# The Superconducting Transformer of the Samsung Superconductor Test Facility (SSTF)

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*Abstract*— **In the frames of designing the SSTF (Samsung Superconductor Test Facility) for the KSTAR (Korea Superconducting Tokamak Advanced Research), the 50 kA transformer charging a CICC (cable-in-conduit conductor) short sample for one second is now under design. The primary winding conductor consists of six NbTi and six stainless steel strands cabled around a low RRR rectangular copper core, which was used by Kurchatov Institute in small SMES (superconducting magnetic energy storage) windings. The secondary winding consists of 24 subcables wrapped around and soldered to a low RRR copper strip. Each subcable consists of six NbTi strands cabled around a copper strand. The strands for primary and secondary windings are 0.85 mm diameter NbTi wires with six micrometer 8910 filaments. Both primary and secondary conductors have large current and temperature margins to ensure a reliable operation of the superconducting transformer. The primary coil is placed in a cylindrical LHe vessel. The four secondary turns are glued to the outer surface of the LHe vessel. The joints between the transformer and the sample are described.**

*Index Terms*—**Duty Cycle, KSTAR, SSTF, Superconducting Transformer.**

## I. Introduction

THE superconducting transformer (ST) which will be installed at the SSTF (Samsung Superconductor Test Facility) [1] for the test of CICC (cable-in-conduit conductors) of the KSTAR (Korea Superconducting Tokamak Advanced Research) Project [2] is now under design by SAIT (Samsung Advanced Institute of Technology) and Kurchatov Institute. ST's can be found in [3]-[5] applied for the similar purpose.

The main requirements of ST are as follows:

| | |
|---|---|
| -Max current in the sample | 50 kA |
| -Max resistance of the secondary circuits (including all joints) | 20 nΩ |
| -Max ramp rate in the secondary coil | 50 kA/s |
| -Min holding time | 300 s |
| -Self quench detection and protection | |
| -Secondary current measurements accuracy | ± 0.5 % |
| -Primary power supply | bipolar |
| -Max operating current | ± 500 A |

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## II. ST Analysis

The electrical circuit of ST is schematically shown in Fig. 1. It consists mainly of the primary and the secondary windings (PW and SW, respectively), the power supply for PW, the load (short sample of CICC), the secondary current measurement system (based on Hall probes), and the heater and the thermometer, attached to SW. The current *I*, the inductance *L* and the resistance *R* of PW have the subscript 'p', while those of SW have the subscript 's'. The subscript 'L' relates to the load. *M* is the mutual inductance between PW and SW.

The circuit can be described by the following equations.

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

where, $E$ is the output voltage of the power supply.

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

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

$$\tau = (L_s + L_L)/R_s \tag{3}$$

where, $\tau$ 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 result in

$$\begin{aligned} L_s + L_L &= 9.9\ \mu\text{H} \\ R_s &\le 20\ \text{n}\Omega . \end{aligned} \tag{4}$$

It gives $\tau$ = 495 s. The charging/discharging time of PW, $t_p$, is less than 50 s. Therefore, $t_p / \tau << 1$ and (2) can be simplified to

$$I_s(t) = -\frac{M \dot{I}_p}{R_s} \cdot \frac{t}{\tau}. \tag{2a}$$

As SW will be charged during the PW discharge ( $\dot{I}_p < 0$ ) we get

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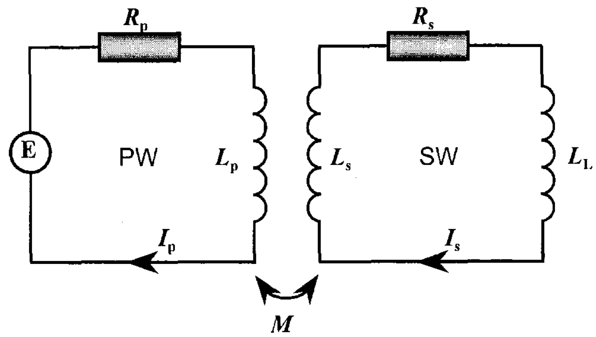


Fig. 1. Schematic circuit of superconducting transformer.

$$I_s = \frac{M}{L_s + L_L} I_p \,. \tag{5}$$

The geometry of PW and SW (it will be described later), as well as the dimensions of the sample result in $L_s = 6.77$ μH, $L_L = 3.12$ μH, $M = 1.29$ mH.

