Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.6, No.4, (2004), pp.51~54

Simulated winding temperature distribution of HTS transformer cooled by sub-cooled liquid nitrogen

J. H Han, K. D. Choi, T. Y. Kim, T. Chang, W. S. Kim *, S. H. Kim*, S. Y.Hahn* and S. R. Kim**

Korea Polytechnic University, *Seoul University, **CVE

jinhohan@kpu.ac.kr

***Abstract--* A 1 MVA single phase high temperature superconducting (HTS) transformer was manufactured. In order to reduce AC loss generated in the HTS winding, winding was concentrically arranged. Operation temperature is set at 65K to increase the critical current and reduce the amount of HTS tape usage and the volume. The cryogenic system which consists of main cryostat with the windings and secondary cryostat with 2 GM coolers and cryopump on top and heat exchanger inside is also designed and the cooling performance is simulated with Fluent. Temperature distribution of the windings is investigated whether the windings are kept under designed operation temperature.**

1. INTRODUCTION

HTS transformers offer several advantages compared to conventional transformers because they have advantage in sizes, weight, energy losses, and the potential fire and environment hazards [1]. And HTS transformer withstands overload without loss of its life and possesses inherent self-protecting capability during the fault of the power system. So HTS transformer is expected to be one of the superconducting power devices that will be installed in the power system at the first stage of commercialization and many kinds of development program of HTS transformers are carried out by major power companies and research institutes [2-6].

Two types of winding which are solenoid and pancake type are used in the HTS transformer. Early research was done with solenoid type due to the low AC loss. But for the high voltage transformer solenoid type winding has a problem in insulation and distribution of surge voltages. For the last three years we underwent the research with pancake type winding for the 1MVA HTS transformer and were frustrated by the large amount of AC loss generated from the strong magnetic field density perpendicular to the surface of the HTS tapes. Recently we designed the 1MVA 22.9kV/6.6kV HTS transformer with the concentrically arranged pancake type windings as is shown in Fig. 1 to reduce AC loss. BSCCO-2223 HTS

tape was used and the characteristic test was performed for the operation verification at 65K. The full system with the cooling system is integrated and waits the full system performance test.

In this research winding temperature distribution is investigated to see if the current cooling system fulfills the operation temperature requirement of 65K.

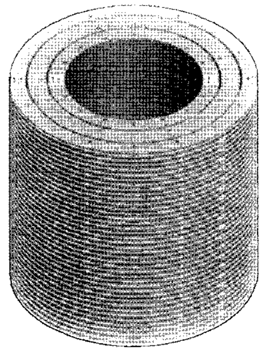

Fig.1. Concentric arrangement of pancake windings.

2. SYSTEM CONFIGURATION

The transformer is designed to operate at 65K to increase the critical current and reduce the tape usage and size. A main cryostat made of GFRP with a room temperature bore has the vacuum jacket and super-insulation layer at the side and the bottom of it to reduce the heat penetration by radiation from outside. HTS windings are supposed to be cooled down to 65 K with sub-cooled liquid nitrogen from the secondary cryostat which supplies the 64K liquid nitrogen. Secondary cryostat made of stainless steel consists of 2 GM cooler, cryopump and the heat exchanger. Fig. 2 shows the assembled GFRP main cryostat and the secondary cryostat. The full system is simply sketched as in Fig. 3.

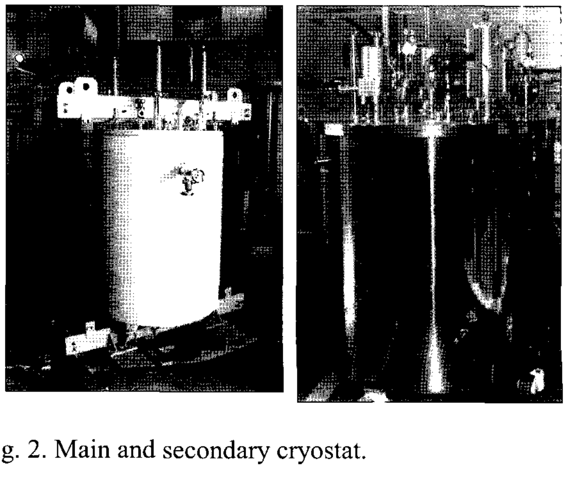

Fig. 2. Main and secondary cryostat.

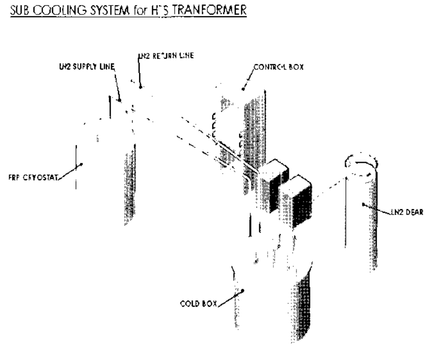

Fig. 3. System configuration.

