EVOLUTION AND PERSPECTIVES OF SECOND GENERATION MAGNET INTERLOCK SYSTEMS AT CERN

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Abstract

The CERN accelerator complex relies on thousands of superconducting and normal conducting magnets to guide the particle beams on their trajectories throughout the accelerator chain. In order to protect magnet and powering equipment from damage, complex magnet interlock systems are deployed and operated in the LHC and its injectors. Despite a very good track record during the first 10 years of operation, important consolidation activities are ongoing and planned to further increase the dependability of the injector chain and enhance the system functionality where required. This paper reviews the performance of the various magnet interlock systems at CERN during the past years of operation and presents the ongoing renovation projects carried out in the LHC injector complex to achieve the high level of dependability and maintainability required for long term operation. Finally, some design aspects of the existing LHC magnet interlocks will be discussed and possibilities to further enhance the dependability and functionality of the magnet powering system will be presented in view of the High Luminosity LHC project.

WARM MAGNET INTERLOCKS

Warm magnet interlocks are present in basically all machines of CERNs accelerator complex from the LINAC to the LHC. They are required to protect normal conducting magnets from damage resulting from overheating. Each magnet is equipped with several thermo-switches connected in series which have the task of signalling temperature increases to the interlock system. When the magnet temperature exceeds a predefined threshold, an interlock is sent to the Beam Interlock System to extract the particle beams from the machine if required and to the Power Converter to stop powering.

Protection Principle

The Warm Magnet Interlock System (hereafter referred to as WIC) provides dependable interlocking using commercial-off-the-self components. The current solution is based on industrial Failsafe SIEMENS PLCs and I/O modules to ensure correct magnet protection by interfacing magnets and power converters (Figure 1). Special care was put into the system design in order to fulfil the requirements in terms of dependability (requesting less than 1 false dump / operational year) and reaction time (less than 1 s). The design principles applied are the following:

- Redundant sensors (multiple magnet thermo-switches connected in series);
- Redundant outputs to power converters (two standard relay outputs connected in series);
- Redundant interface to the Beam Interlock System (e.g. Fast Boolean processor in series with the relay output for diversity to prevent common mode failures and guarantee the fastest possible response time);
- Safety PLCs and I/O modules (to provide increased SIL level and comprehensive diagnostics functions for detecting internal and external faults);
- Watchdog monitoring (to detect a malfunctioning in the execution of the PLC process and put outputs into a failsafe state).

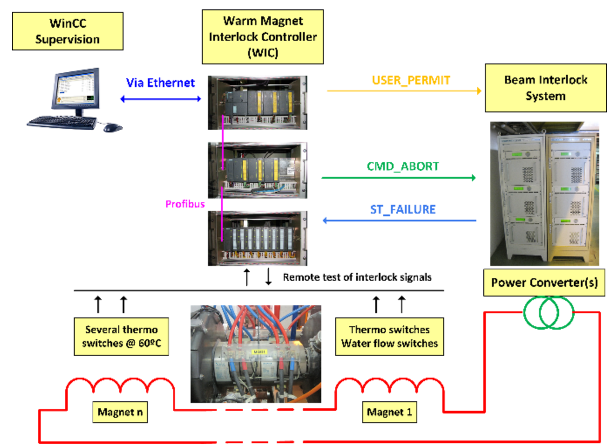

Figure 1: Simplified layout of the WIC.

Performance During the Past Years

The performance of PLC-based magnet interlock systems has been remarkable during the last 10 years of operation and only two preventive dumps have been triggered in the CERN accelerator complex due to a component failure of the interlock system. The only event to be signalled is an intermittent loss of communication between a PLC installed in BA7 and its remote crates installed in TI2. Such loss led to the transition of the outputs into a failsafe state, affecting the availability of the machine. This event occurred in 2012 and has been traced back to a faulty Profibus repeater that weakened the signal over the 3.6 km long Profibus network. As a mitigation measure the communication speed has been lowered from 1.5Mbps to 500kbps. Other external events that contributed to false positives were in most cases related to faulty thermo-switches.

Legacy installations based on relay systems are today a major concern for maintainability, an example of a noteworthy issue has been observed in the magnet interlocks of the SPS, caused by an increase of the total resistance of the ring line interlocks due to degrading contacts. The old magnet interlocks of the SPS have been replaced by a standard WIC solution during the first Long Shutdown (LS1).

