The Magnetic Properties of the Ferromagnetic Materials Used for HTS Transformers at 77 K

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***Abstract*—The properties of the magnetic materials, such as the amorphous alloys and the grain-oriented silicon steels, are essential to the design of high-temperature superconducting transformers. In this paper the magnetic properties and the loss characteristics of different ferromagnetic materials are measured at liquid nitrogen temperature. It is shown from experimental results that at 77 K the saturation flux density of the amorphous metal is about 0.3 T lower than that of the silicon steel, and the loss of amorphous metal is 4 times less than that of the silicon steel. Since the losses of materials at 77 K are higher than those of at room temperature, it is not economical to immerse the transformer core in liquid nitrogen.**

***Index Terms*—Ferromagnetic materials, high-temperature superconducting transformers, magnetic losses, magnetization curves.**

I. Introduction

High-temperature superconducting (HTS) transformers have several advantages including reduced size and weight, low ac loss, high efficiency, over load capability, and environmental benignity over conventional transformers [1], [2]. As HTS manufacturing technology continues to improve, HTS transformers have become one of the most promising superconducting applications in power systems.

A HTS transformer is composed of a ferromagnetic iron core, two sets of HTS windings, and a cryogenic system. Since the ac losses in the HTS transformer winding are usually very small compared to the losses in the iron core, the contribution from the core material is dominant from a view-point of the total transformer losses [3]. The proper adoption of the core steels, which offers considerable reduction in losses, is to a certain extent helpful to the efficiency improvements of transformers. In some HTS design demonstrations, transformer cores are immersed in liquid nitrogen to simplify the structure of it and lower the leakage flux flowing in HTS windings [4]. This improvement makes it important to investigate the magnetic characteristics of the ferromagnetic materials in liquid nitrogen. Amorphous metals are one alternative that become attractive due to their lower iron losses and higher magnetizing volt-amperes (VA) when compared to conventional materials.

In this paper, magnetization curves, power loss curves, and the magnetizing power curves for the amorphous metal and the grain-oriented silicon steel are measured and compared at both ambient and liquid nitrogen temperatures. Considering these results, we investigate the effects of the magnetic characteristics on the structure design of a HTS transformer.

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TABLE I
The Specifications of the Specimens

Trademark of the specimen	27QG110	SA1
Weight of the specimen (10^{-3}kg)	171.5	82.4
Outer radius (mm)	55.37	30.00
Inner radius (mm)	34.54	23.00
Area of the cross section (mm^2)	158.70	137.70
Steel laminations of thickness (mm)	0.270	0.027
Density of the specimen (10^{-6}kg/mm^3)	7.65	7.19

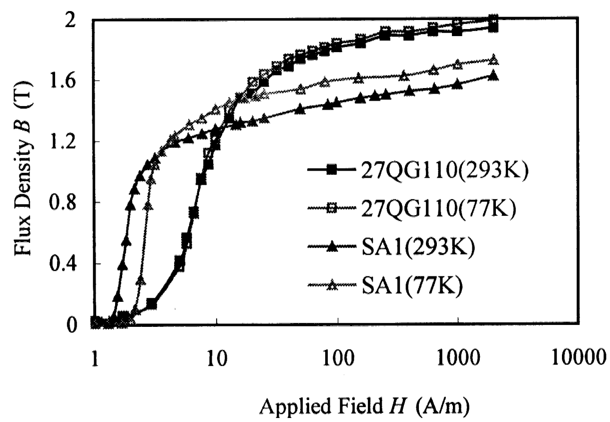

Fig. 1. B–H curves of the specimens.

II. Magnetic Characteristics at Low Temperature

A. The Specification of the Specimens

A grain-oriented silicon steel (27QG110) and an amorphous steel (SA1) are studied. The fundamental magnetization curves, the power losses, and the magnetizing VA are measured at ambient (293 K) and liquid nitrogen (77 K) temperatures, respectively. Parameters such as the saturation flux density, the magnetic remanence, and the coercive force are determined from these measurements. The toroidal specimens were made and their specifications are summarized in Table I.

