Superconducting Transformer and Regulation Circuit for the CERN cable test facility

A P Verweij, C-H Denarie, S Geminian and O Vincent-Viry
CERN AT department, 1211 Geneva, Switzerland

Abstract. Since 1999 a cable test facility at CERN is operational, and each week several 2.5 m long cable samples are tested at 1.9 and 4.3 K and up to 10 T. The current in the samples is supplied by an external 32 kA power supply through a pair of self-cooled copper current leads. In recent years CERN has developed in parallel a 40 kA superconducting transformer, in order to increase the sample current while at the same time reducing the helium consumption. The primary of the transformer, consisting of a 9000 turns solenoidal coil, is wound from a 0.5 mm superconducting wire carrying up to 50 A. The secondary, consisting of 7 turns of LHC cable, is wound directly on top of the primary in order to have a high coupling. The secondary current is measured by integration of the voltage of two Rogowski coils placed around the secondary. Calibration against the 32 kA external power supply has shown that the current in the secondary is known to within 0.5%. With a dedicated feedback and regulation circuit, any type of current ramp or cycle can be performed. This paper describes the transformer, the current measuring unit, and the current regulation system. Furthermore, results are presented of the first year of operation in the Cable Test Facility.

1. Introduction

The FRESCA test station is the CERN facility for the electrical characterisation of superconducting Rutherford cables [1]. In the last 4 years it has been continuously in operation, mainly for acceptance tests of the 15.1 mm wide NbTi cables to be used for the LHC main dipoles and quadrupoles and some smaller NbTi cables for corrector magnets [2]. The test facility comprises a double cryostat geometry, where the inner and outer cryostat are independently cooled and can both be operated at 4.3 K or subcooled 1.9 K by means of two heat exchangers. The background magnet, housed in the outer cryostat, has an aperture of 88mm, and a maximum field of 10.3 T, uniform over a length of 60 cm. The sample insert holds two cable samples in bifilar geometry, connected to an external 32 kA power supply via copper current leads self-cooled by the vapour from the 4.3 K He bath. The typical consumption due to these leads is about 550 liters of liquid helium for a standard day of test.

The facility is presently being upgraded in order to test samples with currents larger than 32 kA, especially focusing on Nb3Sn cables at fields of 8-10 T. In order not to further increase the helium consumption, it has been decided to build a sample insert in which a superconducting DC transformer replaces the function of the external 32 kA current supply. In this case the large copper leads are replaced by small 100 A leads, feeding the primary of the transformer.

In section 2 the design of the transformer will be discussed, and in section 3 the measurement of the secondary current is dealt with, as well as the regulation circuit necessary to perform pre-defined current ramps. The functioning of the transformer is shown in section 4 and its accuracy is compared to critical current measurements performed with the external current supply.

1 To whom any correspondence should be addressed
2. Design of the transformer

The cold part of the transformer consists of a superconducting primary (with inductance \( L_p \)) mutually coupled to a superconducting secondary (with inductance \( L_s \)), see figure 1. The secondary is connected to the two cable samples having inductance \( L_{sam} = L_{sam1} + L_{sam2} \). The resistances between the secondary and the samples are given by \( R_s \) and \( R_{s1} \), while the interconnection between the two samples is given by \( R_{s12} \). The total resistance in the secondary circuit is given by \( R_s = R_s + R_{s1} + R_{s12} \).

\[
\begin{align*}
\frac{dI_p}{dt} &= R_p I_s + L_{tot} \frac{dI_s}{dt} \\
\frac{dI_p}{dt} &= R_p I_p - U + L_p \frac{dI_p}{dt}
\end{align*}
\]

(1)

with \( I_p \) the current in the primary, \( I_s \) the current in the secondary, \( R_p \) the resistance of the primary circuit, \( M \) the mutual inductance between the primary and secondary, \( U \) the voltage of the current supply in the primary circuit, and \( L_{tot} = L_s + L_{sam} \). For more detailed information see for example [3].

