HIGH-DENSITY POWER CONVERTER REAL-TIME CONTROL FOR THE MEDAUSTRON SYNCHROTRON

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Abstract

The MedAustron accelerator is a synchrotron for light-ion therapy, developed under the guidance of CERN within the MedAustron-CERN collaboration. The accelerator is installed at the facility site in Wiener Neustadt, Austria. Procurement of 7 power converter families and development of the control system were carried out concurrently. Control is optimized for unattended clinical operation. Devising a uniform solution for the current regulation of all magnet power converters was paramount to meet the ambitious project plan. Another challenge was the need to operate with about 5'000 different beam cycles initially, scale up to tens of thousands, achieving pipelined operation with cycle-to-cycle re-configuration times in the order of 250 msec. The system is based on commercial-off-the-shelf hardware at front-end level and on the CERN function generator design at equipment level. The system is self-contained, permitting use of parts and the whole elsewhere. The separation of power converter from real-time regulation using CERN's generic Converter Regulation Board makes this approach an attractive choice for integrating existing power converters in new configurations.

INTRODUCTION

The particle accelerator for the MedAustron facility has been designed and constructed under the guidance of CERN [1,2]. It derives from the PIMMS [3] study that was carried out at CERN from the mid to the late nineties. The accelerator features three ECR ion sources for multiple particle species, a linear accelerator consisting of RFQ, buncher, IH-tank and debuncher, a synchrotron and five beamlines, one of them a proton gantry. In total, 283 power converters are controlled via current regulation to generate magnetic fields in up to 360 magnets. The need to permit machine development, research and medical operation with an easy to use, yet flexible control system and uninterrupted, pipelined cycle-to-cycle modulation are the main motivators for the presented scale-out architecture realized in cooperation with a contractor.

NEEDS AND USE CASES

The control system has to permit operation in four modes: in service mode, power converters can be configured and freely operated for hardware commissioning. Machine physics mode permits operating the accelerator with a baseline configuration of setpoints and waveforms. Operators can, however, override the baseline values and waveforms. Medical physics and medical treatment modes restrict operation to released settings with additional security checks enabled.

For service and hardware commissioning, each power converter can be given a current value directly via the operator panels. Such values are not used during beam operation. For machine commissioning, research and medical operation, beam-characteristics dependent current control values are provided. Configuration values, which are bound to specific beam characteristics, can be saved using the accelerator control systems feature to capture the current state of the accelerator. Such snapshots of configuration data can at any time be restored. A beam with specific characteristics is generated in an operation cycle. Beam characteristics are indicated by a cycle identifier broadcast by the main timing system [4] before a cycle is started. Masks for individual bit patterns of the cycle identifier let the operator assign different current control values for different particle types, beam intensities, beam sizes, spill durations, energy levels, particular ion sources, treatment lines and the gantry angle. Theoretically, hundreds of thousands of different settings can be provided for each power converter. In practice, the majority of power converters of ion source branches, LEBT, Linac and MEBT are only particle type dependent. About 30 power converters in the synchrotron require particle type, energy, spill duration and intensity dependent waveforms. Power converters for HEBT and beamlines are mainly particle type, energy and gantry angle dependent. This simplification reduces the amount of individual setpoints and waveforms to about 7 in the injector, 500 to 10’000 in the synchrotron, HEBT and beam lines. Nevertheless, the requirement to pre-configure the control system for the next foreseen beam cycle while the currently active beam cycle is generated leads to performance and safety constraints. Eliminating the hysteresis part of magnets in the synchrotron leaves a 250 msec fall time after the extraction stops from maximum extraction main dipole magnet field level to zero field level. This time represents therefore a target maximum time for reconfiguring power converter controllers for the next beam cycle.

Timing precision is determined by the 2 µsec bunch revolution time at injection level. 1 µsec has been chosen, since a bunch at most occupies half of the synchrotron. For waveform generation, setpoint provision frequency has been set to 2 kHz. Since at the time of control system design and implementation, power converters were not fully specified and were not tendered and acquired, the power converter control subsystem permits changing that

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value. Single setpoints must be given by the power converter controllers to a low-level regulation system within 100 msec in order to have sufficient margin for success and failure checks within the targeted 250 msec. For commercially acquired power converters, a major fraction of time is consumed by low-performance power converter internal microcontrollers and low-baud-rate serial line communication. Several power converters in the Linac require regular triggering for charging and discharging with 1 μsec timing precision. Two special magnet power converters need to be triggered within some tens of nsec. This feature can, however, be realized directly with a main timing system event receiver card.

