Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.6, No.4, (2004), pp.32~36

AC Loss Effects on the Design of HTS Windings for 1 MVA Power Transformer

Jong-Tae Kim, Woo-seok Kim, Sung-Hoon Kim, Kyeong-Dal Choi, Gye-Won Hong, Hyeong-Gil Joo, Song-yop Hahn

Korea Polytechnic University,
Electrical Engineering and Science Research Institute, Seoul National University

cass@kpu.ac.kr

Abstract **- AC loss is one of the important parameters in HTS (High Temperature Superconducting) AC devices. Among the HTS AC power devices, the transformer is an essential part in electrical power system. But, AC loss is one of the most serious problems of the HTS transformer, especially with pancake windings, because high alternating magnetic field is applied perpendicularly to the surface of BSCCO wire in HTS windings of that, comparing with the other HTS AC power devices. For the reason above the calculation of AC loss generated in the HTS windings should be carried out in advance when designing the HTS transformer. In the paper we performed study for optimization of winding design to minimize the magnetization loss of HTS winding such as the spaces between pancake windings and operating temperature of HTS wire. The calculation of the AC loss was accomplished by 2-demensional Finite Element Method.**

1. INTRODUCTION

The HTS(High Temperature Superconducting) transformer is one of the most important elements composing the total superconducting power network[1]. In general, the HTS windings of the transformer are immersed in the liquid nitrogen whose boiling temperature is 77K at atmospheric pressure. But BSCCO wire that is generally used for HTS wire in these days has not enough current capacity at 77K to directly apply to the large capacity HTS power devices. So, in many cases they used to cool it down below the 77K by sub-cooling because operating the HTS wires at lower temperature can increase the critical current, which means the maximum current capacity of the superconducting wire[2].

Considering windings of the large capacity HTS transformer, two kinds of HTS windings have been adopted so far. One is solenoid type winding and the other is pancake type one. In case that rated voltages of the transformer are high, the pancake type winding has lots of advantages such as good insulation and distribution of surge voltages and so on. But unfortunately, strong alternate magnetic field applied perpendicularly to the face of the BSCCO wire in the pancake winding causes very high AC loss as well as degradation of the critical current of the HTS windings of the transformer. This high AC loss is major serious problem of the HTS transformer with pancake type windings. The critical current can be upgraded according to lowering the operating temperature, but the AC loss depends not only on the operating temperature but also on the amount and geometric shape of the magnetic field applied to the BSCCO wire.

In the paper we performed a study for optimal design of the windings for HTS power transformer with pancake type HTS windings to minimize AC loss of HTS winding considering the spaces of HTS pancake windings and operating temperature. We assumed that the capacity of the transformer is 1MVA and the HTS windings are cooled by the liquid nitrogen. The calculation of AC loss was accomplished by 2-dimensional Finite Element Method.

2. FORMULATION FOR AC LOSS

2.1 AC Losses of an HTS Transformer

Assuming that we deal with high voltage and large capacity transformer that causes much of AC losses, only pancake windings will be considered in this paper. Two kinds of AC losses arise in BSCCO wire. One is external-field loss and the other is self-field loss. In case of the pancake type windings, the external-field loss is much greater than the other one so we can ignore the self-field loss. External-field loss is composed of the magnetization loss and the coupling loss, but the coupling loss in the case of the commercial BSCCO wire is negligible [3]. So, we considered only the magnetization loss by external magnetic field as AC loss of HTS pancake winding in and HTS transformer in this paper.