B. Results of the Material Experiments

The fundamental magnetization curves (B–H curves) of the core materials at different temperatures are shown in Fig. 1. The saturation flux density of the grain-oriented silicon steel at liquid nitrogen temperature (77 K) is about 0.05 T higher than

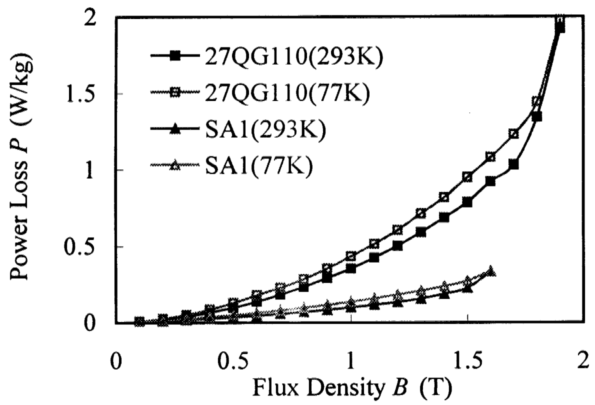

Fig. 2. Power losses of the specimens.

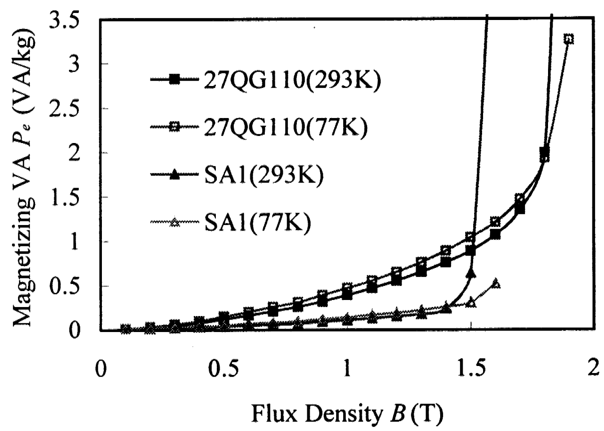

Fig. 3. Magnetizing VA of the specimens.

that at room temperature (293 K), whereas the difference in the saturation flux density for the amorphous alloys is about 0.13 T. At 77 K the amorphous steel has a saturation level of around 1.70 T, which is 0.3 T lower than that of the grain-oriented silicon steel. Therefore in the implementation of amorphous alloys, the nominal flux density should be 0.3–0.4 T lower when compared to the silicon steel.

Figs. 2 and 3 show the power losses and the magnetizing VA of the specimens at 50 Hz, respectively. Similar to the situation at room temperature, while the magnetic saturation is not achieved yet ($B < 1.3$ T), both the power loss and the magnetizing VA of the silicon steel are 1.5–3.5 times greater than the amorphous metal at 77 K, and this difference increasing with the flux density. After the specimen achieves the magnetic saturation, there is a sharp rise in the curve of the magnetizing VA. The power loss increases along with it. Therefore, when $B > 1.3$ T, the magnetizing VA of the amorphous metal will soon surpass that of the silicon steel. According to Figs. 2 and 3, both specimens have higher power losses and the magnetizing VA before saturation at 77 K compared with room temperature. After the specimens are saturated, however, the magnetizing VA at low temperature turns to be lower than that at room temperature.

To make the comparison clearer, Table II lists the performance parameters that can be calculated from Figs. 1–3, such as the saturation flux density B_s, the magnetic remanence B_r,

TABLE II
PERFORMANCE PARAMETERS OF THE SPECIMENS

Trademark of the specimen	27QG110 (293K)	27QG110 (77K)	SA1 (293K)	SA1 (77K)
Saturation Flux Density B_s (T)	1.94	1.99	1.57	1.70
Magnetic Remanence B_r (T)	1.65	1.74	1.28	1.42
Coercive Force H_c (T)	7.00	8.12	2.07	3.02
Power Loss (50Hz) $P_{1.3}$ (W/kg)	0.590	0.712	0.157	0.208
Power Loss (50Hz) $P_{1.7}$ (W/kg)	1.030	1.228	——	——
Magnetizing VA (50Hz) $P_{e1.3}$ (VA/kg)	0.65	0.76	0.18	0.22
Magnetizing VA (50Hz) $P_{e1.7}$ (VA/kg)	1.35	1.47	——	——

