Development of a three-phase HTS power transformer

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We have developed a 26kVA (400V/16V) three-phase HTS transformer cooled by liquid nitrogen. The primary and secondary windings were wound by transposed conductors, which are made from the stainless steel-reinforced multifilamentary Bi2223/Ag tapes. The structures of primary and secondary windings are solenoid and double-pancake respectively. Fundamental characteristics of the transformer are obtained through no-load and short circuit tests. The gas-cooled current leads of secondary windings were optimally designed. The cryostats are made from electrical insulating materials Fiberglass Reinforced Plastics (FRP), which have excellent heat-preservation. The iron cores are made of common scratched Fe-Si steel and operate at room temperature. Based on results of this transformer, we will develop 630 kVA HTS transformer with same rated currents in near future.

INTRODUCTION

The development of high-temperature superconducting (HTS) devices has made remarkable progress in recent years [1-3]. The superconducting transformer is one of the most promising applications in electric power systems. And it offers several merits such as reduced size and weight, high efficiency, oil-free, nonflammable and less environmental hazards. The next step is to investigate and design the apparatus which is near commercialization. For HTS materials, technique to make practical long and stainless steel-reinforced tapes with critical current density J_c more than 10^4 A/cm^2 in liquid nitrogen and self-field have been achieved, which supplies possibility for large capacity HTS transformers.

We designed and fabricated a three-phase 26kVA(400 V/16 V) HTS transformer for the analysis of its fundamental characteristics. The primary and secondary windings were wound by transposed conductors, which are made from the stainless steel-reinforced multifilamentary Bi2223/Ag tapes fabricated by American superconductor (AmSC). The main aims are improvements in basic technology for application of HTS transformers by analyzing the characteristics of electro-magnetism, insulation, thermodynamics and stability for the transformer. Our near goal is to design and build a 630 kVA (10.5 kV/0.4 kV) distribution HTS transformer with amorphous cores which would be tested in field in Xinjiang Tebian Electric Apparatus Stock CO., LTD., China.

The transformer is tested under AC and DC rated current, no-load and short circuit conditions for four hours at power frequency 50Hz in liquid nitrogen. Also we measure the current distributions of double pancakes in secondary windings with and without iron cores. In the paper, we report on developing the basic technology for the HTS transformer, and present the results of individual tests of the HTS transformer.

DESIGN AND CONSTRUCTION OF WINDINGS

Specifications of windings

The primary and secondary windings of the transformer are composed of 2-strand parallel stainless reinforced-steel Bi2223/Ag multifilamentary tapes that have 55 untwisted filaments. The cross-section of the tape is 4.1×0.31mm^2.

The HTS tape must be insulated because it is not insulated by AmSC. We developed a wrapping machine which can be used to wrap the tape automatically with single, double and triple wrapping by polyimide films. The insulation technique can successfully wrap tape about 100m/hr without any degration of the critical current. The thickness of polyimide film is about 25 micrometer. The polyimide film was tested at nitrogen temperature 77 K. The breakdown voltage is 208.4kV/mm and the AC withstand voltage is 147.2kV at power frequency 50Hz for 1min., which is enough for this transformer. Proposed conductors of windings are composed of 2-strand parallel conductors with proper transposition. In the parallel conductors, the strands are electrically insulated with each other.

We designed and fabricated 6 coils, three solenoid coils are for primary windings and the other three are double pancake coils for secondary winding in a three-phase 26 kVA HTS transformer respectively. The secondary winding is made from 24 double pancakes connected in parallel, and the primary coil winding is solenoid. The strand in two kinds of windings is consisted of two parallel transposed multifilamentary tapes in order to prevent unbalanced current flowing because it may cause instability of the HTS coils as well as much of AC loss. Solenoid and double pancake coils are concentric cylindrical. The helical coil is wound with 4 layers and the double pancake one is wound with 3 layers, and the double pancake coil is located coaxially outside the helical coil, Fig. 1 shows the overview of three phase windings.

