Chapter 6B

Warm powering of the superconducting circuits

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6B Warm powering of the superconducting circuits

6B.1 Overview

The warm powering of the HL-LHC involves the new circuits of the Inner Triplets and the Separation/Recombination magnets in Point 1 and Point 5, the powering of the 11 T magnets in Point 7, and the final R2E consolidation phase in LS3. The LHC was built with modular power converters to facilitate maintenance and integrate the redundancy principle [1][2]. Redundancy was foreseen in power converters rated above 600 A. This has proven to be a real asset during operation. The $n + 1$ redundancy indeed allows the converter to be operated even with one module in fault. The advantages are: (i) in case of fault, only one sub-converter is not operational and usually this does not generate a beam dump; (ii) the LHC can run with some faulty sub-converters and all interventions for repairing can be performed during a technical stop of the machine. With the exception of dipole circuits (whose power converters are based on thyristors technology), 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, inducing a size reduction of the hardware. All these design principles will be maintained for the new HL-LHC power converters and the use of switch-mode technology extended to all new designs. The R&D aspects involved in the Warm Powering are discussed in Ref. [3] and will not be addressed here. The main changes with respect to TDR v.0.1 are summarised in Table 6B-1.

Table 6B-1: Summary of the main changes with respect to TDR v.0.1.

	TDR v.0.1	**TDR v.1**	**Reference**
Inner Triplet 18 kA Main PC	Rated voltage: ±8 V	Rated voltage: ±10 V	
Inner Triplet Q2a Trim PC	Ratings: ±120A±10V	no Q2a trim circuit	EDMS 1682952
Inner Triplet Q1a Trim PC	no Q1a trim circuit	Ratings: ±60A±10V	EDMS 1682952
PCs of RD1, RD2 circuits	Rated Current: 13 kA	Rated Current: 14 kA	EDMS 1973948
PCs of Q4/Q5 correctors (*)	8 additional ±120A±10V	no additional circuits	ECR LHC-_-EC-0041
Powering of Super-ferric High Order correctors (**)	from UR15 (by SC-link) from UR55 (by SC-link)	from UL14 & UL16 from UL557 & USC55	ECR LHC-D-EC-0002
Control Electronics	FGC4	FGC3.2	EDMS 1973217
Precision Performance	Table 6B-5	Table 6B-7	CERN-ACC-2019-0030
DCCTs Remote Calibration	IT Main, RD1, RD2	None: manual calibration	CERN-ACC-2019-0030
Circuit Disconnector Boxes		Baseline	LHC-RP-EC-0005

(*) Per IP side: from 8 MCBY to 6 MCBY for Q4, from 6 MCBY to 2 MCBC for Q5.

(**) Local powering.

6B.2 Powering of the new HL-LHC circuits

The circuit layouts for the Insertion Regions in Point 1 and Point 5 together with the 11 T circuits in Point 7 are described in detail in Chapter 6; the corresponding new power converters are presented in detail in 6B.4.

6B.3 Powering upgrade to face new level of radiations after LS3

The present LHC power converters are installed in underground areas. Of the 1710 total units, 1065 are exposed to radiation. During machine operation up to 2013, the power converters generated a number of beam-dumps due to single event effect (SEE). The faults due to SEE represented about 20% of the total power converter failures (which decreased to about 12.5 % during Run 2). The R2E (Radiation To Electronics) Project was launched in 2010 to mitigate radiation issues for the whole LHC machine. In this framework, all power converters connected to the present DFBX (that feeds the Inner Triplet magnets) were relocated to reduce their exposure to radiations. More shielding was added inside the RR alcoves to reduce particle fluences. A new radiation-tolerant version of the FGC (Function Generator/Controller [11]) digital controller system, called FGClite, was developed and deployed in the machine in 2017 (details in 6B.6).

The power converters currently in the RR alcoves will be replaced with radiation-tolerant converters. The consolidation during Long Shutdown 2 (LS2) concerns the 600 A and the 4 kA and the 6 kA families. The new power converters will be able to withstand the doses and the fluences expected during the HL-LHC operation. These radiation-tolerant converters will be used to power the Q4-Q5-Q6 of the new HL-LHC configuration (as conceived by the Matching section Optimization outcome). No extra costs are foreseen for this part of the machine.

The 120 A power converters were not included in the R2E project foreseen in LS2. These converters are installed in the RR galleries: RR13, RR17, RR53 and RR57 from where the matching sections are powered, but also in the RR73 and RR77. A new radiation-tolerant version, called R2E-HL-LHC120A-10V, will be needed to guarantee a good availability of the LHC machine after LS3; high availability will be guaranteed by means of $n + 1$ redundancy. In addition, the present 60 A converters will not be able to withstand the doses estimated during the 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 not compatible with their design limits. It was therefore decided to replace about 55% of the 60 A power converters in the ARCs by the new radiation tolerant one, called R2E-HL-LHC60A-10V. This new design comes with a withstanding limit of 200 Gy total dose and $n + 1$ redundancy which is crucial for the availability of the machine. The replacement of 55% of the units will include the converters installed in areas close to cells 12 to 16 where the highest exposition to radiation is foreseen. It is worth noting that the new 60 A and 120 A converters will be based upon the same power source in order to optimize the design effort, a power module rated: ±60 A/±10 V. Two of such modules will be used for the 60 A converters, whereas three will be needed for 120 A converters.

6B.4 General requirements for power converters

The design of power converters for particle accelerator superconducting magnets needs to consider several criteria such as:

- large inductive loads, with time constants up to several hundred seconds that often require power converters to be able to recover the magnet energy (dissipate it, store it, or re-inject it to the grid);
- very high precision performance which also implies very low electromagnetic interference (which impacts on the choice of the topology);
- magnet, and more in general, circuit protection (as also discussed in 6B.4.5); sometimes, as in the case of the LHC 60A correctors, the protection of the Current Leads is fully delegated to power converters.