2.2 Formulation of Magnetization Loss

The magnetization loss of HTS wire is primary due to an intrinsic hysteretic characteristic of superconducting materials. Because the HTS material has anisotropic molecular structures, the direction of the external magnetic field can affect the amount of the magnetization loss. Moreover, the tape shape of HTS wire also causes anisotropic characteristic. Therefore we should divide the external magnetic field into two components and consider each separately. One is parallel to the surface of the HTS wire and the other is perpendicular to that. The magnetization loss density due to the magnetic field applied parallel and perpendicularly to the surface of the BSCCO wire is expressed as (1) and (2) respectively [4-5]. where f is frequency, B_m is maximum magnetic field, B_p is the field of full penetration, B_c is a critical penetration field, $\beta_{//}$ is ratio of B_m to B_p, $\beta_{\perp}$ is ratio of B_m to B_c, a and b means the twice of width and thickness of HTS tape. The distribution of magnetic field was obtained by 2D FEM.

$$P_{//} = \begin{cases} \dfrac{fB_m^2}{2\mu_0} \cdot \dfrac{\beta_{//}}{3} & \beta_{//} < 1 \\ \dfrac{fB_m^2}{2\mu_0}\left(\dfrac{1}{\beta_{//}} - \dfrac{2}{3\beta_{//}^2}\right) & \beta_{//} > 1 \end{cases} \quad (1)$$

$$P_{\perp} = K\frac{f\pi a}{b\mu_0} B_c B_m \left(\frac{2}{\beta_{\perp}} \ln(\cosh \beta_{\perp}) - \tanh \beta_{\perp}\right) \quad (2)$$

3. MODELING OF THE HTS TRANSFORMER

The target of the optimization process is to determine the locations of the primary and secondary HTS windings and operating temperature to minimize the magnetization loss generated by the BSCCO wire. Before that, the conceptual design of the windings and the iron core for 1MVA HTS transformer was accomplished with two kinds of winding arrangements. The types of each winding arrangements are a reciprocal arrangement and a concentric one. A shell type core with three limbs is adopted into each conceptual design of the HTS transformers. The specification of the target transformer and simple design parameters are shown in Table I and Table II respectively.

TABLE I
SPECIFICATION OF HTS TRANSFORMER.

Specification	Value	Unit
Phase	1	
Capacity	1	MVA
Rated Primary Voltage	22.9	kV
Rated Secondary Voltage	6.6	kV
Rated Primary Current	44	A
Rated Secondary Current	152	A

TABLE II
CONCEPTUAL DESIGN PARAMETERS OF EACH HTS TRANSFORMER.

Reciprocal Arrangement	Value	Concentric Arrangement	Value
Number of turns	832/240[turn]	Number of turns	832/240[turn]
Number of windings	8 / 4	Number of windings	20/20/20/

3.1 Reciprocal HTS Winding

Design of HTS transformer with reciprocal winding arrangement of double pancake type is performed.
The winding of this model has four modules and each module consists of high-low-high winding.
This winding arrangement compared with solenoid one has several advantages such as good distribution of voltages through windings, ease of fabrication, ease of maintenance, small size and good insulation between windings. However, there is high leakage magnetic field between primary and secondary windings [6,7]. This leakage magnetic field causes much of AC loss as well as reduction of critical current in HTS windings because of the strong magnetic field applied perpendicularly to the surface of the BSCCO wires. The shape of model of this type of transformer and analysis result of magnetic field for this model are shown in Fig. 1.

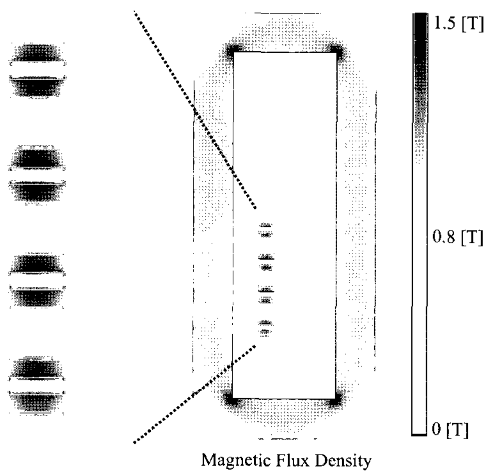

Fig. 1. The model of reciprocal windings for 1MVA HTS transformer and the numerical analysis result of magnetic. field.

