LHC technological challenges: use of digital signal processors in the power converters for the LHC particle accelerator

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Abstract
The Large Hadron Collider (LHC) is the next accelerator being constructed on the CERN site. It will be installed in a 27 km circumference tunnel, about 100 m underground. The LHC design is based on superconducting magnets (up to 9 T) which operate in a superfluid helium bath at 1.9 K. This machine is scheduled to come into operation in 2008. In all, there will be 1720 power converters having a total steady-state input power of 63 MW and a peak power of 86 MW. They will supply a total current of about 1850 kA and are, in general, characterized by having high current (up to 20 kA) and low voltage with very high precision. We describe the main components of the LHC powering and their challenges. The performance, design constraints, and topologies of the power converters will be presented. We discuss in detail the use of CERN-designed digital signal processor boards with the main emphasis being on the control loop design.

1 Introduction – The LHC project

The European Organization for Nuclear Research (CERN) is a European intergovernmental organization with 20 Member States. It has its seat in Geneva but straddles the Swiss-French border. Its objective is to provide necessary tools for physicists to explore what matter is made of and what forces hold it together. CERN designs, constructs, and runs the necessary particle accelerators and the associated experimental areas. At present more than 6000 physicists from research institutes worldwide use the CERN installations for their experiments. It is the world's largest particle physics centre.

The Large Hadron Collider (LHC), now under construction at CERN, will be the most advanced research instrument of the world's high-energy physics community for the next twenty years. It will allow exploration of the energy frontier above 1 TeV per elementary constituent, by providing proton–proton collisions at the unprecedented centre-of-mass energy of 14 TeV and luminosity of 10^{34} cm^{-2}s^{-1} to two large multi-purpose detectors, ATLAS and CMS, and two more specialized experiments ALICE and LHCb. The LHC will also operate as a heavy-ion (Pb) collider. It is served by the CERN injector complex, upgraded to meet the new requirements of the LHC machine.

One outstanding challenge of the LHC is the safe operation with beam energy 7 times, and luminosity 100 times, higher than the previous particle accelerators. The 350 MJ in each beam of the LHC are sufficient to heat up and melt some 500 kg of copper. This requires careful and reliable handling for safe operation and dump of the complete beam within 88 μs in case of failure, as well as controlling beam losses to avoid a transition of a superconducting magnet to the resistive state. A fast, localized beam loss of 10^6 to 10^7 protons ($0.5 \cdot 10^{-6}$ of the nominal beam) could quench a superconducting magnet when operating at 7 TeV.

The high collision energy is achieved by bending and focusing two counter-rotating beams around the circumference of the collider through a system of twin-aperture, high-field superconducting magnets operating at 8.3 T in superfluid helium at 1.9 K, and bringing them into collision at a small crossing angle in the four locations equipped with detectors (Fig. 1). Specific to the LHC is the large number of superconducting magnets: 1232 main dipoles and 392 main quadrupoles, but also many types of auxiliary magnets (dipole, quadrupole, sextupole, octupole, decapole), correcting multipoles, chromaticity and closed orbit and more generally to adjust beam optics. There are about 8000 magnets.

