

# THE NEW MODULAR CONTROL SYSTEM FOR POWER CONVERTERS AT CERN

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## Abstract

The CERN accelerator complex consists of several generations of particle accelerators, with around 5000 power converters supplying regulated current and voltage to normal and superconducting magnet circuits. Today around 12 generations of converter control platforms can be found in the accelerator complex, ranging in age and technology. The diversity of these platforms has a significant impact on operability, maintenance and support of power converters. Over the past few years a new generation of modular controls called *RegFGC3* has been developed by CERN's power conversion group, with a goal to provide a standardised control platform, supporting a wide variety of converter topologies. The aim of this project is to reduce maintenance costs by decreasing the variety and diversity of control systems whilst simultaneously improving the operability and reliability of power converters and their controls. This paper describes the state of the on-going design and realization of the *RegFGC3* platform, focusing on functional requirements using Thyristor based converters as an example.

## INTRODUCTION

The CERN accelerator complex consists of several different machines, each with particular powering characteristics. Power converters are a fundamental requirement of any such machine, being used to provide power to various loads such as magnets (normal, superconducting, dipole, quadrupole ...), radio-frequency (RF) cavities and other powered equipment. Evolutions in both accelerator functional requirements and power technology require a regular updating of approaches for converters and their associated control electronics, in particular with enhanced diagnostics and more demanding regulation performance.

Table 1 gives a break-down of typical power converter control platforms, and their use in the CERN accelerator complex.

This diversity of platforms gives rise to significant challenges:

- The age of legacy platforms is expected to give rise to end-of-life effects, where some platforms are already >30 years old.
- Information about these platforms is not always coherently stored and available for experts.
- Some platforms cannot be re-produced, due to component obsolescence.
- Each control platform generally has an associated software stack, which needs to be maintained.

- The engineers and system responsables for these systems are not always available to help in diagnosing faults and issues.
- Operations increasingly want better control over some of these platforms, working on them is becoming increasingly difficult and risky.

This leads to higher failure rates, longer repair times, and generally lower availability of the CERN accelerator complex.

Table 1: Control Systems and Converters at CERN

Control Platform	Machine / Area	Number of converters
MIL1553	PS	1218
PLC	SPS, AD, LIER	510
RS422	PS	366
Junction Crate	North Area	322
MUGEf	SPS, TTs	652
FGC2	LHC	1782
RegFGC3	Various	497

## A NEW CONTROL SYSTEM

In recent years, new projects and consolidation activities led to the development of a new control platform, as existing solutions were not able to meet requirements. This presented itself as an opportunity to develop a new approach for power converter controls, whereby a single platform could be developed to provide a standard, modular solution for any past, present or future converter at CERN. This new platform is called Regulation based on the 3<sup>rd</sup> Generation Function Generator Controller (RegFGC3).

The aim of this platform is to provide for the new projects (e.g. the LHC Injector Upgrade and LINAC4) but also to be applied to any requirements in the coming years [1, 2]. The medium term goal is to reduce the number of control systems in order to improve system maintainability and operability, reducing the burden on the controls sections in the power converter group. In this framework, the EPC group developed the RegFGC3.

## THE REGFGC3 CONTROL SYSTEM

The RegFGC3 is a modular converter control platform developed at CERN with the main goal of providing a standardised solution and satisfying as many requirements

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as possible for power converter controls, whilst using the minimum diversity of boards as possible. The platform uses a standard interface to the CERN control system, via a Function Generator Controller (FGC), in this case the third generation embedded computer [3,4]. The RegFGC3 platform extends the FGC3 capabilities by providing interface modules in order to control power elements of the power converter. The RegFGC3 board portfolio consists of several FPGA-based generic modules that can be used for numerous applications. This principle allows a flexible approach to configuring a control system, adding or removing boards as required. Modules are grouped into classes as shown in Table 2.

Table 2: List of Generic RegFGC3 Boards

Class	Board
Measurement	VS Measurement, VS V2V, VS I2V, VS HVV2V
Interlock	VS Digital Interlock, VS Analog Interlock, VS Beam Interlock
Regulation	VS Regulation DSP, SIRAMATRIX,
Control	VS State Control
Powering	VS PSU

### Measurement Boards

The measurement class includes all the modules developed for acquiring analogue signals from High Precision Measurement devices such as Direct Current Current Transformers (DCCTs), Hall probes as well as high voltage dividers. The Current to Voltage (I2V) and Voltage to Voltage (V2V) boards interface the DCCT and deliver adapted voltage levels to the rest of the system. The VS Measurement board is a generic ADC-based acquisition board providing up to 11 analogue measurements. The board digitises and dispatches the data to the regulation system.

