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DESIGN, MANUFACTURING AND VALIDATION OF THE NEW QUENCH HEATER DISCHARGE POWER SUPPLIES FOR THE PROTECTION OF SUPERCONDUCTING MAGNETS FOR THE HIGH-LUMINOSITY LHC PROJECT AT CERN*

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Abstract

The Quench Heater Discharge Power Supplies (HDS) are magnet protection devices installed in the Large Hadron Collider (LHC) that, upon detection of a magnet quench, release energy into strip heaters that are in thermal contact with the superconducting coils, inducing a resistive transition all along the coils. The new HDS design for protection of the High Luminosity LHC (HL-LHC) Inner Triplet magnets calls for a more advanced design with up-to-date components resulting in a high reliability of the HDS units.

Several HDS prototypes were produced at CERN, eventually culminating in the development of the HL-LHC HDS version to be installed in the accelerator. This paper describes the design of the upgraded HDS units and the comprehensive safety and electromagnetic compatibility (EMC) tests conducted, coupled with an assessment of readiness under extended operational conditions, including irradiation tests.

INTRODUCTION

The Quench Heater Discharge Power Supplies (HDS) are critical magnet protection devices [1] installed throughout the Large Hadron Collider (LHC. These devices play an important role in the protection by releasing energy into copper-plated stainless-steel strip heaters upon the detection of a magnet quench. As these heaters are in thermal contact with the superconducting coils, though galvanically separated from them, this action induces a resistive transition along the entire length of these coils. The distribution of internal heating over a large volume effectively prevents localized overheating and potential damage to the superconductor and the magnet structure. Since their initial deployment in 2007, over 6000 HDS units have been in operation maintaining the integrity of the LHC superconducting magnets.

The new HDS design for protection of the High Luminosity LHC (HL-LHC) Inner Triplet magnets, to be installed in the LHC Long Shutdown 3 starting in 2026, calls for a more advanced design with up-to-date components, and with improved reliability. These upgraded HDS units will operate in conjunction with the Coupling-Loss-Induced-Quench (CLIQ) units [2,3], forming an integrated system that enhances the overall quench protection strategy of the HL-LHC magnets.

In the event of a CLIQ failure, the new Inner Triplet magnets need a larger fraction of the redundant HDS units to trigger successfully to reliably quench the magnet– 87% at high magnet current [4] compared to the 40-50% required in the present LHC main dipole and quadrupole magnets.

UNIT DESCRIPTION AND UPGRADED DESIGN

HDS Description

Figure 1 shows a simplified diagram of a HL-LHC HDS unit. Each HL-LHC HDS unit contains:

- A capacitor bank with six 4.7 mF aluminium electrolytic capacitors with a grounded mid-point, resulting in a total capacitance of 7.05 mF. The nominal operating voltage of the capacitor bank is 940 V to deliver ≈ 3.1 kJ to a single quench heater strip.
- A trigger and discharge circuit, two thyristors and two current transformers.
- Two redundant 15 V DC lines for powering the electronics.
- A resistor bank installed for internal energy dissipation in case of power off.
- A main power switch, and safety indicators mounted on the front panel.

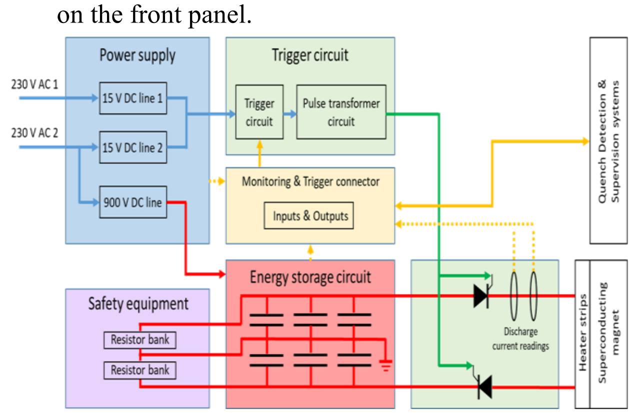

Figure 1: Simplified diagram of an HDS unit.