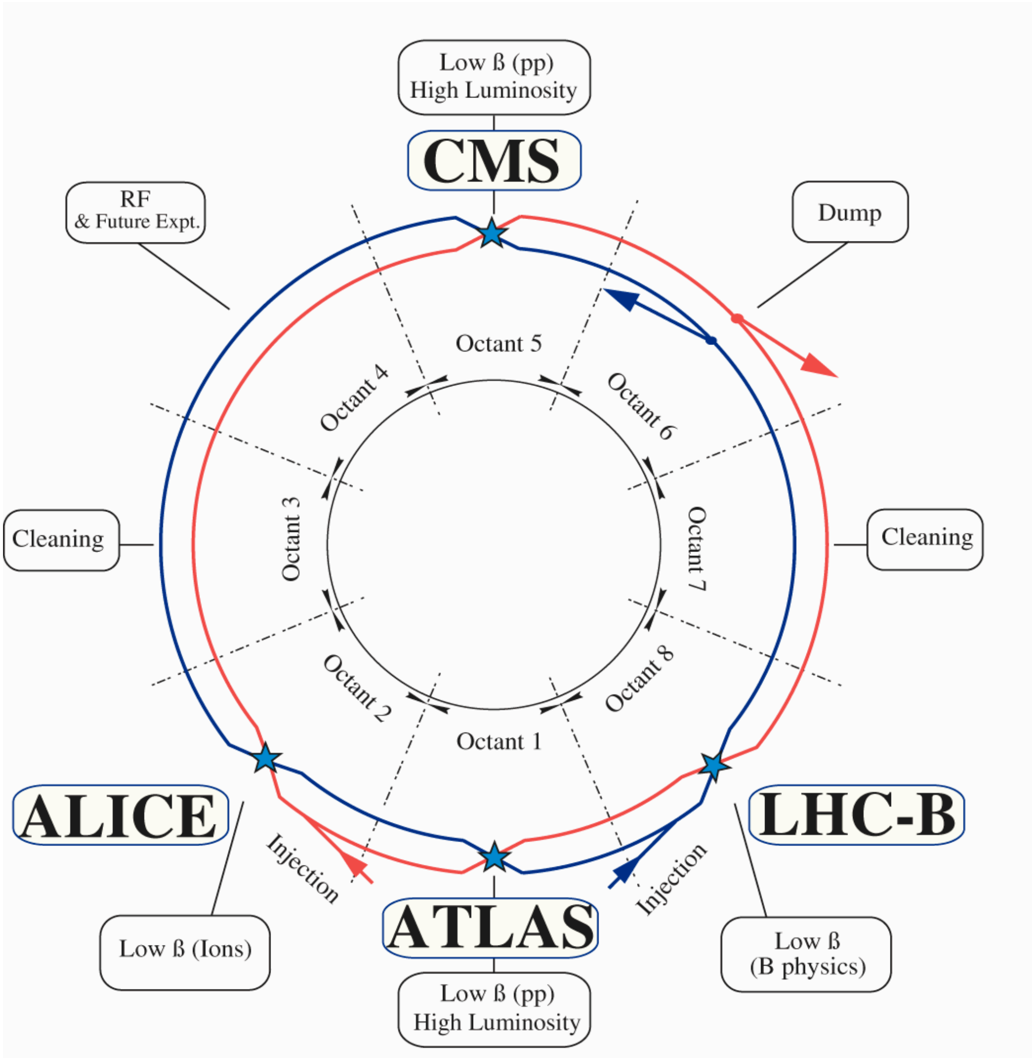

Fig. 1: General layout of the LHC

Another challenge is to handle the huge energy in the magnet system (up to 13 GJ). To illustrate this, 13 GJ corresponds to

- the energy of 3000 kg of TNT
- the energy for heating and melting 15 500 kg of copper
- dropping one LHC main dipole magnet (35 t) from a height of 28 km
- the energy produced by one nuclear power plant unit during about 10 s

Table 1: Main parameters of the LHC

Circumference	27 km
Beam energy at collision	7 TeV
Beam energy at injection	0.45 TeV
Luminosity	10^{34} $cm^{-2}.s^{-1}$
Luminosity lifetime	10 h
Beam current	0.56 A
Protons per bunch	1.1×10^{11}
Number of bunches	2808
Beam size at interaction point	15.9 μm
Typical beam size in arcs	300 μm
Nominal bunch spacing	25 ns 7.5 m
Stored energy per beam	350 MJ
Dipole field at 7 TeV Nominal Ultimate	 8.33 T 9.00 T
Operating temperature	1.9 K
Dipole current at 7 TeV Nominal Ultimate	 11.8 kA 13.0 kA
Dipole current at injection	760 A
Stored energy in magnets Nominal Ultimate	 11 GJ 13 GJ

2 LHC powering

Superconducting magnets have zero resistance and large inductance. As they require high currents, it is important to place the feeding converters close to the cryogenic connections. The consequences are large time constants (e.g. L/R of up to 6 hours for the main dipole circuits, 10 hours for the ATLAS toroid and 39 hours for the CMS solenoid). Management of the electrical stored energy (kJ to GJ range) needs great care.

Superconducting magnets for accelerators are excited very close to their critical current and a small deposition of additional energy (a few mJ) may cause a quench (transition to normal conduction). Such a change of state needs to be rapidly detected and precautions must be taken within the powering system so that the magnet is not destroyed.

A high precision and reproducibility of field is mandatory for LHC to ramp the beam and to get stable physics conditions for the experiments. The field quality in superconducting magnets is determined to a large extent by the current distribution in the coils. While great care is taken in the design and manufacture of the magnets, certain higher-order errors still remain which are of a non-linear and dynamic nature requiring relatively complex correction schemes. The powering system in terms of control, precision, and complexity must take these requirements into account

The LHC reuses the 27 km circumference underground tunnel and technical infrastructure of the former LEP collider. The LHC is divided into eight arcs of 2.9 km with eight straight sections of about 500 m.

The arcs have a continuous cryostat in which are installed the main dipole (bending) and quadrupole (focusing) magnets, as well as various corrector magnets, all operating at cryogenic temperatures.

These circuits, each consisting of up to 154 magnets in series, are powered from one end of the arc by superconducting busbars running through the arc cryostat. The electrical feedboxes, containing high-temperature superconducting (HTS) current leads, are located at the end of the arcs in the machine tunnel. Here, parallel underground galleries were available, or have been excavated, to install the power converters and other equipment needed for powering the machine.

The straight sections have in general individually powered magnets that prepare the beams for collisions or for other machine utilities (RF, collimation, injection, dump). (See Fig. 1.)

