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LIFETIME STUDIES OF MAGNET PROTECTION SYSTEMS FOR THE LARGE HADRON COLLIDER AT CERN

E. de Nicolás[†], D. Carrillo, T. Nielsen, E. Nowak, M. Pojer, CERN, Geneva, Switzerland

Abstract

The Quench Heater Discharge Power Supplies (HDS), Quench Discharge Local Protection Interface Module (DQLIM), Linear Redundant Power supplies (LPR), and Power Packs (LPUS) stand as critical systems, crucial for the protection of the Large Hadron Collider (LHC) superconducting magnets.

This paper provides an in-depth exploration of comprehensive lifetime studies conducted on these systems. The initial segment outlines the methodology employed to estimate their remaining operational lifespan. This encompassing approach involves a detailed analysis of failure modes, evaluating the criticality of electronic components, accelerated ageing of electrolytic capacitors, irradiation tests conducted both at the component and system levels and an inspection plan.

The study concludes by presenting essential findings, including the estimated remaining lifetime for critical components. This research serves as a significant contribution to ensuring the sustained reliability and performance of the magnet protection systems of the LHC.

INTRODUCTION

The Quench Protection Systems (QPS) are crucial systems for the protection of the superconducting magnets in case of quench. In a superconductor, the quench represents the local loss of the superconducting state, mainly due to the local temperature increase in the coil windings over the critical value that may happen for various reasons, e.g. energy deposited by beam losses. Quench protection measures are in place to quickly detect a quench onset, to rapidly cut the current and homogeneously warm up the magnet coil to distribute magnet energy over a large volume, or to extract this energy when necessary [1], such that the local peak temperature and voltages in the magnet remain below the damage level.

When a quench occurs, the HDS discharge a fast pulse of current into copper-plated stainless-steel strips, which are in thermal contact with the coils of the superconducting magnet, and resistively heat up to force the transit of the entire coil from superconducting to the normal conducting (resistive) state.

The DQLIM, LPR and LPUS provide auxiliary functions for the quench detection systems (QDS) (e.g. redundant power supply for QDS, current measurements, power cycling). Thousands of these devices are in operation, some dating back to 2007, and any malfunction within these components directly affects the availability and reliability of the LHC.

The lifetime studies performed on these critical devices aim to forecast the end of life (EOL). Thereby, if the EOL were to occur before the LHC end of operation, a replacement campaign should be planned; being the consolidation of the HDS and auxiliary equipment, a major endeavour. Some of the electronic components of these systems are obsolete, and an extensive redesign would be needed. Furthermore, the production and installation of thousands of units within the LHC tunnel would require several years.

While Prognosis and Health Management (PHM) is a broadly studied topic in nuclear industry [2, 3] and aerospace [4, 5, 6], it is relatively understudied in particle accelerators. The study of the remaining useful life [7, 8] of electronic equipment is common but it usually does not address the challenges of radiation.

In this paper, a predictive maintenance strategy is presented along with a methodology to calculate the remaining lifetime of the equipment.

