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Technical Specifications for the Procurement of the Power Supply System for the Vertical and Radial Stabilization (VS) In-Vessel Coils of the Divertor Tokamak Test (DTT) Facility

DTT S. c. a r. l.

This document is issued for the execution of the DTT project

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Abstract: This document contains the Technical Specifications for the Call for Tender for the Procurement of the DTT vertical and radial stabilization (VS) in-vessel coil power supply system.

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Summary

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Acronyms, abbreviations and definitions

Acronyms	Definitions
AC	Alternating Current
ADP	Acceptance Data Package
Alfresco	DMS environment presently used for the DTT project
BOD	Break-over diode
CCON	Central Control Online Network
CODAS	Control and Data Acquisition System
Contractor	Company or organization to which ENEA will entrust the Procurement covered in these Technical Specifications
CP	(Contractor) Control Plan
CPR	EU Construction Products Regulation No 305/2011
CRM	Current regulation mode
DC	Direct Current
DC-Link	Connection system between input and output converters, consisting of a bank of capacities
DEC	Direttore dell'Esecuzione del Contratto, as defined by Italian laws
DIV	Divertor, used to define coils close to DTT divertor
DMS	Document Management System
DTT	Divertor Tokamak Test facility
DTT site	ENEA Frascati research centre – Via Enrico Fermi 45 – 00044 Frascati (RM) – Italy
DTTU	Divertor Tokamak Test facility Upgrade
DUVRI	Documento Unico di Valutazione dei Rischi da Interferenze, as defined by Legislative Decree 81/2008
EDG	Emergency diesel generator
EF	Error field
ELM	Edge-localized mode
EMC	Electromagnetic Compatibility
ENEA	National Agency for New Technologies, Energy and Sustainable Economic Development
ESR	Equivalent series resistance
FAT	Factory acceptance test
FDR	First Design Report
HIL	Hardware-in-the-loop
HMI	Human Machine Interface
HSE, HSEQ	Health, Safety, Environment (and Quality)

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ICN	In-vessel coil non-axisymmetric (same as NAS coil)
IEC	International Electrotechnical Commission
IP (code)	International Protection code (Standard IEC 60529)
KOM	Kick-Off Meeting
LCC	Local Control Cubicle
LCM	Local Control Mode
LF	Light fault
LSOHFR	Low Smoke, Zero Halogen, Fire Retardant
LTM	Long-Term Maintenance (state)
LV	Low voltage
MPON	Machine Protection Online Network
PQMS	Project and Quality Management Specifications
MV	Medium voltage
NAS	Non-Axisymmetric
NTP	Network Time Protocol
OL	Ordinary Load, loads that require a normal auxiliary power supply
OPC-UA	Open Platform Communications Unified Architecture
OSON	Occupational Safety Online Network
PCB	Polychlorinated biphenyl
PCT	Polychlorinated terphenyl
PHIL	Power-hardware-in-the-loop
PLC	Programmable Logic Controller
PS	Power supply
QP	(Contractor) Quality Plan
QR	Quality Representative
POS	Plasma Operation (state)
RCM	Remote Control Mode
RMS, rms	Root Mean Square
RTON	Real-Time Online Network
RUP	Responsabile Unico del Progetto, as defined by the Italian Law
SAT	Site acceptance test
STM	Short-Term Maintenance (state)
SCADA	Supervisory Control and Data Acquisition
Scarl, S. c. a r. l.	DTT S. c. a r. l., Limited liability consortium company (Società consortile a responsabilità limitata) which manages the DTT project

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SF	Severe fault
Subcontractor	Company or organization to which the Contractor can entrust a specific part of the Procurement
Terna	The Italian TSO
THD	Total harmonic distortion
TRO	Technical Responsible Officer, person in charge of the contract for the Contractor
TS	Technical Specifications
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
VRM	Voltage regulation mode
VS	Vertical and radial stabilization
WBS	Work Breakdown Structure
WINCC-OA	WinCC Open Architecture

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References

[1] "Project and Quality Management Specifications for the Procurement of the Power Supply System for the Vertical and Radial Stabilization (VS) In-Vessel Coils of the Divertor Tokamak Test (DTT) Facility", DTT ID: PSS-SPT-59302.

[2] "Packing & Marking Procedure for Material and Equipment", DTT ID: PRC-PRO-07000.

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1 Scope of the Procurement

1.1 Introduction

The goal of the Divertor Tokamak Test (DTT) project is the creation of an experimental research facility to investigate some of the most complex problems along the path to the exploitation of nuclear fusion as an energy source.

The DTT facility will be located inside the Research Center of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Frascati, Italy hereinafter abbreviated as DTT site.

DTT will be built as a tokamak, that is the most developed configuration for nuclear fusion experiments, achieving a plasma current up to 5.5 MA with a magnetic field of 6 T and an additional heating up to 45 MW coupled to the plasma.

The DTT construction is managed by the DTT S. c. a r. l. (Consortium), denoted simply as “Scarl”, including ENEA and other prestigious members. However, the Procurement described in these specifications is managed by ENEA, under the project “Divertor Tokamak Test facility Upgrade (DTTU)”.

The Procurement described in these specifications will be assigned by ENEA in compliance with the present specifications to an entity (“Economic Operator”, according to the Italian law) denoted as “Contractor” in the following.

