COMMISSIONING OF THE LHC MAGNET POWERING SYSTEM IN 2009

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Abstract

On 19th September 2008 the Large Hadron Collider (LHC) experienced a serious incident, caused by a defective electrical joint, which stopped beam operation just a few days after its beginning. During the following 14 months the damage was repaired, additional protection systems were installed and the measures to avoid a similar incident were taken, i.e. new layer of the Magnet Quench Protection System (nQPS) and more efficient He release valves. As a consequence, a large number of powering tests had to be repeated or carried out for the first time. The re-commissioning of the already existing systems as well as the commissioning of the new ones was carefully studied, then performed taking into account the history of each of the eight LHC sectors (either warmed-up or left at floating temperature). Moreover, a campaign of measurements of the bus-bar splice resistances as well as the ones internal to the cold masses was carried out with the original and the nQPS in order to spot out non conformities, thus assessing the risk of the LHC operation for the initial energy level. This paper discusses how the guidelines for the LHC 2009 re-commissioning were defined, providing a general principle to be used for the future re-commissioning.

THE INCIDENT IN 2008 AND ITS CONSEQUENCES

Shortly after its start-up with beam, on 19th September 2008, the LHC was stopped by a serious incident [1]: a defective electrical joint between a dipole and a quadrupole cryostat in one of the eight sectors (sector 34) heated up when operating at a current of 8.7 kA due to an excessive joint resistance. Because of the high temperature generated, a part of the cable was melted and an electric arc developed, vaporizing both dipole bus bars at the location of the arc, as well as the pipe around them, thus breaking open the helium enclosure of the cold mass and releasing helium into the insulation vacuum of the cryostat. Also the beam vacuum pipes were locally destroyed, thus polluting the vacuum system with soot and debris for several hundred meters. Major damage was caused by the fast discharge of helium into the insulation vacuum space and the resulting overpressure caused a displacement of several magnets.

During the shutdown, compensatory measures were adopted to reduce the probability of having such an incident and to limit possible damage. Part of these measures (strengthening of the anchoring system of the magnets) could be implemented with the cold masses floating at low temperatures; for others (namely the installation of new DN200 relief valves on the cryostats) the warm-up of entire sectors was required. Five sectors were brought to room temperature, thus needing a complete requalification of all circuits. Measurements on copper continuity of the busbar splices were also performed on those sectors. The increase of temperature for the other sectors was nevertheless high enough to require a verification of the electrical integrity and subsequent powering test validation. Furthermore, an upgrade of the quench protection system was performed in all sectors, implying the necessary requalification of all main circuits in the entire machine. A hardware commissioning campaign for all LHC was therefore mandatory.

The new access rules

After the incident, all safety systems and rules were reviewed and an update of the risk analysis for the powering of the superconducting circuits was performed. The rules to ensure personnel safety during powering tests, applied before 19th September 2008, considered two different cases, unrestricted access with people allowed in the underground areas, or forbidden access during powering test for currents higher than 1 kA.

In the light of the data recorded during the incident on He density, quantity and movement, a task force was mandated to review these rules. The outcome of the analysis [2] was used to define the new safety rules [3]:

- Powering phase I (energy stored in the powered circuits smaller than 100kJ) - intervention related to powering tests allowed in the underground area, and in the tunnel only for specialists involved in powering;
- Powering phase II (energy stored in the powered circuits exceeds 100kJ) - no access allowed into the sector under test and in the nearby areas [4].

The new QPS system

One of the major consolidation activities for the LHC during the shutdown 2008-09 was the installation of a new layer of the QPS [5] [6] which has the crucial role of both providing an early warning for any part of the superconducting busbars that develops high resistance and detecting so-called symmetric quenches:

- *Splice Monitor* - the Splice Monitor detectors are designed to monitor the superconducting busbar joints, to prevent similar events as the one of September 19th. The new system measures the busbar resistance down to 100 pΩ precision and provides an early warning for any joint developing high resistance. A total of 2132 detectors were installed around the machine, to monitor each busbar segment.

