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Fabrication and Characteristic Tests of a 1 MVA Single Phase HTS Transformer with Concentrically Arranged Windings

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***Abstract*-- A 1 MVA single phase high temperature superconducting (HTS) transformer was manufactured and tested. The rated voltages of primary and secondary of the HTS transformer are 22.9 kV and 6.6 kV respectively. BSCCO-2223 HTS tape was used for HTS windings of 1 MVA HTS transformer. In order to reduce AC loss generated in the HTS winding, the type of concentric arrangement winding was adopted to a 1 MVA HTS transformer. Single HTS tape for primary windings and 4 parallel HTS tapes for secondary windings were used considering the each rated current of the HTS transformer. A core of HTS transformer was fabricated as a shell type core made of laminated silicon steel plate. And a GFRP cryostat with a room temperature bore was also manufactured. The characteristic tests of 1 MVA HTS transformer were performed such as no load test, short circuit test and several insulation tests at 65 K using sub-cooled liquid nitrogen. From the results of tests, the validity of design of HTS transformer was ascertained.**

1. INTRODUCTION

HTS transformers offer several advantages compared to conventional transformers because there are reduced 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 in progress by major power companies and research institutes [2-6].

Considering windings of HTS transformer, two kinds of HTS windings used to be adopted for the HTS transformer nowadays. One is solenoid type winding and the other is pancake type one. Most researches for HTS transformers in progress are related with solenoid type windings because of disadvantages of pancake windings such as much of ac loss. These disadvantages of pancake windings arise from the stronger magnetic field density perpendicular to the surface of the HTS tapes of pancake windings compared with solenoid ones. But solenoid windings are not so good for insulation and distribution of surge voltages especially according as the rated voltage becomes higher [7,8]. So even in the case of the conventional transformer, the pancake type winding used to be adopted for the windings of high voltage transformer.

This paper describes the manufacture and characteristic tests of 1 MVA 22.9 kV / 6.6 kV HTS transformer. This HTS transformer has the concentric arrangement winding using the double pancake windings (DPWs) made of BSCCO-2223 HTS tapes for each side. A shell type iron core and GFRP cryostat with room temperature bore were also fabricated. Then in order to verify operation as transformer, the characteristic tests such as no load test, short circuit test, and several insulation tests were performed at 65 K which was achieved by sub-cooled liquid nitrogen. And additional experiments for the characteristics of the transformer are in progress.

2. SPECIFICATION AND MANUFACTURE OF 1 MVA SINGLE PHASE HTS TRANSFORMER

The Design and manufacture of HTS transformer is performed. The capacity is 1 MVA and rated primary and secondary voltages are 22.9 kV and 6.6 kV respectively. Then the operating temperature is 65 K. This HTS transformer is composed of HTS windings, iron core and cryostat. The design parameter of 1 MVA HTS transformer with concentric arrangement winding is shown in Table I.

2.1. HTS winding of DPWs

The DPW is adopted in 1 MVA HTS transformer. And BSCCO-2223 HTS tape is used in the DPW. This HTS tape is made by American Superconductor Company (AMSC) and reinforced by stainless steel tape in order to sustain mechanical stresses during winding process and electromagnetic hoop stress in operation. Also the critical current of this HTS tape is more than 150 A in self-field at 65 K.

The HTS winding is concentric type that is arranged as high-low-high windings. And the primary and secondary windings consist of five modules, that one module is made of four DPWs. The total number of turn of each winding is 832 turns and 240 turns. The secondary windings are wound by four HTS tapes in parallel because the rated secondary current exceeds the critical current of the HTS tape. Three times transpositions are performed in the one module in order to distribute the currents equally between HTS tapes and each module is connected in series. Fig. 1(a) shows concentrically arranged HTS winding using the DPWs.

TABLE I
DESIGN PARAMETERS OF 1MVA SINGLE PHASE HTS TRANSFORMER WITH DOUBLE PANCAKE WINDING.

Specification		Value
Rating	Phase	1
	Capacity	1 MVA
	Rated voltage	22.9 kV / 6.6 kV
	Rated current	44 A / 152 A
HTS winding	Type	Concentric arrangement
	Material	BSCCO-2223 HTS tape
	No. of turns	832 turn / 240 turn
	No. of HTS tape	1 ea / 4 ea
	Voltage / turn	27.5 V/turn
	No. of bobbin	20 / 20 /20 ea
	Coolant	65 K sub-cooled LN_2
Iron core	Material	Silicon steel plate
	Height	1,580 mm
	Width	1,340 mm
	Cross section area	715.16 cm^2
	Max. flux density	1.48 T
Cryostat	Material	G(10)FRP
	Outer dia.	948 mm
	Inner dia.	334 mm
	Height	1,200 mm