Power converters are placed in an 800 m^2 hall above the synchrotron and extraction line. The large surface and secured physical access to this area favours control of all power converters at distance via a compact system that comprises only few physical entities that need to be configured, controlled, monitored and maintained.

In terms of diversity, the system needs to control power converters from seven different suppliers and two different CERN groups. Power converter control had to be designed, implemented, installed at the facility site and tested before and during tendering, design and production of the power converters. This was a particular challenge to be mastered in less than three years.

ARCHITECTURE & DESIGN

Historically we observe oscillating trends between monolithic and highly distributed control architectures. In this project we opted for a scale-out architecture. A chassis with CPU and several FPGA carriers controls up to 36 power converters via optical links in real-time. That building block, called Power Converter Controller (PCC) is replicated eight times to control the 283 power converters (see figure 1).

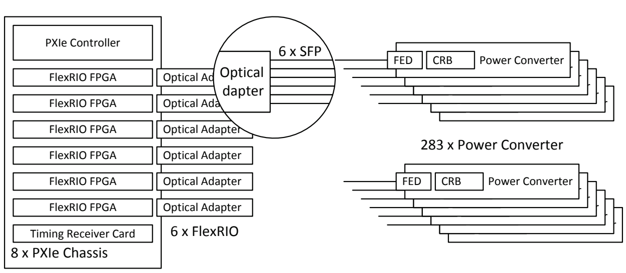

Figure 1: Scale-out control architecture.

We selected a high performance National Instruments PXI Express 8-slot crate with quad-core Intel Core i7-3610QE 2.3 GHz processor and 8 GB RAM running 64 bit Windows 7 as building block. Cycle-dependent setpoints and waveforms for power converters that are connected to one building block are cached on the local hard disk of that CPU. Data format is binary; waveforms are lists of samples at the required regulation loop frequency. The crate is populated with six FlexRIO PXIe-7965R Virtex-5 SX95T FPGA cards. Each card has an adapter module with six optical SFP ports. (figure 2).

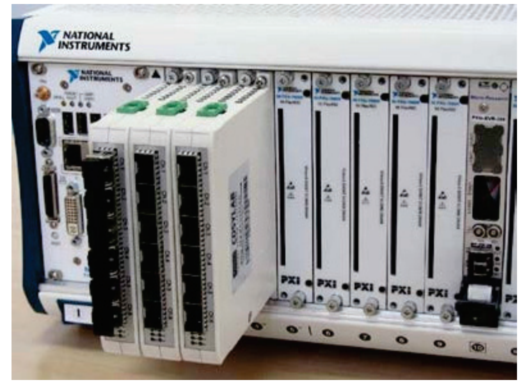

Figure 2: PXIe based frontend co ntroller with FlexRIO cards, six port optical adapter and MRF event receiver cards.

Each port connects via a standard Gigabit Ethernet OM3 fiber pair bi-directionally to an in-house Spartan 6 FPGA based communication daughter board called Front End Device (FED) in the power converter. Distances between PCCs and converters range from 25 to 120 meters fiber length. Although signal propagation time compensation is possible, the distances do not impact function or performance. The optical link implements a bi-directional real-time communication channel from PCC to the power converter with sub-microsecond jitter. Several additional non-real time communication channels can be used concurrently over the same fiber. A 100 MHz frequency that is phase-locked to the GPS wall clock is broadcast to all power converters via the optical link, too.

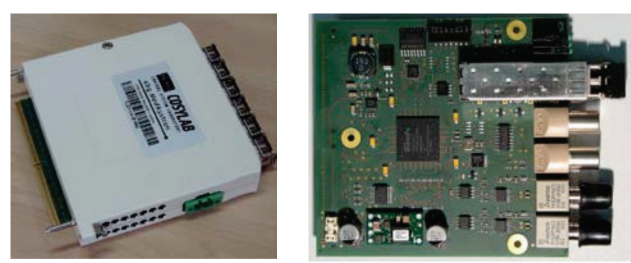

Figure 3: FlexRIO adapter (sender) and generic front-end device (FED) adapter board (receiver).