Where, $P_{1.3}$, $P_{e1.3}$, $P_{1.7}$, $P_{e1.7}$ represent the power loss and the magnetizing VA of the specimens at B=1.3T and at B=1.7T, respectively.

the coercive force H_c, the power loss P, and the magnetizing VA P_e at certain flux density.

As it is seen from Table II, the magnetic remanence and the coercive force will increase at liquid nitrogen temperature, which means the higher hysteresis loss at low temperature. Considering the higher eddy current loss due to the resistivity decline at low temperature, as the result, the total power loss will rise. At liquid nitrogen temperature, both the power loss and the magnetizing VA of the amorphous metal will increase by about 32% and 22% at 1.3 T, respectively, and those of the silicon steel by only about 22% and 14% at 1.3 T, by 19% and 8.8% at 1.7 T, respectively. For the amorphous metal, the ratio of the power loss and the magnetizing VA at 77 K to that at 293 K is larger than that of the silicon steel. However, a 70% reduction in both power loss and the magnetizing VA is possible compared to the silicon steel at 1.3 T, 77 K. Considering the high flux density of the silicon steel, both the power loss and the magnetizing VA of the amorphous metal at 1.3 T are only about 20% those of the silicon steel at 1.7 T, 77 K.

C. Result Analysis

According to the test results, the advantage to adopt the amorphous metal is the considerable reduction in power losses compared to the silicon steel even at low temperature. Another important property benefit is the magnetizing VA. However, the low saturation flux density of the amorphous metal has its limitations. Therefore, if the flux density of the core is not higher than the saturated flux density 1.3 T, the adoption of the amorphous metal is advantageous to reduce the core loss and magnetizing VA; otherwise the silicon steel is preferable but the high magnetizing VA reduces the transformer efficiency.

The other practical problems associated with amorphous steel come from its manufactural techniques [5]. For example, the difficulties of cutting and building it into a conventional core tend to outweigh the benefits gained. The rectangular cross section of the transformer core wound with amorphous metal enlarges the space between the HTS winding and the core. Another problem is its poor stacking factor. For amorphous steel it is only 0.84 compared with 0.95 for silicon steel.

The advantages to immerse the core materials into the liquid nitrogen are high saturation flux density, the slowly increasing of the power loss and the magnetizing VA. But apparently, the disadvantages of high power loss and high magnetizing VA overweigh the effect of the high saturation flux density when the flux density is below the saturation flux density. The reason may be that the rate of the increase of the saturation flux density is less than that of the power loss and the magnetizing VA. For instance, at 1.7 T, 77 K, the saturation flux density of the silicon steel increases by 3.6%, whereas the power loss by 19% and the magnetizing VA by 9%. In the transformer design, the flux density of the core B_c at low temperature should be no more than that at room temperature.

III. Design Example

The performances of the both materials approximately at both ambient and liquid nitrogen temperatures are compared to examine which HTS transformer design is preferable. We assumed a core-type, single-phase, 22 kVA, 220 V/20 V, 50 Hz transformer. A representative sketch is shown in Fig. 4.

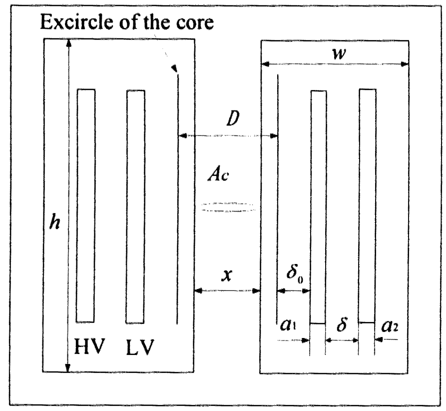

Fig. 4. Sketch of the single-phase transformer.

