A Novel Current Calibration System up to 20 kA

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Abstract—The Large Hadron Collider (LHC) particle accelerator project will require an accuracy of a few parts in 10^6 in the control of the current to the superconducting magnets. A new infrastructure for calibration is being built at CERN based on dc current reference standards rather than voltage. The paper describes the rationale, the infrastructure, the transfer methods, and the performance.

Index Terms—Accelerator control systems, calibration, current comparator, dc, transducer.

I. BACKGROUND

THE Large Hadron Collider (LHC) project [1] aims to build a new proton collider at CERN, working at 7 TeV/beam. This machine is scheduled to come into operation in the year 2007. To achieve this aim, superconducting magnets will be used, working with 13 kA current at 1.9 K. The dipole magnets produce a bending field of 8.4 T over the 27-km circumference tunnel, 100-m underground.

The current in the several thousand magnets must be controlled very accurately to minimize particle losses. Even very small losses would deposit enough energy in the superconducting coils to cause a quench. It is also very important to maintain tracking between the many circuits during the accelerator cycle. Special high-precision dc current transducers (DCCT) are used to control the switch-mode power converters producing the magnet currents.

The main dipole and quadrupole magnet circuits in a conventional accelerator are always powered in series to ensure synchronism and homogeneity in the magnetic field around the circumference. Due to constraints in the protection of the superconducting magnets and the very high stored magnetic energy (12 GJ), the main circuits in the LHC are divided into eight sectors. It, therefore, becomes fundamental to successful operation that the individual sector currents can be controlled with absolute accuracy in amplitude and time. The periodic calibration of the DCCTs and the following analog-to-digital (A/D) converters will be essential to the successful operation of the LHC.

The control systems for the highest precision converters have been planned in clusters to facilitate in-situ calibration and the ensuing environmental control. A complete calibration system has been conceived [2], which is based on the availability of an accurate 10mA dc current standard [3] and a complete infrastructure to maintain traceability to national standards.

II. DCCT CONSIDERATIONS

The new accelerator technology needs higher current and unprecedented accuracy in the current control. The state-of-the-art in DCCT design and calibration needed improvement to achieve this. Experience from DCCT technology shows that current ratios are limited in range, but have long-term stability and are much more precise than the current-to-voltage conversion (in burden resistors) at their output. It is also evident that current-to-voltage conversion is more accurate the lower the power is.

Two avenues were available and the latter was chosen for reasons of reliability and economy.

- Develop a two-stage DCCT, such that current-to-voltage conversion could be done at low current (mA) and power.
- Develop means to easily verify performance of and recalibrate presently available DCCTs operating with medium current (1–5 A) output.

III. CALIBRATION CONSIDERATIONS

Previously, DCCT calibration was limited to verifying the burden resistors with a calibrated DVM. This was no longer deemed sufficient. It was also clear that the DCCTs needed field calibration, as it was no longer feasible to return them to the standards lab for reasons of size, weight, etc. On the other hand, it would not be realistic to take conventional laboratory standards on-site and attempt field calibration. It appeared that a completely new approach was necessary.

It was realized that if the DCCT had a 13-kA turn calibration winding, then injecting an accurate current into this winding would allow on-site calibration, but if and only if the current source could be built to provide full traceable accuracy, even on-site.

The CERN current calibrator (CERNCC) was conceived to provide the required current source, programmable over the range from -10 to $+10$ A for use during on-site calibration. However, this basic current source also allows complete evaluation of DCCTs to be made. Thus, the CERNCC can be used to

- drive calibration windings, using an additional voltage booster amplifier;
- measure directly the primary current fed to the tested DCCT using reference heads [4];
- measure directly the secondary current of any DCCT head under test, thus removing the burden error;
- produce an accurate current to verify burden resistor performance.

