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DEPENDABLE IMPLEMENTATION OF THE BEAM INTERLOCK MECHANISM IN CERN POWER CONVERTER CONTROLLERS

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Abstract

At CERN a Beam Interlock System (BIS) protects accelerators from accidental and uncontrolled release of beam energy, avoiding machine downtime. Throughout the accelerator complex numerous critical subsystems, including power converters, interact with the BIS indicating their readiness for operation with beam. Power converters play a vital role in establishing operational conditions, and an unmitigated power converter malfunction could lead to damage to the machine. For example, a bending magnet converter set at an incorrect current would result in an incorrect field strength, and beam passing through this may impact and damage the machine. A fast and dependable Beam Interlock Mechanism is required between power converters and BIS, verifying that voltage and current levels are within tolerances. This paper describes the design and realisation of the Beam Interlock Mechanism, based on CERN's Function Generator Controller (FGC), the central processing unit of power converter controls. Particular emphasis is placed on the system architecture required to assure the integrity of the power converter parameters, and the protection of the CERN accelerator complex.

THE CERN BEAM INTERLOCK SYSTEM

Beams within the CERN accelerator complex have a significant amount of energy. An uncontrolled and unmitigated release of stored beam energy could lead to damage of machine equipment which could result in long repair times.

Certain machine equipment is difficult to access, and difficult to replace, further compounding this problem. In order to avoid undesired circumstances, a Beam Interlock System (BIS) was developed at CERN with the goal of protecting machines and reduce downtime. Originally conceived and designed for the LHC ring and LHC Injection, the BIS is currently deployed in many distinct but related environments: LHC ring, LHC Injection, SPS Extraction, SPS to LHC Transfer Lines, the SPS Ring and LINAC4. The proper operation of each machine relies on several subsystems; Beam Position Monitors, Vacuum systems, Experiments, Power Converters and others. Nowadays, more than 20 types of system are connected to the BIS as so-called USER SYSTEMS.

As shown in Fig. 1 each USER SYSTEM interacts with the central element of the BIS, the Beam Interlock Controller (BIC), by indicating readiness for operation with beam, giving USER_PERMIT information to the BIC. The BIC collects this information from all the connected systems and generates an overall BEAM_PERMIT flag.

When the BEAM_PERMIT flag transitions from TRUE to FALSE, an immediate abort of circulating beam is executed, and whilst the flag remains FALSE, further injections of beam are inhibited. This entire signal transmission path is redundant, with every USER SYSTEM generating redundant USER_PERMIT signals that are independently evaluated by the BIC [1].

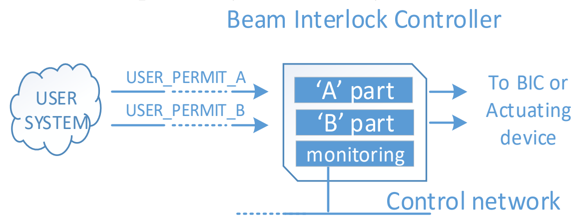

Figure 1: Simplified diagram of user system to BIS interface.

BIS IN POWER CONVERTERS

Power converters directly affect beam dynamics, by establishing the correct magnetic conditions for operation with beam. The CERN accelerator complex has many instances where it is necessary to check that the current (or voltage) of a power converter is within a given tolerance before permitting the passage of beam. A typical example is a bending magnet converter where the current must be set to a correct value. If this is not the case, this would result in an incorrect field strength applied to the beam passing through, which could then impact and damage the machine.

There are numerous means for measuring and evaluating converter output, in order to determine USER_PERMIT within power converters at CERN:

- Systems in the Proton Synchrotron (PS) use analog thresholds to evaluate the measured current. These systems are relatively old, being realised over a decade ago.
- Systems in the Super Proton Synchrotron (SPS) use software to digitise the converter current output value and then evaluate it.
- Systems deployed in the LHC use a standalone system called the Fast Magnet Current Change Monitor, which independently evaluates changes in magnet current, which are compared to fixed thresholds [2].

The deployment throughout the CERN injector complex of the third generation of power converter controls, the Function Generator Controller 3 (FGC3) [3][4], has necessitated the development of a new interface and beam interlock mechanism to communicate with the BIS.

Around 250 power converters are foreseen to be upgraded in the coming years. Table 1 shows their location, the quantity and the requirements in terms of reaction time.

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Table 1: Power Converter USER_PERMIT Requirements

Complex	Quantity	Reaction time[us]
Linac4 - PSB	25	250
PS	25	250
SPS	200	1000

Functional Requirements

The functional requirements of the Beam Interlock Mechanism are defined by several factors, implementation, operations, test and validation.