Because of all these requirements, sometimes together with very specific earth leakage current detection systems, the design of these power converters is often fully carried out "in house" at CERN. The list of circuits and corresponding power converters needed for the HL-LHC Inner Triplet and Separation/Recombination magnets (of LHC Point 1 and Point 5) is reported in Table 6B-2. A summary of the corresponding quantities needed in operation and details of the power converters installation location is reported in Table 6B-9. Two additional circuits: RTB9.L7 and RTB9.R7 are foreseen in operation for the trim of the 11 T magnets MBH.A9L7 and MBH.A9R7 that will replace the MB.A9L7 and MB.A9R7 respectively. The maximum current will be ± 250 A, but the rated current of the power converter will be ± 600 A. As these converters are going to be installed in RR73 and RR77 they will need to be radiation tolerant; furthermore given the trim function of the circuits (used to match the so-called transfer function of the new magnets with respect to the old ones) there are special requirements in terms of operation with common-mode voltage (±85 V in normal operation, 500 V during Energy Extraction, up to 1200V if also an Earth fault happens), as the trim circuits will "sit" on top of the LHC dipole ones as shown in Chapter 6 (Figure 6-13).

Table 6B-2: Inner Triplet and Separation/Recombination circuits and their corresponding Power Converters. The reported value of differential inductance refers to nominal current [4].

Power Converter Equipment Code	Circuit Name	Circuit Description	Main Circuit Parameters		Nominal Current 7 TeV (kA)	Ultimate Current 7.5 TeV (kA)	Converter Rated Current (kA)	Converter Rated Voltage (V)
			L (mH)	R (mΩ)				
HCRPAFE	RQX	Triplet Q1, Q2a, Q2b, Q3	255.4	0.15	16.23*	17.500*	18.000	±10
HCRPBAB	RTQX1	Trim Q1	69.0	1.45	±2.000	±2.000	±2.000	±10
HCRPBAB	RTQX3	Trim Q3	69.0	1.30	±2.000	±2.000	±2.000	±10
HCRPLAD	RTQXA1	Trim Q1a	34.5	227.10	±0.035	±0.035	±0.060	±10
HCRPBAA	RCBXV[1,2]	Orbit correctors Q1/2 – Vert./Inner	58.4	2.38	1.625	1.741	±2.000	±10
HCRPBAA	RCBXH[1,2]	Orbit correctors Q1/2 – Hor./Outer	124.8	2.42	1.474	1.579	±2.000	±10
HCRPBAA	RCBXV3	Orbit correctors Q3 – Vert./Inner	107.1	1.99	1.584	1.702	±2.000	±10
HCRPBAA	RCBXH3	Orbit correctors Q3 – Hor./Outer	232.3	1.98	1.402	1.502	±2.000	±10
HCRPMB	RQSX3	Superferric, order 2	1530.0	18.12	0.174	0.197	±0.600	±10
HCRPLBC	RCS[S]X3	Superferric, order 3, normal [skew]	213.0	54.00	0.099	0.112	±0.120	±10
HCRPLBC	RCO[S]X3	Superferric, order 4, normal [skew]	220.0	54.00	0.102	0.115	±0.120	±10
HCRPLBC	RCD[S]X3	Superferric, order 5, normal [skew]	120.0	54.00	0.092	0.106	±0.120	±10
HCRPLBC	RCTX3	Superferric, order 6	805.0	54.00	0.085	0.097	±0.120	±10
HCRPLBC	RCTSX3	Superferric, order 6, skew	177.0	54.00	0.084	0.094	±0.120	±10
HCRPAFF	RD1	Separation/recomb. dipole D1	24.9	0.41	12.11	13.231	14.000	8
HCRPAFF	RD2	Separation/recomb. dipole D2	27.4	0.18	12.33	13.343	14.000	8
HCRPMBF	RCBRD[V,H]4	Orbit correctors D2	920.0	1.36	0.394	0.422	±0.600	±10

* Values for the nominal current, gradient in the straight section and magnetic length for the Q1, Q2 and Q3 magnets based on present results.

6B.4.1 Power converters architecture

The architecture of modern power converters for particle accelerator is highly modular; different parts will be designed and produced separately, power converters being finally integrated in a housing rack. There are three main parts:

- High precision current measurement chain (described in 6B.4.5) based on DCCT (DC Current Transformer) sensors able to measure currents at the required, often very challenging, precision down to DC.
- Digital control electronics (described in 6B.6) based on a digital controller (FGC) (that is also used to interface with the accelerator control infrastructure by means of WorldFip or dedicated Ethernet protocol).

- Power part: power modules and protection modules.

The power converter internal architecture is illustrated in Figure 6B-1 (left) together with the different “interfaces” with “services” such as Cooling and Ventilation, AC powering, Technical Network and other systems such as Machine Protection. This architecture, including the $n + 1$ parallel implementation of the power part (on the right) is common to all power converters for the HL-LHC.

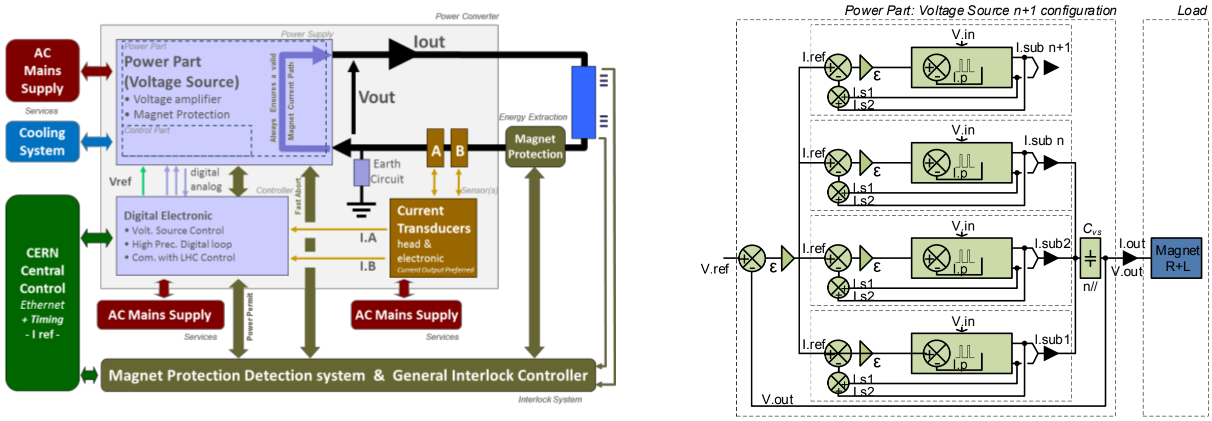

Figure 6B-1: Power converter internal architecture common to all families (on the left): field buses can either be based on WorldFIP or on dedicated Ethernet. Illustration of the parallelization of $n + 1$ power sources to supply the final current to the load (on the right).

