Abstract

The Large Hadron Collider (LHC) 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 at sub-ppm accuracy. The paper describes the design and verification.
DESIGN AND VERIFICATION OF A 24 kA CALIBRATION HEAD FOR A DCCT TEST FACILITY

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Abstract - The Large Hadron Collider (LHC) 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 at sub-ppm accuracy. The paper describes the design and verification.

Index terms - Current comparator, current measurements, DCCT

I. INTRODUCTION

CERN is an international organisation, located close to Geneva, Switzerland, which builds and operates particle accelerators for high-energy physics research. The next accelerator project, LHC, to be commissioned in 2005, requires an extremely accurate control of the currents in the more than 1700 superconducting magnet circuits [1]. CERN has been operating a small standards laboratory for 25 years to support calibration of DC current transducers (DCCT) employed in the power converters feeding the accelerator magnet circuits. Voltage and resistance was maintained at the 5 ppm level and current could be calibrated up to 5 kA at the 20 ppm level. The standards laboratory is being upgraded to cope with the future needs of the LHC [2] i.e. an improvement by a factor of 10. As a part of this effort, CERN is constructing a 20 kA testbed for evaluation of suitable current transducers and calibration heads are part of this device. 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 about 30 years ago. A new 20 kA range extender, also based on the old design by Kusters [3] was ordered from MIL in Canada. These designs all have in common to be relatively slow, the feedback only being based on the magnetic modulation technique. A second, new, 24 kA design was ordered from Danfysik, a manufacturer of industrial DCCTs, to find out if recent core and electronics designs would provide better performance and to have some means for intercomparison of the calibration heads themselves.

II. 24 kA HEAD DESIGN

The system consists of a toroidal measuring head controlled by an electronics module. The centre hole in the transducer head accepts a conductor carrying the primary current, 24 kA, to be measured. A flux balance is established in the toroidal sensing core, using a secondary winding producing the equal and opposite ampere-turns. The number of turns in the secondary winding is determined through an optimisation process, considering the output current, the voltage needed to drive the winding and the winding characteristics affecting the feedback loop stability. The number 4000 was chosen, giving a maximum output current of 6 A.

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 try to 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. A larger number of turns in the feedback winding will increase inductance and stray-capacitance, rendering stability and bandwidth problems of the system more difficult. With an optimised design, a bandwidth of up to 100 kHz can be obtained.

In the range DC to low frequency, a 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 are situated inside the main core 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 double the modulation frequency. The resulting signal is filtered and used to control the compensation amplifier, such that zero flux is obtained in the DC to low frequency range. The detector circuit used has a gain of about one volt per ampere-turn (At) and a resolution better than 1 mAt (0.04 ppm @ 24 kA).

Fig. 3 shows the characteristics of the zero-flux detector. The output signal is positive for a positive difference in primary and secondary ampere-turns and vice-versa. If the difference exceeds around 1 At (about 40 ppm at 24 kA), the output will again decrease to zero and the DCCT will stop operating as the feedback no longer works. For this reason the control circuit has a “catcher circuit”, detecting if the zero detector is inside or outside its operating range. If it is outside the range,
a sweep circuit will start searching by scanning the compensation current through its full bipolar output range. As the zero detector core will have been driven far into saturation during this procedure. Due to the remanence of the core material the zero will then give an offset signal at zero ampere-turns that will decay in time, but a permanent offset of several ppm’s can remain. To restore maximum performance, a complete de-magnetisation cycle has to be applied to the core.

B. External field influence

Without any external influence, the zero flux detector will ensure that the primary ampere-turns are equal to the secondary ampere-turns. Any external magnetic field from current return conductors or other sources will influence the performance of the transducer head.

