FOUR QUADRANT 120 A, 10 V POWER CONVERTERS FOR LHC

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Abstract

The LHC (Large Hadron Collider) particle accelerator makes extensive use of true bipolar power converters, with a high precision regulated output current requirement. A special design and topology is required to allow high performance within the converter operating area, including quadrant transition. This paper presents the ±120A ±10V power converter, well represented in the LHC power converters (300 units). The design is adapted for a wide range of magnet loads [from 10mH to 4 Henry] (time constant load [0.1s..1050s]) with stringent EMC requirements. A quick-connect system was applied to the converter modules allowing easy installation and maintenance operations. Discussion of 4 quadrant control and practical results are presented.

INTRODUCTION

A four quadrant power converter design is very specific, since power has to be handled in both directions with regard to the load. If electrical considerations are crucial, considerations related to its integration in LHC environment (inside a tunnel located at 100m below ground level) also strongly orientated design choices, as well as the high energy which can be stored in the magnet that must be safely handled.

POWER CONVERTER ENVIRONMENT

LHC machine requires up to 1700 power converters feeding superconductive power magnets. These magnets are rated from 60A up to 13kA, and from some mHenrys up to 15 Henrys, depending on their function in the geometric action on the beam (bending, correcting, squeezing). These levels of current flowing in such magnets lead to a high stored energy (1/2.L.I²).

On the other hand, the delivered output current of the Power Converters shall be very precise. Current precision for all power converters are in the range of 1 ppm up to 50 ppm (ppm: part per million) depending on magnet types.

Another constraint comes from the location of the power converter down into the tunnel caverns. To limit cables losses and therefore mains required power, power converters are installed in caverns close to the beam tunnel.

Design has therefore to be set according to a quick removal capability of the - potentially faulty - power module. This constraint was applied to almost all power systems and can be summarized by a plug-in module conception, separating the power converter into sub-parts to minimise weight and size of the removable units.

120A MAGNET FAMILY OVERVIEW

Magnet Family characteristics

Table 1 provides the main 120A magnet characteristics. It can be seen that load family is very wide (300 magnets in total), and thus has an impact on the characteristics of 120A Power Converter Family.

Table 1: 120A Magnet Family

	L [H]	R [Ohm]	τ [s]	|I| [A]	|dI/dt| [$A.s^{-1}$]	E [J]
Min	0.003	0.005	0.035	0	0	18
Max	5.27	0.092	1044	110	1	17 000

Power Converter characteristics (deduced)

A very low voltage ripple is then required (being a current ripple in respect to the – sometimes very low - impedance of the load), with an extra low EMC level to ensure a clean environment for high precision current sensors.

A safety device (called "crowbar") is also required to handle magnet energy in case of power module failure or accidental removal of the power module with current still present in magnet. It is based on a bi-directional thyristor design being fired at a given voltage threshold.

POWER CONVERTER DESCRIPTION

Power Converter Items description

A CERN LHC Power Converter is defined by Figure 1:

- High Precision Electronics (called Function Generator Controller), implementing a digital high precision current loop. The FGC is also in charge of communication through the WordFip bus with CERN Control Room.
- 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.

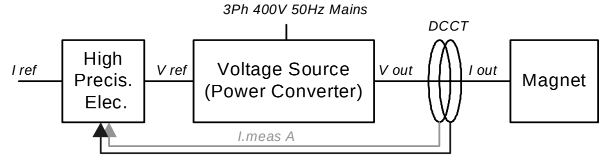

Fig. 1: LHC Power Converter.

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This power converter design allowed the separation and paralleling of development, contract and production phases. It also limits number of families of each item. For example, 2 FGC families are used for the LHC, and the quantity of power voltage source types only has been limited.

Mechanical Layout of 120A Power Converter

120A Power Converters (300 units) are designed to be arranged with up to four units per single 19"x 2m height rack. Air forced cooling is preferred to expensive water cooling. The optimised final arrangement - also strongly maintenance orientated - nevertheless resulted in a non-ideal electrical solution; the DCCTs are placed before the protection device (crowbar, usually a highly capacitive device), and thus do not measure directly the magnet current. Figure 2 shows the final arrangement.

