FOUR QUADRANT 60 A, 8 V POWER CONVERTERS FOR LHC

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Abstract

The LHC (Large Hadron Collider) particle accelerator requires many true bipolar power converters (752), located under the accelerator dipole magnets in a radioactive environment. A special design and topology are required to obtain the necessary performance while meeting the criteria of radiation tolerance and compact size. This paper describes the ±60A ±8V power converter, designed by CERN to meet these requirements. Design aspects, performances and test results of this converter are presented.

MAGNET LAYOUT

LHC accelerator requires 376 pair of horizontal and vertical arc orbit corrector magnets. These pair magnets are superconducting and installed at each focusing and defocusing main quadrupole; see Figure 1.

They are designed to achieve a maximum kick at a nominal current of 55A. These magnets can be adjusted independently which requires individual powering.

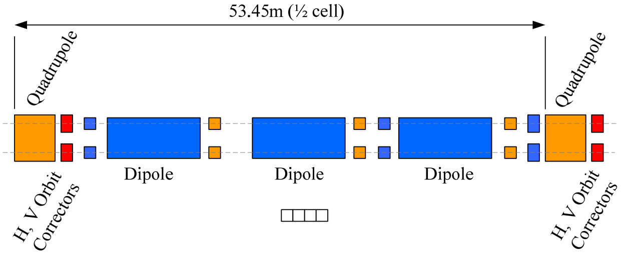

Figure 1: Orbit corrector circuit layout.

POWER CONVERTER ENVIRONMENT

Due to the distribution of the orbit corrector magnets around the machine and to limit the power losses in the cable and so reduce the total converter power required, the converters are installed close to their load. However a drawback of placing the converters in the vicinity of the load is the restricted access and the radioactive environment. This implies that the converters demand a high reliability, fast exchange and radiation hardened devices. The underground installation is the driving force for reduced volume and high efficiency of the converters. The main characteristics of the orbit corrector circuits are defined by the Table 1.

Table 1: Orbit corrector circuit rating

Magnet Inductance [H]	Rcables Typical [mOhm]	τ [s]	|I| [A]	|dI/dt| [A]	Magnet Energy [kJ]
6.02	50	120	55	0.5	9.1

POWER CONVERTER REQUIREMENTS

True bipolar converters are required to manage the high energy of the load ($1/2.L.I^2$) in both directions. Furthermore, high resolution and stability are required for the current delivered by the power converter. This requires a low output voltage ripple with low EMC level to ensure a clean environment for high precision current sensors.

A safety device, named Crowbar, is required to withstand the magnet energy in case of a power converter failure and guarantee a path for the current. The current decay time has been kept deliberately long to allow sufficient time for the LHC orbit feedback to react, so preventing a beam dump due to excessive orbit excursions (operational redundancy).

POWER CONVERTER DESCRIPTION

Power Converter Item description

A LHC Power Converter is defined by Figure 2:

- High Precision Electronics (called FGC as Function Generator Controller), implementing a digital high precision current loop. The FGC is also in charge of communication through the WordFip bus with the CERN Control Center (CCC).
- DC Current Transducer measuring the output current. By using two DCCTs, the reliability and precision of this information is improved.
- Power Voltage Source, that amplifies the reference signal sent from the High Precision Electronics into a high power voltage output [±8V, ±60A].

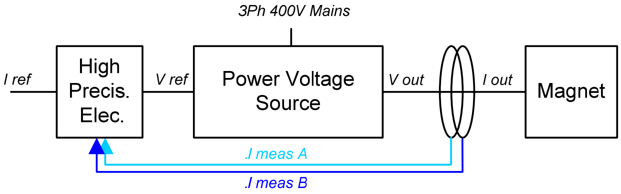

Figure 2: LHC power converter.

Power Converter Mechanical layout

The power converters are installed in horizontal frame under the dipole cryostat (lower radiation), housing up to four converters, powering on each side one pair of horizontal and vertical orbit corrector magnets; see Figure 3. The interfaces between the frame and the converter have been minimized for fast intervention; no electronics are installed inside the frame. All the connections are done from the front side of the converter module. To avoid disconnecting the power converter from the load with current, a contact on the DC cable side is added to short-circuit the voltage output terminals as soon as the connector is disconnected from the module, assuring a safe path for the magnet current.

Figure 3: LHC60A frame under dipole cryostat.