6B.4.2 HL-LHC18kA-10V

In the LHC, the energy stored in the Inner Triplets magnets is not being recovered, and during the ramp-down phase, it is dissipated in the copper cables during a free-wheeling process, whose internal resistance together with magnet’s inductance, define the time constant of the circuit. With the new layout, there is almost no resistance in the magnet circuit, so the power converter has to recover the magnet energy during the ramp down to limit it to about 20 minutes or to reduce it to less. Therefore, a new 2-quadrant design, based on Switch-Mode technology, is required including $n + 1$ redundancy to obtain high-reliability. Furthermore, it is proposed to include Energy Storage inside the converter in order to maximize the overall system efficiency and to limit the peak power drawn from the network (minimizing the cost of electrical infrastructure). The development of the HL-LHC18kA-10V will also aim at guaranteeing a lifetime expectancy of 20 years assuming 1000 cycles per year (including physics runs and all additional cycles).

Table 6B-3: Summary of HL-LHC18kA-10V power source features.

Equipment Code	Converter name	Quadrants	# Sub-Converters × Ratings	IPOWER Installed	IDCCT Rated	Full $n + 1$ Redundancy	Controller
HCRPAFE	HL-LHC18kA-10V	2	10 × ±2kA ±10V	20 kA	18 kA	7.5 TeV	FGC3.2

6B.4.3 HL-LHC14kA-08V

The separation and recombination dipoles (D1 and D2) currently installed in the LHC will be replaced by a new pair, both of them being superconducting. The relatively low inductance of these new magnets allows a natural decrease of the current in the shadow of the Inner Triplets discharge time. The new power converter HL-LHC14kA-08V has therefore being defined as 1st quadrant converter (in the I-V plane). Its design aims at providing a Switch-Mode solution achieving low noise and high-reliability by means of $n + 1$ redundancy.

Table 6B-4: Summary of HL-LHC14kA-08V power source features.

Equipment Code	Converter name	Quadrants	# Sub-Converters × Ratings	IPOWER Installed	IDCCT Rated	Full $n + 1$ Redundancy	Controller
HCRPAFF	HL-LHC14kA-08V	1	8 × 2kA -08V	16 kA	14 kA	7.5 TeV	FGC3.2

6B.4.4 4-Quadrant power converters

As already mentioned, in order to achieve the very high reliability required by physics operation, $n + 1$ redundancy is foreseen (since it has already proven to be the right approach in LHC) despite the increased design complexity. For 4-quadrant converters, implementing this feature is challenging, as some of the parallel power modules could be absorbing the current supplied by some of the other ones hence producing a malfunction of the overall converter. Furthermore, some of the new 4-quadrant converters would need to be radiation tolerant; this will be guaranteed by means of a specific design and qualification process in dedicated CERN facilities like CHARM.

Table 6B-5: Summary of the 4-Quadrant Power Converters.

Equipment Code	Converter name	# Sub-converters × Ratings	I_{POWER} Installed	I_{DCCT} Rated	Full $n + 1$ Redundancy	Controller	R2E
HCRPBAA	HL-LHC2kA-10V	6 × ±400A ±10V	2400 A	2000 A	7.5 TeV	FGC3.2	N
HCRPBAB	HL-LHC2kA-10V	6 × ±400A ±10V	2400 A	2000 A	7.5 TeV	FGC3.2	N
HCRPMBF	HL-LHC600A-10V	2 × ±400A ±10V	800 A	600 A	7.0 TeV (*)	FGC3.2	N
HCRPLAD	R2E-HL-LHC60A-10V	2 × ±60A ±10V	120 A	60 A (**)	7.5 TeV	FGC3.2	N
HCRPMBE	R2E-HL-LHC600A-10V	2 × ±400A ±10V	800 A	600 A	7.5 TeV	FGCLite	Y
HCRPMBD	R2E-LHC600A-10V	2 × ±400A ±10V	800 A	600 A	7.5 TeV	FGCLite	Y
HCRPLBC	R2E-HL-LHC120A-10V	3 × ±60A ±10V	180 A	120 A	7.5 TeV	FGCLite	Y
HCRPLAC	R2E-HL-LHC60A-10V	2 × ±60A ±10V	120 A	60 A (**)	7.5 TeV	FGCLite	Y

(*): the HCRPMBF will power the D2 correctors (MCBRD magnets) for which the nominal current at 7 TeV is 394 A. However even at 7.5 TeV (ultimate current of 422 A) the correctors will likely be operating below 400 A so $n + 1$ redundancy will be guaranteed most of time.

(**): DCCT of 120A with two turns.

HL-LHC2kA-10V Protection Module | R2E-LHC600A-10V Control Module | R2E-LHC600A-10V Power Module

Figure 6B-2: Examples of 4-Q power converters modules that build up the full power converter.

6B.4.5 Power converters and circuits protection

During circuit discharges, the power converter is designed to ensure a safe path of the magnet current. The crowbar existing in every power converter is the system responsible for this safe path to protect the elements in the connected circuit (power converter, DC cables, superconducting link, superconducting bus-bars and the magnet). The crowbar could be constituted by free-wheeling diodes (FWDs) in the case of 1 quadrant power converters, free-wheeling thyristors (FWTs) in case of 2 quadrant converters or free-wheeling thyristors in an anti-parallel configuration for 4 quadrant power converters. In some cases, a resistance is added in series with the free-wheeling elements in order to discharge the circuit faster. Even though the power converter is designed to ensure a safe path, in rare events a short circuit could occur over the crowbar system and the installed resistance is not ensured.

