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ENHANCED DIAGNOSTIC SYSTEMS FOR THE SUPERVISION OF THE SUPERCONDUCTING CIRCUITS OF THE LHC

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Abstract

Being an integral part of the protection system for the superconducting circuits of the LHC, the data acquisition systems used for the circuit supervision underwent a substantial upgrade during the first long shutdown of the LHC (LS1). The sampling rates and resolution of most of the acquired signals increased significantly. Newly added measurements channels like for the supervision of the quench heater circuits of the LHC main dipoles allow identifying specific fault states. All LHC main circuits are meanwhile equipped with earth voltage feelers allowing monitoring the electrical insulation strength, especially during the fast discharges. The protection system for the bus-bar splices is now capable to operate in different modes. By this measure, it is possible fulfilling the requirements for different specific tests like the warm bus-bar measurements and current stabilizer continuity measurements (CSCM) without field interventions.

INTRODUCTION

The protection system for the superconducting circuits of the LHC (QPS) covers 544 circuits with nominal current ratings from 100 A to 11870 A [1]. A total of 2516 data acquisition systems (DAQ) ensure the supervision of the protection system and diagnostics of the superconducting circuits. These systems communicate through field-bus links with the LHC accelerator control system.

Table 1: Circuits covered by the protection system

Circuit type	Quantity	DAQ systems
Main bends and quads	24	2124
Inner triplets	8	8
Insertion region magnets	94	68
Corrector magnet circuits	418	316
Total	**544**	**2516**

While status flags provide information on the state of the protection equipment and its readiness for operation, the majority of recorded analog signals serve for diagnostic purposes.

Based on the experience gained within the LHC operation so far and taking into account requests by equipment specialists, the data acquisition systems have been submitted to a major upgrade during LS1. The enhanced supervision capabilities, e.g. for the quench heater circuits, allow performing more detailed diagnostics of the superconducting circuits and facilitating the event analysis by automatic tools and equipment specialists. During the LHC hardware commissioning campaign in 2014/2015, magnet experts made already extensive use of the enhanced capabilities, e.g. for the analysis of 179 primary quench events recorded during main dipole powering tests [2].

QPS SUPERVISION UPGRADE

The various layers of the QPS supervision underwent a substantial revision, necessary to integrate new equipment, signals and commands. At this occasion, also the sampling rates and resolution of many analog signals have been revised and increased.

QPS Signals

The QPS DAQ transmits about 130000 signals, to the LHC accelerator control system with sampling rates of 0.1, 5 and 10 Samples/sec, when in normal operation mode. Depending on the signal type sampling rates during post mortem events, e.g. a magnet quench can be significantly higher.

Table 2: Signals produced by the QPS DAQ

Circuit type	Analog	Status flags	Total
Main bends and quads	26228	56388	82616
Inner triplets	200	248	448
Insertion region magnets	1408	4044	5452
Corrector magnet circuits	4088	17112	21200
Generic controller signals			22548
Total	**31924**	**77792**	**132264**

Field-bus Network

The QPS field-bus network, based on the WorldFIP™ standard, has been extended during LS1 by changing the network configuration and adding new segments and repeaters. This measure allowed reducing the number of individual clients per field-bus segment and almost doubling the transmission capacity of the physical layer of the QPS field-bus (see table 3). As a result, the time required for the transmission of the significantly larger post mortem data blocks is still within reasonable limits (~10 min). It is noteworthy that this time is independent of the number of simultaneously recorded events. The sampling rate for the majority of QPS analog signals

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stored in the LHC logging database changed from 5 Samples/sec to 10 Samples/sec.

Table 3: QPS DAQ Transmission Rates after LS1

Circuit type	DAQ Qty	kByte/s	TByte/y
Main bends and quads	2124	2039.0	64.3
Inner triplets	8	3.8	0.1
Insertion region magnets	94	45.1	1.4
Corrector magnet circuits	316	151.7	4.8
Total	**2516**	**2239.7**	**70.6**

Configuration Management

Within the LS1 upgrade of the QPS, detection boards and DAQ systems have been adapted to remote configuration management allowing verifying and modifying detection settings, parameters and operational modes by the control system. The system improves considerably the QPS maintainability and safety; it is essential for the proper execution of certain tests like the CSCM described below. Once fully deployed the system will perform as well routine integrity checks and automatic updates of configuration parameters, e.g. after interventions for maintenance.

ENHANCED DIAGNOSTICS FOR QUENCH HEATER CIRCUITS

The LHC main dipole magnets are protected against development of excessive voltage and overheating in case of a resistive transition by quench heaters mounted on the magnet coils [3]. While not yet observed during LHC operation, there exist potential quench heater fault modes compromising the electrical integrity of the magnet by provoking a short to the magnet coil. Based on observation during magnet testing, this risk is non-negligible [4]. The enhanced diagnostics installed during LS1 is supposed to reveal precursor states of such potential failures thus avoiding substantial machine downtime caused by an eventual magnet replacement.

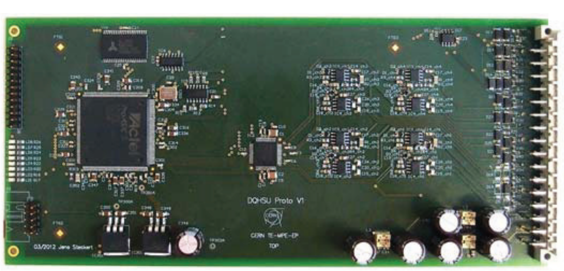

Figure 1: Fast radiation tolerant multi-channel DAQ for the supervision of quench heater circuits.

