ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS028

RELIABILITY ANALYSIS OF THE NEW UNIVERSAL QUENCH DETECTION SYSTEM AND PROTECTION DEVICES SUPERVISION UNIT FOR THE HL-LHC INNER TRIPLET MAGNETS*

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Abstract

The new Universal Quench Detection System (UQDS) and Protection Devices Supervision Unit (PDSU) are pivotal elements for the quench protection system of the new HL-LHC inner triplet superconducting magnets as well as for requesting a beam dump upon activation of the active quench protection systems, the novel Coupling Loss Induced Quench System (CLIQ) and the traditional quench heaters (HDSs). Given the criticality of these functionalities, a thorough reliability analysis has been carried out to ensure that the probability of critical failures meets the stringent reliability requirements under all operational conditions. To determine the failure probabilities, analytical models were developed that consider redundancies, inspection strategies and demand frequencies. The models' failure parameters were identified by a component-based Failure Mode, Effects and Criticality Analysis (FMECA). The results of the models allow the qualification of the system design as well as insights on critical monitoring and testing requirements of the system when in operation.

INTRODUCTION

As part of the High Luminosity LHC project [1], new inner triplet (IT) superconducting magnets are installed around the high luminosity experiments. They are based on Nb3Sn superconducting material and require protection by the novel Coupling Loss Induced Quench Systems (CLIQs) [2]. In beam tracking studies, the spurious discharge of a CLIQ unit was identified as a critical fast failure for the HL-LHC, leading to a critical beam loss level within only five machine turns [3]. Thus, a fast connection with the Beam Interlock System (BIS) is required, provided by the Protection Devices Supervision Unit (PDSU), responsible for triggering, monitoring and interlocking of the quench heaters (HDSs) and CLIQs [4]. In addition, the magnets, busbars (BBs), and superconducting links (SCLs) must be protected against quenches – local temperature increases that result in a loss of superconducting properties. To protect the magnets in the event of a quench, the Universal Quench Detection System (UQDS) detects the quench and triggers the PDSUs, which trigger the HDSs and CLIQs. To ensure full activation of all protection devices, the PDSUs implement a retriggering scheme. Since the execution of magnet protection and the initiation of a beam dump are safety-critical functions, a comprehensive reliability analysis was conducted to ensure the system meets the stringent reliability targets. The corresponding results are presented in this paper and are structured according to the applied methodology. It starts with defining the reliability targets during the risk identification and quantification phase. This is followed by the risk estimation and mitigation phase, conducting subsystem FMECAs and, obtaining quantitative reliability results from analytical models, which feedback to the design and to testing requirements.

RELIABILITY TARGETS

A system-level FMECA was performed to identify potential failure modes and their associated reliability targets. Based on the results, the following two protection relevant failure modes were classified as critical due to their potential impact on the machine:

- **Missed magnet protection** following a magnet quench.
- **Missed beam dump** following a magnet quench or following a spurious firing.

For each failure mode, reliability targets - defined as the maximum accepted failure frequencies - were derived using the LHC Risk Matrix [5], which correlates the required recovery time in a failure scenario with the acceptable failure frequency. Based on the determined recovery time of 1 year for both failure modes and by applying appropriate scaling to account for the multiplicity and complexity of the systems under study, a target of **1 failure in 10000 years** was defined across all the inner triplet UQDSs and PDSUs.

SUBSYSTEM FMECA

As part of the risk estimation, subsystem FMECAs were carried out during which approximately 900 components were individually analysed to identify blind failures - component faults that prevent execution of the protective function/s on demand and can only be detected by dedicated tests. Therefore, failure rates were determined for each component, based on the Reliability Prediction Handbook 217Plus [6] and failure modes were identified based on the FMD-2016 [7] and FMD-91 [8] databooks. The equipment expert assigned to each component-level failure mode the corresponding system level failure mode. Furthermore, it was assessed by which activity (inspections, commissioning, demand or magnet ramp) the blind failures could be detected and repaired. The three following blind failure classes were defined and assigned to each blind failure:

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- **Class 1:** Discovered and resolved upon yearly commissioning (requiring CLIQ/HDS firing tests) or on demand (quench or spurious firing).
- **Class 2:** Detected and resolved at every LHC ramp (assumed every 12 hours) through monitoring of the inductive voltage.
- **Class 3:** Detected unsafe failures, visible from supervision and resolved within 12 hours.

MODEL DESCRIPTION

For the qualification of the design, the expected frequency of a missed magnet protection and beam dump must be quantified and compared to the target. Analytical models that integrate component-level failure probabilities, component-specific inspection strategies, the global system architecture, and varying demand frequencies were developed. The models are based on a minimal cut set approach, using the rare event approximation to perform the calculations. Selected models were validated through Monte Carlo simulations carried out using AvailSim4, a Monte Carlo simulation tool developed at CERN [9, 10]. The functional dependencies underlying the models are shown in Fig. 1.

