high temperature windings; this transformer will be associated with power converters for building a solid-state transformer (SST) used in DC grids. The aim of the study is to bring answers about the maximum operating frequency and flux density that provide the maximum power density and efficiency. A thermal model built from tests on the prototype is presented. This thermal model gives a prediction of the transformer performance for the initial choices of frequency and flux density. It opens perspectives for designing high power density medium-frequency (MF) transformers.

Keywords: Solid-State Transformer (SST), Medium frequency power transformer, Thermal modeling, Grain Oriented Electrical Steel (GOES).

1. Introduction

Solid-State transformers (SST) are promising technologies for connecting future electrical DC grids [1] with a control of the transmitted power flow. The basic SST is made of two power electronic converters connected via a medium or 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 of the main components of the SST; it provides the energy transfer as well as the voltage change and galvanic separation between input and output. Because of high operating frequencies, the volume of the transformer is reduced compared to traditional power transformers working at 50/60 Hz.

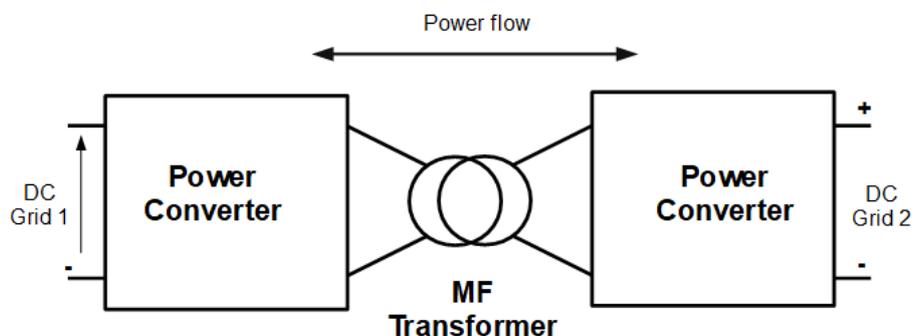


Fig.1. Solid-State Transformer configuration.

The biggest challenge for the SST design consists in getting high efficiencies and power densities with a reasonable costs. A compromise has to be reached considering the selection of the magnetic

materials, the power electronic components and their driver [5]. In most of the reported cases, SSTs combine amorphous or nano-crystalline magnetic materials for the core and wide-bandgap semiconductors technologies with complex control strategies. These Structures are used at frequencies over 10 kHz; they provide high power densities and high efficiencies, however they are rather expensive solutions. Wide-spread thin GOES and well known silicon-based IGBT converters offer an alternative solution for designing high power low-cost SSTs. Thin Wound GOES core presents the advantage of high flux density in the rolling direction, but their losses increase significantly with the frequency.

The aim of the study is to explore the limits of the GOES core. For that purpose, we must afford some degrees of freedom with the frequency, the flux density and the maximum operating temperature to achieve a compromise. In references [6] and [7] the approach used consists of limiting the core losses and the heat that generates, because of the limited operating temperature of the windings. This option limits the flux density for increasing the operating frequency and reducing the transformer size. In our case, we use Nickel-plated copper wires insulated with mica films and glass fiber ribbons. The operating temperature of these wires is up to 500°C, thus it is possible to increase both the frequency and the flux density. A full bridge silicon-based inverter supplies the transformer by a square wave voltage.

The paper focuses on the prototype made with high temperature windings, the performed tests are used to build a thermal model in order to extrapolate the performance of the transformer in more optimized operating conditions. The thermal model is mandatory for predicting the temperatures of the various transformer parts and for avoiding their break down.

2. Transformer Design

The prototype is built with two C-cores; the sizes are shown in figure 2. The C-core is made by rolling the thin GOES sheets (0.18 mm of thickness). The rolled cores are cut after an annealing cycle in order to suppress the magnetic effects of the rolling constrains.

