

Magnetic properties measurement and discussion of an amorphous power transformer core at room and liquid nitrogen temperature

A G Pronto¹, A Maurício², J M Pina¹

¹ CTS, Uninova, Departamento de Engenharia Electrotécnica, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

² Departamento de Engenharia Electrotécnica, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

E-mail: amg1@fct.unl.pt

Abstract. In energy generation, transmission and distribution systems, power transformers are one of the most common and important components. Consequently, the performance of these transformers is crucial to global efficiency of the systems. To optimize transformers efficiency, the selection of an adequate ferromagnetic material is very important. For example, the use of amorphous ferromagnetic materials in transformer cores, replacing crystalline electrical steels, decreases total magnetic losses of the device. Other possible solution to increase energy systems efficiency, is the installation of high temperature superconducting power transformers (HTS transformers), normally cooled by liquid nitrogen at 77 K. In order to contribute to HTS transformer efficiency improvement, a 562.5 VA transformer with an amorphous ferromagnetic core was designed and built. For this core, the most important magnetic properties are measured at room and cryogenic temperature, and then compared with those of a typical crystalline grain-oriented electrical steel. Amorphous material magnetic losses (static and dynamic) at room and 77K are also presented and discussed.

1. Introduction

Amorphous steels used in power transformer cores allow easier magnetization processes and magnetic losses about 60 to 70% lower, when compared to conventional crystalline silicon-steel transformer cores [1, 2]. This loss reduction is very important to optimize conventional transformers efficiency and could become even more important in the optimization of high temperature superconducting power transformers (HTS transformers), where loss reduction has also a direct impact in the cryogenic system.

In order to contribute to HTS transformer efficiency improvement, a 562.5 VA transformer with an amorphous ferromagnetic core (2605SA1 alloy) and copper windings was designed and built. The magnetic properties were measured at room and liquid nitrogen temperature. This paper presents total magnetic losses curves, magnetization curves and hysteresis loops obtained for both temperatures. The experimental results are analysed and compared to others obtained in similar tests made in a typical crystalline grain-oriented electrical steel.

2. Experimental procedure

The 562.5 VA single phase transformer with an amorphous ferromagnetic core (2605SA1 alloy) was designed and built. Table 1 shows the main characteristics of the developed prototype.

Table 1. Specifications of the designed amorphous core transformer

Capacity (VA)	Frequency (Hz)	Voltage (V) (U_1/U_2)	Turns (N_1/N_2)	Current (A) (I_1/I_2)	Core dimensions (mm) (Height×Width×Depth)
562.5	50	112.5 / 56.25	203/102	5 / 10	300×188×60



The measurements were made under sinusoidal induction waveform at 50 Hz through the application of an AC voltage to the primary of the transformer, leaving the secondary in open circuit. The maximum magnetic induction B was controlled through the variation of the applied voltage U_1 , so each voltage imposed a constant B_{\max} . The corresponding waveforms of magnetic induction B and applied magnetic field H were registered in a digital oscilloscope. The magnetic field H is calculated from the voltage drop measurement in a calibrated resistance (which is an image of the primary electric current $i_1(t)$), connected in series with the primary circuit, and the magnetic induction B is obtained from the integration of the open circuit secondary voltage of the transformer, $u_2(t)$. The measurements were made at 298 K for several values of maximum magnetic induction B . Then the transformer were bathed by liquid nitrogen in order to repeat the procedure for the same values of B_{\max} .

To compare the magnetic properties at 77 K and 298 K of the amorphous core with a typical grain-oriented core, a Fe-Si transformer designed and built by A. Pronto [3,4], was chosen because it has a core with the same dimensions. In this paper, the amorphous core transformer will be designated by 'NA' and the grain-oriented core transformer by 'AP'. Table 2 shows the main characteristics of the conventional grain-oriented Fe-Si alloy used in AP.

Table 2. Specifications of silicon-iron sample used to build AP core

Class of silicon-iron	Thickness of laminations (mm)	Grade AISI	DIN 46400	% wt Si	Density ($\text{g}\cdot\text{cm}^{-3}$)
CGO	0.35	M6	VM111-35N	3.9	7.05

3. Experimental results and discussion

The first magnetization curves for the two magnetic cores, NA and AP, at room and cryogenic temperatures, are plotted in figure 1.

