Development of a superconducting transformer for high current conductor testing

H J Ma1,2, H J Liu1*, Y Shi1, F Liu1, H Chen1,2, X T Zhang1,2 and L Lei1

1 Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
2 University of Science and Technology of China, Hefei 230026, China

*Email: liuhj@ipp.ac.cn

Abstract. Critical current (Ic) tests on superconducting conductors require currents on the order of tens of kilo-amperes in combination with sub-microvolt resolution voltage measurements. Instead of traditional expensive DC power supply and complicated current leads, a superconducting transformer has been developed to feed the test sample with current up to 30 kA. The transformer consists of two concentric layer-wound superconducting solenoids with the primary coil inside the secondary. In order to reduce the influence by stray field of background magnet and transformer, a hall array with two hall sensors symmetrically distributed around the secondary conductor is used to achieve accurate secondary current measurement. This paper describes the design and manufacturing of transformer, including accurate secondary current measurement method. The first test results are also presented. The superconducting transformer system enables fast, high resolution, economic and safe tests of high current conductors.

1. Introduction

High-current superconducting conductors are widely used in fusion magnets and high energy accelerators [1], [2], [3]. Currents on the order of tens of kilo-amperes are required for their performance evaluation. There are a handful of test facilities for high-current superconducting conductors all over the world. The JOSEFA test facility installed at CEA/Cadarache and FRESCA at CERN directly use DC power supply and current lead to feed sample conductors [4], [5]. The maximum current of these two facility are 10 kA and 32 kA. The most well-known test facility for superconducting conductors is SULTAN. It uses a superconducting transformer to supply the test current up to 100 kA [6]. Compared to the DC power supply method, the superconducting transformer method has many advantages, such as higher current with lower noise, less construction and operating costs, greater security. Thus, we decided to develop a superconducting transformer for high current conductor testing.

The current of secondary loop is usually measured by Rogowski coil or Hall sensor [7]. The accuracy of Rogowski coil is affected by the zero drift of integrator. For accurate measurement, calibration at the measurement temperature is needed, because the mutual inductance of Rogowski coil changes with temperature [8]. The magnetic sensitivity of Hall sensor (HGCT-3020) changes slightly with temperature. This allows to calibrate at liquid nitrogen or even at room temperature. But the accuracy of Hall sensor is easily affected by the stray field of background magnet and transformer.

In order to achieve accurate secondary current measurement, we developed a new method. We use a hall array with two hall sensors symmetrically distributed around the secondary conductor with
opposite mounting direction. This paper describes the design and manufacturing of transformer, including accurate secondary current measurement method. The first test results are also presented.

2. Transformer design

We already have a dipole magnet with a useful bore of 80 mm which can be used to supply test sample with a maximum transverse background field of about 6 T. Due to the limitation of magnet aperture, we decided to develop a test facility for small-size and middle-size conductors testing. Considering the possible performance of these conductors, a suitable target current for the transformer is therefore on the order of 30 kA. The main requirements of the superconducting transformer are as following:

- Max operating current of primary coil is 150 A
- Max secondary current is 30 kA
- Max resistance of secondary loop is 10 nΩ
- Secondary current measurement accuracy is better than 0.5%

2.1. Optimization of electromagnetic parameters

A superconducting transformer consists of two inductively coupled superconducting coils, a high-turn primary and a low-turn secondary circuit. By energizing the primary coil, a current of tens of kiloamperes will be induced in the secondary circuit. The ideal current amplification factor $\alpha_0$ (resistance of secondary loop equals to 0) can be calculated by equation 1. When taking the resistance into consideration, the actual current amplification factor $\alpha$ can be described by equation 2 [9].

$$\alpha_0 = K \cdot \frac{L_p}{L_s} \left(1 + \frac{L_L}{L_s} \right)^{-1} \quad (1)$$
$$\alpha = -\frac{M}{R_s t} \left(1 - e^{-\frac{R_s t}{L_s + L_L}} \right) \quad (2)$$

Where $K = \frac{M}{\sqrt{L_p L_s}}$ is the coupling coefficient, $M$ is the mutual inductance between primary and secondary coils, $L_p$ and $L_s$ are the self-inductance of the primary and secondary, $L_L$ is the load inductance, $R_s$ is the resistance of secondary loop, t is the time.