- In the case of trim circuits, several considerations have to be considered in order to define the resistance values and the triggering values of the crowbars. These considerations include:
- preventing current looping to limit the currents to the design current value of the sub-circuits,

- in case of the presence of bypass cold diodes in parallel, a very precise system should be used in order to prevent the cold diodes from being brought into conduction by exceeding their characteristic turn-on voltages.

Table 6B-6: Summary of the crowbar values and the energy dissipation capabilities for the HL-LHC circuits.

Power Converter Equipment Code	Power Converter Current Rating (kA)	Crowbar Configuration	Crowbar Resistance Value (mΩ)	Energy Absorption Capability (kJ)	Discharge Time Constant (s)
HCRPAFE	18	FWTs	0.5	42000 (*)	510
HCRPAFF	14	FWDs	0	2300	230
HCRPBAB	2	Anti-parallel FWTs	2	20	510 (**)
HCRPBAA	2	Anti-parallel FWTs	25	80	35
HCRPMB[D,F]	0.6	Anti-parallel FWTs	50	70	20
HCRPMBE	0.6	Anti-parallel FWTs	60	210	110 (***)
HCRPLBC	0.12	Anti-parallel FWTs	80	2	12

(*): estimation assuming circa 25% saturation of the differential inductance at $I_{nominal}$ (and $I_{ultimate}$ [4]) with respect to 0A;
(**): identical to RQX circuit; (***): identical to RB circuit.

6B.5 High precision: requirements, measurement, and regulation technology

Precision requirements are illustrated in Figure 6B-3 and summarized in Table 6B-7; the latest updates are derived from Ref. [5]. The main components of high precision current measurement are depicted in Figure 6B-4; for the HL-LHC the same proven principles adopted in LHC will be implemented [6]. Important R&D activities are being carried out to update and improve the metrological performance of the LHC equipment [3]. Class 1, LHC flagship power converters that currently equip LHC main dipole and quadrupole circuits, proved to perform, in many respects, way better than what was specified during LHC design phase, nevertheless the HL-LHC optics still push this limit a step ahead and the performance required by Class 0 must be further improved by a factor of at least two for some of the metrological figures of merit. One of the main principle of the high precision measurement is the redundancy: all power converters are equipped with two complete measurement "chains". In normal operation the regulation uses the average of the two measured values of the circuit current. In case of a faulty component in one of the chains the regulation can work with the single measurement supplied by the other one.

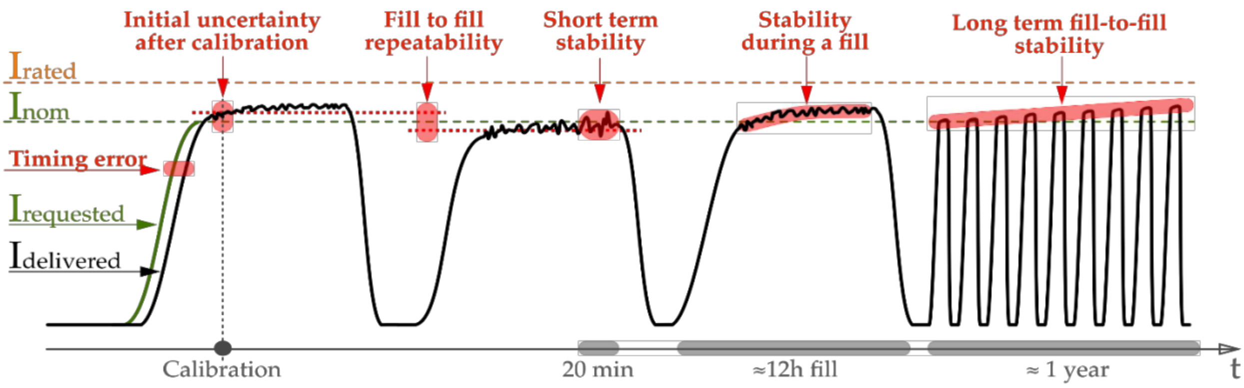

Figure 6B-3: Illustration of the main precision performance figures.

The two main components of the high precision measurement chain are:

- **DCCT:** DC Current Transformer is the transducer at the heart of the high precision measurement chain of the circuit current; DCCTs of different accuracy classes, D0 to D4, will be used.
- **ADC:** the analog-to-digital converter is the other key component of the high precision measurement of the current, its metrological performance combined with the one of the DCCT will determine the overall precision of the power converter (in the low frequency regime where the current regulation is active [7]).

The different types of ADC that will be used for application in the HL-LHC are summarized in Table 6B-8. There will be three main ADCs: FGC3.2 External ADC, FGC3.2 Internal ADC, and FGCLite Internal ADC. An intensive R&D program is being carried to develop FGC3.2 External ADC in order to meet the challenging specifications required by Class 0 [3]. Together with the ADCs themselves finely temperature-controlled racks and software temperature compensation will be used to finally guarantee the required metrological performance for the different classes. A consolidation of the DCCTs test infrastructure and a R&D program for the upgrade of the calibration system [8] (to unprecedented Class 0 performance) are undergoing.

Table 6B-7: Summary of precision requirements per circuit (including LHC mains) [5].