Fig.1 Overview of one phase windings. Inner solenoid coil: Primary winding. Outer double pancake coil: Secondary winding

Table I
Parameters of the transformer

Parameters	Design values	Unit
Capacity	26	kVA
Voltage (Primary/Secondary)	400/16	V
Current (Primary/Secondary)	37.5/938	A
Average Diameter (Primary/Secondary)	152.5/178.5	mm
Core Diameter	90	mm
Height (H_w)	650	mm
Width (M_0)	360	mm
Magnetic flux density	1.27	T
Cryostat		
Height	550	mm
Diameter (outermost/innermost)	300/92	mm
Vector Group	Yyn0	
Impedance x_{cc}	2.83%	
No-load current	1.26%	
Operation Temperature	77	K
Operation Frequency	50	Hz

Specifications of transformer

We designed and fabricated a three-phase HTS transformer with capacity of 26kVA operated in liquid nitrogen of 77K for the primary/secondary voltage of 400V/16V and the primary/secondary current of 37.5A/938A. The main parameters are summarized in Table I. The primary winding is located coaxially outside the secondary one in a FRP cryostat around an iron core of room temperature with diameter of 92mm. The turn ratio is 25. Design of electrical insulation for present transformer is attributed to electrical properties of nitrogen gas in low temperature 77K. The current leads on low voltage side are gas-cooled and those on high voltage side are not cooled. Fig. 2 shows the overview of the three phase 26kVA HTS transformer before installed in box. The level of liquid nitrogen in three cryostats are monitored by sensors which act on the switchgear in case of liquid nitrogen level problems and protect the windings from being destroyed.

CRYOSTAT AND CURRENT LEADS

Since metal cryostat locating around the magnetic path will form a closed loop, same as one turn short circuit winding, it cannot be used in AC field. The Fiber Glass Plastics (FRP) should be used to fabricate cryostat which is electrical insulated and strong enough even it requires permanent use of vacuum pump to maintain thermal insulation between inner and outer walls. We designed three FRP cryostats with room temperature cores for iron cores.

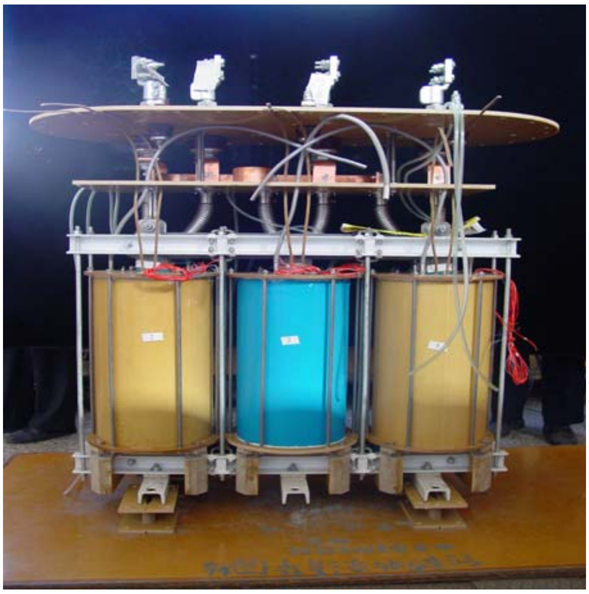

Fig.2 An overview of 26kVA three-phase HTS transformer

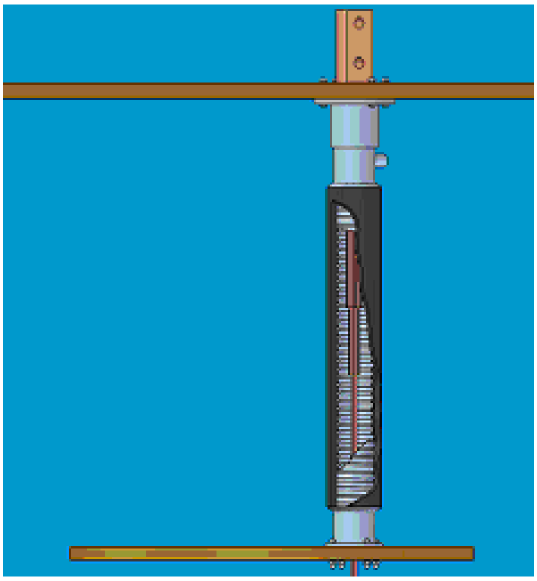

Fig. 3 Schematic of gas-cooled current leads

Current leads made up from copper span from room temperature to 77 K temperature, and heat leakage is important loss considering consumption of liquid nitrogen. We optimized the gas-cooled current leads for secondary windings [4]. In primary winding, the current leads are non cooled since the cross sections of secondary current leads are about 25 times larger than those of primary current leads, heat-conduction in primary leads is very small compared to secondary case. So the current leads of secondary windings are only chosen as traditional boiling gas-cooled current leads in order to reduce consumption of liquid nitrogen. Fig.3 shows schematic diagram of the gas-cooled current lead. The cross section of current lead is different, the top cross section in room temperature is designed as that of traditional transformer, the end cross section near liquid nitrogen is optimized with different loss of transformer, optimal cross section is $64mm^2$. Test was done by caloric method, calculated and experimental results are shown as Fig.4.