The newly developed FPGA based system records simultaneously the discharge voltage and current using sampling rates up to 192 kHz and ADCs of 16 Bit resolution. In total, the system acquires during each quench heater discharge 16384 data samples per each of the eight channels. The discharge current is measured with the help of dedicated precision measurement transformers. As the newly developed circuit boards (see Fig. 1) are installed in the LHC tunnel, care has been taken to ensure that the electronics can withstand the radiation levels during LHC operation [5].

The systems have been already extensively used during the test of the quench heater circuits prior to the first powering of the superconducting circuits. The standard test procedure foresees several test discharges at voltages of 300 V, 500 V and nominal 900 V. Fig. 2 shows an example of a recording related to a potentially dangerous fault in a quench heater circuit. As foreseen in such cases, the concerned magnet has been carefully checked, the corrupted quench heater circuit disabled and replaced by one of the four spare circuits (low field heater) [6].

The full utilization of the capabilities of the new systems depends strongly on sophisticated high-level software tools for the detailed and automatic analysis of the collected data. These tools are currently under development and it is foreseen to launch the analysis automatically e.g. in case of a magnet quench. The analysis will also cover the evolution in time by using recordings of test discharges during the initial system commissioning as a reference.

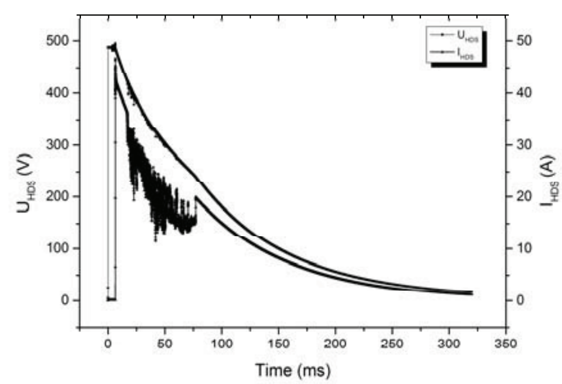

Figure 2: Example of a fault in a main dipole quench heater circuit occurring during a test discharge at U_{HDS} = 500 V.

MAIN BUS-BAR PROTECTION AND DIAGNOSTICS

The functionality of the main bus-bar protection systems [7] has been extended, thus fulfilling better the requirements for different specific tests like the warm bus-bar measurements, current stabilizer continuity measurements (CSCM) [8] and normal LHC operation. The most important new feature, requiring a considerable hardware and firmware upgrade, is the possibility to change between different test and operational modes without field interventions. This upgrade has been essential in performing the CSCM test in all eight LHC

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sectors within the tight schedule of LS1. For this purpose 1308 new bus-bar splice protection systems for the main dipole circuits have been installed and a new release of the protection system and DAQ firmware deployed.

During normal accelerator operation and CSCM operation, the bus-bars of the LHC main circuits require dedicated detection systems triggering a fast power abort sequence in case pre-defined voltage thresholds for the bus-bar segments are exceeded. As the detection settings and analog input stage configuration used during the CSCM test is not compatible with normal operation due to lack of sensitivity, a dedicated safety critical firmware preventing accidental switching of the operational mode has been developed. The implemented safety features include a permanent supervision of the operational mode, a device parameter crosscheck and an automatic beam injection inhibit signal in case the system is not in standard configuration.

EARTH VOLTAGE FEELERS

During LS1, the LHC main circuits have been equipped with specially developed earth voltage feelers, monitoring the electrical insulation strength of the LHC main circuits especially during fast discharges (see Fig. 3). Per LHC sector 54 devices for the main dipole circuit and 55 for each of the main quadrupole circuits have been deployed (1308 in total), allowing to identify the location of an eventual earth fault on the half-cell level. For maintenance purposes and tests within the electrical quality assurance framework (ELQA), the earth voltage feelers can be electrically isolated from the superconducting circuit by remote control.

During the recent LHC hardware commissioning campaign, the systems have been already successfully used in localizing an earth fault in the cold mass of a main dipole, which occurred in sector 3-4 after a training quench.

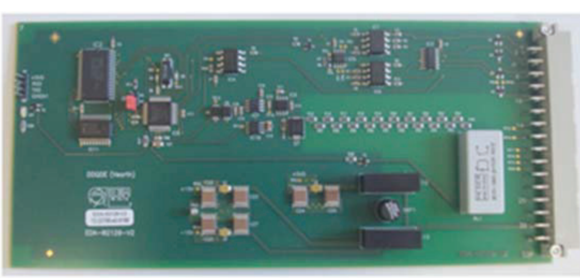

Figure 3: Earth voltage feeler circuit board. The system can measure voltages in the range of ±2 kV with a resolution better than 1 mV.

SUMMARY

During LHC LS1, the QPS data acquisition systems underwent a substantial upgrade.

The enhanced diagnostic capabilities of the revised and newly installed systems allow a by far more detailed analysis of events, pre-emptive fault diagnostics and improve the system reliability and maintainability. The upgrade provides as well additional functionality, necessary for the execution of specific tests like the CSCM.

The QPS individual system test, LHC hardware commissioning and the main dipole magnet training campaign used the new features of the QPS DAQ extensively and proofed its usefulness.

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