# CHAPTER 10

# POWER CONVERTER SYSTEM

## 10.1 INTRODUCTION, DESIGN CONSTRAINTS

While LEP required high voltage and low current for its loads, LHC will require very large currents and rather low voltages for its superconducting magnets. Although it was relatively easy and inexpensive to install the power converters for LEP on the surface and cable them to their underground loads, such an approach would have been prohibitive for LHC because of the high dc currents. Fortunately, LHC will not need the large RF complex used for LEP2 at the even points. Thus the large RF galleries, parallel to the tunnel (UA), have been vacated to allow the underground installation of high current power converters very close to the current feedthroughs. In the odd points, special enlargements of the tunnel (RR) are required to install auxiliary power converters (dispersion suppressors, insertion quadrupoles, insertion orbit correction, with current range from 6 kA to 120 A converters). In the cleaning insertions of points 3 and 7, the insertion quadrupoles and dipole separators use warm magnets which can be powered from the surface using the existing surface buildings and cabling of LEP.

The re-use of the LEP infrastructure and the underground installation is the driving force 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 (Fig. 10.1). 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 minimise the ventilation installation, low air losses was an important requirement for the design of the power converters. All the power converters will be water cooled, except the orbit correctors, [±60 A, ±8 V] and [±120 A, ±10 V].

Due to 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,…), the Electro Magnetic Compatibility (EMC) has been a severe design constraint for the power converters and needs to be studied and measured when all other equipment has been installed.

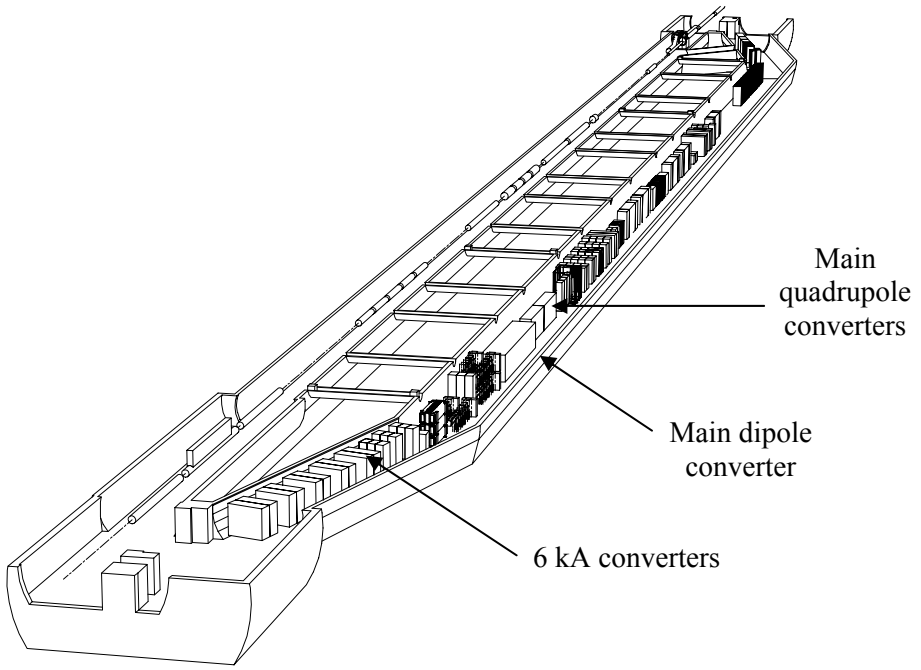


Figure 10.1: UA layout example

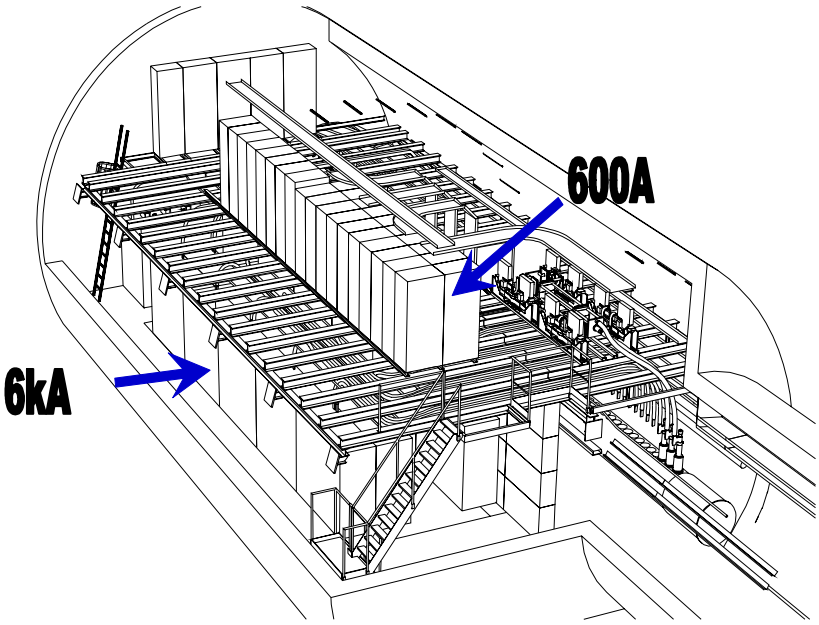


Figure 10.2: RR layout example

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, characterised by having high current and low voltage (see Sec. 10.3).

The performance of the powering system is dominated by the tune tolerance which ultimately should reach 0.003. This is made more complex by the segmentation of the machine (see Chap. 9) and the fact that the field-to-current relationship in a superconducting magnet is a complex function of many parameters, both static and dynamic [1]. 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 magnetisation 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 a maximum of about $1.5 \times 10^{-5}$. However, a resolution and short term stability of the power converters in the order of few $10^{-6}$ will be needed to allow precise cycling and fine adjustment. Because the sectors are basically optically autonomous, the sector-to-sector tracking tolerance is of the same order as that of the global requirements.

To achieve these very difficult goals, great development effort was needed and continues in the following domains: Analogue-to-Digital Conversion techniques, high-current DC current measurements, digital control technologies and new soft-switching power converter topologies (see Sec. 10.4)

The accelerator physics requirements translate into an overall high precision [2] which will be presented in the next section.

## 10.2 POWER CONVERTER PERFORMANCE: PRECISION

The term Precision is only a generic term, covering accuracy, reproducibility and stability.

Before defining these terms, it is useful to recall several basic definitions:

a) Nominal current ($I_{nominal}$): Normal maximum value for a circuit.
b) Rated current ($I_{rated}$): Maximum current of the power converter
c) Calibration current ($I_{calibration}$): Calibration value = software decided maximum current ($\leq I_{rated}$ )
d) Overload Current ($I_{overload}$ ): A hardware protection setting, tripping the converter if exceeded.
e) Ultimate current ($I_{ultimate}$): Current required for the ultimate main dipole field 9.0 T.

For LHC, the nominal current of the power converter is chosen to be equal to the ultimate current and for all the converters with a nominal current above 1 kA:

$I_{calibration} = I_{LHC\text{-}nominal}$ = current required for nominal operation of the machine (8.33 T in the main dipole)

$I_{overload} = 1.1 * I_{calibration} = 1.1 * I_{LHC\text{-}nominal} \cong 1.03 * I_{LHC\text{-}ultimate}$

*Accuracy*

The accuracy is defined as the long-term uncertainty in the setting, taking into consideration the full range of permissible changes of operating and environmental conditions.

The environment is defined in various LHC Engineering Specifications:

- General parameters for equipment installed in the LHC [3] (e.g. $\Delta T = \pm 4°C$ in UAs) [27]
- Main parameters of the LHC 400/230 V distribution system [8].

The accuracy is defined for a period of one year and is expressed in ppm (Parts Per Million) of $I_{nominal}$.

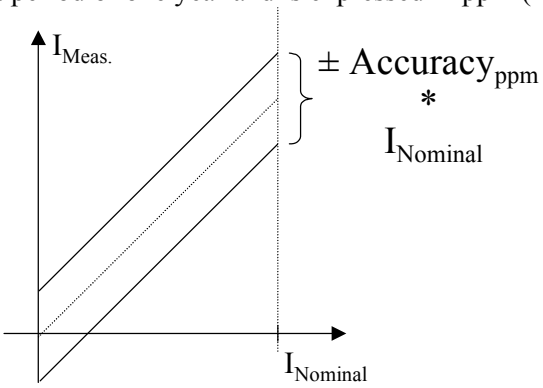


Figure 10.3: Accuracy illustration

If the one year accuracy is not sufficient, the calibration process must be performed more often (e.g. every month). An in-situ quasi-on-line calibration system has been developed for this purpose (see Sec. 10.4.5) Eight of these systems will be installed for the 24 main circuits (main dipoles and main quadrupoles) and eight more systems for the inner triplet quadrupoles.

*Reproducibility*

The reproducibility is defined as the uncertainty in returning to a set of previous working values from cycle to cycle of the machine.

The reproducibility is defined for a period of one day, without any adjustment of the calibrated parts (e.g. DCCT, ADC). The reproducibility is expressed in ppm of $I_{nominal}$.

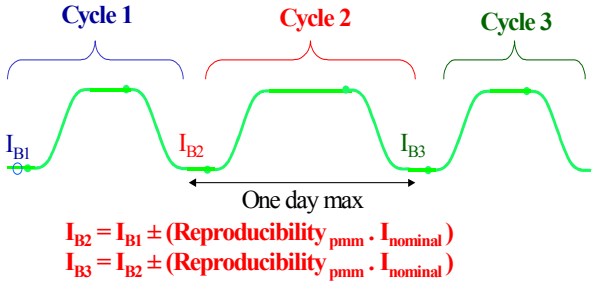


Figure 10.4: Reproducibility illustration

*Stability*

The stability is defined as the maximum deviation over a period of half an hour, with no changes in operating or environmental conditions other than mains network. The stability is expressed in ppm of $I_{nominal}$

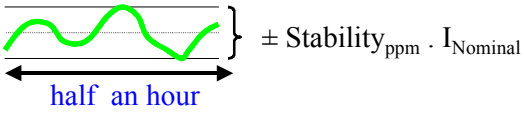


Figure 10.5: Stability illustration

*Resolution*

The resolution is defined as the smallest increment in current that can be induced or discerned. The resolution is expressed in ppm of $I_{nominal}$. Resolution is directly determined by the A/D system.

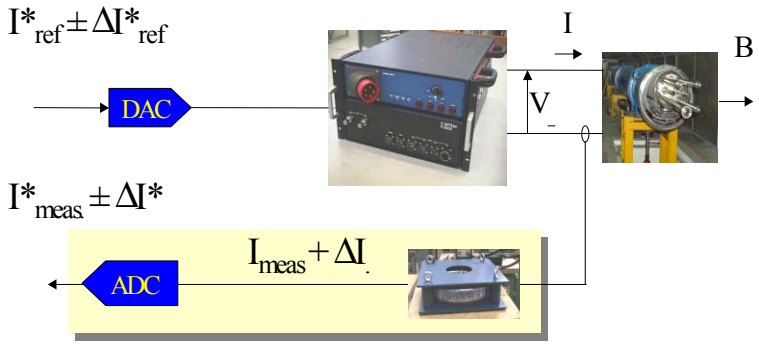


Figure 10.6: Resolution illustration

Tab.10.1 gives a summary of the precision performance of the LHC power converters. These parameters were discussed and defined in the frame of the Dynamic Effects Working Group [4].

Table 10.1: Power Converter Tolerances for LHC

| Circuit Type | Nominal Current (A) | Current Polarity | One Year Accuracy (ppm of Inominal) | One day Reproducibility (ppm of Inominal) | 1/2 hour Stability (ppm of Inominal) | Resolution (ppm of Inominal) |
|---|---|---|---|---|---|---|
| Main Bends, Main Quads | 13000 | Unipolar | ± 50 ± 20 with calibration | ± 5 | ± 3 | 1 |
| Inner triplet | 8000/ 6000 | Unipolar | ± 100 ( ± 20 with calibration) | ± 20 | ± 10 | 15 |
| Dispersion suppressor | 5000/ 6000 | Unipolar | ± 70 | ± 10 | ± 5 | 15 |
| Insertion quadrupoles | 4000/ 5000/ 6000 | Unipolar | ± 70 | ± 10 | ± 5 | 15 |
| Separators (D1,D2,D3,D4) | 5000/ 7000 | Unipolar | ± 70 | ± 10 | ± 5 | 15 |
| Trim quadrupoles | 600 | Bipolar | ± 200 | ± 50 | ± 10 | 30 |
| SSS correctors | 600 | Bipolar | ± 200 | ± 50 | ± 10 | 30 |
| Spool pieces | 600 | Bipolar | ± 200 | ± 50 | ± 10 | 30 |
| Orbit correctors | 120/60 | Bipolar | ± 1000 | ± 100 | ± 50 | 30 |
| Warm magnets | 650/1000 | Unipolar | ± 200 | ± 50 | ± 10 | 15 |

## 10.2.1 Power Converter Tracking

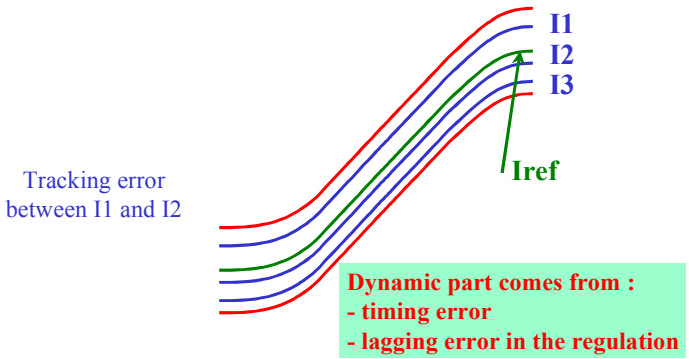


Figure 10.7: Tracking error

*Tracking*

The tracking is defined as the ability of a converter to follow the reference function. This definition is valid for static and dynamic references. The static part is covered by the static performance: accuracy and reproducibility.