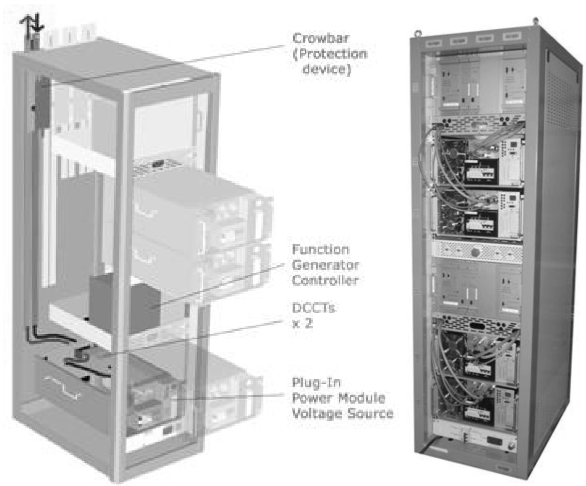

Fig. 2: LHC120A-10V Rack.

The crowbar that also includes the EMC output capacitors was then designed to fulfil both the safety requirements, and the necessity to be transparent to the high precision control loop.

VOLTAGE SOURCE POWER MODULE DESIGN

A high frequency (in the range of [50kHz..70kHz]) switching solution is required to obtain a low volume and low weight 1.2 kW power module. Nevertheless, four quadrant capability was obtained using a dissipative power Mosfet based linear stage to avoid high frequency ripple and high EMC level. The EMC Standard IEC478-3 was imposed on the AC and DC side, that is in the order of some mV_{RMS}, both in common and differential mode, from [9kHz..30MHz]. The low noise range was also extended into the low frequency area [50Hz..10kHz].

The output stage is powered by a symmetrical dual output voltage phase shifted converter. Figure 3 shows a simplified schematic of the power converter.

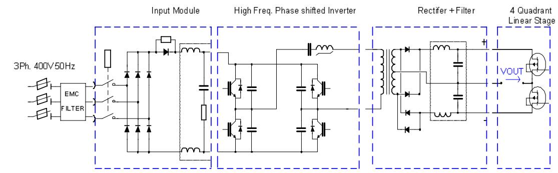

Fig. 3: Voltage Source Power Converter topology.

The main difficulties with such an output linear solution are typically:

- 0A output current transition usually resulting in an output voltage distortion. This distortion comes from main voltage loop step control voltage applied to the gate of the Power Mosfet.
- Control of a highly non linear transistor (Power Mosfet), used over a wide R_{DSON} resistance range.

Figure 4 illustrates circulating current (Icc) principle solving described problems.

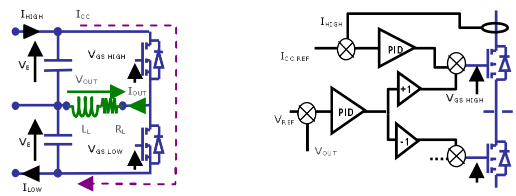

Fig. 4: Circulating Current Principle.

The circulating current control loop:

- Limits the range over which the MOSFET is required to operate, and therefore limits d(R_{DSON}) / d(V_{GS}). See Figure 5.

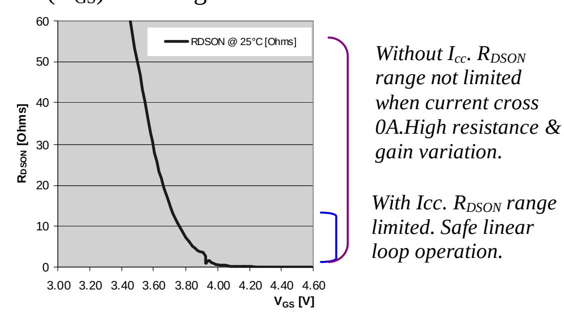

Fig. 5: MOSFET R_{DSON} gain vs V_{GS}.

- Ensures the MOSFET is always conducting and thus avoids a step voltage at the level of gate, hence avoiding any distortion at the output voltage.

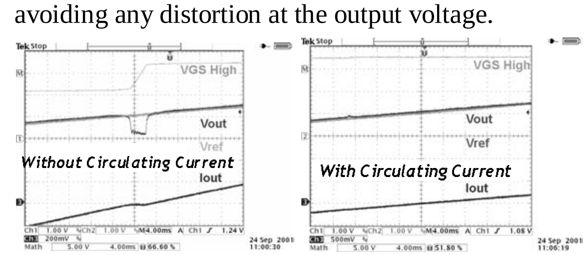

Fig. 6: Circulating current effect.

