DEVELOPMENT OF A 6600 V / 210 V 100 kVA HYBRID-TYPE SUPERCONDUCTING TRANSFORMER

Y.Kito Member
H.Okubo Member
N.Hayakawa Non-member
Nagoya University
Nagoya, Japan

Y.Mita Non-member
M.Yamamoto Non-member
Takaoka Electric MFG. Co., Ltd.
Aichi, Japan

Abstract - A 6600 V / 210 V 100 kVA hybrid-type superconducting transformer has been developed. In this transformer, the low-voltage, high-current winding is made of liquid helium-cooled superconducting wire and the high-voltage winding is made of liquid nitrogen-cooled low-loss copper wire. The iron-core is placed in the environment of the room temperature outside the cryostat vessel. The cryostat vessel has a two-layer configuration of liquid helium- and liquid nitrogen-cooling vessels. Thus, the apparatus developed here is called as the hybrid-type superconducting transformer (H-SCT).

In this paper, the concept, the design feature and measured characteristics of the H-SCT are described. Fundamental characteristics are obtained through short-circuit and no-load tests. Its critical quenching current and inrush current are also included as measured characteristics.

Keywords - Superconducting technology, Transformer, Hybrid type, Cryostat, Quenching current, High voltage

Introduction

Recently various researches on superconducting technology are powerfully accelerated and a superconducting transformer, which will play a major role in a future superconducting power transmission line, is especially being watched with keen interest. In the first, R.McFee [1] presented the superconducting transformer concept and subsequently a number of researchers published reports [2][3][4]. In particular, the paper written by H.Riemersma et al. [5] in 1981, which presented conceptual designs and described economical analyses of a 1000 MVA, 500 kV / 22 kV, 1300 kV-BIL superconducting transformer, had a great impact on this field. Since then, several superconducting transformers have been actually developed.

However, since superconducting wires have to be placed in alternating magnetic fields, the ac loss reduction technique became a key technology. The ultra-fine filament wires, which were developed by A.Fevrier et al. [6][7][8], displayed low-loss characteristics, stable in 50/60 Hz alternating magnetic fields. This technology has accelerated the development of a superconducting transformer. Subsequently 80 kVA and 220 kVA superconducting transformers were actually developed and valuable data on loss evaluation and short-circuit characteristics were reported [9][10].

On the other hand, it should be taken into consideration in developing a superconducting transformer that it would be operated in direct connection with superconducting power transmission lines. On the basis of economical analysis of superconducting power cables, it is anticipated that the superconducting cable would transmit a few giga-watts of power with higher voltage. Thus future superconducting power systems should be developed on the premise of higher voltage operation. Nevertheless, high-voltage superconducting transformer with such 6600 V or more has never been developed up to now. One of the reason is that liquid helium does not show efficient dielectric performances in higher electric fields.

Taking these points into account, we have developed a hybrid-type superconducting transformer which has a liquid helium (LHe)-cooled superconducting winding rated as 476 A for its low-voltage, 210-V winding and a liquid nitrogen (LN_2)-cooled lower resistance winding rated as 15.2 A for high-voltage, 6600-V winding. The iron-core is placed in the environment of the room temperature outside the cryostat vessel. Then, the transformer developed here has a two-layer configuration of LHe- and LN_2- cooling vessels. Thus, the transformer is represented in this paper as the hybrid-type superconducting transformer, in brief, the H-SCT.

This 6600-V H-SCT is regarded as a first step prototype of the higher voltage superconducting transformer. This paper describes its fundamental concept and design features.

Concept of the H-SCT

The hybrid-type superconducting transformer (H-SCT) developed here is rated as 6600 V / 210 V 100 kVA. 6600 V is commonly used in high-voltage distribution lines in Japan and is the actually operating lowest voltage in our electric power systems. It was pointed out in a number of published papers [16][17] that superconducting systems in future will be operated at 60 kV, 100 kV or higher voltages. We consider the 6600-V H-SCT as a first step toward higher voltage superconducting transformers.

The followings are main features of the H-SCT:

- low-voltage winding is constructed by Nb-Ti superconducting bundle wires cooled by LHe,
- high-voltage winding is constructed by lower loss copper wire cooled by LN_2,
- cryostat vessel has two-layer doughnut structure which enables to separate LHe-cooling system from LN_2-cooling system,
- iron-core is placed in the environment of the room temperature, and the main leg passes through the cryostat center hollow and the magnetic passage is closed around the cryostat vessel.

The low-voltage high-current winding is made of LHe-cooled superconducting wire, which contributes to reduce the size of the high-current winding. The LHe is used not only as a coolant but also as insulating material.

On the other hand, current level of the high-voltage winding is not so high as the low-voltage winding, so that the lower loss copper wire could exhibit permissible current carrying performances. The high-voltage winding is cooled and insulated by LN_2 which has about two times higher insulation ability than

90 SM 342-6 PWRD A paper recommended and approved by the IEEE Switchgear Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1990 Summer Meeting, Minneapolis, Minnesota, July 15-19, 1990. Manuscript submitted January 29, 1990; made available for printing June 29, 1990.

0885-8977/91/0400-0816$01.00©1991 IEEE

LHe. In both windings, lower loss characteristics as well as compactness could be achieved compared with the conventional winding.

The cryostat vessel has two-layer structure of LHe and LN_2 vessels. The inner layer is for the LHe-cooled low-voltage winding and the outer layer is for the LN_2-cooled high-voltage winding. From this structure, "HYBRID" is suitable to express the feature of this transformer.