The dynamic part of the tracking error comes from any timing error or lagging error in the regulation.

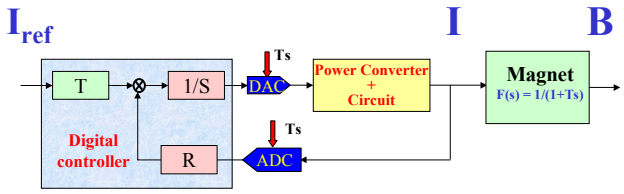


Figure 10.8: Digital control loop principle

To limit the timing error, the measurement and the reference must be synchronised. With a dI/dt equal to 10 A/s, 1 ms timing is necessary to limit the contribution of the timing to the dynamic tracking error to less than 1 ppm.

The digital current loop of the power converters is designed with no lagging error; i.e. independence of the load time constant. The lagging error between the current and the field must be known to be corrected by a timing shift at the start of the ramp. These errors depend mainly on the vacuum chamber and the beam screen.

*Tracking between the 8 main dipole converters*

Due to the electrical segmentation of the machine in eight independent arcs, a good tracking of the main dipole converters is vital for the LHC beam quality.

With an accuracy of 20 ppm for the main dipole converters [6], the energy error in the LHC machine is given by:

$$\Delta B/B_{nom} = \Delta I/I_{nom} = 20 \text{ ppm}$$
$$\text{where } B_{nom} = 9 \text{ T and } I_{nom} = 13 \text{ kA}$$

Then:

$$\Delta B = 9 * 20\ 10^{-6} = 1.8\ 10^{-4} \text{ T}$$
$$\Delta B/B_o = 3.3\ 10^{-4}.$$

This error in the machine leads to an orbit excursion:

$$\Delta X = D_x \,.\, \Delta B/B_o \approx 0.7 \text{ mm with } D_x \approx 2 \text{ m}.$$

This excursion could be corrected with a pilot run. Then after a machine cycle, reproducibility performance defines the orbit excursion. With a reproducibility of 5 ppm, an orbit excursion, better than 0.2 mm, could be achieved. This 20 ppm accuracy and 5 ppm reproducibility are very difficult performance parameters. To reach this performance, high-precision DCCTs (Direct Current Current Transformer) and ADCs (Analogue Digital Converter) as well as in-situ calibration systems are required.

*Tracking between the dipole and quadrupole converter*

With an accuracy of 20 ppm for the main dipole and quadrupole converters, the energy error in the machine is:

$$\Delta B/B_{nom} = \Delta I/I_{nom} = 20 \text{ ppm}$$
$$\text{where } B_{nom} = 9 \text{ T and } I_{nom} = 13 \text{ kA}$$

Then:

$$\Delta B = 9 * 20\ 10^{-6} = 1.8\ 10^{-4} \text{ T}$$
$$\Delta B/B_o = 3.3\ 10^{-4}$$

This energy error in the machine leads to a tune change given by:

$$\Delta Q = Q'_{nat} \,.\, \Delta p/po = Q'_{nat} \,.\, \Delta B/Bo.$$

With a natural chromaticity $Q'_{nat}$ equal to 100: $\Delta Q \approx 100 * 3.3\ 10^{-4} = 0.033$

As the tuning quadrupoles can correct up to $\Delta Q = 0.3$, this tracking error between main dipole and main quadrupole converters is acceptable.

## 10.3 OVERVIEW OF SYSTEM

The list of power converters with their main characteristics is given in Tab. 10.2. More characteristics can be found in the powering database [10]. This list is the result of an optimisation process to reduce the number of power converter types to a minimum.

Table 10.2: List of the LHC power converters

| Equipment code | Current | | Voltage | | | Mains Input | | Power losses | | Qty |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ultimate A | Minimum A | Steady V | Boost V | Peak V | Peak kW | Peak kVA | Water kW | Air kW | |
| RPTE | 13000 | 350 | 10 | ±180 | 190 | 2681 | 3540 | 150 | 50 | 8 |
| RPHE | 13000 | 350 | 13 | ±5 | 18 | 265 | 288 | 28 | 3 | 16 |
| RPHF | 8000 | 160 | 6 | ±2 | 8 | 78 | 85 | 13 | 1.5 | 21 |
| RPHG | 6000 | 120 | 6 | ±2 | 8 | 59 | 64 | 10 | 1.2 | 132 |
| RPHH | 4000 | 80 | 6 | ±2 | 8 | 40 | 42 | 6.5 | 0.7 | 40 |
| RPMB | 600 | Bipolar | ±8 | ±2 | 10 | 8.5 | 9 | 2 | 0.2 | 330 |
| RPMC | 600 | Bipolar | ±35 | ±2 | 40 | 27 | 30 | 3 | 0.3 | 24 |
| RPMB | 600 | 0 | 8 | 2 | 10 | 8.5 | 9 | 2 | 0.2 | 70 |
| RPMC | 600 | 0 | 35 | 5 | 40 | 27 | 30 | 3 | 0.5 | 2 |
| RPLB | 120 | Bipolar | ±8 | ±2 | 10 | 1.7 | 108 | 0 | 0.5 | 290 |
| RPMC | 120 | Bipolar | ±35 | ±5 | 40 | 5.5 | 6 | 0 | 0.1 | 10 |
| RPLA | 60 | Bipolar | ±2 | ±6 | 8 | 0.7 | 0.8 | 0 | 0.2 | 752 |
| RPTL | 650 | 60 | 160 | 0 | 160 | 113 | 141 | 0 | 25 | 3 |
| RPTF | 810 | 70 | 450 | 0 | 450 | 390 | 490 | 0 | 50 | 4 |
| RPTG | 810 | 70 | 950 | 0 | 950 | 820 | 1025 | 0 | 40 | 4 |
| RPTM | 1000 | 50 | 600 | 0 | 600 | 640 | 800 | 0 | 395 | 2 |
| RPTI | 6500 | 350 | 950 | 0 | 950 | 6570 | 8220 | 0 | 14 | 2 |
| RPTN | 1000 | 50 | ±180 | 0 | 180 | 195 | 210 | 0 | 26 | 3 |
| RPTJ | 20000 | 1000 | ±26 | 0 | 26 | 620 | 795 | 76 | 5 | 1 |
| RPHK | 20500 | 1000 | 18 | 0 | 18 | 420 | 455 | 44 | 5 | 1 |
| RPTH | 33000 | 2000 | 170 | 0 | 170 | 6060 | 7610 | 340 | 60 | 1 |
| RPTK | 40 | n.a. | 100000 | 0 | 100000 | 4240 | 5300 | 180 | | 4 |
| TOTAL | | | | | | | | | | 1720 |

This process converged towards five main types of converters:

a) The first type of converter (RPTE) is the main dipole magnet converter. The LHC machine is divided in eight sectors, each powered by a separate power converter (see Chap. 9). These eight power converters need to have a very large dynamic range to supply ±190 V during acceleration and normal de-excitation of the machine within reasonable time (20 minutes), but only about 1 V while at injection energy. The steady state specification for physics is 13 kA, 10 V. Thyristor line-commutated technology will be used for these converters.

b) The second type of converter (RPHE, RPHF, RPHG, RPHH) corresponds to the converters for the main quadrupoles, the insertion quadrupoles, the separators, etc. The output rating specifications are [13 kA, 18 V], [8 kA, 8 V], [6 kA, 8 V] and [4 kA, 8 V]. Switch-mode technology will be used for these converters. 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 ( [3.25 kA, 18 V] or [2 kA, 8 V] ) are placed in parallel; this concept can also provide redundancy. A total of around 700 modules will be used for the LHC.

c) True bipolar power converters [±600 A, ±10 V], [±600 A, ±40 V] and unipolar [600 A, 10 V], [600 A, 40 V] (RPMB, RPMC) are required to power the sextupoles, the sextupole and decapole spool piece circuits,

the octupoles and some warm quadrupoles in the cleaning regions. In total there are 436 converters (10 V: 400; 40 V: 36): 354 bipolar (10 V: 330; 40 V: 24) and 72 unipolar (10 V: 70; 40 V: 2). Based on these ratios and financial considerations, it was decided to have only bipolar converters: [±600 A, ±10 V] and [±600 A, ±40 V]. Furthermore, the [±600 A, ±40 V] converter will be used for the powering of the dispersion suppressor and matching correction dipole in Point 3, instead of [±120 A, ±40 V], which would have needed special development for only 10 units. Switch-mode technology will be used for these converters.

d) Each quadrupole and each aperture of the LHC machine has a small dipole orbit corrector associated with it. In total there are 752 for the arcs (RPLA) and 290 in the dispersion and insertion regions (RPLB). The best solution is to locate the 60 A converters in the LHC tunnel close to the quadrupole magnets: reduction of the cabling costs and of the converter power (±8 V instead of ±115 V for a surface location). The underground installation implies a very high reliability and radiation hardened devices (~10 Gy in 10 years). Switch-mode technology will be used for these converters.

e) For all warm magnets and septa with voltage above 40 V, conventional thyristor, line-commutated, converters will be used.

The actual intention is to reuse the present magnet test bench power converter supply reference magnets. Tab. 10.3 gives the voltage ripple requirements for the different types of power converters.

Table 10.3: Power Converter Voltage Ripple

| Power converter type | 50 HzRipple pk-pk (mV) | 300 HzRipple pk-pk (mV) |
|---|---|---|
| [13kA, 18V] | 60 | 350 |
| [8kA,8V] | 5 | 30 |
| [6kA,8V] | 5 | 30 |
| [4kA,8V] | 5 | 30 |
| | | |
| [±600A,±10V] | 5 | 20 |
| [±600A,±40V] | 5 | 20 |
| | | |
| [±120A,±10V] | 5 | 20 |
| | | |
| [±60A,±8V] | 30 | 120 |
| | | |
| | | 600 HzRipple |
| [13kA, ±190V] | 60 | 350 |
| [810A,450V] | 40 | 250 |
| [810A,950V] | 80 | 450 |
| [1000A,600V] | 600 | 3000 |
| [650A,160V] | 200 | 1000 |
| [1000A,180V] | 200 | 1000 |

The underground installation is the driving force for reduced volume and high efficiency of the power converters.

The main characteristics of these converters are:

- high efficiency (> 80% for the unipolar converters and > 70% for the bipolar converters).
- water cooling of converters with power above 5 kW.
- galvanic isolation between mains and output.
- wide output current range ($I_{max}/I_{min}$ ~ 100).
- very high reliability and operational redundancy; no access to the underground during operation with beam and access underground will take a long time.
- repairability: all converters will be designed with fast plug-in modules or fast exchange parts. The weight of each module will be between 25 and 65 kg to allow one or two operators to carry out a fast exchange with spare modules.

To meet these requirements switch-mode technology will be used in most cases. Operation at high frequencies results in a considerable size reduction (volume and weight) for transformers and filter and

improved dynamics. It also gives a better rejection of the mains 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. Therefore switch-mode power conversion technologies have evolved from the basic PWM converters to a new emphasis on switch commutation currently called soft commutation.

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.

To fulfil the aims of this strategy, all the power converters were split in three independent parts (Fig. 10.7):

- A power part acting as a voltage source (see Sec. 10.4.1).
- Current transducers (all converters will be equipped with two independent current transducers (see Sec. 10.4.2).
- A digital electronics control module, which performs the current regulation and makes the link with the slow control network (see Sec. 10.4.3 and 10.4.4). A special effort has been made towards standardisation, using the same electronic control modules for all types of converter.

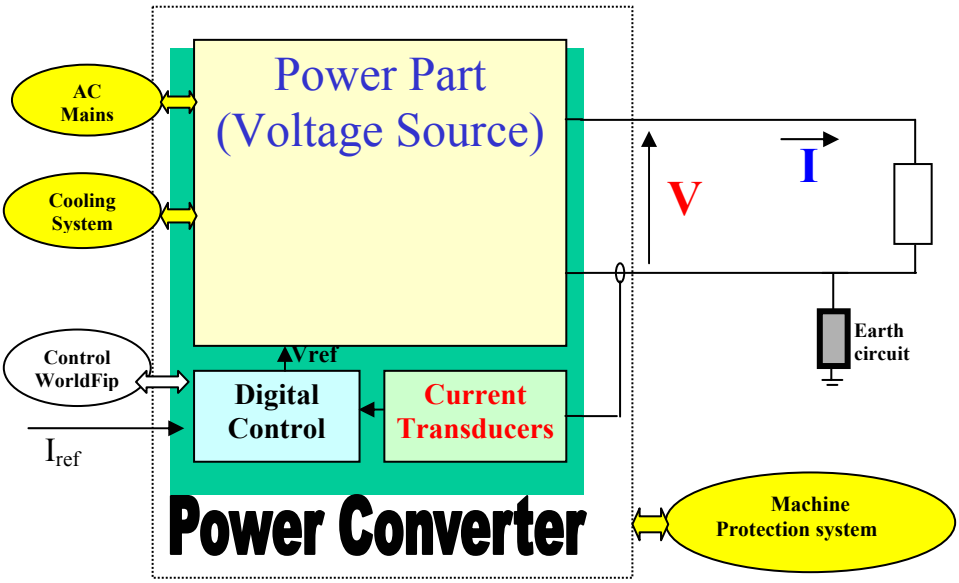


Figure 10.9: Power Converter Structure

The next section describes the design of these equipment subsystems and section 10.5 presents the specific requirements placed on other systems and the interfaces with them.