IV. FUNCTIONAL DESCRIPTION OF THE CERNCC

An ideal current source, providing better than 1 part in 10^6 resolution of the output over the entire range from $+10$ to -10 A, can be realized as an accurate low-current source,

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Fig. 1. Current calibrator schematic diagram Fig. 1 is intended to be page wide, while all the other figures are column wide.

followed by an accurate current multiplier. A 10-mA dc current reference standard module has been developed for this purpose [3]. The current multiplier employs an adjustable turns ratio step-up DCCT, with up to $\times 1000$ multiplication factor. The output current amplifier must be designed to source or sink current and have sufficient compliance such that multiple burden resistors can be connected in series, i.e., up to ± 5 V. Output loads, such as calibration windings, which require additional drive voltage, need to employ an external voltage booster amplifier (not described). The functional diagram of the current calibrator, with the basic components outlined, is shown in Fig. 1.

The first part is a 10-mA current standard, which can be directly calibrated by another portable unit of the same type. The 10 mA is injected into a series of 12 primary windings, having a binary increase in the number of turns. All windings are placed on a shielded, toroidal core assembly. The zero flux detector drives a power amplifier, which powers the secondary windings in series with the external load. The secondary high current windings consist of a smaller number of windings, such that the total number of turns can be varied to produce a maximum output current of 10 A. A single extra primary turn allows a fraction of 10 mA to be injected, such that an overall resolution of about 24 bits can be obtained. This fractional current is obtained from a 16-bit DAC having 10-mA full scale.

V. DESIGN DETAILS OF THE CERNCC

The toroidal core assembly consists of two matched, amorphous cores with identical modulator and detector windings. Since the cores operate at a maximum of only 40 ampere-turns, the stability of the second harmonic zero flux detector (ZFD) and the remanence of the cores are of prime importance. Therefore, all effects normally having only a small influence on the zero sensitivity and stability have had to be taken into account. The modulator cores are screened by a triple, amorphous radial

assembly with mumetal end caps, while being completely enclosed within a thick soft-iron case. The cores are modulated at 10 kHz by a specially shaped current waveform, which allows controlled deep saturation of the cores to 20 ampere-turns and maximizes the sensitivity of the second harmonic detection. The ZFD uses a double-tuned 20-kHz filter, followed by a symmetrical phase detector. This overall approach has reduced the effects of core remanence and winding asymmetries to two parts in 10^7 of full-scale range. The zero stability and noise level is approximately $4 \mu\text{A-turns}$ and is mostly due to core noise, since the associated electronics contribution is now less than half of this figure.

An additional winding on the core assembly provides some ac feedback which is combined with the ZFD output at the feedback loop amplifier. An automatic gain attenuator maintains constant loop gain with varying output range selection. The output of the loop amplifier feeds the power amplifier, which is configured as a transconductance amplifier. The small signal bandwidth of the system is approximately 8 kHz.

The final design of the core and coils has been lengthy, as many second order effects have needed study and correction. In spite of these problems, the reproducibility, after a single zero to full-scale cycle, is now about one part in 10^7 . The instrument has been designed as a computer controlled device from the start, since it is very tedious to operate manually. The use of an isolated USB interface has not revealed any measurable interference problems. The initial software has been written in Visual Basic and allows current settings to be made in either binary or decimal values. More features, such as automatic smooth current ramps, core degaussing, etc., are being developed.

VI. OUTLINE OF THE TRANSFER METHODOLOGY

The system depends completely on the on-site availability of a calibrated 10 mA, traceable to primary standards. A transfer chain, described below, has been elaborated to this end. The current standard (known as PBC) is used in three ways (see Fig. 2).

Fig. 2. PBC transfer chain.

Fig. 3. Calibration of a DCCT with calibration winding.

The first one, on the left, serves to create the primary 10 mA from a 10-V voltage standard and a 1-k Ω resistance standard. Several PBCs are maintained in this setup to reduce uncertainty to an estimated two parts in 10^7 .

The second one is the transfer to travelling standards, reverse connected in series with the first and *concurrently* with the standard resistor. The uncertainty of transfer is determined by the noise in the PBC to three parts in 10^7 .

The third one is the transfer to the local working standard for the CERNCC, with the same uncertainty of three parts in 10^7 .

