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The conductors of the 50 kA superconducting transformer for SSTF

S. Baang [a,*], V.E. Keilin [b], K. Kim [a], S. Kim [a], Y.J. Kim [a], I.A. Kovalev [b], S.L. Kruglov [b], H. Park [a], A.V. Rychagov [c], I.O. Shchegolev [b], M.I. Surin [b], V.E. Sytnikov [c], Q. Wang [a], C.S. Yoon [a]

[a] *Energy Laboratory, Samsung Advanced Institute of Technology (SAIT), 103-6 Moonji-dong, Yusong-gu, Taejon 305-380, South Korea*
[b] *Russian Research Center 'Kurchatov Institute', 1 Kurchatov Square, 123182 Moscow, Russian Federation*
[c] *VNIIKP, Entusiastov Road 5, Moscow 111112, Russian Federation*

Abstract

The 50 kA transformer for Samsung Superconductor Test Facility (SSTF), which will charge the Korean Superconducting Tokamak Advanced Research cable-in-conduit conductor samples for 1 s is under design. The NbTi based conductors for primary and secondary windings are described. The primary winding conductor consists of six NbTi and six stainless steel strands cabled around rectangular copper core. Such a design was previously used by Kurchatov Institute in small SMES windings. The secondary winding conductor consists of 24 subcables wrapped around and soldered to a copper strip. Each subcable consists of six NbTi strands cabled around one copper strand. NbTi strands for both primary and secondary windings are 0.85 mm in diameter. NbTi wires have 8910 6-μm filaments. Both primary and secondary winding conductors have large current and temperature margins to ensure a reliable operation of the superconducting transformer.

Keywords: Superconducting transformer; NbTi; Conductor; Samsung Superconductor Test Facility

1. Introduction

Samsung Superconductor Test Facility (SSTF) has been being built with the primary goal of testing the Korean Superconducting Tokamak Advanced Research (KSTAR) toroidal field and poloidal field magnets as well as cable-in-conduit conductor (CICC) in the most relevant manner [1]. The basic purpose of SSTF is the comprehensive testing of full-size conductors and joints for use in KSTAR magnet system. The major components of SSTF magnet system are the split coil magnet system generating magnetic fields of 8 T in 250 mm gap and the superconducting current transformer (SCT) system. The SCT is used to induce the high current up to 50 kA in the test sample. This induced current (transformer) method [2] allows avoiding the use of high-current power supplies. The design parameters of the SCT are: the maximum sample current 50 kA, the maximum secondary circuit resistance 20 nΩ, the maximum secondary winding ramp rate 50 kA/s, the minimum holding time 300 s, secondary current measurements accuracy 0.5%, and primary power

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* Corresponding author. Fax: +82-42-865-4099.
E-mail address: baang15@samsung.co.kr (S. Baang).

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supply (bipolar) maximum operating current ±500 A. In addition, the device should meet the requirements of self-quench detection and protection.

2. Superconducting transformer

The SCT system (Fig. 1(a)) mainly consists of a high-turn primary coil, a low-turn secondary coil, power supply for the primary coil, quench protection system of the primary coil, the load (CICC sample), the secondary current measurement system (based on Hall probes), the heater H and thermometer T attached to the secondary coil. The current *I*, inductance *L* and resistance *R* of the primary coil have the subscript 'p', while those of the secondary coil have the subscript 's'. The subscript 'L' relates to the load. *M* is the mutual inductance between primary and secondary.

The equivalent circuit of SCT is shown in Fig. 1(b) and can be described by the following equations:

$$\begin{cases} L_p \dot{I}_p + M\dot{I}_s + R_p I_p = E, \\ (L_s + L_L)\dot{I}_s + R_s I_s = -M\dot{I}_p. \end{cases} \tag{1}$$

Here, *E* is the output voltage of the power supply.

Let us take the primary ramp rate as constant ($\dot{I}_p = \text{const.}$). It results in the following solution for I_s:

$$I_s(t) = -\frac{M\dot{I}_p}{R_s}(1 - e^{-t/\tau}). \tag{2}$$

Here, $\tau = (L_s + L_L)/R_s$ is the characteristic time constant of I_s decay (with the sample). For our case, the specification and estimation of the parameters of the secondary circuit results in: $L_s + L_L = 9.9\ \mu\text{H}$, $R_s \leqslant 20\ \text{n}\Omega$. It gives $\tau = 495$ s.

