EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1155

PERFORMANCE OF THE SUPERCONDUCTING CORRECTOR MAGNET CIRCUITS DURING THE COMMISSIONING OF THE LHC

W. Venturini Delsolaro[1], V. Baggiolini[1], A. Ballarino[1], B. Bellesia[1], F. Bordry[1], A. Cantone[1], M. Casas Lino[1], A. Castaneda Serra[1], C. Castillo Trello[1], N. Catalan Lasheras[1], Z. Charifoulline[1], C. Charrondiere[1], K. Dahlerup-Petersen[1], G. D'Angelo[1], R. Denz[1], S. Feher[2], R. Flora[2], M. Gruwe[1], V. Kain[1], M. Karppinen[1], B. Khomenko[1], G. Kirby[1], A. MacPherson[1], A. Marqueta Barbero[1], K.-H. Mess[1], M. Modena[1], R. Mompo[1], V. Montabonnet[1], S. le Naour[1], D. Nisbet[1], V. Parma[1], M. Pojer[1], L. Ponce[1], A. Raimondo[1], S. Redaelli[1], V. Remondino[1], H. Reymond[1], G. de Rijk[1], A. Rijllart[1], I. Romera Ramirez[1], R. Saban[1], S. Sanfilippo[1], K. Schirm[1], R. Schmidt[1], A. Siemko[1], M. Solfaroli Camillocci[1], Y. Thurel[1], H. Thiesen[1], A. Vergara Fernandez[1], A. Verweij[1], R. Wolf[1], M. Zerlauth[1]

Abstract

The LHC is a complex machine requiring more than 7400 superconducting corrector magnets distributed along a circumference of 26.7 km. These magnets are powered in 1446 different electrical circuits at currents ranging from 60 A up to 600 A. Among the corrector circuits the 600 A corrector magnets form the most diverse and differentiated group. All together, about 60000 high current connections had to be made. A fault in a circuit or one of the superconducting connections would have severe consequences for the accelerator operation. All magnets are wound from various types of Nb-Ti superconducting strands, and many contain parallel protection resistors to by-pass the current still flowing in the other magnets of the same circuit when they quench. In this paper the performance of these magnet circuits is presented, focussing on the quench behaviour of the magnets. Quench detection and the performance of the electrical interconnects will be dealt with. The results as measured on the entire circuits are compared to the test results obtained at the reception of the individual magnets.

1 CERN, Geneva, Switzerland
2 FNAL, Batavia, Illinois, USA

Presented at the 11th European Particle Accelerator Conference (EPAC'08)
23-27 June 2008, Genoa, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 20 August 2008

PERFORMANCE OF THE SUPERCONDUCTING CORRECTOR MAGNET CIRCUITS DURING THE COMMISSIONING OF THE LHC

W. Venturini Delsolaro, V. Baggiolini, A. Ballarino, B. Bellesia, F. Bordry, A. Cantone,
M. Casas Lino, A. Castaneda Serra, C. Castillo Trello, N. Catalan Lasheras, Z. Charifoulline,
C. Charrondiere, K. Dahlerup-Petersen, G. D'Angelo, R. Denz, M. Gruwe, V. Kain, M. Karppinen,
B. Khomenko, G. Kirby, A. MacPherson, A. Marqueta Barbero, K.-H. Mess, M. Modena,
R. Mompo, V. Montabonnet, S. le Naour, D. Nisbet, V. Parma, M. Pojer, L. Ponce, A. Raimondo,
S. Redaelli, V. Remondino, H. Reymond, G. de Rijk, A. Rijllart. Romera Ramirez, R. Saban,
S. Sanfilippo, K. Schirm, R. Schmidt, A. Siemko, M. Solfaroli Camillocci, Y. Thurel, H. Thiesen,
A. Vergara Fernandez, A. Verweij, R. Wolf, M. Zerlauth,
CERN, Geneva, Switzerland