Summary of the HDS Upgrades

The main upgrades included in the HL-LHC HDS units are:

- Higher discharge current: adapted to deliver up to 200 A.

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- Increased reliability: two redundant power supplies, two trigger inputs and the possibility for checking if the discharge connectors are plugged in.
- Increased monitoring: addition of two current measurement transformers and redundant power supply surveillance.
- Additional (personnel) safety mechanisms: internal energy discharge activated upon power loss and a voltmeter on the front panel.
- Replacement of the obsolete electronic components and full redesign of the Printed Circuit Boards (PCB), which are split in two main boards to facilitate the assembly and inspection.
- Volume of the metallic enclosure has been reduced by more than 20%.

PROTOTYPING AND PRE-SERIES MANUFACTURING OF HDS

Three consecutive stages of prototype development were conducted in-house, culminating in the successful production of 58 pre-series units at CERN which are shown in Fig. 2. A detailed technical specifications document was thoroughly prepared to ensure that the final product met the functional and quality assurance/control (QA/QC) requirements anticipated for the following series production. Particularly, the production and assembly of the PCB adhered strictly to the IPC Standards Class 3 [5], which is crucial for high-reliability electronic devices. This compliance was especially critical in several areas including the handling of electronic assemblies, installation location and orientation of components, soldering, cleanliness, marking, and the acceptance of surface mount assemblies.

The 58 pre-series units are intended to be installed in the Inner Triplet String Facility that will start operation in 2025 [6] with the aim of testing the magnets in conditions as similar as possible to the final configuration in the LHC tunnel.

Figure 2: HDS pre-series production.

PROTOTYPE VALIDATION AND FINAL QUALIFICATION TESTS

Irradiation at Component and System Level

The HDS for the HL-LHC will be installed in galleries adjacent to the accelerator and are expected to receive a Total Integrated Dose (TID) not surpassing 100 Gy throughout their lifetime. However, other units, e.g. the ones presently installed in the tunnel, are expected to receive higher TID rates, hence a policy of HDS rotation might have to be put in place for these units.

A comprehensive radiation testing of selected components known to be the most susceptible to radiation effects such as regulators, timers, and transistors was performed at the Paul Scherrer Institute – Proton Irradiation Facility (PSI-PIF). Additionally, system-level evaluations of five HDS prototypes were conducted in the CHARM facility at CERN [7], demonstrating that these units could withstand a minimum TID of 325 Gy and a total fluence of 10^{12} p/cm^2. The most radiation-sensitive components, two series-connected thyristors controlling the energy discharge into the magnet heater strips, exhibited an increase in holding current. This was reflected by an increased residual energy bank voltage from the start of irradiation, as shown in Fig. 3, leading to a safe failure mode via short-circuit in both thyristors after a discharge event. Due to the nature of the post-mortem measurement, we can monitor the remaining voltage only ≈ 30 min after the HDS discharge, then the represented value is dominated by the capacitors dielectric absorption and controlled by the thyristor holding current.

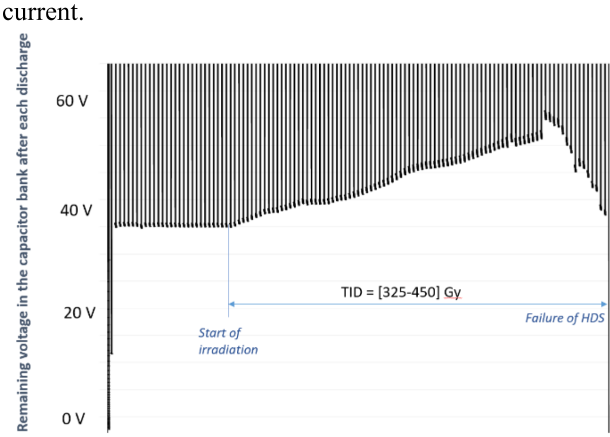

Figure 3: HDS remaining charging voltage vs TID.

It is therefore proposed to monitor the remaining capacitor bank voltage during operation as it is a powerful failure precursor that can be used to anticipate the need for a potential unit replacement. At the moment the voltage trend changes it means that one of the two thyristors of the HDS is about to fail in short.

