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High Current, Low Voltage Power Converter [20 KA,6V] LHC Converter Prototype

H.E. Jorgensen*, F. Bordry**, A. Dupaquier**, G. Fernqvist**

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The superconducting LHC accelerator requires high currents (~12.5kA) and relatively low voltages (~10 V) for its magnets. The need to install the power converters underground is the driving force for reduced volume and high efficiency. Moreover, the LHC machine will require a very high level of performance from the power converters, particularly in terms of DC stability, dynamic response and also in matters of EMC. To meet these requirements soft-switching techniques will be used. This paper describes the development of a [20kA,6V] power converter intended as a stable high-current source for DCCT calibration and an evaluation prototype for the future LHC converters. The converter is made with a modular concept with five current sources [4kA,6V] in parallel. The 4kA sources are built as plug-in modules: a diode rectifier on the AC mains with a damped L-C passive filter, a Zero Voltage Switching inverter working at 20 kHz and an output stage (high frequency transformers, Schottky rectifiers and output filters). The obtained performance (DC stability, bandwidth, efficiency, EMC,...) is presented and discussed.

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HIGH CURRENT, LOW VOLTAGE POWER CONVERTER [20KA,6V] LHC CONVERTER PROTOTYPE

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Abstract

The superconducting LHC accelerator requires high currents (~12.5kA) and relatively low voltages (~10 V) for its magnets. The need to install the power converters underground is the driving force for reduced volume and high efficiency. Moreover, the LHC machine will require a very high level of performance from the power converters, particularly in terms of DC stability, dynamic response and also in matters of EMC. To meet these requirements soft-switching techniques will be used. This paper describes the development of a [20kA,6V] power converter intended as a stable high-current source for DCCT calibration and an evaluation prototype for the future LHC converters. The converter is made with a modular concept with five current sources [4kA,6V] in parallel. The 4kA sources are built as plug-in modules: a diode rectifier on the AC mains with a damped L-C passive filter, a Zero Voltage Switching inverter working at 20 kHz and an output stage (high frequency transformers, Schottky rectifiers and output filters). The obtained performance (DC stability, bandwidth, efficiency, EMC,...) is presented and discussed.

1 INTRODUCTION

The LHC accelerator requires large currents and rather low voltages for its superconducting magnets. The installation of the power converters on the surface and the cabling to their underground magnets would be prohibitive because of the high DC currents. The underground installation is the driving force for reduced volume and high efficiency of the power converters.

A provisional list of power converters is given in the LHC Conceptual Design book [1].

The main requirements for the LHC converters are:

- high precision (<10 ppm)
- drastic reduction of the volume and weight due to the underground installation. All the power converters must fit in the existing underground LEP infrastructure.
- high efficiency (> 80% for the unipolar converters and > 70% for the bipolar converters).
- water cooling of the converters is mandatory.
- galvanic isolation between mains and output
- wide output current range (Imax/Imin ~ 50)
- very high reliability and operational redundancy; access to the underground will take a long time.
- repairability. All converters must be designed with fast plug-in modules. The weight of each module must not exceed 25 kg to permit one operator to do a fast exchange.

An important type of converter covers the need for the main quadrupoles, the insertion quadrupoles, the separators, etc. The output specifications are [13kA, 16V], [13kA, 8V], [9kA, 8V] and [6kA, 8V]. Taking into account that the state-of-the-art for DC-DC power converter modules is in the range of 30 to 50 kW, these converters will be made up using a modular concept where several high-current sources ([3.25kA, 16V],[3.25kA, 8V] or [2kA, 8V]) are placed in parallel; this concept can also provide redundancy.

The LHC will require an unprecedented precision of a few ppm in the control of current in the major magnetic circuits [2]. A precision current transducer, usually a Direct-Current Current-Transformer (DCCT), measures the output current of the power converters. To evaluate these high current DCCT, a program was launched to build a new facility at CERN that will enable full evaluation of DCCT's up to 20kA (figure 1).

A very stable [20kA,6V] high current source was needed. To acquire experience for the future LHC converters, the specification for this converter was defined complying with all the main LHC power converter requirements. To validate the modular concept, it was decided to build the converter from five [4kA,6V] power units.

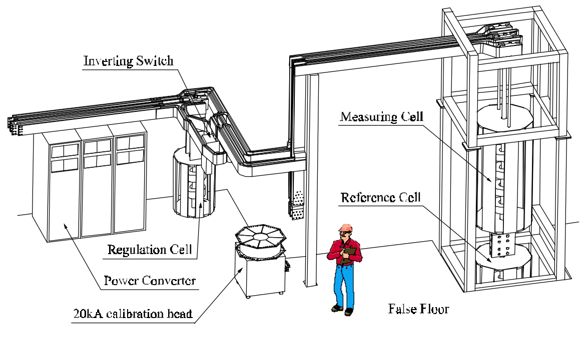

Figure 1: 20kA testbed for DCCTs.

