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PRECISION CURRENT MEASUREMENT AND CALIBRATION SYSTEM FOR THE APS-U UNIPOLAR MAGNET POWER SUPPLIES*

R. Keane†, J. Carwardine, A. Kreps, F. Rafael, J. Wang
Argonne National Laboratory, Lemont, IL, USA
C. Markvardsen, A. Marcussen, Danisense A/S, Taastrup, Denmark

Abstract

The APS Upgrade (APS-U) multi-bend acromat storage ring requires 1000 high-stability unipolar magnet power supplies. A precision current measurement and calibration system has been developed to independently measure the power supply output current to ensure the accuracy and repeatability of the supplies. The measurement system uses custom commercial DCCT current transducers along with APS-U-designed electronics. The calibration system is designed to perform on-demand calibration of all 1000 DC measurement channels simultaneously using a single current reference source instrument. The calibration system includes a precision current multiplier and impedance buffer based on a novel use of DCCT technology that provides a local precision calibration current for up to 6 DCCTs in series through multi-turn low impedance calibration windings. All system components have been received and passed acceptance testing; the full system is currently being installed in the new storage ring and full-scale evaluation will begin in early 2024. This paper describes the system design and presents preliminary test results.

SYSTEM REQUIREMENTS

Table 1 lists the system performance requirements derived from the APS-U design specification documents.

Table 1. System Performance Requirements

Specification	Value	Units
Primary DC Current	0 - 300	A
Linearity Error	2	ppm FS
Offset (uncorrected)	30	ppm FS
Resolution (DC)	2	ppm FS
Resolution (waveform capture)	100	ppm FS
Drift (7 days)	< 5	ppm FS
Magnet-to-magnet repeatability	< 100	ppm FS
Reproducibility after shutdown	< 10	ppm FS

SYSTEM DESIGN

Measurement System

The measurement system is based on standard DCCT sensors. DCCT-based current measurement is non-interrupting and capable of very high levels of accuracy and linearity [1]. The DCCT is an active device and provides an output current that is proportional to the primary current; in our DCCT the output current is reduce by a factor of 500. In order to read the output current with high accuracy it is converted to a voltage using a precision burden resistor mounted on a temperature-controlled copper block. Six resistors are mounted on each copper block, and the voltage across each resistor is digitized by both a precision (slow) ADC for DC measurements and a fast ADC intended for AC measurements and waveform capture diagnostics (see Fig. 1).

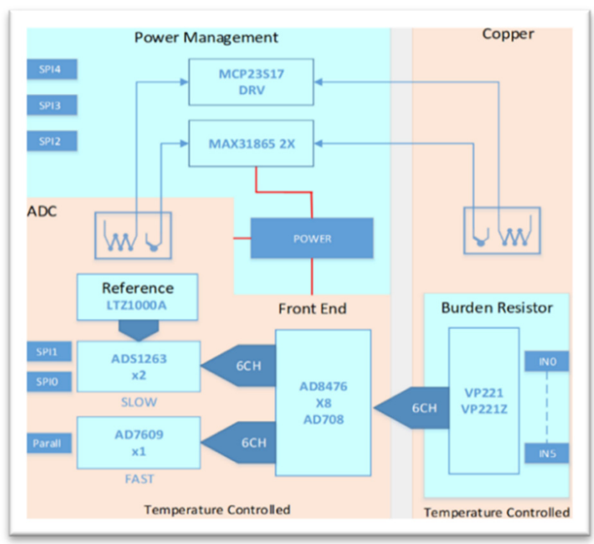

Figure 1: Measurement system components.

The burden resistors are housed in the APS-U-designed unipolar controller chassis, along with the ADC circuit board (see Figs. 2 and 3). The ADC data is sent to the controller baseboard via an SPI link. The baseboard also provides other power supply control functions that are independent of the measurement and calibration systems. The DCCTs are mounted on the power supply positive cables near the tunnel penetrations at the bottom of the

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† keane@anl.gov

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power supply cabinets. Each cabinet houses up to six supplies.

