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Evolution of a 1250-kVa Superconducting Transformer and its Exhibition at the superconducting Substation

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Abstract- *A three-phase high temperature superconducting (HTS) transformer of 1250-kVA/10.5-kV/0.4-kV has been designed and manufactured. The windings of the three phase HTS transformer made of reinforced copper alloy. The formation of the primary and secondary windings of the HTS transformer is solenoid and double pancake, respectively. The core consists of three-limb and is made of domain-refined high-induction-type grain-oriented silicon sheet steel .The cryostat is fabricated of glass-fiber-reinforced plastics. From the transformer tests, the no-load loss is about 2319.2 W at an exciting current of 0.254% of the rated current. The short-circuit impedance of the HTS transformer is about 5.6% of the rated value. The average load loss is 249.6 W. In addition, the leakage current between the primary and secondary windings of the HTS transformer is about 12.6 mA under the situation of 35 kV/1 min/50 Hz.*

Key Words: Bi2223/Ag hermetic tapes, high-temperature superconducting (HTS) transformer, superconducting power substation, transformer test.

1.INTRODUCTION

POWER transformers are one of the most important and significant devices for electrical application. Different types of transformers are constructed for different applications. There are many number of service-ready prototype high-temperature Superconducting (HTS) transformers have been introduced. The usage of HTS transformer results show that it is possible to reduce the energy loss in transformers by 60% or more by replacing the HTS windings over conventional winding With the discovery of High temperature superconductor (HTS) having higher temperature, the electrical applications of low temperature superconductor (LTS) have diminished than high temperature superconductor (HTS). HTS transformer has been expected to be one of the most wanted HTS device applications. Recently research and development about the relevance of HTS transformer have been progressed actively in the world. The market for HTS transformers will become higher and larger with the continued manufacturing of HTS transformers

A transformer is an electrical device which is used in transferring of power from one circuit to another through the basic principle of electromagnetic induction. The power transfer is done without frequency change. In an electrical system, the term power transformer is used to provide a different range of AC supplies of several voltages and appropriate values of current from the public electricity supply. Usually transformer is denoted with kVa rating, 500kVa or greater. The Power transformer is a kind of transformer, which is used to transfer electrical energy in any part of the electrical or electronic system between the generator and the distribution primary circuits. The power transformers are used in distribution systems to interface step up and step down voltages. One of the common type of power transformer used is liquid immersed and the life span of these transformers is around 30 years. Power transformers are classified into three types based on the ranges. They are small, medium and large power transformers

HTS transformers are classified into three : 1) on the basis of windings of different materials, HTS transformers can be classified into HTS conventional transformers were the windings made by HTS materials and HTS hybrid transformers were the windings are made by HTS and copper materials; 2) on the basis of having a magnetic core or not, HTS transformers can be classified into HTS core-type transformers and HTS air-core transformers; 3) on the basis of different application fields, HTS transformers can be classified into HTS power transformers and HTS traction transformers.

The evolution of the 1250-kVA/10.5-kV/0.4-kV HTS Transformer is described in this paper, and from the testing results it is proved that the developed HTS transformer meets the requirement for operating in the grid. By considering the economic efficiency, the HTS conductor Bi2223 from Sumiton other than YBCO is used for the windings. The core of 630-kVA/10.5/0.4-kV HTS power transformer is made of amorphous alloy and the core of the 1250-kVA HTS transformer is made of domain-refined high-induction-type grain oriented silicon sheet steel.

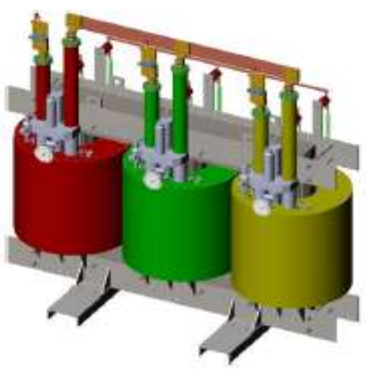


Fig -1: Arrangement of the 1250-kVA/10.5-kV/0.4-kV HTS transformer.