Inventory and Renovation Projects

Most of the magnet interlock installations at CERN currently rely on a standard PLC-based WIC solution for their interlock functionality. However, some installations are still using legacy relay-based systems until the final consolidation with a standard WIC system can be implemented. Table 1 shows the inventory of WIC installations in the LHC and its proton/ion injector chain. This table doesn't include experimental facilities such as HIE-ISOLDE, HiRadMat and AWAKE which are already equipped with a standard WIC solution or still awaiting consolidation such as the North and East area.

Table 1: Inventory of warm magnet interlocks.

Facility	HW solution	Deployment
LHC	PLC-based	2007
TI2/TI8/TT40/T60	PLC-based	2005
SPS	PLC-based	2015
TT2/TT10	Relay-based	1970
PS	Relay-based	1968
LBT/LBTP	Relay-based	1968
PSB	PLC-based	2015
LT/LTB/BI	Relay-based	1980
LINAC2	Relay-based	1978
LINAC3	PLC-based	2016
LINAC4	PLC-based	2015
LEIR	PLC-based	2005

During the second LHC Long Shutdown (2019 - 2020), relay-based magnet interlocks in the PS, TT2/TT10, LBT/LBTP and LT/LTB/BI will be renovated with a standard WIC solution that offers many advantages with respect to the currently installed interlocks. The most important advantages are: improved dependability, reduced maintenance, self-verification capabilities, remote testing features, fault archiving, reduced commissioning time, WinCC SCADA integration, controls integration and automation within ACC-TESTing framework [1].

The renovation of the present interlock infrastructure in the LHC injectors implies significant challenges. One of the most important one is to mitigate the high radiation doses to which parts of the system could be potentially exposed if installed close the machine elements, reaching in some cases dose rates beyond 50Gy/year (such as the SPS-LHC transfer line). As a general rule, sensitive interlock equipment such as the PLC itself is normally installed in radiation protected areas. Nevertheless, some of the protected alcoves are separated by hundreds of meters and would require the installation of long instrumentation cables to reach magnets and power converters. In such cases and in order to limit the cost of the installation, a trade-off has to be made between cable lengths and radiation exposure to electronics.

Dedicated radiation test campaigns with high energy proton and neutron sources have been carried out in the past in CERN-TCC2 and PSI-OPTIS to qualify the use of SIEMENS modules in low radioactive environments such as under the dipole magnets or vacuum pipes in the SPS transfer lines (see Figure 2). The following components have been tested:

- PROFIBUS INTERFACE IM 153-1 ET200M
- 32x DIGITAL INPUT SM 321
- 32x DIGITAL OUTPUT SM 322
- RS485 REPEATER FOR PROFIBUS
- EXISTA ASC-50 24V POWER SUPPLY

The performed tests were conclusive and allowed to identify a catalogue of components that can work well beyond cumulative doses of more than 100Gy.

Figure 2: WIC remote I/O crate installed in the SPS Transfer Lines.

INTERLOCKS FOR SUPERCONDUCTING MAGNETS

The currently installed Powering Interlock System for the LHC superconducting magnets (hereafter referred to as PIC) was designed in 2005 and conceived as a distributed system composed of some 36 PLCs in conjunction with some 500 custom made electronic boards to assure dependable. For this purpose, the PIC interfaces with many client systems such as the Quench Protection System, Power Converters, Cryogenics, Electrical Services (Uninterruptable Power Supplies, Emergency Stops) and the Beam Interlock System.

Operational Experience

The performance of the PIC during the first years of operation was better than the initial dependability expectations [2]. The effect of ionizing radiation has shown to be the main cause of preventive dumps triggered during the LHC Run 1. Besides that, only a few more events affecting the availability of the LHC have been observed during the first years of LHC operation (as shown in Figure 3).

During the first year of Run 2 operation, starting in 2015, two events have been observed on the Quench Interlock Loop (QIL) of the main dipole circuits. The QIL is a hardwire current interlock loop with a length of 3km

ISBN 978-3-95450-147-2

which transmits fail-safe interlock signals between Quench Detection units, Energy Extraction systems and – through the QIL controller – the Power Converters and the PIC (see Figure 4).

