WP06B in a nutshell – Warm Powering

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New power converters are required to power the new superconducting magnets of the HL-LHC project. New types and new topologies of power converters will be required. All new power converters for the inner triplet magnets and matching section magnets will be installed in new underground gallery.

**HL-LHC High Luminosity LHC Project WP06a - Warm Powering**

**WP 06b - Warm Powering - Power Converters**
- WP 6B - Warm Powering - 18kA Converters
- WP 6B - Warm Powering - 13kA Converters
- WP 6B - Warm Powering - 6kA Converters
- WP 6B - Warm Powering - 4-quadrant converters
- WP 6B - Warm Powering - Power converters - Measurement & controls

![Power Converters Diagram](image)

**Fig. 1 - Power converters in the HL-LHC project**
Fig. 2 - From left to right, Power converters for main quadrupoles (13kA/18V) and for ATLAS toroid (20.5kA/18V)

Fig. 3 - Power converters for individual quadrupoles (6kA/8V)

Fig. 4 - Power converters for correctors and for 4-quadrant for correctors
Fig. 5 - Power converters underground installation

Fig. 6 - Integration of new power converters the new underground galleries

Fig. 7 - FGC2 (Function Generator/Controller) at the left and FGC3 at the right
GENERAL PARAMETERS

The LHC was built with modular power converters to facilitate maintenance and integrate the redundancy principle. Redundancy was included in all LHC power converters rated at currents above 600 A. This has proven to be a real asset during operation. The n+1 redundancy allows the power converters to be run even with one module in fault. The advantages are the following:

i) in case of fault, only one sub-converter is not operational and, in most of the cases, the fault does not generate a beam dump;

ii) the LHC can run with some faulty sub-converters in the machine and all interventions for repair can be performed during a machine technical stop.

With the exception of dipole magnets, switch-mode technology was chosen for the LHC power converters in order to minimize their size and assure low output voltage ripple. All LHC power converters rated at currents above 120 A are water-cooled, with the advantage of a reduced size of the hardware. All these design principles will be maintained for the new power converters of the HL-LHC magnets.

POWER CONVERTERS FOR THE HL-LHC

The new power converters for inner triplet and matching section magnets can be seen in the below table:

<table>
<thead>
<tr>
<th>Equipment code</th>
<th>Power converter</th>
<th>Current</th>
<th>Voltage</th>
<th>Quantity per IP side</th>
<th>Quantity per UR</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCRPAFE</td>
<td>Type 1</td>
<td>18 kA</td>
<td>±8 V</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>HCRPAFF</td>
<td>Type 2</td>
<td>13 kA</td>
<td>8 V</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>HCRPBAA</td>
<td>Type 4</td>
<td>±2 kA</td>
<td>±10 V</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>HCRPMBAA</td>
<td>Type 5</td>
<td>±600 A</td>
<td>±10 V</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>HCRPLB</td>
<td>Type 6</td>
<td>±120 A</td>
<td>±10 V</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>

Fig. 8 - List of new power converters for HL-LHC

The HL-LHC will require the development of two types of new power converters:

i) The 2-quadrant converter 18 kA/±8 V, which requires research of new power converter topologies. This development is mandatory for a ramp-down of the Inner Triplet magnets in less than 30 minutes.

ii) The 4-quadrant converter ±2 kA/±10 V, which will be based on a new topology developed for R2E 600 A power converters.

Based on the new integration layout, the length of the warm DC cables, between the power converters and the electrical feed-boxes is drastically reduced. Present DFBX are placed in the LHC machine close to the superconducting magnets while the new DFHX will be placed in the UR galleries very close to the power converters.

As the resistance of the DC cables becomes very low (less than 1 mΩ), the time constant of the circuit \( \tau \) becomes very high (up to thousands of seconds). With classical 1-quadrant converter, the current ramp-down is done in free-wheeling process and the magnet energy is dissipated in the resistive part of the circuit: the cables. It takes around \( 5\tau \) for the free-wheeling process to return to the injection current. In order to improve the ramp-down time, the power converter needs to be able to recover the magnet energy. A way to do so is by applying negative DC voltage on the magnets. The main power converter of the Inner Triplet circuit should then be 2-quadrant, the output current is always positive, the output voltage can be either positive or negative.

Today at CERN, only thyristor rectifiers can operate in 2-quadrant mode but with the drawback of low-order harmonics present in the spectrum of the DC voltage. These harmonics generate blow-up of the beam and shall be avoided to reach the high luminosity performance of HL-LHC.
The 2-quadrant R&D program is targeting power converter topologies able to operate in 2-quadrant which includes the management of the energy given back from the superconducting magnets to the converter during the ramp-down.