Figure 2: System hardware installed in P.S. cabinet.

The figure 2 photo shows an APS-U unipolar controller (top), DCCT interface with DB9 cables to 5 DCCT heads (middle), and a 200A magnet PS (bottom) mounted in a power supply cabinet on the storage ring mezzanine. Each PS cabinet can hold up to 6 power supplies. The 1U DCCT interface chassis includes the Ratio DCCT that provides calibration current in series to the local DCCTs via the DB9 cables.

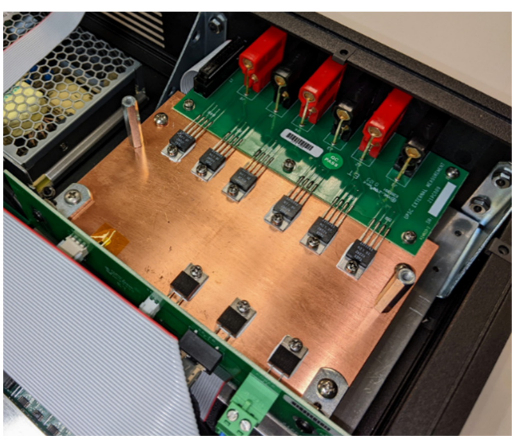
Figure 3: Temperature-controlled burden resistors.

Figure 3 shows six burden resistors (top row) mounted on the temperature-controlled copper block located inside the UPC chassis. The three lower resistors provide heating; the thermal sensor is to the left. The ADC board with separate fast (waveform) and slow (precision) ADCs is located beneath the ribbon cable. The burden resistors convert the DCCT output current to a voltage that is digitized by the ADCs [2]. The digital data is sent out via an SPI link to the main controller baseboard that provides a network link. Calibration factors are applied in software.

Calibration System

The calibration system consists of the following components:

- The calibration current source instrument.
- Ratio DCCTs, one in each of the 200 DCCT interface chassis, that act as an impedance buffer and 5x current multiplier.
- A custom 600 turn, low impedance (< 3.0Ω) winding in each DCCT head.
- A twisted pair shielded cable connecting the inputs of each Ratio DCCT in series around the ring and returning to the source instrument (200 segments totaling ~ 5800 ft.).

Table 2 contains the specifications of the calibration current source instrument (Krohn-Hite Model 523), and Table 3 lists the local calibration system requirements, i.e., those for each of the 200 DCCT interface units. The total impedance of the calibration current path must allow for the full calibration current to be sourced within the voltage limit of the source instrument, which has been achieved at about 730Ω, requiring about 73V @ 100mA source output.

The DCCT interface provides a DB15 connector for control and status monitoring. The Ratio DCCT input can be bypassed via a relay that will short the inputs through a resistor and route the calibration current to the next interface in the chain. Additionally, the Ratio DCCT output is routed through a second 2-pole relay that will direct the 5x calibration current to an internal resistor when calibration is not being performed. Both relays are controlled by the unipolar controller logic via the DB15 connector on the rear of the DCCT interface.

As far as we are aware, the Ratio DCCT is a new use of DCCT technology. Its role as a precision current multiplier and impedance buffer allows the use of an off-the-shelf, versatile, high precision current source instrument that is remotely controllable via GPIB and can be kept in calibration using standard methods.

Table 2. Reference Current Source Specifications

Resolution	Stability (24Hrs)	Max. Output
10 nA	± 2 ppm	±110mA ±110V

Table 3. Local Calibration System Specifications

Specification	Min.	Max.	Units
Number of DCCTs		6	
Reference Current Input	0	100	mA
Ref. Input Impedance		5	Ohms
Linearity Error	-2	2	ppm FS
Offset (uncorrected)	-30	30	ppm FS
Transfer Ratio Error	-20	5	ppm FS

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Ratio DCCT Performance

APS-U acceptance testing included measuring the Ratio DCCT performance over the full range of calibration current for all units. The ideal Ratio DCCT will multiply the input current by exactly a factor of 5; the specification allows for a range of -20 to +5 ppm.