For all existing accelerators, all the main bending and main focusing and defocusing magnets are each connected in series giving three main circuits. For the LHC, it was decided to align the electrical segmentation of the machine on the natural segmentation into eight sectors. This choice was made for the following main reasons:

1. For the main dipole circuits, the stored energy would be dangerously high (up to 13 GJ at ultimate current) and large voltages would be needed to de-energize the magnet and especially to extract the huge energy during a quench.
2. Each sector of the machine is galvanically isolated and the possibility of an avalanche quench through the entire machine is avoided.
3. The warm interconnections across the 500 m straight sections would have been expensive, bulky, and would dissipate high power. Some investigations were made to have a superconducting link between the arcs.
4. Installation, testing, commissioning, and maintenance are easier.

The consequence of this segmentation is to have 24 main circuits instead of 3: eight main bending, focusing and defocusing circuits. A good tracking is vital for the LHC beam quality. The accuracy for these 13 kA circuits must be below 20 ppm (parts per million) and the reproducibility should be close to 5 ppm [1], [2]. The achievement of this high precision is certainly the most difficult challenge for the LHC power converters.

Figure 2 shows the powering and energy extraction of one sector of LHC main dipole magnets.

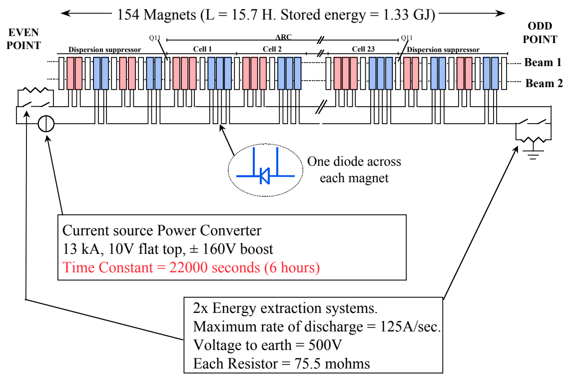

Fig. 2: Powering and energy extraction of one sector of main dipole magnets

In addition to the main circuits, individually powered magnets, mainly located in the straight sections, will require 4, 6 and 8 kA. The correction circuits are powered at 600 A, 120 A and 60 A and the majority will need to operate in four quadrants. With the exception of the main bend circuits, all circuits require rather low voltages (between 8 V and 18 V). The LHC also uses a few warm resistive magnets that will require 100 kW to 1 MW per circuit. In all, the LHC will have about 1800 circuits requiring approximately 1.8 MA in total.

Furthermore, the LHC experiments require large converters for their magnets (dipoles, solenoids, or toroids):

- ATLAS: [20.5 kA, 18 V] for the superconducting toroid magnet (inductance L = 7.5 H and a time constant τ = 37 500 s) and [8 kA, 8 V] for the superconducting solenoid magnet (L = 1.4 H)
- CMS: [20 kA, ±26 V] for the superconducting solenoid (L = 14 H and τ = 140 000 s)
- ALICE: [31 kA, 170 V] for the warm solenoid (L = 0.33H, τ = 80 s); and [6.5 kA, 950 V] for the warm dipole magnet (L = 1 H; τ = 10 s)
- LHCb: [6.5 kA, 950 V] for the warm dipole magnet (L = 1.3 H; τ = 10 s)

3 LHC power converters

3.1 Performance and design constraints

The performance of the powering system is dominated by the stability of the beam. This is made more complex by the segmentation of the machine and the fact that the field-to-current relationship in a superconducting magnet is a complex function of many parameters, both static and dynamic [3]. Superconducting magnets display dynamic effects even when their current is stable, with changes in field and field errors due to an effect known as the decay of persistent currents. These changes alone, if not corrected continuously, would be fatal to the beams. Further, these errors depend greatly on the past powering history of the magnets and vary very rapidly at the start of a current ramp when the errors due to persistent current decay 'snap back' to near their original value. It is particularly delicate at the low currents of injection where great care must be taken to precisely cycle and set the magnets to take into account the effects of DC and AC magnetization and snap-back of the persistent currents. Initial studies have shown that the overall performance of the main circuits, in order to bootstrap the machine, needs to attain about 1.5×10^{-5} of maximum. However, a resolution and short-term stability of the power converters of the order of a few 10^{-6} will be needed to allow precise cycling and fine adjustment.

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. Thus underground installation is obligatory and this leads to the necessity for reduced volume and high efficiency of the power converters. It should be noted that a lot of power converters will be installed back-to-back in a confined space. The difficult and restricted access to the underground zones imposed a modular approach for the converter design, allowing quick replacement of faulty modules and off-line repair in surface workshops. To minimize the ventilation installation, low air loss was an important requirement for the design of the power converters. All the power converters are water cooled, except the low-power converters (<1.5 kW).

Because of the high precision, the compact installation of the power converters and the close vicinity to all the other equipment (magnet protection, beam injection and beam extraction systems, experiments, etc.), the Electro Magnetic Compatibility (EMC) has been a severe design constraint for the power converters. Systematic measurements (immunity and emission) were done on the prototypes and also on all production converters.

To achieve these difficult goals, great development effort was needed in the following domains: soft-switching power converter topologies, analog-to-digital conversion techniques, high DC current measurements, and digital control technologies.