## 10.4 EQUIPMENT SUBSYSTEMS

A power converter for LHC is composed of three main blocks: a voltage source, a current transducer (DCCT) and a function generator/controller (FGC) with built-in analogue/digital converter (ADC). This logical and physical separation was created to subcontract the largest possible portion of the work to industry.

The voltage source is the main power part of the power converter. It is built either with switch-mode, soft-commutated, technology or with thyristor, line-commutated, technology. The task of the voltage source is to receive the mains power and convert it to a suitable dc output voltage, controlled by a reference input.

The output current to the load is measured by a high-precision DCCT, which gives an output voltage of 0-10 V proportional to the output current 0 – 100 %.

The ADC converts the analogue 10 V signal from the DCCT to a digital word stream with sufficient sampling rate and bit resolution for the speed and accuracy of the converter concerned.

The FGC 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 the FGC 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 analogue 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.

The overall accuracy requirements for the magnet current in the different circuits were established between the Accelerator Physics and the Power group, Tab. 10.1. This requirement was then broken down in an accuracy budget for the different subsystems concerned. An example is shown in Tab. 10.4

Table 10.4: Accuracy budget for 13kA converters

| Device | **Device specification** | | **LHC machine impact** | | |
|---|---|---|---|---|---|
| | ppm of FS | ppm of value | Stability 1/2 hr | Reproducibility 1-day | Accuracy 1 year |
| DCCT | | | | | |
| Zero uncertainty (hyst etc.) | 2 | 0 | 0 | 0 | 2 |
| Repeatability | 1 | 0 | 0 | 1 | 1 |
| Uncomp non-linearity | 2 | 0 | 0 | 0 | 2 |
| LF noise, 0.1-10 Hz | 0.5 | 0 | 0.5 | 0.5 | 0.5 |
| Stability 1/2 hr, 1-100 mHz | 0 | 1.5 | 1.5 | 0 | 0 |
| Gain drift 24 hr | 0 | 0.5 | 0 | 0.5 | 0 |
| Gain drift 1 year | 0 | 5 | 0 | 0 | 5 |
| Gain Temperature Coefficient | 0 | 1 | 0 | 1 | 1 |
| Offset drift 24 hr | 0.5 | 0 | 0 | 0.5 | 0 |
| Offset drift 1 year | 3 | 0 | 0 | 0 | 3 |
| Offset Temperature Coefficient | 1 | 0 | 0 | 1 | 1 |
| **DCCT total** | | | **2** | **4.5** | **15.5** |
| A/D converter, 22 bit Sigma-delta | | | | | |
| Uncomp non-linearity | 0.5 | 0 | 0 | 0 | 0.5 |
| LF noise, 0.1-10 Hz | 0.6 | 0 | 0.6 | 0.6 | 0.6 |
| Stability 1/2 hr, 1-100 mHz | 0 | 1 | 1 | 0 | 0 |
| Gain drift 24 hr | 0 | 0.5 | 0 | 0.5 | 0 |
| Gain drift 1 year | 0 | 10 | 0 | 0 | 10 |
| Gain Temp Coeff | 0 | 0.15 | 0 | 0.15 | 0.15 |
| Offset drift 24 hr | 1 | 0 | 0 | 1 | 0 |
| Offset drift 1 year | 10 | 0 | 0 | 0 | 10 |
| Offset Temp Coeff | 0.15 | 0 | 0 | 0.15 | 0.15 |
| **A/D total** | | | **1.6** | **2.4** | **21.4** |
| Miscellaneous | | | 0.3 | 1 | 5 |
| **Total** | | | **3.9** | **7.9** | **41.9** |
| Conditions<br>Temperature change (K)<br>Special temperature control cabinet | | | 0 | 1 | 1 |

It was clear from the outset that the accuracy required in the main 13 kA circuits would not be attainable by conventional means. In particular, to achieve, the severe tracking requirement between all the machine sectors, new technology was necessary. DCCTs are being developed by industry with a built-in calibration winding. An entirely new approach for the A/D conversion and the use of digital control loops were also necessary to handle the unprecedented accuracy and the extremely large load time-constants due to the superconducting magnets. The very high precision needed for the sector tracking also means that an automatic calibration system is necessary to periodically monitor and adjust the calibration of the main dipoles, quadrupoles and other critical converters.

### 10.4.1 Power Part – Voltage Sources

*Main dipole converter:13 kA, 190 V, thyristor converter*

The eight main dipole voltage sources consist of thyristor, line-commutated, 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.10.10) 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 power converter is supplied via 18 kV switchgear located in the power distribution surface building (SE). For safety reasons, a manual off-loaded 18 kV switch is provided close to the power converter.

The thyristor bridges and the filter chokes are water cooled, while the rest of the equipment is air-cooled. For each converter, the losses to the air are ~40 kW, while the losses to the cooling water are ~80 kW.

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 104 s without water-cooling. This represents the time constant of the magnet discharge with its dump resistor inserted.

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.

The main output performance parameters for the main dipole voltage sources are:

- Voltage ripple without active filter: $1 \times 10^{-3}$ @ 50 Hz; $5 \times 10^{-3}$ @ 600 Hz
- Voltage ripple with active filter: $25 \times 10^{-6}$ @ 50Hz; $0.5\times 10^{-3}$ @ 600 Hz
- Low frequency (5 - 20Hz) mains rejection without active filter: 10-20 dB
- Low frequency (5 - 20Hz) mains rejection with active filter: 50-60 dB
- Small signal bandwidth without active filter: 70 Hz
- Small signal bandwidth with active filter (up to 4% of Vmax): 5 kHz.

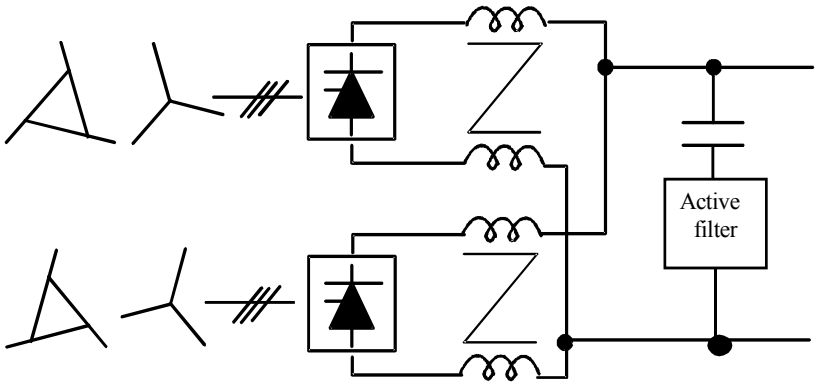


Figure 10.10: Thyristor converter topology

*One-quadrant converters using [3.25 kA, 18 V] and [2 kA ,8 V] switch-mode sub-converters*

The 1-quadrant switch-mode converters are designed as modular water-cooled converters, each one 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.

Tab. 10.5 defines for the 1-quadrant converters the number and the rating of their associated sub-converters.

Table 10.5: Sub-converter rating

| Equipment code | Converter rating | | Sub-converter rating | | Number of sub-converters |
|---|---|---|---|---|---|
| | Current | Voltage | Current | Voltage | |
| RPHK | 20.5 kA | 18 V | 3.25 kA | 18 V | 8 |
| RPHE | 13 kA | 18 V | 3.25 kA | 18 V | 5 |
| RPHF | 8 kA | 8 V | 2 kA | 8 V | 5 |
| RPHG | 6 kA | 8 V | 2 kA | 8 V | 4 |
| RPHH | 4 kA | 8 V | 2 kA | 8 V | 3 |

Each sub-converter can be considered as a controllable stabilised unipolar current source. Under normal conditions, all the sub-converters are working in parallel.

The topology of each sub-converter is split into different stages:

- An input stage with a magnetic and thermal protection, an ac contactor, a diode rectifier, a three-phase six-pulse diode rectifier, the necessary filtering on the ac and 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) with a switching frequency around 20 kHz.
- An output stage with high-frequency (HF) transformers for insulation and adaptation, a rectifier stage and an output filter.

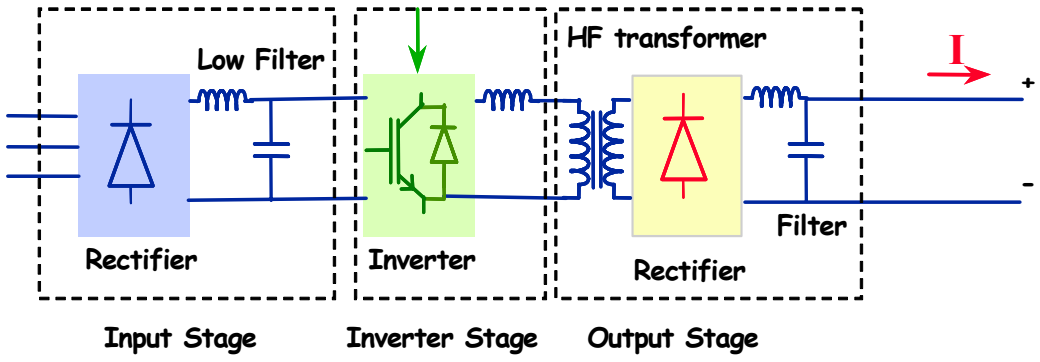


Figure 10.11: Sub-converter topology

Separate common control electronics handles the regulation of the whole converter as a voltage source and provides the reference and other control signals for all the sub-converters. If one or more of the sub-converters fail, the on-state sub-converter reference (even down to one single sub-converter) will increase, so that the current and the voltage of the load do not change.

A water-cooled free-wheel diode circuit provides a bypass path for the current when the converter is stopped. Diagnostic Modules are integrated in the voltage source to collect many status signals (fault list, warning list, status of the sub-converters, etc…) and make them available for diagnostic purposes to FGC through the diagnostic serial bus.

An earthing circuit is connected to the output of the converter to fix the potential of the output circuit versus earth. This circuit detects an earth fault and limits the earth current in case of a fault.

A switch on the front panel provides an adjustable maximum current (five steps up to the nominal current).

Each sub-converter is housed in a 19" rack with individual ac mains, water circuit, dc output, control and protection electronics, such that any sub-converter can work alone. The [3.25 kA, 18 V] sub-converter is housed in a full 19" rack and the [2 kA, 8 V] in half a rack. For rapid exchange of the parts (volume and weight constraints), the sub-converter functions are housed in several plug-in modules. The output stage is also physically duplicated in modules whose outputs are connected in parallel. Tab. 10.6 defines for the 1-quadrant sub-converters the different types of modules and the number used to assemble a sub-converter.

Table 10.6: Sub-converter module rating

| **Module type** | **Function** | **3.25 kA, 18 V modules** | **2 kA, 8 V modules** |
|---|---|---|---|
| Input | Contactor, Rectifier, Filtering | 1 | 1 |
| Inverter | Inverter | 1 | |
| Output | HF transformer, Rectifier, Filtering | 3 | 2 |

The ac mains and the water used for the converter cooling are distributed from a central point located in the central rack. This rack includes the earthing circuit and both DCCT transducer heads.

Busbars placed above the racks connect the outputs of the sub-converters in parallel. A dc connection system connects the converter to the water-cooled load cables.

The common control electronics and the FGC are placed in a separate electronics rack.

All the racks are placed on a steel frame to create a single unit for transport and facilitate installation.

