Design and Verification of a 24 kA Calibration Head for a DCCT Test Facility

Gunnar Fernqvist, Hans-Erik Jorgensen, and Alfredo Saab

***Abstract*—The large hadron collider is CERN's next particle accelerator project, scheduled for commissioning in 2005. The project requires accurate current measurements above 10 kA. Calibration heads have been developed in collaboration with industry to work up to 24 kA with a relative measurement uncertainty of 10^{-6}. This paper describes the design and verification of these heads.**

***Index Terms*—Current comparator, current measurements.**

I. Introduction

CERN (The European Laboratory for Particle Physics) plans to commission its large hadron collider (LHC) in 2005. The LHC requires an extremely accurate control of the currents in the more than 1700 superconducting magnet circuits [1]. CERN has been operating a standards laboratory for 25 years to calibrate dc current transducers (DCCT) employed in the power converters feeding the accelerator magnet circuits. Voltage and resistance standards were maintained with 5×10^{-6} relative uncertainty and current could be calibrated up to 5 kA with 2×10^{-5} relative uncertainty. The standards laboratory is being upgraded for the future needs of the LHC [2] i.e., a ten times improvement. As a part of this, CERN is constructing a 20 kA testbed for evaluation of current transducers and for this purpose new calibration heads are required. The previous test setup used the Guildline 9920 bridge with a 9921 1 kA range extender and a 6 kA power supply. All the Guildline equipment was based on current comparator designs by Kusters and MacMartin at NRC in Ottawa about 30 years ago [3]. A new 20 kA range extender, also based on the old design by Kusters [4] was recently ordered from MIL in Canada. These designs all have a relatively slow response, the feedback only being based on the magnetic modulation technique. A second, new, 24 kA design was ordered from Danfysik, an industrial DCCT manufacturer, to find out if recent core and electronics designs would provide better performance and also to make intercomparison of the calibration heads possible.

II. 24 kA Head Design

The DCCT system consists of a toroidal measuring head controlled by an electronics module. The bore of the transducer head accepts a conductor carrying the primary current to be measured, up to 24 kA. The transducer head has a bore diameter of 160 mm, an outside diameter of 420 mm, and a height of 150 mm. A flux balance is established in the toroidal sensing core, using a secondary winding producing equal and opposite ampere-turns with electronic feedback. The number of turns in the secondary winding is determined through an optimization process, considering the output current, the voltage needed to drive the winding and the winding characteristics affecting the feedback loop stability. The higher the number of secondary turns, the lower the secondary current, i.e., less copper cross-section and less power dissipation in the burden resistor. On the other hand, the higher the number of turns, the higher the winding inductance and the stray capacitances, lowering the inherent resonance frequency, and hence, limiting the bandwidth. An empirical upper limit is (7000 to 8000) turns. Considering that the current calibrator, which will be used to measure the output current, was designed for 6 A output, a conservative 4000 turns was chosen. The physical core size also increases with the primary current, since it has to accommodate a larger total copper cross section in the secondary. This increased dimension will increase sensitivity to external fields and demands more precaution in the magnetic shielding.

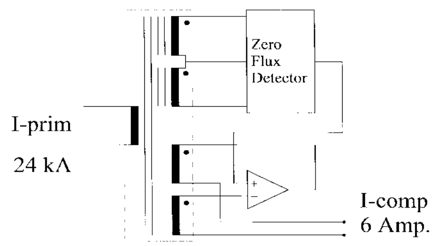

Fig. 1. DCCT principle of operation.

A. Principle of Operation (Fig. 1)

The zero-flux feedback loop is split in two, a fast part and a slow part. For the low to high frequency range the compensation amplifier will keep the voltage from the feedback winding close to zero by driving a current producing opposing ampere-turns in the compensation winding. This implies that no current is used for excitation of the core (zero flux), causing the primary and secondary ampere-turns to cancel. With an optimized design, a bandwidth of up to 100 kHz can be obtained. In the range dc to low frequency (1–10) Hz, a

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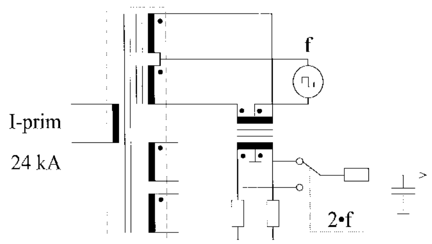

Fig. 2. Zero-flux detector principle.

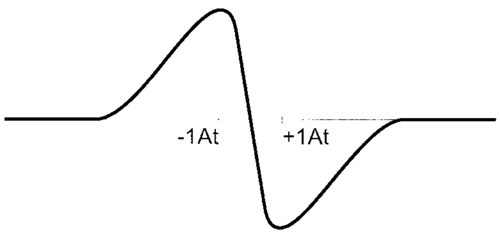

Fig. 3. Characteristics of the zero-flux detector.

separate zero-flux detector ensures that primary and secondary ampere-turns cancel.