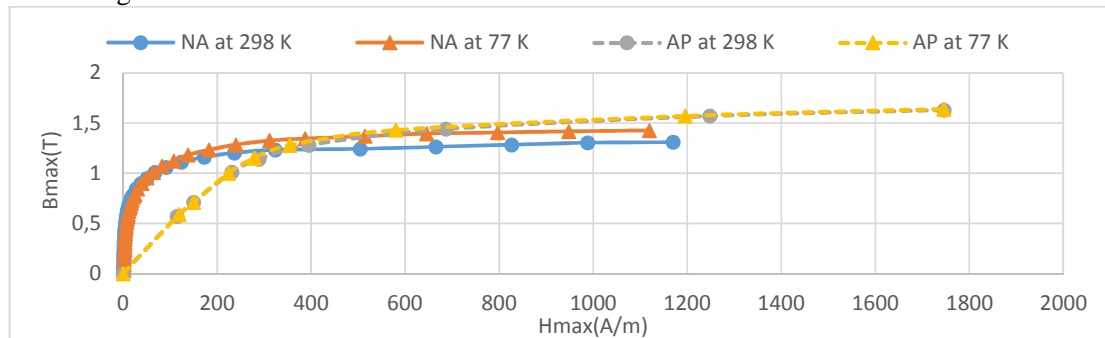


Figure 1. First magnetization curves at 298 K and 77 K for NA and AP (adapted from [3])

Comparing the measured first magnetization curves of NA and AP it can be concluded that:

- For NA core and for maximum magnetic induction B up to 1 T, the magnetization curves are very similar at 298 K and 77 K. The saturation flux density, B_{sat} , is approximately 0.65 T. Above 1 T, and for the same value of magnetic field H , the corresponding maximum magnetic induction B is approximately 10% higher at 77 K. This means that, in this range the same magnetomotive force produce higher induction fields.
- For AP core, B_{sat} is approximately 1.2 T, which is about 85% higher than the corresponding value for NA core. This difference is due to the composition of the amorphous materials, namely the smaller quantity of iron (80%), when compared with crystalline Fe-Si steels, added to the presence of silicon (20%), which leads to a decrease in saturation induction, when compared with other ferromagnetic materials [3,5].

- Amorphous material has a much higher magnetic permeability. For $B \leq 0.6$ T (non-saturated region) the relative magnetic permeability of the amorphous material is $\mu_r = 42952$, approximately eleven times higher than that of the silicon-iron for the same region, which is $\mu_r = 3922$.

The hysteresis loops obtained under dynamic conditions for a maximum magnetic induction $B_{\max} = 0.65$ T at 298 K and 77 K, are represented in figure 2.

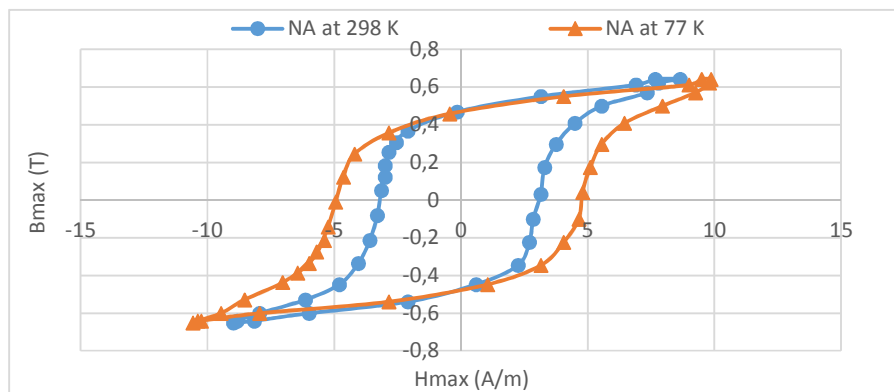


Figure 2. Hysteresis loops at 298 K and 77 K for NA

As can be observed in figure 2, the hysteresis loop obtained at room temperature is narrower, leading to lower total magnetic losses, p_{mag} (0.056 W/Kg at 298 K and 0.084 W/Kg at 77 K). Despite the value of remanence, B_r , remains constant for both temperatures, the coercive magnetic field H_c increase approximately 50% at liquid nitrogen temperature, which corresponds to higher magnetic losses at 77 K.