TEST RESULTS OF THE TRANSFORMER

Firstly, critical currents of windings were measured by standard four probes method with criterion $1\mu V/cm$ at liquid nitrogen temperature 77K. Critical currents of windings are about 180A, which means that critical currents of six windings in the transformer are almost uniforms. In AC operation, AC current in primary winding is same; but since the secondary windings is consisted of 24 double pancakes connected in parallel, the current distribution between double pancakes is different due to different inductance. The currents of double pancakes are very different in both cases. The maximum current is about three times of the average value without iron core, but the currents of the secondary with iron core are almost uniform [5].

In no-load test, we had usual tests of the transformer cooled in saturated liquid nitrogen at 77K in order to get steady characteristics in the rated operation. The transformer was excited from primary side at rated voltage 400V. The exciting current was 0.48A (1.264%) and the total no-load loss was 320W in usual procedure with three power Wattmeters, which can be attributed to a core loss. At the rated condition the designed value for the magnetic induction of the core is 1.27T, we obtained the transformation ratio of 25.01, as shown in Fig.5.

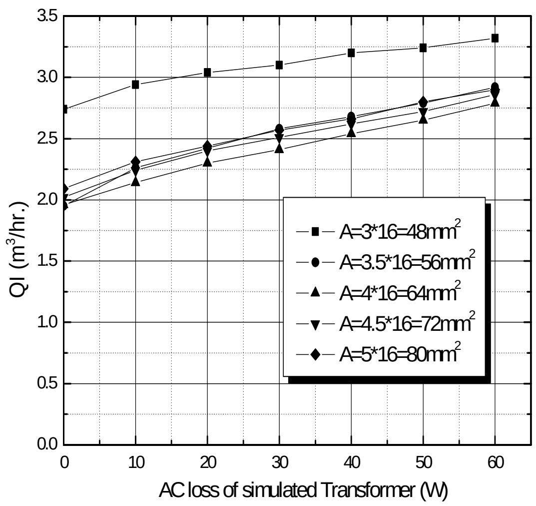

Fig.4 Optimized cross section of gas-cooled current leads

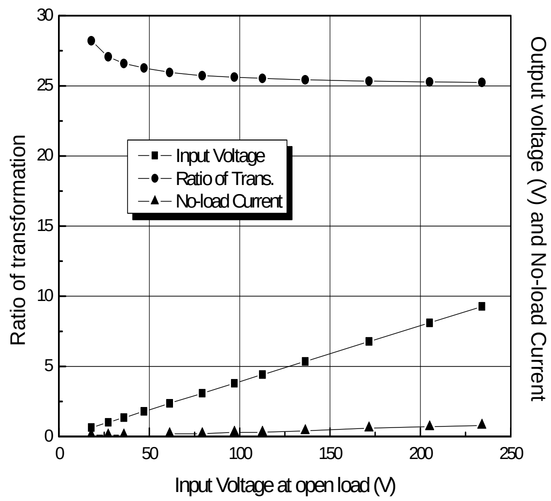

Fig.5 Experimental results of single transformer

Short-circuit test was performed from secondary side at the rated current 938A for 4 hours. The impedance voltage was estimated as 2.8% of the rated level. All of the parameters are in good agreement with designed ones. The ratio at lower input voltage is larger than designed value 25 since there is an error in output voltage measurement, but the ratio is almost exactly 25 at high input voltage. Finally, we performed an overload test of the transformer at 77K, where the current of the windings was increased up to 1200A for 2 hours, about 128% of the rated current. In the overload test, we had a stable operation of the transformer with a 26kVA secondary resistive load.

SUMMARY AND CONCLUSION

A three-phase 26kVA HTS transformer with room temperature iron core was developed and tested at 77K. The primary winding was solenoid coil and the secondary coil was consisted of 24 double pancakes connected in parallel, and the strand of windings was consisted of two parallel transposed stainless steel-enforced multifilamentary Bi2223/Ag tapes which were insulated by wrapping with polyimide films. The rated primary and secondary voltages are 400V and 16V, and rated currents are 37.5A and 938A respectively. The transformation ratio is 25, short circuit impedance is 2.8% and the excited current is 1.26%.

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