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Design of a 1 MVA HTS Transformer with Double Pancake Windings

Woo-Seok Kim*, Kyeong-Dal Choi**, Hyeong-Gil Joo**, Jin-Ho Han**, Gye-Won Hong**, Jungho Park***, Heesuck Song***, Sung-Hoon Kim**** and Song-yop Hahn****

* Electrical Engineering and Science Research Center,
**Graduate School of Energy, Korea Polytechnic University,
*** Hyosung Corporation,
**** School of Electrical Engineering and Computer Science, Seoul National University

ottor@eesri.snu.ac.kr

***Abstract*—A 1 MVA transformer with BSCCO-2223 high Tc superconducting (HTS) tapes was designed. The rated voltages of each sides of the transformer are 22.0 kV and 6.6 kV respectively. Double pancake HTS windings, which have advantages of insulations and distribution of high voltage, were adopted. Four HTS tapes were wound in parallel for the windings of low voltage side. Each winding was composed of several double pancake windings made of four parallel conductors were transposed in order to distribute the currents equally in each conductor. A core of the transformer was designed as a shell type core made of laminated silicon steel plate and the core is separated with the windings by a cryostat with a room temperature bore. The operating temperature of HTS windings will be 65K with liquid nitrogen, and a cooling system using a cryocooler was proposed and designed conceptually. This HTS transformer is going to be manufactured in near future based on the design parameters presented in this paper.**

1. INTRODUCTION

A superconducting 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. Along with the improvement of high temperature superconducting (HTS) tapes, many researches on applications of HTS tapes such as BSCCO-2223 to electrical power devices like transformers have been made so far. An HTS transformer has a lot of advantages such as lighter weight, smaller volume, higher efficiency and so on. Moreover, the HTS transformer withstands overload without loss of lifetime and is environmental-friendly because it uses no insulation oil[1]. Thus worldwide researches and development program of HTS transformers are in progress by major power companies and research institutes such as Waukesha Electric Systems in USA, Kyushu University and Fuji Electric Company in Japan, Siemens and Alsthom in Germany, etc.[2].

This paper presents a design of 1MVA single phase HTS transformer with BSCCO-2223 HTS tapes. The rated primary and the secondary voltages of the transfo rmer will be 22.9kV and 6.6kV respectively. Table I shows the specifications of the target HTS transformer. This is the first phase of a 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 advantages of ease of insulations and uniform distribution of surge voltage in the windings, were adopted. In comparison with the solenoid windings for transformer, the pancake windings also have advantages of easy installation and maintenance. This type of windings is usually accepted for the windings of conventional transformers with higher voltage. An FRP cryostat with a room temperature bore and was designed in order to separate the HTS windings from room temperature iron core. The cryostat has vacuum layers outsides and inside of that for thermal insulation. Configuration of the cryostat with a liquid nitrogen sub-cooling system was presented. The HTS windings

TABLE I
SPECIFICATIONS 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]

inside the cryostat will be cooled down to 65K via natural convection of coolant using a GM-cryocooler. The HTS transformer is going to be manufactured in near future based on the design parameters presented in this paper.

2. WINDINGS

Basic structure of the HTS transformer is not greatly different from that of conventional transformer. Like general transformer, an iron core that accomplishes a magnetic circuit between primary HTS windings and secondary HTS windings should be installed and designed by the same method as a conventional one. But in case of general design of HTS transformer, the number of turns of windings should be increased compared with conventional case in order to decrease the dimensions of iron core and so as core loss. But in this design process, suitable number of turns of windings should be decided because HTS tape is very expensive so far.

2.1. HTS Tape

BSCCO-2223 HTS tape is going to be used in the windings of the HTS transformer. Silver alloy is used as the matrix of the HTS tape, and the critical current of it is 115A at 77K in self-field. Stainless steel plates reinforce the HTS tape mechanically in order to sustain the mechanical forces like tensile or hoop stresses in windings. Table II shows the specifications of the HTS tape. It is expected that the critical current of this HTS tape decreases to about 60% of the critical current at self-field when a double pancake winding is formed by this tape because of the applied magnetic field and bending effect of the HTS tape[3]-[5]. Because the critical current of winding is not enough for the rated current of the transformer, the windings will be cooled down to 65K using sub-cooled liquid nitrogen, in order to overcome the decrease of the critical current. According to the specifications of BSCCO-2223 HTS tape, the critical current of the winding at 65K becomes 200% more than that of windings at 77K.

TABLE II
SPECIFICATION OF BSCCO-2223 HTS TAPE

Specification	VALUE	Unit
Thickness	0.3	[mm]
Width	4.1	[mm]
Critical current*	115	[A]
Max. Stress	265	[Mpa]
Max. Strain	0.4	[%]
Min. bending dia**.	70	[mm]

* 77K, self-field
** 95% IC RETENTION

2.2. Insulation of HTS Tape

Before the HTS tape is applied to the windings, the whole tape should be insulated because it is not insulated by itself. We have to pay more attention to the insulation of the HTS tapes in the pancake windings than that of solenoid windings because the space between turns of pancake winding is shorter than that of solenoid one. In this paper, an insulation method of triple wrapping up the HTS tape with kapton film is presented and tested by experiment. The breakdown voltage measured by the experiment was about 20kV/0.45mm, which is enough for the pancake windings of the transformer considering volt per turn of a usual transformer. The scheme of insulation of the HTS tape is shown at Fig. 1.