1.2 General characteristics of the DTT facility

Table 1 summarized the operative characteristics of the DTT facility. The number of pulses (operations) reported in Table 1 and their time characteristics (duration and distance) are the nominal ones at full power. At reduced power, more daily pulses divided by shorter intervals could be possible (Section 4).

Table 1. Operative characteristics of the DTT facility.

Parameters	Value
Pulses per day	10
Operation days per year	100
Operating life	25 years
Maximum number of pulses	25000
Nominal pulse duration	100 s
Interval between two subsequent pulses in nominal conditions	3600 s
Maximum plasma current	5.5 MA

1.3 The DTT VS coils

In a tokamak, the plasma is controlled by the magnetic field produced by the high current flowing in coils. As the DTT mission is related to the plasma control and shaping, the in-vessel coils are crucial for its operations and then to its success. In particular, the equatorial coils (see Figure 1) shall be able to perform 2 critical functions:

1. The first function consists in the plasma vertical stabilization. Elongated plasmas and alternative configurations, as those expected in DTT, are particularly sensitive to vertical instabilities.
2. Even though the DTT equatorial coils are simply classified as “VS”, they can also produce a radial control action to preserve plasma facing components during fast plasma transients. In the literature, such radial control is classified as “fast” with respect to the actions of other coils, but for the aim of this Procurement, its response can be slower than that required to the VS function.

The main subject of the present specifications consists in the Procurement of a power supply (PS) system to feed the currents in the 2 DTT VS in-vessel coils (shown in Figure 1). The VS coils are axisymmetric, made by copper (Cu) and cooled by water.

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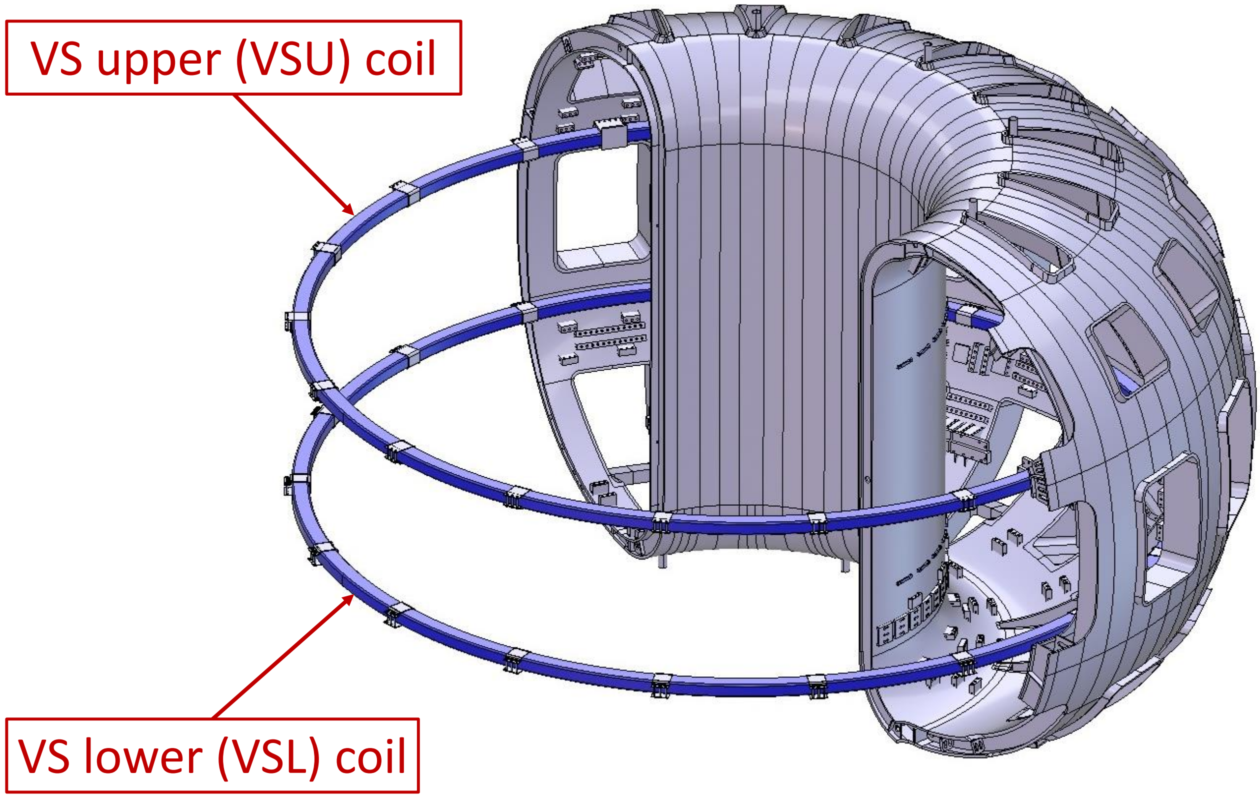

Figure 1. Arrangement of the DTT VS equatorial in-vessel coils.

1.4 Loads of the PS system

The PS system shall feed the 2 VS coils shown in Figure 1.

Because of the tokamak structure and the plasma configuration, each of the 2 coils corresponds to an equivalent load that is not limited to the coil winding. Therefore, the control and regulation algorithms shall take into account the strong inductive coupling phenomena with the other circuits magnetically coupled to the VS coils that could be seen as load variations. The requirements in terms of voltage and energy already consider these phenomena, but the Contractor may request more details after the assignment of the Procurement.