The cross section area of the central limb A_c is calculated by modifying the law of induction, which is twice that of the yokes

$$A_c = \frac{1}{4.44fB_c}\cdot\frac{V}{N} = \frac{1}{4.44fB_cf_0}\frac{V}{N} \quad (1)$$

in which V/N is the volts per turn, f is the frequency of supply, here, $f = 50$ Hz, f_0 is the stacking factor.

The cross section of the laminated silicon steel core can be regarded as circular with diameter D, and that of the amorphous core as foursquare, with the diameter D of its excircle. The x can be calculated by using,

$$x = \begin{cases} \sqrt{\frac{4A_c}{\pi}} & \text{silicon steel core} \\ \sqrt{A_c} & \text{amorphous core.} \end{cases} \quad (2)$$

Then the core volume can be written,

$$V_{\text{core}} = A_t \cdot (4x + 2h + 2w) \quad (3)$$

where, h, w are the height and width of the transformer window.

The required length L for the windings can be estimated from

$$L = \pi(D + 2\delta_0 + a_1)N_1N_{\text{para1}} + \pi(D + 2\delta_0 + 2a_1 + 2\delta + a_2)N_2N_{\text{para2}} \quad (4)$$

where, N_1, N_{para1}, N_2, N_{para2} represent the turns and the parallel numbers of the primary and the secondary windings, δ_0 is the space between the core and the primary windings, δ is the space between the primary and secondary windings.

The total volume of the windings,

$$V_{\text{windings}} = \pi(D + 2\delta_0 + a_1)A_{c1} + \pi(D + 2\delta_0 + 2a_1 + 2\delta + a_2)A_{c2} \quad (5)$$

where, A_{c1} and A_{c2} are the cross section of the primary and the secondary windings, respectively.

The core losses can be calculated as follows,

$$P_c = P_V \cdot \rho \cdot V_{\text{core}} \cdot f_0 \quad (6)$$

where ρ is the density of the core material. P_V represents the iron core loss for unit volume. If ρ_{refrig} is the penalty factor of 20 W/W for the cooling system, P_V can be calculated by,

$$P_v = \begin{cases} P \cdot \rho_{\text{refrig}} & \text{at low temperature} \\ P & \text{at room temperature.} \end{cases} \quad (7)$$

The losses in the HTS tapes are calculated as below,

$$P_{\text{windings}} = \mathcal{Q}_h \cdot V_{\text{windings}} \cdot f \cdot \rho_{\text{refrig}} \quad (8)$$

$\mathcal{Q}_h$ is the hysteresis loss per cycle for unit cubic meter [3].

The total losses can be calculated by,

$$P_{\text{all}} = P_{\text{windings}} + P_c. \quad (9)$$

The initial cost of the transformer is,

$$\text{Cost}_{\text{initial}} = M_s \cdot L \cdot I_c + M_c \cdot G_c \quad (10)$$

where, M_s is the price of the superconducting tape per kilo-ampere for unit length, M_c is the price of the core material for unit weight, G_c is the weight of the core material.

Assuming the life of the transformer is N years, the price of electricity is M_e, the running cost is

$$\text{Cost}_{\text{electricity}} = 365 \times 24 \times N \cdot (P_c + P_{\text{winding}}) \cdot M_e. \quad (11)$$

Given a volts per turn of $V/N = 2$ V, the comparison of the characteristics of the respective transformers is shown in Table III. We assumed the price of the amorphous metal is 5$/kg, the price of the silicon steel is 2$/kg, the price of the HTS tape is 26.45$/m, the price of the electricity is 0.07$/KW · h.

