FOUR-QUADRANT CONVERTER [±600A, ±12V] PROTOTYPE FOR LHC

G. Kniegl, R. Weber, TRANSTECHNIK, Holzkirchen, Germany
F. Bordry, A. Dupaquier, CERN, Geneva, Switzerland

Abstract

The CERN Large Hadron Collider (LHC) project will make extensive use of true bipolar power converters [±600 A, ±12 V]. The need to install the power converters in excavated caverns underground requires considerably reduced dimensions and high efficiency. Moreover, the LHC machine demands a very high level of performance from the power converters, particularly in terms of DC stability, dynamic response and also with regard to ElectroMagnetic Compatibility (EMC). To meet these requirements, soft-switching techniques are used. The design and the performance (DC stability, bandwidth, efficiency, EMC…) of a compact (6U) and high frequency (30kHz) four-quadrant power converters are presented.

1 INTRODUCTION

The CERN Large Hadron Collider (LHC) machine will make extensive use of true bipolar power converters [±600 A, ±12 V] to correct the multipole errors of the main superconducting magnets [1,2]. These power converters feed sextupole and decapole spool piece circuits as well as octupole magnets. Several trim magnets also require 600A four-quadrant converters. In total there are about 450 converters [±600 A, ±12 V]. The need to install the power converters underground requires considerably reduced dimensions and high efficiency. Moreover, the LHC machine demands a very high level of performance from the power converters, particularly in terms of DC stability, dynamic response and also with regard to Electromagnetic Compatibility (EMC). The outstanding feature of four-quadrant [±600 A, ±12 V] power converter is its high regulation precision. The converter module is 6U high and fits into a 19” rack and is thus very compact.

2 POWER CIRCUIT DESIGN

To meet the LHC requirements, soft-commutation switch-mode techniques will be used [3].

The chosen topology for the [±600A,±12V] converter is described in three parts

- Part 1: Circuit-breaker and contactor together with a soft-start circuit, a three-phase six-pulse diode rectifier on the AC mains (400V) with a damped L-C passive filter having a resonance frequency of about 40 Hz.
- Part 2: Full-bridge Zero Voltage Zero Current Switching Phase Shift Inverter (FB-ZVZCS-PS) at 30kHz, high frequency transformers, rectifier stage and 4th order L-C output filter.
- Part 3: Bipolar Linear Output Stage (BLOS)., Controlled high-current linear amplifier stage with paralleled MOSFETs for realisation of smooth zero crossing of output current.

Figure 1 shows the block diagram of the 4-quadrant converter.

2.1 *Zero Voltage Zero Current Switching Chopper*

The 3-phase mains voltage is rectified and smoothed. The resulting DC intermediate voltage feeds the DC/DC chopper operating at 30 kHz. This stage employs a "phase shifting" switching mode inverter (ZVZCS = **Z**ero **V**oltage / **Z**ero **C**urrent **S**witching) and provides a

