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A MODULAR APPROACH FOR ACCELERATOR CONTROLS COMPONENTS DEPLOYMENT FOR HIGH POWER PULSED SYSTEMS

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Abstract

In the context of the LHC Injector Upgrade (LIU) project, significant advancements have been made in enhancing the control systems of the PSB and PS (injection) kickers at CERN during the Long Shutdown 2 (LS2). This upgrade has transitioned these systems from heterogeneous, custom-built electronic solutions to a more flexible and open architecture. Despite the distinct functionalities, power circuit topology and operational requirements of these kickers, a uniform approach was adopted by employing standardized hardware and software control blocks for both accelerator facilities.

The newly implemented control architecture is structured around a series of subsystems, each tailored to perform specific, essential functions necessary for managing high power fast pulsed systems. These functions encompass aspects such as equipment and personnel safety, slow control and protection, high-precision fast timing systems, fast interlocking and protection mechanisms, as well as pulsed signal acquisition and diagnostic analysis. Each of these subsystems involves the integrated utilization of both hardware components and associated software.

This paper aims to present a comprehensive overview of the functionalities inherent to the various subsystems. Additionally, it offers insights into how these subsystems have been effectively integrated to cater to the distinct requirements of the two different use cases.

FINITE STATE MACHINE

In recent years, significant advancements have been achieved in the refinement and enhancement of kicker control systems, driven by a growing emphasis on modularity and the optimization of the creative process and its associated hardware components. Central to this progress is the adoption of a finite state machine approach, which definitively encapsulates each modular aspect, as depicted in Fig. 1. This approach adheres to a well-defined sequence, commencing with the activation of the Power Distributor Controller (PDC) system in the initial stage, responsible for supplying power to the entire installation. Subsequently, industrial distributed PLC systems combined with a generic finite state machine approach involves the carefull management of kicker thyratrons, inclusive of their respective heater controllers and heater power supplies. These general PLC library components ensure also the efficient management of capacitor bank switches, a key element in the majority of kicker systems within Accelerator and Beam Transfer (ABT) kicker systems facility. Typically, these systems incorporate an initial energy storage element, such as a capacitor bank, to effectively store energy from the Direct Current Power Supply (DCPS) and subsequently deliver it by resonant charging to a Pulse Forming Network (PFN), a task tackled by the Capacitor Charger and Protection Unit (CDPU). Upon successful validation of these initial stages within the finite state machine, the DCPS can be activated. The ultimate functionality of the entire state machine hinges on the precise timing system, critical for coordinating the delivery of pulses to the magnet, a process typically governed by the Kicker Timing System (KiTs). Additionally, for post-operational verification, there exists a fast acquisition system known as Internal Post Operation Check (IPOC), enabling pulse-to-pulse acquisition of magnet current and other relevant signals.

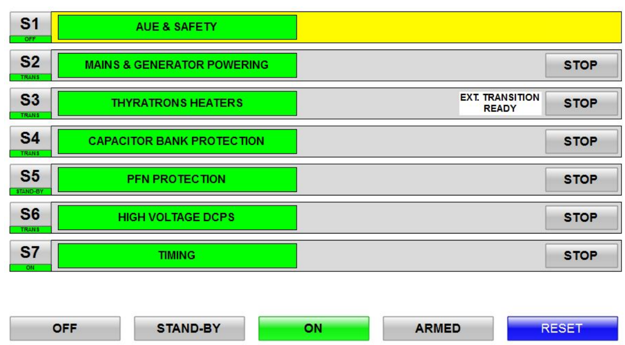

Figure 1: Typical finite state machine view for supervisory control of kicker systems.

Typically the following stages exist:

Stage 1 (AUE and Safety): This initial stage primarily encompasses various low-level security ancillaries and peripheral devices, including emergency stops, thermal switches, and other safety-related components.