Therefore, to charge SW from 0 to 50 kA it is necessary to discharge PW from

$$I_p = 50\times10^3 \text{ A}\cdot\frac{(3.12+6.77)\times10^{-6}\text{ H}}{1.29\times10^{-3}\text{ H}} = 383 \text{ A to } 0 \text{ A}.$$

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

$$\dot{I}_p^* = \; I_s R_s / M \,. \tag{6}$$

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

## III. ST Duty Cycle

The typical duty cycle is shown in Fig. 2. It consists of the following stages (designated in Fig. 2 as the numbers in rectangles).

### *A. 1st Stage (0 →28 s)*

PW is charged from 0 to 383 A. The maximum charging rate depends on the power supply output voltage $V_p$ and of the inductance $L_p$ of PW. In the case $V_p = 6$ V and $L_p = 0.4$ H, the charging rate is ≈ 14 A/s.

During this stage, the portion of SW is kept normal (say at 20 K) by the heater(s) thermally attached to SW conductor.

### *B. 2nd Stage (28 s → 50 s)*

The negative current induced in SW decays to practically zero at its normalized portion(s). Typical time constant $\tau_n$ is 4 s.

### *C. 3rd Stage (50 s → 100 s)*

The heater is OFF and the normalized portions of SW are

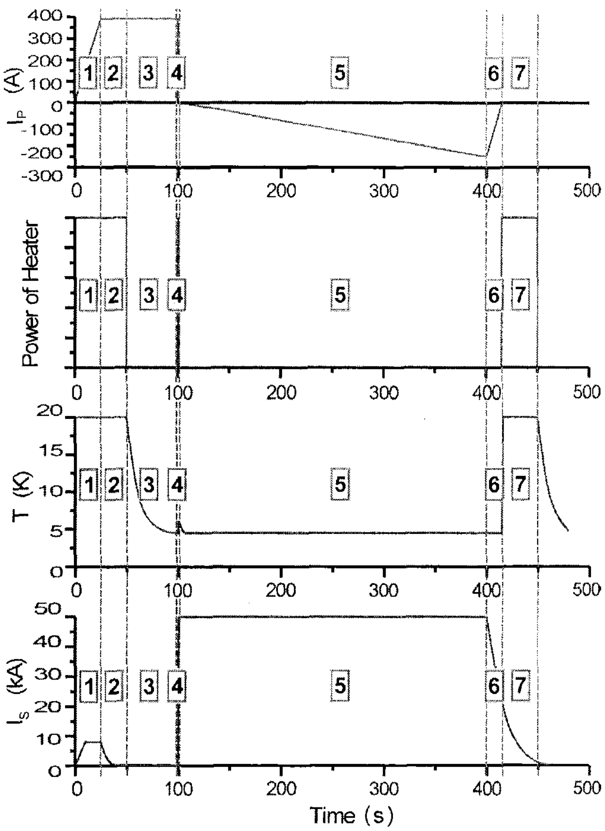


Fig. 2. Typical superconducting transformer duty cycle. Numbers in rectangle denote the operation stages.

cooled to the operating temperature. Typical time constant $\tau_c$ = 20 s. The process is monitored by the thermometer(s).

### *D. 4th Stage (100 s → 101 s)*

PW is discharged from $I_p = 383$ A to approximately 0 A. This discharge induces $I_s = 50$ kA in SW.

