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Design, Assembly, and Commissioning of a Cryogenic DC Current Transformer Designed for Measuring Currents of up to 80 kA

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Keywords: Cryogenic temperatures, measurement current, transformers, superconducting coils, superconducting devices

Abstract

A new cryogenic dc current transformer (Cryo-DCCT) has recently been designed and assembled at CERN. The device, whose design is based on that of a high-accuracy 600 A market solution suitable for room temperature applications, is optimized for measuring currents of up to 80 kA and for operation at 4.2 K. The CryoDCCT has been conceived with the objective of preserving the metrological performance of the original commercial device in the new extended range of operation. For reducing the effect of interfering magnetic fields arising from test conditions, it incorporates ferromagnetic and MgB₂ superconducting shields. In this paper, the design of the CryoDCCT and the results of the commissioning of the device at CERN are reported. The effectiveness of the current transducer is analysed and discussed. This new device will be used for measuring the secondary current of a 80 kA superconducting transformer feeding a sample of NbSn₃ cable at the Facility for Research on Superconducting Cables (FRESCA) at CERN.

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Abstract—A new cryogenic dc current transformer (Cryo-DCCT) has recently been designed and assembled at CERN. The device, whose design is based on that of a high-accuracy 600 A market solution suitable for room temperature applications, is optimized for measuring currents of up to 80 kA and for operation at 4.2 K. The CryoDCCT has been conceived with the objective of preserving the metrological performance of the original commercial device in the new extended range of operation. For reducing the effect of interfering magnetic fields arising from test conditions, it incorporates ferromagnetic and MgB_2 superconducting shields. In this paper, the design of the CryoDCCT and the results of the commissioning of the device at CERN are reported. The effectiveness of the current transducer is analysed and discussed. This new device will be used for measuring the secondary current of a 80 kA superconducting transformer feeding a sample of NbSn_3 cable at the Facility for Research on Superconducting Cables (FRESCA) at CERN.

Index Terms—Cryogenic temperatures, measurement current transformers, superconducting coils, superconducting devices.

I. INTRODUCTION

ASSessment of the electrical performance of superconducting cables is carried out measuring the voltage-current characteristic (V - I curve) of a cable as a function of temperature and magnetic field [1]. From an operating point of view, V - I measurements are straightforward at a given temperature. A magnet provides the desired level of background magnetic flux density while a DC power supply ramps up the current into the sample till a quench occurs. The voltage drop across the sample under test is measured through taps disposed along the cable. This procedure seems to be rather simple, but the required degree of complexity for the implementation of a test facility becomes evident considering the need for i) a dedicated cryogenic system, ii) currents of the order of tens of kA, and iii) superconducting magnets for background fields of several T (for example [2]–[5]). Moreover, high-accuracy measurements of both current and voltage are crucial for test results. When high currents are required for the measurements, supercon-

ducting transformers become an interesting alternative to high-current DC power converters [4], [6]–[10]. On the other hand, in addition to the difficulty of operating a superconducting transformer [11], a major metrological issue is the measurement of the transformer's secondary current, which is the current flowing in the cable under test. The current must be measured via contactless sensors capable of working at cryogenic temperatures [12] (interruptions of the superconducting circuit have to be avoided). Widely used current sensors are Rogowski and pick up coils [6], [7], [9], [11]. This classical solution has drawbacks such as intrinsic AC nature and limited measurement time due to the need of low drift integration (to keep accuracy of the measured current within the range of hundreds of ppm [11]). A transducer that can overcome the aforementioned drawbacks is a DC Current Transformer (DCCT). Commercial DCCT, for room temperature applications, are capable of sensing DC currents having bandwidth of the order of hundreds of kHz with accuracy better than 100 ppm.

A new insert, tailored for hosting a superconducting transformer recently inherited from the CEA laboratory, has been designed and assembled to increase the maximum testing current from 32 kA to 80 kA at the Facility For Research on Superconducting Cable (FRESCA) at CERN [2]. The superconducting transformer reached a maximum current of 80 kA [13] at the CEA test facility. At CEA, the current in the secondary of the transformer was measured using a DC current transformer (DCCT) up to 60 kA [14] and from that current on with a pickup coil [9]–[13]. This first attempt to implement a DCCT capable of operating at 4.2 K was successful, but the device was not able to cover the whole operation range of the transformer.