All the power converters are split into three independent parts:

– A power part acting as a voltage source.
– High-precision current transducers and analog-to-digital converters (ADCs). All converters will be equipped with two independent current transducers and ADCs.
– A digital electronics control module, which performs the current regulation and makes the link with the slow control network.

This logical and physical separation was created in order to subcontract the largest possible portion of the work to industry (see Section 4).

3.2 Main power converter topologies

The main requirements for the LHC power converters could be summarized as follows:

– Underground installation: low volume, low weight, only front access possible, no access during operation
– High reliability (MTBF ≅ 80 000 h)
– Repairability and rapid exchange of different parts
– High efficiency (> 80% for the unipolar converters and > 70% for the bipolar converters) and reduced air losses
– EMC: low emission (conducted noise AC and DC side) and high immunity
– Wide output current range (I_{max}/I_{min} ~ 100)
– High precision: DC current, low voltage ripple, perturbation rejection, etc.

The above requirements for the LHC converters imply the use of high switching frequencies for very large quantities of converters [4]. Operation at higher frequencies results in a considerable size reduction (volume and weight) for transformers and filter and better dynamics. It gives a better rejection of the perturbations and a lower ripple of the output voltage. However, losses associated with high-frequency operation have to be kept as low as possible to achieve efficient power conversion. Switch-mode power conversion technologies have evolved from the basic PWM converters to the soft-switching converters. The PWM converters process power by interrupting the power flow with abrupt switching (hard switching). This operation results in high losses dissipated in the switching elements during the turn-on and turn-off intervals. It is necessary to include complex and lossy protection snubbers against the effects of the hard-switching, resulting from the presence of parasitic components in the converter. High voltage and current stresses are applied to semiconductor devices.

The attractive properties of soft-switching are

– the large reduction of switching losses
– the improved reliability due to reduced stress
– a limited frequency spectrum, which means an advantage with respect to EMI and losses in passive components
– a reduction of weight and volume of the components resulting from the higher switching frequency
– a higher bandwidth resulting from the high internal switching frequency
– integration of parasitic elements in the commutation mechanism (e.g. leakage inductance of the transformer in the resonant or quasi-resonant circuit).

3.2.1 One-quadrant switch-mode converters

To meet the requirement of a relatively large quantity of multi-kA power converters with similar output voltage and current ratings, the concept of parallelling several smaller current sources was adopted. This architecture provides many advantages:

- A modular approach to the converter design could be made. Much effort could initially be focused on optimizing the sub-converter design, both technically and for manufacture, as this would become the fundamental building block of the converter.
- The quantity of sub-converters could be varied to adapt most closely to the circuit requirements.
- Additional sub-converters could be used to enhance the fault tolerance of the converter, thus a fault in one sub-converter would not interrupt the supply of current to the magnet load. A study was made to optimize the number of sub-converters in relation to cost and MTBF.
- Once the complete converter is in operation, management of a series of related converters is greatly enhanced, both from the perspective of training of personnel and of the issue of maintenance and spare parts.
- In spite of the increased quantity of individual elements, a further advantage of the sub-converter architecture is the use of components with lower rating.

After a long optimization process, only two types of sub-converters are necessary for the LHC machine and experiments: [3.25 kA, 18 V] and [2 kA, 8 V]. Each sub-converter can be considered as a controllable, stabilized, unipolar, current source. Under normal conditions, all the sub-converters work in parallel.

The topology of each sub-converter is split into different stages (Fig. 3):

- An input stage with a circuit breaker, an AC contactor, a three-phase six-pulse diode rectifier, the necessary filtering on the AC or DC sides, and a soft-start circuit to limit the inrush current.
- An inverter stage with a Full-Bridge Zero-Voltage-Zero-Current Switching Phase-Shift inverter (FB-ZVZCS-PS) or Full-Bridge Zero-Voltage Switching Phase-Shift inverter (FB-ZVS-PS) with a switching frequency above 20 kHz.
- An output stage with high-frequency transformers for insulation and adaptation, a Schottky diode rectifier stage and an output filter.

