The Quench Protection System for the LHC Test String 2

K. Dahlerup-Petersen, R. Denz, D. Milani, F. Rodriguez-Mateos, and F. Tegenfeldt

Abstract—The Large Hadron Collider (LHC) String program has focused over the years the efforts of many teams that have tested and validated their systems under operating conditions close to the final ones in the LHC machine tunnel and underground areas. During the various phases while commissioning or performing dedicated experiments, the Quench Protection System (QPS) has been tested and improved. A large variety of designs of the QPS equipment have been validated. The experience gained, especially concerning both the commissioning and the interaction with systems working within close interfaces (interlocks, powering, controls), is a valuable expertise to undertake the LHC challenge. In the LHC, the QPS will be the only system monitoring and protecting the superconducting elements: the integrity of all the superconducting magnets, bus bars and high- T_c superconducting current leads will depend on its reliable operation. A description of the system installed in String 2 will be given together with the principal similarities and differences with respect to the equipment planned for installation in the LHC. The key experimental results will be explained.

Index Terms—Accelerators, LHC, quench protection, superconductors.

I. INTRODUCTION

THE LHC [1], presently under construction at CERN, in Geneva, will use a large amount of superconducting components as active elements of its electrical circuits. A reliable quench protection system (QPS) is hence required in order to protect all its superconducting elements (magnets, bus bars and feeding current leads).

In the LHC Full-Cell Test (the so-called String 2), two regular half-cells of an LHC arc are reproduced (Fig. 1) [2]. It is limited on the upstream end by the electrical feed-box (DFB) and on the downstream end by a magnet return box (SRB) [3].

On the DFB side, a powering area comprises the power converters, the quench detection racks, the energy extraction facilities as well as the elements of the general interlock system (the central hardwired matrix which defines the actions as a function of the status of the different systems).

String 2 was assembled in two phases starting in January 2000. It follows the final design of LHC with the cryogenic helium distribution line running alongside the magnets. During the first phase, the facility, which comprised the DFB, a half-cell and an additional short straight section, was assembled using exclusively prototype components specially instrumented for the experimental program. The three dipoles, which were added during Phase 2, are machine worthy pre-series magnets. Phase

Fig. 1. Schematic layout of String 2 including the electrical feed box (DFB), two short straight sections (SSS3 and SSS4), six main cryo-dipoles (MB1 to MB6) and a cryogenic return box (SRB). Overall length is around 110 m.

2 included six, twin-aperture lattice dipoles with their attached multipole correctors, and two short straight sections (including a twin-aperture quadrupole magnet and the lattice correctors).

The electrical circuits installed in Phase 2 are: the main dipole circuit, the main quadrupole circuits, the sextupole corrector circuits, and the closed orbit corrector circuits. A set of spare 600 A bus bars were installed in the N-line, a cold tube bridging consecutive Short Straight Sections that contains the 600 A bus bars feeding the lattice correctors. The spare bus bars mentioned above were powered by the octupole and decapole power converters, but there was no magnet of these types connected to the leads. The latter circuits were subject of extensive tests in order to obtain validation of the cable for its future use as bus bar in the machine.

With the exception of these bus bars in line N, the other electrical circuits consist of power converter, power cables, feeding superconducting current leads, bus bars and magnets.

II. THE QUENCH PROTECTION SYSTEM IN STRING 2

The task of the QPS is to detect resistive transitions (quenches) in any of the superconducting components and to undertake the necessary actions to avoid any damage [4].

The Energy Extraction sub-system is also part of the QPS: its task is to safely dissipate (“extract”) the energy stored in the magnets once a quench is detected in one of them or in a bus bar or current lead.

The following types of quench detectors were installed: floating bridge detectors to protect individually the main magnets (dipoles and quadrupoles); differential voltage detectors to protect the bus bars and the multipole corrector circuits, as well as the current leads.

Every one of the main magnet detectors in String 2 has three identical channels evaluating the resistive voltage increase: a quench is validated when at least two out of the three channels within the same detector exceed the threshold for a period of time longer than a fixed interval. This validation logic has been optimized for the LHC and will be different from the one indicated here [5].

Due to the reduced inductance in the circuits (compared to the circuits in the machine), String 2 only integrated the following three extraction systems:

Manuscript received October 20, 2003.

