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AN ENHANCED QUENCH DETECTION SYSTEM FOR MAIN QUADRUPOLE MAGNETS IN THE LARGE HADRON COLLIDER

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Abstract

To further improve the performance and reliability of the quench detection system (QDS) for main quadrupole magnets in the Large Hadron Collider (LHC), there is a planned upgrade of the system during the long shutdown period of the LHC in 2019-2020. While improving the already existing functionalities of quench detection for quadrupole magnets and field-bus data acquisition, the enhanced QDS will incorporate new functionalities to strengthen and improve the system operation and maintenance. The new functionalities comprise quench heater supervision, interlock loop monitoring, power cycling possibility for the whole QDS and its data acquisition part, monitoring and synchronization of trigger signals, and monitoring of power supplies. In addition, the system will have two redundant power supply feeds. Given that the enhanced QDS units will replace the existing QDS units in the LHC tunnel, the units will be exposed to elevated levels of ionizing radiation. Therefore, it is necessary to design a radiation tolerant detection system. In this work, an overview of the design solution for such enhanced QDS is presented.

INTRODUCTION

The Large Hadron Collider (LHC) [1] incorporates a large amount of magnets to steer and focus the beam of particles, and accompanying power converters and current leads to power the magnet circuits. To achieve the energies of the LHC beams of up to 7 TeV, high magnetic fields of up to 8 T are required. Therefore, the use of superconducting elements is necessary. During the operation of magnet circuits, it may happen that a segment of a superconducting element changes its state from superconductive to resistive one. This transition is known as the quench phenomenon. Due to the large stored energies in the LHC circuits, a non-detected quench can seriously damage the accelerator. Therefore, the LHC requires a highly reliable Quench Detection/Protection System (QDS/QPS) to safely extract the energy and bring the LHC into safe state in case of a quench. The protection systems for the main magnets include quench heaters with the corresponding power supplies [2], cold by-pass diodes [3], energy extraction systems [4], and quench detection systems such as the one described in this paper. Figure 1 shows the block diagram of the powering and protection systems for the LHC main magnets. The quench detection system and the quench heater supplies are integrated into protection racks, which are located inside the LHC tunnel underneath the main dipole magnets.

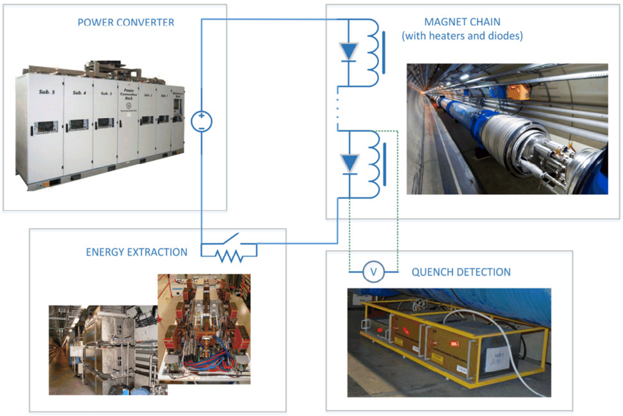

Figure 1: Magnet powering and protection system.

Among thousands of magnets used in the LHC, 392 main quadrupole (MQ) magnets are used as FODO lattice for beams circulating around the LHC ring. The QDS systems for MQ have been successfully used since 2007 without upgrades. Due to the aging of the used components and the need to further improve the performance and reliability of the QDS for MQ, the system is under redesign with a planned upgrade during the long shutdown 2 (LS2). This paper gives an overview of the enhanced QDS for the LHC quadrupoles.

FUNCTIONAL OVERVIEW OF THE QDS

The functional block diagram of the QDS for the main quadrupoles is given in Fig. 2. The QDS consists of 3 functional subsystems [5]: 1) quench detection and accompanying interlock/trigger subsystem, 2) local supervision and timing synchronization, and 3) field-bus controlled acquisition subsystem. The following subsections give more details for each of the functional block of the enhanced QDS.

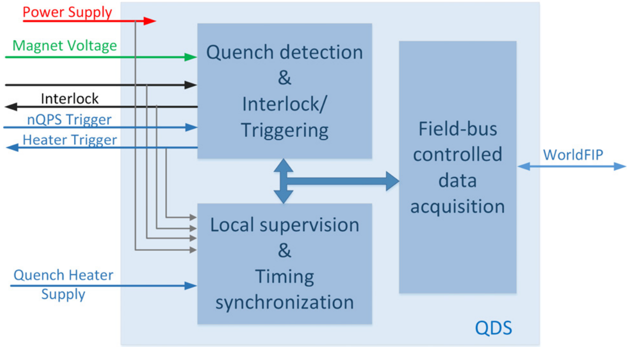

Figure 2: Block diagram of the QDS for MQ.