The design criteria were the following:

- Maximum current in the secondary: 50 kA for a ramp rate of 500 A/s, 30 kA for a ramp rate of 20 A/s.
- Maximum size of the transformer: 240 mm in length and 200 mm in diameter.
- Accuracy of the current measurement: better than 0.5% for a current ramp to 20 kA in 200 s.
- Voltage noise (averaged over one power cycle of 20 ms) over the samples: smaller than 2 \( \mu V \).
- Liquid helium evaporation in case of a quench: less than 2 liters.

The transformer is designed based on values for \( L_{sam} \) and \( R_s \) of 1 \( \mu H \) and 10 n\( \Omega \) respectively, both assumed to be independent of the current. The rather large value for \( R_s \) is due to the fact that the connections between the sample and the secondary are not soldered but clamped at high pressure in order to have a faster and easier sample mounting.

The primary winding of the transformer is wound from insulated NbTi wire with a diameter of 0.542 mm, a Cu/SC ratio of 1.35, a RRR of 82, and a filament diameter of 45 \( \mu m \). The primary has a solenoidal shape with a height of 160 mm and inner and outer radii of 70 and 88 mm respectively. The coil consists of 33 layers with in total 10850 turns, and has an inductance \( L_p \) of 11.75 H. The primary is impregnated with epoxy resin.

The secondary winding is wound directly over the primary, and consists of 7 turns of a 15.1 mm wide NbTi Rutherford cable, similar to the one used for the inner layer of the main dipole magnets for the LHC. All along this cable a copper strip of 1 mm thickness has been soldered (with SnAg) for mechanical and electro-dynamical stability. The insulation thickness between primary and secondary is about 1 mm thick. The secondary is fixed onto the primary by means of G10 bars and stainless steel bolts. The self inductance of the secondary is 9 \( \mu H \), while the mutual inductance between primary and secondary...
secondary is 8.77 mH. For protection purposes, voltage taps are soldered at 5 locations on the primary, at 5 locations on the secondary, and at 3 locations on the samples.

3. Measurement and regulation system

The current flowing in the secondary is measured by integration of the voltage coming from two toroidal Rogowski coils (see figure 1), placed around the two legs of the secondary. Each coil consists of 5528 turns of 0.1 mm copper wire. A perfectly wound Rogowski coil is theoretically insensitive to an external magnetic field change. However, due to winding imprecision, a small perturbation can be picked up from the fields generated by the primary and secondary. In order to minimise this effect, the two coils are connected in anti-series. Measurements have shown that the error on the current measurement due to the stray field of the transformer is less than 0.02%. The sensitivity of the Rogowski coils is calibrated using a 32 kA current supply in combination with a DCCT at room temperature, accurate to within 100 ppm. The sensitivity is 16.38 mV for a current through the aperture of the coils ramped at a rate of 100 A/s. The Rogowski voltage signal is measured by a digital integrator [4] with a maximum resolution corresponding to a secondary current of 30 A. The typical drift of the integrator corresponds to an error in the secondary current of 100 A after 20 min, so less than 0.1 A/s. This type of current measurement is a relative one, so the initial value of the current has to be known when the integration is started. Heaters are therefore mounted on the secondary (see figure 1) to warm up the cable above the critical temperature and hence set the current in the secondary circuit to 0 A. A measurement system based on Hall probes has also been considered, but would in most cases lead to a less precise and/or a less convenient operation due to offset and sensitivity variations in time.

For the application in the cable test facility, the secondary current should have a pre-defined ramp shape, and a regulation system is therefore required in order to counter-balance the resistive losses in the secondary circuit. The regulation is based on comparison of the secondary current (i.e. the voltage \( U_{sec} \) or the output of the digital integrator, after filtering and amplification) with a predefined voltage pattern \( U_{set} \) generated by a programmable voltage generator. The difference of both signals is amplified and integrated and used as steering voltage for the current supply of the primary (see figure 1).