The developed H-SCT is a core-type transformer and the iron-core is placed in the environment of the room temperature. If the iron-core were immersed in cryogenic coolant together with the windings, and kept at cryogenic temperatures, the core-loss would be increased. From this point of view, we place the iron-core outside the cryostat vessel. This results in prevention of excessive consumption of cryogenic coolant. We believe that this core arrangement will be a standard type for a large capacity superconducting transformer in future.

In future, superconducting power systems will be connected to conventional power systems, thus the cryogenic temperature section will be coupled with the room temperature section through this type of the H-SCT. The H-SCT will be suitable for use as the tie transformer between a conventional large capacity generator system and a LHe-cooled superconducting transmission cable. An entire LHe-cooled superconducting generator system also could be connected with a LN_2-cooled high temperature superconducting transmission line.

Design of the H-SCT

The H-SCT was designed as a prospective tie transformer between LHe-cooled system and LN_2-cooled one. The H-SCT has the structure as shown in Fig. 1. It is characterized by the two-layer concentric cylindrical cryostat, the low-voltage winding placed at the inside LHe vessel and the high-voltage winding at the outside LN_2 vessel. Fig. 2 is the photograph of the H-SCT.

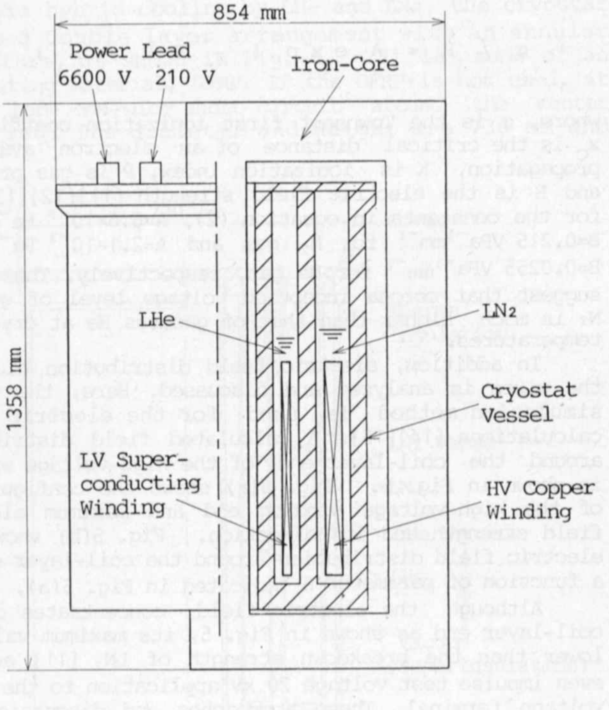


Fig. 1. Structure of the H-SCT.

Winding design

Low-voltage winding

The low-voltage high-current winding is made of Nb-Ti ultra-fine filament wires for ac superconducting use and its various dimensions are listed in Table 1. The Nb-Ti ultra-fine filament has 0.55 μm diameter and 39,546 filaments are bundled and twisted to reduce an ac loss in the conductor and finally an outside diameter of 2.18 mm is obtained. The sectional view of the wires is shown in Fig. 3 in an enlarged photograph.

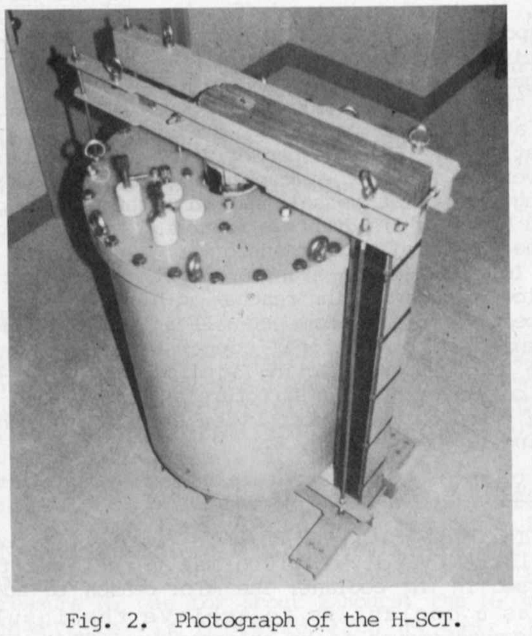


Fig. 2. Photograph of the H-SCT.

Table 1. Ac superconducting wire.

Outside diameter	2.18 mm
Number of strands	7 × 7
Strand diameter	0.22 mm
Nb-Ti filament diameter	0.55 μm
Number of Nb-Ti filaments	39,546
Matrix construction	1 / 1.2 / 1.7 (Nb-Ti/Cu/Cu-Ni)
Twist pitch	2.3 mm
Dc critical current	>1000 A (at 4.2 K, 1 T)

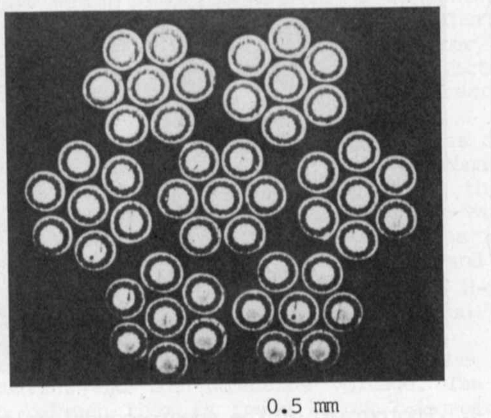


Fig. 3. Ultra-fine superconducting filament wires.

