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A RETROSPECTIVE VIEW TO THE MAGNET INTERLOCK SYSTEMS AT CERN

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Abstract

Several thousands of both, superconducting and normal conducting magnets are in charge of guiding the particle beams in CERN's accelerator complex. In order to protect the magnet and powering equipment from damage, dedicated magnet interlock and protection systems are deployed throughout the various accelerators and transfer lines. These systems have worked extremely well during the first years of LHC operation, providing highly dependable interlocking of magnet powering based on industrial COTS components. This paper reviews the performance and experience with more than 70 individual installations during the first LHC running period and compares the operational experience with the initial expectations of dependability. Additional improvements required to address specific operational needs and observed shortcomings are presented. Finally, we review the existing magnet interlock infrastructure in the LHC injector complex and the ongoing renovation works during the first long shutdown.

PROTECTION PRINCIPLE OF THE POWERING INTERLOCK SYSTEM

The total energy stored in the LHC magnet system during nominal operation amounts to about 11GJ and an uncontrolled release could lead to serious damage of machine components. Therefore, 36 Powering Interlock Controllers (PIC) are deployed in the LHC underground areas to guarantee the protection of the superconducting circuits by interfacing Quench Protection Systems (QPS) and Power Converters (PC).

Each PIC is composed of both in-house and Commercial Off-The-Shelf (COTS) electronic modules to profit from the strengths of the two worlds (reliability, safety, flexibility, maintainability, EMC, controls integration, cost, etc). With regard to the implementation of the protection functions, the PIC is relying on a three-tier model:

Hardwired Current Loops

Safety-critical functions are implemented using hardwired current loops, ensuring the correct transmission of interlock signals between clients involved in the protection (see Figure 1). About 2000 fail-safe loops individually protect the superconducting circuits against powering failures or magnet quenches [1].

PLC and Software Process

Less critical functions such as monitoring and anticipatory protection measures are provided by a Programmable Logic Controller (PLC). The PLC provokes powering aborts of all circuits in a sector in case of losing nominal cryogenic conditions or if a quenching magnet will inevitably propagate to neighbouring magnets, among others.

Software Interlocks

Interlocks implemented on the high-level supervision system allow verifying the integrity of protection systems upon start up. These conditions only prevent rearming the system before operation but will never stop the on-going mission.

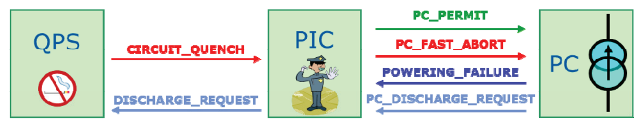

Figure 1: Hardwired interlock loops for the main circuits.

RELIABILITY PREDICTIONS

In order to evaluate and quantify how reliable the design of the system would be during operation, a Failure Mode Effects and Criticality Analysis (FMECA) study was conducted in 2004 [2]. The main goal of such analysis was to evaluate the reliability and availability of the system, with special emphasis on the study of the safety critical current loops. Since a large fraction of the hardwired loops will translate into beam dumps in case of failures, four failure modes were considered for this study (see Figure 2):

1. System ok: System is considered fully operational including enhanced functionalities provided by the PLC.
2. Safe system failure: System or component failure leading to a breaking of the current loop and consequently and in the majority of the cases, leading to a beam dump (i.e: spourious trigger).
3. System blind but still safe: System or component failure leading to a state where reading or acting on the loop is not possible (e.g: a shortened PLC output).
4. System blind and in a dangerous state: System or component failure leading to a state where reading or acting on the loop is not possible and a safety signal is no longer reaching the client (e.g: a short on two pins of a loop).

The failure rates and criticality for each single component on the design were studied using estimations from MIL Handbooks and suppliers. Results of the analysis estimated the probability of an unsafe failure (4) to 0.5×10^{-3} per year, while the probability of a false dump (2) to 1.5 per year on average (+/- 1.2). Furthermore, a dedicated study on the redundant power supplies was also

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carried out, concluding that the failure probability can be neglected assuming that the system is maintained at least once per year (i.e. faulty modules are replaced).