### Interlock Boards

The RegFGC3 control system implements a redundant protection mechanism based on safety daisy chains shared by all the boards through the backplane. The chains can be opened by any of the boards in the system when a fault is detected. When a chain is opened, the power system is safely stopped. Three generic boards are developed for interlock functionality: the Analogue Interlock board, the Digital Interlock board and the Beam Interlock System (BIS) board. The Analogue Interlock board provides analogue fault detection for up to 16 analogue input channels. Every input analogue signal is compared

against converter-dependent thresholds. The Digital Interlock board provides a protection mechanism against discrete fault events such as over-temperature, fast-abort and power rack operation. The Digital Interlock board allows up to 36 discrete signals to be monitored. While the Analogue and Digital interlock boards provide a local protection mechanism for the converter and the load, the BIS board is the interface with the Beam Interlock System, an important component in the accelerator complex which prevents from any accidental release of beam energy [5]. In order to prevent the system from erroneous operation, the BIS board compares the magnet current with four detection windows representing four possible different destinations. When the current value is out of a specific window, the corresponding beam permit is disabled.

### Regulation and Converter Control

In the RegFGC3 system the digital regulation can be performed by three different modules: the FGC3, the VS RegulationDSP board or the SIRAMATRIX. Performance capabilities range from 10kHz to 1MHz in regulation frequency. The FGC3 provides all the functionalities required to control a simple converter. It consists of a main board, a communication board and a high-precision ADC-based acquisition board. The regulation takes place in the TI TMS320C6727 DSP while a Spartan3AN FPGA is used for low level peripherals handling. The DSP Regulation Board is based on the TMS320C2834x DSP and it is mostly used for high-frequency PWM control. The third regulation option is represented by the SIRAMATRIX, an FPGA-based regulation board developed for Fast Pulse Converters control. The board includes fast acquisition ADCs, DACs and a Spartan6 FPGA which runs the control algorithm.

The State Control is a generic board which is used to control the converter state machine and timing. It ensures that the low level sequencing of the power converter is executed correctly. For example first closing the main power contactor, then checking the voltage level is correctly achieved, and verifying all subsystems are operating correctly before permitting power to be applied to the load.

The RegFGC3 platform provides several communication interfaces to exchange data between the FGC3 and the different boards. The SPI is a real time interface used to send the reference value from the FGC3 to the regulation board (VS RegulationDSP or SIRAMATRIX). The SCI is a slow asynchronous serial interface used to exchange general data with any card. Finally, the QSPI is a serial communication link for diagnostic information exchange.

## THYRISTOR CONVERTERS

Three-phase Thyristor-based power converters are a specific family of converters widely used at CERN especially in the injectors and experimental areas. The operating principle of a Thyristor power converter is to

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supply from the electrical grid power to a transformer followed by a Thyristor bridge rectifier. An electronically damped output filter is used for filtering of the rectified noise. A 3-phase bridge can be connected in parallel or in series in order to increase the output current or voltage rating respectively. With the evolution of power electronics technologies, fast switching power converters (exploiting for example high power IGBTs), are increasingly used for low and medium power application (100kW up to 1MW). Thyristor power converters remain valid solution for high power applications (up to 150MW). Figure 1 shows the main Thyristor topologies deployed at CERN including single bridge, two bridges series and parallel converters.

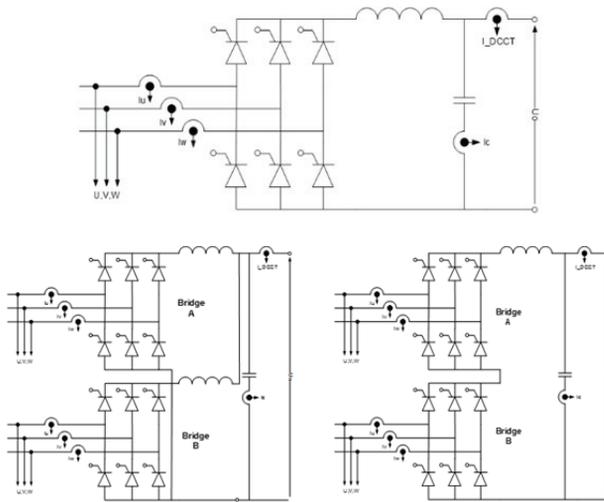


Figure 1 : Thyristor converter topologies.

As shown in Table 3, several power converters are planned to be consolidated in the next five years.

Table 3 : Estimated Number of Converters to Upgrade

Machine	Number of converters	Period
SPS + TTs	218	2016-2020
AD	6	2016-2020
ISOLDE	14	2016-2020
nToF	6	2016-2020
F61	59	2016-2020
LEIR	23	2016-2020
LINAC3	4	2016-2020

The RegFGC3 has been chosen as the candidate for the upcoming upgrade of the Thyristor converter control. Figure 2 shows a control block diagram for a Thyristor converter, using generic electronic boards developed for the platform, and a group of specific boards for the generation of the Thyristor firing pulses (VS Analog Firing, VS Analog Measurement, and VS Drive).

Measurements

The control of a Thyristor converter requires several analogue signals to be monitored for the regulation as well as for protection purposes. This includes input and output voltages and currents as well as the output capacitor current. In the described system, high-voltage measurements are performed using high-voltage dividers while Current Transformers (CT) and DCCTs are used to measure the currents. The I2V board interfaces the DCCT delivering a voltage proportional to the current being measured. The VS Analog Measurement board is a Thyristor converter specific module which receives the voltage measurements from the voltage dividers and makes them available to the rest of the control system.