METHODOLOGY

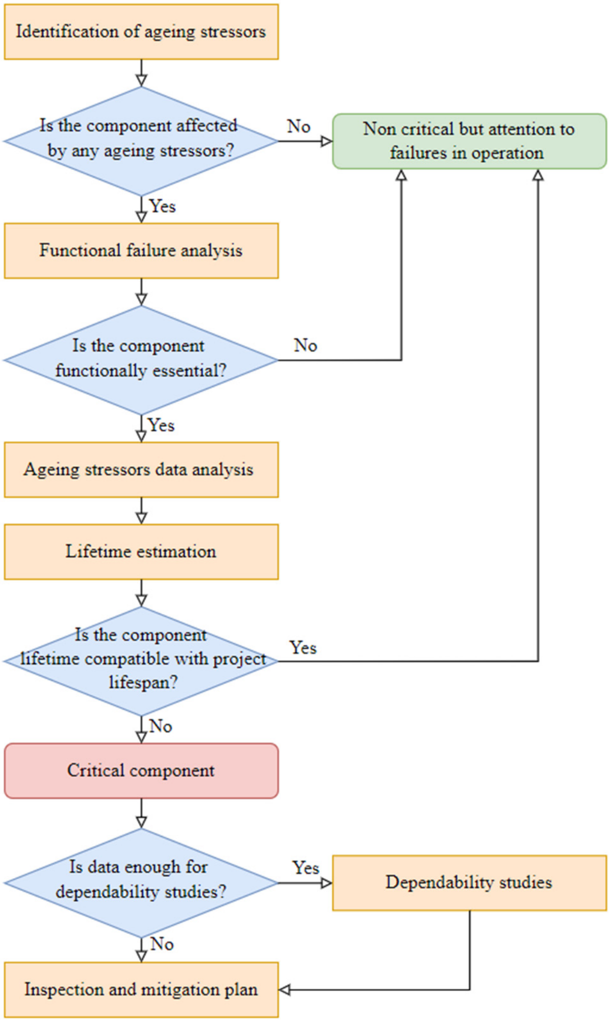

Figure 1: Lifetime studies methodology.

[†] enrique.de.nicolas.lumbreras@cern.ch

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The methodology followed in this study, shown in Fig. 1, aims to identify components that may limit equipment's lifetime. These critical components are affected by the ageing stressors, are functionally essential, and possess estimated lifetimes that are shorter or close to the project lifespan.

Identification of ageing stressors

The study begins with the identification of ageing stressors; by doing so, the methodology focuses on components that are prone to ageing. Other components are considered not critical but attention towards failures in operation is maintained.

The analysis of failures during operation is key to identifying and tracking ageing stressors. This not only contributes to the lifetime estimation but remains important throughout the equipment's lifespan.

Identification of ageing stressors requires a comprehensive knowledge of the studied systems and their operational environment. In our case, two environment-related stressors were identified: radiation and temperature. Additionally, mechanical cycles are considered as system-related stressor.

Functional failure analysis

While many components are affected by the ageing stressors, only a fraction of them are functionally essential to the equipment.

An extensive bibliography research was conducted to find the failure modes for each electronic component. Electronic simulations were carried out allowing to assess the consequential damage of the failure modes. Finally, discussions with experts were conducted to evaluate the criticality of the component's failures within the QPS.

Consequently, the study scope was narrowed down to focus on functionally essential components. By assessing the criticality of components failure, this analysis also provided useful insights about the devices studied and helped to prevent potential consequential damage of certain failures.

Ageing stressors data analysis

Once the functional essential components are defined, the lifetime of these components must be estimated. However, before doing so, the ageing stressor must be quantified. Measurements, environmental data reports, or operational data are the strategies for this purpose.

In the case of radiation, the measurements in the LHC are continuously reported. The equipment studied has received low radiation doses so far [9], less than 10 Gy per year. In the coming years, the radiation across the accelerator is expected to increase one order of magnitude due to an increase in luminosity for the High Luminosity-LHC (HL-LHC) upgrade project [10].

The second ageing stressor, temperature, was measured through infrared temperature measurements and data logger over extended long runs. Finally, for mechanical cycles, equipment operation data were analysed.

Lifetime estimation

Estimating the remaining lifetime is a fundamental part of the methodology, as it allows to identify what components, affected by the ageing stressors, may limit the equipment lifespan. Various methods were used to estimate the remaining lifetime of equipment.

For components with specified lifetimes, the manufacturer typically provides lifetime calculations, which is preferred when possible. In cases when no lifetime information is provided in the datasheet, accelerated ageing tests can be carried out to estimate the remaining lifetime. For doing so, a deep understanding of the ageing mechanism is needed.

In our study, lifetime estimations for relays and most electrolytic capacitors were obtained from datasheets. However, for the main power capacitors of the HDS, no available data existed, so an accelerated ageing was done over more than one year to study the remaining lifetime [11].