From the results we can make the conclusions that at low temperature the adoption of the amorphous metal will have about 1/2 increment in the cross section area and the volume of the core. The price of the amorphous core is about 3 times that of the silicon steel core. The core losses of the amorphous metal are only about 20 percent of that of the silicon steel core. The load losses and the price of the windings of the amorphous core transformer are about 1.4 times those of the silicon steel core transformer due to the enlargement of the winding dimensions. From the viewpoint of the transformer volume or the material price, the amorphous core is not desirable, despite the reduction in power losses, when compared to the silicon steel core. Moreover, the ratios of the cross section area, the core volume,

TABLE III
COMPARISON OF THE TRANSFORMER CHARACTERISTICS

HTS Transformer	Amorphous		Silicon Steel	
	Cold Core	Warm Core	Cold Core	Warm Core
Flux Density B_c (T)	1.3	1.3	1.7	1.7
Cross Section of Core (cm^2)	82.50	82.50	55.78	55.78
Window Area (cm^2)	147.8	323.6	147.8	323.6
Volume of Core (cm^3)	11237	12227	7485	8155
Volume of Winding (cm^3)	6.50	7.82	4.62	5.93
Weight of Core (kg)	67.87	73.85	54.40	59.27
Length of Winding (m)	307.45	369.65	218.29	280.50
No-load Loss[a] (W)	282.0	11.6	1336.0	61.0
Load Loss[a] (W)	85.7	103.1	61.2	78.6
Total Loss[a] (W)	367.7	114.7	1397.2	139.6
Efficiency (%)	98.33%	99.48%	93.65%	99.38%
Cost of the Core ($)	339.4	369.3	108.8	118.5
Cost of the Windings ($)	8132.0	9777.2	5773.8	7419.2
Cost of the Electricity ($)	6764.2	2110.0	25702.9	2568.1
Total Cost[b] ($)	15235.6	12256.5	31585.5	10105.8

[a]No-load loss, load loss and total loss are all calculated with the consideration of the factor of the penalty.
[b]Total cost does not include the cost for the cryostat.

the material price and the power losses of the amorphous core transformer to the silicon steel core transformer at low temperature are very similar to, and a little higher than those at room temperature. If the core is housed inside the cryostat, it is required that about 20 times the dissipated power for cooling the core, the low loss characteristics of the amorphous metal seems to be of the more importance.

The results also show that when the transformer core is immersed in the liquid nitrogen, there is hardly the alteration in the cross section. The magnetic circuit is shortened without cryostat between the core and the superconducting windings. As a result, the volume and the price of the core material are reduced about 8%, while the length, the load losses and the price of the superconducting windings are increased by about 20–30%. However, the loss arises from the dissipated power for cooling the core is about 20–25 times as many as that of the warm core. It seems that the cold core is neither economic nor efficient compared with the warm core. It is better to use the cold core only at the situation when the size of the superconducting transformer tends to dominate all other considerations.

IV. CONCLUSIONS

In this paper the magnetic performances of the silicon steel 27QG110 and the amorphous metal SA1 have been compared both at ambient temperature and at liquid nitrogen temperature. The results can be summarized as follows:

1) Compared with the values at room temperature, the saturation flux density, the power loss, the magnetizing VA, the magnetic remanence, and the coercive force all increase at 77 K.
2) The saturation flux density of the amorphous metal is increased by 0.13 T, whereas that of the silicon steel only by 0.05 T at low temperature. However, the saturation induction density of the silicon steel is still about 0.3 T higher than that of the amorphous metal at 77 K. The ratios of both the loss and the magnetizing VA of the amorphous metal to the silicon steel at low temperature are more than those at room temperature. The results mean that the adoption of the amorphous metal does not take the full advantage of the materials, but it helps to improve the efficiency in the HTS transformer design. The limitation on the usage of the amorphous core lies in the manufactural factor since the sizes of the amorphous strip are still unsuitable for the manufacture of large-power transformer cores.
3) Since the power losses of materials at 77 K are more than 20 times those at room temperature, it is not economical to house the transformer core into cryostat. However, the cryostat between the warm core and the HTS windings loosens the coupling between them. The radial component of the stray field also increases. On the one hand, that reduces the critical current and increases the eddy current loss of the superconducting windings; on the other hand, it increases the transformer inductance. On the normal operating and short-circuit operating conditions, the electromagnetic force as well as the temperature heighten accordingly. Therefore, the future survey should be conducted on the analysis of the leakage fields in the HTS transformer windings.

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