Circuit Name	**Equipment Code**	I_{DCCT} **(kA)**	**Accuracy Class**	**Stability [ppm of $I_{DCCT.rated}$]** expressed as twice the standard deviation		
				Short	**During a fill**	**Long Term fill-to fill**
RB[a]	HCRPTE	13	1	0.4	2	9.5
RQ(D/F)[a]	HCRPHE	13	1	0.4	2	9.5
RQX	HCRPAFE	18	0	0.2	1	9.5
RTQX1	HCRPBAB	2	2	1.2	15.5	26.5
RTQXA1	HCRPALD	0.06	4	5	40	64
RTQX3	HCRPBAB	2	2	1.2	15.5	26.5
RCBX	HCRPBAA	2	2	1.2	15.5	26.5
RQSX[b]	HCRPMBD	0.6	3	2	34	56
RC(S/O)X	HCRPLBC	0.12	4	5	40	64
RC(D/T)X	HCRPLBC	0.12	4	5	40	64
RD(1/2)	HCRPAFF	14	0	0.2	1	9.5
RCBRD	HCRPMBF	0.6	3	2	34	56
RQ4[c]	HCRPHRA	4	2	1.2	15.5	26.5
RCBY	HCRPLBC	0.12	4	5	40	64
RQ(5/6)[c]	HCRPHSB	5	2	1.2	15.5	26.5
RCBC	HCRPLBC	0.12	4	5	40	64
RTB9[d]	HCRPMBE	0.60	3	2	34	56

[a] existing LHC circuits, [b] standard HL-LHC 600 A but I_{max} = 197A in operation, [c] upgraded R2E power converters in LS2 with identical LHC performance, [d] R2E-HL-LHC 600 A but I_{max} = ± 250A in operation.

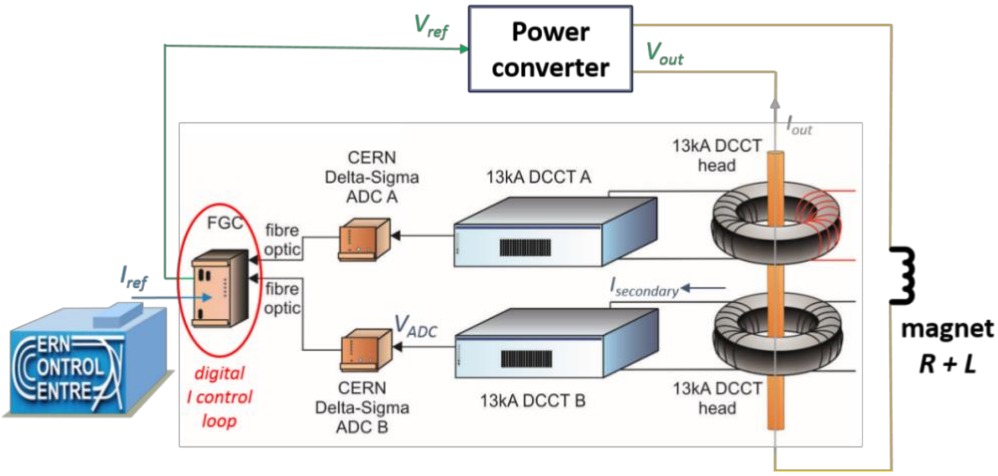

Figure 6B-4: Illustration of the full current measurement chain (main circuits LHC - accuracy Class 1).

Table 6B-8: Summary of measurement equipment for the different converters.

Accuracy Class	Equipment code – Circuit	ADC Configuration	DCCT Ratings	DCCT Class
INNER TRIPLETS and SEPARATION/RECOMBINATION CIRCUITS				
0	HCRPAFE - Main Inner Triplet	FGC3.2 + EXT ADC + AIRCON RACK	18 kA	D0
2	HCRPBAB - Q1 - Q3 trims	FGC3.2 + EXT ADC	2 kA	D2
4	HCRPALD - Q1a trim	FGC3.2 + INTERNAL ADC	120 A (*)	D4
2	HCRPBAA - IT correctors	FGC3.2 + EXT ADC	2 kA	D2
3	HCRPMBD - SuperFerric 2nd order	FGCLITE + INTERNAL ADC + TC COMP	600 A	D3
4	HCRPLBC - HO correctors	FGCLITE + INTERNAL ADC + TC COMP	120 A	D4
0	HCRPAFF - D1 - D2	FGC3.2 + EXT ADC + AIRCON RACK	14 kA	D0
3	HCRPMBF - D2 correctors	FGC3.2 + INTERNAL ADC	600 A	D3
11 T TRIM CIRCUITS				
3	HCRPMBE - 11 T trim	FGCLITE + INTERNAL ADC + TC COMP	600 A	D3
R2E CONSOLIDATION in LS3				
4	HCRPLBC - MS correctors	FGCLITE + INTERNAL ADC + TC COMP	120 A	D4
4	HCRPALC - ARCs correctors	FGCLITE + INTERNAL ADC	120 A (*)	D4

(*): DCCT with two turns to measure (up to) 60 A.

6B.5.1 RST control algorithm

The final component needed to guarantee the demanded precision performance is the control algorithm that elaborates the measured value of the current to calculate the required voltage that the power converter needs to apply to the circuit. As for LHC the control algorithm is a 2-degree-of-freedom polynomial controller (RST) [9]; it will need also to guarantee the required robustness, or stability margins, as magnet (differential) inductances vary a few % from nominal to ultimate. Sometimes the variation is much larger, for the MQSXF indeed, between 0A and ultimate current, differential inductance is expected to change by a factor 3 due to magnetic saturation; in this case a dedicated feature of the control algorithm is needed to handle it [10]. The control for the Inner Triplets, where 4 nested circuits (only 3 in LHC) need to be controlled, is an additional challenge with respect to LHC; a software implemented decoupling strategy is currently being developed [3].

6B.6 Control electronics: FGC3.2 and FGCLite

6B.6.1 Principles and current status

LHC power converter control is based on an “all-digital approach” [11][12][13]. The hardware implementing this is a so-called Function Generator/Controller (FGC). In the LHC, two main variations of FGC are used: FGC2, used in areas without radiation and FGClite, used in areas exposed to radiation (see Figure 6B-6).

The FGClite was a major project combining the challenges of using commercial parts in radiation, with high dependability requirements of the LHC. Around 1700 FGC2/FGCLite are deployed in the LHC, key functions are:

- managing the voltage source state, and providing voltage source diagnostics;
- regulation of the circuit current (by means of an RST control algorithm);
- interfacing with accelerator supervision and controls infrastructure (as depicted in Figure 6B-5).