The electrical characteristics and the related requirements are identical for the 2 VS coils and for the related PSs.

1.5 Functions of the PS system

The VS PS system shall implement the following functions:

- Supply the 2 coils with the necessary power to follow the desired profile (scenario).
- Adjust the current or the voltage to the load.
- Track in real-time, the current or voltage reference scenarios originated from the communication interface (see Section 9).
- Communicate in real-time the defined measurements (see Section 9) to allow the CODAS system to close the regulation and control loop.
- Communicate the internal measurements necessary for its diagnostics.
- Use the electric power from the DTT grid distribution, normal and/or from UPS, for the load needs and for auxiliary purposes.
- Share the power between the load and DC-link or energy storage bank to limit the power drawn from the DTT grid.

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- Implement the necessary systems to protect the PS, such as crowbars, fuses, varistors and snubbers also by sending the relative alarms to the extern.
- To preserve the internal components at an appropriate temperature for their duty cycle and for the plant lifetime through a water cooling system.
- To ensure the safety of the people and the plant.

1.6 Activities and tasks included in the Procurement

The Procurement includes the following activities and tasks:

- Selection and sizing of the components, supported by calculus and simulations.
- Layout components design, including the preparation of the detailed drawings and electric schemes.
- The manufacturing and the assembly of the systems including:
    - Power semiconductor devices.
    - Capacitor (or supercapacitors) banks for the DC-links.
    - Step-down transformer(s), including all the necessary auxiliary and protective devices.
    - Bars, cables, fiber optics and the internal wiring including the input and output terminals.
    - Control and regulation systems.
    - Management software.
    - HMI interface where can be managed all the functionalities.
    - External system interface for remote control purposes equipped with the internal measures.
    - Transducers for voltage and current monitoring.
    - Air or water cooling system, where needed.
    - Safety breakers.
    - All the necessary protection and safety devices and arrangements (for example, ground connections, fuses, crowbars, emergency stop pushbuttons, alarm contacts, etc.), including the necessary protections for the proper functioning of the system and general safety (protections for over temperature, overvoltage, overcurrent, earth current leakage, etc.).
- A protection coil and a resistor on the imbalance (common) branch between output converters.
- Any special tools that may be required to operate, handle, test or maintain the PS system.
- A basic set of spare parts as described in Section 11.17.
- The inspections and acceptance tests in the Contractor's premises and/or at the ENEA or DTT site in Frascati, including at least those required in the Project and Quality Management Specifications (PQMS) [1].
- The technical documentation, in particular the First Design Report, the Test Reports and the Acceptance Data Package (ADP), with subsequent improvements based on the progress of the project.
- Any further project management and quality activity or documentation described in the PQMS [1].

1.7 Procurement interfaces

The Procurement has the following interfaces:

- With the DTT electrical distribution system (EDS) (see Section 5.3):
    - One three-phase connection at medium voltage (MV), that DTT will connect to the AC breaker upstream the input transformer(s).
    - One three-phase connection at 400 V rms for the ordinary load (OL) auxiliary power that DTT will connect to an agreed point of the PS system.
    - One three-phase connection at 400 V rms for the UPS auxiliary power that DTT will connect to an agreed point of the PS system.
- With connection DC busbars or cables (see Section 11.6) via 3 terminals (downstream of disconnectors included in the Procurement).

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- With DTT CODAS trough listed interfaces (Section 9). DTT will connect the different types of cables and fibers to the LCC of the PS system. More connection points can be requested and agreed only for the security interfaces (see Section 9).
- With the DTT water distribution system via two flanges (one inlet, one outlet), (see Section 10).
- With DTT Building 191 (see Section 13) via earth connections and anchors (that are not included in the Procurement).
- With the dummy loads (not included in the Procurement) during the tests if performed with dummy loads.

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2 Reference scheme

Figure 2 summarizes the complete Procurement of the VS PS system. This is a conceptual and reference scheme whose elements and requirements are clarified in the rest of this document. The Contractor may propose alternative schemes and solutions, provided that it demonstrates that they are equivalent or better with respect to the reference ones. The alternative proposals can be adopted only upon formal approval by ENEA either in the FDR or by a Deviation Request (see procedure in PQMS [1]).