The CERN accelerator complex consists of a succession of machines that accelerate particle beams. From the high-level point of view, the exploitation of these particle beams is based on the concept of USER/DESTINATION, which represents the end point for each beam's transmission through the accelerator complex. Each particle beam in the complex is therefore characterised not only by its particle type, energy and intensity, but also by its end USER/DESTINATION.

Multiple USERS/DESTINATIONS are available at the end of the CERN accelerator complex. To accommodate this, a Central Timing system is in place managing the accelerator beam schedules throughout the complex. The control systems dynamically adjust hardware to accommodate the final destinations of beams. In the case of power converters, some powering circuits are set to different current levels depending on the USER/DESTINATION (Fig. 2). This translates into the need for dynamically applying thresholds depending on the final user and destination. The proposed system allows up to four different windows to be evaluated against two thresholds at any given moment (a "High Threshold" and a "Low Threshold"), and this for each configured user (up to 31). A simple mode suppresses the option of evaluating for each user, depending on the application.

Some power converter instances require the magnetic functions to follow precise reference functions (for example the BSW circuits at the injection of the PSB). Therefore, the mechanism has to be sensitive not only to the absolute value of the current/voltage but also to the difference between the reference and the measured value. Additionally, it may also be important to evaluate the rate of change of current/voltage to improve reaction times to erroneous conditions. Finally, the power converter state has to be evaluated in order to ensure that it is consistent with the passage of beam. The proposed solution allows any of the above conditions to be selected to participate to the USER_PERMIT result (see software implementation).

From the setting management point of view, it must be possible to define a set of thresholds for every USER/DESTINATION and to be able to verify at any time the correctness of these thresholds.

In order to facilitate machine commissioning and validation of function, it must be possible to and operate the USER_PERMIT in test mode, where the redundant links are tested in a safe manner, to ensure end-to-end coherence and correct transmission of information.

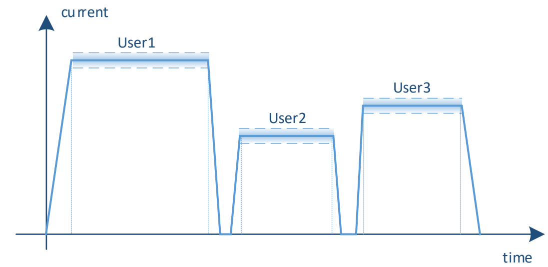

Figure 2: Examples of cycle with three users.

Hardware Implementation

Figure 3 shows the proposed hardware implementation. In such proposal, the FGC3 is the main protagonist having access to measured parameters such as current and voltage, as well as the USER/DESTINATION which is read from the accelerator timing system. Current and voltage values are acquired by Analogue to Digital (ADC) converters, and then propagated to the FGC3's digital signal processor (DSP). The DSP performs the comparison of the measured entity with software thresholds, deriving USER_PERMIT TRUE or FALSE for each of the four windows. The result of this evaluation is encoded by the embedded programmable device (FPGA) and transmitted via the power converter interface electronics (the VS BIS INTLK board). This board acts as the bridge between the FGC3 and the BIC, decoding the received signal into the four redundant output channels named 1A, 1B, … 4A, 4B. The outputs of the VS BIS INTLK Board are connected using physical cables to the BIC, passing though a USER SYSTEM interface module (CIBU).

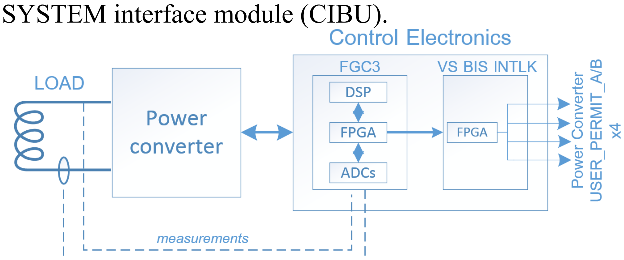

Figure 3: Hardware implementation of power converter user permit.

Power Converter BIS Concentrator

There are cases where more than one converter contributes to the generation of a USER_PERMIT. One such example is the implementation of the Closed-Orbit Correctors (COD) in the SPS complex where up to ten converters generate a single USER_PERMIT. In this case, a Power Converter BIS Concentrator is implemented, capable of merging up to 10 USER_PERMITs (Fig. 4). The concentrator propagates aggregated USER_PERMIT signals to one or more CIBU or, using a scalable approach, to the input of another concentrator. Additionally, the concentrator provides static diagnostic information including the status of internal power supplies, the state of

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each input permit signal, the enabled and disabled channels as well as the state of the output permit signals.