Table -1: Specification of the 1250kVa HTS transformer

thing	Designed value
No. of phase	3
Rated capacity	1250kVa
Rated frequency	50Hz
Rated voltage (prim./second.)	10.5kV/0.5kV
Rated current (prim./second.)	69A/1804A
connection	Y-Y
impedance	6%(std. level)
Operating temperature	77K(LN2)

Fig -2: Arrangement of the core.

2. DESIGN AND FABRICATION OF THE TRANSFORMER

BA three-phase HTS power transformer with a capacity of 1250 kVA/10.5 kV/0.4 kV of 77 K is constructed. Liquefied nitrogen is used as coolant. Fig. 1 shows the arrangement of the 1250-kVA/10.5-kV/0.4-kVHTS transformer. Here the HTS transformer is a three-phase three-limb transformer with Y–Y connection. By comparing with the conventional transformers, the primary and secondary windings of the HTS transformer are made of HTS tapes, and liquefied nitrogen (LN2) at a temperature of77 K is used as the cooling and insulation medium. The specifications of the Superconducting transformer are presented in Table I.

2.1 Iron

Fig. 2 shows the arrangement of the core, where the core is naturally air cooled. The core of the previously constructed 630-kVA HTS transformer is made of an amorphous alloy core.

TABLE 2: SYMBOLS

Item	Symbol	Value
Additional coefficient	K_{p0}	1.2 (mitred joint)
Core loss (W/kg)	p_{tz}	0.62 (1.49T)
Total weight of the core (kg)	G_{tz}	3244
Weights of core limb (kg)	G_{zh}	1281
Weights of core yoke (kg)	G_e	1624
Weights of core corner (kg)	G_Δ	339
Increasing coefficient	K_Δ	4 (mitred joint)
Total number of cores joints	n_j	8 (three-phase three-limbs)
Unit magnetization (VA/kg)	q_{tz}	0.878 (B27R085 at 1.49T)
Joint magnetization (VA/cm^2)	q_j	1.93 (B27R085 at 1.49T)
Rated capacity (kVA)	P_r	1250

By looking through the mechanical and magnetic characteristics of amorphous alloy, the core of a three-phase transformer is usually wound with five limbs, which thereby increases the width and weight of the transformer. Since the HTS transformer is not that reliable as a conventional transformer, the convenience for assembling and maintaining is important. However, the construction of amorphous alloy cores by rolling is not as convenient for assembly and maintenance as silicon sheet steel construction. Therefore the core loss of an amorphous alloy core is much smaller when compared with the silicon sheet steel, conventional silicon sheet steel is used for the construction of core 1250-kVA HTS transformer. The core is constructed from domain-refined high-induction-type grain oriented silicon sheet steel B27R085 from Baosteel. The guaranteed value of the core loss is 0.85 W/kg at a maximum magnetic induction of 1.7 T. at a frequency of 50 Hz. the lamination factor *fd* is 0.97. the power for each limb *Pzh* (in kilovolt amperes) is 417 kVA. The diameter *D*0 of the core limb is taken to be310 mm. Thus, the effective cross sectional area of core limb *Szh* is 698.30 cm2, and the no. of turn of low-voltage winding *Nl* is 10, whereas the turn potential *et* is 23.09 V. the no. of turn of high-voltage winding *Nh* becomes 262, and the magnetic flux density of the core *Bm* is 1.49 T.

2.2 Windings

Fig. 3 shows the arrangement of the winding, where the primary and secondary windings are solenoid and double pancake. Both of the primary and secondary windings of the HTS transformer are made of Bi2223 HT-CA 50 from

Sumitomo with critical current around 170 A (77 K, self-field), and the features of the windings are presented in Table IV.