The authors are with the Accelerator Technology Division at CERN, Geneva, Switzerland (Felix.Rodriguezmateos@cern.ch).

Digital Object Identifier 10.1109/TASC.2004.829063

- A set of eight, 4.5 kA breakers arranged in four branches with full redundancy for the main dipole circuit. As dissipating resistors, four units of the quadrupole design were connected in parallel (see below);
- Two 600 A extraction facilities of different design and manufacturer connected for validation purposes to the two chromaticity sextupole circuits.

III. THE TEST CAMPAIGN

Amongst the tests performed during Phase 2, the following were relevant for the QPS:

- Quench propagation campaign;
- Bus bar cable tests (6 kA, 600 A);
- Validation of the Energy Extraction facilities on 600 A circuits;
- Electro-magnetic compatibility (EMC) tests on the different electronic units.

IV. THE LESSONS LEARNED

A. Installation

The installation of the elements of the QPS required coordination work between transport and installation teams. Prior to this phase, the cabling and services required for the different equipment were prepared (power cables, signal cables, demineralized water, etc). All this infrastructure work represented a good test bench toward the definition of installation procedures for later in the LHC machine.

The racks and their locations are representative of the LHC (racks both under dipoles like in the machine arcs, and in the String-2 powering area like in LHC underground areas).

B. Commissioning

The powering phase of the commissioning involved experts of four systems: interlocks, power converters, electrical engineering (instrumentation, electrical integrity) and quench protection. The interfaces in between those systems were clearly specified by an engineering specification [6]. Other systems experts (cryogenics, current leads, data acquisition, controls) were involved in many occasions.

Once every one of these systems had been individually commissioned (functional checks), interlock tests were performed with systems alive but without possibility to inject current through the circuits (the power cables between power converters-energy extraction and current leads were disconnected). This part of the commissioning “as if connected” showed to be an excellent way to check all power permit and power abort links between systems, under the different conditions and provoked by the different actors (interlock matrix, quench detectors, energy extraction, power converters, etc).

The gradual powering using intermediate plateaux also proved to be very safe to power the circuits for the first time, when the qualification of the splices between bus bars, magnets and leads must be performed. This procedure however is time consuming. A way of automating it must be found for the commissioning of the long list of LHC circuits.

Fig. 2. QPS triggers when the RQD power converter is switched off. The UDIFF signal represents the voltage drop across the magnet chain, while the interlock signal is the flag which represents the QPS activation.

At the start up of the different circuits, some compatibility problems appeared: quench detectors require that power converter switching on/off must be smooth enough not to trigger false quench signals (Fig. 2).

The interface between quench detection and cryogenics must be optimized so that quenches in auxiliary circuits or bus bars do not stop the cooling in order to prepare for a recovery procedure (the energy dissipated in those cases is not large).

In the following sections, summaries are given of the commissioning of each circuit.

1) *Main Dipole*: One problem was encountered which was caused by a differential noise level larger than expected. The noise caused a series of high-frequency spikes which were too fast to be resolved as separate spikes by the global quench detectors. As the amplitude was above the threshold, the quench detectors triggered. It was solved by increasing the thresholds of the detectors; from 150 mV to 1 V for the bus bar detector and 190 mV to 300 mV for the detector monitoring the bus bar in the feed box, which had a reduced copper section. The latter detector was specific to String 2 and will not be present in LHC.

In one case when the heaters were fired in one of the dipole magnets at low current (about 7% of nominal), the resulting quench was highly symmetrical and consequently the corresponding local quench detector could not see the quench. Due to this, the detection threshold for the local quench detectors on the main magnets was lowered from 200 mV to around 100 mV, which was enough to solve the problem.

2) *Chromaticity Sextupole Correctors*: The commissioning of these circuits experienced problems with the initial set-up of the power converter parameters that triggered the global quench detectors. From the quench protection point of view, it was solved by increasing the threshold from 100 mV to 140 mV (100 mV will be nevertheless kept as detection threshold for the machine). Both circuits were successfully commissioned up to ± 600 A.

3) *Closed Orbit Corrector Circuits*: In Phase 2, four orbit corrector circuits were commissioned.