Stage 2 (Mains and Generator Powering): This stage is responsible for delivering power to the entire system, both from the mains and generators. It's an automated process that controls most of the low-voltage distribution to critical subsystems.

Stage 3 (Thyratrons Heaters): This stage handles the power supply for thyratron heaters. It is specifically designed to manage the heating process and reservoir pressure settings. See subsection *Thyratron Heater Power Supplies*.

Stage 4 (Capacitor Bank Protection): In this stage of the state machine, the focus is on managing the earthing scheme and ensuring the security of activating and deactivating mains earthing points within the system.

Stage 5 (PFN Protection): Similar to the previous stage, the PFN system requires careful control to ensure human safety and equipment protection. This stage also manages the relevant components of the PFN.

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Stage 6 (High Voltage DCPS): After successful validation of all preceding stages, the High Voltage DC Power Supply (DCPS) can finally activate the HV switch to pfurnish the power part of the kicker system.

Stage 7 (Timing): The final stage, which comes into play once all the previous stages are validated, involves precise timing triggers. These triggers must be synchronized with the synchrotron general timing to activate specific trigger modules, enabling the transfer of energy from the PFN to the magnet.

It's important to note that the number of stages mentioned here is not exhaustive. Different kicker systems may have a varying number of stages that compose the finite state machine. Each stage encapsulates relevant interlocks that define its validation conditions. For instance, the HV DCPS stage includes a detailed view of internal interlocks related to that block, Fig. 2. These interlocks are essential for determining when a stage is validated and can also be masked if required.

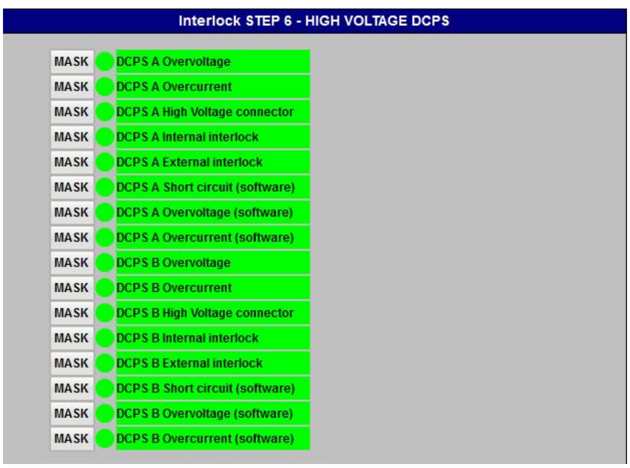

Figure 2: DCPS stage view of detailed interlocks.

STATE CONTROL AND SURVEILLANCE SYSTEM (SCSS)

Prior to the LS2 a concerted effort has been undertaken to optimize the structure of ABT kicker control systems by integrating common elements from various kicker installations. Historically, these shared components were often lacking in generality and interchangeability. However, ABT advancements in off-the-shelf industrial control systems, particularly PLCs, have greatly facilitated this integration. This progress has become particularly evident following the extensive LS2 period at CERN. In pursuing enhanced control system efficiency and long-term sustainability, we selected the latest Siemens industrial automation solution, the S7-1500 series. This choice enables the sharing of Central Processing Units (CPUs) and distributed Input/Output (I/O) modules, underpinning our commitment to ensure system functionality and operational continuity over the next two decades, Fig. 3.

The adopted control system architecture adheres to a classic design paradigm. It comprises a Manager CPU system which is daisy-chained to multiple distributed I/O systems, typically one dedicated for each generator actuation. Local control is facilitated through an operator panel, complemented by the use of the Siemens TIA (Totally Integrated Automation) Portal software development environment. The successful implementation of this architecture has been demonstrated in several installations and has notably contributed to the success of ABT's LIU campaigns.

Furthermore, ABT control system include remote supervision capabilities, employing the Siemens WinCC suite to monitor supervisory type slow control systems remotely. This remote monitoring functionality is an aid for visibility and diagnostics of ABT control systems, enabling operation and management of critical systems from a distance and thus improve and facilitate diagnostics.

