Test Results of a Three Phase HTS Transformer with Double Pan Cake Windings

S. Lee, H. Lee, G. Cha, J. Lee, K. Choi, K. Ryu, and S. Hahn

[1]*Abstract*--**This paper described construction and test results of a 10kVA HTS transformer. Three phase transformer with double pancake windings was constructed. BSCCO-2223 wire, silicon sheet steel core and FRP cryostats were used in that transformer. After the test of basic properties of the 3 phase HTS transformer using no load test, short circuit test and full load test, continuous operation of 100 hours with pure resistive load has been carried out. Test results proved over-load capability and reliability of the HTS transformer.**

Index Terms--**Continuous operation, double pancake winding, three phase HTS transformer, liquid nitrogen auto filling.**

I. Introduction

According to the improvement of the HTS wires performance, several types of HTS machines are being developed, such as, transformer, motor, current limiter, and transmission cable. Manufacturing technique of the long length HTS wire is one of the key technologies in the development of HTS machines. At the early stage of the development of the HTS transformer, energy saving and operating cost reduction due to the high efficiency were considered as the major advantages.

Reduced weight and size of the HTS transformer can be more advantageous than the high efficiency in some situation. For the 30MVA HTS transformers with open-cycle cooling system, weight and size can be reduced up to 1/2 and 2/3, respectively. Other advantage is the capability for over- capacity operation due to the low temperatures at which HTS windings operate [1].

As the results of the intensive analysis of the potential and characteristics of the HTS transformers, HTS transformers are widely understood as a very promising device.

Performance of the HTS transformers has been examined starting with single phase 500kVA HTS transformer that was made by kyushu University, Japan, 1996. They also constructed 1MVA transformer in 2000. Both transformers were operated in 77K [2], [3]. ABB made 3 phase 630kVA transformer in 1997. Waukesha in USA made single phase 1 MVA cryo-cooled HTS transformer in 1998. Among them, 630kVA transformer powered the supply network of the city of Geneva. 10MVA HTS transformer is being developed by the team led by ABB.

This paper described construction and test of a 10kVA HTS transformer. Considering the actual power system adopts the 3 phase, 3 phase transformer has been constructed. Double pancake windings were used for the windings of the HTS transformer.

After the test of basic properties of the 3 phase HTS transformer using no load test, short circuit test and full load test, continuous operation of 100 hours with pure resistive load has been carried out. Test results proved over-load capability and reliability of the HTS transformer.

II. Specifications of the HTS Transformer

To examine the fundamental properties and operating characteristics, we constructed a 10kVA HTS transformer and tested it. We made three phase transformer because most of the transformer are three phase one. And three phase transformer has different characteristics from that of single phase transformer, such as, circulating current if it is connected in delta.

Rated voltage of the primary winding and the secondary winding of the transformer were 440V and 220V. Rated current of both windings were 13.1A and 26.2A, respectively. BSCCO-2223 wire was used in transformer winding because it was easy to make km-length wire using BSCCO-2223 wire.

Two types of HTS wires were used in the winding. The HTS wire whose critical current was 42A at 77K was used for primary winding. Cross section of the wire was 2.9?0.164mm^2. For the HTS wire which was used for the secondary winding, critical current and the cross section were 100A at 77K and 4.1?0.203mm^2, respectively. Total length of the HTS wires for the primary winding and the secondary winding were 75m and 68m. Specifications of the HTS wires which were used for the primary winding and the secondary

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winding are given in Table I.

It is well known that critical current of a HTS wire depends on the direction of the magnetic field that is imposed on the HTS wire. Fig. 1 shows the critical current of the HTS wire which was used for the primary winding. 0° means parallel to the wire and 90° means perpendicular to the wire in Fig. 1 As the direction of the magnetic field changes from parallel to perpendicular, critical current decreases sharply in Fig. 1 At 15° and 30°, I_c has already fallen to 1/3 and 2/3, respectively.

Two types of winding, helical winding and double pancake winding, can be used as the winding of the transformer. Between these windings, pancake windings are easier to wind than helical windings.

In a helical winding, we have to change the whole winding if we find a small defect in the winding. In pancake winding, the whole winding consists of many pancake windings. If we find a defect in the winding, we can change only that bad pancake winding. Most of the large transformers with high operating voltage adopt double pancake winding. At lower currents the pancake coil has higher losses which can be ascribed to the existence of resistive joints within the coil [4]. Considering all aboves, we used double pancake windings.

