UPGRADE OF THE QUENCH PROTECTION SYSTEMS FOR THE SUPERCONDUCTING CIRCUITS OF THE LHC MACHINE AT CERN: FROM CONCEPT AND DESIGN TO THE FIRST OPERATIONAL EXPERIENCE

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Abstract

Two events, occurring in 2008 during commissioning of the LHC circuits, lead to fundamental changes to the scope of circuit protection. The discovery of aperture-symmetric quenches and the accidental rupture at 9kA of an interconnecting busbar resulted in an emergency program for development and implementation of new protection facilities. The new scheme comprises a distributed busbar supervision system with early warning capabilities based on high-precision splice resistance measurements and system interlocks for rapid de-excitation of the circuit in case of sudden splice resistance increase. The developed symmetric quench detectors are digital systems with radiation-resistant FPGA logic controllers, having magnet heater firing capabilities. This program successfully allowed a safe re-powering of the collider. The concept of the new electronics boards and the powering modules will be described. More than 14600 extra cables and 6000 new detector and control cards were added to the existing Quench Protection System (QPS). A first evaluation of the system performance as well as a number of interesting discoveries made during the commissioning will be presented.

THE QPS SYSTEM ARCHITECTURE

New and existing quench protection systems provide full coverage of each element of the LHC superconducting circuits. The splice joints of magnets, busbars and current leads are protected under all conceivable harmful circumstances. The new protection system is in particular complementing the existing system by providing additional safeguards for the individual busbars and the occurrence of symmetric quenches. It also performs as redundant system in case of asymmetric quenches.

The new quench protection system (nQPS) consists of 436 newly added electronics crates (DQLPU) distributed along the 27km LHC tunnel and physically located under the magnet chain. Each crate probes the total resistance across a variable number of splices (2 to 33) of the superconducting circuit, distributed inside the magnets and over the interconnection busbars. The system guarantees the precise measurement of the single splice resistance of a good joint, i.e. 0.3nΩ in average at cryogenic temperature (1.9K).

Two types of detection units (DQQBS and DQQDS) provide respectively monitoring and protection of busbar splices and symmetric quench detection. One controller unit (DQAMGS) interfaces the system to the fieldbus (WorldFIP®) for remote control and monitor actions. Two identical linear power supply units (DQLPUS or Power Packs) provide low voltage power to each crate [1].

Main Functionality of the nQPS

The main features of the detection boards are summarized in the table 1.

Table 1: Main features of detection boards

Unit	DQQBS busbar protection	DQQDS symmetric quench
N. channels	2 hi_res_ch, 2 lo_res_ch	4 hi_res_ch
Resolution	1.5nV/LSB hi_res_ch, 2µV/LSB lo_res_ch	500µV/LSB
Integration	10s	20ms
Threshold	500µV @ 3.5TeV, 300µV @ 7TeV	800mV @ 3.5TeV, 200mV @ 7TeV
Technology	ΣΔ 24b ADC with microcontroller unit	Serial 16b ADC & FPGA state machine

The DQQBS boards have the equivalent functionality of a LHC-wide nano-ohmmeter, constantly sensing all splice joints. The high resolution channel (hi_res_ch) gives the precise measurement of the voltage across the busbar segment. The low resolution channel (lo_res_ch) senses the adjacent magnet voltage to compensate for the busbar dynamic inductance factor and the sensing circuit resistive coupling. The interlock protection is activated in case of high resistance splice detection.

The DQQDS units probe voltages across four electrically contiguous magnets and perform six comparisons. Any voltage differences above threshold will denote a magnet coil resistive transition, due to either a symmetric or an asymmetric quench. Both, interlock and quench heater firing protections are activated in case of quench detection.

The maximum reliability of the system is assured by duplication of every safety channel. Moreover, two independent Uninterruptable Power Supply units (UPS) power the two redundant Power Packs of the crate, as well as the redundant quench heater power supply units. Special banks of 1 Farad buffer capacitors, plugged to each Power Pack, supply energy for overcoming power dips to 50% of nominal voltage and up to 100ms long.

nQPS COMMISSIONING EXPERIENCE

Splice Protection System

The splice protection is assured by 2042 redundant systems installed in the LHC.

The determination of the required detection threshold is based on simulations and tests [2] and has been set to 300µV with 10s integration time at nominal 13kA magnet current. For operation up to 6kA currents, a threshold voltage of 500µV with 10s integration time is regarded as safe.

Recent noise measurements during LHC operation show that more than 99% of the DQQBS systems comply with the very challenging requirements of a 300µV threshold voltage. At this threshold level, crosstalk noise from beam transfer lines gives occasional problem only to a limited number of critically located systems.

Compensation of the busbar inductive term is required to allow continuous splice protection during current ramps or fast power aborts. An automated procedure that computes the coefficients and downloads them to the DQQBS boards has been developed. Fig. 1 shows an example of busbar signals before and after inductance compensation.