3.2 Concentric HTS Winding

In order to reduce the generated AC loss of reciprocally arranged HTS windings, the conceptual design of HTS transformer with concentric winding arrangement is accomplished. The type of winding is also double pancake type. The bobbin of high and low voltage windings are divided into 40 and 20 respectively. In this case, the leakage magnetic field is mostly directed parallel to the BSCCO wire so that less of AC loss arises compared with that of reciprocal ones. The shape of model of this type of transformer and analysis result of magnetic field distribution for this model are shown in Fig. 2.

4. CALCULATION RESULTS

We calculated the magnetization losses of the reciprocal windings and concentric ones. Both calculations are divided into two components caused by the magnetic field applied parallel and perpendicularly to the surface of the BSCCO wire. The calculated magnetization losses for a certain winding design of each type and each component are shown in Fig. 3. These results show that the perpendicular component of magnetization loss is dominant in total magnetization losses, especially in case of reciprocal winding.

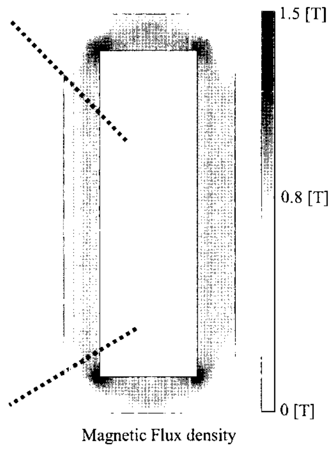

Fig. 2. The model of concentric windings for 1MVA HTS transformer and the numerical analysis result of magnetic field.

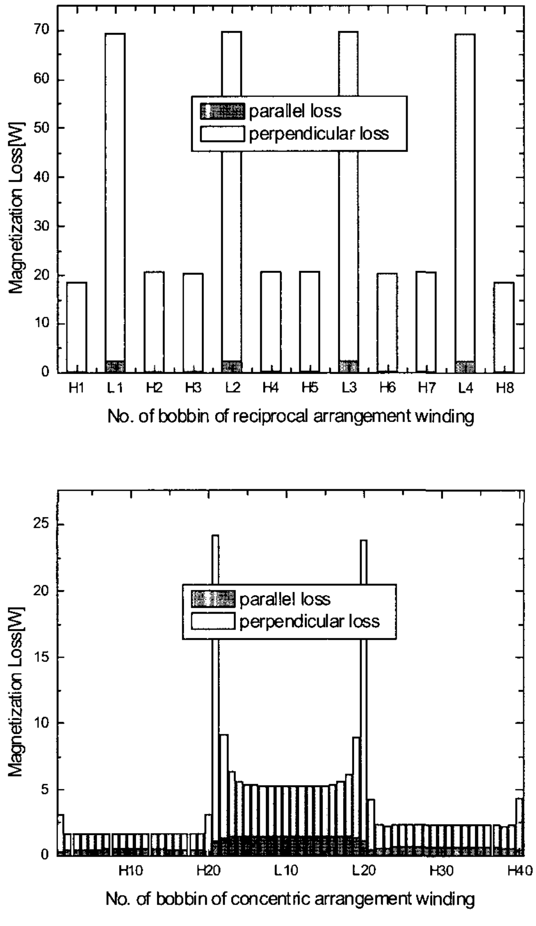

Fig. 3. Calculation results of the magnetization losses of each winding.

4.1 Reciprocally Arranged HTS Windings

4.1.1 Space between pancakes

Fig. 4 shows the calculation results of the magnetization loss generated by the reciprocally arranged HTS windings according to the axial space between HTS pancake windings at 77K. The loss caused by the perpendicular magnetic field component is dominant part, and the total magnetization loss is inversely proportional to the space between pancake windings. We can find when the pancakes located close to each other the loss is so much great and rapidly decreases according to the gap between them, but the larger gap above 40mm hardly affect the loss. Considering a bobbin for the windings and size of the system, we determined this gap to be 40mm. The calculated magnetization loss in this case is 438.2W at 77K.