The FED implements recovery of the 100 MHz reference clock provided by the timing system receiver card at the remote side of the optical link and derives various reference clocks for operation, bus communication and power converter regulation loop from that clock. All clocks are phase synchronized to the GPS wall clock without drift over time. Consequently, all power converter regulation loops are synchronized at sub-microsecond precision. For ordinary power converters the clock is set to 2 kHz and for beam scanning systems it is set to 50 kHz. The board offers optical and electrical trigger outputs and a number of general purpose IO ports for low-level direct communication with power converters if needed. A 32 bit UHPI bus interface is used to communicate with a CERN designed converter regulation board (CRB) that acts as motherboard in real-

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time. Where no CRB is used, the FED directly connects to a power converter via a serial RS232 or RS422 link and/or general purpose IO lines. A variant with a parallel SCSI-5 parallel real-time link also exists for use-cases, where a bus interface would be too complex.

The CRB is a direct derivate from the CERN FGC3 [5]. It interfaces to power converters for slow control tasks and performs digital real-time regulation with analogue voltage reference output and DCCT acquisition. The board features a TI floating point DSP and a Xilinx Spartan 6 FPGA. 8 Mbytes Flash and 32 Mbytes DRAM are available on board for software, calibration and configuration data as well as for buffering measurements. 32 digital input/output pins are freely programmable. Temperature reading with 0.1 C precision can be used to improve regulation stability. Different ADCs are used for slow (2x40 kHz@19 bits) and fast (2x100 kHz@16 bits) regulation use cases. For providing the analogue current reference, one 16 bit DAC with conversion time less than 10 µsec is available. Three input and three output high speed LVDS serial links can be used to exchange digital data with power-converter internal electronics. A USB port is used for configuration and local test purposes.

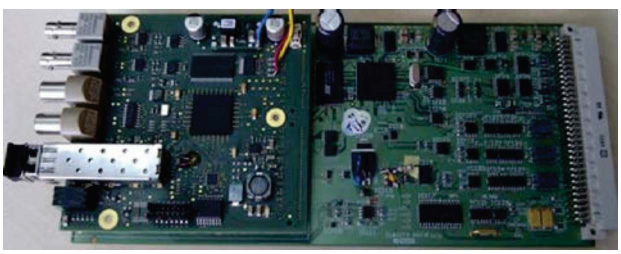

Figure 4: CRB with mounted FED.

The PCC loads all setpoints and waveforms needed for a particular run into main memory. As soon as the next cycle is requested, the CPU downloads the setpoints and waveforms for that cycle into the FlexRIO memories. Depending on the timing event that is received by an MRF main timing system event receiver card the FlexRIOs transmit setpoints and waveforms in real-time via the optical links to the CRBs. PCC applications transmit data in real-time to the CRBs and in parallel acquire generated current and regulation error. CRBs carry out the regulation loop digitally, providing current reference values to the power converter internal electronics via a -10V to +10V analogue signal. Slow control commands are transmitted and monitoring data are received via a non-real time channel on the optical link. Where power converters require relaxed triggering in the microsecond range the event can be transmitted over the same optical fiber, avoiding the need for extra timing receiver cards and additional optical wiring.

The described components are part of a four-tier [6] control system architecture. Tier-1 includes WinCC OA (formerly known as PVSS) implemented panels, such as a power converter and magnet circuit status panel, configuration of measurements and slow controls of individual and sets of power converters. A typical measurement panel showing a waveform, a regulation error and overlapped main timing events is shown below.