Due to their locations, the power converters are as compact as possible (6U height, 480mm width, 360mm depth) and portable (25kg); see Figure 4. The signals, exchanged between the High Precision Electronics and the Power Voltage Source, inside the converter, are connected through a backplane reducing the wiring. The power part (Voltage Source) is mounted around a cubic heatsink, cooled by fans for compactness.

Figure 4: LHC60A-8V power converter.

Voltage Source Design

Switch-mode technology has been chosen due to the reduced volume and weight constraints, and the requested low ripple at the output of the converter.

Figure 5 shows the converter topology. The topology includes:

- mains rectifier stage with a magnetic and thermal protection, a three-phase six-pulse diode rectifier, the necessary filtering on the AC and DC sides and a static relay circuit. The aim of this circuit is to limit the inrush current, protect the inverter stage by isolating the mains from the inverter stage in case of fault. This circuit is based on a power MOSFET, which has been preferred to an electromechanical contactor for a better reliability.
- An inverter stage using a ZVS soft-commutated full bridge with IGBT switching at 100 kHz.
- A high frequency transformer for insulation and voltage adaptation. The transformer is based on planar technology for reproducibility and gain in volume.
- A bipolar output stage providing reversal of the polarity and the fine control of the output voltage. It is based on two power MOSFETs controlled in linear mode. The magnet energy, during the ramp-down of the current, is dissipated by these MOSFETs. The main difficulties of this topology are: the non linearity of the MOSFETs used over a wide R_{DSON} resistance working area; and an output voltage distortion around 0A. To improve this, at low output power, the two MOSFETs are forced to always conduct to ensure a circulating current, limiting the working area of the MOSFET and increasing the load of the inverter.
- An output circuit with the crowbar device, two DCCT transducer heads and the earthing circuit.

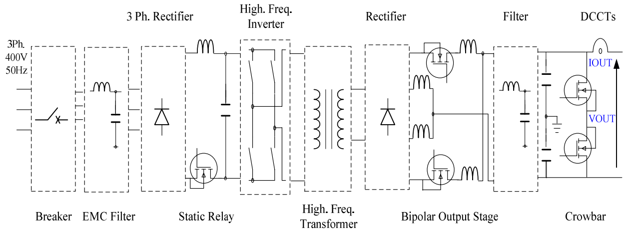

Figure 5: Converter topology.

Crowbar Design

The strategy for the current discharge is to use both the bipolar output stage and the crowbar device. Nevertheless, the crowbar must assure a safe path for the magnet current even if the bipolar output stage is open due to an internal fault. This device does not need auxiliary power supply, making it autonomous in case of simultaneous mains failure. To keep the same time constant with and without the bipolar output stage, the reference of the bipolar output stage is clamped to 1.12V during a stop of the converter.

The crowbar is constituted of two bidirectional power MOSFETs in anti-series. The crowbar turns on when the converter is stopped and/or an over-voltage of 12.2V appears across the voltage source output terminals. The dV/dt has been limited in case of fault by adding differential capacitors.

Radiation Design

Radiation has an adverse effect on electronics and some technologies are more vulnerable than others (programmable devices, digital logic, semi-conductors, optocouplers, tantalum capacitors). The expected dose and hadron fluence (E>20MeV) have been estimated to be respectively 1 Gy and $4x10^{10}cm^{-2}$ per year. The power converters are designed taking into account this consideration, pre-selecting COTS candidate components. Radiation test campaigns on sub-systems have been performed to validate the hardness of such devices under radiation environment. Memories used inside the High Precision Electronics (FGC) are protected by an Error Detection and Correction (EDAC) systems. Tests conducted at CERN and at a Belgian cyclotron facility have demonstrated an acceptable tolerance to the dose and fluence predicted for the LHC tunnel.

Spare Strategy

The MTBF of the power converters has been estimated to be 100’000 hours. Considering the 752 converters in operation over the LHC machine, one converter will fail every 5.5 days. The LHC is however designed to work with 2-4% of orbit corrector converters out of operation (15-30 converters). A two to three monthly campaign is scheduled for the replacement at the same time of the faulty converters; nevertheless, critical cases will have to be replaced immediately. To make this strategy possible, at least 10% of the total quantity of converters must be kept as operational spares.

TEST RESULTS ON LHC MAGNETS

The production of the converters has been carried out by industry throughout the CERN member states. 752 power converters are now installed all around the LHC machine. Tests on the orbit corrector superconductive magnets are on going. Results are presented below:

Voltage Output Ripple

The switch-mode technology allows a low output voltage ripple, never higher than 1.5Vrms.