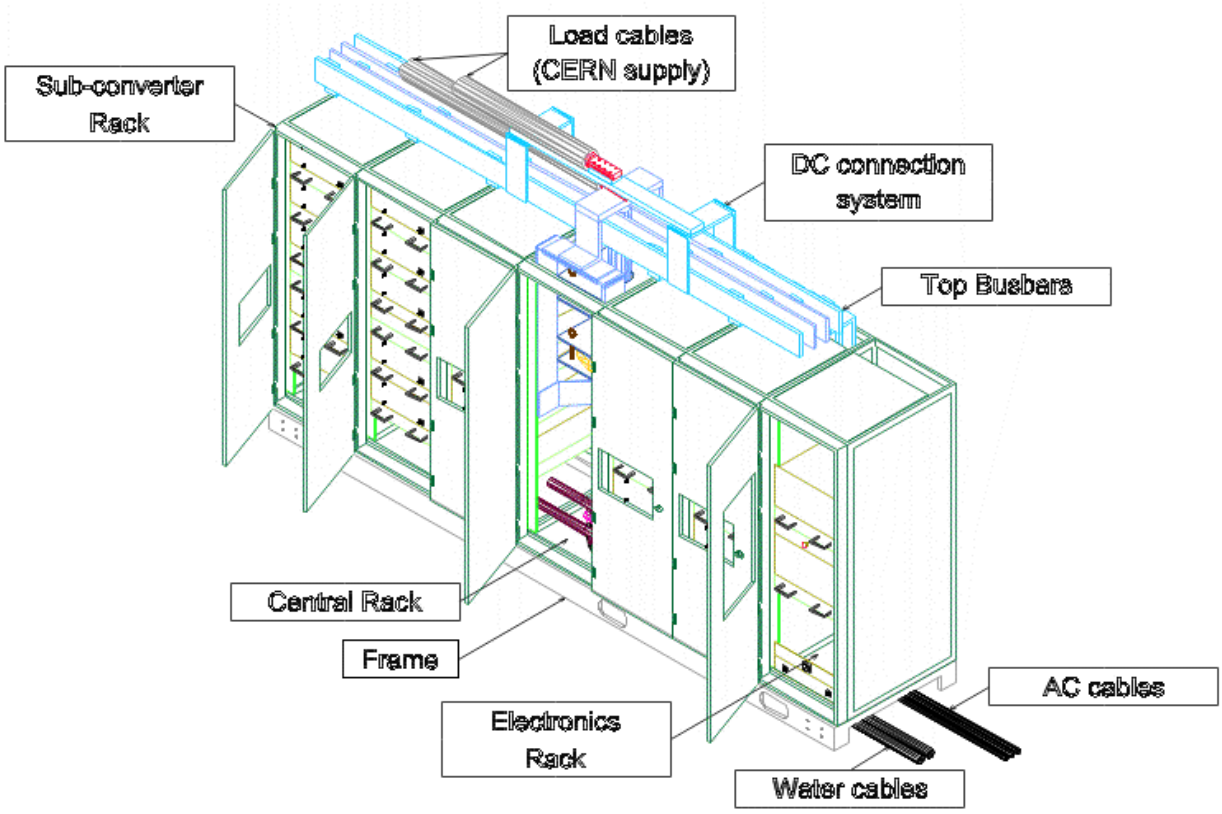


Figure 10.12: 1-quadrant converter enclosure (13 kA configuration)

Note: For the (13 kA, 18 V) converter and the Inner Triplets, the DCCT electronics, associated with the DCCT heads, as well as the Sigma-Delta ADC electronics are placed in a temperature controlled rack with its own mains (UPS).

The main parameters are:

- Small signal bandwidth (200 mV amplitude) over the full voltage range > 800 Hz (-3dB)
- Maximum voltage drop when a sub-converter fails 100 mV during 5 ms
- Voltage output ripple, under normal mains supply conditions:
  - 10 mV peak-peak up to 130 kHz
  - according to IEC 478-3C above 130 kHz
- Free-wheel diode circuit:

| | |
|---|---|
| (13 kA, 18 V) type - with water | 13 kA |
| - without water | $I_{max}\, e^{-t/\tau}$ with $I_{max}$ = 13 kA, $\tau$ = 100 s. |
| (20.5 kA, 18 V) type - with water | 20.5 kA |
| - without water | 20.5 kA during 1 s. |
| (8 kA, 8 V) type - with water | 8 kA |
| - without water | $I_{max}\, e^{-t/\tau}$ with $I_{max}$ = 8 kA, $\tau$ = 70 s. |
| | $\tau$: the time constant of the magnet discharge. |
| (6 kA, 8 V) type for the Inner Triplets - with water | 11.5 kA |
| - without water | $I_{max}\, e^{-t/\tau}$ with $I_{max}$ = 11.5 kA, $\tau$ = 30 s |
| (6 kA, 8 V) type for other circuits - with water | 6 kA |
| - without water | $I_{max}\, e^{-t/\tau}$ with $I_{max}$ = 6 kA, $\tau$ = 160 s |
| (4 kA, 8 V) type - same as for the (6 kA, 8 V) for other circuits | |
| | $\tau$ the time constant of the magnet discharge with the faster energy extraction. |

More details may be found in the following references: Technical Specifications of the 1-quadrant converters [13], [14], the Workshop on LHC Powering [11] and the Review of LHC Power Converters [12].

*Special powering of inner-triplet magnets*

In 1999, the decision was taken that the inner triplet quadrupole magnets MQXA and MQXB will be "mixed" in the four insertions. The magnet types are of different design and thus exhibit different parameters (Chap. 8).

To optimise the powering of these mixed quadrupoles, it was decided to use two nested high-current power converters: [8 kA, 8 V] and [6 kA, 8 V]. A [±600 A, ±1 V] trim power converter, connected across the Q1 magnet, allows the correction of the difference in the integrated gradients of the Q1 and Q3 magnets. Furthermore, the possibility to change only the gradient of the Q1 magnet will facilitate the $\beta^*$ measurements [25]. A schematic of the powering is shown in Fig. 10.13.

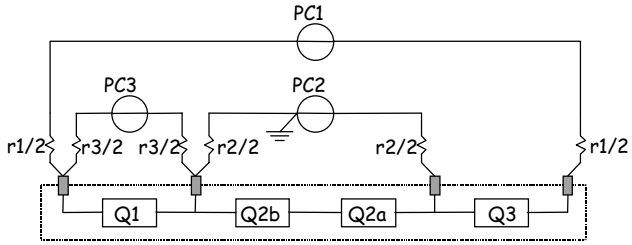


Figure 10.13: Inner triplet powering scheme

Table 10.7: Circuit parameters

| | |
|---|---|
| PC1 | [8 kA, 8 V] |
| r1 | 0.6 mΩ |
| $\tau$1 | 380 s |
| PC2 | [6 kA, 8 V] |
| r2 | 0.8 mΩ |
| $\tau$2 | 50 s |
| PC3 | [±600 A, ±10 V] |
| r3 | 1.4 mΩ |
| $\tau$3 | 65 s |

The consequence of this economical powering layout is the interaction between the three galvanically coupled circuits. A control strategy to decouple the three systems has been developed, using three independent standard LHC digital controllers. The converter protection during the discharge of the magnet energy due to quenches or interlocks of the magnets has been studied [24].

*Four-quadrant switch-mode converters*

The topology of the 4-quadrant switch-mode converters is almost the same for the [±600 A, ±10 V], [±600 A, ±40 V], [±120 A, ±10 V] and [±60 A, ±8 V]. It includes:

- A mains rectifier stage with a magnetic and thermal protection, an AC contactor, a diode rectifier, a three-phase six-pulse diode rectifier, the necessary filtering on the AC and 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 >20 kHz.
- A high frequency transformer and a bipolar output stage: this part comprises a high-frequency transformer for insulation and adaptation. A bipolar output stage provides reversal of the polarity. The magnet energy, during the ramp-down of the current, is dissipated by the converter or sent back to the mains.
- An output circuit with a free-wheel safety and discharge circuit (also called crowbar), both DCCT transducer heads and the earthing circuit.
  The crowbar is composed of a resistor and a switch. This device turns on when an over-voltage appears across the voltage source output terminals. It assures a safe path for the magnet current if the bipolar output stage is stopped whilst current is supplied to the load. During a discharge, the device does not need cooling-water, or an auxiliary power supply, making it autonomous in case of simultaneous mains failure.
  The earthing circuit is connected to the output of the converter to fix the potential of the output circuit versus earth. This circuit detects an earth fault and limits the earth current in case of a fault.

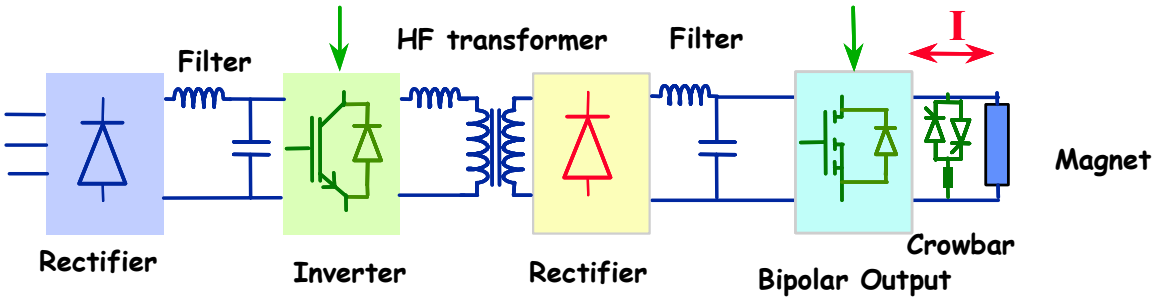


Figure 10.14: 4-quadrant converter topology

*±600 A, ±10 V switch-mode converter specifics*

The main enclosure of this type of converter is a 19" rack, housing one or two converters, a common mains input with an RFI filter, common inlet/outlet water cooling connections and terminals to connect the loads. The mains rectifier stage, the inverter stage, the transformer and the bi-polar output stage are contained in one 6 U high 19" module. The output circuit with the dc contactor, the crowbar and the DCCTs are fixed in the rack. The FGC for the two converters are located in the same crate inside the rack, independent of other electronics.

A switch on the front panel provides an adjustable maximum current (from 120 A to 600 A in five steps).

For circuits operating with very low voltage and small stored energy, the energy extraction system will be a part of the power converter [26]. Such systems consist of a combination of a semiconductor crowbar in series with a 50 mΩ resistance. Installing low-voltage extraction units at the power converters allows a reduction of cost and space in the packed zones where this equipment will be located in the LHC machine. A dc arc-chute contactor rated at 600 A is put between the converter output and the discharge device. It will protect the load against a short circuit in any output stage component by isolating the discharger and the load from the voltage source output. To maximise reliability of the command of this contactor, a redundant way to

open the contactor has been implemented. All of these converters will be equipped with a crowbar and 50 mΩ resistors, whereas 136 circuits will be equipped with the dc contactor.

The main parameters are:

- Small signal bandwidth (amplitude 160 mV) over full voltage range:> 1 kHz
- Voltage output ripple, under normal mains supply conditions:

  1.8 mV r.m.s. up to 50 Hz
  (without precision current control loop)
  7 mV rms in the 300 Hz-60 kHz range
  above 60 kHz according to IEC 478-3C.

- Discharge circuit:

| | |
|---|---|
| Crowbar resistor | 50 mΩ |
| Crowbar activation level | 13 V |
| Maximum power to absorb by the resistive output circuit | 18 kW |
| Maximum energy to dissipate | 108 kJ. |

More details may be found in the following references: [±600A, ±10V] converter Technical Specification [15], the Workshop on LHC Powering [11] and the Review of LHC Power Converters [12].

*±600 A, ±40 V switch-mode converter specifics*

The main enclosure of this type of 4-quadrant converter is a 19" rack, housing one converter, mains input with an RFI filter, inlet/outlet water cooling connections and terminals to connect the load.

The mains rectifier stage, the inverter stage, the transformer as well as the bi-polar output stage is housed in two 6 U high 19" modules. The output circuit with the crowbar and the DCCTs are fixed in the rack. The FGC for the converter is located in a separate crate inside the rack.

A switch on the front panel provides an adjustable maximum current (from 120 A to 600 A in five steps).

An additional function is added for this type of converter, used for the [±120 A, ±40 V] LHC circuit concerning the protection of the current leads (see Sec.10.5 Interlocks and Quench Protection).

The main parameters are:

- Small signal bandwidth (amplitude 160 mV) over full voltage range : > 1 kHz
- Voltage output ripple, under normal mains supply conditions:

  1.8 mV rms up to 50 Hz
  (without precision current control loop)
  7 mV rms in the 300 Hz-60 kHz range
  above 60 kHz according to IEC 478-3C.

- Discharge circuit:

| | |
|---|---|
| Crowbar resistor | 50 mΩ |
| Crowbar activation level | 52 V |
| Maximum power to absorb by the resistive output circuit | 18 kW |
| Maximum energy to dissipate | 108 kJ. |

More details can be found in the following references: [±600 A, ±40 V] converter Technical Specification [15], the Workshop on LHC Powering [11] and the Review of LHC Power Converters [12].

*±120 A, ±10 V switch-mode converter specifics*

This 4-quadrant converter type is forced air-cooled. The main enclosure is a 19" rack, housing up to four converters, a common mains input with an RFI filter, and terminals to connect the loads. The mains rectifier stage, the inverter stage, the transformer, the bi-polar output stage as well as the DCCT are located in one 6U high 19" module. The crowbar as well as the earthing circuit is fixed directly in the rack. The 4 FGC electronics for the 4 converters are located in two separate crates inside the rack, independent of the other electronics. A switch, placed in the rack, provides an adjustable maximum current limit (60 A instead of 120 A).

The voltage detection across the resistive current leads is part of the converter electronics (see Sec.10.5 Interlocks and Quench Protection).

The main parameters are:

- Small signal bandwidth (amplitude 160 mV) over full voltage range: > 800 Hz
- Voltage output ripple, under normal mains supply conditions:
  1.8 mV r.m.s. up to 50 Hz
  (without the precision current control loop)
  7 mV rms in the 300 Hz-60 kHz range
  above 60 kHz according to IEC 478-3C.
- Discharge circuit:

| | |
|---|---|
| Crowbar resistor | 83 mΩ |
| Crowbar activation level | 15 V |
| Maximum power to absorb by the resistive output circuit | 1800 W |
| Maximum energy to dissipate | 13 kJ. |

More details can be found in the following references: [±120 A, ±10 V] converter Technical Specification [16], the Workshop on LHC Powering [11] and the Review of LHC Power Converters [12].

*±60 A, ±8 V switch-mode converter specifics*

This 4-quadrant converter type is forced air-cooled. These 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). The main enclosure of this type of converter is a special horizontal rack, housing up to four converters, a common mains input with an RFI filter, and terminals to connect the loads.