The development performed at CEA was based on the idea of modifying a commercial DCCT and extending its working conditions at 4.2 K to measure currents of up to 100 kA. The main implication of this approach was to keep the device's sensing element unaltered as much as possible.

In a previous paper [15], the authors reported on the design of a new cryogenic sensing element for a DCCT capable to overcome the aforementioned limitation. The proposed sensor is based on: An optimized geometrical design of the sensing element, exploitation of a magnetic alloy suitable for cryogenic applications (referred to as cryogenic permalloy), and mitigation of cores saturation through a combination of ferromagnetic and superconducting shield [16]. As proof of concept, the characterization of a demonstrator rated at 20 kA was described. The demonstrator was built to verify the suitability of the cryogenic permalloy as a material for the ferromagnetic DCCT's cores.

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Fig. 1. Architecture of the cryogenic DC current transformer.

In this paper, the final Cryogenic DCCT prototype (Cryo-DCCT), which will be installed in the new 80 kA superconducting transformer operated at the FRESKA test station is presented. Then, the metrological characterization of the new device showing the effectiveness of development up to 76 kA is illustrated. In Section II, the design principles of the Cryo-DCCT are recalled and attention is also paid to the assembly of the new sensing element. Section III details the experimental set-up used to characterize the device, while Section IV reports on the results of the test campaign on the CryoDCCT.

II. CRYOGENIC DC CURRENT TRANSFORMER

The architecture of the new CryoDCCT is shown in Fig. 1. The working principle of the device is based on the well-known zero flux compensation mechanism [18], for both AC and DC current components [18]–[20], to achieve the ideal current transformer ratio: $N_1 I_1 = -N_2 I_2$.

The unknown current (I_1) is measured through the voltage on the burden resistor ($V_{\text{burden}} = -R_{\text{burden}}(N_1 I_1)/N_2$). An instrumentation amplifier is implemented to map 100 kA current into a 10 V signal for a precision burden resistor of 50 mΩ.

In the design of the new CryoDCCT, the conditioning electronics from a commercial 600 A DC current transformer (MACC+ [21]) is reused. This required the implementation of a new power amplifier and a new sensing element with optimized design for a rated current of 100 kA at 4.2 K.

A. Conditioner Electronic

The MACC+ is a commercial DC current transformer capable of measuring currents of up to 600 A with accuracy of 10 ppm. This transducer accuracy is obtained combining an optimized sensing element and conditioning electronics. We decided to use the available electronics to minimize the development of new circuitry. Fig. 1 highlights the MACC+ electronic components on which the CryoDCCT is based, that is, the AC and DC compensation. However, a minor adjustment of the DC compensation part was required to operate the CryoDCCT properly. In particular, the excitation current of Cores 2.1 and 2.2 is increased by a factor two to achieve the required level of core saturation.

The abovementioned choice allowed then to focus on the optimized design of components, such as the Power Amplifier and the Sensing Element, to implement a new device with extended range of operation.

B. New Power Amplifier

A DCCT can be seen as an ideal current transformer, where the secondary current I_2 has to be supplied by a power amplifier. The MACC+ power amplifier can generate maximum 1 A, that means a coil of 80 000 turns would be required for 80 kA. Hence, the implementation and performance of such a device would be critical [15]–[22]. Consequently, a new power stage is required. The developed power amplifier for the CryoDCCT is rated at 10 A. The design is aimed at preserving the performance of MACC+ through a similar classical bipolar amplifier. Two complementary Darlington transistors (2N6827, 2N6824) are biased through resistances of 42.2 Ω and 487 Ω. A limiting resistor of 0.8 Ω provides the operation in the safe-active region. Moreover, a buffer circuit (OP27, BUF634) is added between the MACC+ control output (V_{out} , Fig. 1) and the biasing resistance network to guarantee the required current.