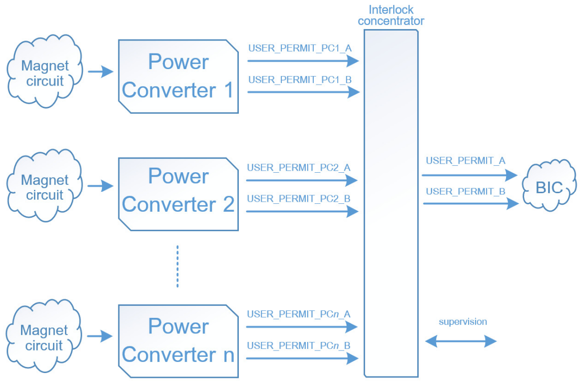

Figure 4: Power Converter permit concentrator.

Software Implementation

The FGC3 control software is based on the Cern Converter Control Libraries v2 (CCLIBS), a collection of libraries written in C and available under the GNU Lesser General Public License by writing to cclibs-info@cern.ch [5, 6]. These libraries support features such as signal calibration, signal logging, event logging, function generation and current or magnetic field regulation. To meet the requirements of the new Beam Interlock System, a new specific library called *libintlk* has been integrated. This library offers concurrent interlocks on absolute value and change rate of current and voltage, regulation error and checks of the state machine. For each of the four channels the six interlock tests are performed sequentially (Figure 5). If any of the tests fails, an internal interlock is enabled and transferred to the FPGA.

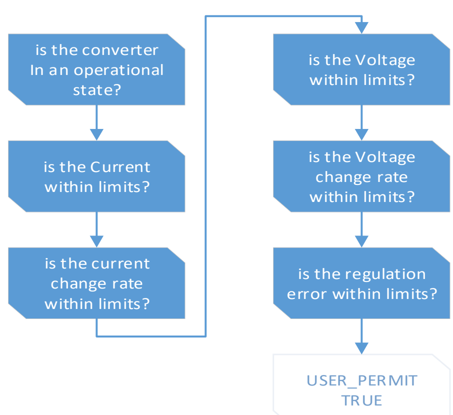

Figure 5: Test perfomed by the libintlk library.

SYSTEM INTEGRITY

The correct functioning of the system is only certain once a test with a safe beam intensity is made to demonstrate the desired operation. Once this is made, a number of features assure the continued system integrity and management of the software thresholds.

USER/DESTINATION Identification

The evaluation of the beam destination from the timing telegram received from the Cern Control Center (CCC) is a fundamental parameter for the operation of all pulse-to-pulse modulated power converters at CERN. Once demonstrated as being correct with a safe beam intensity and/or energy, the value is implicitly correct for subsequent operations.

Interlock Thresholds

An incorrect interlock threshold setting could result in an unwanted beam dump unnecessarily affecting the machine availability or in a missed interlock leading to more significant consequences for the machine. The utilization of software thresholds for interlock functionality has already been proven in the SPS complex using the Machine Critical Settings application (MCS). The MCS framework was developed to handle the most critical configurable parameters such as interlock settings [7]. MCS interfaces the repository of operational settings and implements a secure channel for changes of the interlock settings. The application is managed by a limited number of persons defined by the Role Based Access Control (RBAC), and it is used to periodically verify if the thresholds set in the power converters correspond to the reference values in LHC Software Architecture (LSA).

Measurement

The correct operation of the system depends ultimately also on the analog-to-digital conversion which takes place onboard the FGC. This is first assured by periodic calibration of acquisition circuits using local voltage references. To ensure the correct gain and offset are applied, many DCCT systems have a unique electronic identifier (ID chip) to verify the correct head type is connected to the power converter, and calibration parameter settings in the FGC are automatically loaded from the database based on this information.

CONCLUSIONS

The Beam Interlock System is an essential component of the accelerator complex at CERN serving the functionality of protecting the machine equipment in case of a potential beam loss. A power converter failure can have severe consequences on the machine instrumentation resulting in high repair times and machine unavailability. With the upgrade of the converter controls electronics, a new reliable Beam Interlock System functionality is being designed. This is based on the Function Generator Controller where the interlock is evaluated by acquiring current or voltage measurements and comparing them with software thresholds. The resulting USER_PERMIT signal is transferred to the Beam Interlock System which triggers the immediate dump of circulating beam, and inhibit of further beam injections.

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