Figure 6 shows the low voltage common mode noise over 9kHz to 30MHz frequencies range, below 60dBµV.

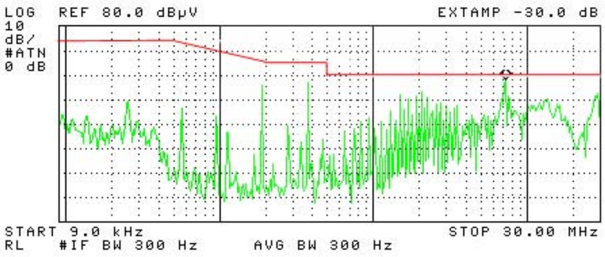

Figure 6: Common mode voltage.

Four-quadrant Operation Performance

Figure 7 shows a current cycle crossing the different quadrants without any major distortion.

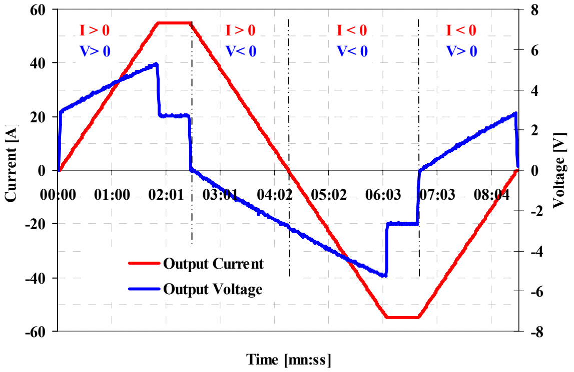

Figure 7: Current cycle.

Crowbar Performance

Figure 8 shows the current sharing between the bipolar output stage and the crowbar device during a discharge. Note that the discharge time decay time is long to keep a chance for the LHC orbit feedback to react to an orbit corrector fault.

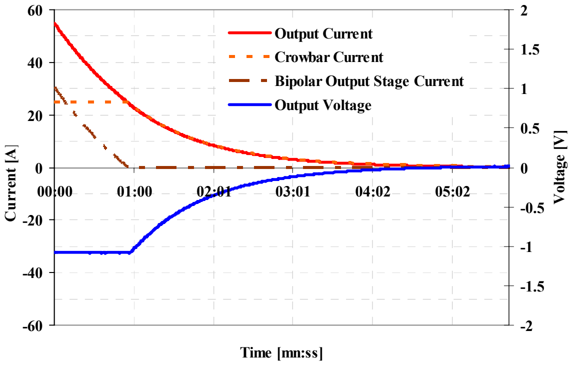

Figure 8: Crowbar performance.

Output Current Noise

Figure 9 shows the typical noise measured at +55A. Output current noise is less than 3mA peak-peak (50ppm peak-peak). This includes both DCCT and digital High Precision Electronics (FGC) noise up to 1kHz frequency.

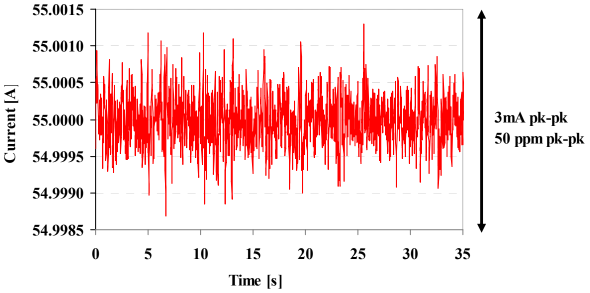

Figure 9: Output current noise.

Stability over ½ hour at +55A gives less than 0.3mA (5ppm) over 1mHz to 0.1Hz frequencies range.

CONCLUSION

282 out of 752 converters have been tested on the orbit corrector superconductive magnets. First results obtained demonstrate that the converters fulfill the requirements. The first data show a good reliability of these power converters.

The start of LHC accelerator operations will determine the level of reliability of these power converters, used extensively around the LHC machine and will provide the first opportunity to check the behaviour of the converter in its radioactive environment.

REFERENCES

[1] F. Bordry and A. Dupaquier, “High Current, Low Voltage Power Converters for LHC. Present Development Directions”, EPAC’96, Sitges, June 1996, MOP0009G, p. 2314 (1996); http://www.JACoW.org.