The mains rectifier stage, the inverter stage, the transformer, the bi-polar output stage, the crowbar and the DCCTs are located in one 6 U high 19" module. The FGC electronics for each converter is located in each module.

The voltage detection across the resistive current leads is part of the converter electronics (See Sec.10.5 Interlocks and Quench Protection).

The main parameters are:

- Small signal bandwidth (amplitude 160 mV) over the full voltage range : > 500 Hz
- Voltage output ripple, under normal mains supply conditions:
  10 mV rms up to 50 Hz
  (without the precision current control loop)
  40 mV rms in the 300 Hz-60 kHz range
  above 60 kHz according to IEC 478-3C.
- Discharge circuit:

| | |
|---|---|
| Crowbar resistor | 100 mΩ |
| Crowbar activation level | 8.4 V |
| Maximum power to absorb by the resistive output circuit | 504 W |
| Maximum energy to dissipate | 12.6 kJ. |

More details can be found in the following references: [±60 A, ±8 V] converter Technical Specification [17] the Workshop on LHC Powering [11] and the Review of LHC Power Converters [12].

*Converters for warm magnets*

This family of power converters powers the following circuits:

- Two dump septa, 1000 A, 600 V.
- Four twin aperture, warm insertion quadrupoles in the cleaning regions, 810 A, 450 V.
- Two twin aperture warm separation dipoles in 3 and 7, 810 A, 950 V.
- Two single aperture recombination dipoles in 1 and 5, 810 A, 950 V.

The topology is similar to the one used for the main dipole converters, e.g. thyristor line-commutated 12-pulse parallel with passive filter and parallel active filter injection. The power converters will be installed in

the existing SR surface buildings. The twin aperture warm quadrupole converters are housed in a single cubicle and fed from the 400 V network. The separation recombination dipoles and the dump septa fed from the 18 kV network are composed of two modules, one containing the two 18 kV transformers and one rectifier filter module. The complete converter is air-cooled. The low time constant of the magnet allows energy discharge by a free-wheel diode. The air losses are ~ 20 kW per converter.

The main output performance parameters of the warm magnet voltage sources are:

- Voltage ripple without active filter: $1 \times 10^{-3}$ @ 50 Hz; $5 \times 10^{-3}$ @ 600 Hz
- Voltage ripple with active filter: $25 \times 10^{-6}$ @ 50 Hz; $0.5 \times 10^{-3}$ @ 600 Hz
- Low frequency (5-20 Hz) mains rejection without active filter: 10-20 dB
- Low frequency (5-20 Hz) mains rejection with active filter: 50-60 dB
- Small signal bandwidth without active filter: 70 Hz
- Small signal bandwidth with active filter (up to 4% of $V_{max}$): 5 kHz.

*The ATLAS converters*

The superconducting magnets of ATLAS will be powered by the same 1-quadrant switch-mode converters as those used for the LHC machine.

The power system of ATLAS includes two electrical circuits:

- 20.5 kA circuit for the Toroid magnet (converter based on [3.25 kA, 18 V] sub-converters).
- 8 kA circuit for the Solenoid magnet (converter based on [2 kA, 8 V] sub-converters).

*The ALICE and LHCb dipole converters*

Both the Alice and LHCb experiments require a 950 V, 6500 A power converter to supply spectrometer dipole magnets. The same topology as the machine main dipoles is used, i.e. 12-pulse parallel rectification with passive filter (Fig.1). The two 4.8 MVA cast resin rectifier transformers are supplied from the 18 kV network. The power converter output is equipped with a mechanical reversal polarity switch, which can only be operated when the power converter is off. The power converters are installed in building SR2 for Alice and SR8 for LHCb. They are composed of two transformers housed in one cubicle, two rectifier modules, two filter-choke modules, one capacitor module and one output module. Cooling is achieved partly by direct cooling and partly by forced-air cooling. The total air losses per converter are ~100 kW.

The main output performance parameters of this voltage source are:

- Voltage ripple: $1 \times 10^{-3}$ @ 50 Hz; $5 \times 10^{-3}$ @ 600 Hz
- Low frequency (5-20 Hz) mains rejection (without active filter): 10-20 dB
- Small signal bandwidth: 70 Hz.

*The Alice and LHCb solenoid converter*

The voltage source for the Alice solenoid is the refurbished LEP L3 power converter. The output ratings are 31 kA, 150 V. The high current is obtained by paralleling of six sub-converters. Each one is rated 5.2 kA, 150 V and composed of an oil-immersed 18 kV transformer, a 6-pulse thyristor bridge and a passive filter. A 30° phase-shift is applied to three sub-converters resulting in a classical 12-pulse configuration.

The converter modules are installed in the surface building SX2, while the six oil-immersed transformers are located in two tanks outside the building. The thyristor bridges are water-cooled, while the rest of the equipment is air-cooled. The total water losses are ~70 kW and are evacuated by a dedicated cooling station. The air losses are ~ 40 kW for the converter part inside SX2.

The main output performance parameters of the voltage source are:

- Voltage ripple $5 \times 10^{-3}$ @ 50 Hz; $2 \times 10^{-2}$ @ 600 Hz
- Low frequency (5-20 Hz) mains rejection without active filter: 10-20 dB
- Small signal bandwidth: 70 Hz.

*The Alice and LHCb compensator converters*

Alice and LHCb each require three compensation circuits: one central compensator and two outer correctors, left and right. The three converters are rated 600 A, 160 V for Alice and 1000 A, 180 V for LHCb.

The basic topology of this family is the same as for the main dipole power converter e.g. thyristor line-commutated 12-pulse parallel system with passive filter. No active filters are required. The power converters are supplied from the 400 V network and, like the Alice and LHCb dipoles, are also equipped with a mechanical polarity reversal switch. They will be installed in buildings SR2 and SR8. They are directly air-cooled and their total losses are ~12 kW per converter.

The main output performance parameters of the voltage sources are:

- Voltage ripple: $1 \times 10^{-3}$ @ 50 Hz; $5 \times 10^{-3}$ @ 600 Hz
- Low frequency (5 – 20 Hz) mains rejection without active filter: 10-20 dB
- Small signal bandwidth: 70 Hz.

*The CMS solenoid converter*

The power converter for the superconducting CMS solenoid is rated 20 kA, 26 V. The high current is obtained by the mounting four sub-converters in parallel. Each one is rated 5 kA, 26 V and composed of a 400 V transformer, a 6-pulse thyristor bridge, and a passive filter choke. A 30° phase-shift is applied to two sub-converters resulting in a classical 12-pulse configuration. The filter capacitors are common for the four sub-converters, acting as current sources. The complete converter is composed of the four sub-converter modules and a central module containing the capacitor and the control electronics. It will be installed underground next to the solenoid in USC55. The thyristor bridges and the filter chokes are water-cooled, while the rest of the equipment is air-cooled. The total water losses are ~70 kW. The total air losses are ~40 kW.

In order to handle the magnet current decay under worst fault conditions, i.e. power cut and no cooling water flow, the power converter is equipped with a free-wheel thyristor. This free-wheeling system is rated to handle the 20 kA up to 180 s without damage.

The main output performance parameters of the voltage source are:

- Voltage ripple: $5 \times 10^{-3}$ @ 50 Hz; $2 \times 10^{-2}$ @ 600 Hz
- Low frequency (5 – 20 Hz) mains rejection without active filter: 10-20 dB
- Small signal bandwidth: 70 Hz.

*The RF Klystron Power Converters*

This consists of four units, each rated 100 kV, 40 A and one spare. The complete LEP PA4 installation will be re-used as it was for LEP2 – see LEP Design Report, Vol. 2, Chap. 7.2, for a detailed description. Minor modifications will be made to the electronics to adapt it to the LHC power converter control system. Specific maintenance will also be carried out on all transformers and diode tanks.

### 10.4.2 DC Current Transducers

A dc current transducer is required to measure the converter output current in order to control it accurately. Presently 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.

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.

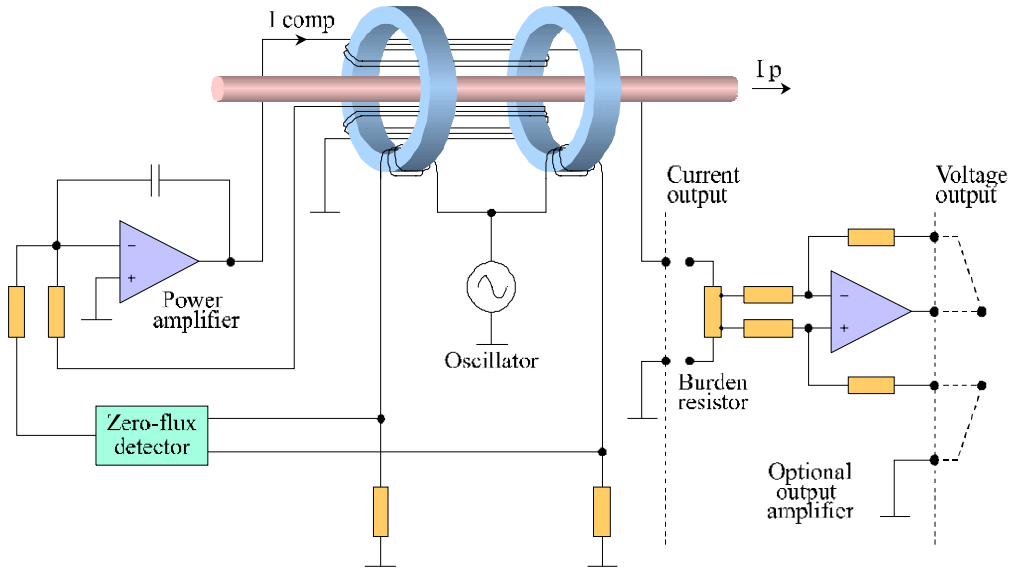

Figure 10.15: DCCT principle

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 (See Sec. 10.4.5). The principle requires that the DCCTs in question are equipped with an integral calibration winding in the transducer head.

Following the standardisation of converters in groups, minimising the number of different types, the DCCTs are also chosen in a small number of standard sizes and ratings. The groups with the largest quantities and the highest precision are in the main ring and all other types including the beam transfer are put together in the last class.

*4-13 kA DCCT with calibration windings*

The high current DCCTs have a separate transducer head including a calibration winding. The compensation current is either 2 or 5 A and the calibration current is standardised to 5 A for nominal ampere turns.

The electronics is housed in a 3U, 19" chassis, powered by 400/230 VAC. The burden resistor is a proprietary design employing specially processed wire to achieve a temperature coefficient of <1 ppm/K.

*600 A DCCT, main ring multipole correctors*

The medium current DCCTs employ a separate transducer head with a compensation current of 0.5 A. The electronics is housed in an 8TE Europa chassis module, powered with ±15 VDC from dedicated power modules located in the same 19” electronics chassis. The burden resistor is a special development, housed in a TO-3 package.

*120 A DCCT, main ring orbit correctors*

The low current DCCTs are fully integrated with the head and electronics in one box, powered with ±15 VDC from the converter electronics. The burden resistor is a standard high precision resistor.

When used in the 60 A corrector converters, the primary current is passed through the centre hole twice.

*800 – 8000 A DCCT, beam transfer, “warm converters” and experiments*

Originally aimed at the needs of the beam transfer, this DCCT requirement was very close to existing standard products on the market. The transducer head is separate with a compensation current of 1 A. The electronics is housed in a 1U, 19” chassis, powered by 230 VAC. The burden resistor is a special development from the DCCT manufacturer, optimising price and accuracy for this application.

For ATLAS and CMS, older 20 kA DCCTs are re-used to minimise cost.

### 10.4.3 Analogue-Digital Converters

The LHC demands an order of magnitude improvement in accuracy over previous CERN accelerators. New technology had to be developed also for the ADCs to satisfy this need and the Sigma-Delta conversion principle was judged to be the most promising to meet this aim. An industrial product was found for the medium precision, but an entirely new circuit had to be developed for the highest precision. A sigma-delta converter is basically a 1-bit analogue-digital converter with a very high conversion rate producing a high frequency bit-stream. This bit-stream is decimated and digitally filtered to obtain the desired word-stream at a much lower data rate. It is inherently monotonic, has a high noise rejection due to the integration stages and requires few high-precision components. The design of the digital part was made so that it is the same for the high-precision and medium-precision versions.

The medium precision converters are integrated in the FGC (Function Generator/Controller) design, but the high-precision version needs its own housing due to size, temperature control, power supply etc. All A/D converters are designed for 10 V full-scale input voltage and are bipolar.

The LHC tunnel environment presents a certain radiation level, which will affect some electronic components. An alternative ADC design, employing successive approximation technology, was also developed for use in the closed orbit correctors. This design has been tested at radiation levels significantly higher than LHC and was found to function correctly.

*22-bit Sigma-Delta ADC*

The analogue portion consists of an input buffer, 3 high-speed integrator stages, a comparator and a switched high-precision voltage reference. Matched precision resistors convert the reference voltage to a current fed back to the input integrator. The comparator produces a 1 MHz bit-stream to an optical fibre driver. Control logic monitors the operation and will reset the integrators if an out-of-range condition is detected. The analogue portion is completely enclosed in its own electrostatic shield box with thermal insulation. The high-precision components are temperature-controlled, the Zener reference at the semi-conductor chip-level and the others by a Peltier system. The unit is designed to minimise EMC problems through further power supply shielding and the use of optical isolation. The design is described in [28].