- *Symmetric quench protection* - during the training quench campaign performed in summer 2008 in one of the sectors, the LHC dipoles experienced the so-called symmetric quench, with both apertures quenching approximately at the same time. The original QPS measures the difference between the voltages in two apertures within one magnet and cannot therefore fully protect against this kind of events. The new detectors protect against symmetric quenches by comparing the voltage across 4 adjacent dipoles (or 2 adjacent quadrupoles). Thousands of new detector boards were installed in 436 crates all around the LHC.

HARDWARE COMMISSIONING

Differently from 2007-08 campaign, the 2009 hardware commissioning was concentrated in a shorter period of about 3 months. The approach had to be necessarily modified, according to several criteria/constraints:

- New access limitations, making the management of the tunnel activities and of powering very complicated;
- Additional tests to qualify recently installed systems;
- Sector qualification status.

Given the limited time available, a significant effort has been dedicated to the optimization of the test procedures, to the definition of the test parameters and to the automation of the test analysis in order to achieve a higher degree of parallelism of the tests in different sectors.

The status of a sector after a shut-down did not really play a relevant role, since all sectors had been warmed up to at least 80 K where an electrical qualification is needed (this aspect will be more important in the re-commissioning of the coming years). Sector 34 was nonetheless considered a special case, since 53 magnets (39 cryo-dipoles and 14 quadrupoles) had been changed, and 16 (9 dipoles and 7 quadrupoles) had been fully re-conditioned.

The new test campaign was focused on the qualification of the main circuits (dipoles and quadrupoles), validating the new protection system together with all magnet interconnections. From electrical measurements performed with the nQPS up to 2 kA, all splice resistances were proven to be below the specification value by the end of 2009.

The 2010 campaign

The commissioning of 2009 was tailored to the operation of the LHC at an initial energy at 3.5 TeV per beam [7]. However, at the end of 2009 the discovery of an electrical insulation problem on some connectors of the nQPS prevented from completing the commissioning to 3.5TeV by November 2009. It was then decided to have a first run without the nQPS fully operating, at a reduced energy level at 1.18TeV (corresponding to 2kA current in the dipole circuits). At this level of energy, indeed, the risk of quenching a busbar is considered negligible and symmetric quenches are not an issue.

The nQPS was set in monitoring mode in one sector to study its behaviour. The final hardware commissioning needed to operate the LHC at 3.5TeV was postponed to January 2010.

The nQPS commissioning

Setting the nQPS in monitoring mode (not connected to the powering interlock) was a key point for its commissioning, as experts had the possibility to carefully observe the system behaviour and calibrate it. This allowed solving the teething problems before operation.

At the beginning of 2010, the nQPS was tested during the commissioning of the dipoles and quadrupoles circuits to their nominal current (6kA for 3.5TeV). The main steps of the commissioning of the nQPS and the main circuits can be summarized as follow:

- Interlock tests;
- Solving cabling issues at low current;
- Heater firing and analysis to check the mapping of nQPS detectors versus heater power supplies;
- Ramp to 2kA to measure the busbar segment inductances (to be used in the inductive voltage compensation during ramp) and following validation;
- Connection of the heater power supplies to the nQPS detectors and to the interlock, before exceeding 2kA;
- Commissioning of the circuits to 4kA;
- Ramp to 5kA (with plateaus at different current levels) for splice mapping;
- Commissioning of the circuits to 6kA.

In February 2010 the LHC was fully commissioned and ready to operate at 3.5TeV.

Multiple-heater firing effects

A new phenomenon was observed during the commissioning of the main dipole circuits, which slowed down the qualification of the nQPS at high current, namely the simultaneous firing of quench heaters of several (up to 50) magnets during a single test with no immediate explanation.

To understand the origin of this event, a long investigation campaign was carried out, which revealed some important aspects.