A winding former for the low-voltage winding is made of glass fiber reinforced plastics (GFRP) with the height of 520 mm and the diameter of 340 mm. The winding former has vertical ducts and helical slots. The vertical ducts enhance the cooling efficiency of wire conductors. Helical slots stabilize wires rigidly with the winding former against electro-magnetic forces.

It must be taken into account in the superconducting winding that the winding might have an opportunity to have quench transition into the normal conducting state, especially when a large fault current passes through it. The quench is assumed to be induced by small local disturbances. For example, microscopic vibrations of bundle wires may cause the disturbance. It is important to remove such causes as much as possible. Thus, the bundle wires are fixed on the winding former by epoxy resin. The epoxy resin used was selected especially for low temperature use to avoid cracks at cryogenic temperatures.

The winding is kept at 4.2 K by LHe coolant under the atmospheric pressure. To suppress the bubble formation in LHe, super critical LHe could be used. However, we selected atmospheric pressure LHe because a stronger cryostat vessel that withstands high pressure would have big disadvantage regarding to the compactness of the superconducting transformer.

In this 100 kVA transformer, the rated current in the low-voltage winding reaches as high as 476 A and the prospective total volume as well as weight will become larger if a conventional copper winding is adopted, while this superconducting winding has only 46 turns with one-layer helical structure and its weight is only 670 *g* (wire only). Outer view of the superconducting winding is shown in Fig. 4.

High-voltage winding

The high-voltage winding is made of copper wire insulated by polyvinyl formal thin layer that is immersed in LN_2 coolant. The main reason to adopt the LN_2 as a coolant is to achieve the insulation performance enough to be operated in 6600 V. LN_2 has about two times higher insulation ability than LHe as

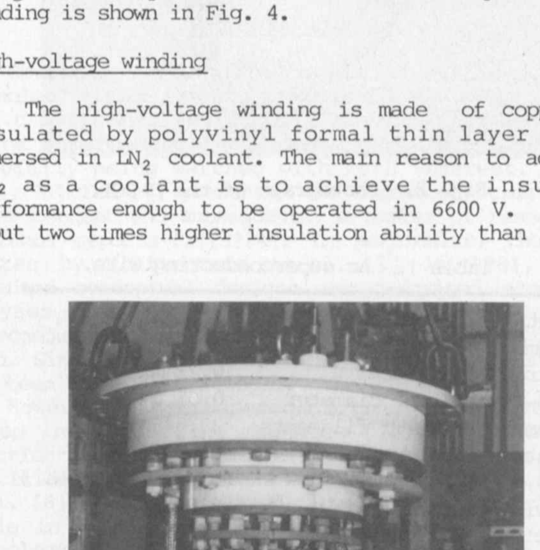


Fig. 4. Photograph of the superconducting low-voltage winding.

will be discussed below and is advantageously used to insulate the high-voltage winding.

The resistivity of copper wire at the LN_2 cooling temperature is reduced into about 1/8 compared with that at the room temperature. The diameter of copper wire is 1.6 mm and the current density is 7.56 A/mm², that is enhanced about three times higher than the conventional transformer winding.

The high-voltage winding has 1446 turns with 468 mm stack-height and with 16 mm coil-width and is cylindrically wound in 6 layers. Consequently, the winding is constructed so much compact, and the enough efficiency is obtained.

The high-voltage winding is to be connected with conventional transmission lines or LN_2-cooled cables. Although this side can be subjected to a large fault current, the adopted low temperature copper wire never quench even under fault conditions. Furthermore, cooling efficiency of LN_2 is much higher than that of LHe, and the adoption of LN_2 enhances the transformer total efficiency.

Insulation design

Data of He and N_2 breakdown characteristics in uniform and non-uniform fields are reported under low temperature gas and liquid states [11][12][13][17][18]. However, dynamic insulation design should be taken into account under actual operating conditions such as bubble formations of LHe and LN_2.

For liquid state, the dielectric withstand voltages of LHe is close to that of insulating oil. The dielectric withstand voltages of LN_2 is about two times higher level than that of LHe, under quasi-uniform field conditions [19].

Under gas state, the difference of the dielectric withstand voltages of He and N_2 is much bigger. The following corona inception criteria can be also used for the cryogenic gas insulation design.

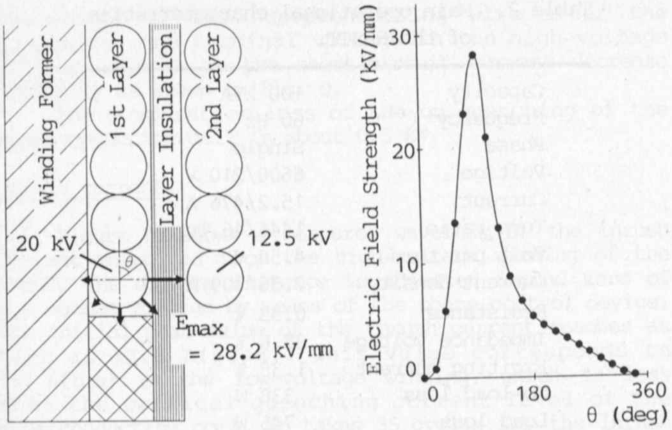
$$\int_0^{x_c} \alpha \, dx = K \quad (1)$$

$$\alpha / P = A \exp(-BP/E) \quad (2)$$

where, α is the Townsent first ionization coefficient, x_c is the critical distance of an electron avalanche propagation, K is ionization index, P is gas pressure and E is the electric field strength [11][12][13]. As for the constants in equation (2), $A=6.6\times10^{-3}$ $Pa^{-1}mm^{-1}$, $B=0.215$ $VPa^{-1}mm^{-1}$ for N_2 gas and $A=2.1\times10^{-3}$ $Pa^{-1}mm^{-1}$, $B=0.0255$ $VPa^{-1}mm^{-1}$ for He gas, respectively. These data suggest that corona inception voltage level of gaseous N_2 is much higher than that of gaseous He at cryogenic temperatures.