Fig. 2 shows the zero-flux detector principle. A square-wave generator drives two identical detector cores into saturation. They form part of the main core structure and, as long as the primary and secondary ampere-turns cancel (zero flux), the current waveforms in the cores are symmetrical. In case of a flux offset, the current waveforms will no longer be symmetrical, implying a content of even harmonics. The even harmonic signals are detected using synchronous rectification with twice the modulation frequency. The assembly of the two detector cores is made such that the primary, the compensation, and the feedback windings only see the difference between the modulation currents. If the cores are well matched dynamically, the resulting signal is small, about 20 μV per turn. The same modulation voltage drives the two detector cores, resulting in almost equal currents in the cores when no offset ampere-turns are present. The fundamental and the odd harmonic currents cancel in the output transformer, resulting in close to zero output. The transformer turns ratio is chosen such that the voltage across the secondary load resistors is suitable for the CMOS switch in the synchronous rectifier.

When there is an offset in ampere-turns, the even harmonic signals from the two cores will add and the synchronous rectifier will only see the error signal and not the modulation signal. The resulting error signal is filtered and fed back to control the compensation amplifier, such that zero flux is obtained in the dc to low frequency range.

Fig. 3 shows the characteristics of the zero-flux detector. The detector circuit used has a gain of about one volt per ampere-turn and a resolution of better than 10^{-3} ampere-turn, i.e., 4×10^{-8} of 24 kA. If the difference exceeds around 1 ampere-turn, i.e., 4×10^{-5} of 24 kA, the output will again decrease to zero and the DCCT will stop operating due to core saturation. This will normally only occur if the primary current is present before the control electronics of the DCCT is switched on. However, should the zero detector be outside its operating range during normal operation, the control circuit will generate an alarm signal. A sweep circuit will then start searching by scanning the compensation current through its full bipolar output range. As the zero detector only operates in a 4×10^{-5} range, the zero detector core will have been driven far into saturation during this procedure. Due to the remanence of the core material, the zero detector will then give an offset signal at zero ampere-turns, slowly decaying with time. However, a permanent offset of several parts in 10^{-6} can remain indefinitely. To restore maximum performance, a complete demagnetization cycle has to be applied to the core.

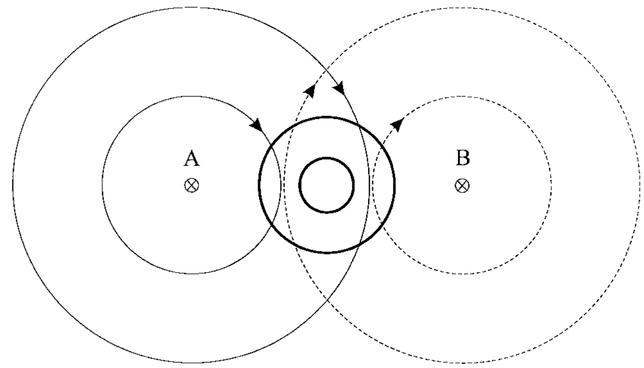

Fig. 4. Flux around two return conductors.

B. External Field Influence

With no external influence, the zero flux detector will ensure that the primary and secondary ampere-turns are equal. Any external magnetic field from current return conductors or other sources will influence the performance of the transducer head. This effect is proportional to the primary current and requires careful consideration at 24 kA.

Fig. 4 shows how the flux from an external conductor A will divide and go in two directions inside the toroid. At a given moment this will drive one part of the detector core more in saturation and another part less in saturation, producing an offset error. If the central conductor has a mechanical offset, it will also result in a dipole field across the core with the same result as before. To reduce this influence to an acceptable value, the topology of the DCCT and busbar assembly has to be optimized first and then the residual offset effect can be reduced by internal magnetic screens in the transducer head. In this 24 kA DCCT head, the two detector cores are embedded in a triple magnetic screen, routing most of the unwanted flux past the detector cores.

The influence from a return conductor can be greatly reduced by splitting it into two or more conductors. Fig. 4 shows how the flux from two conductors, A and B, tends to cancel. Three dimensional calculations, combined with full-scale measurement on detector cores without shielding, have been performed. These show that splitting the return conductor into two symmetrically placed conductors reduces the unwanted influence by a factor of six to eight. Splitting the return conductor into four gives an improvement factor of

12–16. In addition, it should be noted that the two- and four-conductor versions are much less sensitive to influence from external iron structures. The CERN testbed was designed to test these external influences. The number of return conductors can be varied from one to eight around the periphery of the DCCT and the geometry also can be modified through differently shaped conductors.