In order to analyse total magnetic losses behaviour several hysteresis loops were obtained as function of B_{\max} , for both temperatures. These measurements allows the determination of total magnetic losses, $p_{\text{mag,t}}$, through hysteresis loop area calculation. Figure 3 shows specific total magnetization losses curves obtained for NA and also compared them with total losses obtained for AP [3].

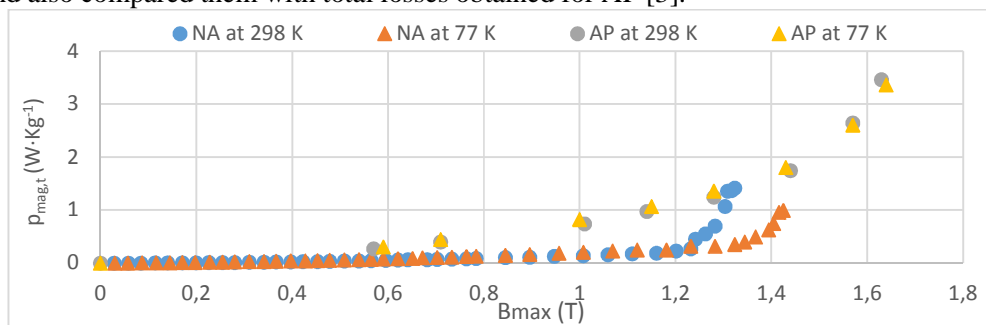


Figure 3. Total specific magnetic losses, $p_{\text{mag,t}}$ at 298 K and 77 K for NA and AP (adapted from [3])

Regarding total specific magnetic losses in NA and, for example, for $B = 1.2$ T, magnetic losses increase at 77K up to 8%. According with the results shown in figure 3, and comparing both materials, total specific magnetic losses obtained in AP tests are much higher. This increase is very significant, reaching values 7-8 times higher than the ones obtained for NA. Nevertheless, for NA, when the magnetic material is strongly saturated ($B_{\max} > 1.2$ T) an inversion on losses behaviour was detected, identically to what happened in AP crystalline core for induction fields equal or higher than 1.5 T: total magnetic losses are lower at 77 K. This difference is much more notorious in ferromagnetic amorphous material than in AP crystalline core. The

loss reduction at low temperature could have its origin in several factors. First, at low temperature, thermal vibration of lattice decreases, which leads to decreasing electric resistivity but, at same time, to increase magnetic permeability of the material. When the material is heavily saturated, the rotation of magnetic domains is the dominant mechanism and it is facilitated by higher permeability, probably reducing hysteresis losses. On the other hand, domain rotation causes a lower variation of dB/dt than that associated with Bloch wall movements, the dominant magnetization mechanism outside saturation region, which contribute to decrease induced electromotive force with corresponding reduction of eddy-currents in amorphous material, and consequent decreasing in excess losses [3,4]. This means that in saturated region, the decreasing in electric resistivity is counterbalanced by easier domain rotation processes which finally results in lower total magnetic losses at cryogenic temperature. [3,4]. For HTS power transformers, this loss reduction would be useful if happens in non-saturated region of the ferromagnetic material.

4. Conclusions

According with the achieved experimental results, it is possible to conclude that:

- amorphous steel has lower saturation flux density than the conventional silicon-steel used in AP, as expected; for this parameter, there are no relevant differences at room temperature and liquid nitrogen temperature for both materials.
- total magnetic losses are much lower in amorphous material when compared with losses obtained in AP core. For example, for a value of $B = 1$ T, the total magnetic losses in AP are 4 times higher at room temperature and 5 times higher at liquid nitrogen temperature, when compared to NA. In transformer useful operation region (outside saturation), there is an increase in losses at 77 K, for both ferromagnetic core materials, which will correspond to a reduction in transformer efficiency if cores are immersed in liquid nitrogen.
- nevertheless, when the core material are strongly saturated, total magnetic losses at 298 K become larger than losses at 77K. This behaviour could be very useful for HTS transformers if occurs at non-saturated region. A possible explanation is presented above, but further investigation is needed in order to understand the origin of this behaviour and if it's possible to shifted it to normal operation region.

Acknowledgements

The authors would like to thank to Dr. Ryusuke Hasegawa and Metglas Inc. for gently built up and offer the amorphous core used in this power transformer prototype.

This work was supported by FCT - Fundação para a Ciência e Tecnologia (CTS multiannual funding) through the PIDDAC Program funds.

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