![Figure 1. Ideal amplification factor.](image1.png)

The inductance of sample conductor is on the order of 1 $\mu$H and the coupling coefficient between primary and secondary coils is about 0.65. The relationship between ideal amplification factor and self-inductance of secondary is shown in figure 1. The maximum ideal amplification factor is obtained when the self-inductance of secondary equals to load inductance. In order to achieve the required amplification factor, the self-inductance of primary should be in the range of 0.5 to 1 H. A larger secondary inductance allows greater time constant and greater allowable secondary resistance.

![Figure 2. Actual amplification factor.](image2.png)
However, the larger the primary inductance, the stronger the magnetic field. Thus taking these two points into consideration, the primary inductance is decided to be 0.8 H.

The actual amplification factor with different inductance of secondary coil is shown in figure 2. In order to achieve a larger allowable secondary resistance, the inductance of secondary coil \( L_s \) should be about 4 \( \mu \)H. The total self-inductance of secondary loop should be about 5 \( \mu \)H. In this situation the allowable secondary resistance is about 16 n\( \Omega \) with the primary current varying rate of 1 A/s.

2.2. Transformer specification

The 30 kA superconducting transformer consists of two concentric layer-wound superconducting solenoids with the primary coil inside the secondary coil. Due to the different magnitudes of operating current, the primary coil was wound by single NbTi strand and the secondary coil was wound by NbTi Cable-in-Conduit conductor (CICC).

The conductor used for primary coil winding was NbTi strand with the dimension of 1.28 mm \( \times \) 0.83 mm. Table 1 lists the main characteristics of the NbTi strand. It is a multi-filamentary wire with Cu:non-Cu ratio of 4.

The secondary CICC uses 0.73 mm diameter multi-filamentary NbTi strands with Cu:non-Cu ratio of 2.34. The NbTi CICC was with a 4-stage layout (3 sc \( \times \) 4 \( \times \) 5 \( \times \) 5) with petal void fraction of 35.4%. The twist pitch of each stage were 45 mm, 85 mm, 145 mm and 250 mm, respectively. The final dimension of the conductor was 19.2 \( \times \) 19.2 mm\(^2\).

| Table 1. Specification of NbTi strand for primary coil |
|------------------------------------------------------|
| Parameter                                             | Value                        |
| Dimension of strand                                   | 1.28 mm \( \times \) 0.83 mm  |
| Cu : NbTi ratio                                       | 4:1                          |
| Diameter of filament                                  | 78 \( \mu \)m                 |
| Number of filaments                                   | 36                           |
| RRR                                                   | 200                          |
| Ic @ 4.2 K, 5 T                                       | \( \geq 465 \) A             |

The main characteristics of the 30 kA superconducting transformer are listed in table 2. The primary coil consists 2336 turns with 16 layers. The secondary coil was wound by 4 turns NbTi CICC. The self-inductance of primary coil and secondary loop are 0.8 H and 5.2 \( \mu \)H respectively. The transformer is cooled by liquid Helium and kept at 4.2 K.

| Table 2. Specification of transformer                  |
|--------------------------------------------------------|
| Items                                                  | Primary coil       | Secondary loop |
| Conductor                                              | NbTi strand        | NbTi CICC      |
| Layers                                                 | 16                | 1              |
| Turns                                                  | 2336              | 4              |
| Inner diameter of coil                                 | 204 mm            | 246 mm         |
| Outer diameter of coil                                 | 230 mm            | 286 mm         |
| Height of coil                                         | 182 mm            | 95 mm          |
| Self-inductance                                        | 0.8 H             | 5.2 \( \mu \)H |
| Mutual inductance                                      | 1.44 mH           |                 |
| Max. operating current                                 | 150 A             | 30 kA          |
| Stored energy                                          | 9000 J            | 2340 J         |
| Cooling method                                         | Pool-boiling by liquid Helium (4.2 K) |

2.3. Terminal for transformer

The conductor joint in secondary loop is a key technology in the manufacture of superconducting transformer. In order to assemble and dismantle the sample conductor easily, terminals for transformer
and sample conductor are used. The terminal for transformer is shown in figure 3. The terminal includes separate components: copper block, stainless steel plate, upper stainless steel block and end plate. Oxygen-free copper with RRR value of higher than 100 is used for copper block. The copper block, stainless steel plate and end plate are connected by vacuum brazing. The upper stainless steel block is used to reduce the void fraction in the terminal from 35.4% to about 24.7%. The upper stainless steel block and stainless steel plate are connected by Argon arc welding. The jacket at the two ends was removed and the cable is soldered to copper block with 60Sn/40Pb. The effective length of the terminal is 280 mm which is more than the last pitch of the secondary NbTi CICC.