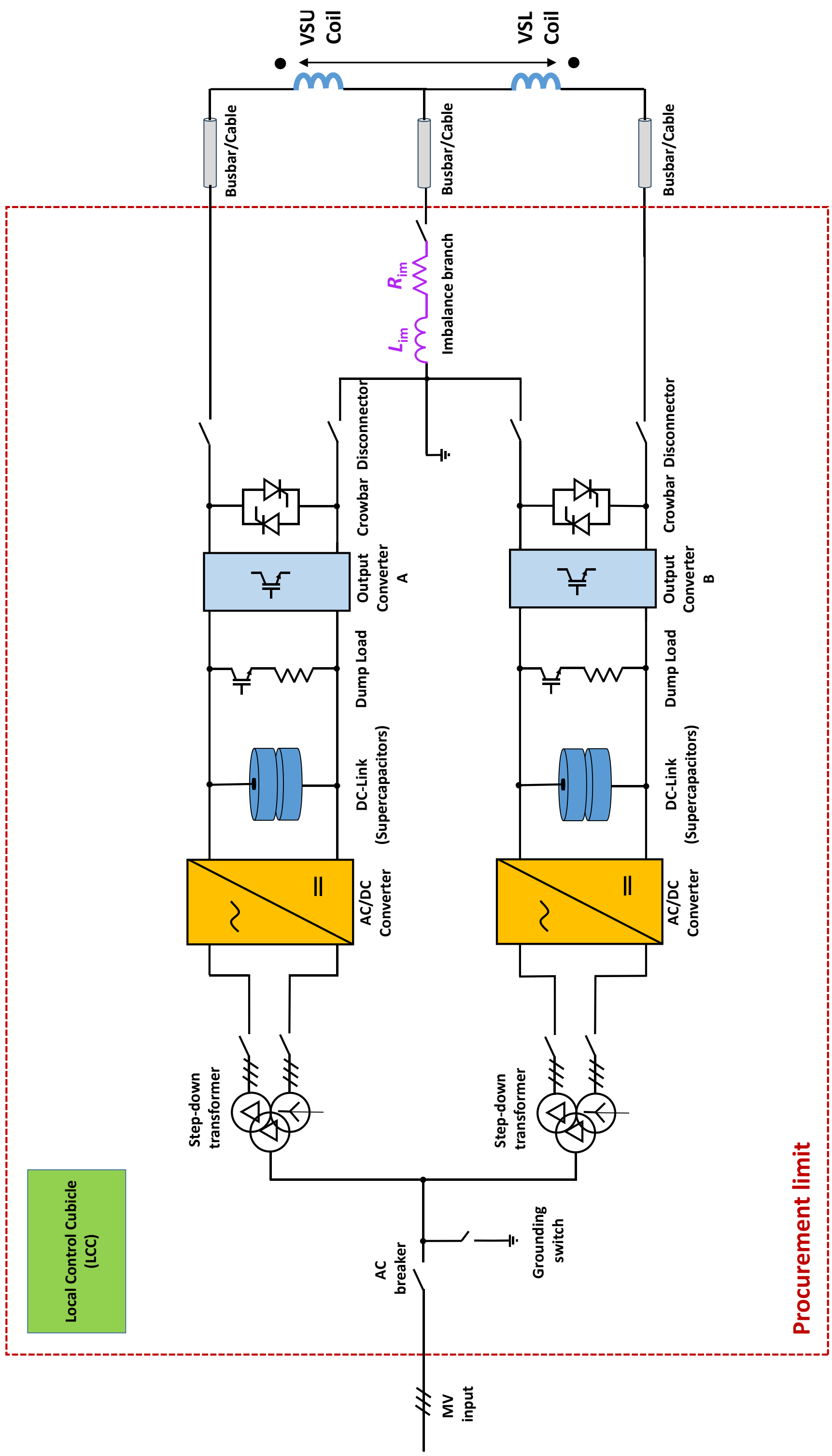

Figure 2. Overview of the VS PS Procurement for the 2 VS coils.

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3 Summary of main specifications and requirements

Table 2 summarizes the main specifications of the PS system covered by these Technical Specifications. More details can be found in the following sections.

Table 2. Main specifications of the PS system. For the most complicated parameters, the table reports the references to the sections where the parameters are fully described.

Characteristic		Value
Location for installation		Indoor (see Section 13)
Load		2 copper coils [(1)]
Number of output converters		2 in the same PS circuit (see Figure 2)
Load inductance (VSU and VSL in series)		9.9 mH [(1, 2)]
Load resistance (VSU and VSL in series)		128 mΩ [(1, 2)]
Expected maximum inductance of single busbar/cable		160 μH [(2)]
Expected maximum resistance of single busbar/cable		3 mΩ [(2)]
Operations of output converters		4 quadrants
Regulation mode		Voltage/Current (CRM/VRM)
Segregation mode		Local/Remote (see Section 9.4.1)
Nominal current of the output converters		±6 kA [(3)]
Nominal voltage for each output converter		±4 kV [(4)]
Regulation on the output current and voltage		0÷100% (continuous)
Nominal duration of PS operations		100 s [(5)]
Repetition time		3600 s [(5)]
Required waveforms (scenarios)		Arbitrary (see Section 4)
Reference waveform		Triangular (see Section 4.3)
Transfer function from requested to applied voltage (see Section 4.6)	Delay	≤50 μs
	Time constant	≤50 μs
Maximum output current accuracy		±0.5% [(6)]
Maximum output current ripple		±1% [(6)]
Maximum output voltage accuracy		±2% [(6)]
Maximum output voltage ripple		±4% [(6)]
Input voltage from the external grid		20 kV (see Section 5)
Maximum input power for the complete system		2.5 MVA (see Section 5 and Section 6)
Minimum energy of supercapacitors in the whole system		38 MJ (see Section 5 and Section 6) [(7)]
Crowbar current and energy		See Section 8
Electric insulation		See Section 12.5
Cooling		Air or/and water (see Section 10)
Inductance of imbalance coil L_{im}		30 mH [(8, 9)]
Resistance of imbalance coil R_{im}		200 mΩ [(8, 9)]
Worst-case current in imbalance branch		6 kA for 1 s for 3 times per PS operation

(1) The main loads consist in copper coils, but also the impedances of the connections (busbars/cables), the mutual inductances with the other windings and the parasitic effects due to the structure of the tokamak shall be considered (see Section 1.4 and 4). For the contributions of connections, see the related table rows.