The digital portion located in the FGC consists of a fibre-optic input, a four-stage decimator/filter and control logic. It produces a 22-bit data word with 5 kHz data rate and a status word signalling validity and error conditions.

*16-bit Sigma-Delta ADC*

The analogue portion is based on a commercial integrated circuit, ADS1201, preceded by a multiplexer to enable monitoring of other analogue signals, including a separate precision voltage reference for periodic calibration to maximise accuracy. A temperature control is provided on the PCB for critical components to improve the temperature characteristics. The ADC produces a 16-bit word with 1 kHz data rate. Two identical channels are located together with the digital filters on a PCB in the FGC assembly. An FPGA contains all the control logic for handling both ADCs and multiplexers.

*16-bit Successive Approximation ADC*

The successive approximation design is made as similar as possible to the 16-bit Sigma-Delta design to simplify the design and the deployment. The analogue front-end is virtually identical with the same multiplexer and signal conditioning. The same data rate and control was adopted to ensure full compatibility with the FGC environment. A significant difference from the sigma-delta version is that there are no memories or control registers prone to single-event upset from radiation.

### 10.4.4 Power Converter Control System

The control system for the LHC power converters will follow the architecture used for LEP, with a dedicated controller embedded in every power converter. The controller will be responsible for function generation (current vs. time), current regulation and power converter state monitoring and control (on, off, reset). As a result, it is known as the Function Generator/Controller (FGC) and is a dedicated design with the following features:

- Compact, robust form, enclosed in an industrial quality metal cassette (6U x 20TE).
- Radiation tolerant design based on two microprocessors (M68HC16Z1 and TMS320C32) and 576KB of error corrected memory.
- WorldFIP 2.5Mbps network interface.
- RS232 9600 baud interface.
- Twin channel analogue inputs for DCCT current measurements.
- High resolution analogue output for voltage reference.
- Direct digital inputs for voltage source status monitoring.
- Direct digital outputs for voltage source and polarity changer control.
- Twin serial diagnostic input buses to collect analogue and digital voltage source signals.
- Dallas 1-wire identification bus to collect identity and, where needed, temperature information.

A small number of FGCs will also be used for function generation only by LHC RF. The FGC cassette will plug into a chassis.

- In the case of the 60 A power converter, the chassis will also contain the power electronics and its control card. The chassis will include a backplane that will have connectors for the FGC cassette, the control card and cables leading to the power electronics and the power supply for the FGC.
- For all the other types of power converter, a dedicated electronics chassis will hold either one or two FGCs, together with a high reliability power supply. This supply will be driven from 48 VDC, derived from 3-phase 400 VAC by an external power module. For the 120 A and 600 A power converters, a second power supply (also using 48 VDC) will be included for the DCCT electronics, and for the 600 A systems, the chassis will actually hold the DCCT electronics cards. The backplane in the chassis will combine DIN connectors on the front and Burndy connectors on the back, and in this way, all intermediate cabling will be avoided.
- There will be a backplane designed for each type of converter: 60 A, 120 A, 600 A, multi-kA switch mode, and thyristor. The FGC will be able to read a code that identifies the type of backplane it is plugged into.

*Function Generation*

In normal operation, each FGC will regulate the current in its circuit. During testing, open loop operation is possible, in which the voltage reference is set directly. In either case, a reference value must be derived as a function of time [37]. The FGC software supports a number of ways to do this by combining a predefined waveform with a real-time value received via the WorldFIP network.

The predefined wave-form can take various forms:

- Steps
- Sine wave
- Square wave
- PELP function (Parabolic Exponential Linear Parabolic)
- PLEP function (Parabolic Linear Exponential Parabolic)
- Table.

The PELP and PLEP functions are standard waveforms, defined by five parameters that combine parabolic start and end segments with linear and exponential middle segments.

A Table is defined by arrays of delta-time (milliseconds) and delta-reference (milliamps or millivolts depending upon the mode). The FGC will use linear interpolation in real-time to generate intermediate reference values. Since all the table values are relative, the complete waveform will also be relative to the reference value present at the moment when the table is armed. The number of points in a table will be limited to about 8000.

In all cases, the reference value is either constant or changing. When it is constant, the definition of the next change (e.g. a PELP or Table, etc…) can be downloaded and armed. The change will be triggered by a timing event. Once the change has been executed, the reference will hold the last value and the change is forgotten.

The actual reference at any moment can combine the predefined reference with a real-time value. Four options are supported:

- Ref. = F(t) Predefined waveform is the reference, no real-time contribution.
- Ref. = $F(t) + dF_{rt}$ Real-time value is an offset from the predefined reference.
- Ref. = $F(f)(1 + G_{rt})$ Real-time value is the fractional gain for the predefined reference.
- Ref. = $F_{rt}$ Real-time value is the reference, no predefined reference.

*Current Regulation*

A key task for each FGC is current regulation. It transforms a voltage source into a current source, which is what the global LHC control system requires for each circuit. In LEP, this was achieved using an analogue circuit; however, this was not an option for LHC. Many circuits have very large time constants (many hours) and yet require very high accuracy, and this can only be achieved with digital regulation. This was the main reason to include a second processor in the design. The device chosen is a low-cost floating-point digital signal processor (DSP) from Texas Instruments. It operates as a coprocessor for the Motorola microcontroller, performing the real-time tasks of function generation, digital filtering and current regulation.

*WorldFIP Gateways*

All the FGCs in the LHC will need to be controlled synchronously from the LHC control room. This will be done using 80 WorldFIP segments. WorldFIP is a 2.5 Mbps transformer coupled real-time fieldbus, based on twisted pair cabling. It can support 500m copper segments and up to 32 nodes between repeaters. gateway systems are needed to link the LHC IP technical network with the WorldFIP segments. The gateways will be based on LynxOS running on a PC platform. They will be installed in the LHC surface buildings. Each Gateway will include a timing receiver interface, connected to the LHC general machine timing network. This will provide the gateway with accurate date/time and millisecond level machine events. It will also generate precise timing pulses to synchronise the WorldFIP interface. Each gateway will drive a single segment with a maximum of 30 FGCs connected. In some cases, the cable will need to be more than 500 m long, in which case a repeater will be included.

The software in the gateway will support operational client applications via the LHC controls middleware (based on CORBA) as well as expert diagnostic client applications via TCP/UDP. It will also publish status information to the LHC alarm system via a central alarms gateway.

*Timing and events*

Each FGC has a 32 MHz quartz oscillator to generate its processor clocks. This can have a frequency error of up to 100 ppm. The WorldFIP network has a real-time behaviour enabling its 50 Hz transmission cycle to be triggered by an external signal, derived from the LHC general machine timing network. The error in the trigger signal will be less than one microsecond, and the jitter of the WorldFIP traffic will be less than 10 microseconds. This enables the FGC to run a software phase-locked loop to discipline a local digital real-time clock, based on the 32 MHz quartz oscillator. This allows frequency errors to be reduced to less than 0.1 ppm if the temperature is stable. If the WorldFIP traffic is lost for a period, the local FGC real-time clock will continue unaffected, smoothly re-synchronising when the traffic returns.

The first transmission of each WorldFIP cycle is a broadcast time/events variable. This includes UTC and event information, if an event is active. All events destined for the LHC FGCs must be warning events, indicating that a change of state should take place at a fixed time (typically 100 ms) in the future. This gives the gateways time to distribute the event via the fieldbus.

*FGC configuration*

Each FGC must be correctly configured for the power converter it is controlling. A subset of the FGC's properties are flagged as non-volatile, meaning they are stored in non-volatile (FRAM) memory within the FGC, and are also maintained in a central database. The local copy enables an FGC to reboot and re-establish control of a power converter in less than two seconds. However, following a reboot, the FGC signals via the gateway that it has been restarted, and a central FGC configuration manager program will interrogate the system during the following minute to check its validity. If an FGC is replaced, the configuration will no longer be correct, so the configuration manager will send the correct values from the database.

Configuration properties include:

- Circuit characteristics (e.g. resistance and inductance, maximum and minimum current and rate of change of current).
- Voltage source characteristics (e.g. maximum and minimum voltage and rate of change of voltage)
- ADC, DAC and DCCT calibrations.
- Current loop parameters (e.g. closed loop bandwidth).

The FGC configuration manager will also maintain the online equipment inventory, based on the Dallas 1-wire ID chips embedded in every FGC card and throughout the voltage sources and DCCT systems. More than 30'000 individual items will be tracked in this way, enabling reliable equipment management.

*FGC software management*

The FGC software is expected to evolve up to and beyond the startup of the LHC. To make this possible, the FGCs include non-volatile Flash memories for their Firmware. These can be reprogrammed as often as needed via the WorldFIP fieldbus or via the RS232 serial interface. Each system includes three separate Flash memory devices, one for the boot programs and two for the main program (the main program has two parts, one for each processor). Two Flash devices are needed so that the system can be running out of one while reprogramming the other.

The boot Flash is divided into two parts so that two different boot programs can be stored:

- Basic boot – this is as simple as possible and is the boot of last resort. It will be written into the boot Flash when the FGC processor boards are manufactured, and will never be changed. It cannot be rewritten over the WorldFIP or serial interface.
- Main boot – this will be a big program with two main objectives:
  1. In normal operation, to launch the main program on the two processors.
  2. When required, to provide extensive self-test functionality, enabling every aspect of the FGC to be tested.

The main program will be able to reprogram the main boot from the WorldFIP. If the reprogramming fails for any reason, the basic boot is always there to enable the system to recover.

The gateways will transmit the main boot and main programs continuously via four bytes of the time/events broadcast variable. It will take about twenty minutes per transmission (100 bytes/second). Both the basic boot and main boot will be capable of receiving this data and reprogramming one or other of the main firmware flash memories. The main program will also be able to receive this data stream in order to reprogram either the main boot, or a new version of the main program (into the other firmware flash memory).

A central FGC firmware manager program will permanently survey software versions, and will be responsible for the distribution of updates.

*Diagnostic system*

The vast majority of LHC power converters will be in underground areas, with nearly a half actually in the tunnel under the cryostat. This will make interventions difficult, so there is a strong need for high quality remote diagnosis of the power converter electronics. This need has been met using a serial diagnostic bus that threads its way through the power converter. Diagnostic Interface Modules (DIMs) can be connected to the bus to collect information. Each DIM has four analogue inputs (converted using a 12-bit ADC) and 24 digital inputs (two banks of 12). The FGC supports two DIM buses, each scanned at 50 Hz and each capable of supporting 15 DIMs for a maximum of 30 per power converter (i.e. 120 analogue inputs and 720 digital inputs). All the diagnostic signals are logged in circular buffers by the FGC, and are also available in real-time via four RT streams exported over the WorldFIP or serial interface. Each stream can send one analogue signal or one bank of 12 digital signals per 20 ms, for a total of 200 channels per second. Diagnostic interfaces are written in Labview to visualise this information. The interface can either run remotely via a gateway, or locally via an RS232 link.

A fundamental requirement of the diagnostic system is to identify the reason for any unsolicited power converter trips. It is common for the initiating fault to trigger a cascade of other faults, masking the original cause. The DIMs are designed to solve this problem by including a trigger input that freezes the state of the 24 digital inputs at the instant of the trigger (analogue inputs are not frozen). An 8 μs resolution counter is also frozen, so that the time of the trigger can be identified. In this way, the trigger order for different DIMs can be determined, and the first fault identified.

### 10.4.5 Current Calibration System

To maintain the high accuracy of the critical sub-systems (DCCTs and ADCs), periodic calibration is necessary. For high current DCCTs this becomes very difficult and cumbersome due to the physical size and adverse effects of transport. In LHC the situation is further complicated by the underground location and difficult access. High accuracy ADCs have similar constraints and are better calibrated in-situ under the typical environmental operating conditions.

A novel principle has been employed [25], calibrating the two devices together as a pair. The DCCT is equipped with a calibration winding, in which an accurate calibration current is injected producing the full nominal ampere-turns. The resulting digital value from the ADC is recorded and used to correct the value used for converter control. The evolution of this correction will determine the maximum interval necessary to achieve the target accuracy.

The problem of calibrating DCCTs and ADCs in the field has now been transformed into one of generating an accurate calibration current in the field, but of a reasonable value. This problem has been solved by the creation of a new 10 mA dc current standard and a remote-controlled, programmable current multiplier, the current calibrator, providing the necessary 5 A calibration current. A voltage booster has been added externally to provide the power necessary for the winding resistance without incurring excessive power dissipation in the sensitive environment of the calibration current source.

A computer will be part of each calibration cluster to manage the full remote control of the current calibrator, the voltage booster and the switching matrix. It will have a network connection to receive and return calibration data from the operations database for each converter under its control. In this way full tracking of calibration history can be maintained for each calibrated sub-system and can be used for further performance improvements over time. The local computer will only have full freedom to perform calibration operations during the calibration mode of the LHC.

*Current Calibrator*

The current calibrator is essentially a current multiplier providing extremely precise current ratios [30]. The input current is 10 mA dc, provided by a current source known as the PBC, see below. The heart of the device is a transformer with primary windings in a binary succession from 1 to 2048, Fig. 10.16, giving a maximum of 40.96 ampere-turns. These primary windings can be switched in and out at will with relays, providing the 12 most significant control bits. An additional 1-turn winding is fed from a DAC with 10 mA full-scale output, providing another 16 bits. The total theoretical resolution is 28 bits, but noise reduces the practical resolution to around 24 bits.