C. Other Design Considerations

One design aim was to achieve low power dissipation and to avoid fans, thereby minimizing thermal disturbance in the standards laboratory from the electronics. This was achieved by choosing switch-mode power supplies (SMPS) for the electronics auxiliary power, while recognizing the increased risk of internal EMC problems.

A standard industrial DCCT provides a voltage output signal by passing the compensation current through a burden resistor. In this case no burden was employed and the output signal is the compensation current, thus preserving the principle of a true current ratio device. Hence, the winding ratio and the zero flux detector performance solely determine the ratio accuracy.

III. Test Program

First functional tests revealed serious internal EMC problems. Radiated and conducted EMI from the commercial SMPS was reduced by placing copper strips around some magnetic components and many ferrite cores were placed strategically in the cabling and harnesses. The internal wiring also had to be rerouted to minimize pick-up in the electronics from the SMPS.

A. Ratio Accuracy Tests

The accuracy tests were performed as a series of intercomparisons between the 1 kA Guildline 9921 range extender, the 20 kA MIL range extender, and the 24 kA Danfysik head. The 24 kA head has only one winding with 4000 turns, but by using one, two, or four primary turns, ratios down to 1000 : 1 can be obtained. The 20 kA MIL head has eight one-turn primary windings and a secondary winding with 2000, 1500, 1000, and 500 turns, giving many ratio possibilities. The 9921 1 kA range extender, combined with the 9920, can also provide from 4000 : 1 to 1000 : 1 ratios.

The units to be compared were connected back-to-back with a common burden resistor. The resistor was bridged with antiparallel power diodes and a filter capacitor. It was also equipped with six terminals, four for current, and two for voltage. The latter were connected to a Keithley 155 microvoltmeter. Fig. 5 shows the measurement circuit. The current source used was a CERN 6 kA, 7 V supply with very low ripple. The voltage was just sufficient to reach 2×10^4 ampere-turns with four primary turns in the 24 kA head, due to a relatively high cable resistance.

The main error sources in the DCCT transfer ratio are nonlinearities and instabilities. Nonlinearities are often caused by unwanted influence from the main current to be measured, either in the core or in other parts of the transducer. The influence can be direct (magnetic fields) or indirect (power dissipation in the electronics assembly).

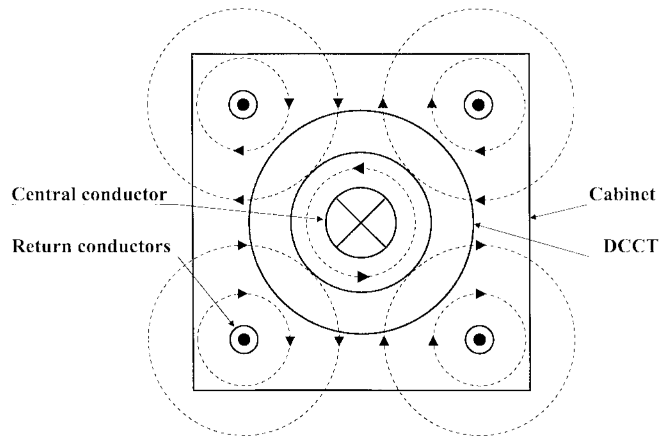

Fig. 5. Comparison circuit for DCCT's.

Instabilities are the result of external influences on the head, the electronics, or the current balance measuring circuit. Typical causes are temperature, RF fields, and magnetic fields, static and dynamic. Care must be taken not to create pickup loops in the heavy current path or the transducer connections. Partial rectification of stray RF fields is a problem at this accuracy level.

Presence of ripple in the main current can be a cause both for instability and nonlinearity. The first assumption is that both devices to be compared respond to changes in the same way and, thus, the output variation will cancel. This is only true if their transfer functions are identical over the frequency range considered. A difference of a few parts per thousand in the ac gain of the transducers at the rectification frequency or its harmonic, could cause large voltage peaks in the balance circuit. If the latter is driven outside its linear range, a large and unstable dc signal will appear, often leading to confusing results. An oscilloscope with a high-gain differential input will help to identify the problem, but a power supply for the main current with a very low ripple is essential for reliable dc ratio determination to a relative uncertainty of 10^{-6}.

The main and secondary circuit insulation resistance has to be evaluated to ensure that there is no leakage current bypassing one of the two transducers. The maximum tolerable leakage in the main circuit is 50 μA/kA and 50 nA/A in the output circuit. Further analysis of leakage and ground loops must also be carried out when all the instrumentation is connected.