(2) Equivalent parameters, also depending on frequency. See also Section 4.2 and Section 4.4.

(3) Only at low frequency, as explained in Section 4.5.

(4) This is the voltage of a single output converter. It is the double for VSU and VSL in series.

(5) Longer durations, more daily pulses divided by shorter intervals could be possible at reduced power (see Section 4).

(6) With reference to full scale.

(7) The energy stored in the supercapacitors shall also keep the DC-link voltage above the required output nominal voltage.

(8) With tolerance ±5% at 25 °C on the declared values.

(9) The elements L_{im} and R_{im} are explicitly shown in Figure 2 because they are both necessary for protection, but they can be merged in a single physical component.

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4 VS PS operations in DTT scenarios

4.1 PS operations and regulations

Each one of the 2 output converters shall be independently controllable to follow an arbitrary waveform (scenario), within the voltage, current, thermal and bandwidth constrains reported in the present Technical Specifications.

The desired VS scenarios to be followed by the PS system is communicated in real-time by the DTT control system (CODAS) according to the methods described in Section 9.

The scenarios for the VS coils can be defined in terms of desired voltage or desired current (the adopted mode is selected by the operators before the beginning of a pulse). Therefore, the output converters shall be able to operate in one of the following modes:

1. Current-regulation mode (CRM), namely following a current profile delivered in real time by the DTT CODAS.
2. Voltage-regulation mode (VRM), namely following a voltage profile delivered in real time by the DTT CODAS.

The CRM is the standard mode during the testing activities, but the VRM is expected to be the final mode during the DTT operations.

Especially for the testing and commissioning activities, some reference and typical waveforms (DC, sinewave, triangular and so on) shall be internally generated with selectable parameters and followed either in CRM or in VRM. These waveforms shall be selectable also via the HMI. The accomplishment of the reference and typical waveforms does not exempt the Contractor with respect of all the requirements in these Technical Specifications.

The nominal duration of a pulse is reported in Table 2. However, the Contractor for its design and tests shall also consider that further time could be necessary to pre-charge the DC-links before starting the scenario requested by the DTT operations.

The pulse duration and the time interval between two subsequent pulses specified in Table 1 are the nominal ones at full power. The possible durations shall not be limited to the maximum. Longer durations, with and at lower time intervals and more pulses per day are possible at reduced power. To ensure safe operations in these cases, the Contractor shall include a status indicator (see Section 9.4) which indicates whether the PS system is ready for the next pulse (for example, the internal temperatures are in the expected ranges). The Contractor shall provide in the final documentation some estimations of the minimum times between successive pulses based on the performed operations.

The control and regulation systems of the converters, designed to follow the current or voltage scenarios in normal conditions, shall include (if necessary, modifying its actions) the appropriate protection actions following internal or external alarms. For example, it shall be able to detect whether the actual current or its derivative are critical and to adjust them accordingly.

4.2 Load variations and reference operations for vertical stabilization

The load coils are magnetically coupled with many tokamak elements including the plasma. Therefore, in the final configuration, the voltages and the currents in the coils are also affected by element external to the PS system. This could be practically modeled as load variations.

In particular, the equivalent inductances and resistances of the load coils changes with the frequency. The inductance and resistance values reported in Table 2 are the stand-alone values, that are in practice the values at very low frequency (DC).

Figure 3 shows the equivalent inductances and resistances as a function of frequency for the VS circuit corresponding to the series (that is strictly an anti-series) of the VSU and VSL coils. The plots neglect the imbalance branch, that will be addressed in next Section 4.4, because in standard vertical stabilization operations the current does not flow in such branch. The final values in the circuit will also include the inductance and resistance of the connections, that will be better defined in the future. ENEA could provide more detailed models for these variations after the Contract assignment.

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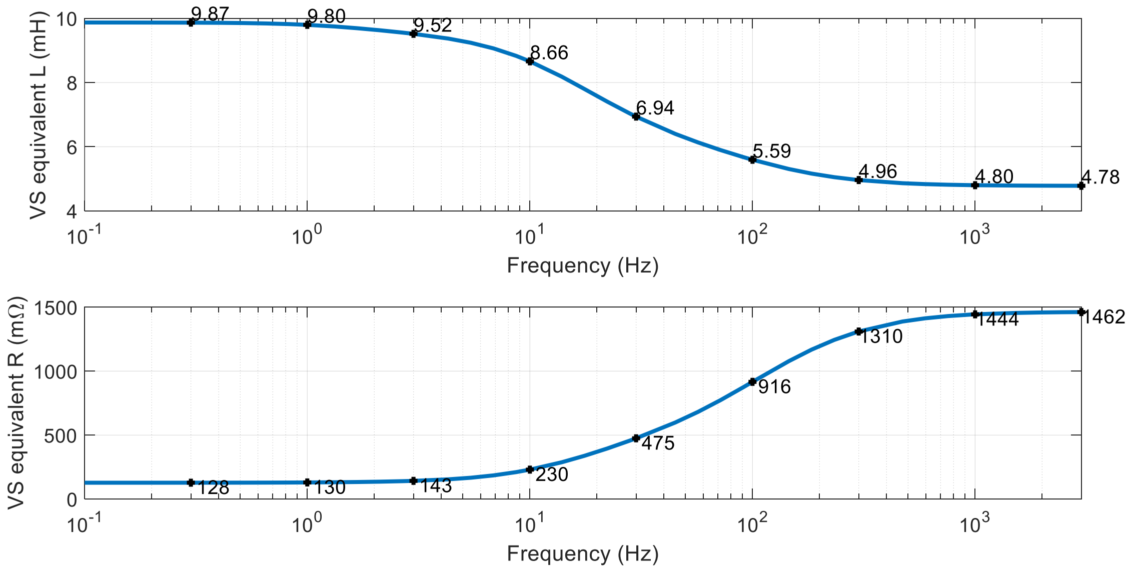

Figure 3. Equivalent inductances and resistances for the series of the 2 VS coils in the interesting range of frequency.