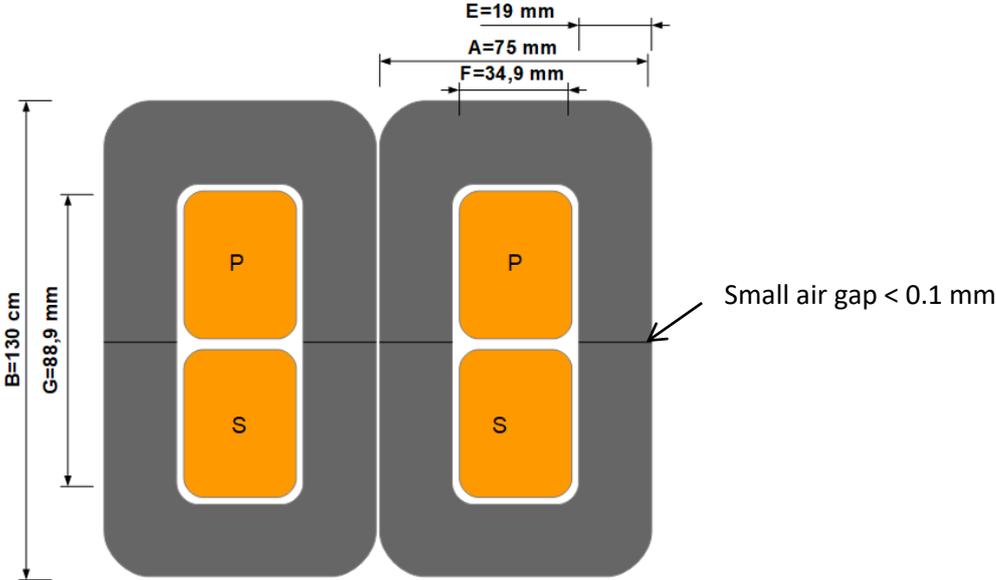


Fig.2. Configuration of the prototype.

The Transformer is designed for operating at 4 kHz and 1.5 T under a voltage of 220 V. For the seek of simplicity we consider the same number of turns for the primary and secondary. The number of turns is calculated by the classical formula (1).

$$N = \frac{U}{K \times B_{max} \times f \times A_c} \quad (1)$$

With:

K : The wave form factor, $K = 4$ for square wave and 4.44 for sinus

B_{max} : Maximum operating flux density

f : Operating frequency

A_c : Effective Cross-sectional area of the core

The wire conducting area A_w is calculated considering the core window area $W_a = G \times F$ (fig.2) and the coefficient of utilization of this area k_u :

$$A_w = \frac{W_a}{2 \times N \times k_u} \quad (2)$$

The constructed prototype consists of two coils; each one is made of ten turns. The conductor is made of 100 nickel-plated cooper wires taped with a very thin mica layer; the diameter of the wire is 0.8 mm. The nickel layer protects the cooper from oxidation a high temperatures. The insulation between the winding and the core is provided by glass fiber tapes, which also can withstand high temperatures.

3. Test Bench

It is well known that a transformer emits acoustic noise due to electromagnetic and magnetostriction forces in the core. The effect of this noise is more important in the range of 1-4 kHz, because the human ears are very sensitive for these frequencies. To avoid the psychoacoustic effects of the noise, the transformer is placed in a soundproof box and the tests are performed inside it. Acoustic foams cover the whole inner surface of the box.

The transformer is supplied by a square wave provided by a silicon based IGBTs inverter; an arduino board provides the inverter commands at the required frequency.

Several thermocouples are placed in different points of the transformer to measure the core and the windings temperatures, and inside the box to get the ambient air temperature. The positions of thermocouples are presented in table 1. The air temperature is a major data for a thermal modeling.



Fig.3. High temperature medium frequency transformer.

Table 1. Position of thermocouples during experiments.

Thermocouple	Position
1	In contact with the left core
2	In contact with the right core
3	Primary - between wires
4	Primary - between turns
5	Secondary between wires
6	Secondary between turns
7	External air at 10 cm in front of the coils
8	External air at 10 cm of the core on the transformer side

4. Thermal model

The proposed thermal static model is based on the following assumptions:

- Uniformity of the temperature in the core and the windings, because of the high thermal conductivity of copper and steel.
- Heat transfer mainly occurred by conduction and convection mechanisms.
- Thermal conductivity is independent from temperature.
- During experiments we observed that the temperature differences between the windings is small, therefore we neglect it and consider one mean temperature for the two windings T_w .
- The ambient temperature is constant.