4. Operation and calibration

The design of the transformer in combination with the Rogowski coils and regulation system fulfills all the design requirements described in section 2. The transformer has been cooled down about 10 times and many measurements have been performed to qualify the performance of the transformer under real operating conditions. Figure 2 shows a typical \( I_c-t \) relation for a programmed linear ramp at 40 A/s until the sample (being a typical LHC cable) quenches. The same figure also shows the difference between the predefined current and the measured current. The rise of the secondary current is very uniform, with deviations from a linear fit that are smaller than ±15 A, demonstrating that the feedback regulation system works correctly. Also above 16 kA, when the superconducting samples enter the resistive transition, the regulation continues to function properly. The error of ±15 A is directly linked to the resolution of the digital integrator. Of course, the real secondary current could be slightly different from the measured current due to possible drift of the integrator, and additional pick-up by the Rogowski coils. For this current ramp, the error could be maximum 50 A, namely 45 A due to drift (assuming 0.1 A/s), and 5 A due to pick-up of stray field (0.02% x 18000 A) as mentioned in section 3. Figure 3 shows a typical \( U_{c}^{-1}I \) relation measured on the same sample. The figure also shows the \( 10^{-14} \Omega \text{m} \) criterion used for the determination of \( I_c \), and the difference between the measured voltage and a best fit to the n-power relation \( U_c/|I|^{n} \). The voltage noise is very small as compared to the \( I_c \) criterion, enabling an accurate determination of the critical current \( I_c \).

The critical current of several samples has been measured in different cool-downs using the transformer as well as the external 32 kA current supply. In all cases, differences were smaller than
2% and no significant systematic error has been observed. However, when remeasuring the same sample in different cool-downs with the external 32 kA, variations of up to 2% are also observed, due to the accuracy in sample mounting, non-uniformity of the connections with the current leads, and small errors in determination of voltage, current, field and temperature. It can therefore be concluded that the accuracy of the transformer is better than the reproducibility of cable $I_c$ measurements, and the transformer can therefore be used for this type of cable testing.

As soon as a quench in the secondary is detected, the current supply in the primary circuit is programmed to ramp to 0 A with a rate limited by the maximum voltage of the current supply. Measurements have shown that the primary will not quench for currents in the secondary smaller than about 25 kA. For higher currents, the primary will quench as well, thereby dissipating some energy into the liquid helium. The exact amount of energy is difficult to measure but repetitive quenching hardly increased the boil-off of the cryostat, showing that using the transformer in operating conditions increases the total helium consumption of the test facility by a negligible amount.

For the moment the maximum current obtained is 38 kA, limited by premature quenching of the secondary due to mechanical movement. Additional reinforcement of the secondary is foreseen to enable operation at higher currents.

5. Discussion and conclusion
CERN has designed and manufactured a 50 kA superconducting transformer together with current measurement, based on integration of the voltage of a pair of Rogowski pick up coils, and regulation system. The transformer has been recently installed in the existing cable test facility FRESCA. The system is perfectly suitable for critical current measurements with a very small current ripple and voltage noise and an estimated accuracy of better than 50 A for measurement durations of up to about 500 s. The LHe consumption is reduced by about 500 liter per day by using the transformer instead of an external 32 kA current supply in combination with self-cooled copper current leads. For the moment the maximum current obtained is 38 kA, limited by premature quenching of the secondary due to mechanical movement. Additional reinforcement of the secondary is foreseen to enable operation at higher currents.

References
[1] Verweij AP 1999 et al 1.9 K test facility for the reception of the superconducting cables for the LHC IEEE Trans. Appl. Superconductivity 9-2 153-156
[2] LHC design report, Vol. I The LHC main ring CERN-2004-003
[3] Ten Kate HHJ 1984 Superconducting Rectifiers PhD thesis Univ. of Twente, The Netherlands
[4] Gailbraith P 1993 Documentation: Portable Digital Integrator CERN AT Technical note 93-50