To keep I_s constant during the required holding time (300 s) the primary should be slowly charged with the reverse polarity. This charging rate $\dot{I}_p^*$ can be estimated from the condition of equality of active and inductive voltages in the secondary coil:

$$\dot{I}_p^* = I_s R_s / M. \tag{3}$$

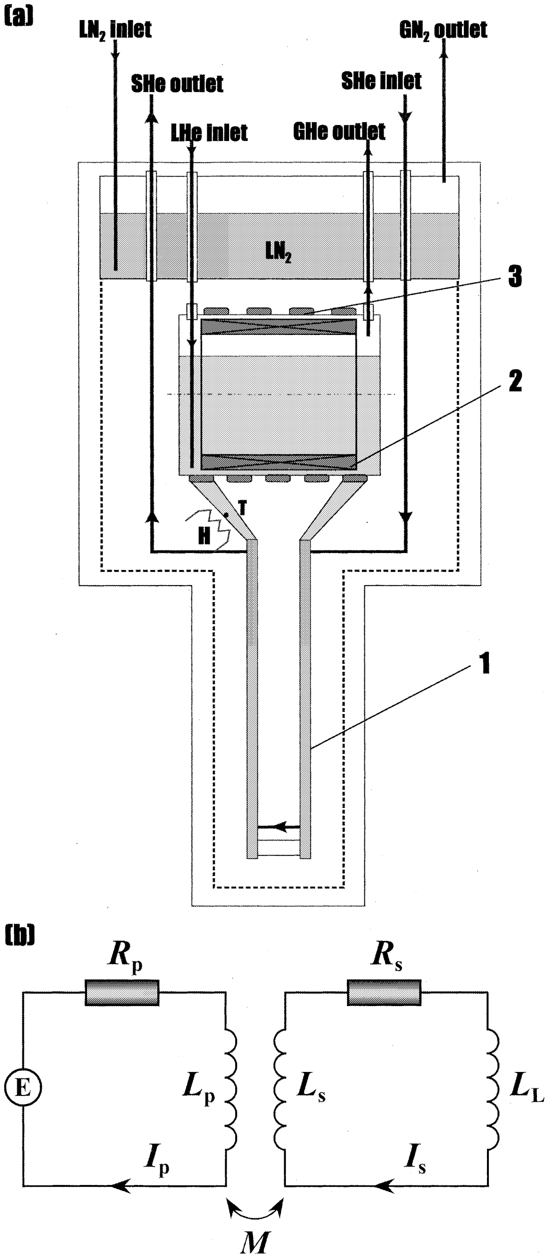

Fig. 1. (a) Schematic view of SCT and the CICC sample: 1 – the CICC sample, 2 – the primary coil, 3 – the secondary coil, H – heater, T – thermometer; L – liquid, G – gas, SC – supercritical; (b) equivalent circuit of the SCT: I_p, L_p and R_p are the current, inductance, resistance of the primary coil. I_s, L_s and R_s are those of the secondary coil. L_L is the inductance of the load. *M* is the mutual inductance between primary coil and secondary coil. *E* is the output voltage of the power supply.

Here, we get $\dot{I}_p^* = 0.8$ A/s. For 300 s holding time, the primary coil must be charged from 0 to 300 $\times 0.8 = 240$ A.

Let us also estimate two other time constants which are important for SCT operation: (i) time constant of I_s decay when some portion of the secondary coil is heated by the heater to the normal state, $\tau_n = (L_s + L_n)/R_s^*$, where R_s^* is the secondary normal portion length resistance; (ii) thermal time to cool the normal portion of the secondary coil to the SC state after the heater is off, $\tau_c = cl^2/\lambda$, where c and λ are the volumetric heat capacity and longitudinal heat conductivity of the secondary conductor, respectively. If the normal portion length from design consideration is taken as 0.63 m, the resistance R_s^* is equal to $\sim 2.5\times 10^{-6}$ Ω and hence $\tau_n = 4$ s. The estimation of cooling time gives $\tau_c \leqslant 20$ s.

3. Conductors

The primary coil conductor should withstand approximately 2 T/s rate field variation without going to normal state. The conductor used in the 0.5 MJ model coils was chosen as a prototype for the primary coil [3]. The conductor cross-section is shown in Fig. 2(a). It includes six NbTi strands. The strand properties are given in the Table 1. Six SC strands and six stainless steel strands of the same (0.85 mm) diameter are cabled around the rounded copper core. To decrease eddy current losses the core is made of low RRR copper (RRR ≈ 20). Cabling pitch is 70 mm. The dual role of the stainless steel strands is to reinforce the conductor and to decouple the SC strands in order to decrease coupling losses. As shown in Ref. [3], the coupling losses in such conductors at approximately 2 T/s

