UPGRADE OF THE PROTECTION SYSTEM FOR SUPERCONDUCTING CIRCUITS IN THE LHC

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Abstract

Prior to the re-start of the Large Hadron Collider LHC in 2009 the protection system for superconducting magnets and bus-bars QPS will be substantially upgraded. The foreseen modifications will enhance the capability of the system in detecting problems related to the electrical interconnections between superconducting magnets as well as the detection of so-called aperture symmetric quenches in the LHC main magnets.

INTRODUCTION

Within the LHC hardware commissioning in 2008 two events have occurred implicating a functional upgrade of the existing QPS (Quench protection System).

The first event concerns the non-destructive discovery of aperture symmetric quenches in the LHC main dipoles the second the incident in sector 3-4 [1]. A highly symmetric secondary quench due the heat propagation from the neighbouring quenching magnet was detected by the QPS during LHC Hardware commissioning much later than required, although previous studies performed within the STRING II experiment with the help of provoked quenches [2] showed a sufficient coverage of such kind of event by the installed QPS. The behaviour seen different in LHC therefore requires a modification in order to timely detect aperture symmetric quenches.

Reviews following the incident in sector 3-4 lead among others to the conclusion that the functionality of the existing protection system should be extended in order to be able to diagnose suspicious resistances in the magnet interconnections and main bus-bar splices with sensitivity of the order of 1 nΩ.

SYMMETRIC QUENCH DETECTION

The additional layer of detection electronics will ensure the safe detection of aperture symmetric quenches by comparing the total voltage drops across magnets. The system will share the instrumentation cables with the suspicious splice detection system and evaluate the signals derived from four neighbouring dipole magnets and two quadrupole magnets. The implementation requires as well additional interlock cabling for triggering of quench heater power supplies.

General Symmetric Quench Detection Layout

The detection layout for the main dipole magnets uses a multiple magnet evaluation scheme minimizing the number of provoked quenches. Hereby the scheme is taking into account the signals of 3 + 1 magnets, the last magnet being protected by the adjacent protection unit. The evaluation logic determines the quenching magnets by comparing the different electrical potentials. For the 1st and 2nd detected quench the systems triggers only the quench heaters of the quenching magnets, whereas in case of a 3rd quenching magnet the remaining not yet triggered magnets will be quenched. As this rather unlikely case will only occur at relatively low currents the impact on the recovery time of the cryogenic system will be marginal. In case of the quadrupole magnets an interleaved two magnet evaluation scheme will be applied.

It is noteworthy that the system will react as well on "normal" quenches and will therefore serve in addition as a back-up of the existing quench detection system. The detection threshold must be slightly higher in order to clearly distinguish the two different cases (existing system U_{Th_old} = 100 mV, new system U_{Th_new} = 200 mV evaluation time for both t_{Dis} = 10 ms).

Symmetric Quench Detection Electronics

For the aperture symmetric quench detection a new design has been developed. It is based on a field programmable gate array FPGA for radiation tolerance use (see Fig. 1).

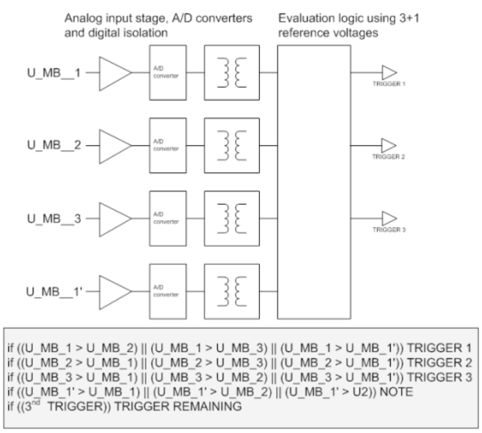

Figure 1: Symmetric quench detection functional circuit diagram.

The analog input stages and the analog-to-digital converters ADC are electrically on the same potential as the magnet, the evaluation logic is on the electrical potential of the crate housing the protection electronics.