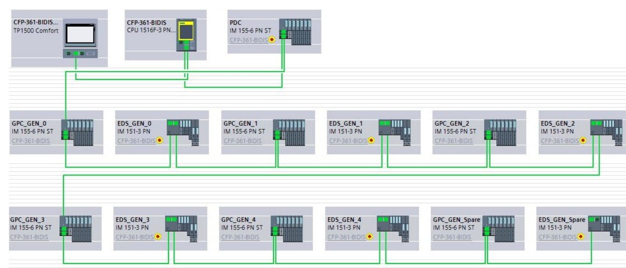

Figure 3: Typical network topology view of the PLC architecture for ABT kicker systems.

In terms of PLC generics, before LS2 a standardised finite state machine slow control library item was developed. This was devised so that multiple systems could 'fit' the entire array of functions and options that make up the control for ABT kicker systems. This block was designed to be tailored for specific types of installations in which the number of internal interlocks, states, mask and so fourth can be employed. The advantage here was to have a block that was multi-user shared with easy integration and implementation.

Kicker Power Distribution

Power distributor Controller At ABT a recent approach is to produce a modular system for each kicker system electrical distribution. The idea is to specify number of circuit breakers and contactors in a modular distributed way, to produce a functional specification that can be finally sent to specialised companies to produce the electrical distribution cabinets upon request of well predefined specifications. Normalised throughout, the system is equipped with a single rack system PDC with primary AC electrical distribution coming from CERN electrical services.

The PDC system houses a phase monitoring system, circuit breakers and contactors technology and these underwent DEKRA approval i.e. an outside independent service that validates the system ratings, functionalities and human safety. The power distribution of the complete systems is achieved by PLC control modules that are integrated into the cabinet with all the low-voltage components and are designed to be easily integrated into the overall PLC structure of the entire kicker system.

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Thyratron Heater Power Supplies

The 19" rack mounted heater power supplies manufactured by CE+T (Fig. 4) provide a remotely adjustable AC output voltage to the kicker thyratron tubes to modify both the temperature/pressure in the reservoir and heating of the cathode gate element (increasing or reducing the length and speed of the discharge pulse). Their output range covers the entire requirements of old and new thyratrons (variable between 130 – 250 V AC), and the power supply modules are redundant (configurable for current share and hot standby options). A Modbus RS485 control/readout interface allows the PLC to transmit and receive control and readback information e.g. Voltage in (Vin) value, Voltage out (Vout) requested, Vout current value, Iout Current out (Cout) value, Output Load, Redundancy status/active modules status, Internal Temperature, On/Off command, Voltage set point command. The power supplies also feature a dedicated hardwired dry contact interlock input for emergency situation/loss of communications, and configurable alarms and faults outputs

Figure 4: Thyratron Heater Power Supplies.

Capacitor Charger and Protection Unit

The Capacitor Discharge and Protection Unit (CDPU) incorporates an electrical resistive discharge mechanism, an identifiable manual grounding device, real-time safety indicators, and a failsafe no-voltage checker (VAT). Additionally, safety is further augmented by interlocking devices and an external control interface, ensuring inadvertent charging is deterred. The CDPU system (Fig. 5) is carefully crafted to align with established safety protocols detailed in C15-100, C18-510, and IEC62601/EN13849-1 standards. The PSB and PS complex's CDPU represents a significant leap in capacitive discharge safety, providing an integrative, standard-compliant solution that prioritizes staff protection.

DCPS (Direct Current Power Supply)

A 19" rack mounted DCPS, with standard output voltages of 330 V and 660 V DC (or higher depending on the installation), is responsible for charging and discharging the capacitor banks on the primary side of the resonant charging circuit of a step up HV transformer Fig. 6. Some of these are capable of both sourcing and sinking current (making for greater dynamic range of kick strength in fast PPM systems by discharging stored capacitor bank energy). It features various isolated plug-and-play control and monitoring interface cards (allowing the output voltage to be set remotely from the KiTS timing system or PLC), and fast inhibit functions (e.g.