When the switch for extracting the energy from the magnets is opened (switching some resistors in series with the magnets), a negative voltage signal is propagated through the dipole line (due to the transient of the current flowing through the resistors) and this could trigger the very sensitive symmetric quench detectors. To avoid this effect, a masking mechanism (so-called *adaptive filter*) was implemented in the detector controllers, to inhibit the detector when a voltage spike of maximum -1.6 V is detected. This masking is valid for 1.3s, after which it can be rearmed only if a positive constant voltage is present (i.e. during the next current ramp).

The firing of the quench heaters of 50 magnets occurred when a converter switched off (due to a fault) during a ramp to high current. The output stage of the power converter produced a voltage oscillation. This signal, transmitted through the dipole line, was detected by the symmetric quench detectors, triggering the *adaptive filter*. When the energy extraction switch was manually opened some minutes later, the *adaptive filter* was inactive and the voltage transient was interpreted as a quench signal for about 50 magnets.

The typical signature of the voltage signal after switching off the converter and activating the energy extraction is shown in Figure 1, where the voltage across some dipole magnets is shown: at the moment when (*a*) the power converter is switched off, followed by the energy extraction switch opening (*b*).

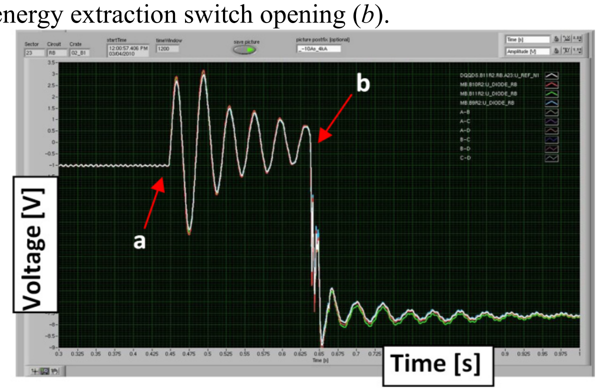

Figure 1: Voltage oscillations observed when the power converter is switched off during a current ramp and the energy extraction is activated.

Following these observations, the detection threshold was raised to 800 mV from the original 200 mV (still keeping a margin) so that the symmetric quench detectors no longer trigger upon the opening of the energy extraction system.

The Energy Extraction delay

The modification of the n-QPS threshold is ineffective in the case of another kind of multiple heater firing effect which was observed during the powering test campaign.

In some cases, the Powering Interlock Controller (PIC) can send a global switch off, called Fast Power Abort (FPA), to all circuits of a same powering sector (reacting, for example, to a trip of one main circuit). A FPA provokes the switching off of the power converters and the opening of the energy extraction system at the same time. This signal is also sent by the QPS when a quench is detected.

During the test meant to power for the first time all circuits of one sector together, the PIC sent a FPA to the other circuits following a trip of the quadrupole circuit. The quench detectors for many magnets detected a quench, and heaters were fired. During the powering tests, FPAs had been issued several times by the QPS, without any consequence. After investigation, it was discovered that the timing between the converter switch off and the energy extraction activation is different if the FPA is sent by the PIC or by the QPS. The small difference is sufficient to have constructive interference between the voltage oscillation generated by the power converter and by the opening of the energy extraction switch. In this case an electrical wave propagates through the circuit triggering the quench detectors.

After some analysis and simulations, a solution was found and later tested successfully, which consists in delaying the opening of the extraction switches by a few hundred milliseconds. Since the implementation of this solution required a development and installation of new control boards, it was decided to start operating the machine without this modification. As the amplitude of the power converter voltage oscillation mainly depends on the current ramp rate (absolute voltage on the converter output), it was decided to initially limit the main circuits ramp rate to 2A/s (nominal is 10A/s), with the drawback of slowing down all operation cycles.

CONCLUSION

The LHC is presently running with an upgraded quench protection system, which was extensively tested and the settings also optimized with the experience of the first run in 2009. A delay to the energy extraction activation has still to be implemented to allow running in nominal conditions, without risking unnecessary firings of quench heaters. New features of the machine have been discovered and others confirmed. All this contributes to an increased knowledge of our machine.

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