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DESIGN OF A 10 mA DC CURRENT REFERENCE STANDARD

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Abstract

A new DC current reference standard, named the PBC, has been developed for high-current power converter calibration in the LHC project at CERN. This standard provides a near ideal 10 mA DC current with long-term drift of less than 1 ppm/year. The paper describes the requirements and the detailed design of the unit.

Introduction

The Large Hadron Collider (LHC) project at CERN [1] requires an unprecedented accuracy ($\sim 10^{-6}$) in the control of the 13 kA current to the superconducting magnets. To achieve this aim, a new calibration infrastructure is being built based on a 10 mA DC current reference and transfer standards. No such standards existed previously and therefore had to be developed. Maximum experience was sought from present voltage standard designs, advantages and drawbacks.

Rationale

The ideas and principles for the whole calibration system were developed in [2] and only the beginning of the calibration chain is summarised here. It was realised from the outset that there was a need for central fixed standards as well as portable units. The value of 10 mA, based on engineering considerations, seemed suitable for all of the following applications allowing this one design of DC current reference, the PBC, to cater for each.

Reference standards A number of reference standards (~5) will be kept in the CERN standards laboratory under near ideal conditions. Periodic comparisons will be made against 10 V voltage standards and 1 Ω - 1 kΩ resistance standards which in turn are compared with primary standards at METAS/Bern to ensure traceability. Periodic inter-comparisons of the PBCs provide short-term stability data.

Traveling standards A small number of standards are dedicated to transferring the 10 mA to the 18 sites located 100 m underground around the 27 km collider ring.

Local current source A 10 mA current source is needed in the Current Calibrator [3], which is a device able to multiply the reference current by a factor up to a 1000 with more than 24 bits resolution. The 5 A output current is used for calibrating large DC current transducers in the power converters which are in turn used for the final transfer up to 13 kA.

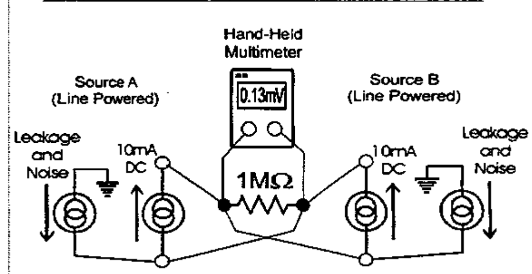
Design requirements

Accuracy/Stability The target is to deliver consistent magnet current accuracy of better than a few ppm under all conditions and with many contributing system uncertainties.. The primary calibration support chain therefore needs a good margin for both confidence and to extend calibration intervals. These considerations demanded performance comparable with the very best DC Voltage references, that is, sub ppm short term and circa 1 ppm per year.

Compliance The unit needs to drive rather poorly defined inductive loads and to tolerate quite high reverse detector voltages in the calibrator application. Further advantage could be gained with the ability to connect loads in series so that the precision current could be monitored to full accuracy by a reference 1 kΩ resistor whilst driving an operating or transfer load. Shorting out the resistor then gives a 10 V compliance change over which the output current must remain constant.

Isolation It was decided that calibration transfers between units would be performed by reverse connecting them and sensing the current difference to 0.1 nA (1 nA = 0.1 ppm!). This requires very low leakage current back to ground via the external supply. Even the AC leakage current has to be kept very low to ensure that it does not interfere with the current null measurement. See Fig. 1.

Fig 1, Back-to-Back Comparison of I-Refs, Delta=0.013ppm!



Portability The portability requirements originate with the unit's use as a transfer standard where autonomy for a working day was needed. To ensure integrity, means of indicating that a power failure had occurred since the last calibration was also necessary.

Description

The basic "Voltage" part of the design was similar to that of a commercial DC Voltage source [4] with a number of modifications to generate the 10 mA reference current and meet the above requirements. See Fig 2 block diagram.

