Document Type	Technical Specification
Document Number	E-ST ESS PC PDR 004
Date	20 June 2017
Revision	1.2
Status	First Release
Confidentiality Level	Internal

PDR-3 of DC Power Converters for Dipole D1 and Quadrupole Q8 Magnets: Extended Technical Specifications

DC Dipole and Quadrupole Power Converters
PCD1 and PCQ8

Author	Checked by – date	Approved by – date
Roberto Visintini	M. Cautero – 20-Jun-17	

Table of Contents

1. Introduction

1.1. Elettra

Elettra – Sincrotrone Trieste S.C.p.A. is a multidisciplinary international research center of excellence, specialized in generating high quality synchrotron and free-electron laser light and applying it in materials and life sciences [1].

The main assets of the research center are two advanced light sources, the electron storage ring Elettra and the free-electron laser (FEL) FERMI supplying light of the selected "color" and quality to more than 30 experimental stations.

1.2. ESS

The European Spallation Source (ESS) is the ERIC (European Research Infrastructure Consortium) that is building and will manage the world's most powerful neutron source [2]. A multi-disciplinary research center, ESS will be up to 100 times brighter than today's similar leading facilities, enabling new opportunities for researchers in the fields of life sciences, energy, environmental technology, cultural heritage and fundamental physics. The ion source generates protons and the following linear accelerator (Linac) accelerates and steers them onto a rotating tungsten target to create neutrons via the spallation process.

Italy is one of the founding Countries of ESS ERIC. The Italian participation to ESS consists in the In-Kind Contribution (IKC) for the construction of the Facility. Three Italian Entities are involved: INFN, Elettra and CNR.

Elettra will provide parts of the linear accelerator and proton beam transport [3, 4, 5].

1.3. Definitions, acronyms and abbreviations

Table 1 describes the abbreviation used in this document.

Table 1 – Abbreviations

Abbreviation	***Explanation of abbreviation***
Elettra	Elettra - Sincrotrone Trieste S.C.p.A.
ERIC	European Research Infrastructure Consortium
ESS	European Spallation Source ERIC
ETH	Ethernet
FAT	Factory Acceptance Tests
MPS	Machine Protection System
PC	Power Converter for magnet
PSS	Personnel Safety System
SMPS	Switched-Mode Power Supply

1.4. References

[1] http://www.elettra.eu
[2] https://europeanspallationsource.se
[3] Schedule AIK 17.2 - Power Converters for magnets to the ESS LINAC to the In-Kind Contribution Agreement signed between European Spallation Source ERIC and the Italian Entity empowered to do so by the Italian Ministry of Education, University and Research (MIUR).
[4] *IKC AIK 17.2 - Technical Requirements Power Converters to Magnets for the ESS Linac*
[5] *R. Visintini, et al., "Power converters for the ESS warm magnets", proc. IPAC 2017, Copenhagen, DK, 2017, paper code WEPVA051.*
[6] *Nexans FXQJ EMC 1kV 2x120/70, ref. 99016098, http://www.nexans.se*

1.5. Purpose of the document

The DC power converters described in this document will energize the Dipole and the quadrupole magnet types D1 and Q8 in the High Energy Beam Transport (HEBT) and Accelerator to Target (A2T) sections of ESS.

This document reports the characteristics and required performances for the power converters to be supplied.

1.6. Brief description of the object

Table 2 summarizes the parameters of the dipole and quadrupole magnets relevant to the PC. The two dipoles are connected in series while the quadrupoles are supplied individually.

Table 2 – D1 and Q8 main parameters (single magnet)

Magnet	**D1**	**Q8**	**Unit**	**Note**
Max Current	400	400	A	
Mag Nominal Current (I_{mag_nom})	371	371	A	
Resistance	81	53.2	mΩ	2 magnets D1 in series
Inductance	860	83.6	mH	2 magnets D1 in series
Max Voltage Drop	32.4	21.3	V	
Voltage Drop at I_{mag_nom}	30	19.7	V	

The proposed cross section of the cable connecting the magnets to their power converters is 2x120 mm^2 in parallel. The resistivity is 153 mΩ/km [6].

We assume a maximum connection length of 100 m from the PC in the Service Gallery to the corresponding quadrupole magnet in the accelerator tunnel and 150 m as overall connection of the two dipoles D1 in series to PCD1. In both cases, the overall length of the conductors is twice the connection length – round loop from the PC to magnet(s) and return. Table 3 reports the main parameters of the connection of the generic quadrupole and the series of the two dipole magnets to the associated PCs.

