STUDIES ON THE LHC SUPERCONDUCTING CIRCUITS AND ROUTINE QUALIFICATION OF THEIR FUNCTIONALITIES

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Abstract

The Large Hadron Collider (LHC) is systematically undergoing periods of maintenance stop (either 4-5 days stops or longer Christmas breaks), after which some or all superconducting circuits have to be re-commissioned to check the correct functionality of all powering and protection systems. Detailed procedures have been developed during the past few years and they have been optimized to increase powering tests efficiency, thus reducing beam downtime. The approach to the routine qualification of the LHC powering systems is described in this paper.

During the technical stops in 2011 various studies on the superconducting circuits were performed, to assess the quality of the superconducting splices of individually powered magnets and to study the quench propagation in the main magnet bus-bars. The methodology of these tests and some results are presented.

INTRODUCTION

In its first years of operation, the CERN Large Hadron Collider (LHC) has known three long stops, one unforeseen stop after the 2008 incident in one of the sectors of the machine [1] and two planned stops. The two planned stops are part of the chosen operational mode, which foresees continuous running from February-March until December and a so-called Christmas break. The Christmas break is used to perform preventive maintenance and upgrades, needed for a safe and reliable operation, leading to reduced downtime all along the year.

At the end of such long technical stops a period of requalification of all systems is mandatory to check their correct functionality. During these stops, hundreds of people access the machine to carry out a large number of interventions on the electrical circuits or in their vicinity. For some circuits the warm cables are disconnected from the cold part of the circuits.

Together with the long technical stops, regular maintenance periods are organized during the year, to keep the reliability of the machine at high level. This is a different approach from what is done in other accelerators, but has demonstrated its efficiency in the past two years of operation.

During these periodic technical stops (performed each 6-8 weeks), interventions on the electrical circuits are kept to a minimum and there is no need for general circuit re-commissioning. However, the regular technical stops are used to carry out specific repairs and tests, after which a partial re-commissioning of the circuits is needed.

PERIODIC REQUALIFICATION OF THE LHC SUPERCONDUCTING CIRCUITS

Restart of the Machine after a Long Stop

During the Christmas break there is a large number of interventions on the superconducting circuits and a global re-commissioning is mandatory. In particular, the superconducting circuits have to be re-validated to confirm their soundness, the integrity of the protection functionalities and the absence of electrical or mechanical non-conformities. Furthermore, cryogenics experts are intervening on their systems, the magnets are consequently left floating and the temperature increase up to 80 K. The magnets are exposed to thermal excursion that could cause damage of the mechanical integrity of the busses or the weakening of the electrical insulation. A guideline [2] was drawn on the maximum temperature excursion that could be accepted for a superconducting circuit and the tests to be performed by the Electrical Quality Assurance (ElQA) team.

Finally what is needed is an almost complete requalification of the superconducting circuits.

The strategy of these powering tests is as described in other papers [3, 4], with the LHC Operation group coordinating and executing the tests and a pool of experts assisting, to certify the correct operation of the circuits and their protection functionalities.

Detailed powering procedures were defined together with the equipment owners and magnet experts in 2007, and they have been modified in the course of the years to take into account new constraints. The procedures were optimized to reduce the number of test steps needed. Test steps include the number of powering cycles used to validate the soundness of a superconducting circuit, the correct operation of its power converter, quench protection system and powering interlock, and their reliable interface, which constitute the basis of the protection logic. The result of this exercise was a reduction of the number of test steps from the 11-12000 of the previous commissioning campaigns down to less than 7000 in 2011 and 2012.

Besides the optimization of test steps, a substantial reduction of time needed for the powering tests came from the improved parallelism and from the optimization of the activity flowchart. The time required for the preparation of all LHC superconducting circuits for the beam commissioning was drastically reduced to less than four weeks in the two last Christmas breaks.

Two major improvements were very important, in view of the rationalization of the powering test activities, in 2012: the introduction of electronic signatures for the

ISBN 978-3-95450-115-1

preparatory phases, prior to circuit powering, and new software including a new GUI for the tracking of the commissioning tests [5]. Electronic signatures were essential to allow a rigorous follow-up of the activities and to avoid the erroneous powering of any circuit. The new software was very effective to simplify testing by the operations team. Test inter-dependences and the automatic checking of all possible parallel powering is part of the new software (taking into account all conditions of magnetic cross-talk and global protection of the circuits in the same powering area).