In addition, electric field distribution close to the wires is analyzed and discussed. Here, the charge simulation method is used for the electric field calculations [14][15]. A calculated field distribution around the coil-layer end of the high-voltage winding is shown in Fig. 5. Fig. 5(a) shows the configuration of the high-voltage winding end and maximum electric field strength and its direction. Fig. 5(b) shows the electric field distribution around the coil-layer end as a function of parameter θ indicated in Fig. 5(a).

Although the electric field concentrates on the coil-layer end as shown in Fig. 5, its maximum value is lower than the breakdown strength of LN_2 [11] against even impulse test voltage 20 kV application to the high-voltage terminal. These approaches and discussions of insulation design would be useful for higher voltage superconducting transformer design in future.



(a) Configuration of the high-voltage winding end (b) Electric field distribution

Fig. 5. Electric field distribution around the coil-layer end of the high-voltage winding.

Iron-core design

The iron-core is placed in the circumstances of the room temperature. This will suppress the increase of the core-loss in the cryogenic circumstances. Its fundamental structure and steel material adopted are similar to those used in a conventional transformer. The main core-leg passes through the center of the cryostat vessel and a closed magnetic passage with the yoke and the side-leg is made. On account of the long upper space of the cryostat vessel for thermal insulation, this type of iron-core has inevitably longer leg structure than the conventional one. Effective cross section area of the iron-core is 120 cm^2. Total weight of the iron-core is 310.5 kg.

Cryostat vessel design

For hybrid cooling by LHe and LN_2, the cryostat takes a double layer arrangement with an annular structure, as shown in Fig. 6. It is made of an insulating material, GFRP. If the GFRP is not used, it would form one-turn short circuit around the center core leg. Its diameter and height are 730 mm and 1020 mm, respectively. High vacuum layer is inserted between the inner LHe- and the outer LN_2- layers. The vacuum layer has W-shape structure and is kept around 10^{-7} torr and superinsulation tape is wound to protect the radiation thermal loss. The superinsulation tape is made of poly-ethylene film with vaporized aluminum foils which have slits to prevent inducing loop currents. Height of the vessel is about twice longer than that of winding stack and rather larger space is kept above the coil for thermal insulation space to impede thermal invasion from the upper cover of the cryostat vessel. The upper space is filled with styrofoam material.

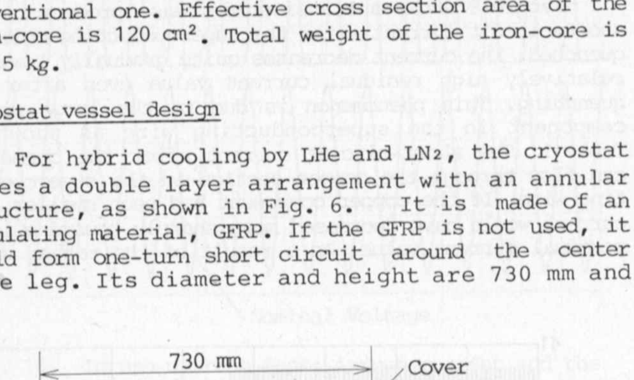


Fig. 6. Structure of the cryostat vessel.

Power lead design

Both the thermal and electrical insulation should be taken into account in power lead design. Cylindrical pipe conductor is adopted as a power lead to make it cool by the flow of low temperature cryogenic gas. From the electrical as well as thermal points of view, epoxy resin is used as a bushing insulation material and 6600 V power lead insulation was achieved.

Experimental results and discussions

Cooling procedure of the H-SCT

The H-SCT has been frequently operated under the cryogenic condition of 4.2 K in the inner low-voltage high-current superconducting winding as well as of 77 K in the outer high-voltage low-current copper winding without any trouble.

Initially, the adiabatic vacuum layer of the cryostat vessel is evacuated to 10^{-7} torr by a diffusion vacuum pump. Then, both the inner and the outer layers are filled with LN_2 for a preliminary cooling for about 15 hours. After LN_2 in the inner layer is drained by the high pressure N_2 gas for about 2 hours, the N_2 gas in the inner layer is replaced with He gas. LHe is gradually poured into the inner layer by taking about 2 hours till the surface level of LHe reaches 40 mm higher than the top of the superconducting winding. About 50 ℓ of LHe is required to fill the inner layer volume of about 20 ℓ, where the low-voltage winding is also cooled down to 4.2 K. The surface level of LHe continuously lowers with the rate of 4 mm/min. Thus, the thermal loss of the inner layer is calculated to be 6.5 W.

Short-circuit test

The leakage reactance of this H-SCT is so large, 168 Ω, viewed from the high-voltage winding. This is due to a considerable distance of the main gap between the high-voltage and the low-voltage windings. Thus, high impedance voltage of a few kV is needed to sustain the nominal current in the short-circuit test. Therefore, when the test is carried out in a weak laboratory power source, a capacitor unit of 16 μF is connected in series, as shown in Fig. 7, to cancel the reactance component in the test circuit.