HTS wires which are commonly used in high voltage power transformer can be classified into two types: the 1st one is generation of Bismuth Strontium Copper Oxides (BSCCO) HTS wires, and the 2nd one is generation of Yttrium-Barium- Copper Oxide (YBCO) HTS wires]. For BSCCO, it is mainly used in two forms: Bi2Sr2CaCu2O (Bi2212) and Bi2Sr2Ca2Cu3O (Bi2223). At present, Bi2223 has been more applied than Bi2212 because its critical temperature is 20 K higher than Bi2212. To deal with high voltage, the superconducting power Transformer needs windings that have hundreds of turns. HTS winding with YBCO wires have higher current density and better current magnetic field characteristics than BSCCO wires.

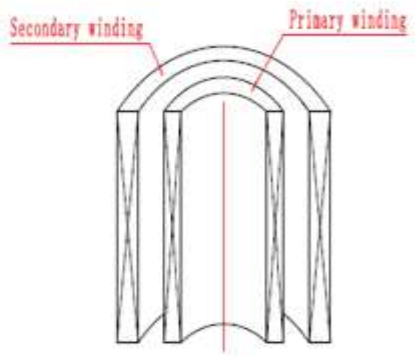


Fig-3: Arrangement of the winding.

TABLE 3: Specification OF THE CORE

Item	Designed value
Type	three-phase three-limbs
Material	grain-oriented silicon steel
Diameter	310mm
Effective sectional area	698.3cm^2
Window height	810mm
Center distance between limbs	770mm
Flux density	1.49T
Turn potential	23.09V
Weight	3244kg
No-load loss	2210W

TABLE -4: SPECIFICATIONS OF WINDINGS

	Item	Designed value
Primary winding	Winding type	Solenoid
	Number of layers	8
	Number of turns	262
	Diameters	410mm
	Height	342.5mm
Secondary winding	Winding type	Double pancake
	Number of pancakes	22
	Turns of each pancake	10
	Diameter	506mm
	Height	349mm

2.3. Cryostat

Fig. 5 shows the arrangement of the cryostat. To reduce the eddy-current loss, the cryostat is to be made of non-metal materials since the magnetic field is alternating. Thus, fiberglass and epoxy that can be applied at a cryogenic environment are used to construct the cryostat of the HTS transformer. Fig. 6 shows the arrangement of the primary current lead. Since the rated current of the primary winding is 69 A and a φ 6-mm Copper wire is used as the current lead. The current lead has to endure a 35-kV/1-min/50-Hz voltage at both cryogenic and room temperatures. So a resin impregnated paper bushing is applied. To avoid the failure of insulation caused by possible condensate water on the bushing, a low-temperature endurable non-metal insulator is developed to reduce the possible discharge along the dielectric surface of the bushing.

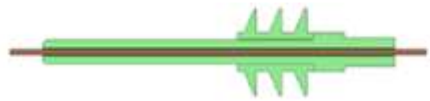
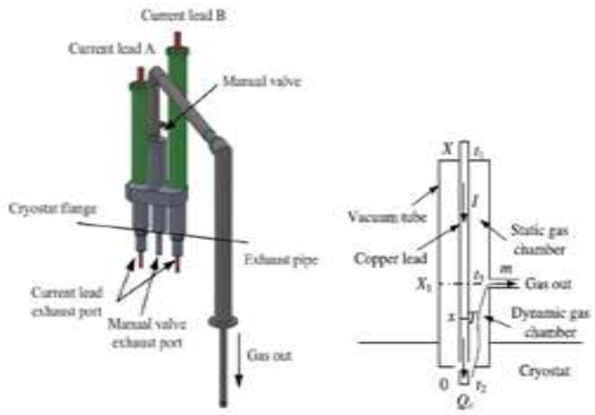


Fig-6: Arrangement of the primary current lead.



(a) (b)

Fig.-7: Secondary current lead.

(a) Arrangement. (b) Schematic.