No Single Event Upsets (SEU) were observed but for future designs, it is planned to perform further studies at component level with higher number of units using the mixed field facilities in CHARM.

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Lifetime Studies of Main Capacitors

As most of the units are expected to operate under low-radiation conditions, their operational lifespan is predominantly determined by the durability of the electrolytic capacitors used in the main energy storage bank. Over a year was dedicated to the qualification of these capacitors through accelerated aging tests. These tests [8], conducted under controlled stress conditions at different temperatures from 75 °C to 105 °C, simulated extended operational periods and provided detailed insights into the capacitors' expected lifespan and degradation mechanisms. The findings from these tests provided confidence in the choice of capacitor type and supplier, projecting a minimum lifespan of 20 years for the new HDS design.

Moreover, the HDS are manufactured with flexibility to accommodate different dimensions of main capacitors, in case a potential replacement will be required.

Safety, Electromagnetic Compatibility (EMC) and Environmental Studies

The HDS prototypes underwent a series of safety, EMC, climatic and vibration tests carried out in collaboration with an independent third party. The assessment of the immunity is critical for the availability of the units when operating in the LHC environment. For the new design this is of special importance because spurious triggering of several units could cause an unwanted kick on the circulating particle beam [9], with consequent serious damages to the machine. The units followed, among other, radiated / conducted emission and immunity tests, electrostatic discharges, voltage interruption and surges. Figure 4 shows the HDS unit within an anechoic chamber during one of the radiated immunity tests.

These studies revealed the need for a few aspects of the initial prototype design to be improved, for example the light indicators on the front panel were replaced after some failures during the surges tests. Also, the vibration studies at 5-500 Hz on each axis, very relevant for the HDS as they are regularly transported by the on-call service, showed some weakness due to the assembly of several bulky coils and resistors assembled on PCB that were eventually glued with a CERN approved epoxy in the final HDS version.

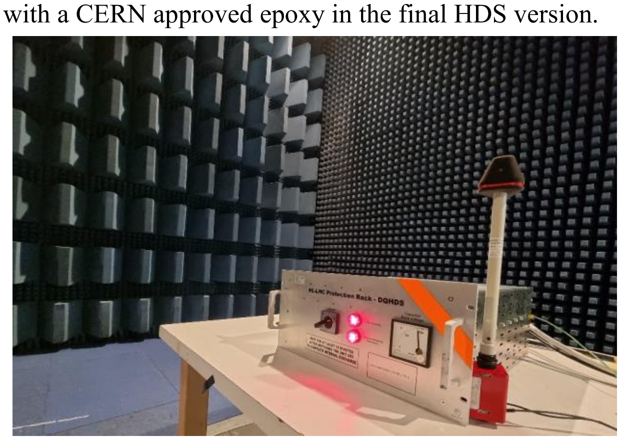

Figure 4: HDS radiated immunity tests.

Prototype and Pre-series Production Tests

A thorough set of high voltage and functional test procedures, with defined acceptance criteria were prepared. More restrictive type test parameters were applied for prototyping and routine values for the pre-series production. The type testing, together with the mentioned EMC, safety, and irradiation test campaigns, helped to select the components and enhance the subsequent prototyping design. The routine testing assured the quality of the production. The series production of a few hundredths of units will be provided through a collaboration with the High Energy Accelerator Research Organization (KEK) in Japan. Delivery of all the HDS units is foreseen before the end of 2026.

CONCLUSION

The new HDS units for the HL-LHC upgrade are equipped with features such as higher discharge currents, enhanced monitoring, and robust safety mechanisms, crucial for meeting the HL-LHC's operational requirements in terms of performance and reliability.

Extended qualification tests, including EMC and safety assessments, irradiation tolerance and lifetime studies, confirmed the HDS units' functionality and robustness.

The upcoming installation and use of these units in the HL-LHC's Inner Triplet String Facility represents a critical final validation step towards ensuring an efficient machine protection throughout the operational period of the HL-LHC project.

The HDS series production will be taking place during the next two years through a collaboration between CERN and KEK.

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