**HIGH CURRENT 2-QUADRANT POWER CONVERTERS**

A new family 2-quadrant power converters should be developed using switch-mode technology in order to keep the same good principles of the present LHC power converters. Energy management will be studied to find the best way to control the recovered magnet energy. The most classical solution is to dissipate in the resistive part of the circuit but thanks to improvements of electrical storage like the last generation of batteries (driven by the development of electric vehicles), this energy could be stored and re-used during the next cycle.

The introduction of energy storage brings another advantage by reducing the power taken from the grid.

The sizing could be done as follow: only the losses of the transmission chain (losses in the converter, heat in the warm DC cables) will be taken from the grid while the magnet energy is provided and recovered by the electrical storage element. The energy flow between grid, storage and magnet should be optimized in order to maximize efficiency and lifetime of the storage element.

Researches will be focused on power converter topologies, energy management and energy storage system. The goal will be to keep reliability as high as possible, while improving size, power quality (harmonics on the grid as well as current ripple on the magnet) and efficiency.

A first demonstration with prototypes is expected to be built by 2019. The series production will take place by 2021.

**2 kA 4-QUADRANT POWER CONVERTERS**

The powering of the corrector magnets usually requires operation in positive and negative current. Three families of 4-quadrant power converters were developed for the LHC machine to cover all corrector magnet families, ranked 60 A, 120 A and 600 A. With HL-LHC project, a new family of 4-quadrant power converter is required as the correction magnets are rated up to 1.6 kA. The present families are made with a unique power module rated at the maximum current, meaning without modularity nor redundancy. In the high current family, the redundancy principle has demonstrated all its interest for the maintenance and for the availability of the machine. In the framework of R2E, the 600 A converter was redesigned with introduction of redundancy. The power module is rated 300 A and two modules are placed in parallel to reach 600 A. In case of fault, and with a magnet current below 300 A, a power module failure will not stop the operation of the machine, as the second one will keep the magnet current constant. The redundancy is limited to 50% of the maximum current but most of the correctors operate far below their maximum current. This improvement shall reduce by 80% the beam dump due to 600 A failure.

For the new 2 kA family, the same redundancy principle will be used. The power converter will be done with five power modules rated 400 A in parallel. They shall be identical or based on the recently developed 600 A power module.

The tendering of these power converters is planned to take place during 2021.

**CONTROL ELECTRONICS: FGC4**

LHC power converter control is based on an “all-digital approach”. The hardware that implements this “all-digital” control is called FGC (Function Generator/Controller); in particular, for LHC more than 1700 FGC2 units are deployed with two main tasks:

- management of the voltage source state;
- regulation of the circuit current (by means of RST control algorithm).

The network interface of FGC2 is based on WordFIP 2.5 MHz fieldbus (see Figure 6B-19 left). Major effort was also devoted to make the controller radiation tolerant and capable of guaranteeing very high reliability.
More recently it has been developed a new version of FGC [11]: FGC3 (see Figure 6B-18 right) which works with the same principles but is produced with up-to-date analogue and digital components. Its network interface is based on a dedicated implementation of 100 Mbps Ethernet called FGC-Ether which is also used for very low jitter synchronization. In addition to the FGC3 control unit itself a broad set of dedicated mixed analogue and digital boards have been developed by EPC under the name of RegFGC3; with this additional dedicated electronics the “all-digital” approach has been extended to the full control of the power converter (not limited anymore simply to current control).

FGC3 is the outcome of a development phase that spanned from 2006 to 2011 and whose production started in 2012. It represents the standard for power converter control for current and upcoming accelerators. However, for HL-LHC, whose installation is foreseen in LS3 (effectively starting in 2024), FGC3 will likely suffer obsolescence. The development of its successor FGC4 is therefore needed. FGC4 will be based on the same principles that have been proven effective in LHC such as direct implementation of current regulation and management/monitoring of the voltage source, but will also allow the full control of the power converter (both current and voltage sources). This approach will allow complete freedom in the commercial strategies: procurement of fully functional voltage sources (as per LHC) or procurement “build-to-print” of power converters fully designed by CERN. In addition to a high reliability design of the control unit itself one of the main features of FGC4 will be the hardware support for the maximization of the availability of power converters strategies currently under development.

The larger bandwidth offered by the 100 Mbps Ethernet will allow much better monitoring compared to the WordFIP network fieldbus currently adopted for LHC. New capabilities will be implemented both in hardware and in software (development of new libraries). These additional features will improve online diagnostics both for the LHC operators and beam physicists to perform their analysis and for the power converter experts to potentially speed up commissioning and troubleshooting.

The control electronics are expected to be purchased after LS2 (after 2020).

