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Design and Fabrication of 1 MVA Single Phase HTS Transformer for Power Distribution with Natural Convection Cooling System

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Abstract

The design and the fabrication of a 1 MVA single-phase HTS transformer are presented in this paper. The rated voltages are 22.9 kV for primary and 6.6 kV for secondary, and the rated currents are 44 A and 152 A respectively. The transformer has HTS double pancake type windings. This type of winding has many advantages such as ease of fabrication and maintenance, good distribution of surge voltage and insulation of windings. Single HTS wire was used for primary winding and four HTS parallel wires were used for secondary winding. These windings are arranged reciprocally with the shell type iron core. An FRP cryostat with room temperature bore was fabricated to isolate the iron core from the coolant. The winding will be cooled down to 65 K with sub-cooled liquid nitrogen using a GM-cryocooler. The sub-cooled liquid nitrogen has advantages of good insulation because of no bubbles as well as increased current capacity of HTS wire.

Keywords : HTS Transformer, double pancake, sub-cooled liquid nitrogen

I. Introduction

A superconducting transformer is expected to be the most important element of electric network as well as one 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 high temperature superconducting (HTS) wires, many researches on the HTS transformer have been done so far [1-3]. An HTS transformer has many 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.

Two types 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 is about solenoid type because of the disadvantages of pancake windings such as larger ac loss. These disadvantages of pancake windings arise from the higher 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 mostly about the solenoid type HTS transformers. The rated voltages of most of these HTS transformers in progress are not so high. When the rated voltage becomes higher, the solenoid type windings are not so good for insulation and

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distribution of surge voltages and so on. So even in the case of the conventional transformer, disk type windings are generally adopted for the windings of high voltage transformer.

This paper presents the design results and the fabrication of 1 MVA single phase HTS transformer with BSCCO-2223 HTS wire. The rated primary and the secondary voltages of the transformer are 22.9 kV and 6.6 kV respectively. This work is the first phase of the development of an HTS transformer for power distribution, which is a project of center for *Applied Superconductivity Technology of the 21st Century Frontier R&D Program* in Korea. Double pancake HTS windings, which have the advantages of ease of insulation and good distribution of surge voltage in the windings, were adopted. The pancake windings also have the advantages of easy installation and maintenance [4]. An FRP cryostat with a room temperature bore was designed and fabricated in order to separate the HTS windings from the room temperature iron core. 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 via natural convection of coolant using a GM-cryocooler.

II. Specification of the HTS transformer

The capacity of the HTS transformer is single phase 1 MVA, and the rated voltages are 22.9 kV for the primary and 6.6 kV for the secondary. Tables 1 and 2 show the specification of the HTS transformer and the HTS wire used for windings, respectively.

III. 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 turns 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 the HTS wire is very expensive so far.

Before the HTS wire is applied to the windings, the whole wire should be insulated because it is not insulated by itself. The HTS wire was wrapped up with kapton film triply. Fig. 1 shows the scheme of this insulation of the HTS tape. The breakdown voltage measured by experiment was about 44 kV/mm, which is enough considering the volt per turn of a usual transformer.

Table 1. The specification of the HTS transformer

Spec.	Value	Unit
Phase	1	
Capacity	1	MVA
Rated voltage	22.9/6.6	kV
Rated current	44/152	A

Table 2. The specification of the HTS wire

Spec.	Value	Unit
Thickness	0.3	mm
Width	4.1	mm
Critical Tensile Stress	265	MPa
Critical Bending Dia.	50	mm
Critical Current	>115	A

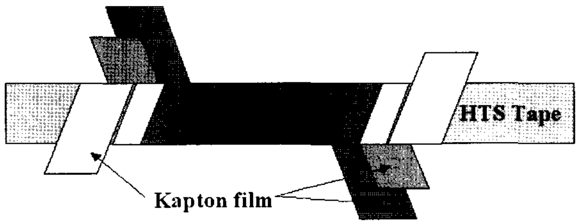

Fig. 1. Configuration of insulation of HTS wire.

Reciprocally arranged double pancake HTS windings were adopted for each side of 1 MVA HTS transformer. The total numbers of turns of each side of the HTS transformer are 832 turns for the primary and 240 turns for the 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. Each was wound with 4 HTS wires in parallel considering the large secondary current. All windings are wound on bobbins made of GFRP and assembled with mechanical support. The secondary double pancakes are inserted between the primary double pancakes in order to reduce the magnitude of the leakage magnetic flux density applied perpendicularly to the HTS wire surface. The design parameters of the HTS windings are listed in Table 3, and the arrangement of HTS windings is shown in Fig. 2.