Quench Detection

The core functionality of the QDS is fast and reliable detection of a magnet quench followed by triggering of the

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protection actions such as energizing the magnet heaters and opening the extraction switches across the dump resistors, sending beam dump and power abort requests.

The quench detection in the LHC quench protection systems is based on detecting a small resistive signal usually superimposed on a large inductive signal. The detection of a resistive component in the QDS for MQ is done by comparing the voltages, over the two halves of an MQ using a measurement bridge (see Fig. 2 and Fig. 3). Given that one quadrupole cold-mass consists of two magnets, one magnet per each beam aperture, the quench detector measures four voltages. The two voltages of one magnet as well as the voltage of the measurement bridge are conditioned in analog domain, digitized, isolated, processed in digital domain, and compared against the quench thresholds, as shown in Fig. 3. The digital detection does not only implement the voltage comparators and time discriminators needed for quench detection but enables as well the implementation of various digital filters and gives the possibility to configure remotely the parameters for quench detection such as detection threshold, discrimination time, filter parameters, and others.

Once a quench has been detected, the quench detection unit takes measures to protect the magnet, the magnet circuits, and the whole LHC. These measures are:

- Triggering of two quench heater power supplies, performed by heater trigger signals shown in Fig. 2, to energize quench heaters and to spread the heat across the magnet. Note that heater trigger signals represent the MQ QDS trigger as well as the nQPS trigger shown in Fig. 2, coming from a detection system for detecting another type of magnet quenches, namely the “symmetric” quenches [6]. Additionally, the trigger links for the two quench heater supplies are mutually independent which makes the triggering subsystem more robust, particularly in case of faults in quench heater supplies.
- Activating the interlocks (interlock signals in Fig. 2), that is, rupturing the hardwired interlock loop, which triggers the energy extraction subsystem to dissipate the energy to dump resistors. Moreover, the state of the interlock loop is transferred to the corresponding powering interlock controller [7], which requests a beam dump to the beam interlock controller and stops powering the subsector.

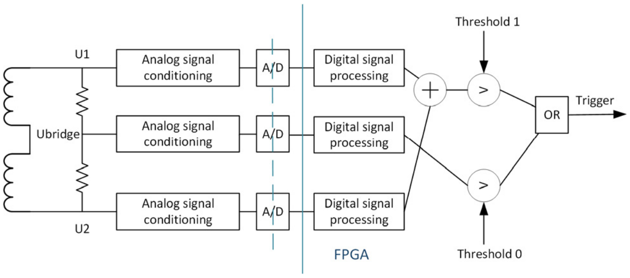

Figure 3: Quench detection – signal measurement, conditioning, filtering, and trigger activation.

Local Supervision and Timing Synchronization

The main requirements for the LHC QDS are high reliability and availability. In order to meet these requirements, any fault in the system has to be detected, understood, and mitigated as fast as possible. In order to do that, all critical system parts are monitored within the local supervision and timing synchronization module. Some of the monitoring subsystems were already introduced in QDS for main dipoles during LS1 [8]. These are monitoring of quench heaters, interlock loop monitoring, monitoring of power supplies, and remote power cycle functionality. Additionally, two new functionalities have been introduced for the QDS for main quadrupoles. These are supervision of heater triggering links, and monitoring and synchronization of various trigger signals.

Quench Heater Supervision The quench heaters are mounted on the magnet coils with the purpose to protect the quadrupole magnets against overheating and excessive voltage in case of quench. To detect faults in quench heaters, the current QDS for MQs monitors the discharge voltage of quench heaters. However, monitoring only the discharge voltage is not sensitive enough to detect all faults in the quench heater circuits. In particular, precursors of failures of the heater strips can be detected with an enhanced heater supervision which simultaneously monitors discharge voltage and currents of quench heaters. Using in-phase measurement of voltage and current of the heater discharge, a dynamic resistance can be calculated which can then be used to detect malfunction of the quench heater.

Interlock Loop Supervision This monitoring functionality has been introduced to improve the maintenance of the QDS by enabling the direct detection of the loop rupture point.

Power Supply Supervision The power supply voltages for the QDS MQ are provided by two independent power supply modules connected to two redundant uninterruptible power supply feeds. In order to detect faults in each redundant voltage supplied to the QPS by these two modules, all the supplied voltages are monitored.

Power Cycling Support to remotely power cycle the complete QDS and its field-bus controlled data acquisition part has been added to mitigate the possible faults caused by the radiation environment of the LHC.

Heater Triggering Link Supervision To facilitate the analysis of quenches and to check the functionality of the heater triggering links, the triggering links are monitored at their exit point of the QDS. Moreover, the monitoring of the trigger links enables the detection of possible faults in the heater discharge supplies.