As radiation is the main source of ageing in electronic components, lifetime estimation is provided in total Integrated Dose (TID) instead of years. The procedure to estimate lifetime requires testing the component in radiation and observing degradation. The Radiation Working Group (RadWG), an essential part of the Radiation to Electronics project (R2E) [12] at CERN, coordinated radiation test campaigns of our equipment. They also have an extensive database of tested components that we have systematically consulted for our research.

Significant considerations were made for irradiation studies, including the type of radiation, TID and fluence, test at component level or system level, biasing, differences in components lots, etc. It is important to note, that the success of a component in an irradiation test does not guarantee that it will not fail under different circumstances. For example, irradiation tests with proton beams produce less Displacement Damage (DD) than mixed-field radiation.

Inspection and mitigation plan

As a result of the lifetime estimations, critical components were identified following the methodology shown in Fig. 1. These components are functionally essential and have a lifetime estimation that is shorter or close to the project lifespan.

In this stage, it is important to confirm the lifetime estimation through inspections over time. For instance, some of the estimations provided by datasheets are conservative due to insufficient data from manufacturers.

Ideally, inspections should be conducted by the regular equipment monitoring systems during operation. For example, the output voltage of the LPRs is continuously monitored, providing measurements of the linear regulator's voltage drift under radiation. When this is not feasible, an inspection campaign is needed, which may require significant manpower and careful planning.

We took advantage of the few devices that experienced a non-reparable failure to perform destructive measurements and gain further insight into the component's ageing evolution. For instance, removed components were useful for checking the capacitance loss of the electrolytic capacitors.

When a component is identified as a limiting factor for the equipment operation within the lifespan of the LHC, mitigation actions must take place. For example, a rotation policy will be implemented for selected equipment placed in high-radiation areas, that will be replaced periodically with equipment from low-radiation areas to prevent rapid degradation of these units.

Additionally, if there is sufficient data about operational failures a dependability analysis can be conducted to predict an increase in failures in the coming years.

RESULTS

Over a hundred components were studied to identify the ones that could limit equipment lifespan. In this section, an overview of the applied methodology to selected components is presented.

Electrolytic capacitors studied presented a lifetime estimation in the range 21 to 46 years, being affected by temperature as the main ageing stressor. However, this estimation is quite conservative as inspections in failed units proved that the remaining capacitance is higher than theoretically foreseen in the manufacturer ageing curves. The divergence is caused by the ideal environmental conditions and underrated capacitors' operation.

It is important to note that, among all the capacitors studied, the lifetime of two models of electrolytic capacitors was found to be limited by the ageing of the sealing rubber of the capacitor rather than by a capacitance loss.

A small number of capacitors were identified as critical components. Further inspection campaigns will verify and monitor the ageing evolution.

HDS, LPR and DQLIM were irradiated at system level and information from irradiation tests at component level was used to estimate the lifetime under radiation. Among all the semiconductor-based components, thyristors, linear regulators and bipolar transistors were considered critical.

Power thyristors were found to be the most critical component regarding radiation, as they consistently fail in the range of 320-450 Gy, being the failure mode always short circuit. Linear regulators presented a voltage drift of approximately 10% after 300 Gy, while bipolar transistors lose approximately 60% of the collector-base current gain after 500 Gy.

Mechanical cycles are the primary ageing stressor of relays. However, since the number of cycles performed will be less than the equipment's lifespan, relays were not considered as a critical component.

The equipment studied demonstrated solid performance during operation, with minimal failures per year, except for a specific type of capacitors of the LPR. For this model, a sufficient number of failures were observed to perform a dependability analysis [13], leading to corrective replacements.

CONCLUSIONS

In this paper, a methodology developed to estimate the remaining lifetime of essential equipment, that has been in operation for more than 15 years, was presented.

The fundamental concept of the methodology is that only a small number of components determine the equipment's lifespan. Thus, the purpose of the methodology is to identify these critical components, monitor them and mitigate ageing whenever possible.

Preliminary results suggest that 15 more years of operation is achievable for the majority of the equipment. Nevertheless, for critical components identified as possibly affected by the ageing stressors, this must be confirmed through operational failure analysis and further inspection campaigns. The conclusion from these campaigns will allow us to plan a potential consolidation project in case it is required.