Table 3. The design parameters of HTS windings

Spec.	Value	Unit
Number of turns	832/240	turns
V/T	27.5	V
Length of HTS wire	1,400/1,616	m
Number of bobbin	8/4	EA
O.D. of bobbin	658	mm
I.D of bobbin	412	mm
Height of winding	480	mm

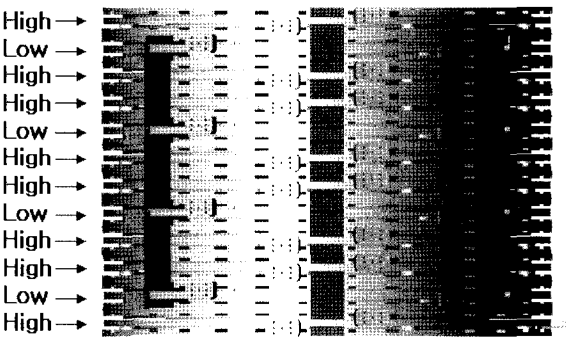

Fig. 2. The arrangement of HTS windings for 1 MVA HTS Transformer.

When two or more wires are wound in parallel, it is necessary to transpose the windings to prevent unbalanced current flowing. It may cause instability of the HTS wires as well as much of AC loss. Because of no resistance of HTS wires in parallel windings, small difference of the inductances among the parallel windings can cause unbalanced current flows greatly. Considering four parallel HTS wires in secondary windings, three times transposition between secondary double pancakes were performed when they are assembled. Fig. 3 shows the assembled HTS windings with a top plate.

IV. Iron core

Conventional processes were used to design the iron core for the HTS transformer in this work. 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 steps is four and the thickness of sheet steel is 0.291 millimeters. For the maximum magnetic flux density inside the core of about 1.488 T, the cross section area of core was determined to be 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 by excluding core loss. Fig. 4 shows the fabricated iron core for the HTS transformer.

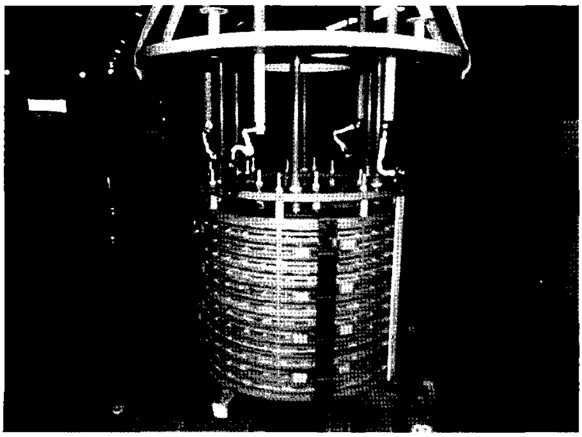

Fig. 3. The assembled HTS windings with a top plate for 1 MVA HTS transformer

Fig. 4. The iron core for 1 MVA single phase HTS transformer

V. Cooling 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. Because there are fewer bubbles 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 the cooling system, 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 GM-cryocooler with multiple cooling channels immerged into the coolant. This heat channels will be made of copper and thermally joined with the 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 sub-cooled system with a GM-cryocooler.

According to [5], a single-stage cryocooler is better than a two-stage cryocooler when an AC device is cooled by a cryocooler, 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.

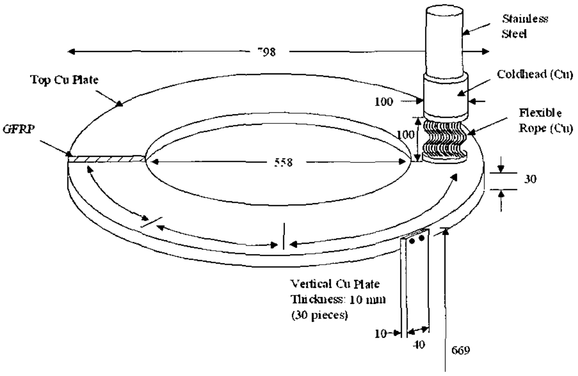

Fig. 5. Configuration of copper cooling channels for natural convection cooling system with a cryocooler.

VI. Conclusion

A 1 MVA HTS transformer with BSCCO-2223 tapes was designed and the essential elements were fabricated in this work. We adopted the pancake type windings that have some advantages for high voltage transformers 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 a room temperature bore of the cryostat for HTS windings. A cryogenic system using a single-stage cryocooler for sub cooling was designed. The HTS transformer will be assembled completely and characteristics test will be performed in near future.

Acknowledgments

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