![Figure 3. Terminal for transformer.](image)

### 3. Secondary current measurement

It is impractical to measure secondary current by current sense resistors due to the large secondary current and the resulting large losses in the system. The current of secondary loop is usually measured by Rogowski coil or Hall sensor. The accuracy of Rogowski coil is affected by the zero drift of integrator. For accurate measurement, calibration at the measurement temperature is needed, because the mutual inductance of Rogowski coil changes with temperature. The magnetic sensitivity of Hall sensor (HGCT-3020) changes slightly with temperature. This allows to calibrate at liquid nitrogen or even at room temperature. But the accuracy of Hall sensor is easily affected by the stray field of background magnet and transformer.

To overcome this problem, on one hand, we adjust the transformer to make sure that the main magnetic field direction of transformer is roughly the same as background magnetic field. On the other hand, we use Hall sensors array to reduce the influence of stray field, as shown in figure 4. Two Hall sensors are respectively installed on the left and right side of secondary conductor with opposite mounting direction.

![Figure 4. Hall sensors array.](image)

The difference of stray field at left and right Hall sensor position is very small and can be ignored. The output voltage of left and right Hall sensor can be described by the following equations.

\[
U_L = k_l I_{sec} + k_l B_{str}
\]

\[
U_R = k_R I_{sec} - k_R B_{str}
\]
Where $I_{sec}$ is current of secondary loop, $B_{str}$ the stray field, $k_1$, $k_2$ the magnetic sensitivity of Hall sensor, $k_L$, $k_R$ the ratio of output voltage to secondary current without stray field. The magnetic sensitivity of the two Hall sensors we used ($k_1$, $k_2$) were 0.937 and 0.914 mV/kG, respectively.

The actual secondary current can be calculated by the following equation.

$$I_{sec} = \frac{U_I k_2 + U_R k_1}{k_1 k_2 + k_R k_1}$$

$k_L$, $k_R$ were preliminary calibrated at room temperature by supplying a current up to 200 A through the open ends of secondary loop. $k_L$, $k_R$ were respectively 0.1358, 0.1345 mV/kA, as shown in figure 5.

![Figure 5. Hall calibration.](image)

4. Transformer performance test

A 1.2 m third-stage sub-cable of secondary CICC was prepared to test the transformer performance and to verify the process of joints manufacture. The third-stage sub-cable contains 60 NbTi strands with cable layout of $3 \times 4 \times 5$. The terminals for sample and superconducting transformer were compacted with Indium for electrical connection, as shown in figure 6. The sample was fixed together with reversed NbTi CICC by G10 fixer. The transformer and sample were soaked in liquid Helium. The resistance of upper joint, lower joint and total resistance of secondary loop were measured at 4.2 K.

![Figure 6. Sample assembly.](image)
5. Test results and discussion

5.1. Error of secondary current measurement
The impact of stray field produced by background magnet on secondary current measurement was investigated. The background magnetic field was ramped from 0 T to 5 T. Due to the small self-inductance of secondary loop, a maximum secondary current of about 5 kA was inducted. Then the secondary current was a little decreased because of resistance of secondary loop. After that the secondary current was killed by heating secondary conductor. The current reading of single Hall sensor (Hall 1 or Hall 2) and Hall sensors array (I_{sec}) are shown in figure 7. Compared to the common single Hall sensor measurement method, the error of secondary current measurement by Hall sensors array method is reduced from about 0.5% to 0.1%.

![Figure 7](image.png)

**Figure 7.** The impact of stray field on secondary current measurement.

5.2. Transformer performance and Joints resistance
The primary current was ramped to 150 A at the rate of 1 A/s. A maximum secondary current of 33.7 kA was inducted in secondary loop. An amplification ratio of 224 was measured, as shown in figure 8.