The communication network interfaces of FGC2 and FGClite are based on the WorldFIP fieldbus. FGC2 uses a MicroFIP transceiver, and FGClite uses CERN’s in-house nanoFIP transceiver. A new version of FGC was developed for use in the injectors, called FGC3.1 (shown in Figure 6B-6 right) [14]. The FGC3.1 uses the same principles as FGC2, but uses modern analogue and digital components. The FGC3.1 network interface is based on a dedicated implementation of 100 Mbps Ethernet called FGC-Ether providing data communication and time synchronization [15]. In addition to the FGC3 control unit, a wider set of dedicated analogue and digital boards have been developed by the power converter group for low-level converter control under the name of RegFGC3 [16]. These additional dedicated electronics extend the "all-digital" approach to the full control of the power converter, beyond the simple current control.

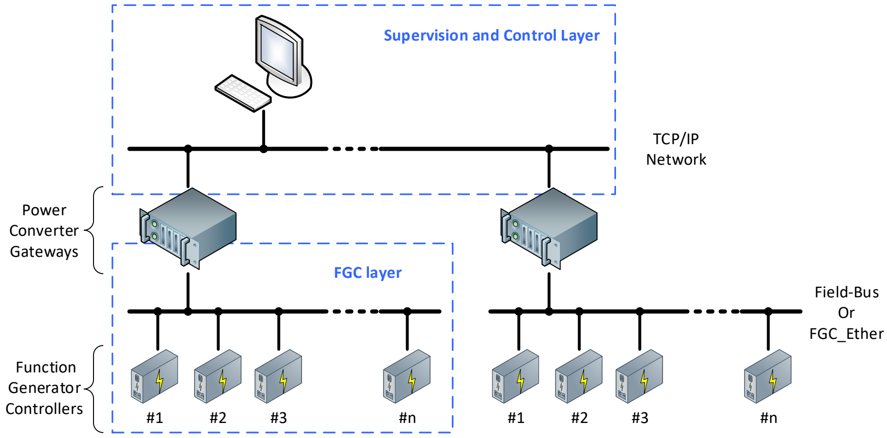

Figure 6B-5: Power Converters Controls Hierarchy

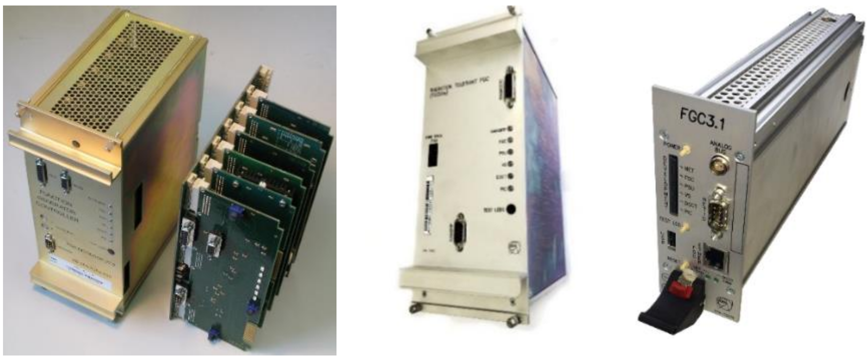

Figure 6B-6: FGC2 (left), FGClite (centre) and FGC3.1 (right) Controller Units

6B.6.2 FGC3.2 control unit for the HL-LHC power converters

The HL-LHC's installation is foreseen around 2025, by which time the FGC3.1 will be obsolete. A new version, FGC3.2, is under development [17]. FGC3.2 is based on the same principles that have proven effective in LHC, such as direct implementation of current regulation and management/monitoring of the voltage source. FGC3.2 adds more processing power for flexibility in low-level control. In addition to the dependable design of the FGC3.2 control unit itself, one of the main features of RegFGC3 electronics is to be native support of $n+1$ redundancy introduced in 6B.4.

The larger bandwidth of the 100 Mbps Ethernet allows more detailed monitoring compared to the WorldFIP fieldbuses currently used in the LHC. New capabilities will be implemented both in hardware and in software, such as the development of new libraries, to improve online diagnostics for both operators, and beam physicists. These are designed to improve analysis to speed up commissioning and decrease the time taken for troubleshooting. They will be particularly beneficial for the monitoring and troubleshooting of complex cases, such as nested circuits powering the Inner Triplets magnets.

6B.7 Integration

The power converters for the Inner Triplets (except higher order correctors) and Separation/Recombination circuits as well as the DFHX and DFHM (electrical feed-boxes) will be placed in the UR gallery to reduce the length of water-cooled DC cables, see Figure 6B-7. The superconducting (SC) link will bring the DC current from the UR, through the UL, to the superconducting magnets in the LHC tunnel. The power converters will be water-cooled to ease heat extraction and reduce the air-conditioning requirements. Two 18 kV line will bring electricity in the UR. Two dedicated 18 kV/400 V transformers will supply all the new power converters separating the feeding of the left and right part of the IP.

