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DESIGN, MANUFACTURING AND VALIDATION OF THE CLIQ UNITS FOR THE PROTECTION OF SUPERCONDUCTING MAGNETS FOR THE HIGH-LUMINOSITY LHC PROJECT AT CERN *

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Abstract

The novel Coupling-Loss-Induced-Quench (CLIQ) concept will be part of the quench protection system of the superconducting Inner Triplet magnets of the High Luminosity Large Hadron Collider (HL-LHC) upgrade at CERN.

Several units of two distinct CLIQ prototype variants were produced to validate the CLIQ protection concept and define the system parameters for the required performance.

Subsequently, these units were further enhanced by introducing additional redundancy, advanced monitoring systems, and improved safety features. These improvements culminated in the development of the third and final version for series production.

This paper provides insights into the evolution from first prototypes to the final version to be installed in the HL-LHC, shedding light on the outcomes of comprehensive safety and electromagnetic compatibility (EMC) tests, coupled with an assessment of readiness under extended operational conditions.

INTRODUCTION

The Coupling-Loss-Induced-Quench (CLIQ) method is a recently developed superconducting magnet protection technology [1, 2]. It is based on a capacitive discharge system that forces an oscillating current into a coil, altering the local magnetic field, inducing high inter-filament and inter-strand coupling losses, rapidly and effectively heating the entire volume of the coil.

It is a very promising method for protecting next-generation high-field, high-energy density magnets as it generates heat directly within the conductor, thereby not relying on heat diffusion to propagate the quench.

To validate this novel protection concept and refine the system parameters for optimal performance, several units of two different CLIQ prototypes, v1 and v2 [3], were developed and extensively used during qualification tests of High Luminosity Large Hadron Collider (HL-LHC) superconducting magnets [4]. The final implementation, CLIQ v3, will be the one used for the protection of the Inner Triplet magnets installed in the LHC tunnel, in conjunction with the Quench Heater Discharge Power Supplies (HDS) [5].

CLIQ v3 incorporates advanced monitoring and safety features, and its design focuses on maximizing reliability and operational availability.

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UNIT DESCRIPTION AND UPGRADED DESIGN

CLIQ v3 Description

A simplified diagram of a CLIQ unit is shown in Fig. 1. Each CLIQ unit contains:

- Redundant power supplies and one capacitor charger that delivers 300 mA constant charging current until the programmed voltage is reached, 600 or 1000 V DC depending on the magnet type to be protected.
- Trigger and discharge circuits including two Bi-directional Controlled Thyristors (BCT) and two pulse transformer boards to control a maximum current discharge of 5 kA, which is redundantly monitored by two current transducers, three current transformers and two Rogowski coils.
- Charge and energy storage circuit with four 40 mF capacitors, with a maximum operational energy of 20 kJ.
- Monitoring and control unit collecting all the signals and managing the communicating with external systems.
- Equipment stop button, relays and bank of resistors, which are installed to internally dissipate the energy if required or in case of power loss.
- The CLIQ rack measures 80 x 100 x 210 cm and has a mass of 630 kg.

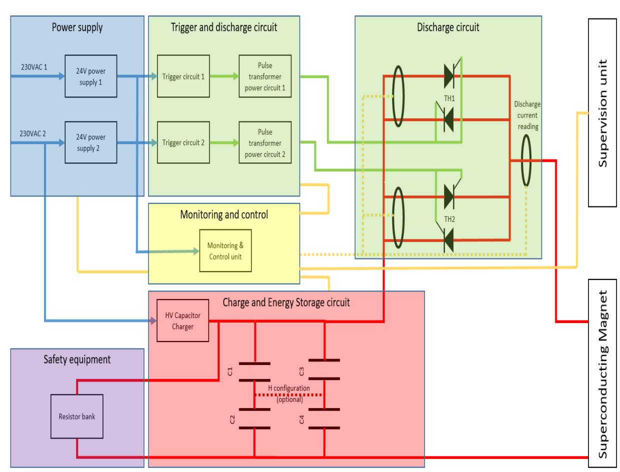

Figure 1: Simplified diagram of CLIQ v3.

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Summary of Upgrades from CLIQ v2 to CLIQ v3

While preserving the fundamental mechanisms for triggering and discharge, the transition from CLIQ v1 and v2 to v3 involved substantial modifications, particularly in terms of reliability, self-diagnostics, and monitoring. The key enhancements are summarized as follows:

- Increased reliability: four capacitors are now arranged in a 'square' configuration as shown in Fig. 1, effectively increasing the unit's reliability by reducing the consequential impact of a short circuit in one of the capacitors. This modification has resulted in increased size and mass compared to the previous versions.
- Advanced control electronics: the CLIQ v3 control and monitoring crate is based on the Distributed IO Tier (DI/OT) crate developed by CERN [6] and it follows the DI/OT specifications for crate design and interfaces.
- Additional sensors: CLIQ v3 also includes additional current transformers and backup Rogowski coils for redundancy and fast detection of spurious firings.
- Power redundancy: the new version features two 230 V AC power input ports.
- Additional safety mechanisms: the unit can report internal failures and disconnect the charging power source in case of e.g. an overpressure in a capacitor. It allows for switches padlocking, and it includes an indicator showing the internal discharge progress that is performed in the event of a power loss or when the equipment button is pushed.

Figure 2 shows the CLIQ v2 and v3 next to each other.

Figure 2: CLIQ v2 (right) and v3 (left).