Thanks to an accurate coordination of the preparation of the powering campaign and of its execution and to the commitment and dedication of a pool of well-trained persons at the beginning of this year, 8395 tests steps were successfully executed on 1572 LHC superconducting circuits. Several electrical non-conformities were identified, which are as well a witness of the efficiency of the overall strategy for quality control.

'Zero-quench' Strategy

The proposal of increasing the operation energy for 2012 to 4 TeV from the previous 3.5 TeV level was endorsed by CERN management. One of the conditions for safe operation at 4 TeV was a reduced number of quenches of the main dipole (RB) magnets during the course of the year. To reach this target, some ad-hoc procedures were developed at the beginning of the commissioning to ensure a minimum risk of quench during the powering tests of the RB circuits when the current is above few kA, which would equally ensure a high reliability in operation.

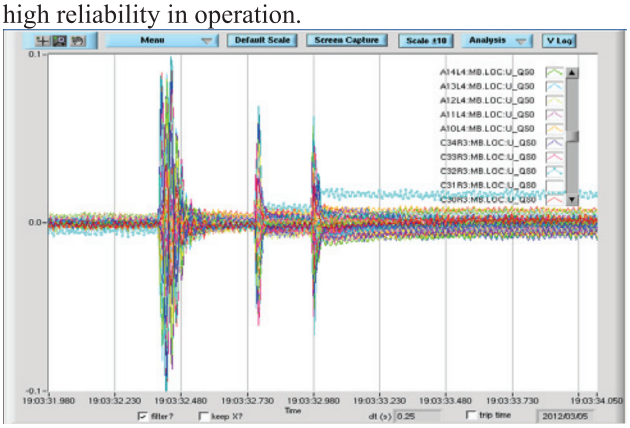

Figure 1: snapshot for the QS0 signals in one LHC sector.

The first step of the so-called 'zero-quench' strategy is an energy extraction during a current ramp at about 2 kA. This is the most stressing condition for the dipole circuit, when the stop of the power converter produces a ringing that propagates into the circuit as a voltage wave, followed by a similar signal coming from the first switches opening and another one originated by the second switches [4]. An example of this behaviour is shown in Figure 1, where the voltages across all magnets in a sector are recorded using the QS0 signals coming from the nQPS boards, which protect the magnets from quenches. In case one (or more) of the signals showed some offset (as in Figure 1), a careful analysis was done to release the circuit for operation at 6.85 kA (4 TeV). The offset is measured and scaled to 6.85 kA. If it could exceed the detection threshold of 100 mV, an action was be taken:

- change the detection board for non-conform boards;
- increase the detection threshold, in case of unbalanced magnet [6].

By adopting this strategy, several issues were identified and treated and not a single quench happened during the commissioning of the circuits.

Requalification after a Technical Stop

Five technical stops were performed in 2011, evenly distributed along the year, to allow the equipment owners to carry out interventions to ensure a minimum downtime of the machine with the maximum effort focused in 4-5 days.

In particular, the cryogenics group, the cooling & ventilation group, the power converter group and the QPS team performed many interventions, either as preventive maintenance or to fix anomalies and non-conformities observed during the operation of the machine. Often these interventions required a re-commissioning of the affected circuits: 866 powering tests were performed on the superconducting circuits, during or at the end of the technical stops. These tests had to be organized to guarantee the presence of the needed conditions (cryogenics, cooling of the power converters, no electrical power cut, etc.). Most tests were performed during night, to avoid interference with the daily activities in the tunnel. Sometimes, due to the lack of one of the conditions, they had to be performed at the very end of the technical stop when the machine was closed for beam operation; this could lead to a delay in the restart of the machine and should be avoided.

SPECIAL STUDIES ON THE SUPERCONDUCTING CIRCUITS

The technical stops in 2011 were also used to perform some special tests that could not be completed during the powering test campaign at the end of the year, or were proposed later. Examples are interconnection splice resistance measurements (ISRM) on individually powered magnets and quench propagation tests. Both series of tests were of great importance for the operation of the machine, and time was allocated for them.