For the DCCT calibration application, the load of the converter is mainly resistive (only 7μH inductance). Due to this fact the voltage ripple has to be extremely low (250μV at 300Hz) to get a 1ppm current ripple

2 [4KA,6V] POWER UNIT

To meet the LHC requirements, switch-mode techniques will be used [3]. The chosen topology for the [4kA,6V] converter is split in three modules [4]:

- Module 1: a diode rectifier on the AC mains (400V, 50Hz) with a damped L-C passive filter (60Hz)

- Module 2: Full-bridge Zero Voltage Switching Phase Shift Inverter (FB-ZVS-PS) at 20kHz
- Module 3: high frequency transformers, rectifier stage and output filter. To fulfil the weight constraint, the module 3 is physically split in four modules of 1kA (Photo 1).

A 4kA power unit occupies one half side of a standard 19 inch rack. For EMC reasons a vertical iron sheet acts as common ground plane for the six modules.
All the 6 modules are water-cooled. To extract a module from the rack, two quick fit cooling water connectors have to be removed and one primary power connector.

2.1 *Inverter module: Zero Voltage Switching*

The control of the power semiconductors are such that, instead of turning off the diagonally opposite switches in the bridge simultaneously as for a classical PWM, a phase shift is introduced between the two legs of the bridge. This phase shift determines the output power and the control is made at fixed frequency [5]. For the switching of the leading leg, the energy for the parallel switch capacitances (parasitic and snubbers) and the parasitic capacitances of the transformer, comes from the series inductance, the leakage inductance and the

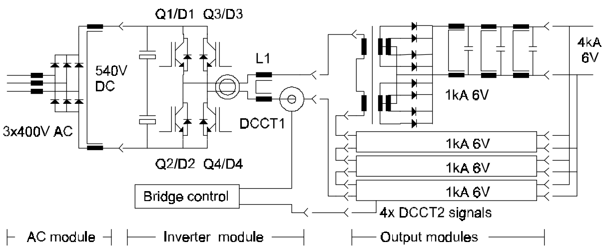

Figure 2: [4kA,6V] power unit

output filter inductance. This means that the energy stored is very large. For the lagging leg, the zero-voltage turn-on is achieved by using only the energy stored in the series inductance ("soft commutation inductance") and the leakage inductance of the transformer. Therefore, the soft-switching condition is lost for low load currents. Due to the unsymmetry between the two legs, the lossless snubbers do not need to have the same rating. It is more optimal to reduce the turn-off losses by using larger capacitances in the leading leg than in the lagging leg. The rating of the soft-commutation inductance is the result of a compromise: a large inductance results in a small effective duty cycle (slope of the rising and falling edges of the primary current) but ZVS is achieved over a greater current range.

For the [4kA,6V] power unit, the soft-commutation inductance was rated to have an effective duty cycle of 80%. Without any added capacitance snubbers across the IGBTs, the ZVS is lost for a current equal to around 30% of the maximum current. At full power, the losses for one IGBT are: 230W for the turn-off losses (140W for the tail losses), and 70W for the conduction losses. The total losses for the four IGBTs are 1200W.

To improve these losses and to keep the soft-commutation over the whole current range, passive poles could be added; these poles permit to add large snubbers to reduce the turn-off losses [6].

2.2 *Output module*

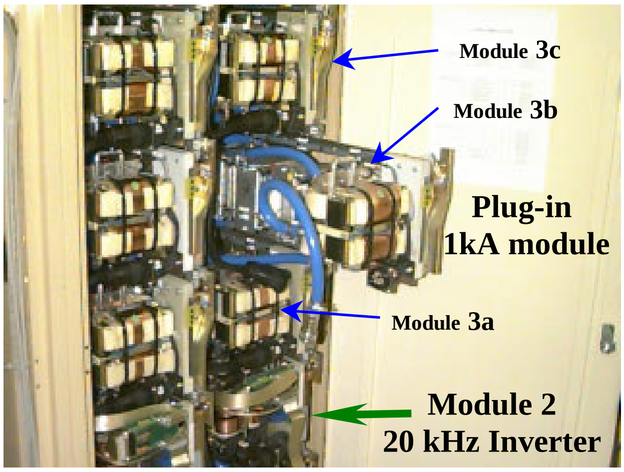

Photo 1: Rack with two power units

The HF transformer is made using two standard U-shaped cores and two standard coil formers. Copper foil is used for both primary and secondary windings. Due to the high output current and low voltage, the secondary of the HF transformers consists of two centertapped windings, which are connected to Schottky diodes Two rectifiers are connected to each coil giving a total of 8 diodes and 250A peak / 125A average per diode.