PROTOTYPING AND PRE-SERIES MANUFACTURING OF CLIQ

A prototype of the CLIQ v3 units, from now on referred to as CLIQ units, was initially produced in-house, followed by the manufacturing of a pre-series unit by industry. Subsequently, eight series units were industrially manufactured, see Fig. 3, and have been installed at the Inner Triplet String Facility, that will start operating in 2025 [7], with the objective of testing the magnet circuits in conditions as similar as possible to the final set-up in the LHC tunnel.

Figure 3: Assembly of the first CLIQ series batch.

Industry is currently manufacturing an additional 24 CLIQ units to meet CERN's requirements for the HL-LHC project, scheduled for installation as of 2026.

Special attention was dedicated to ensuring that the final product met rigorous functional and quality assurance/control (QA/QC) standards necessary for the reliable operation of the CLIQ units throughout the entire HL-LHC lifetime. Specifically, the production and assembly of the Printed Circuit Boards (PCBs) strictly adhered to IPC Standards Class 3 [8], which is essential for high-reliability electronic devices. This compliance was particularly critical in areas including electronic assembly handling, installation location and orientation of components, soldering, cleanliness, marking, and the acceptance of surface mount assemblies.

PROTOTYPE VALIDATION AND FINAL QUALIFICATION TESTS

Qualification of Main Capacitors

CLIQ incorporates four 40 mF metallized polypropylene capacitors with long lifetime and allowing for the corresponding LC oscillation exchange of energy with the magnet. They are included in a stainless-steel casing, each of them having a mass of 75 kg and being rated to 1000 V DC.

A comprehensive set of qualification tests was performed in collaboration with the industrial contractor, with 10 kA discharges and measuring the key capacitor parameters before and after the tests, including capacitance, series resistance and leakage current. Other endurance tests, like environmental, mechanical torque resistance, short-circuit or self-healing induced faults were carried out before the final capacitor selection.

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Extended Operational Tests

To validate the robustness and reliability of the new control and monitoring system, the capacitor charger and the redesigned capacitor configuration, several extended operational tests were conducted. Utilizing up to three CLIQ units, approximately 10,000 charge-discharge cycles were carried out at a nominal current of 3.2 kA on a 2.2 mH coil. These extensive tests and data collections were carried out over a period of three months, with all operational data being meticulously recorded and analysed.

Endurance: the CLIQ units demonstrated exceptional durability with no evidence of aging or degradation in performance throughout the testing period.

Reliability: there was no failure to trigger on demand nor any spurious trigger, affirming the reliability of the system under continuous operational conditions.

These results confirmed the high reliability and operational readiness as well as validated the design enhancements made from previous versions.

Safety and Electromagnetic Compatibility (EMC) Studies

The CLIQ prototype and pre-series underwent a series of safety and EMC tests carried both at CERN and in collaboration with a third party. The assessment of the immunity of the new design was of special importance because spurious triggering of a single CLIQ unit can cause an unwanted kick on the circulating particle beam [9], with consequent serious damages to the machine if the erratic triggering remains undetected. The units followed, among others, radiated/conducted emission and immunity tests, electrostatic discharges, voltage interruption and surges. Figure 4 shows the unit in an anechoic chamber during a radiated immunity test.

The findings of these studies helped improving several aspects of the units. In particular, the EMC fast transient test performed at both 5 and 100 kHz, up to the level 4 of the industrial standard, resulted in an improved cabling and shield connection to be able to reduce the threshold for the detection of spurious triggers.

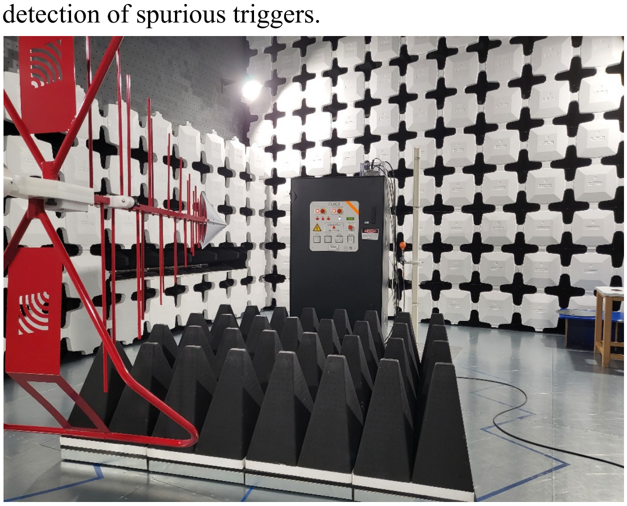

Figure 4: CLIQ radiated immunity tests.

Prototype and Series Production Tests

A systematic set of high voltage and functional test procedures, with defined acceptance criteria were prepared, with more restrictive parameters for prototyping and with routine values for the series production. The type tests, together with the mentioned EMC and safety studies, facilitated the definition of the components specifications and improved the subsequent design. The routine testing assured the quality of the production.

CONCLUSION

The development, manufacturing and deployment of the final CLIQ version in the Inner Triplet String Facility for the protection of the HL-LHC superconducting magnets marks a significant milestone in the field of magnet quench protection. The CLIQ units include advanced safety mechanisms, enhanced reliability, and superior performance capabilities compared to earlier versions. A rigorous validation process involving a comprehensive series of high-voltage, functional, and EMC tests have confirmed the system's robustness and effectiveness, ensuring that they meet the stringent safety and performance standards required for this critical application.

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