Galvanic insulation up to 1.9 kV is needed. It is provided by DC-DC converters for the powering and digital isolators for the signal transmission. The complete detection system consists of two redundant circuit boards with the interlocks wired in a 1 out of 2 configuration.

The basic design phase has been successfully completed and prototype devices were produced, which are currently submitted to a series of type tests verifying the detection logic, the communication interface, the noise immunity (EMC) and the radiation tolerance (see below) of the device.

SUSPICIOUS SPLICE DETECTION

Following the recommendations of the Taskforce on the Analysis of the 19 September 2008 Incident and the recommendations of the external review of the QPS [3], the QPS shall be extended in order to be able to detect and localise so-called “bad splices” representing a potential risk for the LHC integrity in the LHC main circuits (RB, RQD and RQF). According to the outcome of recent simulations [4] a splice developing a resistance in the order of 50 to 100 nΩ is regarded as potentially dangerous at currents above 7 kA. In such a case the system should interlock the concerned circuits by initiating a fast discharge by activation of the energy extraction systems. The necessary detection threshold has been determined to U_{Thr} = 300 µV with 10 s evaluation time. In addition the system will provide data for enhanced diagnostics via the QPS supervision allowing a measurement of the splice resistance with a resolution of about 1 nΩ.

The new system can only access the superconducting circuits via the existing voltage taps routed to the magnet interface box connectors (diode voltage taps), there is no access to a single splice.

Suspicious Splice Detection System

The suspicious splice detection system is based on the existing design for the protection of the high temperature superconducting leads in the LHC [5]. This solution has been endorsed by CERN management after the QPS review held end of 2008 and confirmed by the various internal and external review committees. Currently there are 1200 units installed in the LHC and very few hardware problems have been revealed during commissioning.

The suspicious splice detection system will consist of 2016 new units. For the new application only a few minor hardware modifications such as increased isolation strength of DC-DC converters and replacement of some, meanwhile obsolete components, have been implemented. In addition a new detector firmware is under development, where preliminary versions have been already used within the field tests end of 2008.

The upgrade, which is covering so far the LHC main circuits, will be extended to the insertion region magnets at a later stage. The necessary cabling work however will be completed within the current update phase.

Suspicious Splice Detection Electronics

The design is based on an ADuC834™ micro-converter incorporating a micro-controller and a 24 Bit ΣΔ ADC. The circuit has two analog input channels with ±12.5 mV and ±250 mV voltage range. The 2nd channel will be used for the compensation of the inductive bus-bar voltage during ramping by measuring the voltage drop across the adjacent magnet. It is connected to the respective magnet by an external 1:100 voltage divider shared with symmetric quench detection. The circuit board comprises two redundant circuits with interlocks wired in a logical OR configuration.

In order to make full use of the capabilities of the system a dedicated powering cycle in LHC will be required. A typical cycle will start from injection current up to 2 kA with intermediate steps every 200 A. On each plateau coasting of about 10 minutes will be necessary to collect enough data at a sampling frequency of 5 Hz. The offline analysis of the acquired data is supposed to give an expected resolution for the resistance of less than 1 nΩ. This has been confirmed within prototype testing performed in October and November 2008. Software tools allowing the fully automatic analysis of such a test are currently being developed [6].

RADIATION TOLERANCE OF THE NEW QPS ELECTRONICS

Radiation tests have been performed on individual components such as micro-controllers, field-bus couplers, instrumentation amplifiers, DC-DC converters (CERN TCC2 target area and PSI Villigen) as well as on complete circuit boards (CERN CNGS service gallery in 2008) over the last years and show that the board will withstand the radiation levels expected below mid dipole position (hadron fluence (E > 20 MeV) up to 10^{10} cm^{-2} $year^{-1}$). For electronic components to be used in the newly developed circuit boards for the symmetric quench detection a radiation test campaign at PSI Villigen has been successfully concluded. Hereby especially the radiation tolerance of the FPGA and the analog-to-digital converters been verified.

