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ELECTRONIC SYSTEMS FOR THE PROTECTION OF SUPERCONDUCTING ELEMENTS IN THE LHC

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Accelerator Technology Department

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Electronic Systems for the Protection of Superconducting Elements in the LHC

R. Denz and F. Rodriguez-Mateos
Accelerator Technology Division, CERN Geneva, Switzerland

Abstract. This paper gives an overview about the electronic systems used in the protection system for the LHC superconducting elements. The final design of a variety of electronic devices, where the production has recently been launched, is presented and discussed.

1. Introduction

The Large Hadron Collider LHC [1], which is presently under construction at CERN, will incorporate a large amount of superconducting components like magnets, current leads and busbars. Most of these components will require active protection means in case of a transition from the superconducting to the resistive state, the so-called quench. For this purpose, a variety of electronic devices, which can be classified into three functional groups, have been developed at CERN.

- Analog and digital quench detectors, which have to be able to identify quenches in any state of the powering cycle of the accelerator.
- Quench heater power supplies, which energize in case of a quench the quench heater strips mounted on the coils of many LHC superconducting magnets.
- Acquisition and monitoring controllers enable the supervision of all these devices and transfer the data via a fieldbus link to the higher-level LHC control systems.

All these electronic systems will be installed in the LHC tunnel and its adjacent underground areas. Some of the systems will be exposed to ionizing radiation and all devices must work correctly in an industrial environment. Table 1 summarizes the various equipment types and their quantities.

Table 1: Electronic devices for the protection of LHC superconducting elements

Functional group	Type	Quantity
Quench detector	Local quench detector	2016
	Global quench detector	606
	Protection system for HTS current leads	1198
Quench heater power supply	Quench heater power supply	6076
Acquisition and monitoring controller	Supervision of local protection units	1624
	Supervision of global protection units	214
	Supervision of energy extraction systems	232

2. Analog quench detectors for the protection of the LHC main magnets

The detection of quenches in the LHC main dipole and lattice quadrupole magnets is based on floating-bridge type analog detection systems named local quench detectors. Hereby a classical Wheatstone bridge design is applied, where the magnet coils and balancing precision resistors inside the input stage of the detector form the bridge. These quench detectors are located in racks under the main dipoles inside the LHC tunnel together with the associated quench heater power supplies and acquisition and monitoring controllers.

2.1. Detector design

The detector design incorporates several functional blocks shown in Figure 1.

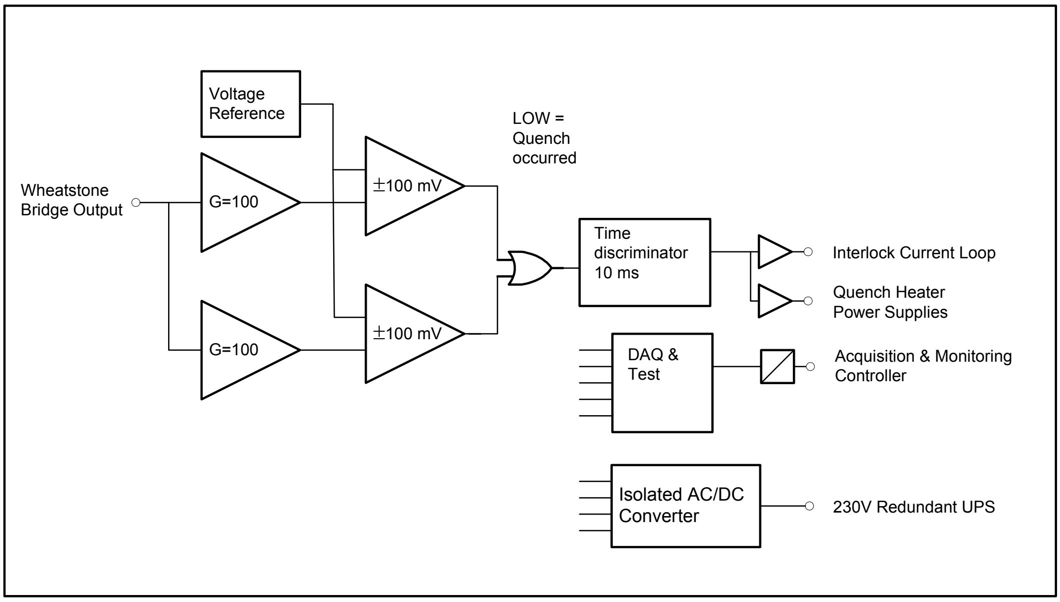

Figure 1: Functional design of the local quench detector.

The output signal of the Wheatstone bridge is buffered and amplified by means of high precision, fixed gain instrumentation amplifiers. In the following stage analog comparator circuits evaluate the signal. In case the fixed detection threshold of U_{th} = 100 mV is exceeded a time discriminator is triggered. In case the signal persists longer than the fixed discrimination time of t_{dis} = 10 ms the detector will activate directly the associated quench heater power supplies. At the same time the detector opens the respective interlocking current loop, which triggers the machine protection system [2]. The detector design incorporates a small single-chip data acquisition system, which transmits supervision data to the associated acquisition and monitoring controller via an isolated serial interface. Additionally this system is used as a generator for test signals within the detector self-test procedure. The quench detector board is electrically isolated and floating with respect to common ground.