The HL-LHC inner triplet consists of six quadrupole magnets housed in four cryostats. Q1 and Q3 each comprise two shorter MQXFA magnets (Q1a/Q1b and Q3a/Q3b, respectively) housed together in a common cryostat, while the longer MQXFB magnets (Q2a and Q2b) are each housed in individual cryostats [1]. To describe the functional sequence in a quench scenario, a quench in Q1 is assumed. In this scenario, UQDS Q1 A and B independently detect the quench and trigger each other. Upon detection, the UQDSs individually trigger all six PDSUs. To account for the case where a PDSU is not triggered, the A PDSUs trigger each other, and the same mechanism is applied by the B PDSUs. Once triggered, the PDSUs initiate both magnet protection and a beam dump request:

a) **Magnet protection:** PDSU Qx A and B trigger individually both CLIQs and all 16 HDSs of Qx. This is done for Q1, Q2a/b and Q3.

b) **Beam dump request:** Each PDSU individually sends a beam abort request to the BIS via a dedicated interface card, which has been subject to a separate reliability analysis [11].

To describe the functional sequence in a spurious firing situation, a firing of a single Q1 CLIQ is assumed. The PDSU Q1 A and B independently detect the firing. Upon detection, the PDSU Q1 A triggers the other A PDSUs and the same mechanism is applied by the B PDSUs. All PDSUs execute both magnet protection and beam dump request as described above.

Based on these sequences, a model for each function was developed, as shown in Fig. 2. Model (a) represents the magnet protection function during a quench event, while Model (b) captures the beam dump request in a spurious firing scenario. Each model isolates one of the two functions - magnet protection or beam dump. If the reliability requirements are fulfilled for both models individually, they are satisfied in both scenarios.

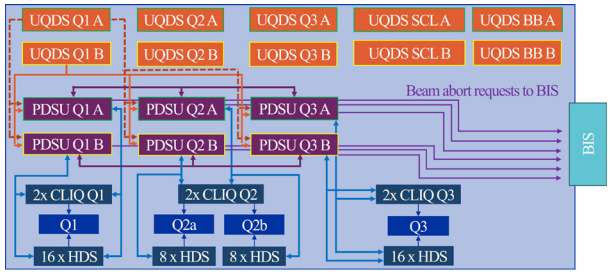

Figure 1: Top-level system functional diagram of the magnet protection and beam dump functionality. Adapted from [12].

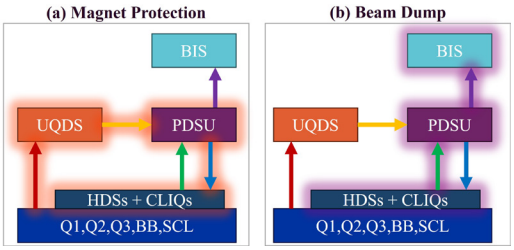

Figure 2: Overview of function models – relevant modelled paths are highlighted. (a) Magnet protection model - ignores beam dump functionality. (b) Beam dump model - ignores magnet protection functionality.

Reliability Block Diagram

Reliability Block Diagrams (RBDs) were developed for the two functional models. The resulting RBD for the magnet protection function is shown in Fig. 3. The magnet protection functionality is ensured if a path with functional systems exists, starting from left to right. Each block in the diagram corresponds to a series configuration of subsystems, with failure rates estimated in dedicated FMECAs. Starting from the left, at least one of the UQDSs must be functional to detect the quench and trigger the PDSUs. To trigger the HDSs and CLIQs, at least one PDSU per Qx magnet must be functional. For simplicity, the retriggering process for the UQDSs and A and B PDSUs has been omitted, which, while simplifying the model, ensures a conservative estimate of the failure frequency.

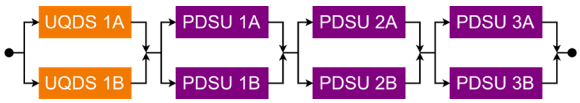

Figure 3: RBD for the Magnet Protection functionality.

RELIABILITY RESULTS

The results obtained from the described analytical models are depicted in Fig. 4 for both, magnet protection and beam dump as a function of the interval between demands per operational year (1 op. year = 7200 hours), i.e. the number of yearly quenches or spurious CLIQ/HDS firings. The results are scaled to all protected HL inner triplet elements, 96 coils and 32 BB & SCL elements for the magnet protection and 24 CLIQs and 192 HDSs for the beam dump model. Expected demand intervals for magnet quenches and spurious CLIQ/HDS firings are shown with vertical shaded bars. The maximum number of failures occurs when the demand interval approaches the commissioning

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interval (1 per year). Magnet protection is less reliable, primarily due to the longer chain of systems in the critical path. Nevertheless, the reliability target of maximum 1 failure per 10000 years is comfortably met for both functions, provided that the assumed testing and inspection policy for the three different blind failure classes, described in the section on the subsystem FMECA, is rigorously applied.