These assumptions lead to the equivalent circuit of the thermal model shown in fig.4. The circuit is made of three nodes T_c , T_w and T_a corresponding respectively to the core, the windings and the air temperatures ($^{\circ}\text{C}$). P_c and P_w are respectively the core and the winding total losses (W).

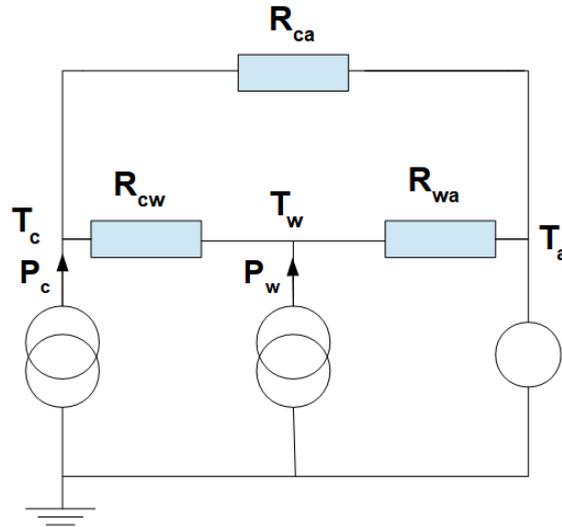


Fig.5. Thermal model.

The equivalent circuit is described by the system (3), written with thermal conductances $G = R^{-1}$

$$\begin{bmatrix} P_c \\ P_w \end{bmatrix} = \begin{bmatrix} G_{cw} + G_{ca} & -G_{cw} \\ -G_{cw} & G_{cw} + G_{wa} \end{bmatrix} \begin{bmatrix} T_c \\ T_w \end{bmatrix} - \begin{bmatrix} G_{ca} \\ G_{wa} \end{bmatrix} T_a \quad (3)$$

The temperature of the air is imposed and the other temperatures are obtained by inverting the matrix of the thermal conductances :

$$\begin{bmatrix} T_c \\ T_w \end{bmatrix} = \begin{bmatrix} G_{cw} + G_{ca} & -G_{cw} \\ -G_{cw} & G_{cw} + G_{wa} \end{bmatrix}^{-1} \times \left(\begin{bmatrix} P_c \\ P_w \end{bmatrix} + \begin{bmatrix} G_{ca} \\ G_{wa} \end{bmatrix} T_a \right) \quad (4)$$

However, for determining the thermal conductances of the model, an experimental method is proposed. It is based on performing different tests and measuring directly the temperatures by thermocouples placed in different points of the transformer for measuring the core, windings and air temperatures.

Two main tests are made, the first is the no-load one and the second is the short-circuited one. The conditions of each test are chosen in order to ensure the linear independence of the equations.

The no-load test is made at $f = 1$ kHz and $B_{\max} = 1.5$ T, the core losses is 123 W and we neglect the winding losses; thus we get the following equations:

$$P_c = G_{wa}(T_w - T_a) + G_{ca}(T_c - T_a) \quad (5)$$

$$\frac{T_c - T_w}{T_w - T_a} = \frac{G_{wa}}{G_{cw}} \quad (6)$$

The temperatures at steady states of the no-load test are presented in table 2.

The short-circuit test is made at $f = 2$ kHz, the total winding losses is 100 W and the core losses are neglected; we obtain equation (7).

$$P_w = G_{wa}(T_w - T_a) + G_{ca}(T_c - T_a) \quad (7)$$

The temperatures at steady state of the short-circuit test are presented in the table 3.

The values of thermal resistances calculated from (5), (6) and (7) are shown in table 4.

To get an idea about the accuracy of the model we simulated a no-load and a load tests using the conductances we obtained, then we compared the results with real measuring. The obtained results are shown in table 5.

Table 2. Temperatures of model nodes at steady states from the no-load test at 1 kHz 1.5 T

T_c	T_w	T_a
186 °C	123.5 °C	76.25 °C

Table 3. Temperatures of model nodes at steady states from the short-circuit test at 2 kHz.