4.1.2 Temperature

Fig. 5 shows the calculation results of the magnetization loss generated by the reciprocally arranged HTS windings according to the operating temperature. This result shows that it is not always good to lower the temperature for the AC losses, although it is always good for the critical current of HTS winding. Assuming the HTS windings are cooled by the liquid nitrogen, it generates the smallest loss that we keep the temperature of the HTS winding at 77K which is the boiling point of liquid nitrogen under the atmospheric pressure.

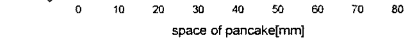

Fig. 4. The calculation results of the magnetization loss generated by the reciprocally arranged HTS windings according to the axial space between HTS pancake windings at 77K.

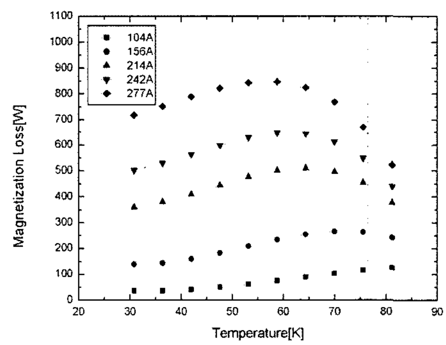

Fig. 5. The calculation results of the magnetization loss generated by the reciprocally arranged HTS windings according to the operating temperature.

4.2 Concentrically Arranged HTS Windings

4.2.1 Spaces between pancakes or windings

Fig. 6 and Fig. 7 show the variations of the magnetization loss generated by concentrically arranged HTS windings according to the axial space between HTS pancake windings, and the radial space between primary winding and secondary windings respectively. More axial space between primary windings and secondary one makes the perpendicular component of the magnetic field larger that cause more loss generation. Considering the loss, it is better to make the primary and secondary winding as close as possible, but the insulation problem arises when it is too close. An electric field analysis tells us that the radial space should be above 40mm at least in case of 22.9kV transformer, so we can determine the radial space between primary and secondary winding to be 40mm.

There is an optimal point for the axial space between pancakes in case of concentric arrangement as we can see in Fig. 6. When we decide the radial space to be 40mm, the optimal axial space is calculated as 5mm.

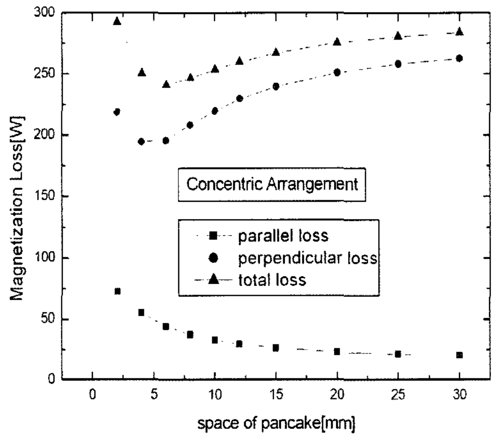

Fig. 6. The calculation results of the magnetization loss generated by the concentrically arranged HTS windings according to the axial space.

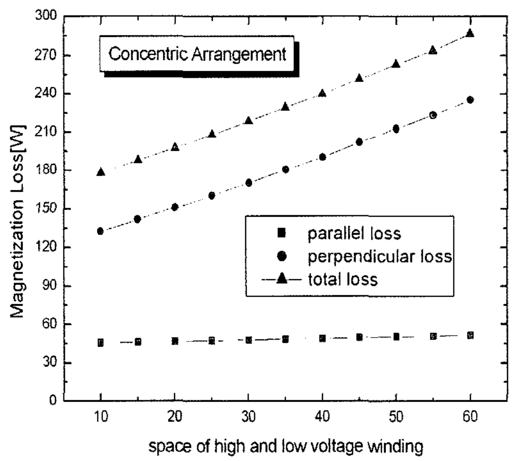

Fig. 7. The calculation results of the magnetization loss generated by the concentrically arranged HTS windings according to the radial space between the primary and the secondary winding at 77K.