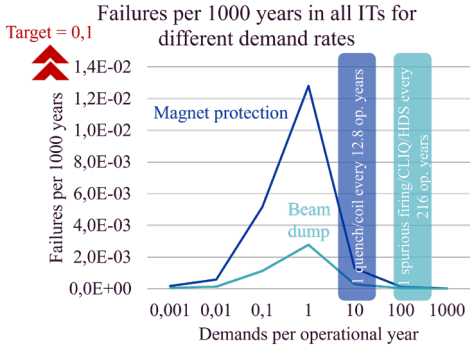

Figure 4: Resulting failure rates for magnet protection and beam dump functionality as a function of the interval between demands across all HL ITs, i.e. number of yearly quenches or spurious CLIQ/HDS firings. Expected demand intervals for magnet quenches and spurious CLIQ/HDS firings are shown with vertical shaded bars.

Impact of Interlock Test Interval

The assumed yearly interlock test – including firing of the CLIQs/HDSs is relevant for resolving Class 1 blind failures. Extending the testing interval to three years results in an increased failure rate, primarily due to the accumulation of blind failures that are only detected during commissioning or on demand, as shown in Fig. 5. The reliability target is comfortably met with annual testing, regardless of the demand rate. When the testing interval is extended to three years the target can no longer be achieved at demand frequencies of approximately 0.1 to 10 per operational year. Accordingly, interlock tests to check full redundancy are necessary every year.

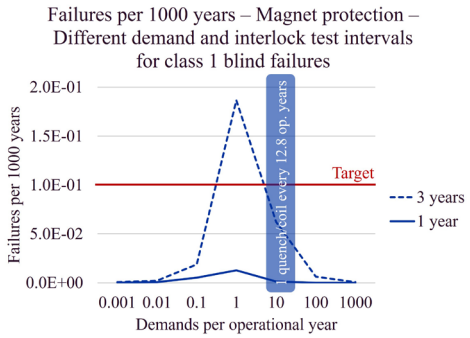

Figure 5: Resulting failure rates for magnet protection under one- and three-year interlock test intervals as a function of the interval between demands across all HL ITs, i.e. quenches. The expected demand interval for magnet quenches is shown with a vertical shaded bar.

Impact of Inductive Voltage Monitoring & Reaction to Supervision

The time to repair for Class 2 and 3 blind failures has a strong impact on system reliability. This was studied by varying the repair time from 12 hours to one operational year. As baseline, a yearly interlock test and a demand of ten quenches per year is assumed. If Class 2 & 3 failures are detected and repaired within 72 hours instead of 12 hours, the increase in failures per 1000 operating years remains negligible, as shown in Fig. 6. However, if failures are only identified during technical stops every 10 weeks or during yearly commissioning, a maximum of 6.8E-01 failures can be reached.[1] In conclusion, implementing continuous monitoring and ramp testing is essential for maintaining protection functionality. However, immediate repair of identified issues is not strictly necessary; delaying repair up to three days is possible and minimizes the impact on LHC operations.

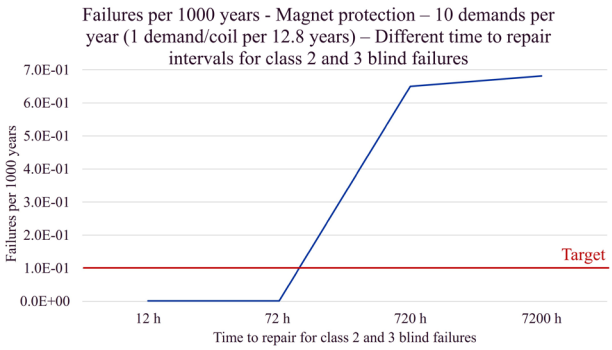

Figure 6: Resulting failure rate for magnet protection under different time to repair intervals considering a demand equivalent to ten quenches per year across all HL ITs.

CONCLUSION

The conducted reliability analysis for the quench protection and beam dump function in the context of the new HL inner triplet magnet protection indicates that the proposed UQDS and PDSU hardware design meets the defined reliability targets, provided that:

- Yearly interlock tests are performed as part of the yearly commissioning to ensure full redundancy of the system.
- Monitoring of inductive voltages is performed as part of each LHC magnet current ramp.
- Potential blind failures identified via inductive voltage monitoring or in general system supervision are resolved within 72 hours.

Recommended follow-up actions include analysing critical firmware, software, and configuration management, as well as reviewing the implementation of monitoring and testing strategies to complement the hardware assessment. In addition, the system's availability in the presence of failures causing spurious protection function execution must be thoroughly evaluated.

[1] Assumes a Software Interlock System (SIS) that halts operation if both critical paths lose supervision; without a SIS, failure rates rise by ~10%.

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