HIGH PRECISION CURRENT CONTROL FOR THE LHC MAIN POWER CONVERTERS

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Abstract

Since restarting at the end of 2009, the LHC has reached a new energy record in March 2010 with the two 3.5 TeV beams. To achieve the performance required for the good functioning of the accelerator, the currents in the main circuits (Main Bends and Main Quadrupoles) must be controlled with a higher precision than ever previously requested for a particle accelerator at CERN: a few parts per million (ppm) of nominal current. This paper describes the different challenges that were overcome to achieve the required precision for the current control of the main circuits. Precision tests performed during the hardware commissioning of the LHC illustrate this paper.

LHC MAIN POWER CONVERTERS

The LHC is composed of 8 independent powering sectors. It can be considered as 8 accelerators placed end to end with one main dipole circuit and two main quadrupole circuits for each accelerator.

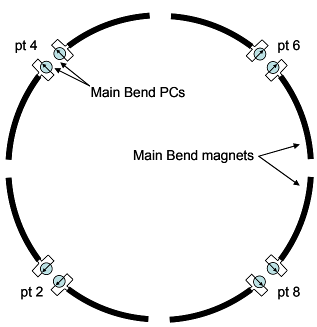


Figure 1: the 8 main dipole circuits.

To permit the two beams to circulate in the LHC and to be accelerated to high energies, the currents in the 24 main circuits (8 MB and 2x8 MQ) must be controlled with a precision of a few ppm or a few tens of milliamps, the nominal currents being approximately 13 kA. To achieve the required current precision for the main circuits, three main challenges have been resolved: (i) the generation of the 24 different current references and their synchronisation along the 27 km circumference of the LHC, (ii) the measurement of the 24 main currents with the same absolute high precision and (iii) the control of these 24 currents with high precision.

HIGH PRECISION CURRENT CONTROL

Remote Control

Each power converter (PC) in the LHC has a dedicated controls electronics unit known as a Function Generator/Controller (FGC). An FGC is an embedded microcontroller-based computer and is capable of performing full local state control, reference function generation and measurement acquisition as well as running a digital current regulation loop. Groups of up to 30 FGCs are connected to WorldFIP real-time fieldbuses (of which there are 73 in the LHC), each of which is managed by a gateway front-end computer that integrates the FGCs into the LHC control system [1].

The reference functions of the LHC power converters must be synchronised around the ring, particularly since the main dipole and quadrupole magnet circuits are divided into 8 independently powered sectors. In order to achieve this, each gateway has a timing receiver connected to the LHC timing network, providing GPS-synchronised UTC time and LHC timing event data. The timing signal is used to generate a UTC-aligned 50Hz trigger to synchronise the cycles of all WorldFIP buses. Each FGC uses the start of each WorldFIP cycle in a phase-locked loop to discipline the frequency of its local clock to within 10^{-7} and with a jitter of less than 1µs [2]. In the cases where either the LHC timing signal or WorldFIP traffic is lost, the FGCs can continue to run their references for some time within the required performance constraints.

Reference functions across multiple power converters must be started at the same time. This may involve the main magnet circuits across the 8 powering sectors or groups of power converters involved in trims or squeezes. Synchronisation of the starting and aborting of references is achieved using timing events sent over the LHC timing network. These events are received by the gateway computers and are relayed over the WorldFIP buses to the connected FGCs. An event consists of an ID which indicates whether a start or abort is being requested, and a data payload. The payload is used to identify the group of power converters for which references are to be started or aborted. FGCs are configured in advance to be triggered by a particular payload value, allowing power converters to be grouped arbitrarily.

Current Measurement

The LHC main power converters output current accuracy and reproducibility is greatly determined by the DCCT (Direct Current Current Transducer) and ADC (Analogue-Digital Converter) employed.

The accuracy requirements for the LHC main power converters have led to the development of a new generation of DCCTs [3] and a new ADC design with 22 bit resolution [4].

The DCCTs are equipped with 5A calibration windings for easy on-line calibration. A very sophisticated burden resistor is used for the voltage-to-current conversion and an output amplifier is necessary to keep dissipation in the burden down to a reasonable level.

The DCCTs were delivered calibrated by the manufacturer and verified in specially built 6kA and 20kA test beds [5] before installation. In particular, the correspondence between real primary current and current injected in the calibration winding was measured to the best possible accuracy.

As for the ADC, a Delta-Sigma converter capable of delivering 22-bit resolution at 1 kHz output data rate was developed at CERN for this application. Its stability and linearity have been verified as part of routine performance checks after manufacturing and proved to be in the sub-ppm range.