Measuring two currents to single digit ppm accuracy over a 5x range is challenging, and describing the APS-U test setup is outside the scope of this paper. We are confident that our measuring apparatus is accurate to within +/- 2 ppm.

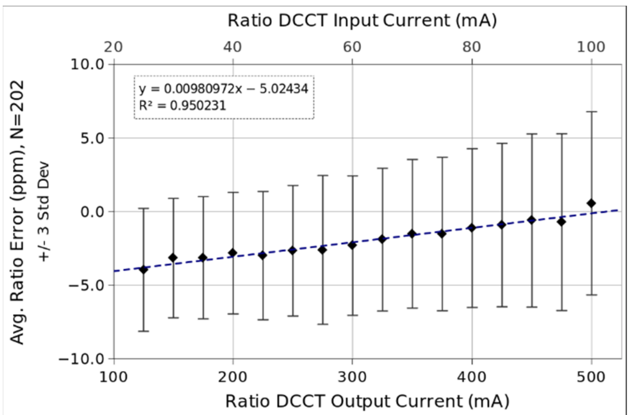

Figure 4: Average Ratio DCCT transfer error.

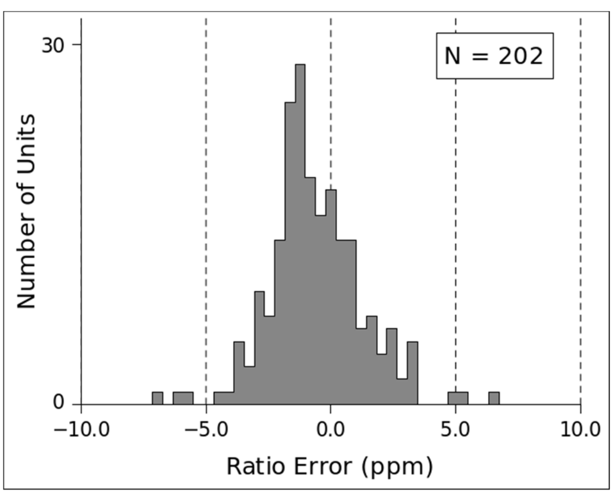

Figure 5: Histogram of Ratio DCCT transfer error at 90% full scale (450mA output).

Figures 4 and 5 show the results of acceptance testing of 202 of the 205 DCCT interface units (three outlying units are excluded from the data). Figure 4 shows the average Ratio DCCT transfer error for all units over the full current range. Figure 5 shows the transfer error at an input/output current of 90/450mA (90% F.S.), corresponding to a measurement DCCT primary current of 270A due to the 600-turn calibration windings in the DCCT head. The data confirm that the performance is adequate to meet the system requirements in Table 1. The data also show a linear error indicating a systematic origin in the Ratio DCCT and/or the measurement, which should be further investigated.

CURRENT STATUS

The measurement system includes two independent ADCs for each measurement channel. By design the fast measurement ADC is intended for waveform capture at a ~22KHz rate, and the slow ADC for precision DC measurements. Due to software and firmware delays, the precision ADC is not operational at this time; however, the fast ADC is fully functional and has been placed into service in the new storage ring to measure the DC magnet current for all 1000 power supplies, but with reduced accuracy and precision than that expected from the precision ADC. Calibration of all 1000 fast ADC DC measurement channels was performed successfully by calibrating each sector (25 channels) in sequence around the ring using a Python script to automate the process. We will continue development of the calibration software with the goal of simultaneously calibrating all 1000 channels in parallel.

CONCLUSION

All hardware has been installed for the APS Upgrade unipolar power supply external current measurement and calibration system. All components are operational, with the exception of the precision (slow) ADC. In initial testing the calibration system performed as expected at the precision available with the fast ADC measurement. We look forward to evaluating and characterizing the precision measurement system when it becomes operational in the near future. We plan to continue evaluating and improving the calibration and measurement software and automation of the calibration process.

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