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Design of 1 MVA Single Phase HTS Transformer with Pancake Windings Cooled by Natural Convection of Sub-cooled Liquid Nitrogen

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***Abstract*—A 1 MVA single-phase high temperature superconducting (HTS) transformer with BSCCO-2223 wire was designed in this paper. The rated voltages of each sides of the transformer are 22.9 kV and 6.6 kV respectively. Double pancake HTS windings arranged reciprocally will be used for the transformer windings, because of the advantages of insulation and distribution of surge voltage in case of a large power and high voltage transformer. Single HTS wire was used for the primary windings and four parallel wires were used for the secondary windings of the transformer with transposition. A core of the transformer was designed as a shell type core separated with the windings by a cryostat made of GFRP with a room temperature bore. The operating temperature of the HTS windings will be about 65K with sub-cooled liquid nitrogen. A cryogenic cooling system using a GM-cryocooler for this HTS transformer by natural convection of liquid nitrogen was designed. This type of cooling system can be a good option for compactness, efficiency, and reliability of the HTS transformer.**

Keywords : HTS transformer, pancake winding, sub-cooled liquid nitrogen.

1. INTRODUCTION

A superconducting transformer is expected to be the most important element of electric network as well as on of the superconducting power devices which will be installed in the power system at the first stage of commercialization of superconducting devices. Along with the improvement of the technique of the high temperature superconducting (HTS) wires, lots of researches on the HTS transformer have been made so far [1]. An HTS transformer has a lot of advantages such as lighter weight, smaller volume, higher efficiency and so on compared with a conventional one. Moreover the HTS transformer withstands overload without loss of lifetime and is environmental-friendly because it never uses any oil for insulation and cooling [2].

Two kinds of HTS windings can be adopted for the HTS power transformer. One is solenoid type winding and the other is pancake type one. Most researches of HTS transformer have the solenoid type windings because of the disadvantages of pancake windings such as much of ac loss. These disadvantages of pancake windings arise from the strong magnetic field perpendicular to the HTS wires of pancake windings. Thus worldwide researches and development programs of HTS transformers in progress by major power companies and research institutes are almost about the solenoid type HTS transformers. But, the rated voltages of most of these HTS transformers are no so much high. When the rated voltage becomes higher, the solenoid type windings are no so good for the insulation and distribution of surge voltages. So even in the case of the conventional transformer, the disk type windings used to be adopted for the windings of high voltage transformer.

This paper presents the design results of 1 MVA single phase HTS transformer with BSCCO-2223 HTS wire. The rated primary and secondary voltages of the transformer are 22.9 kV and 6.6 kV respectively. Table I shows the specification of the target HTS transformer. This is the first phase of the development of an HTS transformer for power distribution of *Applied Superconductivity Technology of the 21st Century Frontier R&D Program* in Korea. Double pancake HTS windings, which have the advantages of ease of the insulations and the good distribution of surge voltage in the windings, were adopted. The pancake windings also have the advantages of easy installation and maintenance. An FRP cryostat with a room temperature bore was designed in order to separate the HTS windings from the room temperature iron core.

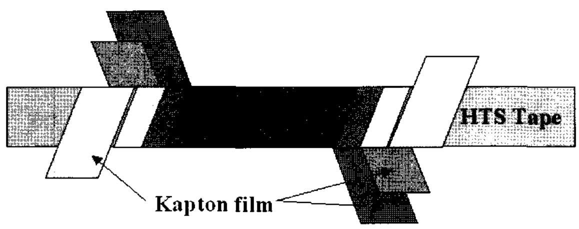

Fig. 1. Configuration of insulation of HTS wire

TABLE I
THE SPECIFICATION OF THE TARGET HTS TRANSFORMER

Specifications	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]

The cryostat has vacuum layers outside and inside of that for thermal insulation. The HTS windings inside the cryostat will be cooled down to 65 K by natural convection of coolant using a GM-cryocooler. The cryogenic system was designed by performing a relevant heat transfer analysis, aiming simultaneously at compactness and efficiency of the HTS transformer.

2. HTS WINDINGS

Basic structure of the HTS transformer is not greatly different from that of conventional one. But in the case of general design of HTS transformer, the number of tu rns of windings should be increased compared with conventional case in order to decrease the dimensions of iron core and so as core loss. However, suitable number of turns should be decided because HTS wire is very expensive so far.