Secondary windings are provided with 4 to 40 turns, giving secondary output current ranges from 1 to 10 A. The compliance of the device is only a few volts at the output terminals.

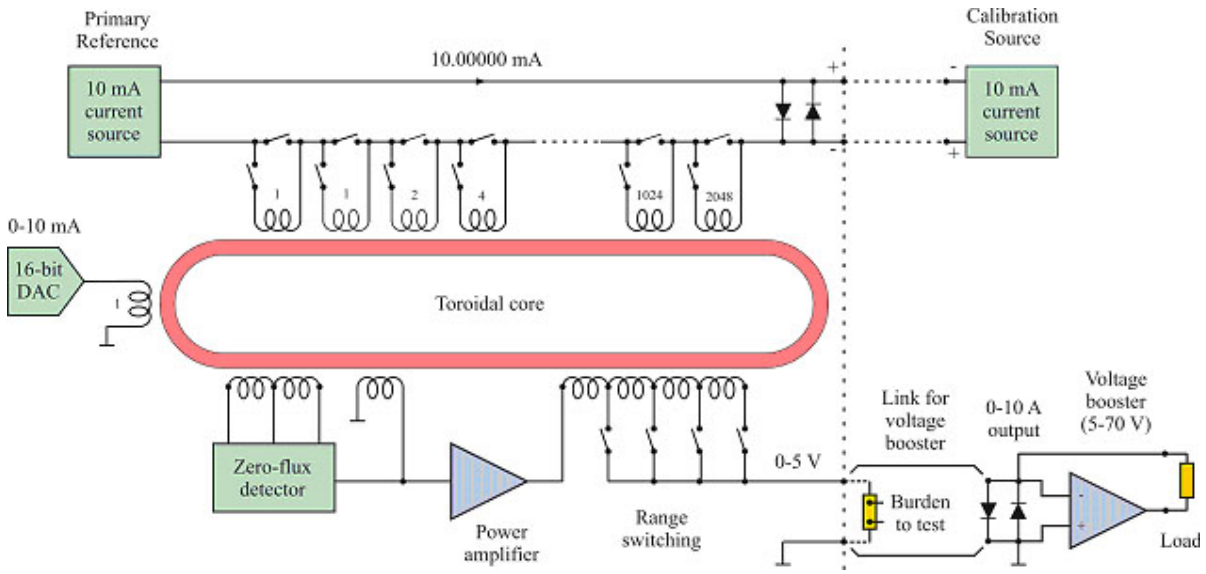


Figure 10.16: Current calibrator principle

*Primary standards and calibration infrastructure*

Any calibration structure starts with the traceability to national standards. The CERN standards lab has several sets of reference voltage and resistance standards. Mobile standards are employed to transport the Volt and the Ohm from the Swiss National Standards Laboratory (METAS) in Bern to Geneva. Fixed standards, maintained in a well controlled environment, provide the local calibration platform at CERN. Intercomparison with METAS is performed at least once per year and provides a local accuracy of better than 0.5 ppm for both voltage and resistance.

At CERN's initiative a new 10 mA dc current standard (named PBC) was developed and has already been produced and proven in sufficient numbers [31]. Through the use of 10 V voltage standards and 1 kΩ resistance standards, the PBC can be calibrated to better than 0.5 ppm uncertainty and is the beginning of the current calibration chain. Certain PBCs are assigned as mobile transfer standards and move the 10 mA to the different LHC locations. There the 10 mA is transferred to the PBCs located in the current calibrators described earlier. The transfer procedure maintains the highest accuracy and is well adapted to field use. The aim is to maintain the local 10 mA with an uncertainty better than 1 ppm.

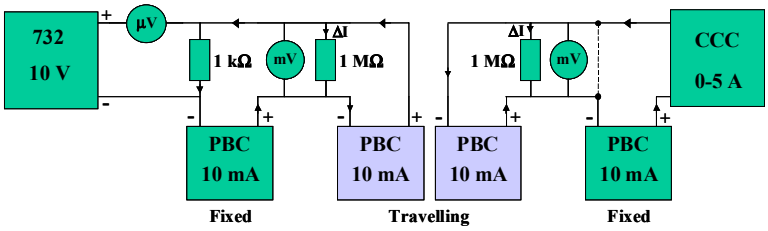


Figure 10.17: Calibration transfer chain

*Ancillary equipment – Voltage booster*

The current calibrator has a compliance of only a few volts, to limit internal power dissipation and its variation. The calibration windings in the DCCT heads have a resistance of several Ohms so the voltage drop will be substantial. A voltage booster has been designed to bridge this gap, also considering that a calibration

winding has to be driven from a high-impedance source not to disturb the DCCT zero-flux detector and control loop. The booster output voltage is controlled by a loop maintaining zero voltage at the output of the current calibrator. The output stage is a trans-conductance amplifier with a compliance voltage of up to 70 V.

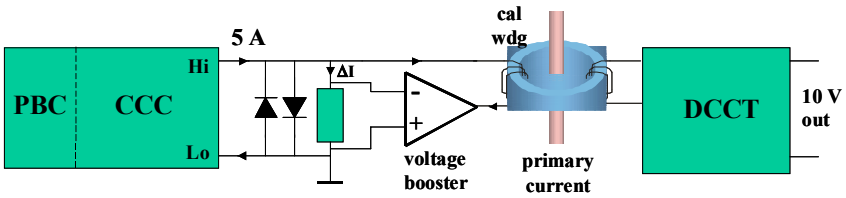


Figure 10.18: Voltage booster configuration

This configuration will ensure that all of the current delivered by the current calibrator will pass through the calibration winding and that problems of leakage currents are virtually eliminated.

*Ancillary equipment – Switching matrix*

Several DCCTs have to be handled by each cluster and its current calibrator. The booster output voltage will therefore be routed through a relay switching matrix. The relays will determine which DCCT(s) will be connected and which will be bypassed. An output voltage measurement and a zero-current measurement are also included to provide some self-checking of the calibration operation.

*Ancillary equipment – Air-conditioned racks*

All the high-precision equipment will be located in air-conditioned 19" racks to provide a temperature-controlled environment with predictable accuracy in the calibration results. The temperature control is fixed to 23 ±1°C. Industrial air-conditioning equipment fed with CERN's chilled water. The controller is of PID type, steering a proportional valve for best performance and to minimise EMC problems.

The racks are designed with consideration to the potential EMC problems in the vicinity of high-power switch-mode converters.

## 10.5 SPECIFIC REQUIREMENTS PLACED ON OTHER SYSTEMS AND THEIR INTERFACES

*AC Power Requirements of the Power Converter System for the LHC magnets*

All power converters located underground are fed from a 3-phase 400 V source with the exception of the eight power converters for the main dipole circuits which are fed directly from 18 kV. The electrical input parameters for each type of converter are given in LHC Powering Database.

To be able to monitor the magnet current even in case of mains failure, the FGC as well as the DCCT and the Sigma-Delta ADC are supplied by UPS for circuits above 4 kA [32]. It concerns the 1-quadrant converters (type RPHE, RPHF, RPHG, RPHH) and the main dipole converters.

All the power converters conform to the Engineering Specification concerning the main parameters of the LHC 400 V/230 V distribution system [8]. This document defines the main parameters of the 400 V and the user requirement.

For the UPS grids, the power converters conform to the Engineering Specification concerning the Underground Uninterrupted Power Supply (UPS) for LHC [34].

For more details of the harmonics generated by the switch-mode converters, see technical notes [22] and [23].

Tab. 10.8 gives the power consumption of the power converters for the machine in steady-state (collision) and peak (just at the end of the energy ramp) for a main dipole field of 9 Tesla. They are given for the eight points of the machine and various areas within those points. Tab. 10.8 corresponds to the LHC Powering Database V6.4.

Table 10.8: AC power consumption

| Location(s) | | Steady State Power | | Peak Power | | UPS |
|---|---|---|---|---|---|---|
| | | Real kW | Apparent kVA | Real kW | Apparent kVA | Apparent kVA |
| Point 1 | RR13/RR17 | 407/407 | 443/443 | 457/457 | 488/488 | 16.5/16.5 |
| | UJ14 | 124 | 135 | 142 | 152 | 4.3 |
| | UJ16 | 125 | 136 | 143 | 153 | 4.3 |
| | SR1 | 462 | 917 | 465 | 917 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **1550** | **2101** | **1722** | **2260** | **41.6** |
| Point 2 | UA23 ** | 1408 | 1536 | 3745 | 4877 | 26.5 |
| | UA27 ** | 1443 | 1573 | 3780 | 4914 | 26.5 |
| | UJ23 | 6 | 7 | 8 | 9 | --- |
| | SR2 | 180 | 412 | 181 | 412 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **3062** | **3555** | **7772** | **10274** | **53.0** |
| Point 3 | UJ33 | 603 | 652 | 629 | 676 | --- |
| | SR3 | 1367 | 2000 | 1375 | 2000 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **1995** | **2679** | **2062** | **2738** | **0.0** |
| Point 4 | UA43 ** | 1314 | 1435 | 3622 | 4747 | 20.1 |
| | UA47 ** | 1314 | 1435 | 3616 | 4740 | 20.1 |
| | UJ43/UJ47 | 8/8 | 9/9 | 11/11 | 11.5/11.5 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **2669** | **2915** | **7318** | **9572** | **40.2** |
| Point 5 | RR53/RR57 | 407/407 | 443/443 | 457/457 | 487/487 | 16.5/16.5 |
| | UJ56 | 131 | 142 | 149 | 159 | 4.3 |
| | USC55 | 146 | 159 | 164 | 176 | 4.3 |
| | SR5 | 463 | 917 | 466 | 917 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **1579** | **2131** | **1751** | **2288** | **41.6** |
| Point 6 | UA63 ** | 859 | 936 | 3127 | 4213 | 15.7 |
| | UA67 ** | 859 | 936 | 3133 | 4219 | 15.7 |
| | UJ63/UJ67 | 152/152 | 1677167 | 169/169 | 181/181 | --- |
| | SR6 | 1117 | 1585 | 1135 | 1585 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **3164** | **3818** | **7791** | **10441** | **31.4** |
| Point 7 | RR73 | 80 | 86 | 92 | 97 | --- |
| | RR77 | 81 | 87 | 93 | 98 | --- |
| | UJ76 | 264 | 286 | 265 | 287 | --- |
| | SR7 | 1063 | 2000 | 1069 | 2000 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **1513** | **2486** | **1577** | **2544** | **0.0** |
| Point 8 | UA83 ** | 1391 | 1518 | 3725 | 4855 | 26.5 |
| | UA87 ** | 1411 | 1540 | 3749 | 4881 | 26.5 |
| | UJ83 | 8 | 9 | 11 | 12 | --- |
| | UJ87 | 7 | 8 | 10 | 11 | --- |
| | SR8 | 149 | 160 | 149 | 161 | --- |
| | Octant * | 25 | 27 | 58 | 62 | --- |
| | **Total** | **2991** | **3262** | **7702** | **9982** | **53.0** |
| **Power Converters*** ** | **Total** | **18523** | **22947** | **37695** | **50099** | **260.8** |

* Orbit corrector Power Converters distributed along the tunnel

** Including power taken directly from 18 kV

*** Only Power Converters for the magnets of the LHC machine. Does not include RF system nor the main experiment's magnets (central and outer compensators for Alice and LHCb are included)

*Cooling Requirements of the Power Converter System for the LHC magnets*

Considering the large currents involved, most of the power converters used for the LHC magnets are water-cooled. However, it is impossible to capture all losses in water and it is estimated that approximately 10% of the total losses are lost to air. The power converters of 120 A and less which are installed underground, are only air-cooled, as are all power converters installed on the surface. The losses for each type of converter are given in LHC Powering Database.

The rack housing the DCCT electronics and the Sigma-Delta for the high precision circuits (Main Dipoles and Inner Triplets) are cooled by chilled water. All water-cooled converters are tested at 22 bars pressure for half an hour. All the power converters conform to the Engineering Specification concerning the LHC demineralised water circuit [21]. The rack housing the DCCT electronics and the sigma-delta for the circuits with high precision, conform to the engineering specification for the LHC chilled and mixed water circuit [27]. This document defines the main parameters of the demineralised water circuits and the user requirement. All power converters conform to the Engineering Specification concerning the Air Handling of the LHC Tunnel and its Underground Areas [27].

Tab. 10.9 gives the water consumption and air losses of the power converters for a main dipole field of 9 Tesla. They are given for the eight points of the machine and various areas within those points. Tab. 10.9 corresponds to the LHC Powering Database V6.4 [10].