S. Feher, R. Flora, FNAL, Batavia, Illinois, USA

Abstract

The LHC is a complex machine requiring more than 7400 superconducting corrector magnets distributed along a circumference of 26.7 km. These magnets are powered in 1446 different electrical circuits at currents ranging from 60 A up to 600 A. Among the corrector circuits the 600 A corrector magnets form the most diverse and differentiated group. All together, about 60000 high current connections had to be made. A fault in a circuit or one of the superconducting connections would have severe consequences for the accelerator operation. All magnets are wound from various types of Nb-Ti superconducting strands, and many contain parallel protection resistors to by-pass the current still flowing in the other magnets of the same circuit when they quench. In this paper the performance of these magnet circuits is presented, focussing on the quench behaviour of the magnets. Quench detection and the performance of the electrical interconnects will be dealt with. The results as measured on the entire circuits are compared to the test results obtained at the reception of the individual magnets.

INTRODUCTION

The correction circuits represent 92% of the LHC magnet system in number of circuits and a large share of the commissioning workload, due to their diversity. Commissioning procedures have been prepared, detailing the levels of current to be reached, the nominal current ramp rates, and accelerations. Following these, each circuit must go through specific tests to qualify the quench protection systems, the regulation of the power converter on the load, the bus bars, interconnects and the magnets themselves. The commissioning steps are implemented in software sequences and most tests are run in automatic mode from the CERN Control Centre.

At the time of writing three LHC sectors (45, 56, and 78) have been commissioned to various degrees. We focus here on sectors 56 and 78 whose corrector circuits have been completely commissioned.

MAGNET TYPES, TARGETS

Compared to the main magnets, the LHC correctors operate rather far from the critical current (table 1).

On the other hand, the challenge of mass production called for a cheap and robust design [2], with relatively large mechanical tolerances. Therefore some training could be expected and was indeed observed in production.

Table 1: Performance parameters of LHC correctors. Stored energies refer to the circuits with maximum number of magnets, for any given magnet type.

Magnet	*Nominal Strength (Tm at 0.017m)*	*Nominal Current (A)*	*Max Stored energy [kJ]*	*Fraction of Ic at 1.9K (4.2K)*
MCD MCO	0.00661 0.00266	550 100	4.7 0.15	0.44 (0.60) 0.34 (0.51)
MCS	0.0518	550	18.6	0.42 (0.58)
MS	0.472	550	65.3	0.62 (0.84)
MO	0.0990	550	3	0.42 (0.60)
MQT/S	0.669	550	37.5	0.58 (0.82)
MCB	1.876	55	9.1	0.57 (0.77)
MQTL	2.718	550	57.6	0.58 (0.82)
MCBC	2.802	100	14.2	0.58 (0.79)
MCBY	2.248	72	13.6	(0.60)
MCBXH	1.565	550	43.4	0.44

Many corrector magnets are connected in series in the machine to form circuits that in some cases extend over one machine sector and can include up to 154 magnets.

The voltage signals used for quench protection are always taken across the whole circuit.

MCB/MCBC and MCBY (orbit correctors) are individually powered and only protected though their power converters whereas all 600 A circuits rely on a dedicated quench detection system (QPS) [3]. In this case, the quench detection in the QPS is based on the absolute measurements of the current and voltage on the cold part of the circuit. The measured current (I) is differentiated to get dI/dt which, together with the current dependent inductance, gives the inductive voltage. The latter is subtracted from the total measured voltage to give the quench signal in real time. Detection thresholds are set at 0.1 V and the discrimination time- to filter off spikes- is 10 ms. The protection system acts by switching off the power converter, and in many cases by extracting energy in external dump resistors and/or bypass resistors [5].

In the commissioning campaign currently under way, all corrector circuits will be qualified up to a maximum current deemed sufficient for beam operation at 5 TeV. In most cases, the nominal design current of 550 A is used, but for some circuits that was reduced to 400 A to save commissioning time. Some MQTL circuits known to contain weaker performers have already been installed in slots where the requirements from the optics are low; their nominal current is 300 A.

Part of the commissioning effort goes in insuring that the circuits can be operated at the required current ramp rates and accelerations, as high values of these parameters can induce spurious signals in the quench detectors.