TABLE I
SPECIFICATIONS OF HTS WIRES

	Primary	Secondary
Material	BSCCO-2223	BSCCO-2223
No. of filament	55	55
Width	2.9mm	4.1mm
Height	0.164mm	0.203mm
Critical current	42A, 77K	100A, 77K
Twist	No	No
Matrix	Ag	Ag alloy
Total length	75m	68m

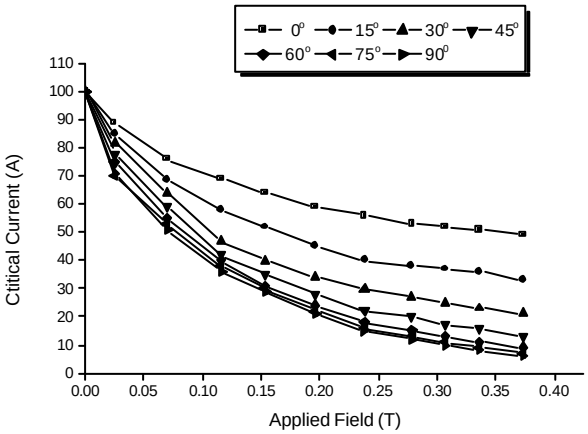

Fig. 1. Critical current variation of the HTS wire which was used for the primary winding. Degree means the direction of the external magnetic field.

Three windings were stacked in one cryostat. Among the three windings, two double pancake windings were connected in series for the primary winding and one double pancake winding was used for the secondary winding. Total number of turns of the primary winding and the secondary winding were 112turns and 98turns, respectively. To reduce the leakage magnetic field, secondary winding were placed between the two primary windings.

Polyvinyl insulating tape whose thickness was 0.23mm was inserted between the turns of double pancake winding, and 0.5mm FRP spacers were placed between the bobbins of the pancake winding. This FRP spacer also worked for the cooling channel as well as the electric insulator. To measure the perpendicular and parallel magnetic field of the winding, Hall sensors were installed at the upper and outer part of one bobbin.

To measure the temperature variation during the over-load test of the transformer, thermocouple was put at the innermost part of the winding. Because this transformer was the step-down transformer, primary side and secondary side were connected in Y and ?, respectively.

Silicon sheet steel of 0.23mm was used for the room-temperature core. Cross-section and the loss density of the core were 80?80mm^2, 0.98W/kg, respectively. Total weight of the core was 155kg and it reaches 57% of the transformer total weight.

Three cryostats were located around the three cores to house the HTS windings. To eliminate the eddy current that was generated by the stray magnetic field in the wall of the cryostat, GFRP cryostat was used. Inner/outer diameter and height of the cryostat were 180mm, 380mm and 470mm, respectively. Table II shows the specifications of the HTS transformer.

TABLE II
SPECIFICATIONS OF THE 10KVA TRANSFORMER

Capacity	10kVA	No. of phase	3
Frequency	60Hz	Temperature	77K
Total height	680mm	Total width	1020mm
Total weight	271kg		
Connection	wye-delta		
Ratings			
Voltage	440V/220V	Current	13.1A/26.2A
No. of turns	112/98	Volt/turns	2.27V
Core			
Material	silicon sheet steel	Max. flux density	1.8T
Width	80mm	Depth	80mm
Weight	155kg	Loss	0.98W/kg
Cryostat			
Material	G10 FRP	No. of cryostat	3
Inner diameter	180mm	Outer diameter	380mm
Height	470mm	Capacity of LN_2	23 *l*
Weight	33kg		

Fig. 2 shows the sectional diagram of the HTS transformer. Among 12 current leads(4 leads for one phase), only 6 current leads are shown in this figure.

III. Construction and Test circuit of the Transformer

Fig. 3 shows the constructed 3 phase transformer with 3 cryostats and room-temperature common core. Auto filling system of LN_2 was equipped for the continuous operation of the transformer. 3 solenoid valves, one for each cryostat, were connected to the same liquid nitrogen tank. Those valves controlled the level of liquid nitrogen of each cryostat separately. At the beginning of the LN_2 refilling, liquid nitrogen turn into high pressurized gas when it flowed through the warm LN_2 transfer tube. This gas evaporated the remaining liquid nitrogen in the cryostat. To prevent this situation, pressure relief device was installed in the cryostat.