C. Optimized Sensing Element

As previously stated, the design of a sensing element for a DCCT rated at 80 kA working at 4.2 K is a challenging task. In [20] it is clearly recalled that the magnetic circuit has to be designed with the aim of (i) increasing the sensitivity to the primary magnetic field (generated by the unknown current), (ii) minimizing the sensitivity to external magnetic fields and (iii) minimizing the sensitivity to the sensing element centring and to the return bus-bar configuration. High sensitivity to the primary magnetic field is guaranteed using soft magnetic material with high magnetic permeability and low coercive force. In this regard, MACC+'s cores are implemented using μ -metal material to achieve best performance. For this reason, it is of foremost importance to choose CryoDCCT core's magnetic alloy with high-uniformity characteristics at 4.2 K, as close as possible to the μ -metal characteristics at room temperature, to preserve high sensitivity to unknown currents. Then, an optimized geometrical cores' design has to be carried out with the aim of keeping the sensing element in a zero-flux condition (or within a maximum required accuracy) at the rated current of 100 kA (refer to [14] for the optimization process). Primary bus-bar off-centering is addressed using an iron magnetic shield. Sensitivity to external magnetic field, due also to the return bus-bar, is minimized by means of a cylindrical superconducting shield made of MgB_2 composite [16]. In Fig. 2, the cross section view of the optimized sensing element is reported.

The cores of the CryoDCCT are wound with a tape of soft Ni 81-Mo 5-Fe magnetic alloy (referred to as cryogenic permalloy [23]), having a thickness of 0.2 mm. In Fig. 3(a), one of the cores used for the CryoDCCT sensing element with the optimized dimensions is shown. The sensing coil (200 turns) is insulated from a core through Teflon tape (thickness of 0.1 mm). Teflon is also used to mutually insulate the three cores (see Fig. 3(b)).

Fig. 2. Cross-section view of the optimized CryoDCCT sensing element.

Fig. 3. Cryogenic permalloy core of optimized dimensions (a) and final preparation with sensing coil and Teflon insulation tape (b).

Fig. 4. Measured hysteresis loop for the cores 2.1, 2.2, and 1.1 at 4.2 K.

The uniformity of the cryogenic permalloy magnetic characteristics was assessed through hysteresis loop measurements. In Fig. 4, the hysteresis loop measured at 4.2 K, for a maximum excitation field of 27 A m^{-1} (the measurement set-up is described in [15]), of the three CryoDCCT's cores is shown (out of a batch of six cores): Differences are within 8%. The only remarkable difference of these results, compared to the μ -metal characteristics at room temperature, is a smaller residual field of 30%.

The off-centering issue was addressed by implementing a 2 mm thick cylindrical pure iron shell at the location where the three cores are housed (Fig. 5(a)) and enclosed (Fig. 5(b)).

Fig. 5. Housing (a) and enclosing (b) of the cores into the iron shield: geometrical dimensions are also reported.

Fig. 6. Final CryoDCCT sensing element assembly: Superconducting compensation coil (a) with fiberglass tape (b); the wire from the central voltage tap is highlighted too.

Gauges of epoxyglass (1 mm thick) were used to center the cores into the cylinder.

The iron shield works up to an external magnetic field of 0.3 T and the expulsion of the external field is extended up to 1 T through a cylindrical superconducting shield made of an MgB_2 bulk superconducting material. The design of the superconducting shield is described in [16] and the final object is being produced [24].

The need of an 8000 turns superconducting compensation coil arose from the requirements of limiting the unavoidable loss of bandwidth due to the increased secondary inductance and of reducing the cryogenic load. A copper wire would turn into excessive power dissipation, about 1 W/kA. Therefore, a Nb-Ti superconducting wire capable of carrying 76 A at 4 T was chosen (referred to as type 1 LHC corrector strand, [25]). Probability of quench occurrence is minimized because the maximum expected working field is below 1 T. In Fig. 6(a), the final sensing element is shown. A voltage tap at the centre of the compensation coil was introduced for quench protection of the device (see Section III). A layer of fibreglass adhesive tape is used to minimize movements of the superconducting compensation coil, see Fig. 6(b).

III. EXPERIMENTAL SETUP FOR DEVICE CHARACTERIZATION

The achievement of a high accuracy CryoDCCT depends also on the preparatory work for the final assembly of the sensing element. In particular, before operation of the transducer, cores have to be fully demagnetized. Non-uniform residual magnetization can result into a high loss of accuracy and it may affect the stability of the device in the worst case.

Fig. 7. CryoDCCT assembly for characterization measurements.

Fig. 8. Experimental setup for the CryoDCCT characterization.