After deducting both the dielectric loss of the series capacitor and the ohmic loss of the connecting leads from the measured value of the wattmeter, the load loss is eventually calculated to be 745 W. This value is made up as follows: 536 W for the ohmic loss in the high-voltage copper winding immersed in LN_2 and 209 W for the stray load loss. The load loss in the H-SCT is reduced about half of conventional oil-immersed transformers with a similar capacity.

Figure 8 shows a measured waveform of the short-circuit current and the impedance voltage. The phase difference between them is found as 88.7 degrees. The phase difference is estimated as $\tan^{-1}(X/R)$=88.9 degrees, where X is the leakage reactance of the H-SCT,

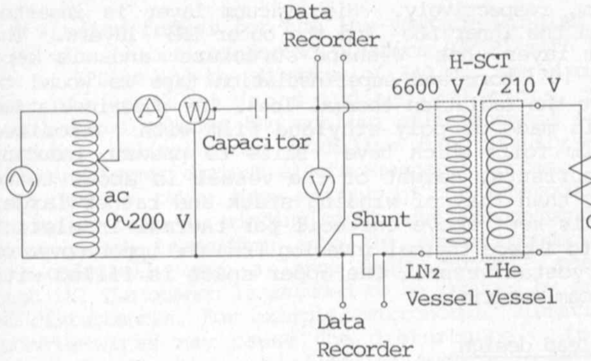


Fig. 7. A circuit diagram of the short-circuit test for the H-SCT.

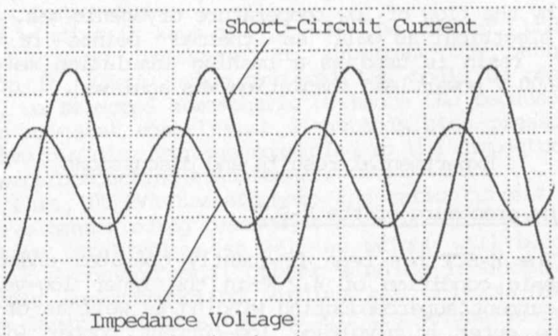


Fig. 8. Short-circuit test: short-circuit current and impedance voltage in the high-voltage winding (current : 8.3 A/div, voltage : 3000 V/div, time : 5 msec/div).

R is the equivalent resistance of 3.22 Ω obtained from the total load loss, in which 2.32 Ω is included as the resistance of the high-voltage winding. The measured phase difference is in good agreement with the estimated one.

No-load test

The no-load loss is measured to be 338 W, which is not improved compared with the conventional oil-immersed transformers with a similar capacity. This is due to the longer iron-core length of the H-SCT to keep the adiabatic distance above the surface of LHe as mentioned previously. Moreover, the measured value of the no-load loss in the H-SCT has slightly increased by 7 % compared with the one measured before the coolant has been poured into the each layer of the cryostat vessel. This small increment is considered to be brought about by slight cooling of the iron-core in the center hollow of the cryostat vessel. In an another type of superconducting transformer, 200 V 50 kVA, that has been developed in our laboratory differently from the H-SCT, the increment of the no-load loss has been found as 17 %, in which the iron-core with the same magnetic material as the H-SCT is immersed in LHe together with the both windings. Thus, the increment of the no-load loss can be said much improved by setting the iron-core outside the cryostat vessel in the H-SCT.

Table 2 summarizes the obtained main operational characteristics of the H-SCT that are evaluated from the short-circuit and the no-load tests.

Critical quenching current

When the short-circuit current in the low-voltage superconducting winding is gradually increased by applying the higher voltage in the modified test circuit

Table 2. Main operational characteristics of the H-SCT.

Capacity	100 kVA
Frequency	60 Hz
Phase	Single
Voltage	6600/210 V
Current	15.2/476 A
Turn ratio	1446/46 Turn
Volt per turn	4.56 V
Current density	7.56/309 A/mm²
Resistance	0.53 %
Impedance voltage	38.6 %
Exciting current	1.38 %
No-load loss	338 W
Load loss	745 W
Total loss	1083 W

as shown in Fig. 7, the quenching is induced at the current of 780 A(rms). The quenching occurs repetitively at the current level around 780 A(rms) in several times of the trials. This value is 1.64 times of the nominal current of 476 A(rms) in the low-voltage winding.

On the other hand, the critical quenching current measured by using a straight sample of 15 cm length of the adopted superconducting wire was 1220 A(rms) without the external magnetic field. Thus, there is a degradation by 36 % in the current carrying performance of the superconducting coil to the wire itself. This degradation is considered to be brought about by the applied magnetic field on the superconducting wire or the manufacturing stress in a coil formation. This degree of the degradation is in good agreement with the reported value of 35 % in the reference [9].

Figure 9 shows a transient decrease process of the short-circuit current after the superconducting coil has quenched. The current decreases quite gradually toward a relatively high residual current value even after the quenching. This phenomenon is due to the large copper component in the superconducting wire as shown in Table 1. The short-circuit current after the quenching can flow through the copper section in the superconducting wire. If the copper component had been smaller, the current would have decreased more sharply toward a lower residual current value. As a result of the rather small