### *E. 5th Stage (101 s → 401 s)*

The secondary current is kept constant by charging PW with reverse current at the ramp rate $\dot{I}_p = 0.8$ A/s during 300 s. The process is controlled by the current meter and a proper feedback system.

### *F. 6th Stage (401 s → 417 s)*

Discharging PW from -240 A to 0 A with 15 A/s ramp rate. The value of $I_s$ decreases from 50 kA to 20 kA in this process.

### *G. 7th Stage (417 s → 450 s)*

The heater is ON and the residual $I_s$ decays at the normal portions of SW.

## IV. Conductors

### *A. PW Conductor*

The PW conductor should withstand approximately 2 T/s

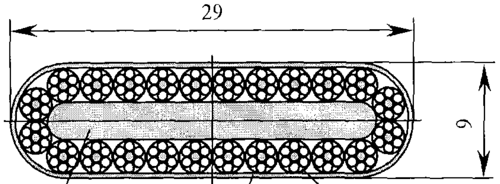


Fig. 3. The secondary winding conductor cross-section (unit: mm).

ramp rate without going normal state. The conductor used in the 0.5 MJ model coils was chosen as a prototype for PW [5]. It consists of six superconducting and six stainless steel strands of the same (0.85 mm) diameter cabled around the round copper core. To decrease eddy current losses, the core is made of low RRR copper (RRR ≈ 20). Cabling pitch is 70 mm. Then, the cable is formed to a rectangular cross-section 4.10 mm × 3.20 mm by a turks-head machine and is wrapped by the double-overlapping pre-impregnated glass-fiber tape as an electrical insulation. The final dimension of the conductor is 4.75 mm × 3.70 mm.

The dual role of the stainless steel strands is to reinforce the conductor and to decouple the superconducting strands decreasing the coupling losses. As shown in [6], the coupling losses in such conductors at approximately 2 T/s ramp rate are essentially equal to those in separate strands, i.e. the interstrand coupling losses are negligibly small.

### B. SW Conductor

The conductor design for SW takes into account the necessity of large (at least 3 times) current margin, as well as manufacturer (Russian Cable Institute) capabilities. The SW conductor cross-section is shown in Fig. 3.

The initial NbTi strands are the same as those for the PW conductor. First, six NbTi strands are cabled around the central copper wire. Cabling pitch is 25 mm. Second, 24 such subcables are cabled around the central copper strip. To decrease eddy currents the strip has low (~20) RRR. Cabling pitch is 200 mm. Then, the cable is enclosed by the braid made of copper wires and soldered by high resistivity soft-solder. The electrical insulation is 0.6 mm thick, made by wrapping the conductor with a preimpregnated glass-fiber.

## V. ST Windings

PW is essentially a pool-boiling layer wound solenoid. It has inner diameter = 440 mm, outer diameter = 520 mm, height = 550 mm, and self inductance = 0.4 H. The spacers between the layers will allow for proper cooling by LHe, which is especially important in the fast charging/discharging modes of operation. To allow a stable operation of SW when LHe level is not high enough, the conductor has very large current margin.

TABLE I
Main Parameters of the Secondary Winding

| Parameter | Units | Value |
|---|---|---|
| Inner Diameter | mm | 576 |
| Outer Diameter | mm | 600 |
| Number of turns | | 4 |
| Inductance | μH | 6.77 |
| PW-SW mutual inductance (coupling coefficient $k = 0.8$) | mH | 1.29 |
| Inductance of the short sample load | μH | 3.12 |

The parameters of SW are given in Table I. The transformation ratio $I_s/I_p$ can be calculated as in [3].

$$\frac{I_s}{I_p} = \frac{M_{ps}}{L_s(1 + L_L / L_s)} ,$$

where $M_{ps}$ is the PW-SW mutual inductance.

The four turns of SW are tightly wound and mechanically fixed onto the surface of LHe cylindrical vessel that contains PW. The thermal contact will be assured by gluing the conductor to the outer surface of LHe container.