To address this potential issue it is of foremost importance to wind an additional coil on the sensing element for demagnetization purposes.

For the characterization measurements, a 1000 turns excitation coil (cross section of 0.5 mm^2) was wound on the top of the sensing element to achieve an equivalent primary current (I_1) of 80 kA for 80 A supplied. In other words, this coil is equivalent to a bus bar carrying a current up to 80 kA. Fig. 7 shows the sensing element with the excitation coil. Moreover, an additional 27 turns demagnetizing coil is depicted (insulated Cu wire with cross section of 1 mm^2). The number of turns was chosen as a compromise between the minimum field available for demagnetization and the need of being able to overcome the maximum field generated by the continuity tests (maximum current used of 1 mA).

In Fig. 8, the experimental setup for the characterization of the CryoDCCT final prototype is shown. The voltage Controlled Power Supply is (i) a high-accuracy $\pm 40 \text{ A}$ (from A&D Products AG) device or (ii) a $\pm 125 \text{ A}$ (from LakeShore, Mod. 622) power supply (control input 100 A V^{-1}). Both devices were used for the different tests that were carried out. The Voltage

Generator is a $\pm 10 \text{ V}$ analogue output (16 bit- resolution) of a multipurpose NI board (NI PXI 6281). The reference DCCT is a MACC+ [21]: Output $\pm 10 \text{ V}$ for a primary of $\pm 120 \text{ A}$, namely, 12 kA V^{-1} considering the 1000 turns excitation coil. The value of I_1 is retrieved via the output voltage $V_{\text{MACC+}}(I_1)$ and the reading is carried out by means of the $6\frac{1}{2}$ -digits multimeter KEITHLEY 2000 (Digital Voltmeter).

The sensing element is placed in a cryogenic insert housed in a cryostat. The top plate of the cryostat provides the connection of the cables from/to the sensing element, the CryoDCCT transducer electronics, the bus bars for the excitation coil, and the Cu braids for the compensation coils. The voltage $V_{\text{CryoDCCT}}(I_2)$ is the output of the instrumentation amplifier: with the ideal gain of 16, the voltage is proportional to I_2 through the equation

$$V_{\text{CryoDCCT}}(I_2) = GR_{\text{burden}}I_2$$

that is, $\pm 8 \text{ V}$ for a primary current of $\pm 80 \text{ kA}$ (10 kA V^{-1}).

The reading of this voltage is carried out by means of a multimeter KEITHLEY 2000. The set-up includes the protection against quench of the superconducting compensation coil. A protection board, implementing a differential inductive voltage subtraction detection scheme developed at CERN, is used. When the difference of the voltage drop between the two halves of the compensation coil stays above 100 mV for 10 ms , the protection circuit is triggered by means of a 15 V signal. This notification allows a power switch to open the current path on the two bus bar branches, discharging the primary current (a 12 V bi-directional transient suppressor diode is used for overvoltage protection). Electrical connection can be established back via a manual reset. Direct cutting of the CryoDCCT current was not considered to avoid current unbalances during discharge that can bring cores in deep saturation. Resistance build-up in the superconducting wire is not of concern, as long as the collector-emitter voltage drop of a power amplifier's output transistor is higher than the specific collector-emitter saturation voltage.

IV. TEST CAMPAIGN RESULTS

The aim of the characterization test campaign was twofold: a) the steady state characteristic of the CryoDCCT was assessed through the difference between the device reading and the values from the reference DCCT at specific current plateaus; b) current ramp-up measurements were carried out to identify the rated current of the new device.

In Table I the results of the static characterization, using the $\pm 40 \text{ A}$ primary power supply, up to a current of 20 kA in the secondary are reported. The maximum testing current was limited by the heating up of the excitation coil (wound with copper wire). In other words, leaving a current plateau higher than 20 kA for several seconds induced a quench in the superconducting compensation coil. The current in the excitation coil I_1 was ramped up from 1 kA to 20 kA , with intermediate plateaus of 3 kA , 5 kA , and 10 kA , and back to 1 kA five times. On each current plateau both the reference I_1 and the secondary current I_2 were recorded, setting the sample frequency of the multimeter at the slowest rate (one reading per second) to increase the rejection to noise. The data were corrected from the