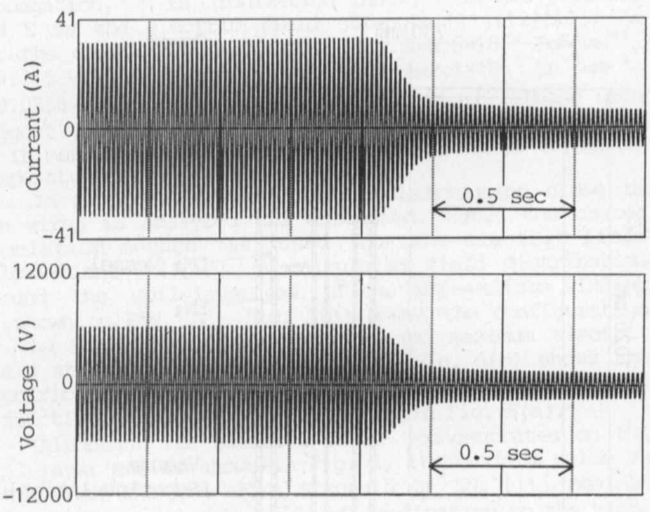


Fig. 9. Critical quenching current test: short-circuit current and the terminal voltage in the high-voltage winding.

resistance of the superconducting wire after the quenching, the terminal voltage in the high-voltage winding as well as the short-circuit current decrease gradually as shown in Fig. 9.

The evaporation loss of LHe on quenching of the superconducting coil is about 0.5 kW.

Inrush current

Figure 10 shows a measured waveform of the inrush current energized from the high-voltage winding of the H-SCT. The closing instance is adjusted around zero of the source voltage by means of the phase control device. The initial peak value of the inrush current reaches as high as 33.8 A(peak). This value corresponds to 751 A(rms) in the low-voltage winding, which is less than the critical quenching current level of the superconducting coil. It takes 35 cycles for the inrush current in Fig. 10 to decrease to half of the initial peak value.

In total, seven trials have been conducted to make sure of the influence of the residual magnetism upon the inrush current. The highest inrush current in the trials was found to reach 46.3 A(peak). This value corresponds to 1030 A(rms) in the low-voltage winding, which can cause the quenching in the superconducting coil. Although the possibility to be energized on the severest condition for the inrush current is relatively little, it will be favorable to introduce the synchronous or resistive closing on energizing superconducting transformers in a future power system.

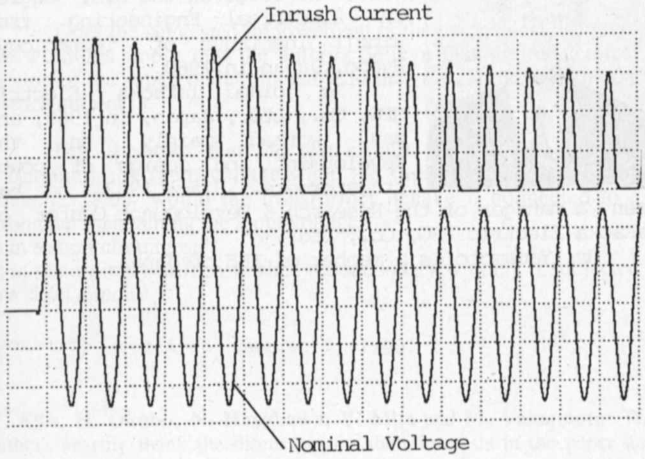


Fig. 10. Inrush current test: inrush current and the nominal voltage in the high-voltage winding (current : 8.3 A/div, voltage : 3700 V/div, time : 20 msec/div).

Problems to be solved

Through the development of the H-SCT, it is considered important to solve the following problems in future:

- reduction of the leakage reactance by the improvement of the winding arrangement,
- optimization of the design of the high-voltage winding immersed in LN_2 to balance the lower loss property with the compactness,
- improvement of the mechanical design of the windings to withstand the electro-magnetic forces due to continuous operating current and especially large fault current.

Conclusions

A 6600 V / 210 V 100 kVA hybrid-type superconducting transformer (H-SCT) has been developed and its concepts, design features and measured characteristics are described in this paper. Main features of this H-SCT are as follows:

- adoption of superconducting conductor for the low-voltage high-current winding cooled by LHe,
- adoption of 6600 V for rated voltage of the high-voltage winding cooled by LN_2,
- iron-core placed in the environment of the room temperature.

These features are actually realized by taking the two-layer structure in its cryostat vessel. Thus, it has been represented as the hybrid-type superconducting transformer (H-SCT) in this paper.

A totally enclosed superconducting power line would effectively support an extraordinary large amount of electric power demand in future urban area. This kind of hybrid transformer would be expected as a tie transformer which bridges between a superconducting power transmission line and the conventional underground cable system.

Acknowledgment

The authors wish to express their appreciation to Sumitomo Electric Industries for producing the ultra-fine superconducting wires for ac use.

References

[1] R.McFee," Superconducting Power Transformers - A Feasibility Study," Electrical Engineering, Vol.80, October 1961, pp.754-760

[2] K.J.R.Wilkinson," Superconductive Windings in Power Transformers," Proc. IEE, Vol.110, No.12, December 1963, pp.2271-2279

[3] K.J.R.Wilkinson," Prospects to the Employment of Superconductors in Alternating Magnetic Fields," IEEE Trans., Vol.MAG-2, No.3, September 1966, pp.369-374

[4] P.H.Borchers," Physical Limitations on the Use of Superconducting Transformers," Proc. IEE, Vol.113, No.12, December 1966, pp.1953-1956

[5] H.Riemersma, et al.," Application of Superconducting Technology to Power Transformers," IEEE Trans., Vol.PAS-100, No.7, July 1981, pp.3398-3405

[6] A.Fevrier, et al.," Thermo-Electromagnetic Stability of Ultra-fine Multifilamentary Superconducting Wires for 50-60 Herz Use," Applied Superconductivity Conference - San Francisco 1988, pp.21-25