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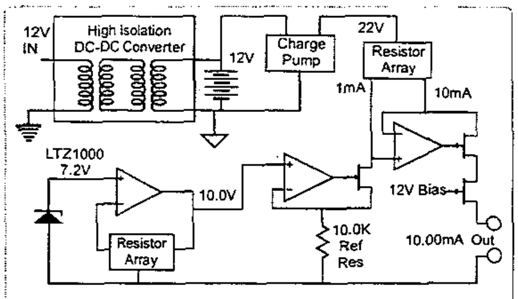

Fig 2. Block Diagram

The gain step to 10V from the well known and predictable LTZ1000A, at 7.2V, is defined by "statistical" TaN film resistor arrays [4]. These have been shown to maintain stable ratios to fractions of a ppm over time and temperature. A very special 10 kΩ, near zero temperature coefficient, multi-chip reference resistor was developed in conjunction with Vishay and in appropriate circuits used to define 1mA from the 10 V. This is amplified by a factor of 10, defined by further use of TaN film arrays in a 10:1 current mirror referred up to 22 V to achieve the compliance. This current is made adjustable over ±50 ppm via a front panel, 10 turn, indicating potentiometer in order to allow the transfer of current between devices to be an exact null, the potentiometer indication being recorded to track drift performance between calibrations.

Design for Compliance

In an opamp assisted current mirror, in its simplest form, the output compliance is a function of the loop gain of the controlling opamp which means that reactive loads can interfere with the performance to the point of becoming unstable. The circuit used added a cascode stage making it very "stiff" with the opamp being buffered from the output voltage. Furthermore, by using small geometry JFETs and adding bipolar transistors to boost the current handling, an output resistance in excess of 20 GΩ was achieved, independent of load dynamics. The Thevenin equivalent is 200E6 Volts in series with 20 GΩ!

Design for Isolation

The back-to-back calibration configuration is shown in Fig. 1 and inspection shows that if the power supplies generate Common mode current then this current will flow through the sense resistor and constitutes an error if it is DC or a disturbance if it is AC. A new DC-DC converter using a patented double screened transformer construction [4] together with a slew limited low noise switching controller was chosen so that there would be virtually no distinguishable difference between use with external power supplied and use under battery power with the external supply completely disconnected. The double screened transformer uses two toroidal cores, independently wound, one each for primary and for secondary. Each is independently fully screened within injection molded conductive plastic shrouds and coupled with an external "shorted turn" winding around BOTH cores. The resulting coupling capacitance from primary winding to secondary screen is less than 0.1 pF and in use ~10 nA of AC coupling current is achieved compared with hundreds of micro-amps in commercial units.

Design for Portability

The application requires that autonomy is maintained over a working day and that the unit is left on charge whenever not being used for transfers. Consequently, great care was taken to minimize power consumption, which was kept down to about 1.9 W including trickle charge. The battery chosen for convenience and cost was a "block" of NiMH AA cells with 1200 mAh capacity. However, the trickle charge rate was kept down to 10 mA so that the internal power dissipation change between line and battery power was minimized. This is essential to minimize possible changes in output Voltage or Current due to thermal differences.

It proved difficult to ascertain the charge state of units with unknown recent history so a new "Boost" mode was designed whereby an operator can force a state of fairly rapid charge during which normal use is inhibited. The boost charge takes some 12 hours and would normally be performed overnight. Subsequent to this, autonomy of 14 hours can be guaranteed with a 1600 mAh battery.

Of course, if the battery completely discharges it is essential that when power is restored the unit wakes up in a state that indicates that power has previously failed. This is signalled to a monitoring system and visually so that appropriate action can be taken. In most cases a calibration reset cycle can be initiated by the user and this is guaranteed, under normal conditions, to return the unit to being within 0.5 ppm of its pre-failure condition.

Conclusions

All of the design objectives were met and the PBC allows very high performance transfers to be made based on Current rather than Voltage. It also supplies near error free current to the Current Calibrator in the presence of harsh inductive loading and back EMFs. Final accuracy is primarily limited by the Zener and the internal reference resistor. The design principles could perhaps be the basis for a new class of current standards so primary electron counting devices that will fit within are eagerly awaited!

References

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[4] J. Pickering, "A Solid State DC Reference System", NCSL Conf 1995.