ST and the short sample are placed in the vacuum space. Its upper part has copper thermal shield (see Fig. 4) attached to LN2 cylindrical vessel made of stainless steel. PW is placed in a cylindrical stainless steel container with horizontal axis. The LHe container is suspended by a central stainless steel 100 mm diameter neck tube and 4 fiberglass supporters.

The preliminary cross-sectional design of the joints between the ends of SW and those of CICC is schematically shown in Fig. 5. The bundles of subcables from the both ends of SW are placed in the grooves of two 30 mm thick plates which surround the cold finger of the LHe container. The use of the cold finger is to cool the joints between the ends of SW and the short sample. The heaters and the thermometers are attached near the ends of SW, which are not directly attached to the LHe container, to control the duty cycle of ST, as described in section III. The characteristic recovery time constant from normal-to-superconducting state does not exceed 20 s. Each of the subcables is soft-soldered into the grooves at the internal ellipsoidal surfaces of two copper blocks. The copper terminations of the short sample are tightly pressed to the outer surfaces of these blocks. The contact surfaces are thoroughly cleaned. The indium interface foils will be also considered. To cool the joints the copper blocks are tightly pressed by screws to the electrically insulated surface of the cold finger.

The design allows placing either the joint between the two legs of short sample or the short sample itself in the central background field. For this purpose both windings and the short sample can be moved vertically (see Fig. 4) with 400 mm stroke inside the vacuum vessel without breaking the insulating vacuum. The movement is realized by hand rotation of 6 wheels, connected with a bicycle chain. The rotation is transferred into vertical movement through 6 vertical screws.

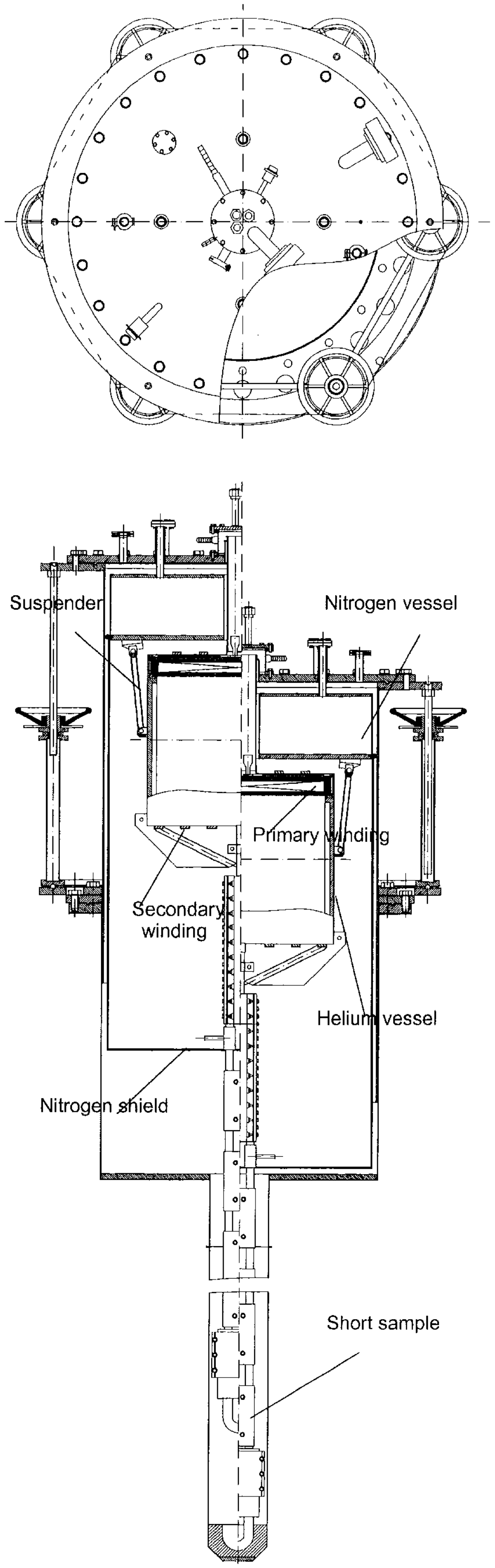


Fig. 4. Superconducting Transformer design; top view and side view. Note that left half drawing shows the upper boundary state of superconducting transformer.