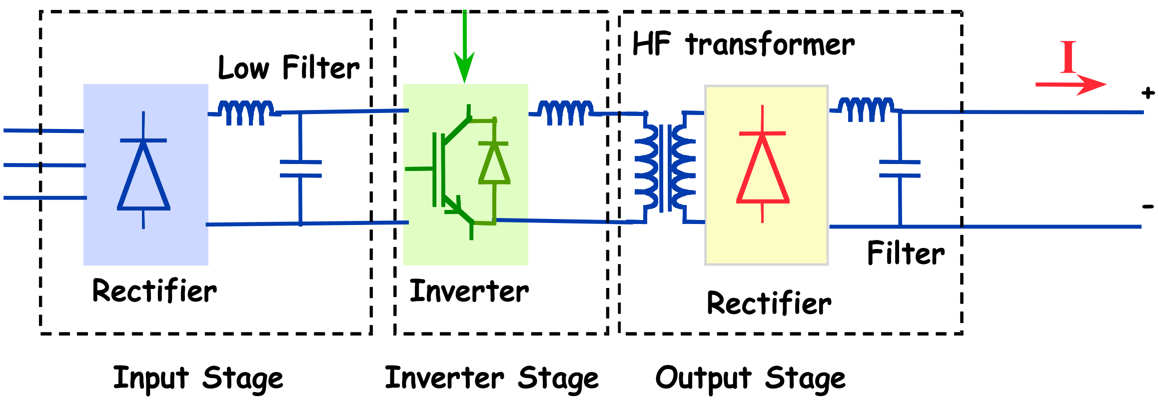

Fig. 3: Sub-converter topology

Thus LHC one-quadrant switch-mode converters were designed as modular water-cooled converters, each with a number of sub-converters, whose outputs are connected in parallel. To improve system availability, each converter uses one sub-converter more than required by the load current. Each sub-converter is identical for all power converter output current ratings. More technical details are given in Refs. [5] and [6].

Fig. 4: [20.5 kA, 18 V] ATLAS converter

Two large contracts have been placed for the design, according to a detailed CERN specification, and the production of these 1-quadrant converters:

– [13 kA, 18 V] converters (18 units made of (4+1) [3.25 kA, 18 V] sub-converters) and one [20.5 kA, 18 V] converter (made of (7+1) [3.25 kA, 18 V] sub-converters) were designed and are being produced by Transtechnik GmbH & Co. (Germany) (Fig. 4) [7].

Fig. 5: [6 kA, 8 V] power converter

– [8 kA, 8 V] (24 units made of (4+1) [2 kA, 8 V] sub-converters) and [6 kA, 8 V] (176 units made of (3+1) [2 kA, 8 V] sub-converters) were designed by Kempower Oy and are being built by Kemppi Oy (Finland) (Fig. 5) [8].

3.2.2 Four-quadrant switch-mode converters

The LHC machine will make extensive use of true bipolar power converters with soft zero-crossing (without discontinuity) of the current and the voltage. The industrial use of four-quadrant converters is very limited. From the approval of the project in 1994, special development programmes were launched at CERN in collaboration with universities and industries on different topologies [9], [10].

The topology of the four-quadrant switch-mode converters is similar for all four types of converter: [±600 A, ±10 V], [±600 A, ±40 V], [±120 A, ±10 V], and [±60 A, ±8 V] (Fig. 6).

It includes:

- A mains rectifier stage with a circuit breaker; an AC contactor; a three-phase, six-pulse diode rectifier; the necessary filtering on the AC or DC sides; and a soft-start circuit to limit the inrush current.
- An inverter stage using a soft-commutated bridge with IGBT switching at high frequencies from 25 kHz to 100 kHz.
- A high-frequency transformer, output filter and a bipolar output stage. A bipolar output stage provides reversal of the polarity. The magnet energy, during the ramp-down of the current, is dissipated by the bipolar output stage.
- An output protection circuit with a free-wheel safety and discharge circuit (also called crowbar).

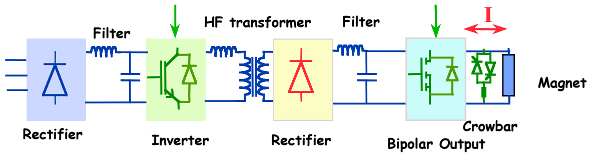

Fig. 6: Four-quadrant converter topology

The topologies of these converters are presented in Refs. [11] and [12].

For the medium water-cooled power converters, two contracts have been placed for the design, according to a detailed CERN specification, and the production of the 600 A power converters:

– [±600 A, ±10 V] (440 units) were designed and are being produced by Cirtem (France) [13] and EEI (Italy) (Fig. 7) [14].

– [±600 A, ±40 V] (50 units) were designed and are being produced by Transtechnik GmbH & Co. (Germany) (Fig. 8) [7].

Fig. 7 Two [±600 A, ±10 V] converters in a rack

For the low-power four-quadrant converters, the design was made at CERN and two production contracts have been placed:

– [±120 A, ±10 V] (330 units) are being produced by Efacec (Portugal) [15].

– [±60 A, ±8 V] (832 units) are being produced by CEL Groupe Cofidur (France) [16].

Fig. 8: One [±600A, ±40V] converter in a rack

The [±60 A, ±8 V] converters are used as dipole orbit correctors for the arc regions. They are located under the magnet and are in radiation areas (~10 Gy in 10 years). Special developments, component selection, and radiation tests were necessary to withstand the radiation dose and Single Event Upset (SEU) phenomena.

Figure 9 illustrates the zero crossing of the voltage and Fig. 10 the zero crossing of the current for a [±600 A, ±40 V] converter.