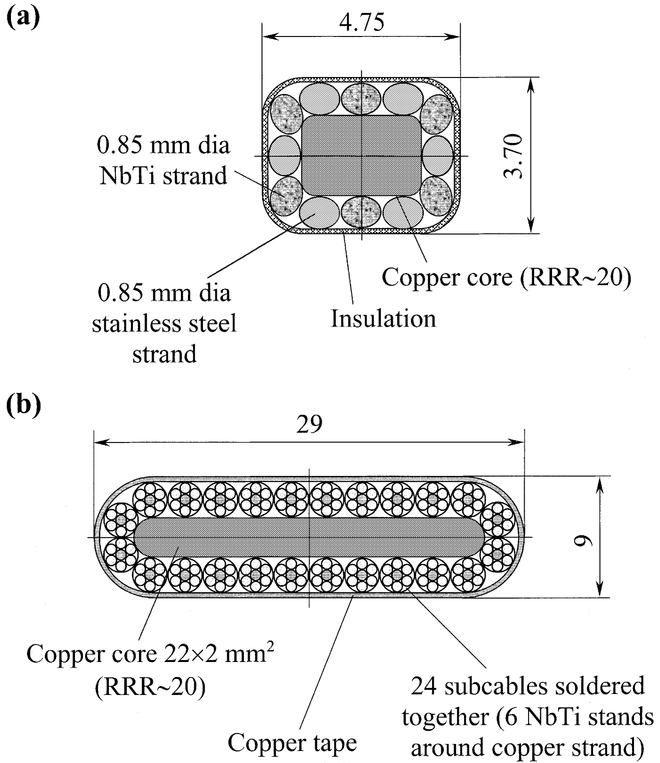

Fig. 2. SCT conductors: (a) the primary coil conductor; (b) the secondary coil conductor (all dimensions are in mm).

Table 1
Main parameters of NbTi strand

Parameter	Units	Value
Diameter	mm	0.85
Cu:Sc ratio		1.38:1
Filament size	μm	5.8
Longitudinal resistivity at 5 T	Ω m	2×10^{-10}
Effective transverse resistivity	Ω m	3×10^{-10}
Critical current density at 5 T	A/m^2	$>2.3\times10^9$

ramp rate are essentially equal to those in separate strands, i.e. the interstrand coupling losses are negligibly small.

The conductor design for the secondary coil takes into account the necessity of large (at least three times) current margin as well as manufacturer (Russian Cable Institute) capabilities. The secondary coil conductor cross-section is shown in Fig. 2(b). The initial NbTi strands are the same as those for the primary coil conductor. First, six NbTi strands are cabled around the central copper wire. Cabling pitch is 40 mm. Then, 24 such subcables are cabled around the central copper strip. To decrease eddy currents, the copper strip has low (∼20) RRR. Cabling pitch is 200 mm. The cable is wrapped with copper tape and soldered by high resistivity soft solder. The electrical insulation is 0.6 mm thick, properly overlapped preimpregnated glass-fiber tape.

4. Transformer design description

The secondary coil and the CICC sample are placed in the vacuum space. Its upper part has copper thermal shield (see Fig. 1) attached to LN$_2$ cylindrical vessel made of stainless steel. The primary coil is placed in a cylindrical stainless steel container with horizontal axis (OD of the container is 580 mm, its length is 630 mm). The primary coil is essentially a pool-boiling layer wound solenoid. The spacers between the primary coil turns will allow for proper cooling of the winding by LHe, which is especially important in the fast charging/discharging modes of operation. To allow a stable operation of secondary coil not fully covered with LHe, the conductor has very large (approximately 5) current margin.

Table 2
Main parameters of the primary and the secondary coils

Parameter	Value
Primary coil	
Inner diameter	445 mm
Outer diameter	525 mm
Height	547 mm
Number of layers	10
Number of turns	1180
Inductance	0.4 H
Maximum field at 500 A	1.1 T
Secondary coil	
Inner diameter	576 mm
Outer diameter	600 mm
Number of turns	4
Inductance	6.77 μH
primary–secondary mutual inductance (coupling coefficient $k = 0.8$)	1.29 mH

The secondary consists of four turns of a large (29 × 9 mm^2) conductor and is placed onto the outer surface of LHe container. Main parameters of the primary and the secondary coils are given in Table 2.

The transformation ratio I_s/I_p can be written as [4]:

$$\frac{I_s}{I_p} = \frac{M}{L_s + L_L}. \tag{4}$$

Then, we have $I_s/I_p = 130.4$. To induce the current of 50 kA in the CICC sample, it is enough to charge the primary coil with less than 400 A. The I_s value will be measured by the calibrated Hall probes placed near the heated portions of the secondary coil conductor.

AC losses, heating and temperature margin of the secondary coil conductor at the most dangerous scenario (charging from 0 to 50 kA in 1 s) have been calculated. The total AC loss value for the total length of secondary winding conductor is 21.1 J.

The estimation of influence of helium level on a temperature margin of the secondary coil conductor has shown that, even in the case of half-filled container, the increase of temperature will not exceed 0.7 K.

The thermal calculations for the secondary coil conductor during its charging as well as for the primary coil in the main operating stages have revealed that the temperature margin is not less than 1.5 K for the secondary coil, while the primary coil heating is no more than 0.3 K.

5. Conclusions

The design and configuration of the superconducting transformer generating currents up to 50 kA for SSTF have been presented. The windings of the transformer are made of NbTi based conductors. Their design is chosen on the basis of small SMES development experience and also from experience of Russian Cable Institute in high-current conductor fabrication. The thermal analysis of the transformer windings shows that the conductors have a sufficient temperature margin and are capable to ensure stable operation of the superconducting transformer.

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