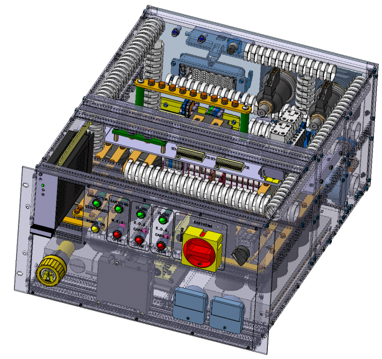

Figure 5: Capacitor Charger and Protection Unit.

to make sure output current is set to zero during discharge of the capacitor banks into the PFL/PFN) or switching off the current if the length of the output current signal is evaluated to be too long as well as programmable power limits to protect against overload/short-circuit or to limit inrush current.

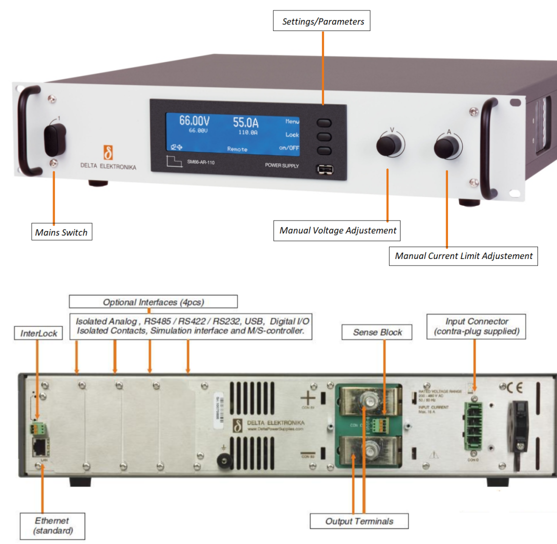

Figure 6: DC Power Supply (DCPS).

EQUIPMENT PROTECTION ELEMENTS

Fast Interlock Detection System At CERN fast pulsed kicker magnet systems necessitate precise control and monitoring of high-voltage and high-current pulse generators. The utilization of fast high-voltage switches, such as thyratrons, GTOs, and IGBTs are essential for managing the rapid energy discharge process. The hardware architecture of FIDS (Fast Interlock Detection System) is designed with specific functionalities in mind. An AMD Zynq-7000 SoC has been selected to implement these functions. The Field Programmable Gate Array (FPGA) within the SoC handles the rapid detection and interlocking logic, while the ARM processors provide flexibility for integration within CERN's Front-End Software Architecture (FESA) framework Fig. 7. This setup also enables advanced diagnostics and automated self-parametrization [1]. The FIDS consists mainly of open hardware available on ohwr.org [1].

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The FIDS incorporates several mechanisms for fast interlock detection:

Normal Conduction Monitoring: Although not a fast interlock itself, tracking normal conduction cases for statistical purposes is valuable and allows for fast full-chain validation upon restart.

Missing Conduction Detection: This occurs when a trigger is generated, but the switch does not conduct. It typically indicates a lack of current in a high-voltage switch or a missing load current after a specified time following the trigger event.

Erratic Conduction Identification: Erratic conduction refers to spontaneous high-voltage switch activation caused by tube or semiconductor malfunctions, distinct from conduction following the normal triggering action. The FIDS registers erratic conduction when the switch conducts without a corresponding trigger pulse.

Short-Circuit Detection can occur at various locations within the system, from the PFN up to a terminating resistor. Detection techniques for short-circuited magnets vary based on the magnet configuration. Method involves comparing the delay between the forward main switch pulse and the dump switch inverse current. In normal operation, this delay should represent the two-way transmission delay through the cable and magnet, plus the single-way delay through the PFN.