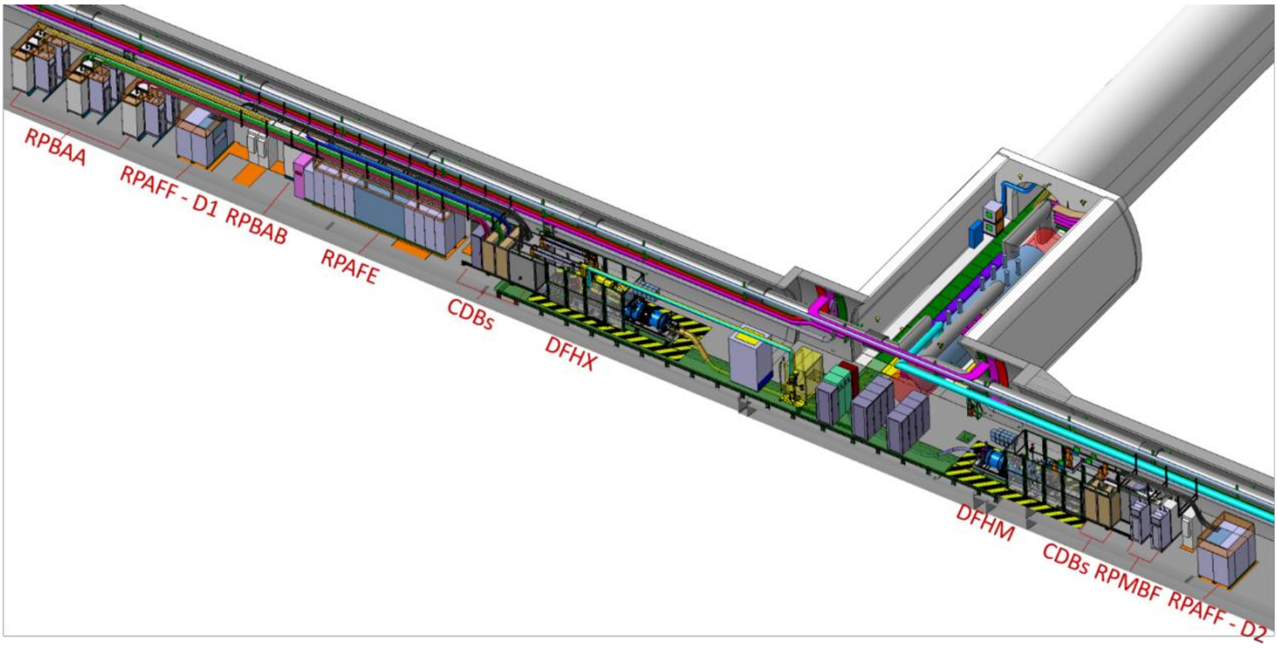

Figure 6B-7: Details of the power converters integration in UR15 right (connection to UL17 is also shown); RYABC (Class 0 measurement) and RYCHB (control) racks and RPLAD power converter (Q1a trim circuit) are shown in the illustration but not explicitly tagged to help readability.

The power converters for the higher order correctors of the Inner Triplets circuits will be placed in the UL14 and UL16 for Point 1 circuits and UL557 and USC55 for Point 5 circuits. The correctors will be powered locally (not through the SC link). It must be noted that during the HL-LHC operation the UL14 and UL16 will require radiation tolerant equipment; it has been therefore decided that also power converters in UL557 and US55 will be radiation tolerant. The 120A power converters were already designed to be radiation tolerant, so the local powering of these circuits only imposed the HCRPMBD to be radiation tolerant (4 converters in total).

More details on the interface of power converters are illustrated in Figure 6B-8 with reference to HL-LHC14kA-08V – HCRPAFF; as a general feature for all power converters: DC connections are foreseen on the top of the racks, cooling water and AC power connections are foreseen at the bottom.

As already mentioned, new power converters will be powering the Matching sections correctors (the quadrupoles power converters will be replaced in LS2 within the scope of R2E Project) and the 11 T trim circuits (new units to be installed also during LS2). Furthermore, all the 120 A corrector circuits powered from the RRs and about 55% of the 60 A correctors powered directly from the ARCs (installed below the dipoles) will have new converters. The main integration information concerning all the new power converters is summarized in Table 6B-9).

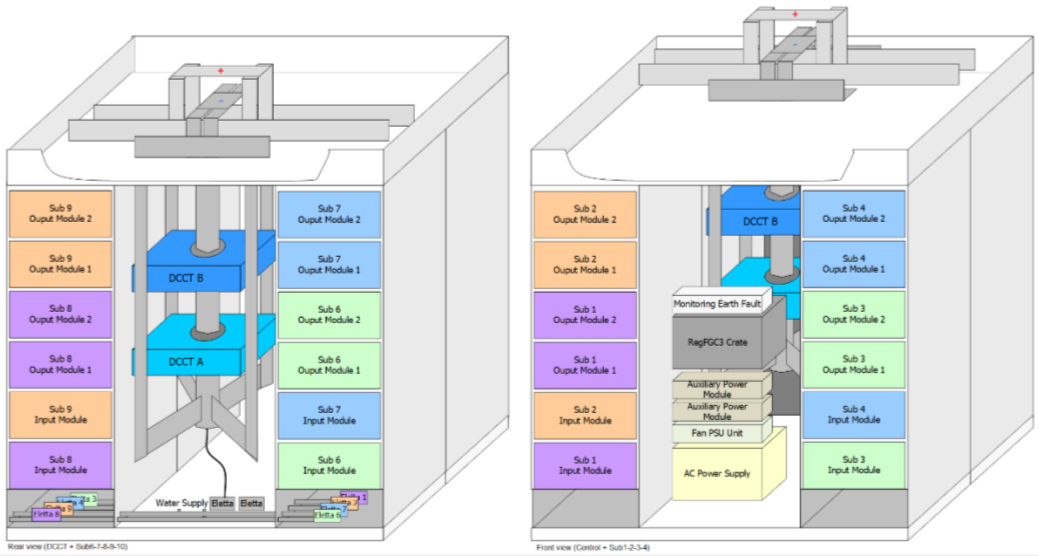

Figure 6B-8: Illustration of the HL-LHC14kA-08V – HCRPAFF power converter. Rear view (on the left) front view (on the right).

Table 6B-9: Main integration parameters. "Standard Racks" are hereby assumed 600 mm x 900 mm. Racks height is not standardized, however all racks will be, at least, 42U tall.