Fig. 4 shows how the flux from an external source 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 in less saturation, producing an offset error. To reduce this influence to an acceptable value, the two detector cores are embedded in a core system made as a triple screen, routing most of the unwanted flux past the detector cores. The influence from a return conductor can be much reduced by splitting it into two or more conductors. Fig. 4 also shows how the flux from two conductors, A and B, tends to cancel. 3-D calculations, combined with full scale measurement on detector cores without shielding, has been performed. They show that splitting the return conductor into two symmetrically placed conductors reduces the unwanted influence by a factor of 6 to 8. Splitting the return conductor into 4 gives an improvement factor of 12 to 16. In addition it should be noted that the two-conductor version is much less sensitive to influence from external iron structures. AC fields from nearby transformers and chokes also tend to cancel.

It will be possible to test these calculated external influences in the CERN testbed. The return conductors can there be varied in numbers from 1 to 8 around the periphery of the DCCT.

C. Other design considerations

To achieve low dissipation and avoid fans, switch-mode power supplies (SMPS) are used. The output signal from the calibration head is the compensation current itself. The use of an internal burden resistor would have decreased overall accuracy.

D. Mechanical dimensions

The transducer head has a hole of 160 mm, outside diameter of 420 mm and height 150 mm. The weight of the head is approximately 80 kg. The electronics is housed in a 19” crate, 5 units high.

III. TEST PROGRAMME

First functional tests showed EMC problems. Radiated and conducted EMI from the commercial SMPS was reduced by placing copper strips around some magnetic components and many ferrite cores strategically placed in the cabling and harnesses.

Performance tests started with a comparison up to 6 kA against a known DCCT with an uncertainty of about 30 ppm. The results from the new head corresponded to expectations well within this uncertainty.

A. Ratio accuracy tests

The accuracy tests were performed as a series of tests against the 20 kA MIL range extender head, previously verified at NRC, Ottawa.

The 24 kA head has only one winding with 4000 turns, but by using 1, 2 or 4 primary turns, the ratios 4000:1, 2000:1 and 1000:1 can be obtained. The 20 kA MIL head has 8 one-turn primary windings and a secondary winding with 2000, 1500, 1000 and 500 turns, giving many ratio possibilities. The original 9921 1 kA range extender can also, combined with the 9920, provide 4000:1 to 1000:1 ratios, but its accuracy is limited to 2.5 ppm.

The two objects to be compared were connected back-to-back with a common burden resistor. The resistor was bridged with anti-parallel 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 μV-meter. 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 20 kAt with 4 primary turns in the 24 kA head due to a relatively high cable resistance.

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 12 kAt. 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 20 kAt. The results of the measurements are given in Table I.

B. Offset problems

The electronics will produce an offset current, which stems from the zero-flux detection principle and electronics imperfections. It can be nulled at any given instant, but will increase the uncertainty if it moves during the measurement. It was found to have several sources:

- drift with time : ~ 5 ppm/day
- drift with temperature : mainly thermal emf’s, not measured precisely
- noise : ~ 0.1 ppm
- non-reversible turn-on uncertainty : ~ 5 ppm.
After a reasonable warm-up time and in a temperature controlled environment, the offset drift could be made small (~ 0.1 ppm) with respect to the desired accuracy and the measurement time.

IV. CONCLUSIONS

The two calibration heads, 20 kA and 24 kA, employing somewhat different manufacturing technologies, have shown a promising sub-ppm performance at 6 kA primary current. Commissioning will continue during 1998 up to the full primary current of 20 kA.

REFERENCES


Table I Results from comparison of DCCT heads

<table>
<thead>
<tr>
<th>At</th>
<th>24 kA: 4000:2</th>
<th>MIL 2000:1</th>
<th>24 kA: 4000:4</th>
<th>MIL 2000:2</th>
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<tbody>
<tr>
<td></td>
<td>+ polarity</td>
<td>- polarity</td>
<td>+ polarity</td>
<td>- polarity</td>
</tr>
<tr>
<td>800</td>
<td>-0.03</td>
<td>-0.08</td>
<td>0.00</td>
<td>-0.30</td>
</tr>
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<td>0.02</td>
<td>0.05</td>
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<td>0.12</td>
</tr>
<tr>
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<td>0.08</td>
<td>0.12</td>
</tr>
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<tr>
<td>2000</td>
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</table>

All values in ppm of 24000 At. *= problems with overheating.