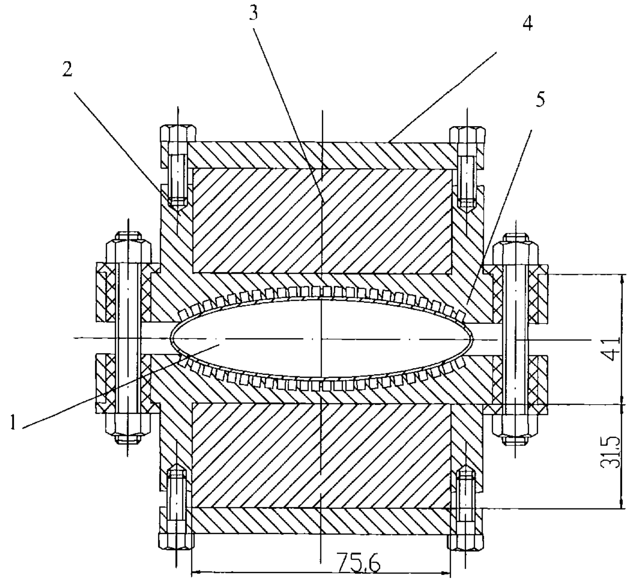


Fig. 5. Design of the joints between the SW-SS ends: 1 – cold finger of the LHe container, 2 – copper mandrel, 3 – copper SS termination, 4 – strengthening plate, 5 – subcable (6 strands) of SW conductor.

## VI. Conclusion

The superconducting transformer generating currents up to 50 kA for SSTF has been described. The conductor is being manufacturing at the Russian Cable Institute.

## References


[1] S. Baang, S.H. Baek, H.J. Choi, E.J. Chung, Y.B.Chang et al., "The test facility for the KSTAR superconducting magnets at SAIT," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp 645-648, 2000.

[2] B.A. Smith, J.R. Hale, A. Zhukovsky, P.C. Michael, J.V. Minervini et al., PTF, "A new facility for pulse field testing of large scale superconducting cables and joints," *IEEE Trans. Appl. Supercond.*, Vol. 7, pp. 1049-1052, 1997.

[3] KSTAR Magnet System Review, Aug. 25-27, 1999.

[4] G. Pasztor, A. Anghel, B. Blau, A.M. Fuchs, B. Jakob, C. Marinucci, "Design, fabrication and testing of a 100 kA superconducting transformer for the SULTAN test facility," *Proc. 15th Int. Conf. on Magnet Technology (MT-15)*, Sci. Press, Beijing, China, eds.: Lin Liangthen, Shen Guoliao, Yan Luguang, Part two, pp. 839-842, 1998.

[5] A. Ddudarev, V. Keilin, S. Kruglov, A. Nikolaev, V. Shcherbakov, S. Pradhan, Y.C. Saxena, "Testing of a low-resistance joint of CICC for Indian tokamak SST-1," *IEEE Trans. Appl. Supercond.*, Vol. 10, pp. 1114-1117, 2000.

[6] V.P. Agalakov, O.P. Anashkin, N.N. Britousov, A.V. Dudarev, V.E. Keilin, A.V. Krivich, A.S. Kulikov, V.V. Lysenko, S.V. Miklyaev, S.A. Shevchenko, M.I. Surin, "Development and test results of a double 0.5 MJ coil SMES system," *IEEE Trans. Magn.*, Vol. 32, No. 4, pp. 2312-2315, 1996.