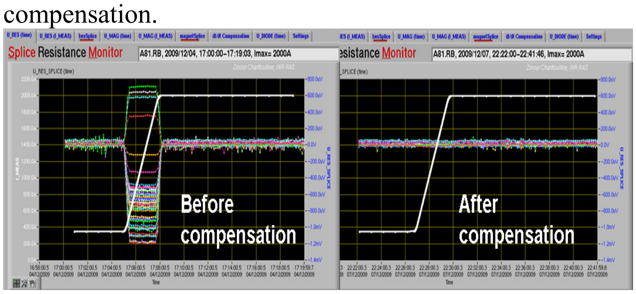

Figure 1: Busbar signals before and after compensation

Busbar Splice Resistance Measurements

The new system provides data for the enhanced diagnostics of the superconducting circuits via the QPS supervision.

Dedicated powering cycles allows measuring on-line the busbar splice resistance with a resolution of typically 50pΩ at 1.9K. The data is averaged during a number of steady current steps in the current ramping (each step 10min to 30min long) and can be used to trace the development of splice resistances in time. This measurement can inhibit the LHC start-up operation procedure, preventing potential damages to the superconducting circuits.

Effective software routines have been designed to allow mapping of all LHC splice resistances (Fig. 2).

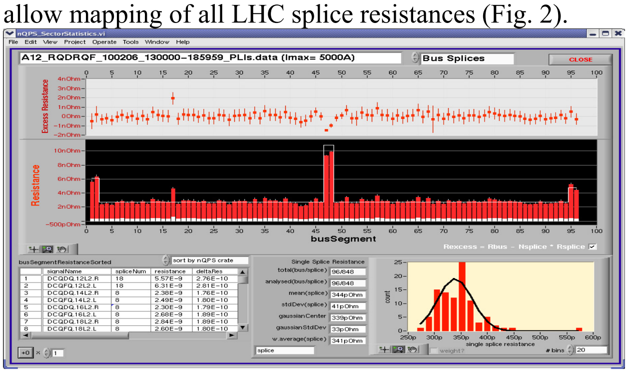

Figure 2: Splice mapping for quadrupoles in sector 12

The same system architecture can also be applied for measuring the busbar resistances at ambient temperature, with the purpose to diagnose the correct continuity of the cable copper stabilizer at the splice joints [3].

Symmetric Quench Protection System

During the fast current discharge tests, the symmetric quench detection system fired several magnets in a number of occasions. These fake quenches were provoked by dynamic differences in the fall-off behaviour of the sensed magnet voltages.

An early solution to this problem consisted in developing a new adaptive threshold filter that, when it is triggered by the large negative pulse caused by a fast current discharge, raises the quench detection threshold from ±200mV to ±1.3V for a limited time window of 1.3s. The perturbations on the magnet string are consequently filtered by this temporarily increased threshold (Fig. 3).

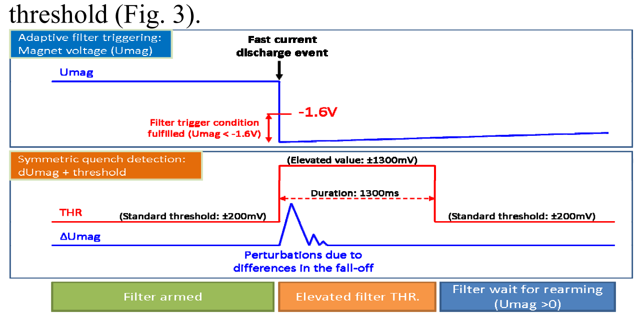

Figure 3: Symmetric quench adaptive filter logic

The discovery of a problem in the filter re-arming condition, occurring when the power converter switch OFF action was followed by a fast power abort, induced to a modification of this solution.

The final implementation, valid for the present case of maximum 6kA magnet current, consisted in re-tuning the original ±200mV symmetric quench quench detection threshold to ±800mV. This value complies with the largest perturbation voltage amplitude seen in measured data (Fig. 4) and it is within the 1V thermal runaway upper limit allowed by the superconducting cable. The new threshold of ±800mV is also compatible with the need for triggering in case of genuine symmetric quenches.

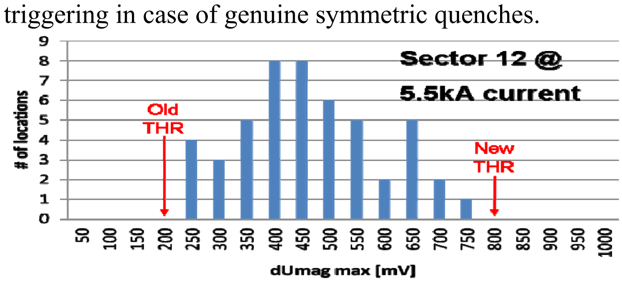

Figure 4: Statistics of perturbation voltage amplitudes

New Cabling

Globally, about 4400 new I/O cables and 10200 internal cable segments, equivalent to about 250km in length, had to be installed for the nQPS.