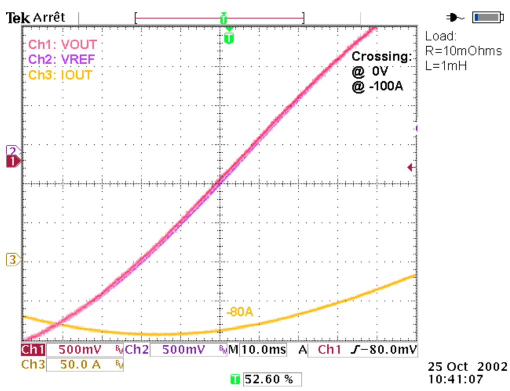

Fig. 9: Zero crossing of voltage for –100 A current (converter [±600 A, ±40 V] with a 10 mΩ and 1 mH load)

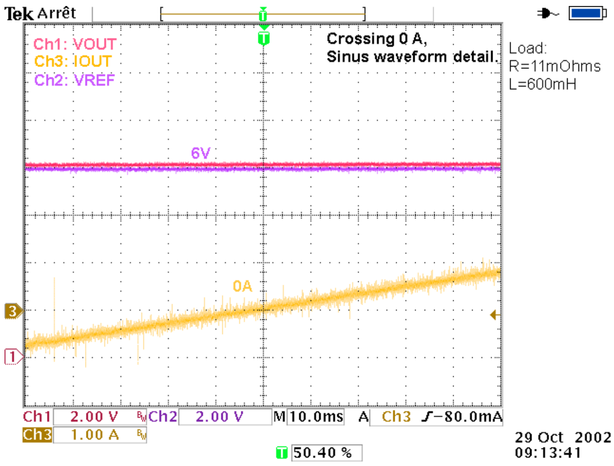

Fig. 10: Zero crossing of current for 6 V current (converter [±600 A, ±40 V] with a 11 mΩ and 600 mH load)

3.2.3 *Output voltage ripple and EMC*

The level of conducted noise emission was a very difficult constraint for the development of the LHC power converter. The curve C of the IEC 478-3 norm was applied on the AC side and on the DC side for all the switched-mode power converters (20.5 kA to 60 A). For the output ripple of the voltage source, the C curve was extended for all the frequencies up to 9 kHz according to the dashed curve of Fig. 11.

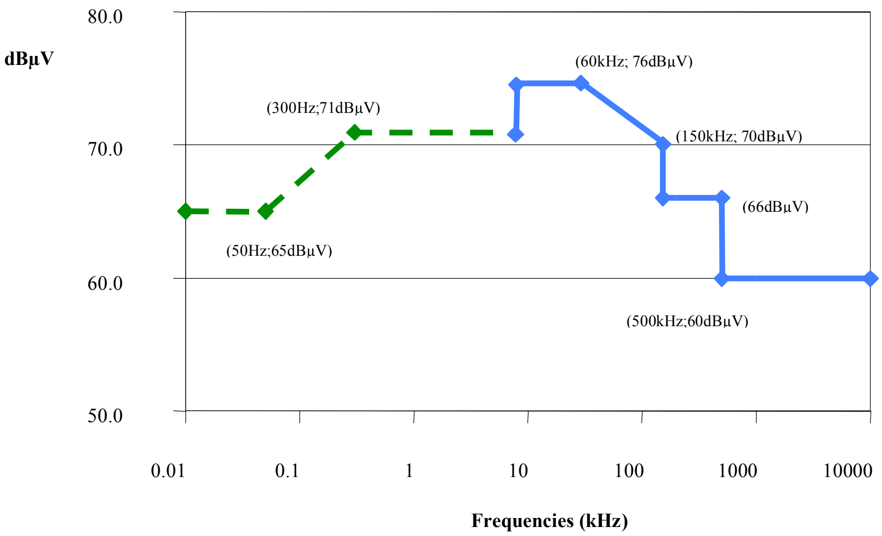

Fig. 11: Differential and common-mode noise levels for the LHC power converters on DC output

Figure 12 illustrates the common-mode measurement on the DC side on one converter type. Similar results have been obtained on all converters.

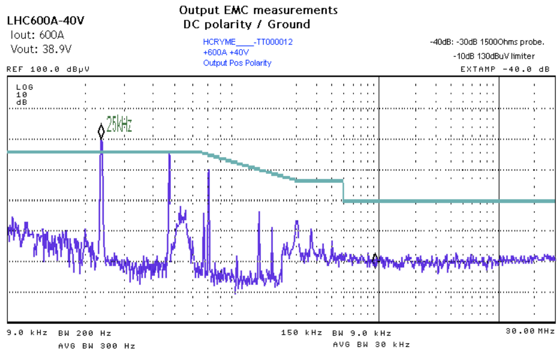

Fig. 12: Common-mode noise measurement on the DC output of [±120 A, ±10 V] converter (9 kHz to 30 Mhz)

3.2.4 Main dipole power converter: [13 kA, ± 190 V]

Development studies were undertaken to design a suitable switch-mode topology for the main dipole converter [17]. Owing to the large energy and the necessity to have a two-quadrant converter (bipolar in voltage), a line-commutated, phase-controlled thyristor technology was still the most simple, economical, and reliable choice. The gain in volume with switch-mode topology was less than a factor 2.