Before the HTS wire is applied to the windings, the whole wire should be insulated enough. We have to pay more attention to the insulation of the HTS wires in the pancake windings than that of solenoid windings because the space between turns of pancake winding is shorter than that of solenoid one. This paper presents an insulation method of triple wrapping up with kapton film. Figure 1 shows the scheme of this insulation of HTS wire. The breakdown voltage measured by experiment was about 44 kV/mm, which is enough considering the volt per turn of a usual transformer with pancake type windings.

Reciprocally arranged double pancake HTS windings were adopted for each side of 1 MVA HTS transformer. Both of the primary and secondary windings are formed as the double pancake and use the same HTS wire. In this type of windings, high leakage magnetic flux density is applied perpendicular to the HTS wire, which causes much of AC loss as well as degradation of critical current of the HTS wire in general [3-5]. These effects are going to be compensated by lower temperature of HTS windings of 65 K by sub-cooling.

The total numbers of turns of each side are 832 turns for primary and 240 turns for secondary. The primary winding consists of 8 double pancake HTS windings and these windings are all connected in series. The secondary winding consists of 4 double pancake HTS windings also connected in series and wound with 4 HTS wires in parallel because the rated secondary current exceeds the transformer critical current of the HTS wire. Each pancake will be wound on bobbins made of GFRP and assembled by mechanical support. The secondary double pancakes are inserted between the primary double pancakes in order to reduce the leakage magnetic flux density applied perpendicularly to the HTS wire surface. Figure 2 shows the arrangement of the HTS windings and their connections.

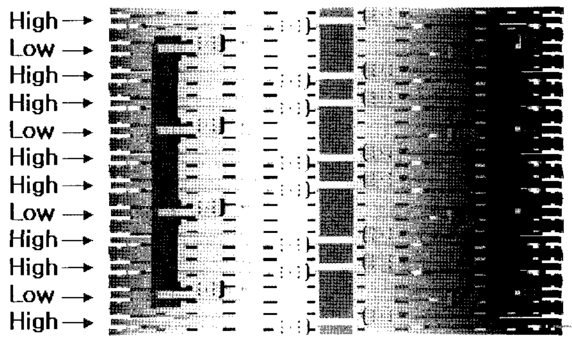

Fig. 2. The arrangement of HTS windings for 1 MVA HTS

When two or more tapes are wound in parallel, it is necessary to transpose the windings to prevent unbalanced current flowing because it may cause instability of the HTS tapes as well as much of AC loss. Because the secondary winding consists of four double pancakes wound in four parallel HTS tapes, they will be transposed three times between double pancakes considering numbe rs of turns of each pancakes when they are assembled.

3. IRON CORE

Conventional processes were used to design the iron core for the HTS transformer in this paper. A shell type iron core for single phase made of laminated PG-10 silicon steel plate was designed as symmetric D-core. The number of step is four and the thickness of sheet steel is 0.291 millimeters. When we decide the maximum magnetic flux density inside the core becomes about 1.488 T, the cross section area of core becomes about 715.16 cm^2. The height of the iron core is designed as 1,580 millimeters. The core is thermally separated from the HTS windings by a cryostat with a room temperature bore in order to increase the cooling efficiency excluding core loss from the cryostat. Figure 3 shows the configuration and dimensions of the designed iron core.

4. CRYOGENIC SYSTEM

An FRP cryostat with a room temperature bore and a new cryogenic system for the 1 MVA HTS transformer was proposed and then its thermal characteristics by performing a relevant heat tr ansfer analysis were evaluated. Figure 4 is a schematic representation of the proposed cooling system.