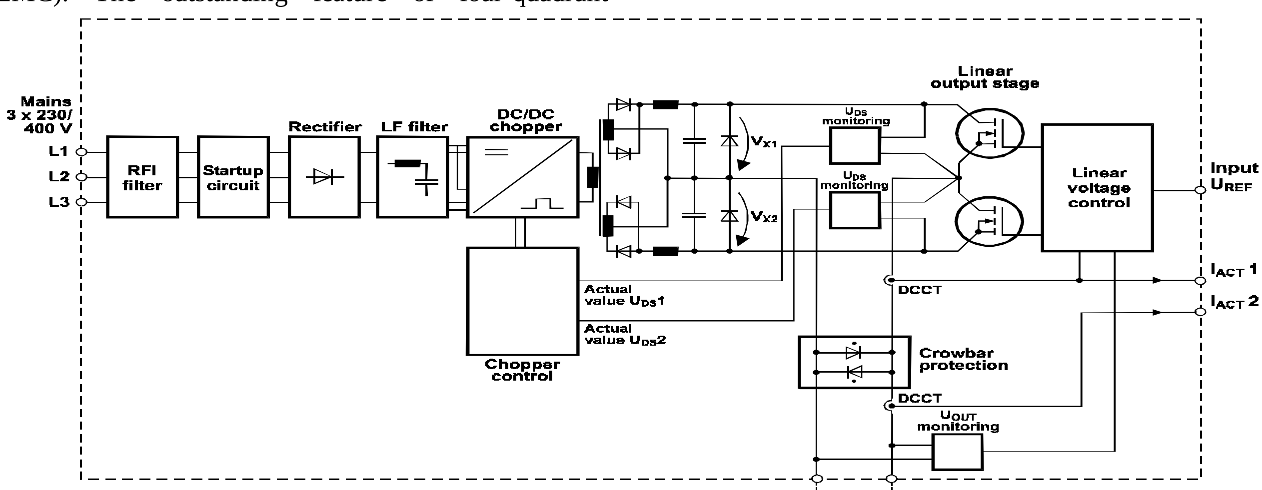

Figure 1 : [±600A,±12V] Power converter block diagram

stabilized, electrically isolated, bipolar, variable output voltage. The control of the power semiconductors (IGBTs) is done, instead of turning off the diagonally opposite switches in the bridge simultaneously as for a classical PWM, by introducing a phase shift between the two legs of the bridge. This phase shift determines the output power whereas the switching frequency is fixed to 30 kHz. The needed energy to achieve soft-commutation conditions for the switching of the leading leg (ZVS) comes from the series inductance, the leakage inductance and the output filter inductance. This means that the energy stored is very large to charge and discharge the parallel switch capacitances (parasitic and snubbers) and the parasitic capacitances of the transformer. By using a dc blocking capacitor and a saturable inductance, the primary current is reset during the freewheeling period, which provides ZCS conditions for the lagging-leg switches.

2.2 Bipolar Linear Output Stage

The chopper's output filter has to filter a 60 kHz square wave to obtain a 4mVrms output voltage ripple and it is designed as a two stage, 4th order filter.

The two choppers' outputs are used as supply voltages for the two halves of the complementary final output stage BLOS (**B**ipolar **L**inear **O**utput **S**tage). The BLOS is used for feeding or discharging the coils of the superconducting correction magnets of the LHC with a high-precision current and a very precise crossing of zero current. In order to keep the losses down in BLOS to a reasonable level during energizing of the superconducting magnet, the drain-source voltage (Vds) of the active MOSFET is monitored and kept constant at about 2 volts. The duty cycle of the inverter is controlled to maintain constant Vds voltage.

The energy stored in the superconducting magnet (maximum inductance is 570mH) is dissipated in the BLOS and in the cable resistance (minimum resistance is 2.8mΩ). The DC/DC chopper is then switched off, the energy discharged through the linear power stage and a free-wheeling diode connected across the output of the DC/DC chopper.

A soft zero-crossing without discontinuity is realised by a regulated constant bias current flowing through both halves of the BLOS.

An electronic device assure a safe path for the magnet current at any fault. The device is constituted of two back-to-back thyristors, called crowbar. One of them turns on if an over-voltage (>20V) appears at the converter output. The triggering of the crowbar is completely autonomous and does not need any auxiliary voltage.

2.3 Control loops

The outstanding feature of the four-quadrant [±600 A, ±12 V] power converter is its high regulation precision. The device provides a DC output voltage which is extremely accurate, follows a predefined reference value without delay and boasts an extremely low output ripple in the mV range.

The converter itself works as a voltage controlled voltage source which is inside CERN's highly accurate current control loop. This loop makes use of precise current transducers (DCCTs), to get a current accuracy in the 100 ppm range.

The DC output voltage is adjusted by the Bipolar Linear Output Stage (BLOS) according to the given reference value by CERN, which is an inner control value of the outer current control loop.

To obtain a smooth zero crossing all MOSFETs, both the active and the passive branch, are held in a conductive state by an additional bias current control loop. This avoids the occurring jump in the gate voltage of the MOSFETs just beginning to conduct current. This loop makes use of two current transducers, which measure the current through each branch. The regulator takes the minimum of both signals as actual value and adjusts the driving voltage for the MOSFETs to maintain a constant circulating bias current of about 10 Amps in the BLOS.

3 MECHANICAL DESIGN

The four-quadrant converter [±600 A, ±12 V] is designed as a 6 U module inserted in a 19"rack and is thus extremely compact. The weight of one power module is 65 kg. To allow easy insertion and extraction, which can be done by one operator, it is placed upon a special drawer system (cf. photo 1). Once withdrawn, it can be carried by two people using the hinged side handles.

Two complete power converters, each including a power module, an output circuit with two DCCT, the crow-bar protection, and two 6U CERN electronics chassis are housed in one 19" rack with a total height of 2 meters.

The water distribution system with valves and flow

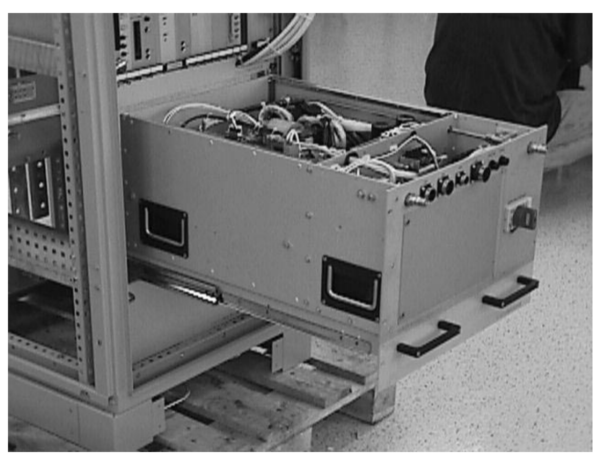

Photo 1 : [±600A,±12V] converter; 6U module meter and an input EMI filter are placed at the bottom of the rack. Each power module is supplied with cooling water independently and are thus fully independent. Before un-plugging a module, only the signal cables to the CERN electronics and the water inlet and outlet have to be removed with self-sealing connectors directly on the front panel. The output bus bars for the connection to the magnets are placed at the rear side of the rack and the connection to the magnet can be made either at the top or at the bottom of the rack.