INTEGRATION OF THE NEW QPS ELECTRONICS INTO LHC

The new protection electronics will be integrated into a crate to be installed in the existing QPS rack type DYPB underneath dipole B in each LHC half cell. This crate, baptised Local Protection Unit DQLPU type S, will house all the new devices associated to circuits RB, RQD and RQF, i.e. the suspicious splice protection system, the symmetric quench protection system, the field-bus coupler for data transmission to QPS supervision and the potential to earth measurement. The latter one is a pure diagnostic tool and not mandatory for the start-up and exploitation of LHC. The DQLPU type S will be connected to the existing infrastructure as the WorldFip™ field-bus and the QPS internal interlocks (patches required). It will acquire signals from 4 dipoles and 2 quadrupoles and there will be one crate per LHC half cell, i.e. 54 or 55 per sector. The unit will be powered via two redundant dedicated AC-DC power supplies. With the re-configuration of the LHC UPS powering layout [7] each of these power supplies will be fed by one existing 230 V 50 Hz single phase UPS. The implementation of the DQLPU type S makes sure that the impact on the existing QPS electronics is minimized.

Installation and Test of Cables

The installation of the measurement and interlock cables is one of the essential parts of the upgrade. In total there will be about 240 km length of cables and 4400 individual cables. In addition local patches for field-bus, interlock and powering have to be made. An example of the rather complex cabling layout is given in Fig. 2.

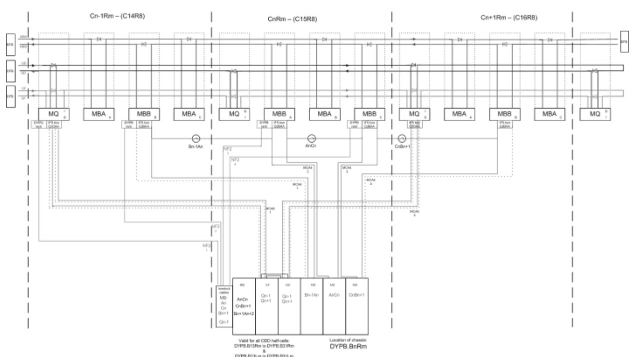

Figure 2: Cabling layout for the QPS upgrade in an LHC half cell.

Wherever possible the installation will make use of existing cable trays; a few new cable supports will be necessary or shared with the beam instrumentation. All cables will be fully assembled and tested on the surface by the contractor. In addition there will be final checks performed by the contractor and independently by the QPS team after installation in order to verify the correct layout of the continuity and the isolation.

QPS Supervision

The supervision hardware has to be modified in order to transmit the data generated by the new QPS devices. The increased number of QPS field-bus clients will require slight modifications of the QPS networks in the LHC tunnel, i.e. more repeaters and local patches.

Table 1: Supervision Hardware Upgrade.

Item	**Present**	**Future**
QPS Field-bus Clients	2100	2536
Clients per Field-bus Segments	60	75
Clients per Front-end Computer	120	150

With respect to the QPS supervision software there will be three new equipment types associated to a new QPS controller type. In total there will be about 40000 new signal channels with a maximum data transfer rate of 5 Samples/s.

In addition to the firmware of the new QPS controller type, also all other levels of involved QPS and LHC control systems have to be adapted to the new QPS system. This concerns for example the real time applications on the front-end computers, the high level supervision, the layout and logging data bases.

SUMMARY

The new layer of QPS will significantly enhance protection capabilities of the LHC superconducting circuits and will provide powerful diagnostic for identifying potentially dangerous problems. The scanning of the superconducting circuits including the magnets on a regular basis will be necessary to detect potential problems in time.

All the new systems need to be very carefully commissioned in order to guarantee their proper function and to limit the number of false triggers. The proper functioning of the new protection system strongly depends on the correct testing and validation of the instrumentation and interlock cabling.

The QPS upgrade is on the critical path for the re-start of LHC, the suspicious splice and symmetric quench detection must work prior to the re-commissioning of LHC. At the time of writing the implementation of the upgrade is still on schedule but production, installation and commissioning until re-start of LHC remain nevertheless challenging.

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