Table 3 – Cable parameters

Parameter	Value	Unit
Cable section (2x120 mm^2 in parallel)	240	mm^2
Max current DC	400	A
Current density	1.7	A/mm^2
Quadrupole connections		
Length of connection between PC and the associated Quadrupole	100	m
Overall Current Loop length (from PC to magnet and return)	200	m
Cable resistance – Quadrupole	15.3	mΩ
Max DC voltage drop on cable – Quadrupole	6.1	V
Dipoles connection (two dipoles in series)		
Length of connection between PC and the two Dipoles in series	150	m
Overall Current Loop length (from PC to magnets and return)	300	m
Cable resistance – Dipoles in series	23	mΩ
Max DC voltage drop on cable – Dipoles in series	9.2	V

The estimated maximum total DC voltage drop (magnet + cable) at 400 A is:

$$\mathbf{V_{Tot\_D1}} = 2 \times 32.4\ V + 9.2\ V \mathbf{= 74\ V}$$

$$\mathbf{V_{Tot\_Q8}} = 21.3\ V + 6.1\ V \mathbf{= 27.4\ V}$$

Table 4 reports the number of power converters and their nominal output values (including the required dynamics according to Table 6).

Table 4 – Power Converters to be supplied

Type	Number of PC	Rated DC output Current [A]	Calculated DC Output Voltage [V]	Minimum PC Nominal Output Voltage [V]*1
PCD1	1	400	74	100
PCQ8	6	400	27	45

*1: guaranteed at nominal current and lowest AC mains voltage (400 V_{ac} -10%).

Standardization plays an important role in the reliability of the overall ESS Facility by easing the management of spare units and repair. We expect the supplier will do any effort to reduce the number of different components/units in the power converters, without affecting their performances as reported in the relevant Sections of this document.

2. General Remarks

2.1. General conditions

2.1.1. This document collects the parameters and the operational characteristics of the power converters for the dipole and quadrupole magnets reported in Table 4. Next Chapter 3 contains the detailed description of the power converters.

2.1.2. Whenever in the document the term "*must*" is used, it means that the power converters has to be totally adherent to the cited parameter or functionality.

2.1.3. Whenever in the document the term "*should*" is used, it means that the tenderer may propose solutions that will achieve or overcome the required specification, according to his experience and/or standards.

2.2. Contractor's Duties

2.2.1. Through a detailed and robust electrical and mechanical design, the contractor will manufacture, assemble, test and deliver to ESS the dipole and quadrupole power converters ready for installation in standard 19" racks (provided by ESS). Due to the power, the size of the Dipole power converter could be such to require its own rack that, in this case, is part of the delivery.

2.2.2. Installation of the PC in the racks (or, for the dipole only, of the PC rack itself) is not part of the supply. Installation will be carried out by ESS.

2.2.3. The Contractor shall be responsible for carrying out a series factory tests in order to verify the performance of the power converters in compliance with the technical specifications before delivering them to ESS. The tests and the measurement procedures will be preliminarily discussed with Elettra and ESS; both reserve the right to witness the final factory tests (FAT). The load for the tests should have – if possible - the same characteristics of the final one, at least in terms of maximum power (max current and max voltage) and, preferably, inductance (to verify the ripple content in the current).

2.2.4. The delivery of the power converters will occur in one batch, within 8 months from the start of contract. Other time plans must be agreed and approved before placing the order.

Commented [RV1]: See Appendix 2.

2.2.5. After the installation of the PCs and their connection to the final loads, Elettra and ESS will execute SATs (on-site acceptance tests) to verify the matching of the actual performances of the power converters with the required specifications. The contractor will be informed in advance in case he wants to witness the tests. The warranty period for each power converter shall be two (2) years starting with the acceptance of the power converters following the on-site tests. Nevertheless, the design and the chosen components (e.g. filter capacitors, power semiconductors, etc.) should assure undisturbed, safe operation for at least 25 years.

2.2.6. The contractor will provide a complete set of technical documentation as well as Operating and Servicing Manuals (including a Troubleshooting Guide) for the power converters.

2.2.7. The contractor will certify the compliance of the supplied equipment to the relevant IEC (or national equivalent) Standards. CE marking is preferable but not strictly required.

2.2.8. The contractor must operate according to a quality certification ISO-9001 or other national equivalent for the design, production, and test of the power converters. In case of sub-contracts, the contractor has the responsibility to verify that all sub-contractors are also conformal to the same quality standards.

2.3. Limit of Supply

2.3.1. The Boundaries of the Supply are defined by (see Figure 1):

- The AC input terminals (3-phase+PE, 400 VAC, 50 Hz) for supplying the main power part;
- The AC input terminal for supplying the power supply control electronics (1-phase+Neutral, 230 VAC, 50 Hz from UPS);
- The DC output terminals for connecting to the magnets;
- Terminal blocks or connectors for the connections to the ESS Interlock System;
- RJ45 ETH connector to the ESS Control System.