To ensure the best accuracy possible, the main power converters' DCCTs and ADCs are installed in EMC, temperature controlled racks. Temperature is regulated to 23°C ± 0.5°C. The output of the ADC is transmitted to the digital controller via fibre optics.

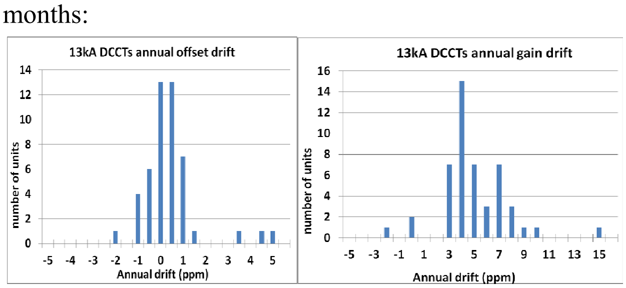
The accuracy of these devices needs to be maintained over the life of the accelerator. Maintenance includes periodic calibration to contend with long-term drift, and verification after repair or exchange:

- The calibration of the ADC is performed by applying a short circuit, +10V and -10V in sequence to the input, as the design is inherently bipolar. The values of the errors are recorded in the digital controller (FGC).
- For the DCCTs a 5A reference current is injected into the DCCT calibration winding producing the same Ampere-turns as the primary current. The output of the DCCT is then measured using the (calibrated) Delta-Sigma ADC and the value of the error is recorded in the digital controller (FGC).

Both DCCT and ADC errors are stored locally in the FGC and also in a central database. The digital values are used to continuously calculate the primary current from the DCCT output value.

For the calibration in the tunnel, a remote controlled calibration system is installed in the tunnel, in the same EMC, temperature controlled racks as the DCCTs and ADCs. This calibration system includes a ppm accurate programmable current reference: the CERN DCCT Calibrator (CDC) [6] and a switching system that allows three converters to be calibrated by a single CDC.

The following pictures Figure 2 shows annual drifts for the DCCTs and ADCs on the LHC main power converters, resulting from calibration data from the last 12 months:



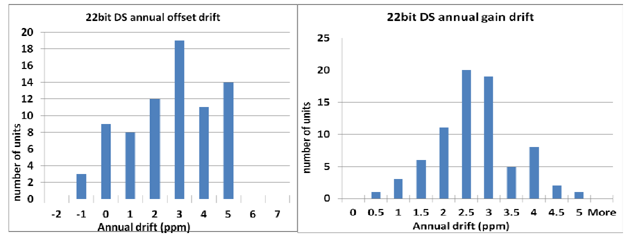


Figure 2: Annual DCCT and ADC drifts.

Current Loop

To achieve the high precision requested for the control of the currents in the LHC main circuits, CERN chose to use an RST digital current loop, implemented within each power converter's digital controller (FGC) [7].

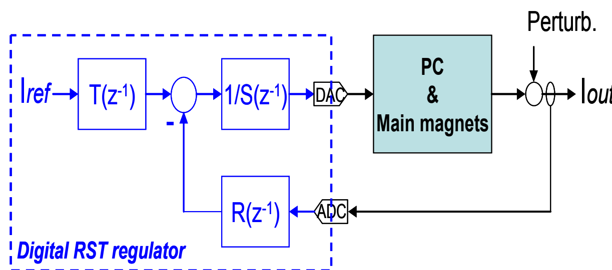


Figure 3: Digital RST regulator.

This type of current loop has the advantage of decoupling the issues of tracking (follow of the reference) from the issues of regulation (rejection of perturbations).

$$\begin{cases} \dfrac{I_{out}}{I_{ref}} = z^{-1} \\ \dfrac{I_{out}}{p} = \dfrac{N\left(z^{-1}\right)}{D\left(z^{-1}\right)} \end{cases}$$

The perturbations mainly originate from the AC electrical distribution network and they are rejected by the power converter voltage loop whose bandwidth is between 100 Hz and 1 kHz, but with a low precision, in the order of 1 %.

The role of the current loop essentially is to follow the current reference sent by the LHC control room with high precision (in the order of ppm) and to compensate for the imperfection of the model used to define the current loop. In this case, the bandwidth of the current loop can be relatively low, between 0.4 and 1 Hz, and the current loop sampling period can be relatively large (0.1 s).