LN2 cooled down to 65K at the cold head of cooler flows through the 1-in diameter pipe and divided by 4 of half-in diameter pipes and is supplied from the bottom to cool the windings. Warmed LN2 is sent back to secondary cryostat through the 1-in diameter outlet at the top. The heat removed is the sum of AC loss, the radiation from the wall and the heat conduction through the current lead.

3. SIMULATION

3.1. Modeling

Fluent 5.0 using SIMPLE algorithm is used for computational analysis. Since the number of outlet is one instead of four, the whole cryostat is supposed to be computational domain to give the real physical phenomenon. But one quarter of the main cryostat is chosen as a computational domain due to hardware capability such as computer RAM size and the calculation speed with a small loss of accuracy. Circumferential 3D effect is expected to be minimal since the main driving force of flow is upward natural convection not forced convection[7] and the quite large volume of LN2 above the winding is acting as buffer . Geometry of radial cross-section is shown in Fig. 4. The HTS winding is concentric type that is arranged in high-low-high voltage windings. Number of bobbin is 60. Each bobbin has two windings and end up with 120 heating area.

Liquid nitrogen of 64K flows into the cryostat and the flow rate is 7L/min to cover the heat load inside the cryostat. The amount of heat to be removed from the cryostat is generated at the winding due to the AC loss, the radiation heat transfer at the cryostat wall and the heat conduction through the current lead.

Boussinesq approximation as in (1) is used to incorporate the natural convection. Volume expansion coefficient of liquid nitrogen is substantial and the natural convection can not be neglected

$$(\rho-\rho_0)g=-\rho_0\beta(T-T_0)g \qquad (1)$$

Thermophysical properties of liquid nitrogen at 65K as is shown in Table 1 is used because the winding is aimed to be remained under 65K.

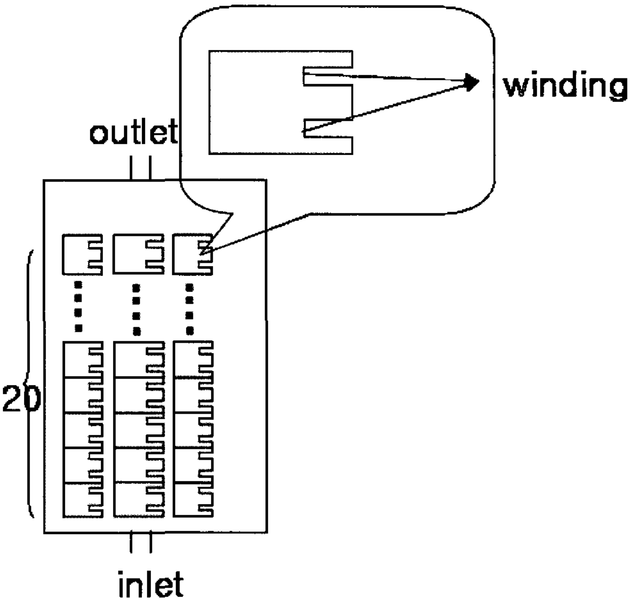

Fig. 4. Cross-Section of the computational domain.

TABLE I
THERMOPHYSICAL PROPERTIES OF LN2 AT 65K.

Density	861 (kg/m^3)
Specific Heat	2010 (J/kgK)
Viscosity	2.78e-4(Pa s)
Thermal conductivity	0.159 W/mK
Prandtl number	3.52
Thermal expansion coefficient	0.00471 (1/K)

3.2. Boundary conditions

Heat flux value due to the AC loss of each winding was resulted from the 2D FEM simulation, which is shown in Fig. 5. Low voltage winding in the middle generates 60% of all AC loss and the summation of all AC loss is approximately 220W.

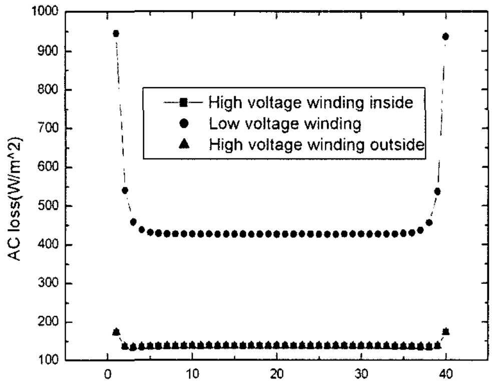

Fig. 5. AC loss at the windings.

The heat penetration due to the radiation and the conduction through the current lead is considered as 78W [7] which is the summation of conduction 19W, radiation 42W and current lead 18W. In this simulation about 40% of additional penetration is added for conservative analysis thus 110W is assumed to be distributed evenly at the boundary wall for conveniency.

Two inlet flow velocity of 0.337m/s and 0.674m/s for 7L/min, 14L/min are tried to see the flow rate effect on winding temperature.

