ELECTRONIC SYSTEMS FOR THE PROTECTION OF SUPERCONDUCTING DEVICES IN THE LHC

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Abstract

The Large Hadron Collider LHC [1] incorporates an unprecedented amount of superconducting components: magnets, bus-bars, and current leads. Most of them require active protection in case of a transition from the superconducting to the resistive state, the so-called quench. The electronic systems ensuring the reliable quench detection and further protection of these devices have been developed and produced over the last years and are currently being put into operation.

INTRODUCTION

Protection of the superconducting elements of the LHC is ensured by electronic quench detection systems in combination with other elements such as quench heater power supplies and energy extraction systems [2]. After installation in the LHC these systems undergo a final test phase and operate then for the first time during the LHC hardware commissioning [3].

PROTECTION OF SUPERCONDUCTING ELEMENTS IN THE LHC

Main Magnets

The protection systems for the LHC main dipole and lattice quadrupole magnets are located in racks placed underneath the main dipoles inside the LHC tunnel together with the data acquisition system and the associated quench heater power supplies, which energize in case of a quench the heater strips mounted on the magnet coils. The detector design is based on an analog floating-bridge type detection system [4]. The technology of the quench heater power supplies, which are also used for the protection of the insertion region quadrupoles, dipoles and inner triplets, is based on a thyristor-triggered discharge of aluminium electrolytic capacitors.

Main Bus-Bars

The superconducting bus-bars of the LHC main dipole and quadrupole circuits are protected by a dedicated protection system made up with a cluster of data acquisition systems, which are coordinated by an industrial PC via a fieldbus link.

Insertion Region Magnets and Inner Triplets

The insertion region magnets and the inner triplets use digital quench detection systems comparing two half coil or half circuit voltages depending on the actual configuration of the circuit.

Corrector Magnet Circuits

All corrector magnet circuits except those limited to 120 A and 60 A nominal current are as well protected by a digital quench detection system based on a digital signal processor DSP. The detector calculates the resistive voltage using a pre-loaded inductance table, the measured current and the differential voltage across the superconducting part of the circuit as inputs.

HTS Current Leads

The hybrid HTS current leads are individually protected by a dedicated system using high precision sigma-delta converters in order to reach the required low detection threshold of U_{TH} = 3 mV for the superconducting part of the lead.

Data Acquisition Systems

The protection systems are among the major data sources for the LHC control systems. Data from the superconducting circuits are acquired and fed into the post mortem system [5] and the logging database. This task is accomplished by means of 2200 fieldbus controlled data acquisition systems and 31 front-end computers (so-called gateways), which are transmitting about 70000 signals.

FINAL TESTING

Prior to its installation in the LHC each protection device was submitted to a thorough test programme verifying the full functionality of each device. In this way more than 8000 quench detection systems and quench heater discharge power supplies were successfully qualified for use in the LHC.

After installation in the LHC an individual system test (IST) was performed. Within the IST the interlocks, the quench heater circuits and the communication link to the LHC supervision applications are tested. In addition the instrumentation cable links to the electrical feed-boxes were checked for cabling errors and isolation faults. A sub-set of the IST will be repeated on a regular basis in order to assure the availability and reliability of the system.

Non-Conformities Revealed During the IST

Most of the non-conformities revealed so far were related to cabling errors and could be resolved in short time. There were also two cases of damaged quench heater circuits observed.

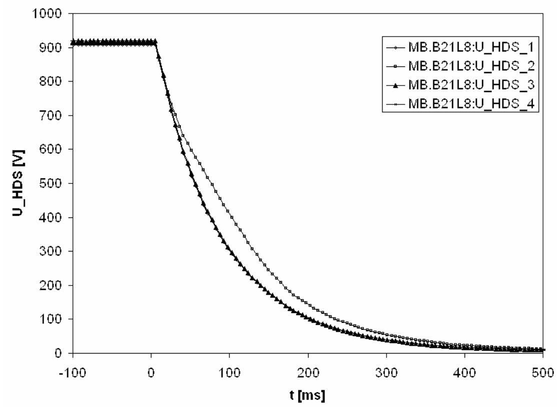

Figure 1: Failure of a quench heater within a discharge test on a dipole magnet. After further electrical tests and quench simulations [6] it has been decided to replace the broken heater by two low field heaters.