Few minor problems during the first powering of these circuits focused our attention to the problems related to bad contact resistances between warm power cables and current leads feeding the superconducting circuit. This aspect, if neglected, could lead to problems during operation in the LHC.

4) *600 A Test Bus Bars*: A set of 600 A bus bars were installed in String 2 for experimental studies. They were connected to 3 available power converters and the obtained circuits were then commissioned.

In one of these circuits a problem emerged related to a bad soldering between the current leads and the bus bars feeding the magnets, again focusing our attention to the necessity of a careful and accurate check of all the electrical connections during installation and commissioning of the collider.

C. Measurements and Experiments

1) *Energy Extraction*: Before String 2, all the high current (up to 15 kA) extraction facilities at CERN were built on site and implemented a combination of semiconductor devices (thyristors) and mechanical switch gears (e.g., facilities at Bloc-4, Test Benches, Superconducting Cable Test Laboratory, String-1). For the first time, redundant mechanical breakers corresponding to the final machine version were assembled and installed. Also for the first time, resistors corresponding to the final machine version were installed. The coincidence that 4 proto-types of the LHC quadrupole dump resistors gave, with minor changes, the desired time constant to the dipole circuit when one of the dipoles quenches, made this solution fully adequate.

Moreover, in two of the 600 A circuits (the two chromaticity sextupoles for each beam) newly designed energy extraction prototypes were installed. One of the two designs was validated and retained for the production of 205 units for the LHC machine.

In both cases (13 kA and 600 A) the switchgears had been qualified by an independent expert institute, and designs accepted through type and lifetime tests. But it was for the first time that those systems acted connected to considerable inductances and energies (more than 40 MJ in the case of the dipole circuit).

The control systems for all the three facilities corresponded to prototypes newly developed for LHC. The control cabinets for the dipole extraction facility are prototypes produced outside CERN through a collaboration agreement.

2) *Quench Detectors: Current Leads, Bus Bars, Magnets*: As soon as the resistance of the circuits disappears during the cool down process, verifications on both active parts and attached instrumentation turn out to be very difficult. This is the very case of the voltage taps across the superconducting part of a current lead: it is difficult to firmly assess whether the two wires are short-circuited or not.

The calculations on the quench velocities and the speed of the quench detectors needed to properly protect the corrector magnets and their connecting bus bars have been confirmed by experiments. The designs of prototype detectors of families a) main bus bars, b) current leads as well as c) corrector magnets and bus bars have been qualified for the first time. The values chosen for thresholds and discrimination periods were sound

and only needed minor corrections which were applied during the commissioning phase.

3) *Acquisition and Monitoring*: The quench protection system incorporated a monitoring and acquisition system with a supervision layer. This system provided a direct interface to the QPS hardware units, through which their proper functioning could be assessed from the control room. It also included acquisition buffers recording the main signals after a quench event. Interfaces to the logging database as well as to the post mortem application eased the analysis and diagnostics during the experiments.

Although the design of this facility did not exactly correspond to the final design for LHC, functionalities and other aspects, e.g., the required flexibility, have been tested and assessed. This is certainly a very important issue when commissioning a complex system like the QPS in LHC, which is distributed all over the arcs and underground areas. The supervision layer of the QPS controls in LHC was an extremely useful tool when starting-up the commissioning of the String. The communications structure has been qualified and even if the hybrid-type structure is certainly not the best solution for the controls of QPS in LHC, many aspects will be retained for the final version.

4) *Quench Heater Discharge (Power) Supplies*: The quench heater power supplies in String 2 correspond to a design that is very similar to the final one. All components appearing in the final design are already incorporated within those units. Some of the supplies were already produced at the factory retained for series production. The prototype production has been extremely useful to set up and tune many aspects, like the components to be used in a radiation environment like the LHC tunnel, as well as the appropriate quality assurance program.

5) *6 kA Superconducting Cables Tests*: The goal of this test campaign was the validation of the superconducting cables both for the 6 kA and the 600 A, the study of the quench propagation, the mutual interference between adjacent strands in the cable and the validation of the quench protection parameters: threshold voltage and time delay to minimize the energy released into the cable in case of quench.