2.1. Radiation tolerance, maintainability and reliability

The radiation tolerance of all critical components of the local quench detectors has been tested and confirmed in several studies at CERN. The switch-mode type isolated AC/DC converters used for the powering of the quench detector have been modified by their

manufacturers and successfully tested at CERN in order to comply with the enhanced requirements of radiation tolerance [3].
The local quench detector design does not require any adjustments prior to and after commissioning. Drifts of the analog input stages are expected to be minor compared to the required precision of the detection threshold.
The LHC quench protection system as a whole and the local quench detectors in particular have been subject to a detailed and exhaustive reliability analysis [4]. The outcome of the study favours a multi-channel evaluation scheme with two redundant quench detector boards using a “(2 out of 2) OR (2 out of 2)” scheme. This scheme, which is implemented into the final design of the detector, is expected to reduce the number of faulty trigger signals to a minimum but ensuring at the same time the proper detection of all eventually occurring quenches. As an option a redundant second power supply can be integrated into the powering scheme for the local quench detectors. With respect to cost savings, this measure will only be taken in case the performance of the single power supply solution is not satisfactory.

3. Quench heater power supplies

This type of power supply will be used in case of a quench to energize the quench heater strips mounted on the coils of LHC main bending and quadrupole magnets as well as many other superconducting magnets installed in the LHC insertion areas. In total 6076 units will be installed. The function is based on a thyristor-triggered discharge of aluminium electrolytic capacitors. The thyristors are of 1.8kV, 80A rating and the capacitor bank is formed with 2 x 3 capacitors of 4.7mF, 500V rating. These components have been extensively tested with respect to reliability, useful lifetime and radiation tolerance [5][3]. Several completed power supply units have been submitted to radiation tests and confirmed the validity of the present design with respect to the required radiation tolerance of 200 Gy. Hereby the useful lifetime of the power supply under radiation is mainly limited by the two thyristors used for the discharge of the capacitor bank.

4. Digital quench detectors

Digital quench detectors, whose working principles were first applied within the TEVATRON quench protection system [6], are used within the protection systems for LHC insertion region magnets, corrector magnets, the inner triplet magnets as well as superconducting current leads and busbars.

4.1. General purpose digital quench detector

In order to conform to the requirements imposed by the design and powering schemes of the LHC insertion region magnets, corrector magnets and inner triplet magnets, a general-purpose digital quench detection board has been developed. The design implements a two-channel detection system based on 14 bit, 200 kSPS analog-digital converters and a digital signal processor (DSP) of the TMS320C6211 ™ type.
In case of the corrector magnet circuits one channel is reading the current by means of a 600 A Hall-type current sensing device. The other channel measures the differential voltage drop across the superconducting part of the circuit. The DSP is processing the incoming signals, calculates the derivative of the measured current and extracts the resistive fraction of the differential voltage. Hereby, the DSP uses preloaded inductance tables, thus providing active compensation of the inductive voltages. These tables will be generated and updated during special calibration cycles. In case the resistive fraction

exceeds the detection threshold of 100 mV for more than 10 ms a quench signal will be generated and transmitted to the machine protection system.
For the protection of the insertion region and inner triplet magnets this approach is not feasible due to the higher nominal current rating of these magnets. The installation of dedicated current sensors for the protection system has been discarded for space and cost reasons. Voltage taps connected to the midpoints of the respective circuits and the cold ends of the current leads however offer the possibility to create a bridge type detector, which is also including the superconducting busbars. The digital quench detector compares constantly the two differential input voltages, compensates if necessary different inductances of the two branches, and determines the resistive fraction of the circuit voltage. The detector firmware has implemented two thresholds, one for the resistive fraction and a second for the absolute sum of the measured input voltages. In both cases a quench signal will be generated and the associated quench heater power supplies will be triggered.

4.2. Protection system for HTS current leads

Each of the of HTS-based superconducting current leads [7], which are used for powering all superconducting circuits with current ratings of 600 A and higher, is protected by a specially designed detector, which supervises the resistive part of the leads as well as the superconducting part. The design of this type of current lead requires a detection of U_{th} = 3 mV for the superconducting and U_{th} = 100 mV for the normal conducting part. The accepted response time for the detections system is t_{dis} = 5s. Based on these boundary conditions a high precision detection system has been designed. The hardware is based on an analog input stage built up with precision instrumentation amplifiers and a micro-converter of the ADuC834 ™ type, which incorporates basically a 24 bit analog-digital converter of the Sigma-Delta type and a microcontroller core. Recent tests of this type of detection system on a test bench for HTS current leads have confirmed the validity of the design and the ability of the system to detect properly quenches in the superconducting part of the lead.