Trigger and Timing Synchronization When a quench is detected by the QDS, the important signals such as the monitored magnet voltages, the heater discharge voltages and currents are recorded into so-called Post Mortem (PM) buffers at relatively high frequency to enhance the quench analysis. It is crucial that the signals recorded in the PM buffers are synchronized in order to correctly correlate the recorded data. For that purpose, a synchronization mechanism is provided in the enhanced QDS for MQs within the trigger and timing synchronization module. Moreover, the relative time is recorded between the last absolute time stamp from the controls system and the first trigger detected by the QDS leading to the absolute timing precision of PM buffers of 1 ms.

Field-bus Controlled Data Acquisition

All QDS for the LHC magnets communicate their data to the higher-level LHC controls software through their field-bus controlled data acquisition modules. The field-bus used for data communication is the WorldFIP™ and currently data transfer is performed every 100 ms. The QDS has two modes of data acquisitions: 1) the logging mode during which there is no quench and 2) the post mortem mode, which device enters after a quench has been detected. In both cases the same signals are transferred, and the only difference is the time resolution of the transmitted signals. Additionally, some of the transferred signals are used as software interlocks. With the enhanced supervision of the new QDS, the number of signals transmitted to the LHC controls becomes larger. As introduced earlier, there is a possibility to change certain parameters of the QDS through higher-level software. As some of these parameters influence the quench detection, it is necessary to supervise these parameters. Moreover, the quench detection parameters can only be modified within predefined safe limits. Therefore, to ensure their proper setting, the configuration parameters are transmitted back during the logging state of the QDS acquisition subsystem.

IMPLEMENTATION OF THE QDS

The actual implementation of the QDS is determined by the following four requirements: high system reliability, high system availability, high system maintainability, and the proper system operation in the presence of ionizing radiation.

As mentioned earlier, due to high stored energies in the LHC beams and magnet circuits, highly reliable QDS is necessary. Therefore, design of QDS is focussed on the reliability requirement. The redundancy principle is used as an essential method to improve the QDS reliability. First of all, the QDS is powered by redundant power supplies. In terms of the quench detection, there is a redundancy in both the voltage signals coming from the magnets as well as in the quench detection boards that are measuring the magnet signals. Redundancy is implemented for the interlocks and heater triggers as well. Moreover, redundant voltage sources are used for generating heater trigger signals. To increase the reliability further, the interlocks are hardwired. Additionally, a reliability study of most critical subsystems is performed, critical components in terms of the reliability are identified, and preferred design solution in terms of the reliability are proposed [9] and implemented.

To enhance the system availability and maintenance, a large part of the QDS is supervised and controlled remotely. This allows early detection of faults in the QDS, which then improves the fault mitigation as well. Another improvement in the system availability and maintenance is the implementation of the test modes which enable remote testing of the main QDS functionalities – quench detection, interlocking and heater triggering.

To ensure proper system functioning in presence of ionizing radiation in the LHC tunnel, all used components have been qualified for a maximum total integrated dose of 200 Gy, taking a maximum dose rate of 10 Gy/year [10] for the location in the LHC tunnel where the QDS will be installed. Additionally, digital circuits that are susceptible to single event upsets are protected by triple modular redundancy. The functionality of the whole QDS will be tested at the CERN's irradiation facility CHARM [11].

Figure 4 shows the hardware module implementing the quench detection functionality, and the crate representing the complete QDS. The QDS crate houses two quench detection boards, one board implementing supervision and synchronization, and one board implementing field-bus data acquisition. Each board is placed in a cassette which provides better protection during maintenance. A passive back plane provides all necessary links between the cards and is also equipped with all necessary connectors to connect to the magnet, the quench heaters, the interlock system, and the power supply modules.

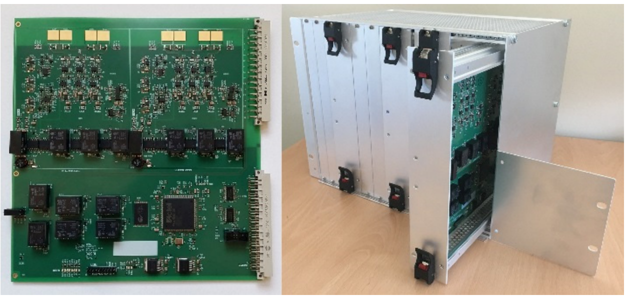

Figure 4: The QDS system with the quench detection board on the left-hand side.

CONCLUSION

The enhancements in quench detection, supervision of critical signals and their synchronization, radiation tolerant and testability oriented design methodology will increase the level of reliability, availability, and maintainability of the new QDS for main quadrupoles, which are the most important metrics of quench detection systems for the safe and successful operation of the LHC.

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