The achieved current ramp rates and accelerations range from 1 to 5 A/s and from 0.1 to 1 A/s^2 respectively. These comply with the anticipated constraints arising from the energy ramp, beta squeeze, and from the beam based feedback.

COMMISSIONING ISSUES

60/80/120 A circuits (orbit correctors)

No major issues were found on these circuits. Being cryogenically and electrically decoupled, it was possible to run tests in parallel, resulting in high execution efficiency. In view of the high number of these circuits, fully automatic analysis tools were made available since the start of the commissioning campaign.

600 A circuits

Compensation of inductive voltages for QPS

As detailed above, the protection technique adopted relies on the detailed knowledge of the non linear inductance L(I). The inductance curves of all types of magnets were carefully measured in laboratory before the start of the commissioning campaign and stored in the quench detectors. The accuracy of the compensation is checked with a bipolar current cycle at ± 45 A. The detection threshold is kept at 2 V below 50 A to allow first powering and to cope with the hysteretic behaviour of the inductance.

Check of circuit splices

The cable used for the circuit bus-bars is cryostable below about 200 A [4], where hot spots can exist without quench propagation; therefore care must be taken when first powering a circuit as the numerous splices of the circuits see current for the first time. A dedicated test at ± 200 A is carried out whereby the resistance of the cold part of the circuits is estimated.

Zero voltage crossing upon ramp down

During ramp down the inductive voltage momentarily equals the resistive drop on the warm cables and the current leads. At this time, the power converter has to output a vanishing voltage and small voltage oscillations develop for a very short time. Occasionally this caused spurious triggers from the QPS. The problem was tackled in the QPS by using a non-linear median filter and, when possible by modifying the nominal dI/dt to shift the occurrence of the oscillation below 50 A, where the detection threshold is higher.

Quenches during fast discharges

As the values of the extraction resistors are standardized at 0.7 Ω, current decay can be very fast for the low inductance circuits. As a result some magnets quench due to the heat generated in the parallel resistors and by eddy currents in the magnet during the discharge. Fig. 1 shows an example, in the case of a sextupole circuit. This behaviour is not a problem for beam operation, but the magnets are submitted to unnecessary thermo mechanical stresses.

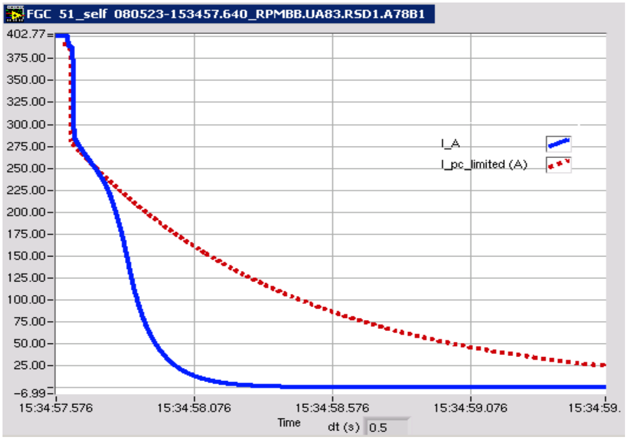

Figure 1 Quench during discharge in a sextupole circuit. The dashed line is the expected current decay with no quench

EMC

The bus bars of the corrector circuits run parallel in ducts across the continuous cryostat. As a consequence, some circuits are magnetically coupled. In some cases a fast power abort in a circuit will be propagated to the other ones, with possible impact on the efficiency of beam operations. Like the quenches during discharge, this phenomenon is caused by the very short time constants for some circuits.

TRAINING QUENCHES

All corrector magnets have been cold tested in industry or at CERN, and trained up to nominal field. Re-training after thermal cycle has been observed in most cases, but typically related to production flaws that were fixed and should not be represented in the installed machine.