The first ratio comparisons were carried out at reduced current between the 9921 1 kA head and the 24 kA head. A nonlinearity of around 2×10^{-6} was found. After investigation, this was shown to be caused by the magnetic field from the main dc current affecting the transformer core in the Royer oscillator supplying the ac drive to the 9921 head. This resulted in a small asymmetry in the duty cycle, causing the 2×10^{-6} nonlinearity. The problem was corrected by placing a mu-metal shield around the oscillator transformer.

Many sets of measurements were then made between all three units over a period of a month, all confirming their

TABLE I
MEASURED DIFFERENCE FROM COMPARISON OF THE CALIBRATION HEADS

Ampere-turns	Danfysik 24 kA with 4000:2 MIL 20 kA with 2000:1				Danfysik 24 kA with 4000:4 MIL 20 kA with 2000:2			
	Positive polarity		Negative polarity		Positive polarity		Negative polarity	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
800	-0.03	-0.08	0.00	0.10	-0.30	-0.41	-0.16	-0.22
2000	-0.04	-0.10	0.02	0.05	-	-	-	-
4000	-0.08	-0.12	0.05	0.12	-0.41	0.00	-0.12	0.00
6000	-0.10	-0.12	0.08	0.12	-	-	-	-
8000	-0.15	-0.16	0.08	0.13	-0.50	-0.08	-0.12	0.00
10000	-0.16	-0.17	0.25	0.25	-	-	-	-
12000	-0.16	-0.21	*	*	-0.53	-0.16	-0.15	0.04
16000					-0.58	-0.20	-0.12	0.08
20000					-0.53	-0.23	0.08	0.08

Values in 10^{6} of 24 kAturns

* = problems with overheating

ratio accuracy and linearity to well below 1 part in 10^6. Table I shows the detailed results from one representative set of measurements comparing the 24 and 20 kA heads. The 24 kA head with a 4000 : 2 ratio was first compared to the MIL 20 kA head with a 2000 : 1 ratio up to 1.2×10^4 ampere-turns. Then the 24 kA head with a 4000 : 4 ratio was compared to the MIL 20 kA head with a 2000 : 2 ratio up to 2.0×10^4 ampere-turns. It can be seen that the ratio error variation during any run is well below 3×10^{-7}. The offset was not always trimmed to zero completely, as this does not affect the ratio accuracy. The virtually identical performance of the heads at different ratios gives confidence that their individual performance is indeed as expected.

B. Offset Problems

The electronics will produce an offset current, which stems from the zero-flux detection principle and imperfections in the electronics. Offset current can be trimmed to zero at any given instant, but this will increase the uncertainty if it changes during the measurement. It was found to have several sources: the drift with time was about 5×10^{-6}/day; the drift with temperature, mainly thermal voltage noise was about 1×10^{-7}. There was also a random uncertainty at turn-on and at recovery from core saturation of about 5×10^{-6}. After a few hours warm-up time and in a temperature controlled environment ($\pm$1K), the offset drift could be made sufficiently small ($\sim 10^{-7}$/day).

IV. CONCLUSIONS

The experience at the CERN standards laboratory indicates that the transfer ratio of well designed modern DCCT's is stable, linear, and relatively independent of external influences at the 10^{-6} level of relative measurement uncertainty. Confidence is built up through a series of comparisons, as described in this paper, with several DCCT heads. The method of current cancellation has proven to be a good method for finding nonlinearities and instabilities, if proper care is given to the test set-up. Some problems remain with zero offset and its stability, in particular at unusual operating conditions. The two calibration heads, 20 and 24 kA, employing somewhat different principles and manufacturing technologies for the heads and signal processing electronics, have shown an identical performance to a relative uncertainty of around 3×10^{-7} up to 6 kA primary current. This result represents a very important milestone toward the construction of an absolute current calibration system up to 20 kA with a relative uncertainty of 10^{-6}. It requires that the output current of 6 A can be measured with an uncertainty better than 5×10^{-7} and this appears to be attainable [2]. Commissioning will continue during 1998 up to the full primary current of 20 kA. It is expected that with the new testbed, with very stable test current and control of the field distribution, and with accumulated operational experience, protocols will develop for transducer testing, characterization, and calibration to the 10^{-6} level on a routine basis.

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Alfredo Saab was born in Buenos Aires, Argentina, where he also did his university studies.

He worked for the Argentinean Atomic Energy Commission from 1962 to 1968 and then in the electronics industry until 1978. He joined the Bates Laboratory, Massachusetts Institute of Technology, Cambridge, in 1978 and was Instrumentation Group Leader from 1983 to 1989. In 1989, he joined Stanford University, Stanford, CA, and was Department Head for power conversion until 1995. Between 1995 and 1997, he worked at CERN, Geneva, Switzerland, as a Scientific Associate in the Standards Laboratory and then returned to SLAC. He is presently working as a Consultant for Danfysik, Denmark.