Test of the transformer was done using the circuit in Fig. 4 Rated voltage of the primary side, 440V, was supplied by the variable voltage source and pure resistive load was connected to the secondary side. 20 modules of 1kW resistor are used so that 20kW was consumed at the rated voltage.

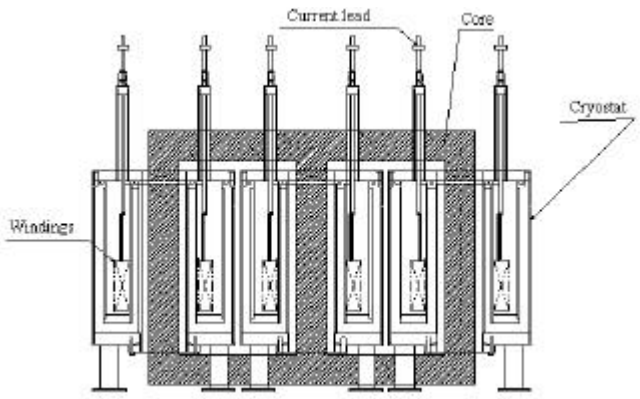

Fig. 2. Sectional diagram of the HTS transformer.

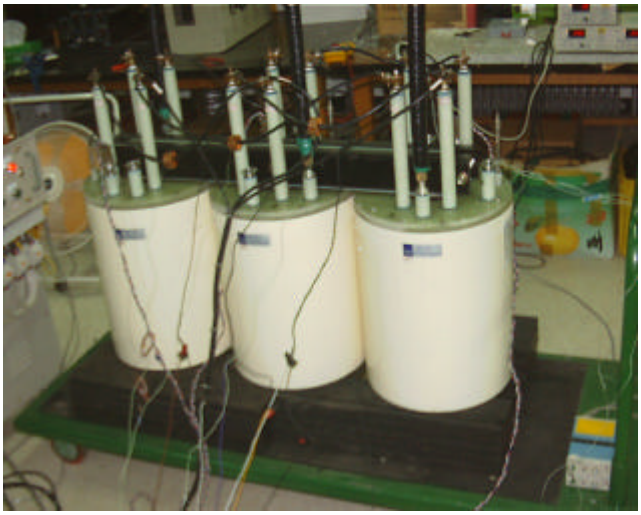

Fig. 3. 3 phase HTS transformer

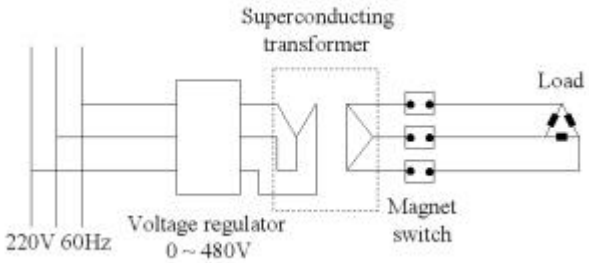

Fig. 4. Circuit of the HTS transformer test.

IV. Test Results

No load test and the short circuit test were carried out to determine the parameters of the transformer. After those tests, full load was applied to the transformer. Fig. 5 shows the secondary voltage and the primary current at the switching of full load. When the full load was connected, the secondary voltage dropped to 215.2V, so voltage regulation was calculated as 2.2%.

Continuous operation under full load of 10kW was performed for 100 hours. After the 100 hours operation, no decrement of critical current was observed at the pancake windings. We conclude that there's no deterioration of the HTS tape during the normal operation of the transformer.

Auto filling system of liquid nitrogen turned on and off regularly during the continuous operation. During the full load operation, it filled the cryostat with LN_2 about every 3 hours.

When the transformer is switched on, large current can flow the transformer due to the magnetic property of the core. Magnitude of this current, so-called inrush current, depends on the phase of the switching. Fig. 6 shows the inrush current during the switching of the transformer without load. Magnitude of the inrush current was 43.9A and it was more than twice of the rated current. It was confirmed that the HTS transformer withstood the inrush current without any problems.