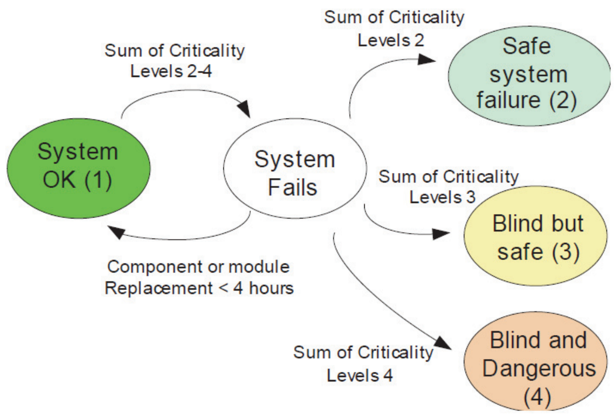

Figure 2: Markov model with the system transitions in between the different states.

FAILURES OBSERVED DURING RUN1 OPERATION

During the first LHC running period (2010-2012) the PIC has successfully relayed and triggered more than 200 beam dumps. Despite the system did not fail in a dangerous state, a couple of non-critical events affecting the availability of the machine have been observed. Table 1 summarizes them.

Table 1: PIC Failures during Operation

Failure Mode	Source	Cause	Occurrence
2	PLC	SEE	5
2	software interlock	wrong logic implemented	1
2	hardwired current loop	voltage spike	1
1	redundant power supply	single AC/DC converter fail	4

PLC Failures

The effect of ionizing radiation on PLCs has been the main cause of preventive dumps triggered by the PIC while operating the LHC with stable beams at 3.5 TeV up to the end of 2011 and 4 TeV in 2012. PLCs located in areas close to the accelerator (UJ14/16 and UJ56) were affected by single-event effects (SEE) due to high-energy hadron fluences of up to $1x10^8$ cm^{-2} per year, which provoked some memory corruption issues. After the relocation of the sensitive PLC part of the system in 2012 to less exposed areas, this phenomenon was not observed anymore.

Software Interlock Logic

Power converters ensure the protection of the 60A dipole orbit correctors without the need of additional hardware interlocks. However, non-critical software interlocks prevent unnecessary magnet and current lead quenches and assist operations to assure safe conditions for the start of powering. The PIC SCADA provides a 60A power permit signal for each LHC sector, which is derived from the cryogenic and powering conditions in the sector and then transmitted to the converter controls. A communication problem, together with an erroneous implementation of the interlock logic led to the loss of the powering permit during a physics fill and forced Beam Loss Monitors (BLM) to trigger a beam dump on beam losses.

Hardwired Current Loops

An optocoupler in charge of reading the quench status of the main dipole circuit in sector 81 was found faulty after an intervention on the QPS system on this circuit. Investigations showed a thermal degradation of the chip as well as a broken electrical insulation to ground, which could have been caused by a voltage spike entering the system during the QPS intervention in the tunnel.

Redundant Power Supplies

The PIC requires in addition to the 24V to power the current loops, two additional 5V supplies for the Profibus slave modules and the TTL electronics. Thanks to a redundant power supply design and to a periodic maintenance, there was no impact on the availability of the machine due to power supply failures.

OPERATIONAL IMPROVEMENTS

After several years of operation, no obvious weak points of the design have been identified to justify major changes of the present architecture. However, additional features have been proposed to smooth operations.

Interlocking Access and Powering

After the incident occurred on September 2008, new rules were defined to access the LHC underground areas during periods of magnet powering. In order to avoid relying purely on procedures, two mechanisms have been put in place on the PIC side to limit the current on the power converters and to interlock powering if magnet currents exceed a safe limit when access is allowed [3].

Masking Global Interlocks

In order to prevent propagation of quenches across neighbouring magnets within the same powering subsector, a global interlock is implemented on the PLC. Experience during the past hardware commissioning campaigns has demonstrated that this implementation represents a bottleneck for testing since it prevents the commissioning of several circuits in parallel. Future plans are to implement a mechanism to mask the global

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protection mechanism during commissioning, which will considerably speed up the commissioning process.