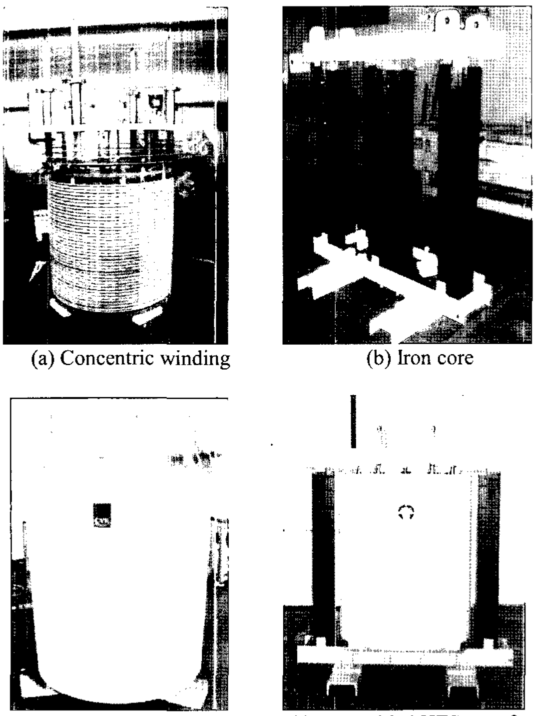

(a) Concentric winding (b) Iron core
(c) GFRP cryostat (d) Assembled HTS transformer

Fig. 1. Manufacture and assembling of 1 MVA HTS transformer. (a) Concentric winding made of HTS DPWs, (b) Shell type iron core, (c) G(10)FRP cryostat with room temperature bore, (d) Configuration of assembled 1 MVA HTS transformer.

3. CHARACTERISITC TESTS AND INSULATION TESTS OF 1 MVA SINGLE PHASE HTS TRANSFOMRER

The several kinds of characteristic test and insulation test for manufactured 1 MVA HTS transformer are accomplished at 65 K. Test method and criteria for conventional oil transformer were applied to the HTS transformer. And liquid nitrogen was used for coolant to maintain the temperature of 65 K. The applied tests are the following

Characteristic tests:
- *Turn ratio test*
- *Open circuit test*
- *Short circuit test*

Insulation tests:
- *Megger test*
- *Low frequency voltage test*
- *Induced voltage test*

The measured results through both characteristic tests and insulation tests are summarized in Table II. The turn ratio of this HTS transformer was measured 3.469, which is within 0.02 percent error from the designed value of 3.466. And the resistance of both primary and secondary winding was 2.8 mΩ and 1.6 mΩ at 65 K respectively.

Insulation resistances between the primary and the secondary windings, between the primary and the earth, and between the secondary and the earth are more than 2,000 MΩ, which satisfy the standard criterion on typical power transformer. Fig. 2 shows experiments of 1 MVA HTS transformer.

TABLE II
RESULTS OF BOTH CHARACTERISTIC TESTS AND INSULATION TESTS OF 1 MVA HTS TRANSFORMER AT 65 K.

A. Characteristic Tests		
Specification		Value
Turn ratio	Designed ratio	3.466
	Measured ratio	3.469
Insulation resistance	HV-LV	> 2,000 MΩ
	HV-E	> 2,000 MΩ
	LV-E	> 2,000 MΩ
Resistance	Primary winding	2.8 mΩ
	Secondary winding	1.6 mΩ
Open circuit test	No-load exciting current	0.251 A
	No-load loss	2,652 W
Short circuit test	% Impedance voltage	1,075 V
	% Impedance	4.67 %
	Total load loss*	405 W
B. Insulation Tests		
Specification		Value
Low frequency voltage test	Primary (50 kV rms, 1 min)	OK
	Secondary (22 kV rms, 1 mm)	OK
Induced voltage test	2 × Rated voltage (180 Hz, 40 sec)	OK

* Total load loss is made of the AC loss of HTS winding, resistance loss of terminal, eddy current loss of copper connections, and core loss.

3.1. Characteristic test

Short circuit test: To determine the transformer percent impedance, short circuit test was performed in primary winding voltage increments of 100 V, starting at 100 V. Each increment of voltage was held for approximately one minute. The rated secondary current was carried when the short circuit voltage was 1,075 V. And the percent impedance of 4.67 % was calculated. This is smaller than the design value of 5.7 %. Fig. 3(a) shows the variations of both % impedance and total load loss for the applied primary voltage. % impedance is almost constant over all primary voltage range as can be seen in Fig. 3(a) and the total load loss was increased according to increasing primary voltage. The measured total load loss was 405 W at the rated secondary winding current.