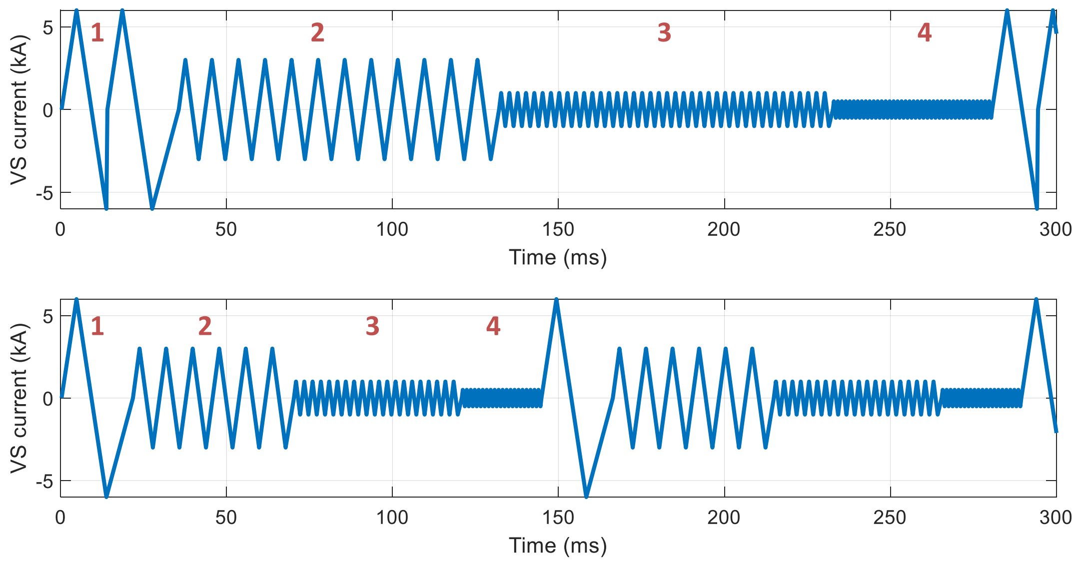

Figure 4. Typical scenarios (characterized by different repetitions of successive cycles) in the VS circuit during standard operations for plasma vertical stabilization. The currents are identical in all the VS coils and output converters. The characteristics of the triangular waveforms denoted as 1, 2, 3,4 are described in Table 3.

Table 3. Characteristics of the basic triangular waveforms in the typical scenarios in Figure 4.

Triangular waveform	Peak value	Period	Frequency	Repeated consecutive cycles	
				Figure 4 top	Figure 4 bottom
1	6 kA	18 ms	55.6 Hz	2	1
2	3 kA	8 ms	125 Hz	12	6
3	1 kA	2.5 ms	400 Hz	40	20
4	0.5 kA	1.2 ms	833 Hz	40	20

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4.3 Reference scenarios

The expected reference scenarios of the PS system for vertical stabilization are sketched in Figure 4 and detailed in Table 3. This kind of waveforms with a succession of triangular waves is expected to be repeated continuously during the operations (namely for about 100 s). Actually, the waveforms achievable in the circuit will be not exactly triangular but the first part of exponential charges.

The rms value of the currents in Figure 4 is about 1.7 kA. The corresponding stored and dissipated powers can be calculated through the inductances and the resistances at each working frequency (also considering the harmonic contents).

4.4 Imbalance for radial control

Since a part of the PS current and voltage shall be available to implement a radial control, in practice the output converters will operate at reduced performances for most of time (as in the scenarios in Figure 4).

In the scenarios in Figure 4 , the 2 VS output converters operates in the same way and the current in the imbalance branch (containing L_{im} and R_{im} in Figure 2) is ideally zero. This behavior is modified only in limited cases to implement radial control of plasma. Only in these limited cases, the CODAS will require different currents in the 2 VS output converters in order to drive a current in the imbalance branch and to unbalance the currents in the VS coils.

In practice, in the imbalance branch, a current up to 6 kA shall flow for maximum 3 intervals during a 100 s operation (twice close to the start of the operation and a third time close to its end). Each of these intervals will last less than 1 s.

A current can flow in the imbalance branch for a short time also in case of disruption (see Section 8), but this event is in practice a fault that terminates the pulse and the PS operations.

These considerations, together with the effect of plasma disruptions in Section 8.4, are important also for the thermal design of the inductance and resistance in the imbalance branch.

The PS system shall also monitor the current flowing in the imbalance branch to verify that it is zero during reference vertical stabilization operations or equal to the desired unbalance value when radial control is requested.