- Can also be used to load the inverter at a minimum required level to maintain a continuous level current in the high frequency output inductor.

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The circulating current topology adds complexity (up to three control loops are to work together with high margin criteria required by the wide range of different loads), and the start-up sequence must also be carefully managed.

CROWBAR DESIGN

The design of this crucial element was made to limit the differential capacitors generally used to clamp the dV/dt initiated by a superconductive magnet current source. This protection device also includes earth protection and magnet current lead protection. Figure 7 shows crowbar film capacitors (10µF in total in differential mode) used in the design, limiting the dV/dt at 12V/µs, requiring a very fast trigger and power action from the crowbar.

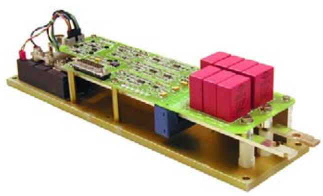

Fig. 7: LHC120A-10V Crowbar.

1ST TEST ON LHC MAGNETS

Power converters were produced by the company EFACEC (Portugal). The production has resulted in a very high quality product, which was tested in 2007 on a variety of different superconductive magnets. Figure 8 shows a LHC120A-10V Voltage Source Power Module (top cover being removed).

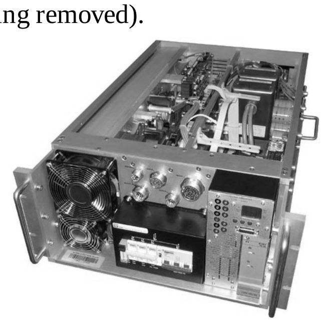

Fig. 8: LHC120A-10V Power Module.

Output noise

The chosen topology makes it possible to obtain a low noise at the output of the power converter. In the frequency range [50Hz..10MHz], the output noise is never higher than 1.7mVrms, in differential mode and common mode. See Figure 9 focusing on EMC differential noise in the standard range [9kHz..30MHz].

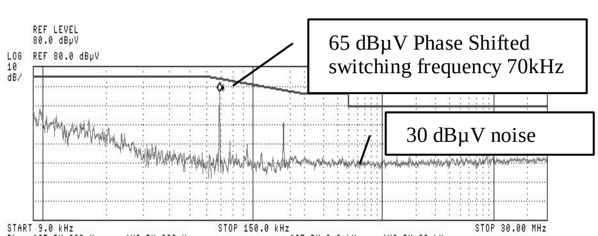

Fig. 9: Differential mode output voltage noise.

Crowbar validation

A transfer function analysis was performed (Figure 10) to validate that the crowbar does not affect the load impedance that is controlled by the FGC. A typical result can be seen on Figure 10 – 2.8H magnet (closed current loop up to 1Hz, with the influence of the crowbar being visible above 10Hz).

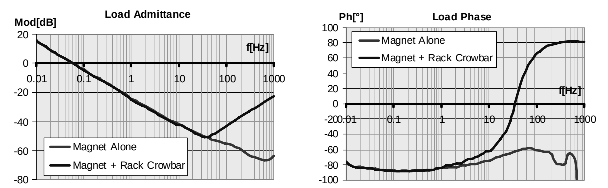

Fig. 10: Output load transfer function.

Output current accuracy result

Figure 11 shows the typical noise measured at a stabilized current of 10A, the measurement showing less than 0.8mApk-pk (6ppm pk-pk). This noise includes both digital control loop and DCCT noise.

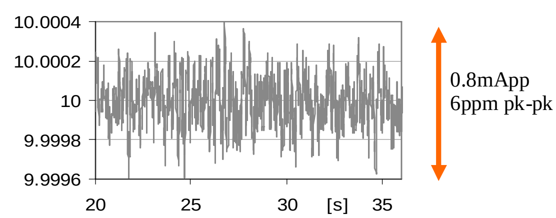

Fig. 11: Typical current noise measurement.

CONCLUSION

First results obtained through tests on a variety of LHC superconductive magnets show that the topology fulfils the requirements.

This design can nevertheless be improved in the receptor quadrant. The current design dissipates the received energy as heat in the MOSFET. A "slow" machine like the LHC fits perfectly with this concept, however a pulsed system would require further development to improve the management of this energy and thus improve the converter efficiency.

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