No Dump Switch Forward Current: In cases of short-circuited magnets or systems with a clipper switch, the short-circuit reflects the traveling wave, causing the dump switch to withstand an inverse current (i.e., current from cathode to anode in case of a thyratron). The FIDS being generic can also be configured to cater for application specific roles, for example surveillance of two IGBTs in series and their associated fast interlock mechanisms.

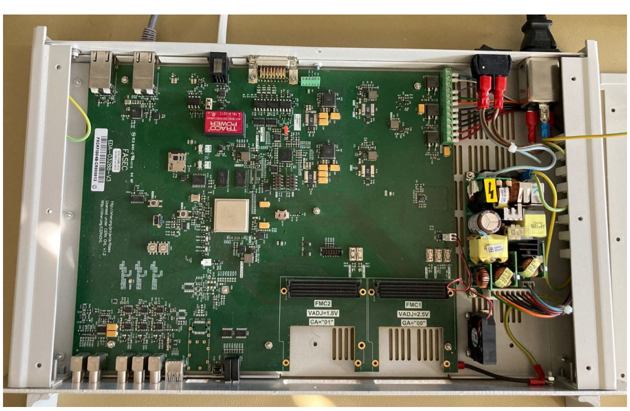

Figure 7: FIDS system deployed at the PS Booster injection chain.

Fire prevention system Particle accelerator kicker systems are vital components in beam manipulation, relying predominantly on PFNs. PFNs can employ either oil or air as HV insulating mediums. However, due to their susceptibility to fire hazards, these systems must be equipped with efficient fire protection units and exhibit non-destructive behaviors when responding to potential fire risks.

During extended operational phases, a PFN housing (in air type) and associated components may experience significant temperature increases, estimated at approximately 80 °C typically for the case of the PS Booster kicker. To address this concern, the system incorporates thermoswitches and thermal protection mechanisms. In the event of a fire, CO2 bottles are fixed onto the PFN housing to induce oxygen starvation within the air medium, thus suppressing the fire. This system also interfaces with the main control system, providing an external interlock mechanism designed to deactivate power supplies when a suspected fire event is detected.

Additionally RCPS elements contains power electronics components susceptible to heat, and due to the near surrounding can ignite a fire. A campaign of deployment of early fire detection systems is ongoing [2].

EQUIPMENT TIMING

Kicker Timing System The Kicker Timing System (KiTS) software is the ABT standard software used for the control of the main kicker operational parameters: delay, length and strength [3]. It is a generic software, capable of adaptation to different kicker system configurations, with various number of RCPS, PFN or PFLs and presence of main, dump and clipper HV switches. It is responsible for the generation of the triggers for RCPS based and CERN timing events, as well as the MS, DS and CS triggers synchronised with Beam based on RF pre-pulses, and it provides the voltage reference for the DCPS. It performs the acquisition of voltages and timing event timestamps for RCPS triggers for diagnosis by controls expert. For large systems equipped with more than one kicker magnet and associated HV generator, it provides load balancing functionalities to share the total kick strength requested by operation between available generators, and so allows for increased availability in case of generators transitioning into an erroneous condition thus increasing strength on the other available kickers to guarantee a constant total kick strength. It is a software developed using the Front-End Software Architecture (FESA) framework available at CERN, to provide interfaces to CERN controls middleware (CMW) for operation and expert interaction, as well as Real-Time part to control the hardware for strength and timing control. A dedicated GUI application is used by controls and kicker experts for configuration and diagnostic. It makes use of a Hardware abstraction layer, allowing to make use of with various brands of hardware implementing the functions needed, i.e. A/D, D/A, TDC, FineDelays. It also makes use of Functions implemented into FPGA, to replace individual electronic modules for functions like local timing generator or A/D D/A, allowing for better integration of fast timing functions. The KiTS is connected to the PLC for settings control by expert using the local HMI , or for automatic magnet conditioning [4].