Similarly to Figure 3, Figure 5 shows the equivalent inductances and resistances between the imbalance terminal to ground and the external coil terminals (see Figure 2) as a function of frequency. These can be considered as the inductances and resistances for radial control (when current flows in the imbalance branch). The final values in the circuit will also include the inductance and resistance of the connections.

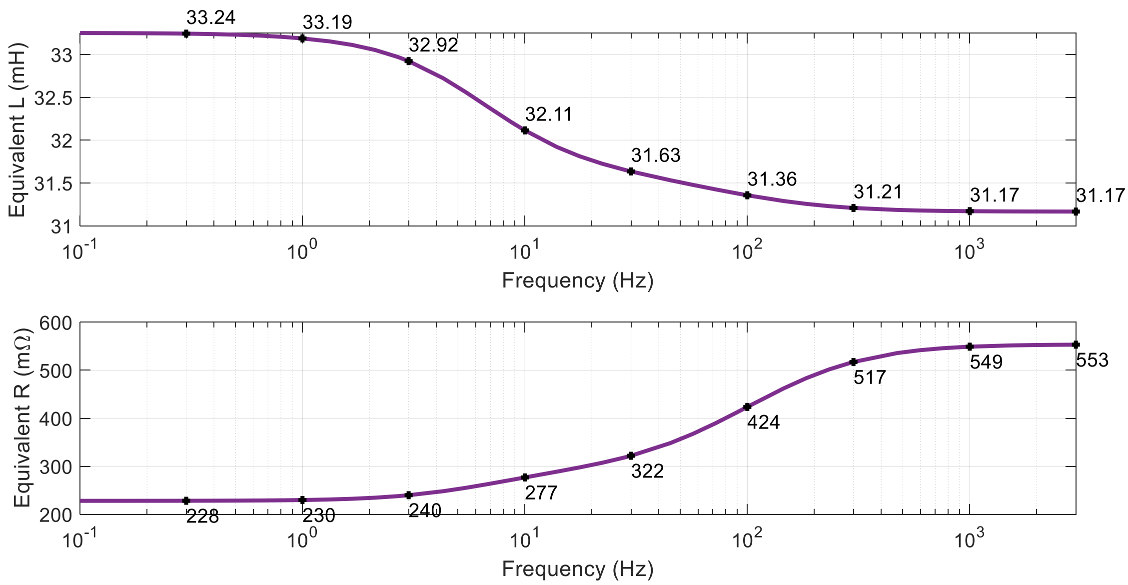

Figure 5. Equivalent inductances and resistances for the radial control in the interesting range of frequency.

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4.5 Constraints in the required current

The output converters shall be able to produce sinewaves up to 3 kHz.

However, the frequency dependance of the circuit reactance, together with the inductance and resistance variations in Figure 3 and Figure 5, affect the current that the converters can actually drive at the different frequencies.

At higher frequencies (above 20 Hz for vertical stabilization and above 2 Hz for radial control), ENEA will accept lower currents with respects to the nominal current of 6 kA, as summarized in Figure 6. The output converters shall produce at least the value reported for each frequency. For example, the required current for the output converter at 100 Hz shall be at least 2091 A in vertical stabilization and at least 193 A in radial control.

Figure 6 confirms that the dynamics of the two functions implemented by the VS PS system are different, as required by the related plasma phenomena.

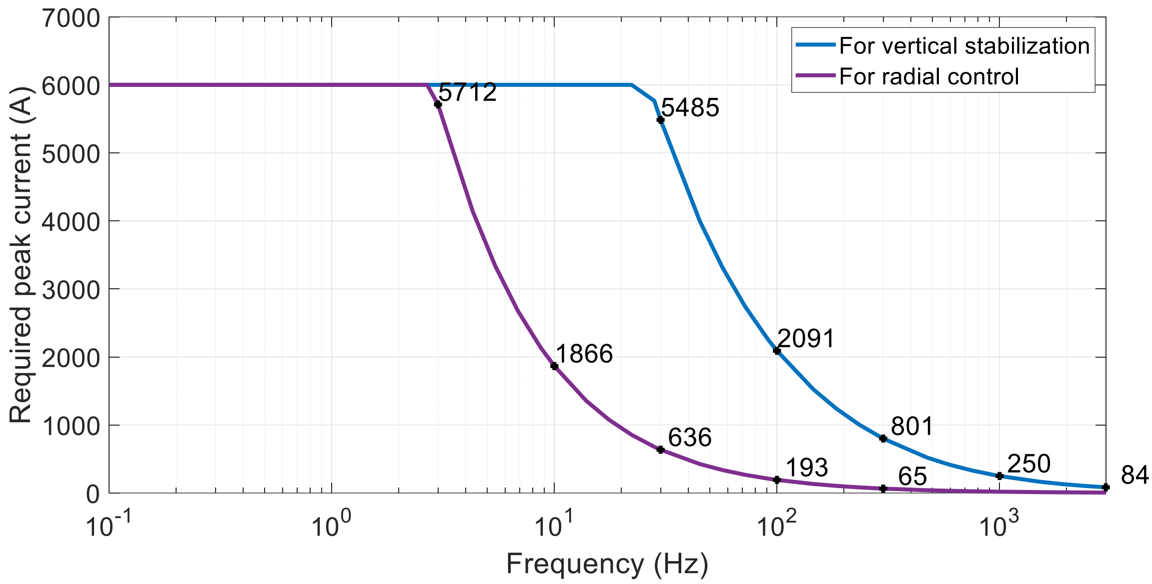

Figure 6. Required current as a function of the frequency. Below 5 Hz the nominal current of 5000 A is always required.