Enhanced Monitoring of Current Loops

During Run1 we have experienced upon a few occasions difficulties to identify the system responsible for opening the interlock loop, especially on the main circuits involving several 100 clients. On such circuits, the QPS interfaces with the PIC through a dedicated quench interlock loop, increasing the complexity and the number of clients that can actually trigger an interlock event. In order to provide enhanced diagnostic capabilities, it is foreseen to review the existing hardwired interfaces between PIC, QPS and PC.

WARM MAGNET INTERLOCKS

The Warm Magnet Interlock System (WIC) protects the resistive magnets from overheating by switching off the power converters when a fault occurs. Some 30 interlock installations have been successfully operating in the past years and only a few minor problems have been reported during operation. These issues are usually caused by aging of electromechanical components in old interlock installations.

A standard WIC solution, based on failsafe SIEMENS PLCs, is currently deployed in LEIR, LINAC3, SPS-TLs (TI2, TI8, TT40, TT41 and TT60), HiRadMat (TT66) and the LHC. In addition, the first long shutdown has served to undertake a full renovation of the existing magnet interlock infrastructure in the PS Booster and the SPS, and to deploy a new instance of the WIC in LINAC4. One of the main challenges of renewing the present interlock infrastructure in the LHC injectors is how to cope with the high radiation doses to which the system is exposed in certain areas, reaching in some cases up to some 100 Gy/year.

NEW WIC DEPLOYMENTS

SPS

The protection of normal conducting magnets relies on three different interlock systems, which are grouped by circuit families: mains, auxiliaries and ring-line. While the mains and auxiliary interlock systems are split per surface buildings (BAs), where interlock signals from two half-sextants are collected, the ring-line interlock system is made of interlock loops going around the SPS and terminated in a single rack installed in BB3 (see Figure 3). Due to the lack of diagnostics in case of faults and due to the difficulties to maintain such an old interlock system designed in the 70's and based on electro-mechanical components, a new PLC-based interlock system is being deployed during the first long shutdown.

PS Booster

It represents the biggest WIC installation at CERN in terms of number of magnets to protect. 4 PLCs and 50 remote crates will be in charge of protecting more than 250 magnets installed over the 16 periods of the machine.

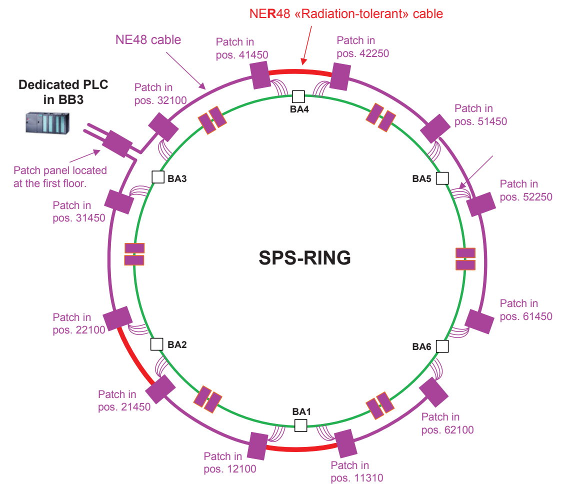

Figure 3: Ring-line interlocks in SPS.

LINAC4

A new WIC installation, in charge of protecting the magnets of the LINAC4 line and its transfer line, has been deployed during LS1. The system consists of two PLCs and will protect a total of 89 magnets.

CONCLUSIONS

Comparing model predictions to field failure data is a challenge due to the time it takes to accumulate and process meaningful data from the field, especially when dealing with highly dependable systems. Nevertheless, if we do not consider radiation induced failures which were not taken into account on the FMECA study, we can preliminarely conclude that the availability of the magnet interlock systems largely exceeds the initial predictions. More accurate field data will be only available over a long period of time.

With regard to the WIC, efforts are ongoing to renew and standardize the existing magnet powering interlocks in the LHC injector complex. This task will considerably ease the explotation of the system and will at the same time reduce significantly the efforts to commission the system during the test campaigns.

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