4. RESULTS AND DISCUSSION

Fig.6 shows the temperature distribution of the three windings. As we can expect, top winding of the low voltage windings is in the worst cooling condition – highest AC loss generation and narrow flow path for coolant and the the hottest point of low voltage top winding is located at the farthest from the outlet and the temperature is 67.5K. Both high voltage windings generate almost same amount of AC loss and end up with the same temperature of 66.5K at the top winding. But the number of windings kept under 66K is more in the outer low voltage winding than the inner low voltage windings due to the high exposure level to the cold LN2. The inner low voltage windings have limited exposure to the LN2 due to the narrow and unfavorable flow path.

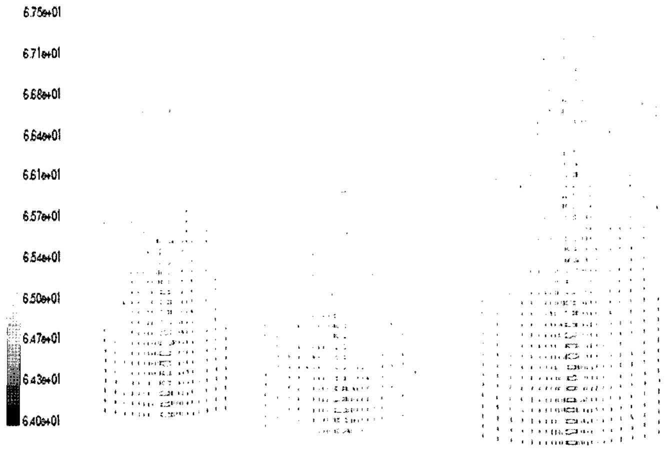

Fig. 6. Winding temperature distribution with the flow rate of 7L/min.

Fig.7, 8 and 9 shows the windings kept under 66K with different flow rate. Left one is with flow rate 7L/min, right one is with 14L/min. With the flow rate increase, large portion of the winding whose temperature is under 66K is increased. Though the winding's average temperature decreases a lot, the flow rate increase doesn't help much to decrease the highest temperature. The hottest point temperature decrease is approximately 1K. Comparing the Fig.7 and 9, the outer high voltage winding's temperature is lower than the inner high voltage windings due to the easy LN2 flow path. Inner high voltage winding and the center low voltage winding have a narrow and unfavorable flow path. Worst of all, low voltage winding generate more AC loss thus about 40% of the low voltage windings are in the condition of the 66K over.

The winding's temperature is supposed to be under 65K and the current design need to be changed. Streamline-shaped geometry of bobbin should be tried and the operation temperature change is another option to be considered. With the combination of the effective flow path and the flow rate increase, the current pump-circulated sub-cooling cryogenic system will fully satisfy the HTS transformer design requirement.

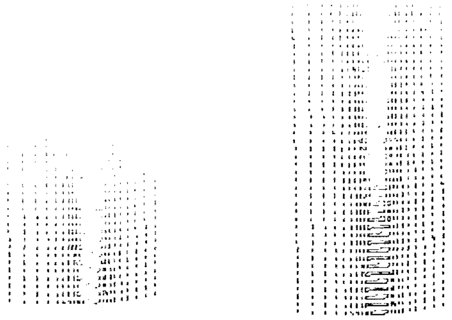

Fig. 7. Winding whose temperature is under 66K (High voltage inner winding).

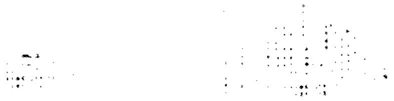

Fig. 8. Winding whose temperature is under 66K (Low voltage center winding).

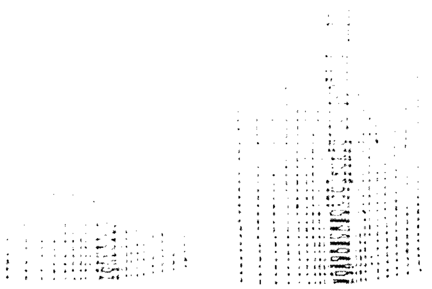

Fig. 9. Winding whose temperature is under 66K (High voltage outer winding).

5. CONCLUSION

To reduce the AC loss generated in HTS winding, the concentric arrangement type using the double pancake windings was adopted in this HTS transformer. 22.9 kV / 6.6 kV, 1 MVA single phase HTS transformer was designed and the cooling performance was simulated. Though the HTS windings were supposed to be cooled down to 65 K, the current cooling system is not perfect to satisfy the operation requirement. The flow rate increase had a limited effect on the winding temperature. The number and location change of inlet and outlet pipe should be tried and the new bobbin and winding geometry which is more flow friendly is required.

ACKNOWLED GMENT

This work was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier Research and Development Program funded by the Ministry of Science and Technology, Republic of Korea.

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