Power Converter State Machine Control

The power converter operation can be represented by a state machine which defines the different actuations and statuses the converter handles during operation. Usually, the state machine depends on the converter topology being considered. Figure 3 shows the state machine for a Thyristor converter which is implemented in the VS State Control board. The converter starts in the OFF state where the MCB is open, the circuits are not powered and the regulation is disabled. Following a start command, the converter transits into the Starting state, the MCB is closed and the circuits are powered after some delay. Once the circuits are powered, the converter enters the Blocking state waiting for the ON command. When the converter transits into the ON state the regulation and the firing signals are enabled. In the Stopping state the MCB is opened following a control stop procedure. The FAULT state can be reached from any of the states when a fault condition occurs. In this state the MCB is opened and the regulation is disabled. The converter will stay in the fault state until the fault disappears and it is acknowledged by an operator. At this point the converter will transit to the OFF state.

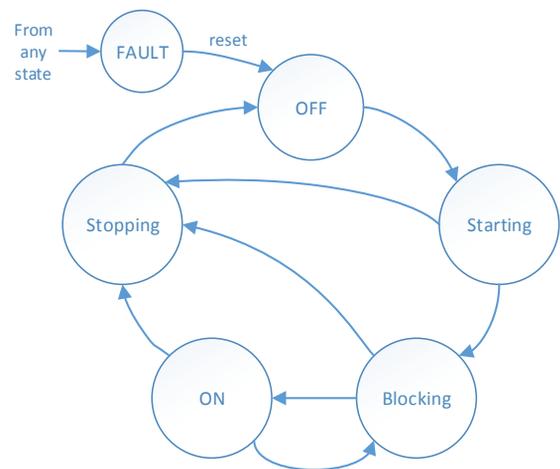


Figure 3 : Thyristor converter state machine.

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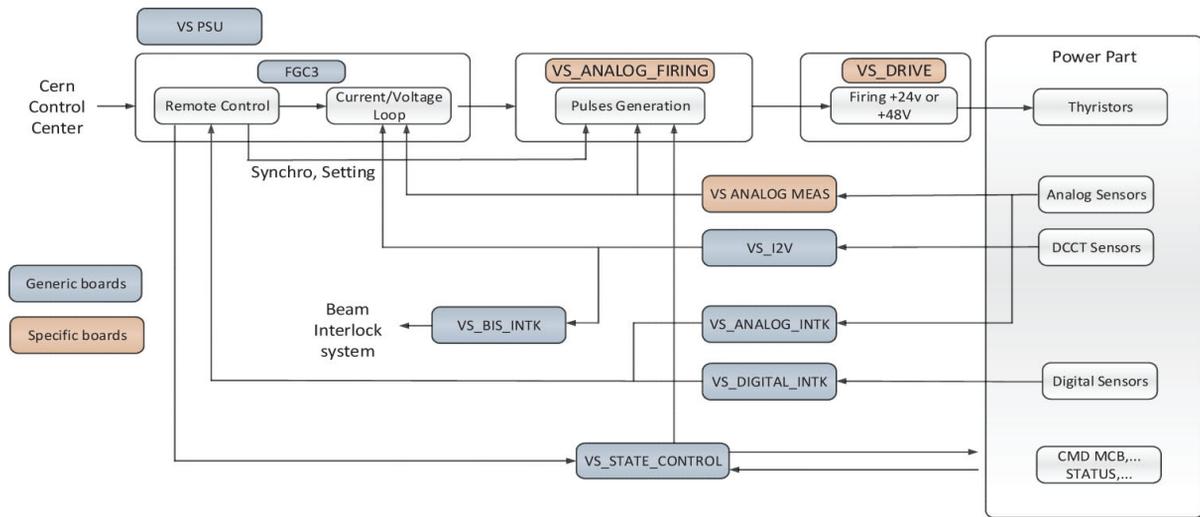


Figure 2 : Thyristor converter control diagram.

### Regulation and Thyristor Firing

The core component of the regulation for Thyristor converters is the VS Firing board which is based on an evolution of the Cassel/van der Meer principle used at CERN since the SPS era [6]. The FGC3 implements the current and voltage loop receiving the user external reference through the network and a series of analogue signals required for the regulation. The analogue signals are digitised using four high precision ADCs (MAX5541). The regulation algorithm takes place in the DSP where the RST coefficients for the regulation are calculated using a collection of libraries written in C for function generation and control [7]. The regulation algorithm generates a voltage reference which is sent to the VS Analog Firing board which generates up to 24 low power firing pulses allowing the control of a two-bridge converter. Finally the firing pulses are adapted to high-power Thyristor-gate pulses by the VS Drive board which can drive up to 12 Thyristor gates.

### CONCLUSIONS

One of the most challenging objectives for the Electronic Power Converter group at CERN is to reduce the number of converter control systems by using adaptable and scalable modular electronics. The RegFGC3 platform offers a standard solution that can be adapted to many different user requirements using a set of generic boards. Development time and costs are decreased by taking advantage of a common platform. Additionally, the remote diagnostic features provided by the RegFGC3 platform significantly improve troubleshooting and operational issues solving.

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