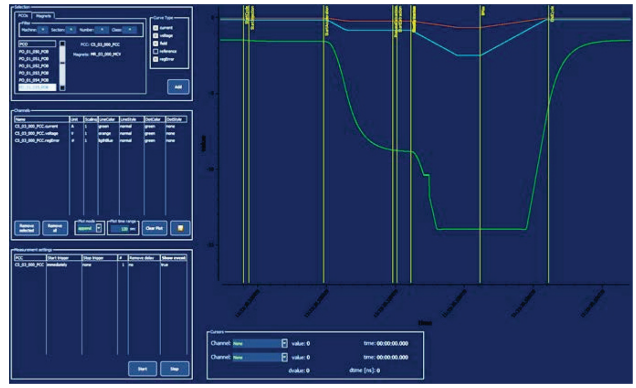

Figure 5: WinCC OA power converter control user interface panel with real -time display of timing events, generated waveform and regulation error.

A settings generator application that is based on an XML accelerator model defining the optics characteristics of the machine generates setpoints and waveforms for a configurable set of power converters for a configurable set of beam characteristics. The resulting field values are emitted as individual values for setpoints and binary sample sequences for waveforms. Data for different power converters and for different beam cycles can be overlaid and compared as shown below.

Figure 6: Settings generator showing waveforms for two magnets for one particular beam cycle.

Magnet measurement curves taking into consideration a working direction along a certain hysteresis curve are subsequently used to convert field into current. This happens either by directly importing field values into the running control system for machine development or when exporting released configuration data from the configuration database for medical operation. Since setpoints and waveforms are provided to the power converters as sampled data that are generated without transformation by the PCCs, the residual risks relevant for medical application can be well understood.

Tier-2 hosts the SCADA system based on SIEMENS/ETM WinCC OA and a number of in-house written C# application services [7]. Accelerator control system hardware and software configuration, configuration parameters and beam-characteristics dependent setpoints and waveforms are managed in a

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database application at this tier. Released configurations are exported as WinCC OA configuration data, front-end controller configuration files and cycle-dependent data to a Web server. Frontend controllers check autonomously on startup if their configuration is up-to-date, update software and download data if needed.

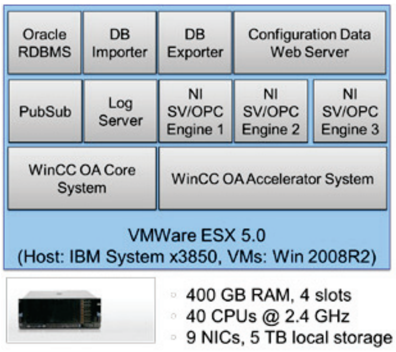

Figure 7: Supervisory control components.

Figure 8: Full-scale system deployed at facility site.

PERFORMANCE

Initial performance evaluation revealed an implementation with average cycle-to-cycle re-configuration times of 450 msec and worst cases up to 2.5 seconds. After code optimization, the average worst-case re-configuration time per cycle over all PCC applications and crates was brought down to 131 msec (62 msec RMS). For 0.015% of the measured cycles insignificant worst cases between 300 and 700 msec have been observed. An implemented acknowledgement mechanism from all PCC crates to the timing event generator can be used to postpone the next cycle generation until re-configuration has completed successfully.

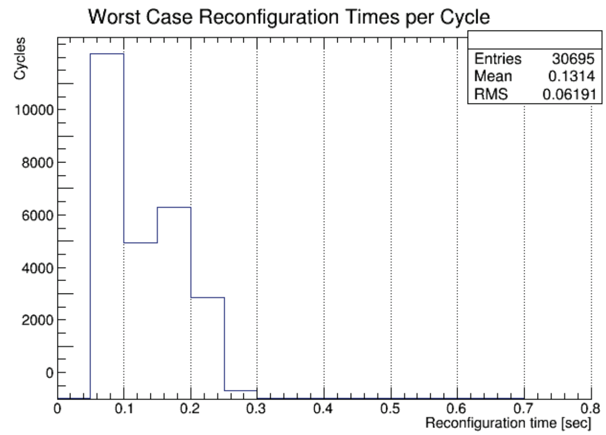

Figure 9: Observed worst case reconfiguration times of over 30 kCycles after code optimization.

SUMMARY

The full scale control system [8] has been installed and handed over for accelerator commissioning in July 2013. On-site tests with simulators and real power converters were carried out. Performance was evaluated and optimizations have been implemented, yielding a system that is compatible with the performance requirements. So far, power converters with triggered single setpoint, triggered waveform and triggered charge/discharge operation, covering all specified use-cases. The system is currently used for injector beam commissioning.

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