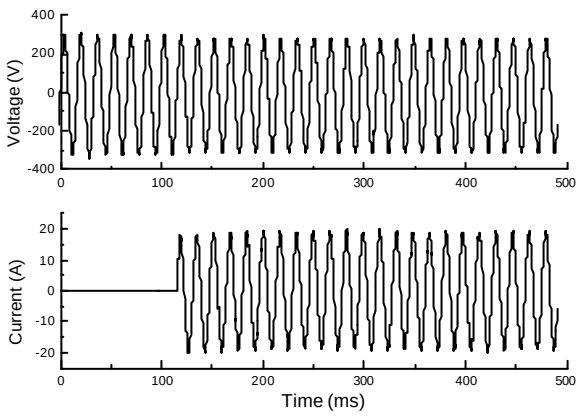

Fig. 5. Full load switching, upper : secondary voltage, lower : primary current

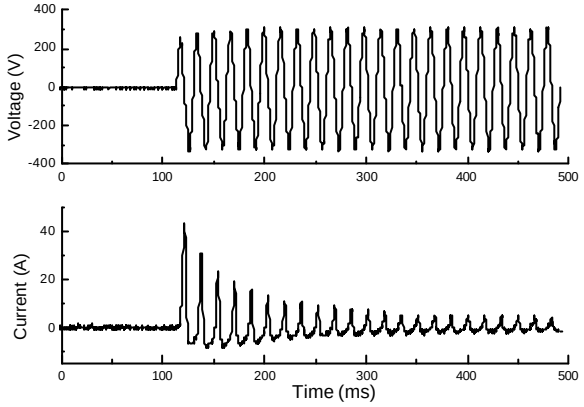

Fig. 6. Inrush current during the switching of the transformer, upper : secondary voltage, lower : primary current.

One of the advantages of the HTS transformer is the over-load capability. To examine the properties of the over-load operation, load was increased from 10kW to 20kW. During the over-load operation, the temperature of the HTS winding did not increase because windings are immersed in the LN_2. Fig. 7 shows the secondary voltage and primary current of one phase winding. When 20 modules of 1kW resistor were connected, secondary current increased from 25.8A to 46.6A.

As a final test, we intended to apply 3 times of the rated load but it exceeded the capacity of the variable voltage source. We shorted the secondary of the transformer and conducted 3 times of the rated current. Fig. 8 shows the primary voltage and secondary current while 3 times of rated current, 78A, were conducting the transformer.

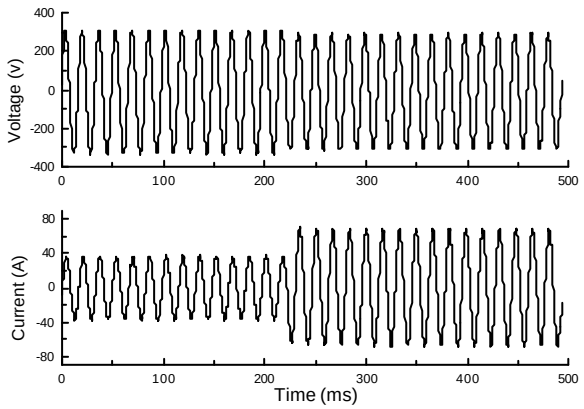

Fig. 7. over-load operation, upper : secondary voltage, lower : secondary current.

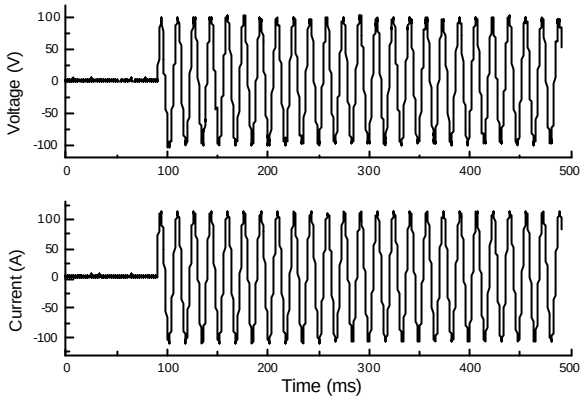

Fig. 8. Over current of three times of the rated current, upper : primary voltage, lower : secondary current.

Special attentions were paid to check the circulating current in secondary ?. Harmonic voltages and unequal reactances of the pancake winding could generates circulating current in secondary ?. In this test, negligible circulating current was observed in the secondary ?.

V. Conclusion

A 10kVA HTS transformer was constructed and tested. Considering most of the large transformers are 3 phase transformers, we constructed the 3 phase transformer with double pancake windings.

After the basic tests, such as, no load test, short circuit test and load test, continuous operation of 100 hours with full load of 10kVA was carried out. According to our measurement, there's no deterioration of the HTS wires during the full load operation of the transformer.

Finally, over-load properties were observed. The HTS transformer conducted 3 times of the rated current without temperature rise in the windings. According to the results of the tests, the HTS transformer was rigid and reliable.

VI. References

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