HIGH PRECISION MEASUREMENT AND REGULATION

For operational purposes all LHC converters have been assigned to an “Accuracy Class” which summarizes its main precision performances. For HL-LHC the same proven principles will be adopted, important R&D activities will be devoted to the update and potential performance improvement of existing LHC equipment. The main principles of high precision measurement are depicted in the figure below:
- **DCCT**: DC Current Transformer is the transducer at the heart of the high precision measurement chain of the circuit current.

- **ADC**: For Class 1 power converters a special Delta-Sigma ADC is used; the CERN designed DS22 was characterized by unprecedented precision when LHC was built. The final precision is also determined by the subsequent digital filter implemented in the FGC2 as the output of the DS22 is a 1-bit bitstream sent to FGC2 via optic fibre.

- **Redundancy**: Each power converter is equipped with two complete measurement “chains” comprising DCCTs and ADCs (CERN DS22 for Class 1); in normal operation the average of the two measured values of the circuit current is used for regulation whereas in case of a faulty component in one of the measurement chain the regulation can work with the single measurement supplied by the normal operating chain.

- **Remote Calibration**: The system is equipped with remote calibration capabilities (based on the CDC – CERN DCCT Calibrator) in order to perform periodic calibration and keep the overall uncertainty within the tight limits imposed by Class 1.

**R&D ACTIVITIES**

The DCCT is a mature and highly reliable technology, however some improvement might be achieved especially in the “current to voltage” conversion where the DCCT current (which can be assumed to be a known, small, fraction of the measurand current) is converted in voltage readily available for digitization. The R&D activities will mostly focus on the high-precision current sensing resistors (a.k.a. the burden resistors) which represent a strategic know-how that CERN should keep in house as much as possible. Other aspects such as noise reduction by bandwidth optimization, minimization of modulation induced perturbations and optimization of the interface (to maximize common mode immunity) will also be considered.

The CERN DS22 is a 22-bit resolution Delta-Sigma ADC that currently equip Class1 LHC power converters. It was designed at the end of the 90’s expressly for LHC; as such it is now close to obsolescence and an R&D project was already launched with the main objective of its redesign with components that will need to be still available during HL-LHC operation. Another direction of R&D is a completely new design with comparable or improved performance; this will include market surveys for commercial ADCs that might have now filled the performance gap with respect to the CERN DS22.

LHC calibration and test infrastructure up to 20 kA was crucial for the performance verification of the high precision DCCTs that equip LHC power converters. Such an infrastructure is going to be strategic for HL-LHC as well. This test setup is now close to obsolescence and it will require consolidation in coming years. A new (or refurbished) 20 kA power converter will also be needed together with new equipment of the reference cell.

The main quadrupole circuits for the ITs of LHC comprise three nested circuits. From the control point of view, this represents a MIMO (Multiple Input Multiple Output) system. The strategy adopted for its control is based on the “decoupling” principle and it is realized by means of a dedicated hardware board. For HL-LHC ITs four nested circuits are foreseen in the baseline so a new strategy is to be found. Given the upgraded monitoring and control capabilities of the control infrastructure based on Ethernet (which is going to drastically reduce “delays”) a fully software solution is to be developed. This will require the development of new libraries which will extend FGC control capabilities beyond the current SISO (Single Input Single Output) paradigm.

**RADIATION HARDNESS AND MACHINE AVAILABILITY**

The power converters currently in the RR alcoves will be replaced with radiation-tolerant converters. This development concerns the 600A and the 4kA, 6kA, and 8kA families. The new power converters will be able to withstand the doses and the fluencies expected during the HL-LHC operation.
The present 60 A converters will not withstand the doses estimated during HL-LHC operation. They were designed for tolerating a maximum total dose of about 50 Gy, and the power converters placed in or close to the matching sections will receive a dose of up to 32 Gy/year. These converters will be replaced with new ones designed for withstanding a total dose of 200 Gy. This target corresponds to the maximum dose that can be tolerated by a design based on commercial off-the-shelf (COTS) components. A rotation between highly exposed and less exposed power converters is also foreseen.

Global machine availability is affected by the pre-cycle needed to degauss the magnets and by the magnets ramp-down time. In the present LHC, the most limiting circuits are those of the inner triplet quadrupoles and of the main quadrupoles. All of these circuits are powered via one-quadrant converters, which are the cause for the long ramp-down time. Two upgrades can be envisaged if machine availability needs to be improved:

i) replacement of these power converters with two-quadrant converter types;

ii) use of external dump resistors to accelerate the discharge.

As an illustration, by replacing the present 13 kA/18 V power converters of the main quadrupole circuits with two-quadrant 13 kA/±18 V power converters, the ramp down of the machine can be reduced by 30 minutes. It is estimated that the replacement of both power converters powering the inner triplet quadrupole and main quadrupole circuits will increase the global availability of the machine by about 4%. More work is necessary to assess the best solution, also in conjunction with the LHC Consolidation project.