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RELIABILITY ANALYSIS OF THE HL-LHC ENERGY EXTRACTION SYSTEMS

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Abstract

The energy extraction systems for the protection of the new HL-LHC superconducting magnet circuits are based on vacuum breakers. This technology allows a significant reduction of the switch opening time and increases the reliability of the overall system with reduced maintenance needs. This paper presents the results of detailed reliability studies performed for these new energy extraction systems. The study quantifies the risk of a failure preventing the proper protection of a magnet circuit and identifies the most critical components of the system. To do this, the model considers factors such as failure probabilities at the block or component level, different maintenance strategies, and repair procedures. Reliability simulations were performed using AvailSim4, a novel Monte Carlo code for availability and reliability simulations. The results are compared against the system's reliability requirements and provide insights into the most critical components.

INTRODUCTION

The Energy Extraction (EE) systems are essential elements for the protection of LHC's superconducting circuits in case of magnet quenches. Following the transition from the superconducting to the normal-conducing state, the energy stored in the magnet rapidly transforms into heat which can cause damage in a magnet, as report [1] shows. Quenches in magnets are unavoidable and, as such, are an accepted failure mode. The EE systems are responsible for extracting a maximum of the energy stored in the superconducting circuits upon receiving a signal from the Quench Detection System (QDS) [2] or the power converter [3] via the Powering Interlock Controller (PIC) [4]. The EE systems react in several milliseconds after receiving the triggering signal and redirect the circuit current into resistor banks that dissipate the remaining energy stored in the circuit.

The new EE design for HL-LHC is conceived to offer an even more resilient, reliable and maintenance-free solution that will cover the increased reliability requirements of the HL-LHC. The key design change is the circuit breaker technology: the new systems are to use vacuum interrupters instead of mechanical DC breakers. The new interrupters offer maintenance-free operation, while ensuring a better reaction time than other solutions [5, 6]. Detailed studies have been performed to validate the compliance of the new HL-LHC EE systems to the protection and reliability requirements derived in section "**RELIABILITY TARGET**".

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Table 1: Number of protection systems considered in this study to derive the reliability target

Magnets	Protection	Number
Inner Triplet Quadrupole	CLIQ + QH	6 × 4
2 kA orbit correctors	EE	6 × 4
600 A and 200 A high order correctors	EE	5 × 4
D1, D2	QH	2 × 4
Total		19 × 4 = 76

The EE systems for HL-LHC will exist in two versions: 2 kA and 600 A. Both are based on similar hardware.

METHODOLOGY

The reliability model of the EE system was prepared and simulated in AvailSim4 framework [7], a tool developed at CERN for availability and reliability simulations. It offers a generic Monte Carlo approach to predict system reliability and availability, while allowing for the incorporation of additional custom strategies and protection measures, specific for accelerator technologies.

The Monte Carlo approach requires performing numerous iterations, each simulating the system behavior over its expected lifetime. The occurrence of simulated events is based on failure probability distributions defined for each component based on experience, manufacturer data or the military handbook MIL-HDBK-217 [8].

The reliability model is described by a list of components, their failure dependencies and a list of failure modes with failure and repair probability distributions. Complex failure behaviors, as well as advanced repair and maintenance strategies can also be defined. High/low system loads can be simulated by means of so-called *phases*. In addition, periodic inspections and repair of *minimal replaceable units* allow to closely reproduce the adopted maintenance strategies in use for machine protection systems. More details about the methodology used with AvailSim4, a description of the tool and instructions of its usage are available in [7].

RELIABILITY TARGET

The study focused on the critical failure of a missed energy extraction upon the occurrence of a quench. Due to the high degree of redundancy implemented in the system design, this can only occur due to a combination of independent failures in different components of the system. In case of a