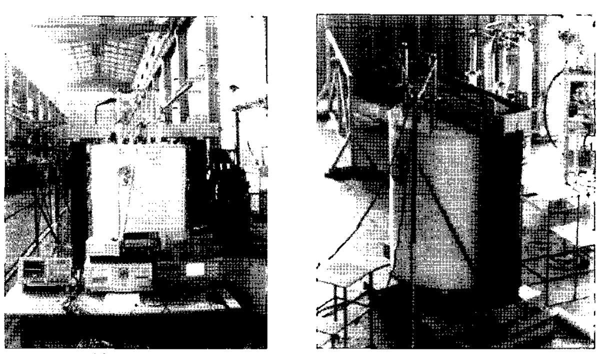
Open circuit test: Open circuit test was carried out to determine the no-load exciting current of the HTS transformer. Open circuit voltages were stepped up in 1 kV increments, with a one minute hold at each level. The no-load exciting current of 0.125 A, and the core loss of 2,652 W were measured in the rated primary voltage respectively. Results of no-load test are shown in Fig. 3(b). As shown in Fig 3(b), the no-load exciting current, I_{10}, and no-load loss increase linearly up to the rated primary voltage.

3.2. Insulation tests

As shown in Table II, two kinds of AC withstand voltage tests which are low frequency voltage test and induced voltage test, were carried out at 65 K with sub-cooled liquid nitrogen. And the ANSI regulations were applied to the insulation test of HTS transformer.

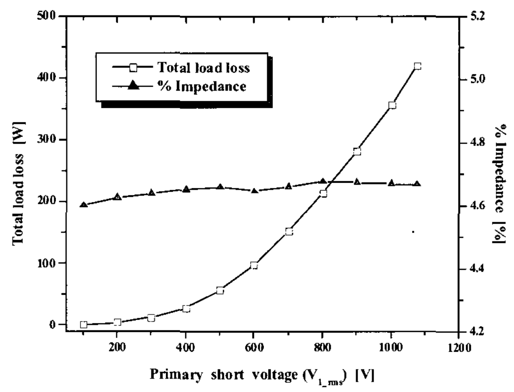
Low frequency (60 Hz) voltage test: In applying sinusoidal voltage of 50 kV_{rms} and 22 kV_{rms} to the primary and secondary winding during one minute, there was no electrical breakdown in the test.

Induced voltage test: when 180 Hz, twice rated voltage was applied to the secondary winding, we ascertained that insulation breakdown did not happen for 40 seconds too. Fig. 2(b) shows the insulation test of HTS transformer.

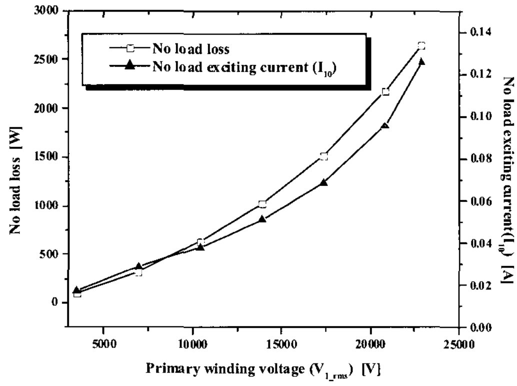


(a) Characteristic test (b) Insulation test

Fig. 2. Characteristic test and insulation test of the manufactured 1 MVA single phase HTS transformer. (a) Short circuit test and no-load test was carried out at 65 K. (b) Several kinds of insulation test such as low frequency test, and induced voltage test were also performed at 65 K.



(a) Total loss and % impedance



(b) No-load exciting current and no-load loss

Fig. 3. Results of no-load test and short circuit test. (a) Values of total loss and percent impedance according as the secondary current is varied in short circuit test. (b) Values of no-load exciting current and no-load loss according to the applied primary voltage in no-load test.

From the results of these tests, the efficiency of manufactured 1 MVA HTS transformer was calculated 99.3 % in due consideration of refrigeration penalty for liquid nitrogen in the rated operation.

4. CONCLUSION

22.9 kV / 6.6 kV, 1 MVA single phase HTS transformer was fabricated and tested. Four BSCCO-2223 HTS tapes were wound in parallel for the secondary windings and transposed three times in the connections between the DPWs of one module. In order to reduce the AC loss in HTS winding, the concentric arrangement type using the DPWs was adopted in this HTS transformer. And a shell type iron core using the silicon steel plate and a GFRP cryostat with a room temperature bore were designed and fabricated. The HTS windings were cooled down to 65 K with sub-cooled liquid nitrogen. The several kinds of characteristic and insulation tests using the fabricated 1 MVA HTS transformer were carried out at 65 K. From the results of tests, the validity of design parameters such as insulation, cooling, and etc. was verified and the operation as transformer was also ascertained. Then the rest of the characteristic tests of the HTS transformer are in progress.

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