The detection of one of these damaged heaters is illustrated in Figure 1. The heater develops during the discharge a higher resistance therefore a slower voltage decrease in comparison with the voltage across the other 3 healthy heaters.

COMMISSIONING

All quench protection and energy extraction systems [7] [8] are fully operational prior to the first powering of a superconducting circuit. Within the LHC hardware commissioning [3] however depending on the circuit type various adjustments and tests with powered circuits still have to be conducted. The procedures described below are needed to achieve the nominal powering parameters of a given circuit, e.g. ramp rate and current acceleration.

Main Circuits

When the main dipole circuit is being ramped at nominal rate the main bus-bar protection system must be capable of compensating the full boost voltage of U = 160 V in order to detect possible quenches. This requires that the cluster of data acquisition systems is carefully calibrated and the digital filters adapted to the noise spectrum in the circuit. The latter task can only be performed in the field during the first powering of the corresponding circuit. The protection system is using two magnets as references for measuring the inductive voltage.

Insertion Region Magnets and Inner Triplets

The protection systems used for the protection of the insertion region and inner triplet magnets are of the bridge type and exhibit a very good noise immunity allowing the commissioning in relatively short time. During the hardware commissioning tests so far these systems detected quenches in the magnets as well as in the superconducting busbars. The complex nested powering scheme of the inner triplet magnet circuits did not affect the efficiency of the protection system, which has proven fully adequate.

Corrector Magnet Circuits

The design of the protection system for the corrector magnets has the advantage that it requires only a very limited number of voltage taps and detection electronics to protect circuits straddling a complete sector. However in contrary to bridge type detection systems signal noise and distortions are not cancelled out by the topology itself but must be filtered digitally. In other terms the detection system must be able to distinguish in a reliable manner between the signature of a real quench and other noise related patterns.

The resistive voltage drop across a corrector circuit is calculated as follows.

$$U_{RES} = U + L(I) \cdot (\dot{I} + \frac{\dot{U}}{R_{PAR}})$$

U is the voltage drop across the superconducting part of the circuit, I the current, L (I) the circuit inductance as a function of the current, and R_{PAR} the internal protection resistor mounted in parallel to the corrector magnets in a majority of circuits.

The pre-loaded inductance tables, which are based on measurements performed on individual magnets [9], turned out to be very precise and reproducible requiring only minor corrections. The necessary corrections were applied during the hardware commissioning.

During the first phases of commissioning however frequent triggers of the detection system due to non-periodic distortions, interpreted as the signature of a magnet quench, were observed. The detailed analysis of the acquired signals led to the conclusion that a proper rejection cannot be achieved with the help of classical linear filters. Consequently non-linear filtering techniques commonly used for image processing were implemented and successfully tested.

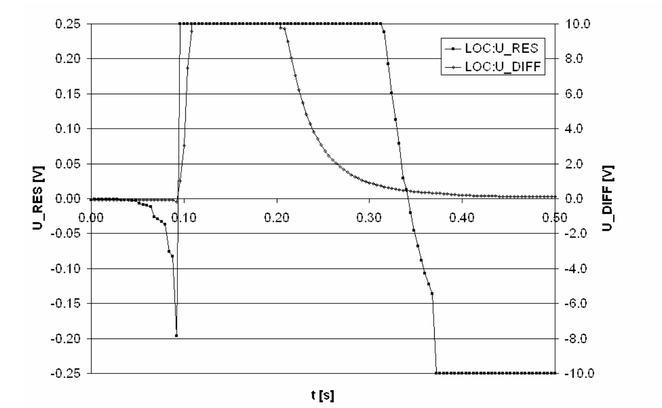

Figure 2: Natural quench observed in the RCD.A56B1 corrector magnet circuit at I = 535 A during first powering to nominal current (I = 550 A). The circuit comprises 77 decapole spool piece correctors type MCD. The calculated resistive voltage U_RES and the measured voltage U_DIFF saturate respectively at ±0.25 V and ±10 V.

SYSTEM PERFORMANCE

Magnet Training Campaign

The full availability and reliability of the quench protection and energy extraction systems is crucial for the current magnet training campaign launched in sector 5-6 and to be continued in other sectors. The protection system for one main dipole circuit consists of 1099 functional entities and 159 field-bus nodes for the supervision of these devices. At the time of writing 30 training quenches were successfully performed.