TABLE I
MEASURED REFERENCE PRIMARY CURRENT I_1 AND SECONDARY
CURRENT I_2 ALONG WITH THE RELATIVE UNCERTAINTIES
($u(I_i)/I_i$) AND ERROR ($(I_1 - I_2)/I_1$)

I_1 (A)	$u(I_1)/I_1$ ppm	I_2 (A)	$u(I_2)/I_2$ ppm	$(I_1 - I_2)/I_1$ %
998.4744	36	996.3080	44	0.22
2,997.5520	22	2,991.0200	28	0.22
4,996.6560	11	4,985.6200	17	0.22
9,995.9520	14	9,973.7600	11	0.22
19,992.9600	3	19,948.9000	22	0.22
9,996.1440	10	9,973.9400	11	0.22
4,996.7280	13	4,985.7200	26	0.22
2,996.7408	641	2,990.9400	30	0.19
998.4336	20	996.3240	120	0.21

Fig. 9. CryoDCCT nonlinearity in ppm (10^{-6}) of the measurement range (80 kA).

offset of the two instruments, -2.16 ± 0.12 A for the reference DCCT and $+1.9 \pm 0.2$ A for the CryoDCCT, respectively. The experimental relative uncertainty, $u(I_i)/I_i$, of the measured I_1 and I_2 are reported in ppm (10^{-6}). The uncertainties from the reference DCCT and the CryoDCCT are of the same order of magnitude, i.e. less than 50 ppm (neglecting two values out of bounds). In the last column of Table I, the error, which is the difference between I_1 and I_2 , relative to reference I_1 is reported. It is worth to highlight that this error is almost constant and it can be assumed to be 0.22%. This means the CryoDCCT shows a gain error with respect to the reference DCCT. However, the error is systematic and therefore it can be corrected. In Fig. 9, the nonlinearity of the CryoDCCT is shown. In particular, the data are expressed in ppm (10^{-6}) of the measurement range (80 kA). This highlights the good performance of the CryoDCCT, namely, nonlinearity of better than 5 ppm.

Finally, in Fig. 10 the result of a ramp-up current measurement is shown. The primary (dashed) and secondary (solid) current curves are acquired through two analogue inputs, ± 10 V with 16-bit resolution, of a multipurpose NI board (NI USB-6363) at a sample frequency of 1 kS/s. The current on the primary was ramped up, using the ± 125 A power supply, with a effective ramp rate of 26 kAs^{-1} . This was the maximum

Fig. 10. Measured current (top) by means of the reference MACC+ (dashed) and cryogenic DCCT prototype (solid) during a current ramp-up cycle and relative difference (bottom) between the curves in ppm (10^{-6}) of the measurement range (80 kA).

ramp rate that allowed to avoid a quench of the compensation coil and to achieve almost the target of 80 kA. Indeed, a current of 76 kA is reached before the compensation coil quenches (in Fig. 10 (top) the sudden drop to 0 A of the current due to the protection). Fig. 10 (bottom) shows the relative difference between the two curves referred to the range of 80 kA: no appreciable differences between the reference DCCT and CryoDCCT are recognizable. The quench starts to develop where the difference between the curves deviates by about 1 ppm (at the end of the ramp-up).

V. CONCLUSION

In this paper the design, assembly, and commissioning of a new cryogenic DC current transformer, capable of measuring currents of up to 80 kA at 4.2 K, is described. In particular, the design proposed in [15] is recalled, and assembly and commissioning of the new current transducer are described.

An experimental setup was conceived for the commissioning of the CryoDCCT. The primary of the CryoDCCT sensing element is wound with 1000 turns coil to reach 80 kA for an excitation of 80 A. The primary current reference is retrieved using a reference DC current transformer at room temperature.

Static metrological characterization up to 20 kA highlighted outstanding performance of the proposed device, that is, measurement precision better than 50 ppm and nonlinearity better than 5 ppm. Moreover, tests to inspect the device rated current were carried out and a current of 76 kA was measured. The design target of 80 kA was not reached due to limitations of the experimental setup, namely, overheating of the 1000 turns excitation coil. However, the effectiveness of the new CryoDCCT was completely proven.

The proposed transducer is going to be installed in the new insert at the FRESKA test station for the characterization of superconducting cables up to 80 kA.

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