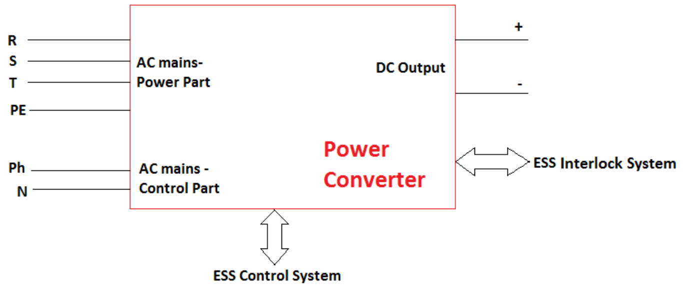

Figure 1 – Boundary Limit of Supply

2.4. Documentation and Manuals

2.4.1. English is the only language allowed for any document, report, memo, manual, drawing, schematic, and source code comments.

2.4.2. The only allowed Unit System is SI. The only exception is the use of Imperial Units for the water manifolds in case of water-cooling of PCD1.

2.4.3. The contractor will provide the documents as two full sets in printed copy and three full sets in electronic format. The file types must be common standards, otherwise, if needed, the contractor must provide suitable viewers, free for corporate use.

2.4.4. The operating manual should comprise (at least):

a. Procedures for the installation, set up and operation of the equipment.
b. Detailed description of the power converter and its principles of operations (including all needed schematics, drawings, cables and connections lists, pin assignment of connectors, labels on terminal blocks, etc.).
c. Maintenance instruction, including calibration and adjustment procedures.
d. Troubleshooting guide, comprising the list of faults indications (local and remote), interlocks (with description of their actions) and suggested repair actions.

2.4.5. The above-mentioned documentation, integrated with the records of the factory tests carried on each power converter, is part of the supply and it must be approved and accepted by Elettra. At the time of the delivery to ESS for installation, connection to the load, and SATs, the contractor will provide a first set of schemes, cable connection diagrams, basic installation, operating and troubleshooting instructions.

3. Technical Requirements for the Power Converters

3.1. General Remarks

High reliability is mandatory: the magnet power converters are critical components within the structure of ESS. Any malfunctioning or fault can spoil or even prevent the operability of the accelerator and, therefore, of the whole facility.

3.1.1. The Tenderer is encouraged to propose the solution he thinks most suitable for the realization of the power converters in order to obtain the best compromise between the cost, efficiency and reliability of the system, the ease of maintenance and repair without affecting the required performances.

3.1.2. The design of the power converters must minimize the intervention time for fault detection and substitution of malfunctioning components. Diagnostic tools to help technicians in their intervention must be foreseen. Parts more likely to fail must be easy to replace and their repair, whenever possible, should occur at the workshop or in the laboratory, not in place.

3.1.3. Critical components and electronic boards must be available for at least 10 years after the acceptance of the power converters in the same or improved – but fully compatible – design.

3.2. Main parameters

The power converters’ output current is DC, adjustable within an operating range without losing the required performances. The following tables summarize the required parameters and performances of the dipole and quadrupole power converters (PCD1 and PCQ8), along with the mains, ambient characteristics and the type of control.

More in detail:

a. Table 5 reports the main output parameters of PCD1 and PCQ8.
b. Table 6 reports the required performances in terms of ripple and stability.
c. Table 7 summarizes AC mains and environment characteristics.
d. Table 8 details the requirements for the control of the power converters.
e. Table 9 presents the EMC/Safety and reliability figures.

See also the notes reported after Tables 5 and 6.

Table 5 – PCD1 and PCQ8: main output parameters and ratings

	Symbol	PCD1	PCQ8	Note
Type	SMPS, Single quadrant, DC, current regulated			
# of Power Converters		1	6	
Nominal Output Current [A]	I_{nom}	400	400	
Nominal Output Voltage [V]	U_{nom}	100	50	Guaranteed at I_{nom} and lowest AC mains voltage (400 Vac - 10%)
Nominal Output Power [kW]	P_{nom}	40	20	
Maximum load inductance [mH]	L_M	1720	83.6	Estimated from calculations
Maximum load resistance [mΩ]	R_M	185	69	Magnet + cables

Notes:

- *Nominal Output Current: the maximum current accepted by the magnets.*
- *Nominal Output Voltage: the voltage required to supply the nominal, inductive load with the PC nominal current – including the required dynamics.*
- *Maximum Output Power: the maximum peak power of the power converters, including dynamics.*

Table 6 – PCD1 and PCQ8: Accuracy and dynamics (common to both)