2.3. HTS Windings for the Transformer

Reciprocally arranged double pancake windings were adopted for HTS windings of each side of 1MVA HTS transformer in this paper. The primary and secondary windings both will be formed as the double pancake and use the same HTS tape. This type of arrangement has some advantages compared with concentric arrangement of solenoid windings such as ease of manufacture and maintenance caused by simple structure, uniform distribution of surge voltage caused by large capacitance between turns of winding, and so on. But there is also disadvantage of pancake windings such as high leakage flux perpendicular to HTS tape surface. This leakage flux causes much of AC loss of HTS material as well as decrease of critical current of the HTS tapes in general. This effect will be compensated by lower temperature of HTS windings of 65K in sub-cooled liquid nitrogen.

The total numbers of turns of each side of HTS transformer are 832 turns for primary winding and 240 turns for secondary one. 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 the double pancakes of the secondary winding are wound with 4 HTS tapes in parallel because the rated secondary current exceeds the critical current of the HTS tape. 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 tape surface. Fig. 2 shows dimensions and arrangement of the HTS windings.

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 of no resistance of HTS tapes in parallel windings, small difference of the inductances among the parallel windings causes unbalanced current flows greatly. Because the secondary winding consists of four double pancakes wound in four parallel HTS tapes, they will be transposed three times between double pancakes when they are assembled.

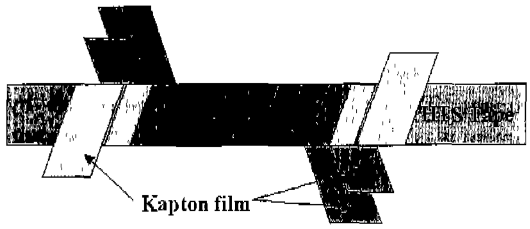


Fig. 1. Configuration of insulation of HTS tape.

3. IRON CORE

Conventional processes were used to design the core for the HTS transformer in this paper. A shell type iron core for single phase made of silicon steel plate was designed as a symmetric D-core. The number of step of core is six and the thickness of sheet steel is 0.291 millimeters. When we decide the maximum magnetic flux density to be 1.4T, the cross section area of core becomes about 742 cm^2. Fig. 2 shows the configuration of lamination of the core.

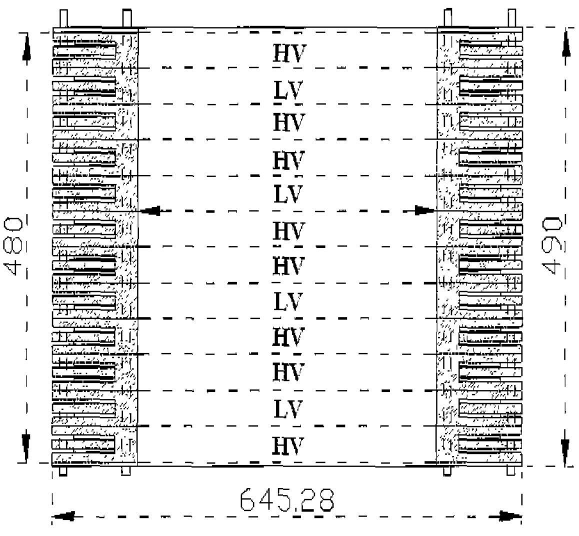
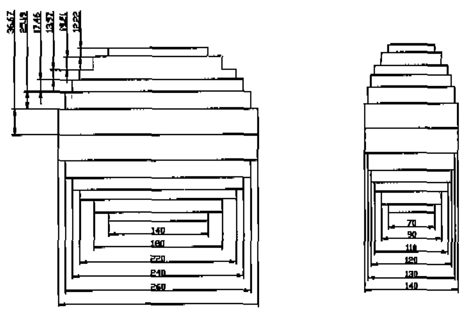


Fig. 2. Dimension and arrangement of the double pancake windings of high and low voltages of 1MVA HTS transformer.

The core is separated from the HTS windings by a cryostat with room temperature bore to increase the cooling efficiency excluding core loss from cryostat. Considering the windings and cryogenic structure, the window size of the core can be designed. Fig. 3 shows the dimensions of iron core and the design parameters for 1MVA HTS transformer are shown in Table III.