The quench protection system worked well and proved capable to actively limit the amount of energy released during a quench. The flexibility of the system allowed also for changes of the quench detection parameters. Indeed, in order to explore quenches at lower current levels these parameters have been adjusted to allow a controlled increase of the energy released into the cable before the intervention of the protection system.

6) *Quench Propagation Studies*: During this test campaign several quenches have been provoked in different magnets with the aim to study the thermo-hydraulic quench propagation across magnets and half-cells (Fig. 3) [7].

One of the most important outcomes of these experiments and subsequent analysis is that in the worst case, a quench will never propagate through sections longer than a full-cell.

D. Confirmation of Known Facts

The chosen protection scheme (quench heaters and cold diodes) matches perfectly the requirements for the main magnets (dipoles, quadrupoles) at all current levels. This is a confirmation of simulations performed since long and of

Fig. 3. Quench propagation tests. Magnet called MB6 quenched first, followed by MB5, MB4, MB3 and MB2. In the graph the voltages across the protection diodes installed in parallel to each dipole are shown: the positive spikes represent the turn on of the diodes.

studies on single magnet on the test benches. It also confirms all results that had been extrapolated from String-1 to the final design magnets.

1) *Quench Heaters*: When quenching a magnet by the effect of heaters, the detection threshold must be low enough to avoid that symmetric quenches lead to long detection times. This is true especially at low currents. In String 2, this was observed with one of the dipole magnets (see above).

2) *Diodes*: Checking of diodes polarity at commissioning, as well as their integrity over the operation time is a crucial aspect.

E. EMC Under Kicker Generator Pulses

All QPS equipment (quench detectors of both types, being analogue or digital, the energy extraction facilities and their controllers, the quench heater power supplies) had a robust behavior in front of radiated and conducted interferences coming from fast, high current pulses performed using a kicker generator installed at the powering area.

Previous EMC measurements performed together with the CERN Power Converters team using a burst generator had already demonstrated the immunity of the quench protection equipment (level 4 according to the IEC norm).

V. CONCLUSION

From the quench protection point of view, the String 2 experiment was completely successful. Together with the already

described lessons learned, few other aspects made the experience extremely successful: team spirit built up; the training of QPS team members has been very effective; the procedures for the common work between different teams have been further developed.

In conclusion, String 2 has been a perfect exercise in order to have a final validation on the technical choices for quench protection in LHC. It has also trained the QPS team to manage production, installation as well as external manpower contracts under the pressure of an established, firm planning. Finally, it has been a valuable opportunity to increase personnel motivation and confidence toward the construction and operation of LHC.

ACKNOWLEDGMENT

The authors would like to thank all the persons who worked on the String 2 program and who contributed, with their help, to the final success of its commissioning and the powering experiments.

Thanks are given in particular to G.-J. Coelingh, B. Eidesheim, N. Fournier, A. Gharib and J. Mourao for their full support and enthusiasm.

Our gratitude goes to R. Saban, D. Hagedorn, N. Siegel and K. H. Mess for their input and guidance through all this exciting time working with a "reduced scale LHC".

The cryogenics team deserves our deep appreciation for their hard, impeccable work and help.

Special thanks are due to D. Bozzini for his continuous and fundamental assessments with respect to all the aspects of the electrical integrity of both instrumentation and circuits.

REFERENCES

- [1] The LHC Study Group 1995, The Large Hadron Collider Conceptual Design, CERN, Geneva, Switzerland, 1995.
- [2] F. Bordry *et al.*, "First powering of the LHC test string 2," *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 232–235, March 2002.
- [3] L. Serio, The cryogenic circuits of string 2, in LHC Engineering Specification, October 2000.
- [4] R. Denz and F. Rodriguez-Mateos, "Electronic systems for the protection of superconducting elements in the LHC," in *EUCAS*, 2003.
- [5] F. Rodriguez-Mateos and A. V. Fernandez, "What do we hope to achieve for the LHC quench protection and beam availability?," in *Proceedings of the Workshop on LHC Performance*, March 2003.
- [6] F. Bordry *et al.*, The interlock system for string 2: power abort and power permit, in LHC Project Document.
- [7] L. Bottura and C. Rosso, "Flower, a model for the analysis of hydraulic networks and processes," in *CHATS 2002*, September 2002.