A NEW CONCEPT OF HIGH CURRENT POWER SUPPLY FOR THE MAIN CYCLOTRON MAGNET AT TRIUMF*

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Abstract

A sophisticated power supply was studied and designed to supply a high current to the main magnet of the TRIUMF cyclotron. The power supply will be operated with a current up to 20000 A in DC mode. It has been designed using a modular approach, with a 12-pulse input rectifier and two DC link which feeds sixteen DC/DC chopper modules in parallel connection.

The conceived power supply integrates a sophisticated control and a precise current measurement chain developed at CERN for the Large Hadron Collider (LHC).

This paper presents the solution described in the design report, the choice of the main purchased components which will lead to a final assembly and test before the end of 2016.

CONVERTER TOPOLOGY

The main components are:

- Input Circuit Breakers and Pre-charge Circuit.
- Two Rectifier Transformers.
- Two Main Rectifier stages (with fuses).
- Two passive RLC Filters downstream from each Main Rectifier stage.
- Output stage composed of 16 switching IGBT modules operating in parallel.
- Freewheeling diodes across the output bars.

The main input contactor/breaker (MCB) is realized by a motorized circuit breaker, which provides manual and remote ON/OFF functionality to the power supply.

The ground breaker is located at the input of the power supply: it is a manual switch with a keyed lock-out feature which allows the output of the breaker to be connected to ground only when the main input contactor/breaker is open.

To limit the inrush current during the start-up of the power supply a pre-charge resistive branch is used, remotely enabled via an auxiliary contactor.

The input stage realizes a 12-pulse topology through two three-phase transformers, phase-shifted by 30 degrees.

The two rectifier stages, each composed of a rectifier bridge plus a damped LC filter, realize two separated DC-links for the downstream chopper modules. Each DC-link provides the input for the following switching stage, each composed of eight chopper modules operating in parallel.

All the switching modules have an output filter inductor, and converge on a damped capacitive filter, placed at the output of the power supply.

A free-wheeling diode (realized with 3 devices in parallel) is located across the output bus bars to correctly discharge the energy stored in the magnet when the power supply turns off.

Technical Specifications

A list of main technical specifications for the power supply is presented in Table 1.

Table 1: Main ratings of the power supply

PARAMETER	VALUE
Output Current/Voltage	20000 A / 80 V
Output Power	1600 kW
Mode of operation	DC
Regulation Mode	Constant Current
Topology	IGBT based buck converter
Equivalent Output Switching Frequency	16 x 10 kHz = 160 kHz (10 kHz for each module and 8 PWM carriers phase-shifted)
Absolute Accuracy	±1 part in 10^4
Current Ripple	±2 ppm of 20 kA for the range 17 kA to 20 kA
Short Term Stability (5 min) @ max I_{OUT}	≤ 2 ppm of 20 kA
Long Term Stability (8 hour) @ max I_{OUT}	≤ 5 ppm of 20 kA
Power Factor	≥ 0.96
THDin	Typical of a 12-pulse rectifier stage
AC Input	3ϕ, 3-wire, 800 VAC
Cooling	Air and Water cooling
Footprint	20.7 x 8.4 feet

Chopper Modules

The output stage is a chopper converter that consists of 16 modules in parallel. Each module has three IGBTs in parallel with the same PWM and every IGBT has its own inductor (see Fig. 1). The switching frequency is exactly 10 kHz and the power of each module is up to 100 kW.

The 16 modules are controlled with a phase-shift to increase the effective switching frequency to 160 kHz and thus reduce the ripple in the output current.

Layout

The power supply is composed of five cubicles (max dimensions per cubicle 2500x1500 mm) plus an air-conditioned control cabinet (see Fig. 2).