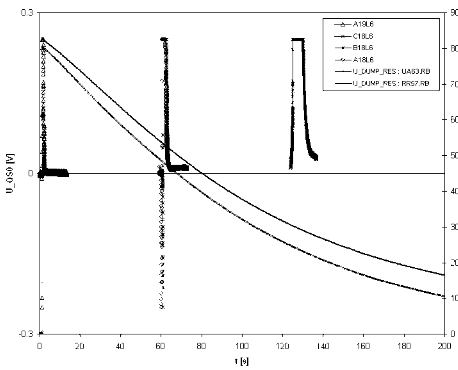

Figure 3: Example of a training quench in a main dipole magnet at I = 11019 A with propagation to three neighbouring magnets. The plot also shows the voltage across the two dump resistors installed in the odd and even point of the sector.

Powering of All Circuits in a Sector

The ramping of all circuits together using real operational scenarios for the current levels and ramp rates is the last step in the LHC hardware commissioning procedure for a sector. This challenging phase requires the full availability of all detection and energy extraction systems [2].

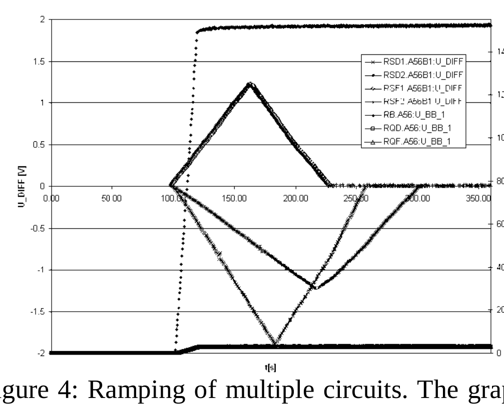

Figure 4: Ramping of multiple circuits. The graph shows the differential voltages across the superconducting part of the main dipole and quadrupole circuits as well as a selection of lattice sextupole circuits.

The first ramping tests conducted in sector 5-6 did not reveal any particular problems with respect to the protection systems. In some cases electro-magnetic cross-talk between circuits was observed, especially when the powering sequence of circuit had to be aborted, e.g. a quench in one corrector circuits provoked power aborts in other corrector circuits.

LHC OPERATION

Once LHC hardware commissioning is completed the protection system will be switched to operation mode and should become almost transparent to LHC operation. This step has recently started in the first fully commissioned sector. It will imply the deployment of additional features such as

- user macro functions to facilitate certain operations like the closing the switches of the energy extraction systems
- full alarm functionality
- automatic re-arming of the data acquisition systems
- installation of remote reset units

CONCLUSION

Within the hardware commissioning of the LHC the electronic systems for the protection of the superconducting devices of the LHC have successfully proven the reliability and readiness required for operation with beam. Future developments will focus first of all on consolidation of the LHC as well as on the necessary replacements of obsolete electronic components.

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REFERENCES

[1] Bordry F., “Status of the LHC “, EPAC’08, Genova, June 2008
[2] Mess K. H., Coelingh G., Dahlerup-Petersen K., “Results from Commissioning of the Energy Extraction Facilities of the LHC Machine”, EPAC’08, Genova, June 2008
[3] Saban R., “LHC Hardware Commissioning Summary”, EPAC’08, Genova, June 2008
[4] Denz R., IEEE Trans. ASC, vol. 16, no. 2, (2006), pp. 1725-1728
[5] Reymond H. et al.” The Post-Mortem Analysis Software Used for the Electrical Circuit Commissioning of the LHC”, EPAC’08, Genova, June 2008
[6] Russenschuck S., Schwerg N., private communication
[7] Coelingh G., Dahlerup-Petersen K., Medvedko A., Erokhin A., Gorchakov K, “Design and Commissioning of the Energy Extraction Systems for the LHC Corrector Magnet Circuits”, PMC’08, Las Vegas, May 2008
[8] Dahlerup-Petersen K., Coelingh G., Kazmin B., “Simulation and Operational Experience with Energy Extraction in the LHC Superconducting Magnet Chains”, PMC’08, Las Vegas, May 2008
[9] Venturini W., private communication