The eight main dipole voltage sources consist of line-commutated, phase-controlled power converters to which a parallel injection active filter is added to improve mains rejection and ripple performance. To achieve the 13 kA 190 V output rating, a parallel topology (Fig. 13) is used consisting of two sub-converters, each containing an 18 kV–2 MVA cast resin transformer, a six-pulse thyristor rectifier, and a passive filter. The rectifiers are phase-shifted by 30° and connected in parallel. For installation purposes the power converters are made of seven modules: two transformer modules, two thyristor bridge modules, two filter choke modules, and one central module containing the filter capacitors and the output current measurement transducer (DCCT). The thyristor bridges and the filter chokes are water-cooled, while the rest of the equipment is air-cooled.

In order to handle the magnet current run-down under the worst fault condition, e.g., power cut and no cooling water flow, the power converter is equipped with free-wheel thyristors. This free-wheeling system is rated to handle the 13 kA up to 100 s without water-cooling.

In normal operation, the magnet current run-down is made under feedback control with the thyristor bridges used as reverse voltage source, or through the free-wheel thyristors.

The active filter, connected in the passive filter capacitor branch, has a working range of 4% of the total output voltage. This provides rejection of mains transients and gives a wide dynamic range for the control loops.

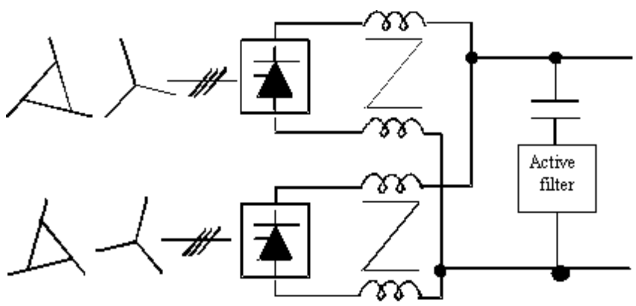

Fig. 13: Main dipole power converter topology

Production contracts have been placed:

– 18 kV/190 V cast resin transformer with Trasfor SA (18 units) (Switzerland) [18].

– Thyristor rectifier parts (9 units) with OCEM (Italy) [19].

Fig. 14: Photo of main dipole converter

(L =11 m, w = 1.8 m, h = 2.4 m; total weight = 28 t)

3.3 High-precision DC current transducers

A DC current transducer is required to measure the converter output current in order to control it accurately. Currently there is only one technology that will fulfil the LHC accuracy requirements, the zero-flux DC current transducer. The primary current is passed through a toroidal transducer core of special high-μ magnetic material creating a one-turn transformer (Fig. 15).

In the first stage the current is divided with a fixed ratio to a low level. Its bandwidth is extended down to DC through a feedback loop, measuring the DC flux in the core and producing a compensation current, which will balance the flux to zero at all times. The ratio can be established to the ppm (part per million) level.

In the second stage the low-level compensation current is passed through a high-precision burden resistor. The voltage chosen is a compromise between power dissipation and producing enough voltage to overcome noise and thermal emf effects. This voltage is then amplified in a high-precision amplifier providing 10 V output at the nominal primary current.

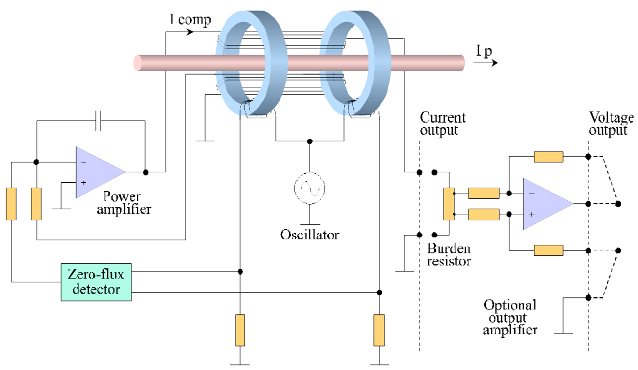

Fig. 15: DCCT principle

The long-term accuracy of a DCCT depends on several factors and needs periodic re-calibration if the highest performance is required. A complete system has been developed to perform calibrations on-site in a fully automated fashion [20]. The principle requires that the DCCTs in question be equipped with an integral calibration winding in the transducer head (Fig. 16).

Fig. 16: 13 kA DCCT (head and electronics)

Three contracts have been placed for the development and production of the LHC DCCTs:

- High-current DCCTs (4 to 13 kA, 473 units) with Hitec Power Protection BV (The Netherlands) [21].
- 600 A DCCTs (1060 units) with Hitec Power Protection BV (The Netherlands).
- 120 A DCCTs (2430 units) with KG Ritz Messwandler gmbh [22].

3.4 Digital control module and high-precision regulation loop

As already mentioned, the LHC demands an order of magnitude improvement in accuracy and reproducibility over previous accelerators. The power converters must follow a very precise acceleration curve with absolutely no over- or under-shoot. It was therefore necessary to use a digital loop for the high-precision current loop. Furthermore it would have been difficult to realize an analog current loop with the high time constant of the magnets.