The transfers between PBCs are very easy to perform with 1-M Ω current detectors as shown, because thermal EMFs and contact resistances can be ignored; 1 mV corresponds to one part in 10^7 .

VII. CURRENT CALIBRATOR APPLICATIONS

The CERNCC has already found three main applications, each one outlined below.

- 1) *Generation of current for the DCCT calibration winding.* The CERNCC can generate up to 10 A at a few volts compliance. Calibration windings with nominal ampere-turns on large DCCTs, however, have a nonnegligible resistance and need around 20-V drive voltage. To further improve the uncertainty and calibration speed, two DCCTs will often be calibrated simultaneously. To provide the additional compliance voltage needed for this task a special voltage booster has been developed for the CERNCC. As shown in Fig. 3, this also works on the current null principle and provides up to 70-V output voltage. The current null is sensed across a 1-k Ω resistor by a differential amplifier. This makes connection of the voltage booster extremely simple, while ensuring that the accuracy of the CERNCC is inherently conserved. One of the major advantages of the CERNCC is its ability to deliver an output current with extremely good linearity. The present performance is estimated to better than three parts in 10^7 . It is, in fact, a nontrivial task to verify how good its linearity is, since very few, if any, burden resistors can match this.
- 2) *Measurement of output current from reference or normal DCCT heads.* In the calibration laboratory, a high current

Fig. 4. Measuring high current with successive approximation.

Fig. 5. Resistor characterization.

test bed provides primary currents up to 20 kA. Specially developed reference DCCTs are used to measure this primary current [4] and divide it by a factor up to 4000. To obtain the highest accuracy, the reference DCCT secondary current has to be measured directly, in order to avoid the additional uncertainty from a burden resistor (current-to-voltage conversion). The CERNCC is used with a μ V-meter, in a successive approximation mode, to measure this secondary current. The complete setup, shown in Fig. 4, enables primary current measurements up to 20 kA at the highest possible accuracy.

- 3) *Characterization of burden resistors.* The burden resistor is of crucial importance to the performance of a DCCT. It is, therefore, often evaluated separately to determine its characteristics. Part per million level measurements of linearity, repeatability, and reproducibility, as well as settling time, can be made using the simple arrangement shown in Fig. 5. Of particular merit is the ability to evaluate burden resistors up to their full rated power and to create true current steps with essentially zero settling time. This allows study of time-dependent phenomena in burden resistors from less than 1 s upwards.

VIII. INITIAL RESULTS

The CERNCC has recently been employed to calibrate the magnet currents in a mock-up of the LHC tunnel installation. The DCCTs were calibrated in the calibration laboratory prior to installation. On-site calibration was then performed and showed that the overall calibration uncertainty was better than two parts in 10^6 . A second on-site calibration two months later revealed an unexpected relative drift of about (10 to 20 parts in 10^6)/month. This was later traced to a suspect batch of burden resistors. This

type of problem would, more than likely, never have been observed after installation and shows the potential of this calibration technique.

In the 20-kA testbed, employed for evaluating and measuring large DCCTs, the CERNCC has allowed many measurements to be made which were previously impossible or at least inaccurate. These measurements include direct measurement of ratio accuracy, linearity, hysteresis, bus-bar configuration effects, and saturation effects. The primary current can be measured with an uncertainty of less than 1.2 parts in 10^6 .

The CERNCC also has proven exceptionally useful to evaluate the power coefficient, settling time, and humidity absorption related hysteresis effects in burden resistors because of its "turns ratio" linearity and stability, both of which are better than one part in 10^6 . On-going work with manufacturers to improve the resistors has been initiated directly due to these measurements.

All indications are that these measurements are within an uncertainty less than 1.6 parts in 10^6 . However, this has proven very difficult to confirm with independent means. Collaboration with the National Physical Laboratory (U.K.) is underway to advance such confirmatory measurements.

IX. CONCLUSION

The system considerations have led to a calibration chain based almost entirely on dc current standards and transfer of current and current ratios. The necessary components have been developed and early deployment has proven the expected advantages. Currents up to 20 kA can be measured with an uncertainty less than two parts in 10^6 .

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