T_c	T_w	T_a
68 °C	89 °C	45 °C

Table 4. Values of the thermal resistances

R_{cw}	R_{wa}	R_{ca}
0.6 °C/W	0.46 °C/W	5.1 °C/W

Table 5. Comparison between simulated and measured values.

	No-load test $f = 2$ kHz / $B_{\max} = 1$ T Core losses : 168 W			Resistive load test : $f = 2$ kHz / $B_{\max} = 1$ T, $U_p=78$ V, $I_p=14.6$ A, $U_s=73$ V , $I_s = 12$ A		
	T_c	T_w	T_a	T_c	T_w	T_a
Measures	227 °C	157 °C	94.6	240 °C	181	110 °C
Simulation	248 °C	160.6 °C		265 °C	183	
accuracy	9%	2%		10%	1%	

5. Thermal model exploitation

Now we got an idea about the accuracy of the model, the next step is to simulate a loaded test in order to obtain the maximum transmissible power and efficiency that could be provided by the prototype. Therefore, we suppose that the core losses remain constant for a given operating frequency and flux density, then we give different values for the current and calculate the windings losses, the transmitted power and the efficiency. We also supposed that the transformer is put in ambient air of 25 °C.

The figure 6 and 7 show the evolution of losses, efficiency and temperatures with transmitted power $P_o(W)$.

The maximum of efficiency is obtained when the core losses are equal to windings losses. This operating point corresponds to the optimal power that can pass through the transformer for a resistive load. Table 6 presents this operating point for several frequencies and maximum flux densities, the temperature is also computed.

The figure 6 and 7 show the evolution of temperatures, losses and efficiency with transmitted power.