	Symbol	PCD1	PCQ8	Note
Maximum current ripple [ppm]	Δi_{pk-pk}	±50		Referred to I_{nom}
Minimum current reproducibility [ppm]	$\tilde{i}_k$	±50		Referred to I_{nom}

Stability of current [ppm]: - over 5 hours, without warm-up : - over 24 hours, after 5 hours warm-up : - over 1 year, after 5 hours warm-up :	$\bar{I}_K$	±100 ±50 ±200		Referred to I_{nom}
Line Voltage Regulation [ppm]	LI_K	±100		±10% line voltage change, instantaneous step change on all three phases. Worst load case, referred to I_{nom}
Output current Range [A]	I_{min}, I_{max}	37-370		10% - 100% of I_{mag_nom}
Maximum current settling time [s]	T_R	30	2	From I_{min} to I_{max}
Output current over-/undershoot [ppm]		100		Of the setting value; in the range I_{min} to I_{max}
Resolution of the Output Current setting [bit]		≥16		
Resolution/accuracy of the read back values of Output Current and Output Voltage [bit]		≥16		

Commented [RV2]: The settling time is critical for the dipoles, due to the relatively high inductance.

Notes:

- *Current Ripple is defined as the peak-to-peak variation in the output current – referred to its maximum (400 A) – at frequencies from 1 Hz to 200 kHz. The ripple tolerance must be achieved in the required current range on the minimum inductive load.*
- *The Current Stability is the variation of the output current – referred to its maximum - from its mean value at a fixed set over a period.*
- *Output Current Range: the range within which must be possible to vary the DC level of the output current without exceeding the required performances (current ripple, stability and line regulation).*
- *Maximum Current Settling Time: the time needed to pass from 37 A up to 370 A without exceeding the required performances (current ripple, stability and line regulation).*

Commented [RV3]: More details/comments from ESS

Table 7 – PCD1 and PCQ8: AC mains, ambient temperature and cooling (all)

	Symbol	Value	Unit
Nominal line-to-line AC voltage, power part	U_{AC_P}	400	V
Nominal line-to-neutral AC voltage, control part	U_{AC_C}	230	V
AC voltage source type, power part		3-phase + PE, 50 Hz	
AC voltage source type, control part		1-phase + N, 50 Hz	

Earthing system, control/power part (common to both)		TNS	
Line voltage operating variations, step changes simultaneously on the 3-phases, permanent (maximum), power part	ΔU_{AC}	±10	%
Line voltage total harmonic distortion (maximum), power part	THD (U_{AC_P})	10	% rms
Line short circuit power (maximum), power part	$S_{AC}sc$	30	MVA
Line voltage peak mains surges, phase-to-phase, power part (95% of all mains surges; remaining 5% outside this range).		1.5	kV, for 0.2 ms
Line voltage over-voltage, power part (95% of all over voltages; remaining 5% outside this range).		1.5 x nominal voltage, for 20 ms	
Minimum efficiency at nominal conditions	η	85	%
Ambient Temperature: - Operating range (@ 100% load) - Expected operating point for accuracy - Storage		0…40 27,5 -10….50	°C
Ambient Humidity (non-condensing)		20…90	% RH
Input power factor (nominal conditions)		>0.8	
Input current harmonic distortion	THDi	< 30	%
Cooling of Power Converter (water for PCD1 only)		Forced air / Water	

Commented [RV4]: ESS describe better, plot?

Table 8 – PCD1 and PCQ8: control and monitoring (all)

Remote control fieldbus	Ethernet (RJ45 socket), TCP-IP protocol
Local control interface	- Local/remote selector (selectable only locally); - Setting of current reference; - Diagnostics of internal and external faults; - Indication of actual output current and output voltage; - Local reset of faults.
Hardwired status and interlock signals: - Outputs from each power converter - Inputs to each power converter	 - PC ON/OFF status. - External interlocks 1 & 2 – require Reset to clear.

Table 9 – PCD1 and PCQ8: EMC/Safety compliance and reliability (all)

EMC standard on emission conductive disturbances	according to CISPR 11; EN 55011 class B, for AC mains
EMC standard on immunity to fast transients	according to IEC-61000-4-4 (Level 4)
EMC standard on electrostatic discharge immunity test	According to IEC 61000-4-2: Part 4-2: Testing and measurement techniques
EMC standard on voltage dips, short interruptions and voltage variations immunity tests	According to IEC 61000-4-11: Part 4-11: Testing and measurement techniques
Safety requirements for power electronic converter systems and equipment	According to IEC 62477-1: Part 1: General
Mean Time Between Failures (MTBF)	70'000 hours or better

4. Design and Construction requirements

This section describes more in detail the information presented in tables 3 – 9.