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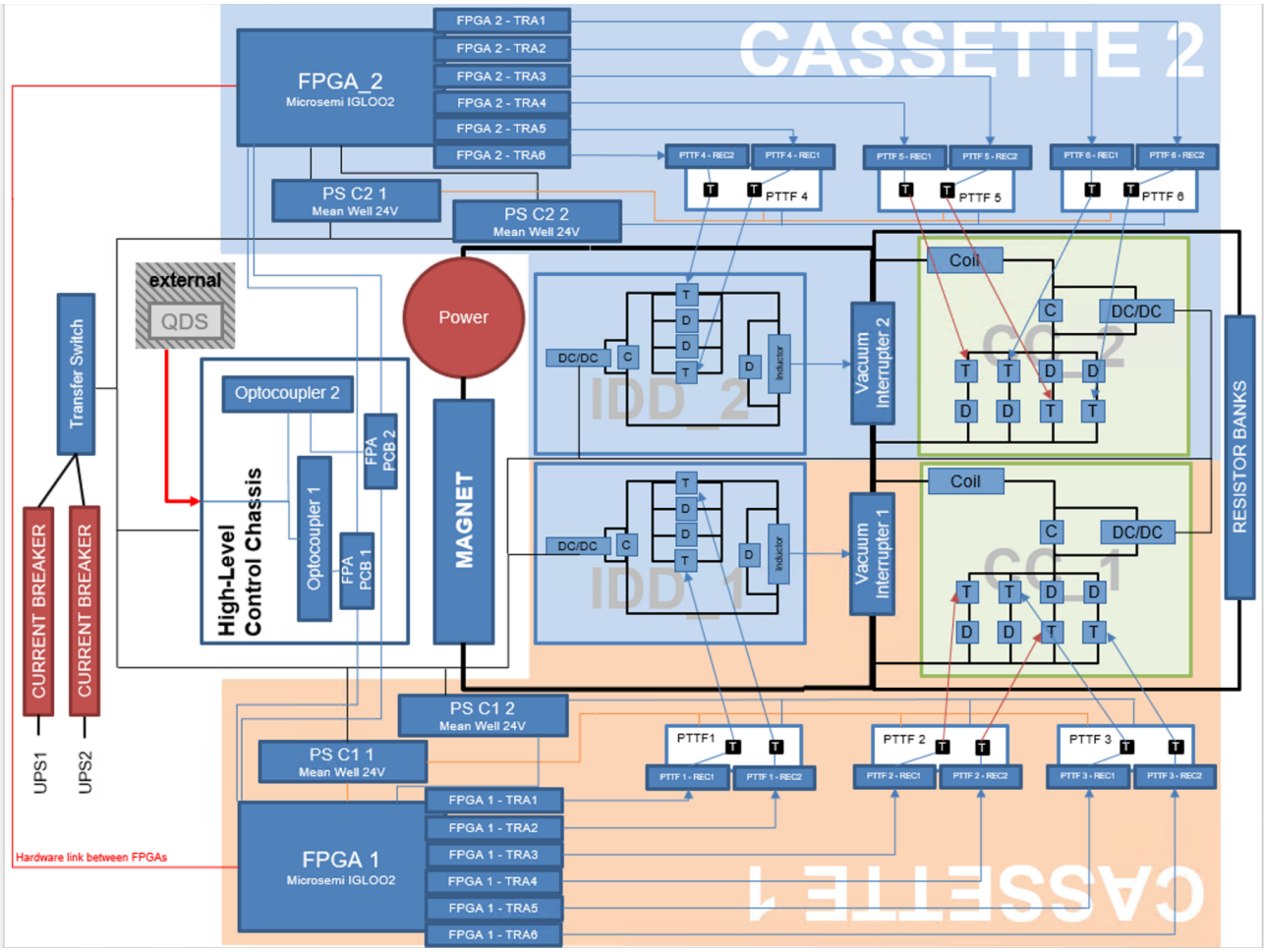

Figure 1: Functional block diagram of the new HL-LHC EE system.

missed energy extraction during nominal powering of the circuit, magnet damage will demand an intervention for the magnet replacement. The target reliability for the HL-LHC EE systems is derived from the LHC risk matrix defined in [9]. The recovery time is quantified to be in the order of *one month to one year*. According to the risk matrix in use, this yields an acceptable failure frequency of 1 in 100 years.

An additional safety margin is taken by defining the target as follows: after 100 years of operation, the failure probability should be below 10%, or conversely the expected system reliability is 90% after 100 years. The reliability target R_M scaled to the system lifetime b= 20 years is defined as follows: $R_M = r^{\frac{l}{b}} = 0.9^{\frac{20}{100}} = 0.97914$, where r is the reliability target over 100 years. The reliability threshold for an individual system must comply with the overall target when combined for 76 relevant systems (all systems which failure may lead to a critical failure) listed in Table 1.

The reliability target R_S for a single EE system is defined as $R_S = R_M^{\frac{1}{n}} = 0.97914^{\frac{1}{76}} = 0.999723$, where n is the number of considered systems. This value can be interpreted as the maximum acceptable unreliability of 2.77×10^{-4} over a system lifetime of 20 years. Within each year, the LHC will be operating for approximately 250 days – the operational period is assumed to be of 120,000 hours.

MODEL DESCRIPTION

The model is defined as a group of interconnected components organized in a hierarchy that describes the entire system. Each physical component is assigned a failure rate, provided as Mean Time To Failure (MTTF).

The developed reliability model is based on technical reports and the system functional description reported in [10]. The functional dependencies are presented in Fig. 1. Each system consists of two redundant switches connected in series to the powering circuit of the magnet. Each switch is contained in a physical *cassette*, a unit which is to be removed and replaced upon switch failure.

A signal coming from the Quench Detection System (QDS) is provided to a High-Level Control Chassis (HLCC). The signal is active-high and provided in parallel to both switches. A single switch involves operation of a dedicated FPGA, a Pulse Train Thyristor Firing (PTTF) units, Inductive Dynamic Drive (IDD – triggering the interrupter) and the Counter Current (CC – responsible for extinguishing the

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arc). FPGAs have a dedicated hardware link to exchange information about their status.