Table 10.9: Water and air losses

| Location(s) | | Mixed Water Consumption ($m^3/h$) | Water Losses (mixed water) kW | Air Losses kW |
|---|---|---|---|---|
| **Point 1** | RR13 | --- | 150.9 | 32.2 |
| | RR17 | --- | 150.9 | 32.2 |
| | UJ14 | 0.4 | 39.5 | 8.7 |
| | UJ16 | 0.4 | 39.5 | 8.7 |
| | SR1 | --- | --- | 39.9 |
| | Octant* | --- | --- | 22.0 |
| | Atlas | --- | 44.0 | 4.9 |
| | **Total** | **0.8** | **424.8** | **148.6** |
| **Point 2** | UA23 | 1.0 | 428.4 | 102.1 |
| | UA27 | 1.0 | 430.0 | 106.7 |
| | UJ23 | --- | --- | 4.4 |
| | SR2 | --- | --- | 347.2 |
| | Octant * | --- | --- | 22.0 |
| | Alice | --- | --- | 12.0 |
| | **Total** | **2.0** | **858.4** | **594.4** |
| **Point 3** | UJ33 | --- | 135.3 | 32.6 |
| | SR3 | --- | --- | 99.6 |
| | Octant * | --- | --- | 22.0 |
| | **Total** | **0.0** | **135.3** | **154.2** |
| **Point 4** | UA43 | 0.6 | 380.8 | 88.5 |
| | UA47 | 0.6 | 380.8 | 88.5 |
| | UJ43 | --- | --- | 4.4 |
| | UJ47 | --- | --- | 4.4 |
| | Octant * | --- | --- | 22.0 |
| | **Total** | **1.2** | **761.8** | **207.8** |
| **Point 5** | RR53 | --- | 150.9 | 32.2 |
| | RR57 | --- | 150.9 | 32.2 |
| | UJ56 | 0.4 | 39.5 | 8.7 |
| | USC55 | 0.4 | 39.5 | 8.7 |

| Location(s) | | Mixed Water Consumption ($m^3/h$) | Water Losses (mixed water) kW | Air Losses kW |
|---|---|---|---|---|
| | SR5 | --- | --- | 39.9 |
| | Octant * | --- | --- | 22.0 |
| | CMS | --- | 70.0 | 40.0 |
| | Total | 0.8 | 450.8 | 183.7 |
| **Point 6** | UA63 | 0.6 | 286.9 | 77.4 |
| | UA67 | 0.6 | 286.9 | 77.4 |
| | UJ63 | --- | 55.5 | 8.6 |
| | UJ67 | --- | 55.5 | 8.6 |
| | SR6 | --- | --- | 78.3 |
| | Octant * | --- | --- | 22.0 |
| | Total | 1.2 | 684.8 | 272.3 |
| **Point 7** | RR73 | --- | 49.7 | 12.8 |
| | RR77 | --- | 49.7 | 12.8 |
| | UJ76 | --- | 34.6 | 4.9 |
| | SR7 | --- | --- | 99.6 |
| | Octant * | --- | --- | 22.0 |
| | Total | 0.0 | 134.0 | 152.1 |
| **Point 8** | UA83 | 1.0 | 430.0 | 102.3 |
| | UA87 | 1.0 | 428.4 | 102.1 |
| | UJ83 | --- | --- | 4.4 |
| | UJ87 | --- | --- | 4.4 |
| | SR8 | --- | --- | 346.0 |
| | Octant * | --- | --- | 22.0 |
| | LHCb | --- | --- | 12.0 |
| | Total | 2.0 | 858.4 | 593.2 |

* Orbit corrector Power Converters distributed along the tunnel

*Interlocks and quench protection*

In addition to circuits for its own protection, the converters also include:

**Machine protection**

- All converters are part of the LHC machine protection, managed by the powering interlock system. The interface between power converters and powering interlock system depends on the type of electrical circuit (energy stored in the circuit and function of the magnets).
- A "green light" for powering, PC_PERMIT, is required for all circuits. This signal interlock will inhibit any start command, if not present.
- In case of a failure noticed by the power converter, a POWERING_FAILURE signal is issued. Such failures include failures of the power converter itself, failures in the supply (water, electricity) etc. This signal could, depending on the type of circuit, request a beam dump.
- For an emergency stop of the power converter, for example after a quench, the power converter receives the PC_FAST_ABORT signal. Due to the fact that the emergency stop must be as reliable as possible, a redundant way to switch off the converter is implemented in each converter managing this signal.
- To verify if the connection between power converter and powering interlock system is made, a PC_CONNECT signal will be used by the powering interlock system.

For more details, see the converter Technical Specification [13, 14, 15, 16, 17] and the Engineering Specifications on the Powering Interlock System [18].

**Earth fault detection**

The earthing circuit is part of the power converter electronics. This circuit has 4 roles:

- earthing of the load circuit (DC side) for safety reasons.

- detection of an earth fault.
- monitoring of the leakage current.
- limitation of the earth current in case of an earth fault to avoid damaging the circuit elements.

Earthing of the circuits is made with active detection so that an earth fault can be detected before powering the circuits.
For more details, see the converter Technical Specifications [13, 14, 15, 16, 17] and the Engineering Specification on the Earthing Circuit [36].

**Water-cooled load cables for the 1-Quadrant converters**
A flow-meter signal is transmitted to the 1-Quadrant converters for the protection of the water-cooled cables going from the output of the converter to the DFB to avoid a burnout of the cable in case of water-cooling failure. Should this event occur, each converter will receive an open contact indicating no water flow in the cable. The converter will switch off immediately and trigger the fastest extraction of the magnet energy (dump resistor insertion or quench heater firing).
For more details, see the converter Technical Specifications [13, 14].

**Over-current**
All converters types will switch off when an over-current condition is detected. In most cases, the threshold is adjustable in a series of steps.
For more details, see the converter Technical Specifications [13, 14, 15, 16, 17].

**Resistive Current lead protection**
In order to determine the electrical resistance and the heat dissipation of the resistive current leads, voltage taps are used at the warm and cold ends of the current leads (Fig. 10.19). The voltage drop between the warm and cold ends of a current lead is measured by the converter. If the voltage drop across one of the leads goes beyond a certain threshold, the power converter will switch off within 100 ms. Special hardware will be installed in the (±600 A, ±40 V) used as (±120 A, ±40 V), the (±120 A, ±10 V) and (±60 A, ±8 V) converters that are used for powering LHC circuits up to 120 A.
In addition, a test routine will be performed periodically to verify the validity of the measurement, i.e. whether the voltage tap connections are open-circuit or in short-circuit. The test routine consists of delivering maximum current to the magnet and checking if the voltage drop across the lead is above a certain threshold (which is lower than the normal trip threshold).
For more details, see the Engineering Specification on the Current Leads protection for LHC circuits up to 120 A [35].

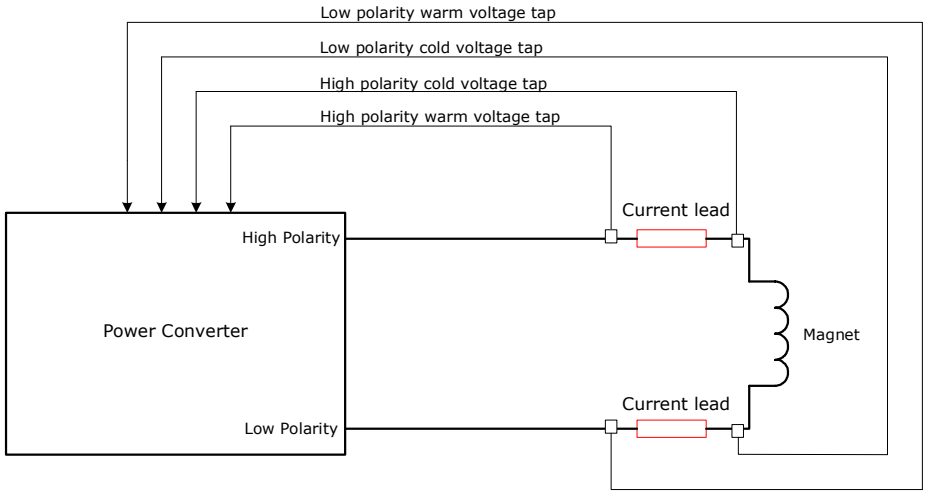


Figure 10.19: Current lead voltage taps

*EMC*

The power converters fulfil EMI standards for the immunity of the equipment and for conductive noise emission.

- Electrical fast transient/Burst immunity test IEC 6100-4-4, level 4
- Conductive noise emission

| | |
|---|---|
| Common Mode (AC and DC sides) | IEC 478-3, curve C (1mV above 0.5 MHz) |
| Differential Common Mode under 130 kHz | See the ripple requirement depending of the converter type (See Sec. 10.4) |
| above 130 kHz | IEC 478-3, curve C (1 mV above 0.5 MHz). |

## 10.6 OPERATIONAL ASPECTS

Unlike the LEP power converters, the LHC power converters will be installed underground, where access is difficult. As a consequence, the various systems will not be accessible during the machine runs. It will also be very difficult to repair them in the tunnel as large quantities of equipment will be installed in areas with limited access (radiation and cryogenic risks).

To meet these new constraints, different strategies have been developed depending on the type of equipment installed (Voltage source, DCCT or Function Generator Controller FGC).

### 10.6.1 Voltage Sources

The voltage sources (VS) MTBFs are estimated to be 100'000 hours. From this we obtain the fault frequencies versus the voltage sources categories.

Table 10.10: Voltage sources

| VS categories | Number of VS | Fault frequencies |
|---|---|---|
| Thyristors | 32 | 130.21 days |
| High Current (2 kA et 3.25 kA) | 208 | 20 days |
| Medium Current (600 A et 120 A) | 726 | 5.7 days |
| Corrector (60 A) | 752 | 5.5 days |

According to the voltage source categories, different operating strategies will be chosen.

*a. Thyristor voltage sources*

The thyristor voltage sources are easy to repair and the failures usually occur in the control electronics. It is planned to have spare units for main power elements (transformer, inductance, capacitors and semiconductors). In addition only the main dipole power converters and the CMS power converter are installed underground – all others are installed on the surface in the SR buildings. In the event of failure (once or twice per year) the operator will repair the voltage source by simply changing an electronics card. A major problem would be the exchange of an 18 kV transformer or a passive filter choke in the main dipole converter. This event could take 2 or 3 days, but the probability of such an event is only one in ten years.

*b. 2 kA/3.25 kA voltage sources*

The 2 kA/3.25 kA voltage sources are switch-mode power converters with several sub-converters in parallel to achieve the high output currents. These voltage sources were designed with an additional sub-converter as an active spare. If one sub-converter fails, the other sub-converters are able to deliver the required output current. The operator may then wait until the end of the run to change the failed module. The travel and the access procedure could take up to 1h30min and the change of the module will take around 15 minutes. The maintenance of the failed module will be performed on the surface without any operational constraints. Furthermore this redundancy strategy leads to less stress on the module components: normal operation will be at 75 to 80% of rated power.

*c. 600 A and 120 A voltage sources*

These voltage sources are modular (as are the other power converters installed in the tunnel), however it is not possible to have an active spare for these voltage sources due to cost and volume constraints. Although a large number of interventions will be required, these will be short as the failed module will simply be replaced, taking very little time.

*d. 60 A voltage sources*

The 60 A voltage sources will cause a large percentage of the total voltage source interventions. The LHC is however designed to work with 2 - 4% of the corrector power converters out of operation. A monthly campaign is scheduled for the replacement at the same time of all faulty corrector converters; critical cases will have to be replaced immediately. To make this strategy possible, at least 10% of the total 60 A converter quantity must be kept ready as spares.

### 10.6.2 DCCTs

In each power converter there are two DCCTs. With digital current regulation, the FGC is able to automatically change to the second DCCT for regulation, if the first one fails. Some types of DCCT failures can be detected and signalled. Other failures are of such character that it will be impossible to tell which one of the two DCCTs has failed. This strategy should minimise the downtime in case of a DCCT failure.

In line with other power equipment, the DCCTs are of modular design to minimise the intervention time. The only lengthy operation is the change of a DCCT head (this operation could take up to 5 hours for the high current DCCTs) but it should be very rare (one change every 3 years).

### 10.6.3 Function Generator Controller (FGC)

The FGC has been designed with an MTBF of 1’000’000 hours. With approximately 1750 units installed in the machine, the fault rate will be in the order of one every 24 days. However, with half of the FGC systems being installed in the 60 A correctors, it is estimated that an FGC failure will only cause a machine shut down once every 48 days. It is virtually impossible to design in full redundancy to eliminate this problem.

### 10.6.4 Diagnostic Interface Module (DIM)

A diagnostic system has been developed to optimise efficiency of interventions. This system identifies the failure prior to sending personnel on site and interventions can be better planned to limit the downtime. The second functionality of this system is to follow the power converter parameters during machine running and identify areas requiring maintenance before a failure occurs.

### 10.6.5 Radiation

It is well understood that radiation has an adverse affect on electronics and that some technologies are more vulnerable than others. Both the 60 A voltage source and the FGC control electronics have been designed taking this into consideration, thus failures due to radiation damage are simply an additional factor contributing to the MTBF mentioned in Chaps. 10.6.1 and 10.6.3. Tests conducted both at CERN and at a Belgian cyclotron facility have demonstrated an acceptable tolerance to the doses and fluences predicted for the LHC tunnel. However, a significant number of larger power converters will be installed in the RR and UJ underground areas, where recent studies indicate that while the cumulative radiation dose will be low, there will be a non-zero neutron fluence that may cause disruption to electronics due to Single Event Upsets. Extra shielding is now being designed to reduce the levels in these areas, and the FGC electronics are not expected to have a problem. However the larger voltage sources and DCCTs have not been designed to withstand radiation of any sort, so there is some level of uncertainty in the performance of these systems. These designs will shortly be audited to determine the expected levels of susceptibility, following which an action plan will be developed.

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