4.1. Mode of operation: general description

4.1.1. The power converters will operate in constant current mode, on inductive loads, without any foreseen interruption for weeks.

4.1.2. The output current is adjustable within a given range (10% – 100% of I_{mag_nom}) according to the requirements of the proton beam. During the transitions from one set to another, the output current must keep its characteristics in terms of ripple and the regulation must follow the over and undershoot specifications.

4.1.3. The design of the power converters must minimize the effects on the AC mains and attend the specified power factor. Efficiency is also a feature of considerable importance and the design must aim to maximize this aspect.

4.1.4. The power converters will operate both under remote and local control. The former via the interface to the Control System of ESS, the latter for test and maintenance purposes, only. Passing from remote to local control must be as smooth and simple as possible without affecting the status of the PC. A careful design must be adopted in order to assure safe operations both for the equipment and for the personnel using it.

4.1.5. The "LOCAL/REMOTE" (L/R) switch/command is available and operable only locally: it is not possible to pass from remote to local and vice versa via a remote command. L/R acts on the "ON/OFF" command of the power converter. The "OFF" command remains possible in any operating mode, both locally and from control system. The "ON" command depends from the operating mode. If the power converter is in "LOCAL", the "ON" command is only local. The switching over from the local to remote or reverse must not

Commented [RV5]: According to PDR2 Recommendation #6, April 11, 2017.

change the running conditions of the power converter (e.g. changing the current set and the output current).

4.2. Design and Construction considerations

4.2.1. The power converters must be of at least Class 2 according to IEC 61000-4-11 – Voltage dips, short interruptions, and voltage variations, immunity tests.

4.2.2. The equipment must have a galvanic isolation between the input AC mains and the load.

4.2.3. Adequate safety margins must be adopted in the choice of the power semiconductors and modules. Both the electrical and the thermal aspects have to be considered.

4.2.4. The high power capacitors used in the input and output filters and in the DC-Links must be designed to withstand a short circuit across their terminals.

4.2.5. Suitable capacitors shall be used to meet the required operating lifetime of at least 25 years.

4.2.6. The design of the power converter must include an output overvoltage protection (e.g. freewheeling diodes / crowbar protection) in case of sudden stop of the output current not to damage the power converter, the magnet(s), and the connecting cables.

4.3. Electrical Connections.

4.3.1. The connectors to the power mains and the control mains should prevent accidental contacts of live parts with a protection degree IP20 (finger protected) or better.

4.3.2. ESS will provide a connection to the 3 x 400 VAC + PE, 50 Hz mains for powering the Power Converter.

4.3.3. A separate 1-phase, 230 VAC, 50 Hz, mains line, connected to a UPS in the ESS substation is available to supply the electronics for the regulation and control of the power converter. The power converter must keep its digital communication and control operating while this power source is available.

4.3.4. The foreseen cables connecting the power converters to the magnet(s) are 2 x 2x120 mm^2 with suitable bolted connections.

4.3.5. The PC design has to take into consideration the possible connection of the negative output to the ground, either directly or through a small resistor.

4.4. Internal Cabling.

4.4.1. The ends of the wires and cables must be clearly marked and identified according to the circuit diagrams and tables.

4.4.2. All wiring must be adequately supported and securely braced. Power cables must be well separated from signal ones.

4.5. Cooling.

4.5.1. Air cooling through forced ventilation with high efficiency and reliable fans is expected with useful life of at least 70.000 hours. An easy way of substitution of the fans on periodical maintenance service is expected.

4.5.2. Water cooling is an option that can be considered, even if it is not the preferred one, for the dipole power converter.

4.6. Power converter enclosure.

4.6.1. The enclosure of the power converters has to be compact but this must not prevent nor complicate the maintenance or repair of the power converter itself. The minimum protection degree of the enclosure is IP20 (finger protected).

4.6.2. The enclosure (sub-rack) must respect the standards for its easy mounting in a 19" rack. In order to optimize the distribution of PC racks in the ESS Service Area, each sub-rack must stay within the following dimensions (depth x width x height): 700 mm x 19" x 8U.

4.6.3. For the dipole PC only, it is possible to consider an independent 19" rack, that is part of the delivery

4.6.4. All screws, bolts, nuts, etc. must have ISO metric threads. All screws heads must have a common standard screw drive (i.e. Slot, Philips, Pozidriv, Torx, Hex socket).

4.6.5. The components of the power converters must be easily accessible and safely dismountable for maintenance or repair.

4.6.6. The power converter module should have on its enclosure a nameplate with (at least) the following information:

a. Manufacture's name and address
b. Power converter type and serial number
c. Input rating
d. Output rating
e. Gross weight
f. Date of manufacture

4.7. Commands, Indications, and Interlocks

4.7.1. The normal control status of the power converters is remote via the ESS control system. Trained personnel can run the power converters under local control for test and maintenance purposes, only.