(a) (b)

Fig. 3. Co nfigurations and dimensions of the cross section of the iron core (a) li mb (b) yoke

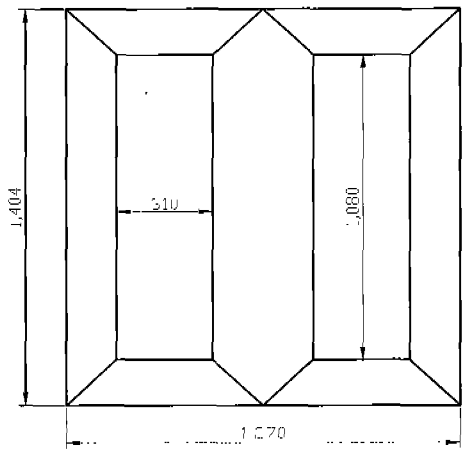


Fig. 4. Dimension of the shell type core for 1MVA HTS transformer

4. CRYOGENIC SYSTEM

An FRP cryostat and liquid nitrogen sub-cooling system for 1MVA HTS transformer was designed. The cryostat has a room temperature bore at the center of it to exclude an iron core from the low temperature region. Only HTS windings will be cooled down to 65K with sub-cooled liquid nitrogen and the liquid nitrogen temperature of 65K is maintained by a cryocooler. Because there is less bubble from boiling in sub-cooled liquid nitrogen, it has advantages for the insulation of windings as well as the increment of the critical current of HTS tape and reduction of AC loss.

In order to increase the cooling efficiency of cryocooler, the cryostat has vacuum shields at the inner wall, the outer wall, and the bottom. Multiple sheets of super-insulation with slit will be installed at the vacuum shields to reduce the radiation heat penetration into the coolant. The coolant temperature of 65K will be maintained by a cryocooler with multiple heat channels immerged into the coolant. This heat channels will be made by copper and thermally joined with cold head of the cryocooler. The HTS windings will be cooled via natural convection of the liquid nitrogen between cold copper plate and HTS windings, which generate the AC loss. Fig. 5 shows the configuration of the cryostat and sub-cooled system with a cryocooler.

According to [6], single-stage cryocooler is better than two-stage cryocooler when an AC device is cooled by a cryocooler because a single-staged cooler is more efficient than two-staged one considering the required electric power consumption. Thus, a single-stage cryocooler will be used in the vacuum cryostat and cool down the inside tank by conduction.

TABLE III
DESIGN PARAMETERS OF 1MVA HTS TRANSFORMER

Specifications		VALUE	Dimension
Rating	Capacity	1	[MVA]
	Voltage	22.9/6.6	[kV]
	Current	44/152	[A]
HTS windings	No. of turns	832/240	[m]
	Voltage/turn	27.5	[V/turn]
	Length of tape	1,384/1,600	[m]
	No. of bobbin	8/4	EA
	Outer diameter	646/646	[mm]
	Inner diameter	412/412	[mm]
Iron core	Material	SILICON STEEL PLATE	
	Height	1,404	[mm]
	Width	1,270	[mm]
	Cross section area	742	[cm^2]
	Max. flux density	1.4	[T]
Cryostat	Material	FRP	
	Outer diameter	885	[mm]
	Inner diameter	334	[mm]
	Height	990	[mm]

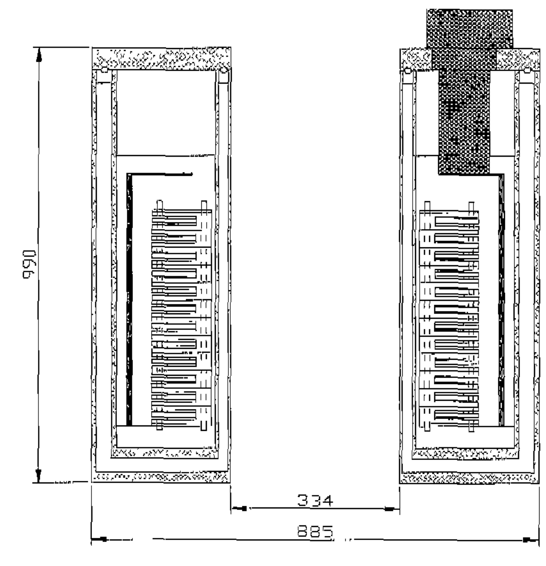


Fig. 5. The configuration of the sub-cooling cryogenic system using a single stage cryocooler for 1MVA HTS transformer

5. CONCLUSION

1MVA HTS transformer with BSCCO-2223 tape was designed in this paper. The rated primary and secondary voltages are 22.9kV and 6.6kV, respectively. We suggested the pancake type windings that have some advantages for high voltage transformer compared with solenoid windings. In order to compensate the effect of leakage flux to HTS tape, 65K sub-cooled liquid nitrogen was adopted as a coolant. The HTS windings will be cooled via natural convection between the HTS windings and the cold plate, which is joined with a cryocooler. The shell type iron core was designed using a conventional design process. The iron core will be placed at room temperature bore of the cryostat for HTS windings. A cryogenic system using a single-stage cryocooler for sub cooling was designed. On the basis of the result of this paper, the HTS transformer will be manufactured in near future.

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