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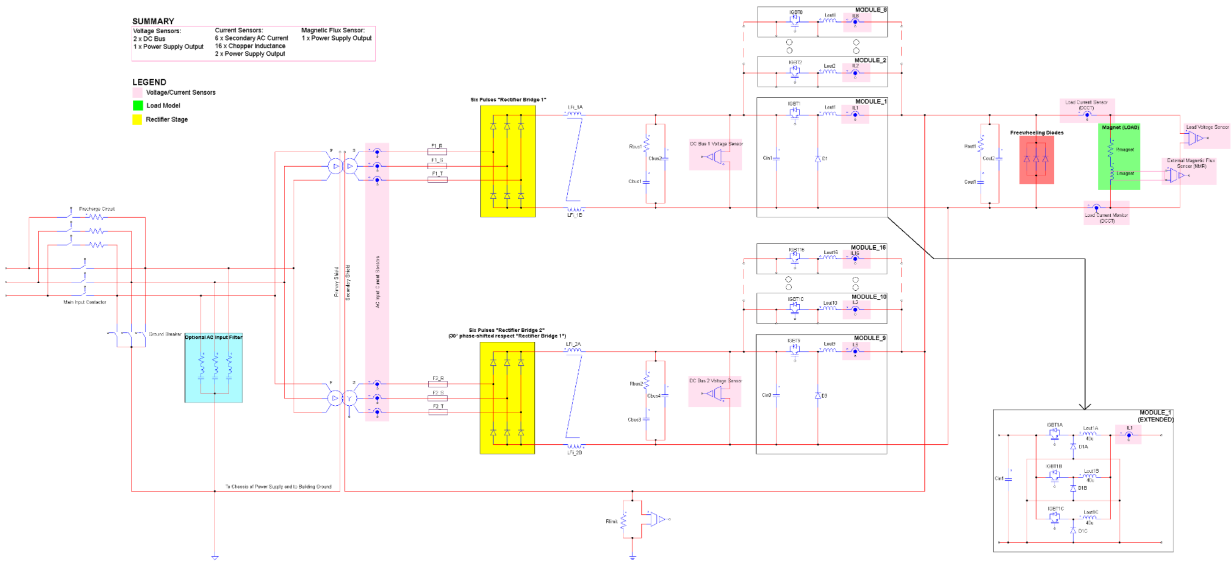

Figure 1: Power supply schematic.

In the first cubicle there is the input circuit breaker and pre-charge circuit, the second and third cubicles house the rectifier stages, each composed of a transformer, diode stack and DC filter. In the fourth cabinet there are the sixteen switching modules. In the fifth cubicle are located the two high-precision Direct-Current Current Transducer (DCCT) heads. Four symmetric vertical return bus-bars surround the DCCT heads, which are themselves around a single central vertical conductor. This symmetry is important as it avoids local saturation of the DCCT cores and maximises their performance.

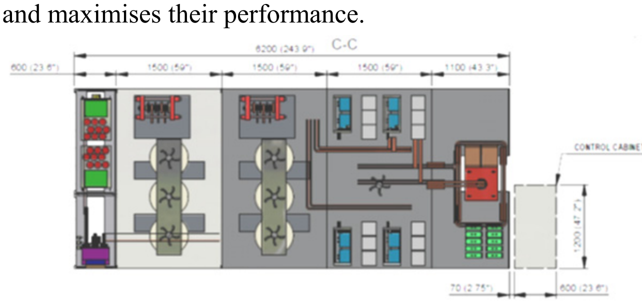

Figure 2: Top view of the power supply cubicles.

CONTROL ELECTRONICS

In order to guarantee the stability, accuracy and precision requirements in the output current are met, the power supply will use a reliable control system developed at CERN.

The CERN Type-10 RegFGC3 crate is an evolution of the controls originally created for the power supplies used in the Large Hadron Collider (LHC) [1, 2]. It is based on a CERN-designed embedded control computer called a Function Generator/Controller (FGC). The RegFGC3 platform uses a third generation FGC (see Fig. 3) in combination with other specialised cards to provide all the regulation, control and interlocking services needed by a switch-mode power supply.

The FGC3 has a USB interface and an Ethernet interface. Normally the Ethernet interface is used to connect the FGC3 to an FGC_Ether fieldbus [3], however, at least initially at TRIUMF, the new power supply will be controlled through the USB interface. This is simpler but significantly slower than the Ethernet interface, but for short commands and responses, it is fast enough. It is also possible to monitor the performance of the regulation through the USB interface as it has two channels, one for commands and responses and the other used to stream six signals at 1 ksps. The six signals transmitted can be selected from a long list of signals in the FGC3.

Figure 3: FGC3 controller and Type-10 RegFGC3 Crate.

Current Regulation

The FGC3 contains a TI TMS320C6727 DSP running the CERN Converter Control Libraries [4, 5]. The regulation library implements a 15th-order RST algorithm and can synthesize the RST coefficients to support a dead-beat PII regulator, as used in the LHC. It is also possible to calculate the RST coefficient externally using Matlab or equivalent.

The existing power supply uses a flux-loop to stabilise the field to better than 1 ppm of nominal, using a fully analogue regulation circuit [6]. The FGC3 will implement the same functionality digitally by using the fourth ADC input to digitize the flux-loop signal and modulating the current reference based on this measurement.

The TRIUMF cyclotron magnet has an inductance of 120 mH and a resistance of 3.9 mOhms. The time constant is thus about 30 seconds and the stored energy will be 24 MJ at 20 kA.