[7] P.Dubots, et al.," Nb-Ti Wires with Ultra-fine Filaments for 50-60 Hz Use," IEEE Trans., Vol.MAG-21, 1985, pp.177-180

[8] A.Fevrier, et al.," Prospective Uses of Superconductors for 50/60 Herz Applications" Proc. ICEC 11 Berlin, 1986, pp.139-147

[9] A.Fevrier, et al.," Preliminary Tests on a Superconducting Power Transformer," IEEE Trans., Vol.MAG-24, No.2, March 1988, pp.1477-1480

[10] A.Fevrier, et al.," 220 kVA Superconducting Transformer," Proc. ICEC 11 Berlin, 1986, pp.474-478

[11] M.Hara, et al.," Thermal-Bubble Initiated Breakdown Characteristics of Liquid Helium and Nitrogen at Atmospheric Pressure," IEEE Trans., Vol.EI-23, No.4, August 1988, pp.769-778

[12] M.Hara, et al.," Electrical Breakdown Mechanism of Liquid Nitrogen in the Presence of Thermally Induced Bubbles," Cryogenics, Vol.27, February 1987, pp.93-101

[13] M.Hara, et al.," Breakdown Characteristics of

Cryogenic Gaseous Nitrogen and Estimation of its Electrical Insulation Properties," IEEE Trans., Vol.EI-24, August 1989, pp.609-617

[14] H.Singer, et al.," A Charge Simulation Method for the Calculation of High Voltage Fields," IEEE Trans., Vol.PAS-93, 1974, pp.1660-1668

[15] H.Okubo, et al.," Electric Field Analysis by Combination Method," IEEE Trans., Vol.PAS-101, No.10, 1982, pp.4039-4048

[16] M.Yamamoto, et al.," Preliminary Study on ac Superconducting Machines," IEEE Trans., Vol.MAG-24, No.2, March 1988, pp.1473-1476

[17] M.Yamamoto, et al.," High Voltage Technique Application to Superconductivity," ISH 93.04 Braunschweig, August 1987

[18] B.Fallou, et al.," Insulation Component for High Voltage Cryogenic Equipment," CIGRE paper 15-04, 1974

[19] J.Gerhold," Dielectric Breakdown of Cryogenic Gases and Liquids," Cryogenics, Vol.19, 1979, pp.571-584

Yukio Kito (M'70) was born in Nagoya, Japan on March 12, 1933. He received the B.S. degree in 1955, the M.S. degree in 1957 and the Ph.D. in 1962, all in Electrical Engineering from Nagoya University, Nagoya, Japan.

Since 1960, he has been on the faculty of Nagoya University. He was a Visiting Professor at the University of Texas at Arlington, U.S.A. from 1970 to 1971. Presently, he is a professor of Nagoya University, at the Department of Electrical Engineering.

Dr. Kito is a Investigating Director, IEE of Japan. He is a member of IEEE and Eta Kappa Nu.

Hitoshi Okubo (M'82) was born in Nagoya, Japan on October 29, 1948. He received the B.S. degree in 1971, the M.S. degree in 1973 and the Ph.D. in 1984, all in Electrical Engineering from Nagoya University, Nagoya, Japan.

He joined Toshiba Corporation, Japan in 1973, and from 1976 to 1978 he was at the Technical University of Aachen and Technical University of Munich, West Germany, where he studied high-voltage technique. Since 1989, he is an associate professor of Nagoya University, at the Department of Electrical Engineering.

Dr. Okubo is a member of IEE of Japan and IEEE.

Naoki Hayakawa (Non-member) was born in Nagoya, Japan on September 9, 1962. He received the B.S. degree in 1985 and the M.S. degree in 1987, both in Electrical Engineering from Nagoya University, Nagoya, Japan.

He is a Ph.D. candidate student at the Department of Electrical Engineering of Nagoya University. He is presently involved in the study of a superconducting power transmission system.

Mr. Hayakawa is a member of IEE of Japan.

Yukimasa Mita (Non-member) was born in Aichi, Japan on June 20, 1965. He received the B.S. degree in Electrical Engineering from Nagoya University, Nagoya, Japan in 1988.

He is a master course student at the Department of Electrical Engineering of Nagoya University. He is presently involved in the study of a superconducting transformer.

Mr. Mita is a member of IEE of Japan.

Masanori Yamamoto (Non-member) was born in Hyogo, Japan on January 18, 1937. He received the B.S. degree in Electrical Engineering from Himeji Institute of Technology, Hyogo, Japan in 1960.

He joined Takaoka Electric MFG. Co., Ltd., Japan, in 1960, and has worked mainly on the development and design of power transformers. Since 1982, he has been a manager of the Research & Development Center of Takaoka Electric MFG. Co., Ltd..

Mr. Yamamoto is a member of IEE of Japan.

Discussion

L. W. PIERCE (General Electric Company, Rome, Ga.) During the presentation of this paper, Mr. Hayakawa described subsequent testing which resulted in burn-out of the prototype transformer. In order to complete the paper and accurately report the results this information should be given in the published transactions. Would the authors describe the tests which led to burn-out and describe the failure location?

Manuscript received August 13, 1990.

S. HÖRNFELDT and **O. ALBERTSSON**, ABB Corporate Research, Västerås, Sweden. We like to compliment the authors for an informative paper of the design and construction of a new type of transformer utilizing superconductivity. We would appreciate if the authors would clarify the following points:

1. It is concluded that the load losses in the H-SCT is reduced to about half of that in a conventional oil immersed transformer with a similar capacity. It is not obvious to us if the heat dissipated at 78K and 4K are weighted with the relevant cooling factors (≈10 for 78K and ≈300 for 4K) in this comparison.