4.2.2 Temperature

Fig. 8 shows the calculation results of the magnetization loss generated by the concentrically arranged HTS windings according to the operating temperature. The tendency of variation of loss is not so much different from that of the reciprocal case. But assuming liquid nitrogen cooling, it generates the smallest loss that we keep the temperature of the HTS winding at 64K which is the lowest temperature of the liquid nitrogen under the atmospheric pressure. At this temperature and above conditions, the calculated magnetization loss is 241.9W.

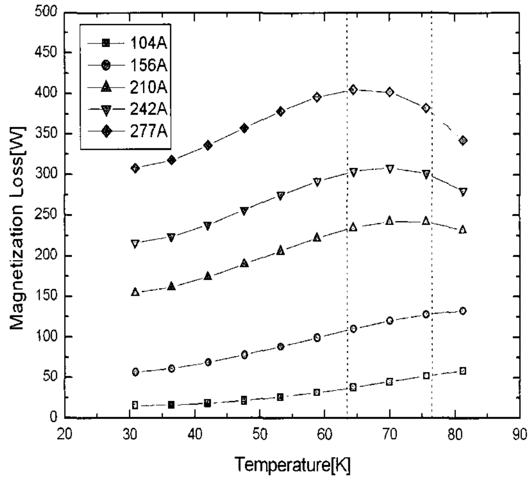

Fig. 8. The calculation results of the magnetization loss generated by the concentrically arranged HTS windings according to the operating temperature.

5. CONCLUSION

The HTS winding design for a 1MVA 22.9kV HTS power transformer considering the lowest AC loss in BSCCO wire is performed in this paper. The design parameters are axial and radial space between windings and the temperature assuming the cooling by liquid nitrogen. The optimal designs of the HTS windings were accomplished for two kinds of winding arrangement which are a reciprocal arrangement and a concentric one. The reciprocal arrangement of the HTS windings has an advantage of good insulation and uniform distribution of the surge voltages but generates so much more AC loss than the concentric arrangement of the windings

ACKNOWLEDGMENT

Manuscript received October 4, 2004. This work was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

REFERENCES

[1] K. Funaki, et al., "Development of a 22kV/6.9kV single-phase model for a 3MVA HTS power transformer," IEEE Transactions on ASC, vol. 11, No.1, pp.1578-1581, 2001.

[2] W. S. Kim, et al., "Design of a 1MVA high Tc superconducting transformer," IEEE Transactions on ASC, vol. 13, pp.2291-2293, June 2003.

[3] J. K. Lee and G. Cha, "AC loss calculation of a multi-layer HTS transmission cable considering the twist of each layer," IEEE Transactions on ASC, vol. 11, pp.2433-2436, March 2001

[4] A. Wolfbrandt, N. Magusson and S. Hornfeldt, "AC losses in a BSCCO/Ag tape carrying ac transport currents in AC magnetic fields applied in different orientations," IEEE Transactions on ASC, vol. 11, pp.4123-4127, 2001.

[5] M. N Wilson, "Superconducting Magnet", Clarendon Press, Oxford, 1983.

[6] K.D Choi, H.J. Lee, G. Cha, K.W. Ryu, W.S. Kim and S.Y. Hahn, "Test of a High Tc Superconducting Power Transformer" IEEE Transactions on Applied Superconductivity, Vol. 10, Issue 1, March, pp. 853-856, 2000.

[7] Sung-Hoon Kim, et al., "Comparison of reciprocal and concentric winding arrangement of HTS transformer," Progress in Superconductivity, vol. 5, No. 1, pp61-64, 2003.