The power for the system is supplied by two Uninterruptible Power Supplies (UPSs) with separate current breakers. When one UPS stops providing energy, the other one takes over within milliseconds — capacitors in PTTFs have enough energy to operate in the meantime. In case of a power shortage, switches also open preventively.

Monitoring & Repairs

The model distinguishes between *detectable* and *blind* failures. A third monitoring approach, *blind with passive monitoring* applies to entire switches. Each interrupter has a dedicated opening sensor and a missing opening of an interrupter would be detected. This improves the reliability significantly, as each extraction effectively acts as a test of the system.

As mentioned above, a large part of the Energy Extraction system, i.e. the switches, are physically contained in two cassettes, which are minimal replaceable units. This strategy of repairs reduces the intervention time and also implies that all blind failures in a cassette will be parasitically removed once it is replaced.

Additional Considerations

A mechanical spring at the level of the vacuum breaker used to keep the magnet powering circuit closed is a fail-safe component (not included in the model), as damage leads to an energy extraction. However, simulations of critical spring failures have also been studied (results in an internal report and the appendix of [11]). The transfer switch and UPS are excluded from the model, as they are considered fail-safe components (due to being surveyed by the PIC system). Failures of the QDS fall outside the scope of this study. Coil and inductors failures were neglected based on operational experience. Optical fiber connections are excluded with only a qualitative reliability assessment provided by experts (also fail-safe, as failures cause an extraction).

RELIABILITY RESULTS

Figure 2 shows the simulated probability of failures of the system. The probability to have at least one failure in one EE system in 20 years is below 3.13×10^{-5} which is below the target of 2.77×10^{-4}. The results leave one order of magnitude for a margin in all tested parameter configurations and were obtained using conservative values of input parameters (pessimistic mean time to failure values).

The system demand rate is the number of quenches detected by the QDS. Quenches are a relatively rare phenomenon, in the order of a few events per year combined. Only during the circuit commissioning and magnet training phase each magnet can experience several quenches over a few weeks. To account for this variability, the results of the reliability analysis are presented as with Mean Time To Energy Extraction (MTTEE) ranging from 320 to 6,000 hours.

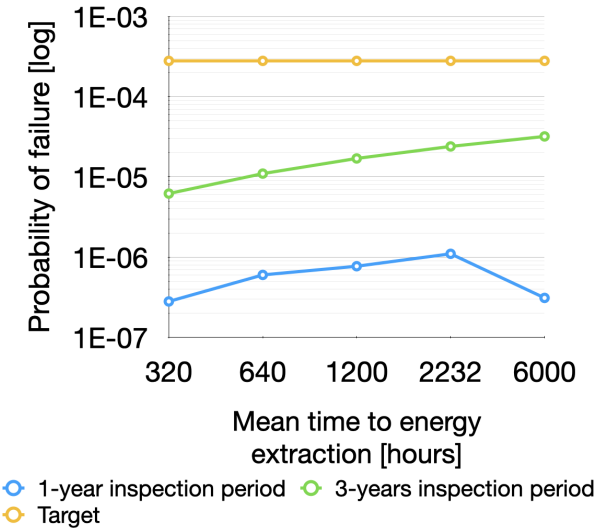

Figure 2: Probability of a critical failure occurring in 20 years of operation.

As shown in Fig. 2, the system reliability meets the target with a margin of one order of magnitude, even for the case of inspections every three years, and by more than two orders of magnitude with annual inspections. In both cases, the probability of a failure increases with the MTTEE. Performed extractions often allow for detection of blind failures while the other switch provides the required functionality. If there are less extractions, blind failures accumulate. In simulations with annual inspections and yearly (average) extractions, we see a change in the trend due to failures detected with an inspection and not extractions. Due to the computational weight and impracticability of such a scenario, simulation campaigns did not cover extractions every 3 years with the 3-years inspection period. It is expected to see a similar dip.

CONCLUSION

The conducted reliability analysis confirms that the HL-LHC design for the EE system meets the identified reliability target. High reliability is obtained primarily thanks to a fully redundant, fail-safe design and the implemented diagnostics capabilities, which allow for timely interventions in case of detected failures.

Monitoring of the values sent in optical channels could further improve the system reliability. Such a monitoring would provide information on functioning of a separate switch and allow for faster diagnostics in case of loss of redundancy. Results show impact of regular inspections performed on the system. Differences between 1-year and 3-year inspection periods highlight the importance of periodic system checks, which are vital for proper functioning of the system.

Furthermore, an important element to understand the HL-LHC EE systems reliability is its redundant design. Leveraging the fact that each activation of the system acts as a *de facto* test of the system, allowing for the replacement of a potentially faulty switch, is a major factor shaping the system's overall reliability.

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