2. Have the dielectric losses of the parts of the cryostat walls that are situated in the main duct been estimated?

3. It would be interesting to know how much the current in the superconducting winding increase the losses dissipated in the LHe bath.

4. Does the suggested improvement of the mechanical design of the windings imply that the authors believe that the mechanical motion of the superconducting cable in the vertical ducts limits the quench current?

5. Fig. 9 shows that the test circuit used is incapable of maintaining the input voltage when the superconducting winding quenches. How would the transformer behave if connected to a strong net maintaining the input voltage
a) in a short circuit test?
b) in the ordinary drift case when the secondary winding is subjected to a short circuit?

Manuscript received August 7, 1990.

Y. Kito, H. Okubo, N. Hayakawa, Y. Mita and **M. Yamamoto**: The authors heartily thank the discussers for their interests in the paper and pertinent questions.

In response to Mr. L. W. Pierce:

This paper mainly describes our experience to develop a new type of superconducting transformer with a higher voltage rating: its concept, structure and fundamental test results. During the presentation, we have introduced not only the measured characteristics described in the paper but also, additionally, one of the newest test results we carried out as the second step after submitting this paper. An additional test was a quenching current test of the H-SCT connected to a constant voltage source without the compensating capacitor shown in Fig. 7. This test was carried out to find whether a quenching current level was different from that obtained by the condenser-compensated resonant source. Short-circuit current in the H-SCT was controlled through an induction voltage-regulator energized by the 6600 V distribution line. When the short-circuit current was gradually increased, the quenching was induced at the current of 790 A(rms). This quenching current level was nearly equal to that described in the paper, as 780 A(rms). This current is 1.6 times as high as the specified rated current. At that time, decreasing rate of the current was smaller than that with the condenser-compensated resonant source. The time-lag to interrupt the overcurrent was about 1 second. Thus, a part of the superconducting winding, one and a half turns, was burnt out in this time as we have represented in the meeting. This doesn't mean that the H-SCT was burnt out when it was connected to the rated 6600 V source.

After that, we have tried to estimate temperature rise in the wire from microscopic observation of wire cross-sections as well as from a computer simulation. We would like to report these results in a next paper soon.

In response to Messrs. S. Hörnfeldt and O. Albertsson:

1. The load loss was estimated from the electrically measured data. Produced heat produced by the load loss is removed by the oil flow driven by oil-pumps and by the air blowing induced by fans in conventional transformers. The power consumption necessary to drive these pumps or fans is usually classified as the cooling power loss. In the superconducting power apparatus, the power consumption should be weighted with the relevant cooling factor of the adopted coolant. As the result, the cooling power consumption usually reach as being extraordinary large and this is regarded as a big problem in the superconducting apparatus. However, the authors would like to point out that the large cooling power should be balanced with various excellent attributes of the superconducting power apparatus superior to the conventional ones. For example, the superconducting power transmission system could transmit much higher power in a single route without any lightning hazard. This would improve reliability of future power supply in the coming information-oriented urban society.

2. No, they haven't. In this transformer, the dielectric losses are considered to be much less than the load or no-load losses, if any, because the electric field strength is so weak at the cryostat vessel. The highest electric field is induced at the partition wall between the high- and the low-voltage windings. The space is about 55 mm and the voltage difference is about 6600 V. Thus, the electric field strength is simply estimated as 120 V/mm, that is a quite low magnitude compared with that in underground power cables.

3. In the paper, we described that the thermal loss of LHe was 6.5 W by the natural vaporization without current flowing. The evaporation loss of LHe after the quenching of the superconducting winding was measured as 30 kW in the quenching current test with the constant voltage source. However, we have not evaluated the dependence of the consumption of LHe on the current in the superconducting winding.

4. Yes, it does. For the ac operation of superconducting power apparatus, local heat produced by the mechanical microscopic vibrations of the ultra-fine filaments are considered to be one of the disturbances to induce quenching. It is important to remove such heat as much as possible. Thus, we fixed the superconducting windings rigidly in the helical slots of the winding former by epoxy resin. The associated vertical ducts are also expected to be effective to remove any heat produced by microscopic vibrations even if it would be.

5. (a) Please refer to the response to Mr. L. W. Pierce.

(b) We have not carried out such a quenching transition of the H-SCT in the drift mode. However, we would like to introduce our experience in an another model superconducting transformer, 200 V/100 V 50 kVA, which had been developed in our laboratory different from the H-SCT. In this superconducting transformer, both of the high- and the low-voltage windings were constructed by Nb-Ti superconducting wire cooled by LHe. The superconducting wire was the same as that adopted for the H-SCT. The iron-core was immersed in LHe together with the both windings. The quenching current level of the superconducting winding was measured as 660 A(rms) in the low-voltage, high-current side. In the quenching transition test in the drift mode, this superconducting transformer was energized from the low-voltage side by reduced voltage, 37 V. A resistive load was connected to the high-voltage terminal with the current, 50 A(rms). When the high-voltage terminal was short-circuited, quenching occurred in the low-voltage, high-current superconducting winding. Its initial peak value of the short-circuit current reached as high as about 1200 A(peak), which was resolved into dc component, 500 A and ac symmetrical component, 700 A(peak). However, at that time, it didn't result in the burn-out. The evaporation loss of LHe was estimated as about 8 kW after the quenching. It should be important to investigate the thermal behavior of the superconducting transformer for the actual operation in future.

Manuscript received October 1, 1990.