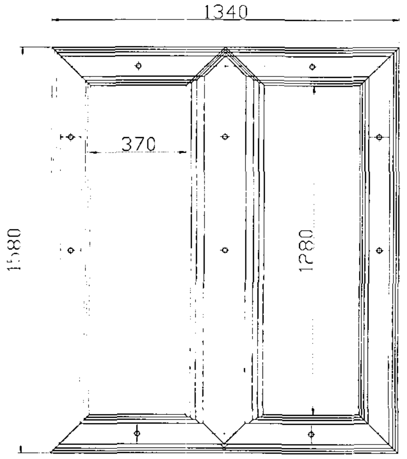

Fig. 3. Configuration and dimensions of the iron core

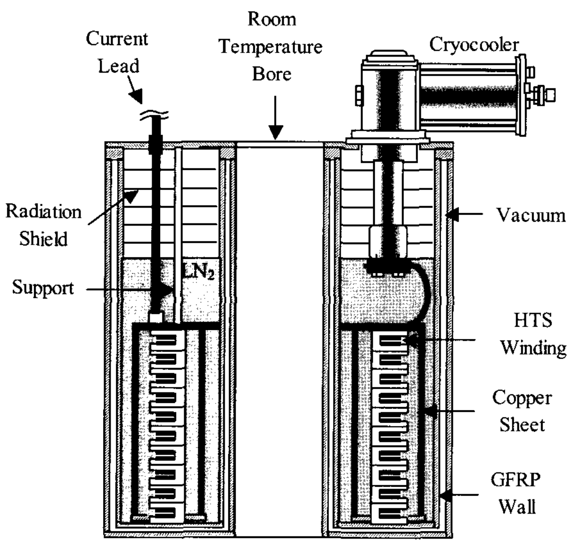

Fig. 4. Proposed design of cryogenic cooling system by natural convection of sub-cooled liquid nitrogen for 1 MVA HTS transformer

The HTS pancake windings are immersed in a liquid nitrogen bath where the liquid is cooled simply by cold copper sheets vertically extended from the coldhead of a closed-cycle cryocooler located above. Liquid nitrogen in the gap between the windings and the copper sheets will develop a circulating flow by buoyancy force in sub-cooled state close to the normal freezing point. Nitrogen functions as a heat transfer medium and an electrical insulating fluid at the same time. Since no circulating pump or transfer line is necessary, the proposed cooling by natural convection has great advantages in all aspects of compactness, efficiency, and reliability, over the forced-flow cooling of the conventional system [6]. On the other hand, the heat transfer coefficient in natural convection is generally much smaller than in forced convection, which may cause an excessively high temperature of the HTS windings or diminish the essential merits of the low temperature operation below 77 K.

The temperature distribution calculated with the analytical and the numerical methods assuming relevant approximations by integral method are compared in Figure 5. The temperature of the HTS windings shows a noticeable amount of discrepancy in the middle of axial location, but an excellent agreement at the ends.

5. Conclusions

1 MVA HTS transformer with BSCCO-2223 wire was designed in this paper. The rated primary and secondary voltages are 22.9 kV and 6.6 kV respectively. We suggested the pancake windings that have some advantages for high voltage transformer compared with solenoid ones. The design parameters of this transformer are listed in Table II. In order to compensate the effect of

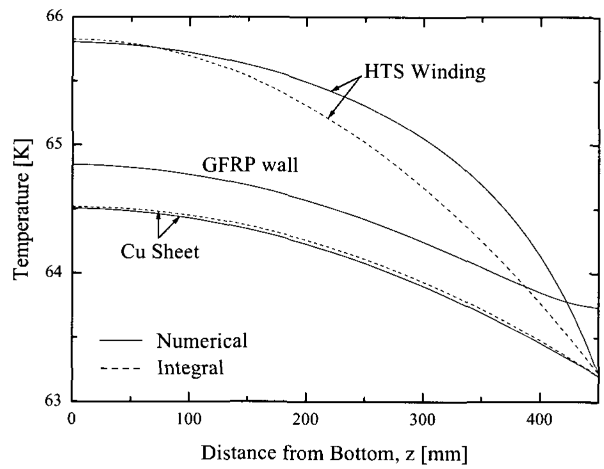

Fig. 5. Calculated wall and HTS winding temperature distributions from analytic and numerical method

TABLE II
Design Parameters of 1MVA HTS Transformer

Specifications		Value	Dimensions
Rating	Capacity	1	[MVA]
Windings	Voltage	22.9/6.6	[kV]
	Current	44/152	[A]
	No. of turns	832/240	[m]
	Voltage/turn	27.5	[V/turn]
	Length of wire	1,384/1,600	[m]
	No. of pancakes	8/4	[EA]
	Outer diameter	646/646	[mm]
	Inner diameter	412/412	[mm]
Iron core	Material	Silicon steel	
	Height	1,404	[mm]
	Width	1,270	[mm]
	Cross section area	742	[cm^2]
	Max. flux density	1.4	[T]
Cryostat	Material	GFRP	
	Outer diameter	885	[mm]
	Inner diameter	334	[mm]
	Height	990	[mm]

leakage flux perpendicular to HTS wire surface, the operation temperature of HTS windings was decided about 65 K using sub-cooled liquid nitrogen.

The HTS windings will be cooled by natural convection between the HTS windings and the cold plate, which is joined with a GM-cryocooler. The shell type iron core was designed and will be placed at room temperature bore of the cryostat for HTS windings. The HTS transformer is under construction on the basis of the result of this paper and characteristics test is going to be performed

ACKNOWLED GMENT

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