§2. Design Study of 100 kA Superconducting Current Transformer and Conductor Production

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Fusion magnets need 100 kA class conductors to suppress the highest voltage at quick discharge for quench protection. A superconducting current transformer is useful for the measurement of critical currents and for load cycles by electromagnetic force. Therefore, a 100 kA transformer is designed, and the secondary conductor is manufactured.

The design criteria are as follows: (1) A bipolar power supply of ±200 A is adopted for the primary coil. (2) The inductance of the primary coil is 2.5 H to maintain 100 kA for longer than 600 s in the case of resistance of secondary circuit of 10 nΩ. (3) A quench heater is installed in the secondary coil to diminish the secondary current that is the sample current. (4) The coils are immersed in liquid helium except for the terminal of the secondary coil.

The equivalent circuit of the transformer is shown in Fig. 1, and the basic equations are given by

$$E = R_1 I_1 + L_1\, dI_1/dt + M\, dI_2/dt$$
$$0 = R_2 I_2 + (L_2 + L_3)\, dI_2/dt + M\, dI_1/dt$$

where R, I, L, M, E are the resistance, current, self-inductance, mutual inductance, and voltage of the power supply, respectively. The suffix number of 1, 2, and 3 means the primary coil, secondary coil, and sample. In the case of constant E, the currents are given by

$$I_1 = \frac{E}{R_1}\left(1 - e^{-pt}\left(\cosh(qt) - \frac{(p^2 - q^2)(L_2 + L_3) - pR_2}{qR_2}\sinh(qt)\right)\right)$$
$$I_2 = -\frac{(p^2 - q^2)ME}{qR_1R_2}e^{-pt}\sinh(qt)$$
$$p = \frac{R_1(L_2 + L_3) + R_2L_1}{2(L_1(L_2 + L_3) - M^2)}$$
$$q = \frac{\sqrt{(R_1(L_2 + L_3) - R_2L_1)^2 + 4R_1R_2M^2}}{2(L_1(L_2 + L_3) - M^2)}.$$

In the case of holding the secondary current after reaching to b at t_0

$$I_1 = I_1(t_0) - R_2 b(t - t_0)/M$$
$$E = R_1 I_1 - L_1 R_2 b/M.$$

The design parameters of the 100 kA transformer is listed in Table 1. Calculated results using these equations for E=10 V are shown in Fig. 2. In the case that the resistance of the secondary circuit is 10 nΩ, I_2 reaches 100 kA at 19.5 s, and the current can be kept for 630 s.

In order to enlarge the current holding time, the mutual inductance must be large. Therefore, high current densities and thin coils are preferred. The photograph of the manufactured secondary coil is shown in Fig. 3. The final stage of twisting is similar to that of a Rutherford cable.

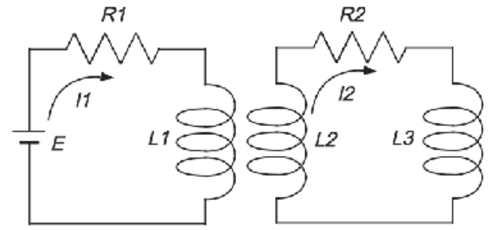

Fig. 1. Equivalent circuit of a current transformer.

Table 1. Specifications of the current transformer

	Primary	Secondary
Winding inner diameter (m)	0.364	0.34
Winding outer diameter (m)	0.3996	0.3624
Winding length (m)	0.1524	0.1288
NbTi conductor		
Filament diameter (mm)	0.078	0.010
Number of Filaments	42	1773
Strand diameter (mm)	-	0.811
Strand number	1	3×3×6×10
Twisting pitch (mm)	-	45, 85, 124, 330
Height x width (mm)	0.85×1.23	13×38
Cu/SC ratio (-)	3.5	2.7
Maximum field, B_{max} (T)	2.64	2.6
Operating temperature, T_{op} (K)	4.4	5
Critical current at B_{max} (kA)	0.60	240
Number of turns × layers	120×20	4×1
Operating current (kA)	±0.20	100
Stored energy (kJ)	49.7	33.5
Self inductance (H)	2.486	6.69E-06
Mutual inductance (H)	0.0035 (k=0.86)	
Weight (kg)	22.1	11.7

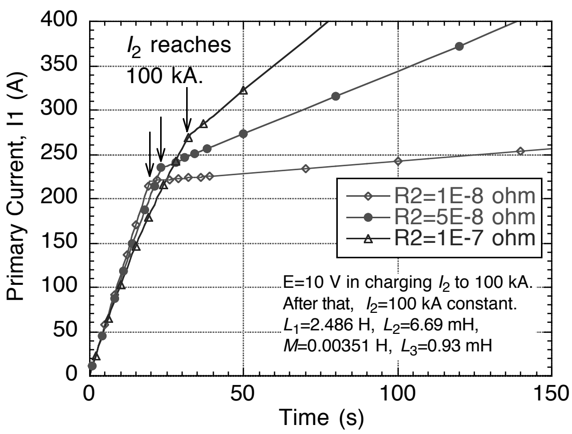

Fig. 2. Calculated primary currents to charge the secondary current to 100 kA with 10 V and to keep the current.

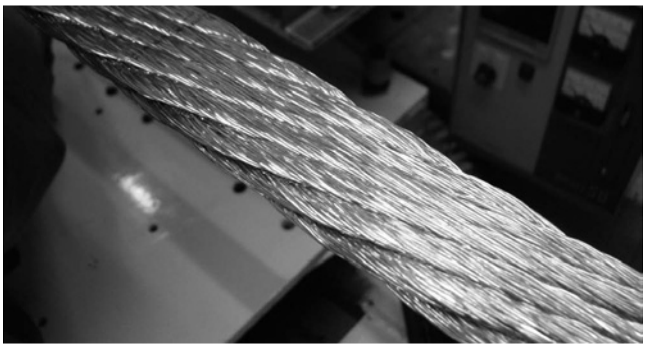

Fig. 3. The manufactured NbTi/Cu multi-stage twisted cable for the secondary coil.