![Figure 8](image.png)

**Figure 8.** Test result of transformer.

The resistance of joints at 4.2 K were measured by two methods, V-I curve method and current exponential decay method. The secondary current was kept at about 0, 10, 14.5, 19 and 25 kA to measure the joints resistance, as shown in figure 9. The measured resistance of upper and lower joint were 1.4 and 1.6 nΩ respectively. The measured total resistance was about 3.0 nΩ. The accuracy of
voltage measurement is affected by voltmeter, inductive voltage and thermoelectric voltage. The voltage was measured by 2182A Nano-voltmeter. The error of 2182A is ± 0.1 μV. The error of voltage measurement caused by inductive voltage due to slight change of secondary current is estimated to be ± 0.1 μV. The error caused by thermoelectric voltage is very small, because pure copper conductor was used and voltage taps were at same temperature. The resistance of joint can be calculated by equation $R = (U_I - U_0)/I$. Where $I$ is the flat current, $U_I$ is the voltage at flat current, $U_0$ is the voltage at 0 A. The uncertainty of resistance measurement can be estimated by equation.

$$\frac{\Delta R}{R} = \left( \frac{|\Delta U_I| + |\Delta U_0| + |\Delta I|}{U_I - U_0} \right)$$

(6)

Where $\Delta R$, $\Delta U_I$, $\Delta U_0$, $\Delta I$ are the absolute error of resistance, $U_I$, $U_0$ and current, respectively. Thus the uncertainty of resistance measurement is estimated to be about 2%.

Figure 10 shows the exponential decay curve of secondary current. From this curve, the current time constant was calculated to be 1881.5 s. The total resistance of secondary loop was deduced to be 2.8 nΩ. This is consistent with the results obtained by V-I curve method. This slight difference is mainly caused by the calculation error of secondary self-inductance.

![Figure 9. V-I curve method.](image1)

![Figure 10. Current exponential decay method.](image2)

6. Conclusions

In order to carry out experimental research on new high-current conductors, we decided to develop a new test facility for high-current conductor. We have developed a 30 kA superconducting transformer to feed the sample conductor. It consists of two concentric layer-wound superconducting solenoids with the primary coil inside the secondary coil. A maximum secondary current of 33.7 kA with current amplification ratio of 224 was measured in secondary loop. The current time constant was 1881.5 s. The total resistance of secondary loop was about 3 nΩ.

In order to achieve accurate secondary current measurement, we use a hall array with two hall sensors symmetrically distributed around the secondary conductor with opposite mounting direction. Compared to the common single Hall sensor measurement method, the error of secondary current measurement by Hall sensors array method is reduced from about 0.5% to 0.1%.

Acknowledgments

This work was supported by National Magnetic Confinement Fusion Science Program under Grant 2014GB105004 and National Key R&D Program of China under Grant 2017YFE0301405. The authors would like to thank Keye Electro Physical Equipment Manufacturing Co., Ltd. for parts manufacturing.

References

[1] Devred A et al. 2012 IEEE Trans. Appl. Supercond. 22 4804909
[2] Barzi E et al. 2013 *IEEE Trans. Appl. Supercond.* **23** 6001112
[3] D C van der Laan, Goodrich L F and Haugan T J 2011 *Supercond. Sci. and Tech.* **25** 014003
[4] Decool P et al. 2004 *IEEE Trans. Appl. Supercond.* **14** 1473-6
[5] Ambrosio G et al. 2005 *IEEE Trans. Appl. Supercond.* **15** 1545-9
[6] Bruzzone P, Anghel A, Fuchs A, Pasztor G, Stepanov B, Vogel M and Vecsey G 2002 *IEEE Trans. Appl. Supercond.* **12** 520-3
[7] Petter J, McCarthy J, Pollak P and Smith C C 1991 *IEEE Nuclear Science Symposium and Medical Imaging Conf.* 961-7
[8] Hewson C R and Ray W F 2010 *Proc. 25th Annu. IEEE Appl. Power Electron. Conf. Expo.* 2050–6
[9] Pasztor G, Anghel A, Blau B, Fuchs A M, Jakob B and Marinucci C 1998 *Proc. 15th International Conference on Magnet Technology* 839-42