New technology had to be developed for the ADCs to satisfy the need of precision and the Sigma-Delta conversion principle was judged to be the most promising to meet this aim. An entirely new circuit had to be developed for the highest precision ADCs [23].

The digital control module receives control vectors from the central accelerator control computers and converts them to an output current reference value every millisecond. A digital regulation loop also resides in this module comparing the reference value and the ADC output to calculate the appropriate control value for the voltage source periodically (10–100 ms). This digital value is converted by a digital/analog converter (DAC) to a 0–10 V analog control signal, which is sent as a reference voltage to the voltage source, thereby closing the loop. This current control loop is designed to make the complete system behave like a ‘perfect’ current source.

A special effort has been made towards standardization, using the same electronic control modules for all types of converters. The development of these modules was realized by CERN and a large production contract for 2000 electronics modules was placed with Glentronics Limited (Ireland) [24].

The basic structure of the digital loop is shown in Fig. 17. The general structure of the digital controller can be described by a tri-branched structure known as RST structure.

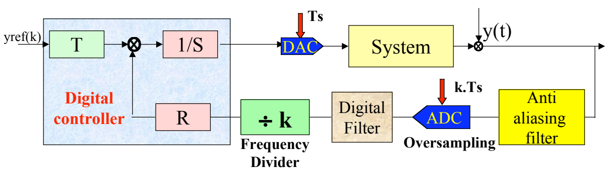

Fig. 17: RST digital control loop

The RST controller makes it possible to obtain the desired tracking behaviour (following the reference) independent of the desired regulation behaviour (rejection of a disturbance). The RST control can be evaluated by the 'Tracking and Regulation with Independent Objectives' method (R and S give the regulation behaviour and T gives the tracking behaviour) [25]. This method obtains good tracking of the reference: no lagging error and no overshoot.

Figure 18 shows as an example the round-off at the end of the LHC acceleration ramp. It can be noted that the overshoot is equal to zero.

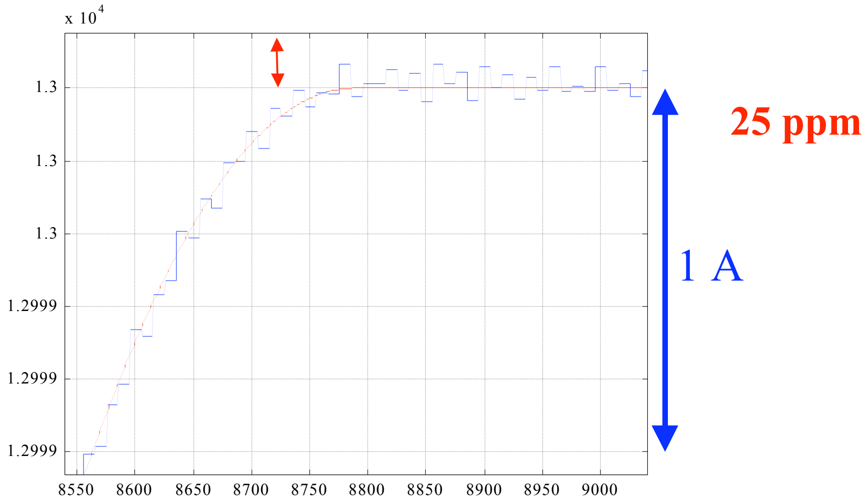

Fig. 18: End of the ramp: from 12 999 A to 13 000 A

4 Production of LHC power converters

It is CERN's policy to broaden the involvement of industry in all its activities. Only specialized equipment, for which industry would have little or no interest, is designed by CERN.

In line with the previous statement, the strategy for the design, production, and test of the LHC power converters was based on the following considerations:

- Identify subsystems that are suitable for industrial design and production
- Place development and production contracts
- Design and build prototypes of remaining subsystems
- Place production contracts with industry
- Assume system integration responsibility
- Carry out integration and system test at CERN before installation.

With a cost to completion of around 40 million euros, the production of the LHC power converters represents a large industrial project in advanced technologies. Special developments on soft-switching topologies, high-precision ADC and DCCTs, digital control and calibration system and their validation on prototypes were spread over almost one decade. Validations of the performance of the power converters were realized on individual superconducting magnet but also on a full-sized model of a regular cell in the LHC (two quadrupoles and six dipole magnets in series) [26]. After this, the placement of contracts for series production was launched through competitive tendering and adjudication of commercial contracts.

Acknowledgements

The work reported here is mainly that of the CERN staff participating in the LHC powering and in particular the members of the Power Converter Group, as well as of our partners in industry. The author wishes to thank the many CERN, academic, and industrial colleagues who participated in the projects described in this paper. In particular the author would like to thank Frederick Bordry (head of the Power Converter Group at CERN), who has helped enormously in preparing the seminar in Sweden with his slides and who has provided a good part of the manuscript for the write-up. Originally it was foreseen, that Frederick would give the seminar himself, but time constraints did not allow him to teach at the CAS in Sigtuna.

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