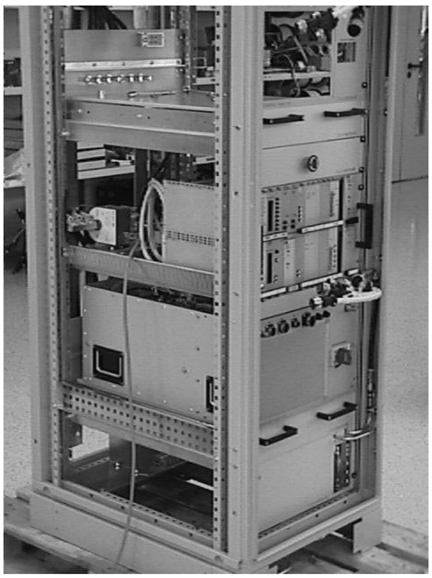

Photo 2 : 6U module inserted in a 19"rack

4 PERFORMANCE

The measured efficiency is 75% at full power and 70% at half power. Most of the main losses are coming from the linear output stage (~65% of the losses).

The measured output voltage ripple is less than 1 mVrms in the 50 - 300Hz frequency band and less than 2mVrms at the switching frequency and its harmonics (Figure 2 and 3).

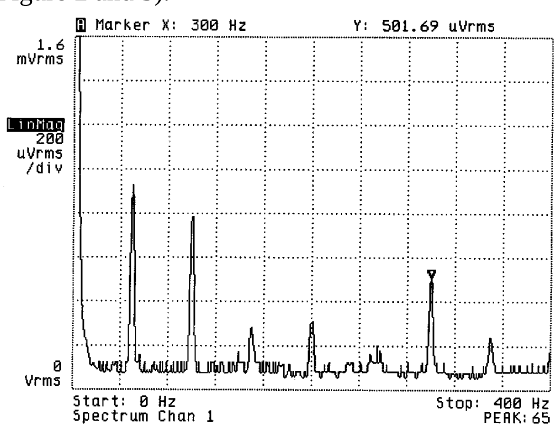

Figure 2: Spectrum Analysis : 0 – 400 Hz

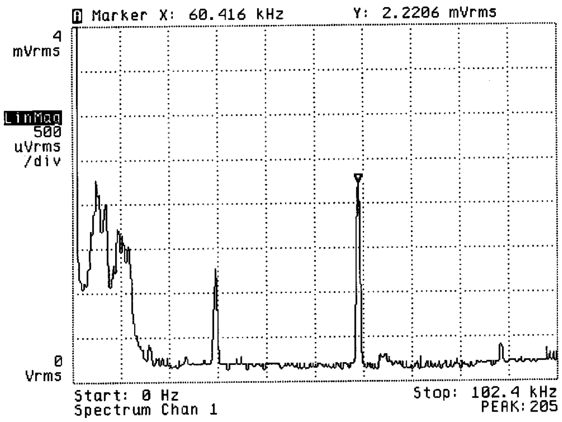

Figure 3: Spectrum Analysis : 0 – 100kHz

The noise emission (EMI) is in compliance with the IEC478-3, curve C (1mV above 0.5 MHz).

Figure 4 presents the zero-crossing of the output voltage with a 0.1Hz sine voltage reference

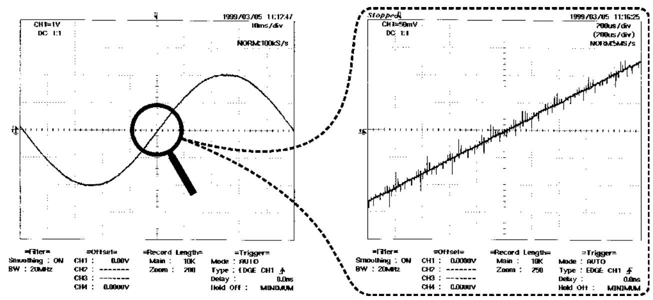

Figure 4: Output-Voltage Zero Crossing

5 CONCLUSION

The performance requirements have been achieved under the severe constraint of small volume. Especially, zero crossings of the output current without discontinuity, i.e. true 4-quadrant operation and extremely low output voltage ripple of lower than 1 mVrms at 300 Hz and of lower than 2 mVrms at the switching frequency of 30 kHz and its harmonics have been realized. This [±600A,±12V] converter can be considered as a full-size LHC prototype. Six converters are built by Transtechnik according to CERN's specification and will be used intensively for the LHC magnet tests.

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