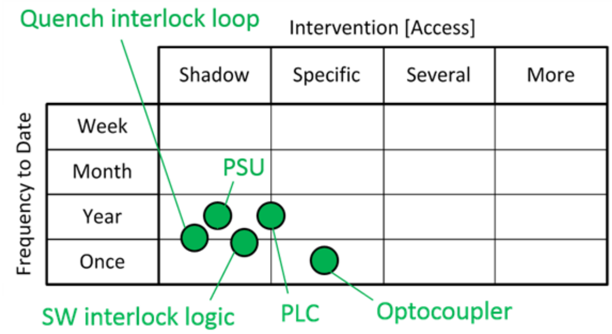

Figure 3: PIC availability matrix.

During the LS1, the DQQBS boards required for protecting the busbar segments and splices were replaced by new ones to provide compatibility with CSCM measurements [3]. These new boards were equipped with new SRAM memories which turned out to be much more sensitive to radiation than the ones previously installed. The SEE non-conform openings of the QIL were leading to a misbehaviour of the clients connected to the current loop. During these events, the loop opened during a short amount of time which did not allow the current in the loop to decay completely and therefore some of the clients such as the EE systems and the PIC located in the even side of the arc did not detect the interruption of the QIL. This undesired behaviour has not reappeared after putting back the old DQQBS boards. As a mitigation measure and in order to enhance the reliability of the QIL, a new software mechanism has been implemented to force the redundant opening of the two EE switches as soon as one of the two PICs in the arcs detects the rupture of the QIL [4]. This software interlock is only activated when the current in the main dipole circuits is above 2kA in order to avoid perturbations during the individual system tests or when the opening of the EE systems is not vital for machine protection.

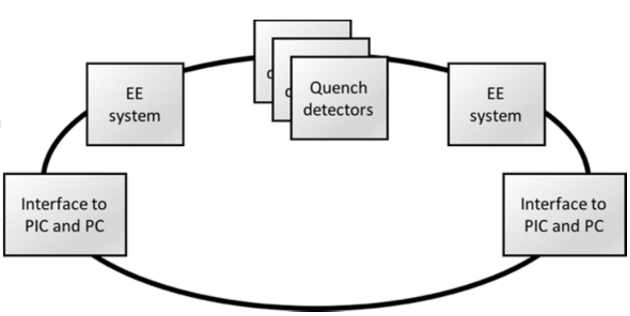

Figure 4: Simplified layout of the Quench Interlock Loop for the LHC main dipole magnets.

Future Plans

While the dependability of the PIC system has largely exceeded the predictions during the initial phase of LHC operation, a number of improvements have been identified that shall be addressed in the second generation of the system, which can be summarized in the following main objectives of the upgrade project:

- address the obsolescence of critical components in the system design as well as the radiation effects in exposed locations such as the RRs in order to guarantee the long term availability and maintainability of the system until the end of the expected LHC lifetime in 2040;
- assure compatibility with High Luminosity LHC project (HL-LHC) protection requirements, both in terms of reliability and improved system architecture (e.g. taking into account architecture changes of client systems such as the quench detection system);
- address the shortcomings observed during initial LHC operation and further improve diagnostic means in order to enhance remote operation and diagnostics of the system and its connected client systems;
- maintain the initial design goal for the overall system dependability, not exceeding a total of 1 false dumps / operational year throughout HL-LHC operation

The second generation Powering Interlock System will be deployed during the third LHC Long Shutdown (2024-2025) foreseen in 2024 and will be ready for the start of HL-LHC operation in 2026.

CONCLUSIONS

Both the warm and the cold magnet interlock systems have been working extremely well during the first years of LHC operation and dependability was better than initially predicted. Nevertheless, a number of operational improvements have been identified and mitigations have been implemented to ensure protection of the electrical circuits. In addition, during the last years substantial efforts have been put to progressively replace the legacy magnet interlock installations in the LHC injectors by standard WIC systems in order to improve the dependability and maintainability of the system.

A second generation of the Powering Interlock System will be developed to meet the dependability objectives of HL-LHC which will address not only architectural improvements but also changes in the HL-LHC circuit layout. Moreover, it will guarantee the current dependability and maintainability of the magnet interlock system for the lifetime of the HL-LHC project.

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ISBN 978-3-95450-147-2