4.3. Protection of superconducting busbars for 13kA main circuits

The superconducting busbars, which are used for powering the LHC main dipole and quadrupole magnets, require a dedicated quench detection system. The basic layout is shown in Figure 2. The detection system consists of a cluster of digital voltmeters, which are coordinated by a master device via a fieldbus link. The WorldFip ™ type fieldbus, which is running at a data transfer rate of 1 Mbit/s, is deterministic in time with a precision of 1 ms. The master device, an industrial PC running the LynxOs ™ real time operating system, collects the data from the various measuring points and calculates the resistive fraction of the differential voltage drop across the respective superconducting circuit. During the current ramp from injection to nominal current the inductive voltage generated within these superconducting circuits is large compared to the detection threshold of U_{th} = 1 V, e.g. for the main dipole circuit about 160 V. Therefore a precision digital voltmeter with a fieldbus interface has been developed. The voltmeter part is based on the design for the protection system for HTS current leads, whereas the fieldbus link is inherited from the acquisition and monitoring controller design (see below).

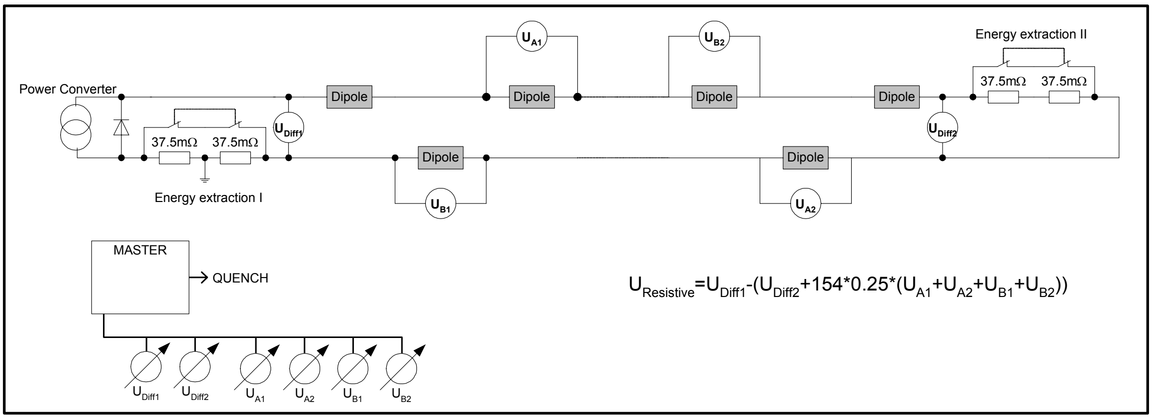

Figure 2: Protection system for 13 kA superconducting busbars. The figure shows the case of a dipole circuit. In total there will be 8 master and 80 slave (voltmeter) devices installed.

4.4. Reliability

As for the local quench detectors the reliability of the digital quench detection systems has been extensively studied [4]. Following the outcome of these studies a "1 out of 2" multi-channel evaluation system using two redundant detectors has been applied. All digital quench detection systems make use of a redundant powering scheme with two power supplies circuited in parallel.

5. Acquisition and monitoring controllers

Acquisition and monitoring controllers enable the supervision of all electronic devices belonging to the quench protection and energy extraction system and transfer the data via a fieldbus link and a gateway computer to the higher-level LHC control systems [8]. The acquisition and monitoring controllers exist in three different variants, which differ in the number of analog and digital I/O channels, the type of local control interfaces and the number of supervised devices. The hardware is based on a micro-converter of the ADuC831 ™ type, which incorporates basically a 12 bit, 8-channel analog-digital converter and a microcontroller core, which is compatible to the 8052 standard with respect to the programming interface. The coupling to the fieldbus is realized with an ASIC of the VY27257 MicroFip ™ type implementing the WorldFip ™ fieldbus protocol. The microcontroller interfaces to the MicroFip ™ by direct read/write access to the device registers. All controllers are equipped with 62 kbyte flash EEPROM (electrical erasable programmable read only memory) and 32 kbyte SRAM (static random access memory). Using the Harvard-type programming architecture of the microcontroller, the program code will be stored in the flash EEPROM memory and acquired data in the SRAM. All dynamic data will be written to three physically different locations inside the SRAM and read back by a software with implemented 2 out of 3 bitwise error correction scheme. By this approach the radiation tolerance of the device has been significantly improved also due to the stability of the EEPROM in a radiation environment. Prototypes of the acquisition and monitoring controllers have been successfully tested with respect to the radiation tolerance levels required in the LHC tunnel (200 Gy) [3].

6. Conclusions

Prototype and pre-series devices of the different types of electronic devices required for the protection of the LHC superconducting elements have been built and successfully tested. Most of them were installed in the String II [9] experiment, which is a full-scale mock-up of the LHC standard cell and whose experimental programme has been recently completed. The qualification of devices components qualification including radiation tests has been concluded. The final technical specifications have been prepared and the industrial production has been launched. First deliveries are expected within 2003, the installation and commissioning of the first systems will start in 2004.

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