ISRM on Individually Powered Magnets

Following the incident of 2008, it was decided that all high current superconducting splices in the LHC should be mapped to eventually spot outliers limiting the machine performance (to be fixed in a long shut-down). The main (13 kA) circuits were tested already since the end of 2008 using different methods; the individually powered magnets (single quadrupoles and dipoles on stand-alone circuits) were not measured. A measurement method was therefore developed by the ElQA team [7], which allows measuring the voltage over the interconnection busbars for these circuits, by means of specific powering cycles, as shown in Figure 2. The voltage taps used for these measurements are the same used by the QPS to protect the magnets in case of quench, and a special interface to re-route the signals was developed. Once installed, the whole apparatus is high-voltage tested to ensure that no insulation fault can compromise the circuit safety, when energized.

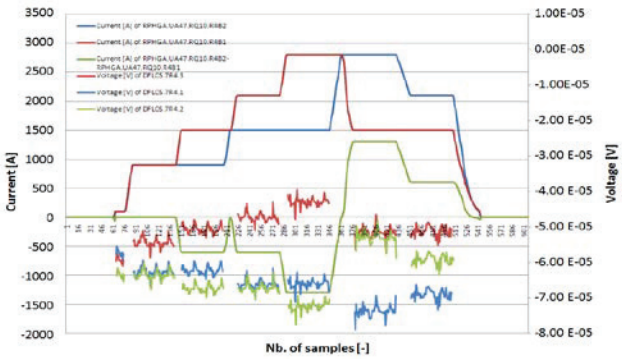

Figure 2: powering cycle for the ISRM tests on IPQs.

The acquisition system is based on a NI-PXI® that ensures (with the chosen setup) a precision of 50 nV in the measured voltage. In Figure 2, an example of the voltage signals recorded at the different current values is shown: on a voltage-current characteristics, the resistance of the splices under investigation is derived.

All IPQs (78 magnets) and IPDs (12 magnets) were tested by the end of 2011, profiting mainly of the technical stops. The result of these measurements (see details in [7]) was an average resistance value per splice of 1nΩ, with a maximum value of 1.8 nΩ. Even when powered to their maximum current, these splices would generate a negligible thermal charge of few tens of mW. All splices are therefore considered safe for operation.

During the 2012 re-commissioning campaign, the interconnection splices of the Inner Triplets and associated dipole magnets were as well tested. The results were similar and all splices are considered equally sound.

Quench Test

In Chamonix 2011, the request came to check the possibility for a 13 kA circuit quench to propagate through the bus-bars and eventually damage them in case of non-conform splices. When a quench occurs, the voltage drop inside the magnet is increasing; the diode starts conducting and the current flows inside the bypass line (red line in Figure 3). The diode is resistive and starts to heat up and the heat could propagate through the cable up to the splice and eventually quench it. Tests were therefore performed in 2011 technical stops, where some of the magnets of a sector were artificially quenched by firing the quench heaters and the voltages all along the bypass line were recorded. Interesting results emerged from these tests. At half of nominal current, the propagation through the line arrives up to few cm from the splice (translated to full current this means a clear propagation through the splice).

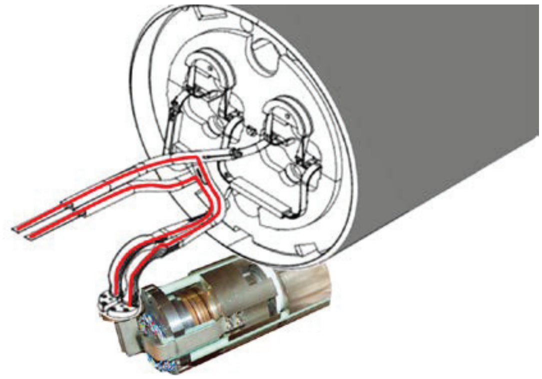

Figure 3: dipole bypass path; the red line indicates the flow of current in case of a quench.

The most interesting (and surprising) result came from the voltages recorded over the diodes. It turned out that the diodes plus the connections with the busses have a resistance that sometimes exceeds the maximum acceptable: values as large as 48 μΩ were observed on one branch of the diode circuit in one of the magnets tested [8]; if a quench at high current occurred on one of the magnets with high resistance in the bypass line, the diode and the line could be seriously damaged, with important consequences on the whole dipole circuit.

If the splice will be consolidated in 2013-14, no systematic action is for the moment foreseen on the diodes.

ACKNOWLEDGMENT

The authors would like to thank all persons who constantly and indefatigably participate in the powering tests.

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ISBN 978-3-95450-115-1