4.7.2. The interface to the ESS Control system must be Ethernet, using TCP/IP protocol, and via a RJ45 socket. Other digital interfaces for remote control must be converted to Ethernet with suitable and reliable adapters. These adapters must be provided with the power converters and previously accepted by Elettra and ESS.

4.7.3. The “local control” must be enabled/disabled only locally. It has to be possible without physically disconnecting the power converter from the ESS control system. The “local control” can be provided either via a dedicated panel mounted on the power converter (preferred solution) or via a serial connection (RS232 or USB), requiring the use of a portable computer. The “Locally remote” control via a computer directly connected to the RJ45 Ethernet port is – obviously – always possible but it must be considered as an exceptional case, only for special test or maintenance purposes.

Commented [RV6]: According to PDR2 Recommendation #6, April 11, 2017.

4.7.4. The status (including the read back of the output current and voltage with the required precision) and the command signals must be available locally as well remotely via the digital interface. Along with the Contractor’s standard commands and indications some commands and indications should be present locally on the front panel of the power converter:

a. Presence of the voltage of the 3-Ph mains (or, alternatively, “Mains Fault”).
b. Status ON/OFF
c. Status READY/NOT READY
d. Status PS FAULT
e. Status EXTERNAL Interlock 1
f. Status EXTERNAL Interlock 2
g. Status LOCAL/REMOTE
h. Command LOCAL/REMOTE (protected from accidental commutations)
i. Command ON/OFF
j. Command RESET (for faults)
k. Command Output current set
l. Read Output current set (read set value)
m. Read Output current (from the internal current transducer)
n. Read Output voltage

The Tenderer is strongly encouraged to propose, according to his experience and standards, additional diagnostics tools/signals to be implemented in the power converter in order to facilitate the diagnosis of faults.

4.7.5. Interlocks must be foreseen both for internal (e.g. overcurrent, over-temperature, etc.) and external protection (i.e. to protect the load and the personnel). In both cases, faults must be latched: the power converter has to be switched off by the intervention of the protection and must remain off – even if the cause is removed – until the intervention of the operator either locally or remotely. The logic for interlocks and protections has to be fail-safe. The design and implementation of the interlocks must be such to guarantee a safe and reliable operation even in the event of malfunctioning of any part of the power converter. The switch-on of the power converter must be enabled by the external interlock signals as well as from an internal one.

4.7.6. Besides the internal self-protections listed in Appendix 1, the power converters will be connected to the ESS Interlock System by means of two input and one

Commented [RV7]: Why two? It could be sufficient one if the enable signal is coming from a PLC.

output signals described below (the interlock logic – not the circuitry – is shown in Figure 2).

a. Interlock Inputs:
the ESS Interlock System will provide two separated 24 VDC signals to enable the switching on of the power converter. If any of these signals is not present, the power converter cannot be switched on. If the power converter is on and at least one of the signals is not anymore present, the power converter must be immediately switched off.

b. Interlock Output:
potential free normally open contact(s) (e.g. relay contacts) indicating the ON/OFF status of the power converter. The contacts must be open when the power converter is "ON" and supplying current (output enabled) to the load.

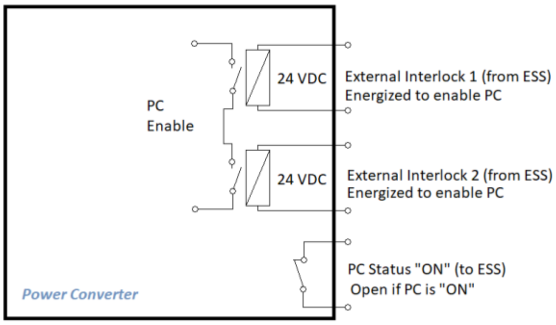

Figure 2 – Interlock Logic of the PC

4.7.7. Access to regulation parameters: the final user must have local access to the internal regulation parameters of the PC for tuning it according to the final application. The manufacturer must provide instructions and tools for this operation.

4.7.8. Firmware updates: final user must have local access for firmware upgrades. The manufacturer must provide instructions and tools for this operation.

4.7.9. Output current limit: the PC shall have a local adjustable parameter to allow the user setting its maximum output current. This maximum output current value shall not be overridden by any external command or control.

4.8. Operation and maintenance

4.8.1. The power converters will operate on a 24-hours/day, 7-days/week basis for several weeks in a row, with no scheduled interruptions in between.

4.8.2. The design of the power converter must facilitate the maintenance during the scheduled shutdown periods and repair in case of failure.