3. TESTS OF THE TRANSFORMER

Tests on transformer includes: No-Load Test Short-Circuit Test Insulation Test

TABLE-5: INSULATION RESISTANCE

Item	Required value	Tested value
Primary-Secondary windings	1GΩ	20GΩ
Primary-Ground(Iron)	1GΩ	20GΩ
Secondary-Ground(Iron)	200MΩ	2GΩ

TABLE-6: TEST RESULTS FOR THE 1250-kVA HTS TRANSFORMER

Item	Designed value	Tested value
Transformer ratio	26.25	26.184
Connection symbol	Yyn0	Yyn0
No-load current	< 0.3%	0.254%
No-load loss	2350W	2319.2W
Short-circuit impedance	6% (±10%)	5.6%
Loss in windings(77K) and current leads	< 300W	249.6W
Withstand voltage	35kV/1min/50Hz	OK
Lighting impulse	75kV/1.5/50μs	OK

3.1. No-Load Test

These tests include insulation resistance among the primary and secondary windings and core (ground), transformer ratio and connection group, and the no-load current and loss test. The tests are carried out under the condition that the windings are completely immersed in liquefied nitrogen (LN2) for more than 24 hr Table V shows the insulation test results including the insulation resistance between the primary and secondary winding, the primary winding and iron connected with ground, and the secondary winding and core connected with ground. It's not that difficult to find that the tested values are far above the required values. The main test results of no-load tests for the HTS transformer are shown in Table VI.

3.2. Short-Circuit Test

The conventional electric method with a power analyzer was applied in the short-circuit test .and the HTS transformer was excited from the primary side at 69 A/50 Hz for 24 h. The accuracy of the applied power analyzer is 0.3% under the power factor of 0.01.According to the insulation test, the short-circuit impedance of the HTS transformer is 5.6% of the rated value, and the average load loss is 249.6W, which includes the ac loss of windings and the joule heat of current leads.

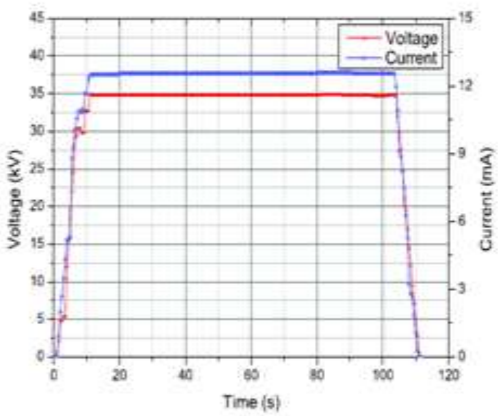


Fig-8: Showing Insulation between the primary and secondary windings

3.3. Insulation Test

Fig. 9 shows the insulation between the primary and secondary windings of the HTS transformer under the condition of 35 kV/1 min/50 Hz. It is able to see that the leakage current is about 12.6mAat the voltage of 35 kV,

4. EXHIBITION OF THE TRANSFORMER

After all the tests conducted, the constructed HTS transformer was assembled in the superconducting power substation.

Connection

Fig. 11 presents the accessing of the developed HTS transformer in the superconducting power substation. Here the 10.5-kV/1.5-kV superconducting fault current limiter (SFCL), the 1250-kVA/10.5-kV/0.4-kV superconducting transformer, and the 10.5-kV/1.5-kA superconducting cable are connected in series. The input10.5-kV bus is connected with the bridge-type SFCL, which is used for the application of fault current limitation. The output of the SFCL is then connected to the constructed HTS transformer with a Y–Y connection group in series, and the voltage is transferred to0.4 kV; the power is supplied to the load through the three-phase superconducting cable

Fig-11: Accessing of the superconducting transformer.

5. CONCLUSION

The evolution of a 1250-kVA/10.5-kV/0.4-kV HTS transformer and its exhibition at a superconducting power substation shows that it is now possible to operate HTS transformers in the network. While comparing with the conventional power transformer at the same rated capacity, the potential load loss, size, and weight savings of the HTS transformer are of great interest. Here, LN2 used as coolant and dielectric also provides fire safety to the conventional oil-immersed-type transformer, which is of considerable interest for underground substations or some sensitive regions.

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