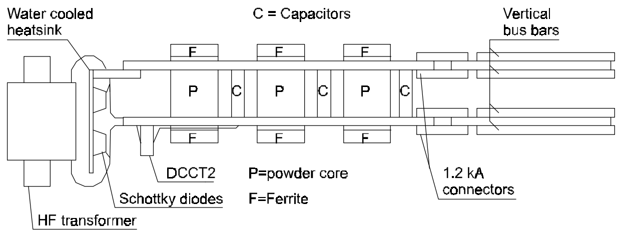

Figure 3: [1kA,6V] module

The terminals of the secondary of the HF transformer are interleaved giving a very strong coupling between the center-tapped secondary. The result is that the induced voltage spike seen when a rectifier diode is switched off can be eliminated with a single RC network between the two anodes of each dual rectifier.
The output filter has to filter a 40kHz square wave to obtain 1mV$_{rms}$ and it is made as a three-stage LC filter for each 1kA module. The practical solution is two straight 10*80*350mm copper bars with 3 blocks of ferrite used as inductors. The use of discrete air gaps could result in power dissipation due to proximity effects in the first inductor. For this reason the central block is made from a low μ powder core (cooled). Aluminum brackets clamp the ferrite slabs together and they also reduce the stray field to the environment.

2.3 Control loops

A small current transducer (DCTT1 in figure 2) is used to measure the primary current of the transformers. A peak detector switches off the bridge every half cycle at the selected value leaving the current in the inductor circulating for the rest of the half period. This system eliminates any DC offset in the primary current, which would saturate the transformer.

The ZVS phase-shift converter behaves as a voltage source. A fast voltage loop gives a high rejection at low frequency (more than 30dB at 300Hz). From a series connection of one turn on each of the four output transformers, an electronic circuit gives the true averaged voltage output with a 40kHz resolution. The bandwidth of the voltage loop is 10kHz (the sampled signal is delayed up to one half cycle).

Finally, the power unit is current controlled to permit paralleling of several units. The compact construction makes it impossible to measure the full 1kA output current but a fraction is measured by means of DCCT2 (figure 3) connected to a copper foil in parallel with a part of one of the filter bus bars. About 12 A is measured and the relative accuracy between the rectifiers is within a few percent. The output current from each of the four small DCCT's in a converter is compared with the average of the four currents. If one current deviates more than 10% from the average it indicates an error and the converter shuts down but the system continues with the remaining converters. If the current is below a preset

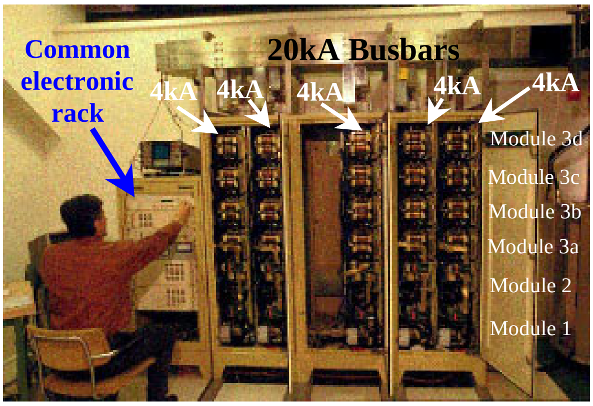

Photo 2: [20kA,6V] power converter

negative value it indicates an error that results in current from the converter system going into the rectifier circuit. To avoid a fire hazard a "global off" command is then issued to all parallel connected converters.

3 PARALLEL OPERATION

Each [4kA, 6V] power unit is current regulated and the necessary number can be parallel connected to achieve the desired output current. A common voltage control is used giving 6V on the output terminals for 6V control input. A high stability current loop is implemented using a precision 20kA DCCT [2].

The redundancy is achieved when there is one converter more than needed: one or several units can switch off without affecting the operation (bandwidth of the fast current loop at 1kHz).

4 PERFORMANCE

The operating range of current is from 1% to 100% of the 20kA maximum current. The measured efficiency is around 80% at full power and 70% at half power. Obviously the main losses are coming from the output rectifiers (0.55V*20kA).

In terms of performance, the main problem was the rejection of the low frequency ripple (mainly 300Hz) with the paralleling of several converters, which behave as voltage sources. The control loop design should take this into account to avoid any beating between the paralleled converters. The measured output voltage ripple is 220µVrms for 300Hz frequency and 1mVrms for the switching frequency (2*20kHz) and its harmonics. The noise emission (EMI) is in compliance with the IEC478-3, curve C (1mV above 0.5 MHz).

5 CONCLUSION

The performance requirements have been achieved and especially the challenging output voltage ripple value (250µVrms). This [20kA,6V] converter can be considered as the first full-size LHC prototype. For the test of the LHC superconducting cable, 32kA (8*4kA) and 16kA (4*4kA) similar converters have been built and are being commissioned.

Although the voltage ripple for the LHC magnets is less severe (around 3mVrms), the paralleling of converters is the key point and it must be taken into account in the first design phase.

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