Table 2 Statistics on number of quenches to reach nominal field during production. For the spool pieces the number indicates the producer

magnet	average	sigma	Retraining
MCO (1)	0.32	0.65	YES
MCD (1)	0.39	0.61	YES
MCO (2)	0.01	0.09	YES
MCD (2)	0.01	0.1	YES
MO	0.07	0.35	NO
MS	0.31	0.65	yes
MCS (2)	0	0.07	NO
MCS (1)	0.03	0.26	NO
MQTL	**17.87**	14.09	YES
MQS	**7.03**	2.56	YES
MQT	**6.15**	3.11	YES
MCB	1.94	1.54	YES
MCBC	2.96	1.51	YES
MCBY	1.18	0.9	NO

Natural quenches during machine commissioning were only observed in a few families of magnets: the spool pieces circuits, one MS, one MO, the MQTL and MQT, as expected from the production statistics (table 2).

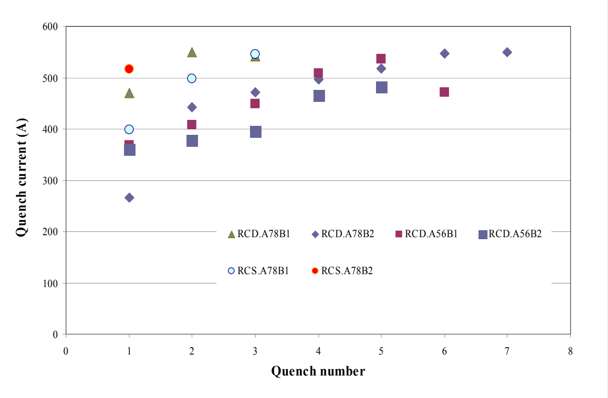

Fig. 1 Quenches of the spool correctors during commissioning

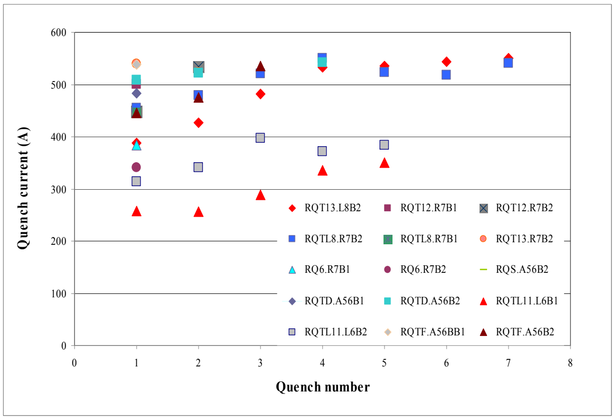

Figure 2 Quenches of MQTL and MQT magnets during commissioning

CONCLUSIONS

Hardware commissioning of the LHC corrector circuits is proceeding well. The performance targets defined for the first run of the LHC at 5 TeV have been met so far in two sectors of the machine. The main difficulties that had to be solved arose from the absolute detection technique used for quench protection, and from the coexistence of tight detection thresholds with the high precision standards of the power converters.

A few natural quenches were observed in the spool pieces chains containing 154 or 77 magnets, and in the MQT and MQTL circuits, which were known from production to require some training to reach nominal field.

The total number of training quenches was 38 in sector 7-8 and 30 in sector 5-6.

It should be noted that corrector quenches are easily absorbed by the cryogenic system and thus represent a negligible overhead on the commissioning time.

REFERENCES

[1] LHC design report, on http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html

[2] D. E. Bayham, R. C. Coombs, A. Ijspeert, R. Perin, “Design of superconducting corrector magnets for LHC” IEEE, Trans. Magnetics 30, 1823-1826 (1994)

[3] R. Denz, K. Dahlerup-Petersen and K. H. Mess; “Electronic systems for the protection of superconducting devices in LHC”, this conference

[4] M. Calvi, L. Bottura, F. Rodriguez-Mateos; “Proposed Method for the Verification of the LHC Bus Bar Splices during Commissioning at Cryogenic Conditions” CERN-LHC-PROJECT-Report-1004

[5] G.-J. Coelingh, K. Dahlerup-Petersen, A. Erokhin, K. Gorchakov and A. Medvedko “Design and Commissioning of the Energy Extraction Systems for the LHC Corrector Magnet Circuits”. Presented at the IEEE International Power Modulator Conference 2008, Nevada, USA.