This strategy of control is particularly well adapted for superconducting magnet strings which have high inductances and time constants (16.6 H and 20'000 s for the MB circuits and 0.25 H and 250 s for the MQ circuits). It avoids unstable zeros due to a too small sampling period of the current loop and allows the current reference to be followed with high precision without tracking error or overshoot and minimizes voltage noise at the power converter output which can affect the beam.

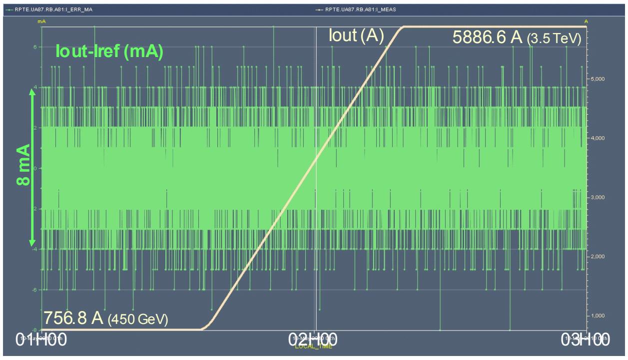


Figure 4: Ramp to 3.5 Tev for RB.A81 circuits.

TRACKING TESTS

To validate the global performance of the LHC power converters before the beam commissioning phase, several accuracy tests, called Tracking Tests, were performed during the Hardware Commissioning of the accelerator.

For each sector, these tests validated that the three main power converters were able to follow the same current reference sent from the LHC control room with an accuracy of a few ppm.

As the FGCs of the main circuit power converters are equipped with two external 22-bit ADCs which can read with high precision the output current of the converter, an inversion of the connections between the ADCs of the three main power converters was used to measure the global accuracy of the three main circuits. This inversion has been facilitated by the fact that the DCCTs and the ADCs of the three main circuits of a same sector are located in the same calibration racks.

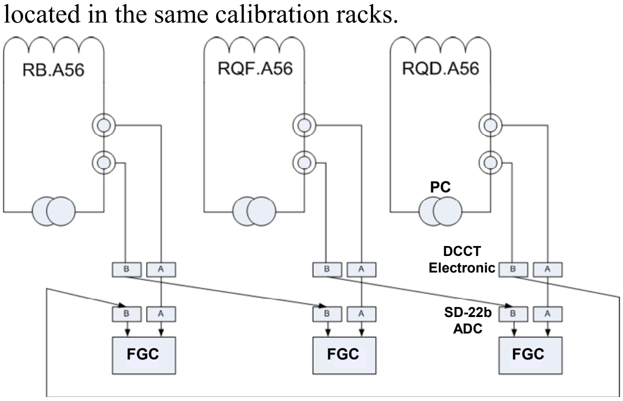


Figure 5: Tracking test configuration.

For two adjacent sectors, the tests compared only the performance of the main quadrupole power converters.

Special fibre-optic cables were installed between the 22-bit ADCs and the FGCs to verify that the main quadrupole power converters of two adjacent sectors were able to follow the same current reference sent from the LHC control room. As the length of the fibre-optic cables was less than 500 m, the signal propagation time of less than 0.1 µs has been ignored.

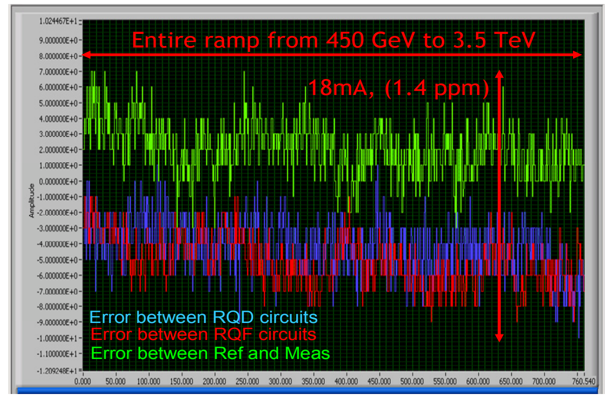


Figure 6: Tracking test results.

Figure 6 shows the results obtained during the tacking tests between sector 12 and sector 23. The tracking error between the two sectors is less than 20 mA or 2 ppm.

CONCLUSION

The LHC requires a precision for the control of the main circuit currents never reached before for an accelerator at CERN, mainly due to the division of the machine into eight independent machines from a powering point of view. This paper has shown how the objective has been achieved and how the main challenges have been solved.

Various developments made for the LHC are now being used in consolidation programs for improving the performance of the older machines at CERN.

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