4.8.3. The substitution of faulty components or sub-units, generally, should be possible using conventional tools. Any needed special tool must be mentioned and delivered with the power converters as part of the supply.

5. Appendix 1 – List of minimum internal protections

In the following, there is a list of possible internal interlocks and protections. The contractor is encouraged to add or modify some items according to his experience, standards and design.

A. Protection on output overvoltage
The load is inductive. The case of a sudden stop of the output current (e.g. due to an interlock trip) or interruption of the output connection has to be foreseen. Adequate devices (e.g. freewheeling diodes, crowbar systems) must be used to protect the output stage of the power converter from excessive voltages.

B. Protection against excessive warming
Over temperature switches for semiconductors, transformers, and chokes have to be foreseen.

C. Control of mains voltages
PC must not suffer any damages due to interruptions of the AC mains voltage of any kind.

D. Overcurrent
All overcurrent and short circuit indications of the power part as well as the control of the fuses shall act on the circuit breaker. All the other fault indications are determined by the standards of the producer.

6. Appendix 2 – Some considerations on the dipoles degaussing

ESS has expressed some concerns about the remnant field in the dipoles that could spoil the proper trajectory along the straight direction through the Dump Line. The degaussing procedure could require the inversion of the current flow in the magnets. It is remarkable that, since normal operation is bringing the protons to the target, this procedure is not a routine one but it occurs only when the proton accelerator has to be “tuned” or optimized, an operation that requires adequate time for completion.

There are two practical ways to perform this polarity change.

a. Four-quadrant Power converter
A fully bipolar – both in voltage and current – power converter can execute the degaussing procedure (e.g. cycling the current in the magnet, from positive to negative and viceversa) relatively fast.

   The main drawback is the need for a bipolar (and more expensive) power converter for an operation that is occasionally performed.

b. Electromechanical or solid state Polarity Switcher
At the output of single quadrant DC power converter, there is a remotely controlled power switch that allows the inversion of the polarity on the line connected to the magnets (Figure 3 shows the principle).

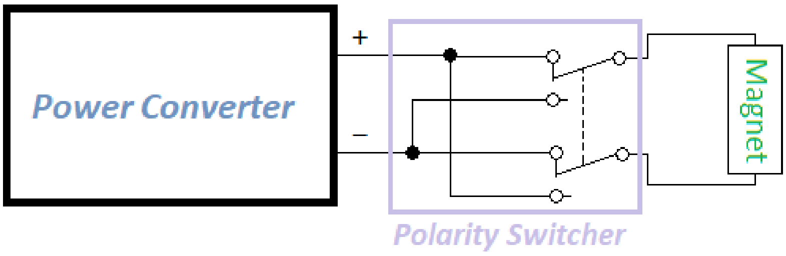

Figure 3 – Polarity switcher (remotely controlled, internal interlocks are not shown)

The polarity switcher does not operate in "live mode", i.e. while the current is flowing in the magnets. The change of polarity occurs only when the PC is OFF and an interlock, internal to the system PC-Switcher, verifies this condition. The polarity switcher can be part of the delivery and integrated inside the rack of PCD1.

In case the manufacturer wants to implement a solid state switch, its power loss has to be taken in account.

A possible variation is the connection, trough the polarity switcher, of a small bipolar power converter (e.g. an A2720, the same of correctors C5, C6, and C8) as shown in Figure 4.

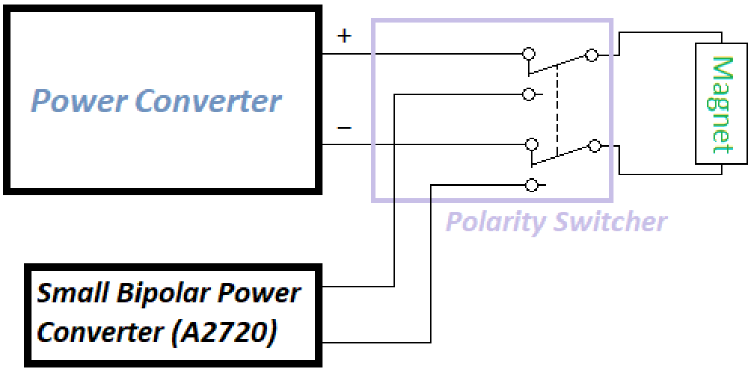

Figure 4 – Small bipolar PC connected to the dipole magnets through the polarity switcher (remotely controlled, internal interlocks are not shown)

In this case, interlocks have to be foreseen to avoid live commutation for any of the two power converters.

7. Appendix 3 – Some considerations on the ramping speed (slew-rate)

The following voltage vs. time plots (Figure 4) show the calculated output voltage required to PCD1 when ramping the current from 0 to 400 A (quite pejorative case).