The new scheme needed a systematic study of the cable layout for dipoles and quadrupoles. The logical wiring of sensing cables, the heater triggering cables and their relative channel-to-channel correlation has implied important changes compared to the original wiring scheme. It has been necessary to apply cable swapping for one half of the sector crates and to re-code the quench heater trigger mapping in the firmware of the corresponding DQQDS boards. For optimal signal-to-noise performance, shield grounding was only applied to the magnet end of the signal cables.

ADDITIONAL ONGOING STUDIES

Improved Energy Extraction (EE)

For the first low current operation of the LHC, up to a maximum of 6kA, energy extraction can be performed more safely with shorter decay time constants, thus, today higher resistances than nominal have been installed: 147mΩ for dipoles (vs. 75mΩ nominal) and 30mΩ for quadrupoles (vs. 7.7mΩ nominal). The upper limit on the damping resistor increase was imposed by the maximum allowed voltage peak across the switches (1kV for dipoles and 240V for quadrupoles)

Moreover, suppression of the perturbations occurring during the switch first instant commutation will be achieved by adding snubber capacitors in parallel to the switch (4 x 13.3mF for dipoles and 4 x 40mF for quadrupoles). Polypropylene self-healing dry capacitors offer the best performance for our application.

Oscillations on the Magnet Power Circuits

The large amplitude oscillation of the magnet sensing voltages, provoked by the power converter abort and the energy extraction, triggered avalanches of quenches in the existing QPS. This problem became very critical when the two events described above overlapped in time.

This problem has been fixed, without changing the detection thresholds, by delaying the energy extraction switch openings with respect to the power converter abort. The best compromise was found when the openings of the two switches were respectively delayed by 340ns and 580ns.

System Simulations

The behaviour of the dipole magnet string has been simulated by means of a complete PSpice® model [4]. The simulation comprises a precise model of the dipole magnets [5], the energy extraction switches [6], the power converters, and the circuit cables. By changing the parameter setting, equivalent simulations will be performed for the quadrupole circuit as well.

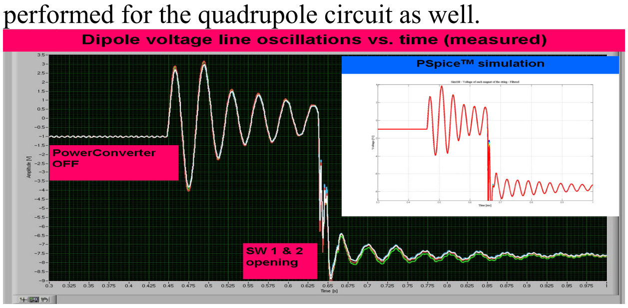

Figure 5: Measured and simulated voltage across a dipole

These system simulations have been finalized later than the nQPS conception. Nonetheless they provided an important way to perform comprehensive QPS system behaviour analysis when parameter changes were required. As an example, Fig. 5 shows a comparative study of the power converter abort action, shortly followed by EE switch openings, in the specific case of a dipole of the string. The measured data was taken from the internal buffer memory of the DQQDS board.

CONCLUSIONS

The nQPS project has been challenging in many aspects. First of all, the definition and follow-up of a realistic planning had no time contingency, owing to schedule constraints. Secondly, the preparation of a large outsourcing plan required overcoming the limited manpower of the QPS team. Finally, a massive coordination effort was needed to keep all the collaborators and suppliers synchronized in their execution times and deliveries.

All the different components of the nQPS system have been conceived, designed, prototyped, produced and qualified, in a record time, from September 2008 to August 2009. The new system installation in the LHC started on September 2009. The first beams were injected and collided successfully at a reduced energy of 1.2TeV (2kA magnet current) in December 2009.

In these initial operating conditions the nQPS was only running as monitor system, as the existing QPS could assure the full machine protection. The nQPS is now fully and actively operated as from February 2010, when the LHC was restarted for commissioning to 3.5TeV, and will continue with stable physics running until end of 2011.

REFERENCES

[1] R. Denz, et al., "Upgrade of the protection system for superconducting circuits in the LHC", PAC09, Vancouver, CND, May 2009
[2] A. Verweij, "Minimum requirements for 13 kA splices", LHC Performance Workshop, Chamonix, January 2010
[3] M. Koratzinos et al., "High current bus splice resistances and implications for the operating energy of the LHC", IPAC10, Kyoto, JP, May 2010
[4] E. Ravaioli, "Simulations of the voltage oscillations in the LHC dipole magnet chain", CERN internal note, EDMS 1076045, May 2010
[5] F. Bourgeois, K. Dahlerup-Petersen, "Methods and results of modelling and transmission line calculations of the superconducting dipole chains of CERN's LHC collider", LHC project report 497, CERN, August 2001
[6] K. Dahlerup-Petersen, et al., "Simulation and operational experience with energy extraction in the LHC superconducting magnet chains", IEEE IPMC, Las Vegas, USA, May 2008