Power Converter Name / Equipment Code	Integration					AC Powering per converter		Cooling and Ventilation (**)	
	Location	Quantities		Dimensions in "Standard Racks"	Operational Converters per Rack	Load Average (kW)	Load Average (kVA)	Dissipated Power Water (kW)	Dissipated Power Air (kW)
		Operation	Equivalent Spare (*)						
INNER TRIPLETS and SEPARATION/RECOMBINATION CIRCUITS									
HCRPAFE	UR15/55	4	1.4[a]	13 x 2	Multi-rack	45	50	47.5	10.8
HCRPAFF	UR15/55	8	1	4 x 2	Multi-rack	60	75	19.5,15.2	8.3,6.5
HCRPBAA	UR15/55	24	4[b]	2 x 1	Multi-rack	28.8	30.7	<4.7>	<2.5>
HCRPBAB	UR15/55	8						5.7	3.1
HCRPLAD	UR15/55	4	2	1 x 1	1	0.77	0.85	/	0.4
HCRPMBF	UR15/55	16	4	1 x 1	2	9.1	9.6	1.5	0.65
HCRPMBD	UL14/16/557 - USC55	4	4	1 x 1	1	9.1	9.6	1.5	0.65
HCRPLBC	UL14/16/557 - USC55	32	4	1 x 1	3	1.52	1.68	/	0.6
11 T TRIM CIRCUITS									
HCRPMBE	RR73/77	2	3[c]	1 x 1	1	9.1	9.6	1.5	0.65
R2E CONSOLIDATION in LS3									
HCRPLBC	RR13/17/53/57	72	8	1 x 1	3	1.52	1.68	/	0.6
HCRPLBC	RR73/77	20							
HCRPLAC	ARCs	414	22	"4 in a row under LHC dipoles"		0.77	0.85	/	0.4

[a] : 1 full spare unit (in EPC facilities) + 1 x 2kA sub-converter per IP side; [b] : common recommended spare parts + individual crow-bar components; [c] : high quantities of spares due to special/non-standard components.

(*): All power converters are modular, so no full spare converters are foreseen; conversely spare components (power modules, control and measurement electronics, interface equipment) will be installed in dedicated racks in close proximity to the operational converters.

(**): Values estimated at $I_{ultimate}$; value between < > is the average for the HCRPBAA circuits, individual values for HCRPAFE of D1 and D2, respectively.

6B.8 Circuit disconnector boxes

In the LHC powering systems, many compensatory measures and equipment are added to the warm to cold transition to comply with the different electrical standards used for electrical installations (i.e. NF-C18-510 for the lockout procedure, NF-C15-100 and IEC-60364 for the rules on electrical installations and EN-60529 for the Ingress Protection, IP, for enclosures). In addition, disconnection and reconnection of the water-cooled cables, a risky mechanical action, becomes necessary, in average, once a year around the DFBAs (for high current circuits) mostly for the purpose of ElQA tests [18].

For the magnet circuits of the HL-LHC insertion regions, Circuit Disconnector Boxes (CDBs) are foreseen in between the warm and cold powering systems in order to comply with the above-mentioned standards. In addition, this system will eliminate the need for disconnection and reconnection of cables (except for maintenance and/or repairing of current leads). The proposed CDBs include two earthing systems in order to provide a safe intervention environment both on the warm powering side and on the cold powering side according to the electrical safety rules and standards. Moreover, a short circuit connection would make possible to perform specific tests on power converters and provide the possibility to disconnect a sub-circuit (i.e. a trim and the main circuit in the inner triplets) to efficiently perform fault diagnosis on the powering systems. Figure 6B-9 shows the electrical scheme, the possible connections, and the manipulation scheme for the proposed HL-LHC Circuit Disconnector Boxes.

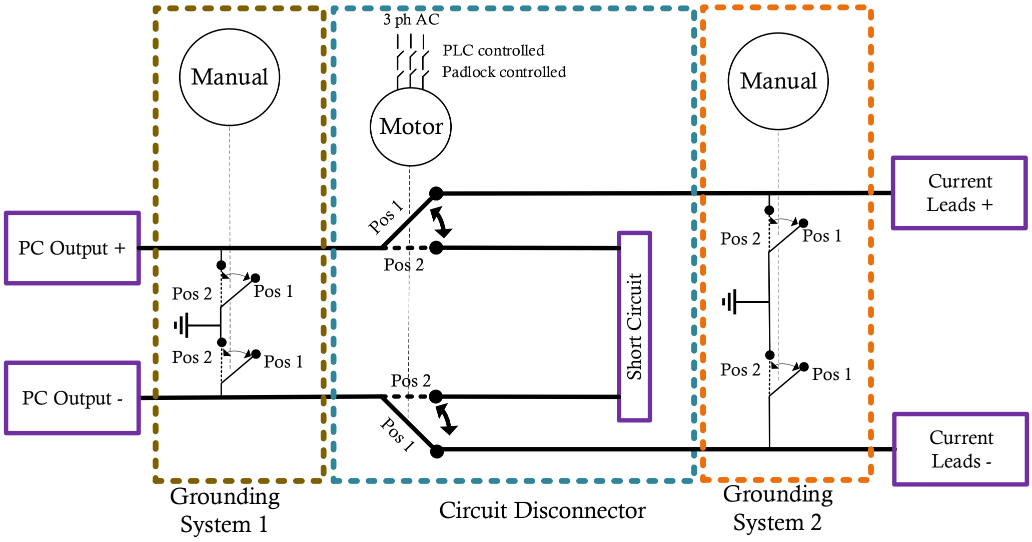

Figure 6B-9: Electrical schematic and the manipulation scheme for the HL-LHC circuit disconnector boxes.

6B.9 Options

6B.9.1 Class 0 upgrade of ATS main dipole circuits power converters

Currently in LHC the eight main dipole circuits are powered by Class 1 Power Converters as indicated in Table 6B-7. Upgrading the four main dipole circuits involved in the Achromatic Telescopic Squeezing ATS (namely RB.A12, RB.A45, RB.A56 and RB.A81) to Class 0, an improvement on tune stability of more than 30% is expected [7]. Such an upgrade will only involve the control and measurement electronics (including the remote calibration capability already available for these converters) whereas the power electronics will not need interventions; this upgrade could therefore also be planned at a later stage (after the start of the HL-LHC operation) if needed.

6B.10 References

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