The equipment studied has demonstrated a solid and reliable performance in operation, and dependability analyses are conducted whenever sufficient data is available.

A rotation policy will be implemented in the coming years to mitigate the effects of radiation.

This research serves as a significant contribution to ensuring the sustained reliability and availability of the magnet protection systems of the LHC.

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REFERENCES

[1] K. Dahlerup-Petersen *et al.,* "The protection system for the superconducting elements of the Large Hadron Collider at CERN," Proceedings of the 1999 Particle Accelerator Conference (Cat. No.99CH36366), New York, NY, USA, 1999, pp. 3200-3202 vol.5, `doi: 10.1109/PAC.1999.792249.`

[2] "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Electrical Equipment Used in Nuclear Power Generating Stations and Other Nuclear Facilities," in *IEEE Std IEEE Std 1205-2014* (Revision of IEEE Std 1205-2000) (Revision of IEEE Std 1205-2000), vol., no., pp.1-77, 16 May 2014, `doi: 10.1109/IEEESTD.2014.6819766.`

[3] L. Fei, "Research on Prognostics and Health Management System Technology in the Field of Nuclear Power Plant," *2021 Global Reliability and Prognostics and Health Management (PHM-Nanjing),* Nanjing, China, 2021, pp. 1-5, `doi: 10.1109/PHM-Nanjing52125.2021.9613010.`

[4] Z. Wen and Y. Liu, "Applications of Prognostics and Health Management in aviation industry," *2011 Prognostics and System Health Managment Confernece,* Shenzhen, China, 2011, pp. 1-5, `doi: 10.1109/PHM.2011.5939539.`

[5] C. Li and L. Ru, "Prognostics and health management techniques for integrated avionics systems," 2019 Prognostics and System Health Management Conference (PHM-Qingdao), Qingdao, China, pp. 1-5, 2019. `doi: 10.1109/PHM-Qingdao46334.2019.8942890.`

[6] H. Zhao, H. Yang and X. Xiong, "Satellite lifetime prediction with random failure," 2016 11th International Conference on Reliability, Maintainability and Safety (ICRMS), Hangzhou, China, pp. 1-4, 2016. `doi: 10.1109/ICRMS.2016.8050129.`

[7] P. Suskis, J. Zakis, A. Suzdalenko, H. Van Khang and R. Pomarnacki, "A Study on Electrolytic Capacitor Aging in Power Converters and Parameter Change Over the Lifespan," 2023 IEEE 10th Jubilee Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Vilnius, Lithuania, pp. 1-5, 2023. `doi: 10.1109/AIEEE58915.2023.10135053.`

[8] Z. Ni, X. Lyu, O. P. Yadav *et al.,* "Overview of Real-Time Lifetime Prediction and Extension for SiC Power Converters," in *IEEE Transactions on Power Electronics*, vol. 35, no. 8, pp. 7765-7794, Aug. 2020. `doi: 10.1109/TPEL.2019.2962503.`

[9] O. Stein and K. Bilko, “Report on the Prompt Dose Distribution Along the LHC Based on BLM Data for proton-proton operation in Run 2”, CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2019-040, Oct. 2019. `https://cds.cern.ch/record/2692574/`

[10] G. Lerner *et al*., “Radiation level specifications for HL-LHC”, CERN, Geneva, Switzerland, Rep. LHC-N-ES-0001, Sep. 2020.

[11] J. Guasch-Martínez *et al.*, " Reliability run and data analysis of the accelerated aging of present and future electrolytic capacitors installed in the protection systems of superconducting magnets of the Large Hadron Collider at CERN," 2024 JINST 19 C03003. `doi: 10.1088/1748-0221/19/03/C03003.`

[12] R2E, `https://r2e.web.cern.ch`

[13] L. Felsberger *et al*., “Lifetime analysis and prediction of the super capacitors”, CERN internal communication, CERN, Geneva, Switzerland, Oct 2022. `https://edms.cern.ch/document/3092350/1.`