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Voltage Regulation

The Type-10 RegFGC3 crate was developed for the control of modular switch-mode power supplies in the range from 50 kW to several MW. It includes an FGC3 and a CERN-designed DSP board dedicated to implementing the voltage regulation and the generation of the PWM firing signals (see Fig. 4).

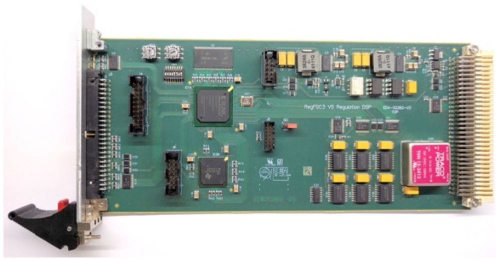

Figure 4: RegFGC3 DSP board for voltage regulation and generation of PWM firing signals.

This board uses a TI TMS320C28346 DSP, which includes nine high- and nine low-resolution PWM generators. The DSP software is flexible and is configured to drive eight high-resolution PWM signals, phase shifted, at 10 kHz. Adaptation logic in the power supply uses these PWM signals to create the IGBT control signals for the 16 modules.

Current Acquisition

The TRIUMF application requires short term stability for the current in the order of two part per million (ppm) of nominal (20 kA), after the first five minutes following a current change (see Table 1). Repeatability must be of the same order and current ripple must be within ±2 ppm of 20 kA for the range from 17 kA to 20 kA.

The performance of the current regulation, in particular stability and repeatability, greatly depends on the current measurement system. The current measurement chain for the new power supply is composed of a DCCT head, DCCT electronics and an Analog-to-Digital Converter (ADC).

Two independent measurement chains are used for redundancy purposes. The DCCTs are 20 kA TOPACC-HC (LHC type) from PM Special Measuring Systems. This is the same model as the LHC 13 kA DCCTs [7], proven to deliver ppm level stability over many years of operation of the LHC. As for the ADCs, four channels based on the LTC2378-20 are available on the FGC3 analogue board. An on-board temperature stabilized reference voltage is included for automatic ADC calibration.

The DCCTs and the ADCs have sub ppm level short term stability after warm up and under stable temperature conditions. The DCCT Temperature Coefficient (TC) is in the order of 1 ppm/ºC and the ADC TC is about 2 ppm/ºC. To guarantee stable conditions and therefore meet the stability requirements, the DCCTs and the Type-10 RegFGC3 crate will be permanently powered and will be housed in an air-conditioned cabinet (see Fig. 5). The temperature inside the cabinet is kept stable to ±1ºC by the air conditioning unit.

In addition, to further reduce temperature dependent errors, the TC of the ADCs will be measured and used with an online correction algorithm in the FGC3 to correct for temperature dependency.

Figure 5: Air-conditioned cabinet for the DCCT and controls electronics.

SUMMARY

The upgrade of the TRIUMF cyclotron main magnet power supply is a key part of the global consolidation project for the cyclotron. The new power supply must fit within the same floor space as the existing supply, and deliver the same high-level of performance, while assuring high reliability and maintainability for at least the next twenty years.

REFERENCES

[1] F. Bordry, H. Thiesen, "RST Digital Algorithm for controlling the LHC magnet current", CERN, Geneva, Switzerland, LHC Project Report 258, Dec. 1998.

[2] Q. King *et al*, "The All-Digital approach to LHC power converter current control", *Proc. 8th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'01)*, San Jose, USA, Nov. 2001, paper THBT004, pp. 453-455.

[3] S. Page *et al*., "Migration from WorldFIP to a low-cost Ethernet fieldbus for power converter control at CERN", *Proc. 14th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'13)*, San Francisco, USA, Oct. 2015, paper TUPPC096, pp. 805-808.

[4] Q. King *et al*., "Function generation and regulation libraries and their application to the control of the new main power converter (POPS) at the CERN CPS", *Proc. 13th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'11)*, Grenoble, France, Oct. 2011, paper WEPMN008, pp. 886-889.

[5] Q. King *et al*., "CCLIBS: The CERN Power Converter Control Libraries", *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'15)*, Melbourne, Australia, Oct. 2015, paper WEPGF106, pp. 950-953.

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[6] K. Reiniger *et al.*, “Stability Improvements in the TRIUMF Cyclotron magnetic field to ± 0.7ppm”. *Journal de Physique Colloques*, 1984, 45 (C1), pp.C1-225-C1-228.

[7] G. Hudson, K. Bouwknegt, “4-13kA DC current transducers enabling accurate in-situ calibration for a new particle accelerator project, LHC”, *11th European Conf. on Power Electronics (EPE),* Dresden, Germany, Sept. 2005

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