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EQUIPMENT MONITORING

Internal Post Operation Check The acquisition of signal waveforms such as kicker magnet current, terminating resistor voltages, HV switches currents, power trigger currents, RCPS current and voltage in Figs. (8 and 9) reveals to be extremely useful to diagnose problems, and follow-up equipment performance stability. A software framework, called Internal Post Operation Check (IPOC), was developed to acquire and analyse waveforms [5]. Initially developed for the surveillance of LHC Beam Dumping System (LBDS) extraction and dilution kicker current waveforms, it is planned to be deployed over all kicker system at CERN. It was implemented using the FESA framework, and make use of many CERN control services, like NXCALS logging system to save waveforms and analysis results. It is connected to the state control PLC systems for interlock in case a abnormal waveform is detected outside nominal values. It makes use of a hardware abstraction layer to interface to various off-the-shelf digitiser cards, allowing a transparent integration of new digitiser types into the system. The waveform analysis algorithms are provided as external plug-in libraries, leaving their specific implementation to the kicker system experts. It also allows for closed-loop control system, for instance used for drift stabilisation of high voltage thyrathron switches, computing fine delay corrections and send them to KiTS.

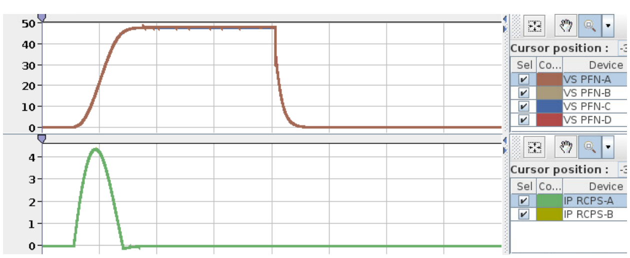

Figure 8: RCPS current and PFN voltage captured by IPOC.

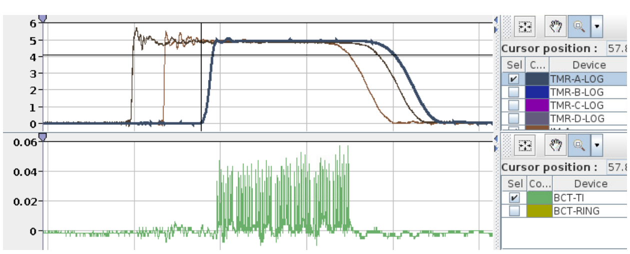

Figure 9: MS, DS and magnet currents, with injected beam captured by IPOC.

CONCLUSION

In summary, this paper elucidates the transformation of the control systems for the PSB and PS injection kickers at CERN, highlighting the transition to a modular and open architecture, the role of standardized hardware and software control blocks, and the multifaceted functionalities of the integrated subsystems. It also explores the adaptability of these solutions for future projects during LS3 while drawing from the experiences gained in the process.

The integration of common elements and the adoption of modern control systems, specifically the Siemens S7-1500 series, have significantly improved the kicker control structures at CERN and ABT. This approach not only ensures the sustainability of these systems over the next two decades but also enhances their flexibility and maintainability. The experiences gained from this endeavor offer valuable insights for similar projects in the field of particle accelerators.

The concerted efforts to streamline kicker control systems through the integration of common elements, coupled with the adoption of modern Siemens technology, have yielded significant improvements in control system efficiency, reliability, and maintainability. These experiences provide valuable insights for similar projects within the field of particle accelerators and underscore our commitment to advancing scientific research at CERN and ABT.

The integration of comprehensive fire protection and thermal safety measures in particle accelerator kicker systems, such as the upgraded Booster distributor, is essential for ensuring the safety and operational continuity of high-energy physics experiments. These measures not only reduce fire risks but also provide real-time feedback and facilitate a coordinated emergency response, ultimately enhancing the reliability and safety of accelerator facilities.

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