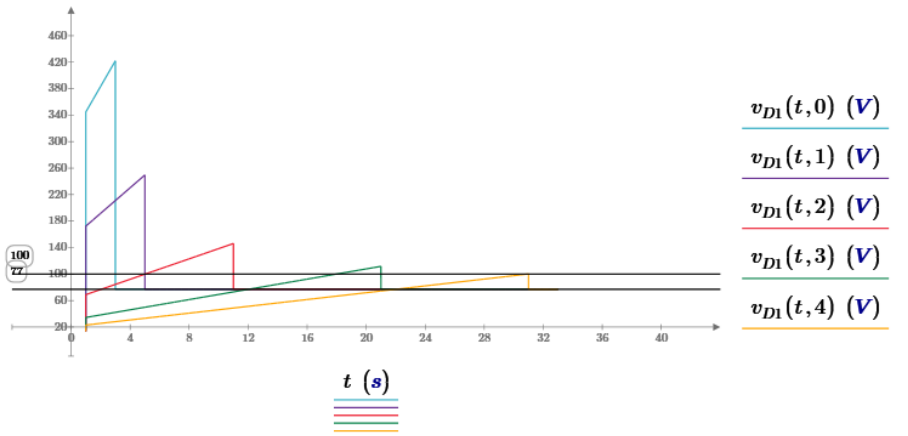

Figure 4 – Output voltage at 2, 4, 10, 20, and 30 second ramp duration)

The maximum estimated DC output voltage is 77 V; the dynamics for a 30 s-ramp brings to a peak voltage of 100 V. If there are no specific reasons for requiring a shorter ramp duration, in our opinion a 100 V / 400 A power converter is the proper choice. Increasing too much the output peak voltage requires a more powerful PC, over dimensioned for the expected actual use (I_{mag_nom} is 370 A) with higher costs and – probably – less efficient.

8. Appendix 4 – Some procurement considerations

As shown in Table 5, there will be six power converters supplying the quadrupoles Q8 and one power converter for the two dipoles D1. They have the same output current and therefore we could group them in a single procurement procedure, independent from those for the other power converters.

On the other hand, to supply the quadrupoles Q8 we propose a power converter whose output parameters are 50 V / 400 A. This could be realized either as a single device or by putting in parallel two units, 50 V / 200 A each.
In PDR-2, we showed that PCQ5, PCQ6, and PCQ7 require 30 V / 200 A. Increasing their output voltage to 50 V (without affecting the required performances) make them suitable as “building” blocks for PCQ8.
From the survey presented in PDR-2, we know that at least two “COTS” types are already capable of operating in parallel, not considering those that could be built (or modified) “on purpose” by other manufacturers.
Consequently, we could unify the procurement of the six quadrupole PCQ8 (they would become 12 “basic” units) with that one of the other quadrupole PCs. The

advantage of such solution is the reduction of different power converters' types, improving the maintenance and spares strategies. In addition, this solution would increase by ~9% the number of (30) 50 V / 200 A units, and could help in reducing the overall cost.

For what concerns PCD1, the high inductance of the magnet dominates the output voltage, worsened by the fact of having two magnets in series. Considering a 30 s-ramp, the choice (tight but reasonable, considering the safety margins on the magnets, the cable length, and the foreseen ramp range from 10% to 100% of nominal current, about 370 A) is a 100 V / 400 A power converter, as reported in Table 5. This could be realized either as a single device or putting in series two 50 V / 400 A units (the latter is compatible with PCQ8, in case it is realized as a single block).

Summing up, there are four options, two for PCQ8 and two for PCD1.

PCQ8:

a. 6 units, 50 V / 400 A;
b. 12 units, 50 V / 200 A, connected in couples in parallel (these could be included in the same lot of PCQ5, PCQ6, PCQ7).

PCD1:

c. 1 unit, 100 V / 400 A;
d. 2 units, 50 V / 400 A, connected in series (that could be included in the same lot of PCQ8 in case a.).

Both options b. and d. bring to a reduction of different types of power converters, facilitating maintenance and spare parts managing.

Options c. and d. are both compatible with the polarity switcher solution for the degaussing of the dipoles.

We could take into consideration the option of having a single Call for Tender for all large power converters, divided in three lots:

Lot 1 - 133 units 30 (50) V / 200 A for Q5, Q6, and Q7;

Lot 2 - the tenderer can choose and quote option a. or b. for PCQ8;

Lot 3 - the tenderer can choose and quote option c. or d. for PCD1;

with possible mergers of the lots according to the chosen options.

Tenderers can quote single lots or combination of lots and separated lots can be assigned to different tenderers.

This strategy, of course, has to be agreed and developed also with whom will operate the European Call for Tenders.