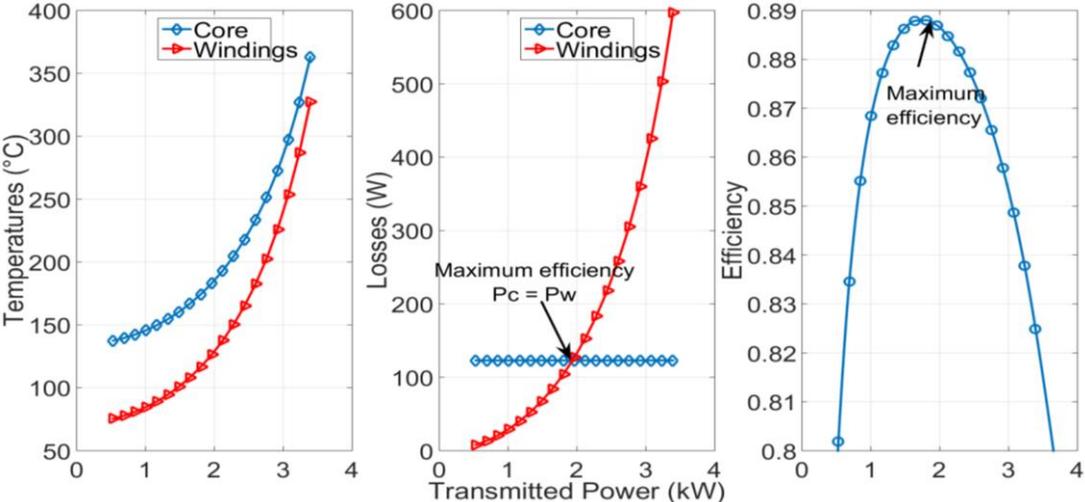


Fig.6.Simulation for $f = 1 \text{ kHz}$ and $B_{\text{max}}=1.5 \text{ T}$

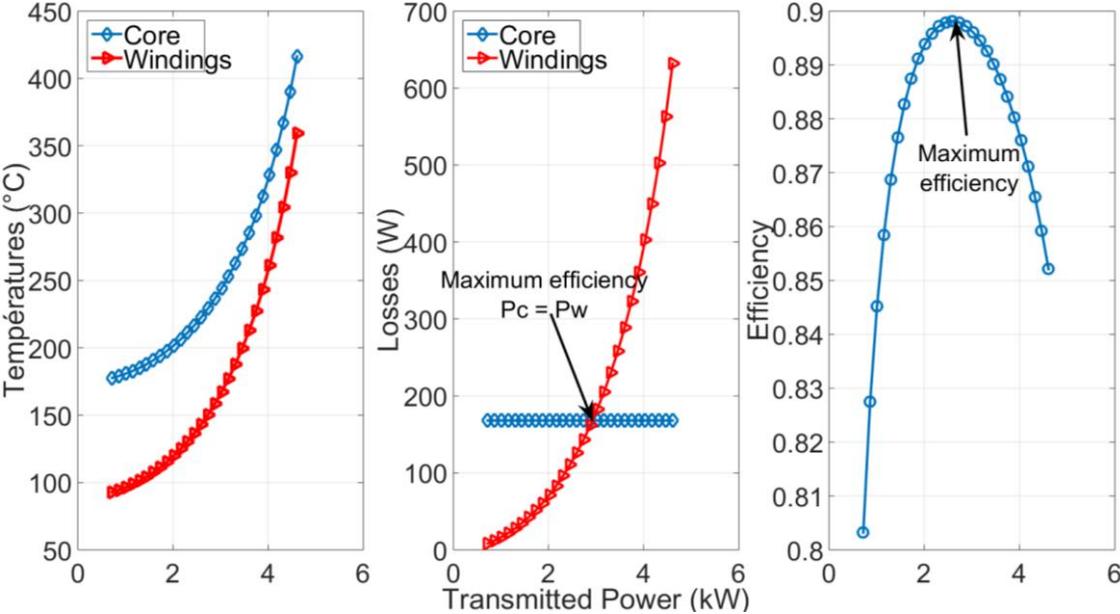


Fig.7.Simulation for $f = 2 \text{ kHz}$ and $B_{\text{max}}=1.5 \text{ T}$

Table 6. Results of simulation by the thermal model
Transmissible power for the maximum efficiency

F (kHz)	B _{max} (T)	P _o (kW)	Max η (%)	T _w (°C)	T _c (°C)
1	1.5	1.8	89	122	182
2	1	3	90	160	238
	1.5	5.4	88	260	445
4	0.5	2.9	91	131	197
	1	8.1	89	448	694

Table 7. Maximum transmissible power, for windings temperature limited at 450°C

F (kHz)	B _{max} (T)	Max P _o (kW)	η (%)	T _w (°C)	T _c (°C)
1	1.5	3.6	80	403	434
2	1	4.8	84	405	458
	1.5	6.1	87	407	577
4	0.5	4.8	84	407	440
	1	8.1	89	448	694

For 1 kHz and 2 kHz of table 6 high temperatures remains acceptable. The transmitted power can be increased, however the efficiency decreases. In the last line, the temperature becomes too high, it cannot be accepted. Table 7 presents similar results considering that the coil temperature must remain under 450 °C.

the results above show that the best compromise would be between 2 kHz 1.5 T and 4 kHz and 1 T. At 4 kHz and 1 T the maximum transmissible power is 8.1 kW for efficiency of 0.89; however the temperatures are extremely high especially within the core, where it reaches 694 °, this result is plausible, because the measured core losses are 512 W besides the transformer is uncooled.

These results can be optimized by redesigning the transformer windings, for that we recalculate the number of turns for 220 V, 4 kHz and 1T using the equation (1), we obtain 15 turns. In that case the transmitted power increased to 9.1 kW and the efficiency to 91%.

6. Conclusion

The paper presents a medium frequency power transformer prototype built with GOES wound core and high temperature windings. We investigate the limits of the prototype in terms of operating frequency and flux density using a simple thermal model. The accuracy of the thermal model has been controlled by comparing its predictions with experiments. The results show that the maximum operating conditions are 4 kHz and 1 T, and the transmissible power can reach 9 kW for an efficiency of 91%, despite the high operating temperatures. The mass of the core is 2 kg, thus we get a power density of 4.5 kW/kg of steel. This result will be furthermore optimized by increasing filling factor of the core window and by cooling the transformer with forced convection for getting lower thermal resistances. In addition, the thermal model will be used to extrapolate the study for industrial windings such as 180 and 240 thermal class windings.

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