4.6 Transfer function in voltage-regulation mode

It is important to stress that, even though Figure 6 (like Figure 3 and Figure 5) models the output currents as sinewaves and Figure 4 as triangular waves, the outputs converters shall be able to produce arbitrary waveforms (as requested in Table 2) and communicated in real time (see Table 2 and Section 4.1).

The VRM will be the preferred mode for DTT operations. In fact, a faster and more efficient control of the plasma is expected to be achieved if the PS reproduces in "open-loop" a voltage scenario communicated by the DTT CODAS. The PS is considered to operate in open-loop because it is not requested to apply a regulation controller, that is instead implemented in the CODAS. Nevertheless, the PS control shall always operate to avoid faults or dangerous situation (overcurrents, excessive derivatives and so on).

In this situation, the PS can operate at its maximum speed. The performance of the PS will be evaluated by its equivalent transfer function from requested to applied voltage:

$$F(s) = \frac{e^{-s\tau_1}}{1 + s\tau_2}$$

In this transfer function, τ_1 models the delay between the input and the output and τ_2 models the time constant at the output. Adopting these definitions, the PS shall have $\tau_1 \leq 50$ µs and $\tau_2 \leq 50$ µs.

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5 Input power

5.1 Assumed conditions

The input power and the power ratings of the components shall be optimized to allow the scenarios in Figure 4 for the entire duration of the pulse and 3 intervals at full current in the imbalance for radial control (see Table 2). The energy stored in the supercapacitors of the DC-link (see Section 6) can be also exploited to accomplish this goal.

5.2 Grid connections

The VS PS system will receive power from the DTT electrical distribution load center classified as “SS1”. More details on the DTT distribution network can be provided upon request. The characteristics of the electrical powers available for the complete VS PS system (including the 2 output converters and the LCC) are summarized in Table 4.

The Contractor shall provide in the FDR all the information useful to model the effects of the PS system on the input distribution network in terms of power quality (in particular, for the harmonic analysis).

The internal measurements acquired by the PS system shall include the input power and its power factor.

Table 4. Characteristics of the electrical powers available for the complete VS PS system.

Characteristic		MV input	Auxiliary power	
			OL	UPS
Connection		3P	3P+N	3P+N
Neutral grounding		57.7 Ω resistance	TN-S (1)	IT (1)
Frequency		50±0.2% Hz (2)	50±0.2% Hz (2)	50±1% Hz
Voltage		20±10% kV rms	400±10% V rms	400±2% V rms
Maximum available power (3)		2.5 MVA	60 kVA	30 kVA
Expected short-circuit withstand capability	I_k (t_k =1 s)	25 kA rms	20 kA rms	10 kA rms
	I_p	62.5 kA	40 kA	20 kA
Minimum power factor		0.7 (4)	0.9	0.9
Time duration		≈100 s (5)	Steady state	900 s (6)

(1) Italian standards.
(2) According to the Grid Code of the Italian TSO Terna, the grid frequency could range between 47.5 Hz and 51.5 Hz in the event of an emergency or restoration of the external grid, but this is not a normal operating condition.
(3) The reported power is available, but there is no requirement to absorb the maximum power. The Contractor shall optimize the power demand also considering the assumptions in Section 5.1.
(4) The conditions for the evaluation of the power factor will be agreed during the preparation of the FDR.
(5) The power duration can be extended beyond the nominal pulse duration to include the pre-charge phases (see Section 4).
(6) The UPS batteries are sized for 900 s at the maximum power. No emergency diesel generator (EDG) is available.

5.3 Input transformers

The reference scheme in Figure 2 shows 2 transformers, but a different number of transformers could be accepted if well justified by the Contractor, also taking into account the consequences on the layout.

The transformers shall be included in the Procurement and shall be rated for the input power as specified in Section 5.1.

The transformers shall be insulated in cast resin and suitable for an indoor installation. The insulating material of the windings shall be Class F or better.

In principle, the operation shall be considered continuous. A de-rating due to the pulsed operations could be accepted if well justified by the Contractor, but also considering the insertion transients, the DC-link charging time and assuming that the DC-links could be kept charged between two pulses.

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The voltage at the secondary winding(s) can be selected by the Contractor to comply with the general specifications. The electrical insulation withstand levels and distances shall be adjusted accordingly. However, standardized and not excessive values are preferred.

The upstream protection switch at the primary winding (MV side) of the transformer is included in this Procurement. The Contractor shall insert a line and earth switch with interlock and status indication upstream of the transformer.

The transformer shall be equipped with all the protection tools necessary for its safe operation, including at least a temperature monitoring system in the most critical points with related protections. The transformer protection control unit shall provide to the upstream circuit breaker the dry contacts (at least two for redundancy) for the trip commands, according to the requirements listed in Sections 9.4 and 9.5. The trip commands will be probably polarized at 110 V dc. The 110 V dc (redundant) auxiliary PS for control, protection and metering is in the Contractor's scope and shall be derived from the UPS power.

An electrostatic screen, connected to ground, shall be placed between the primary and secondary windings of the transformer, with the dual purpose of reducing the parasitic capacities and enhancing the insulation between the windings.

In principle, the transformer star points are insulated. This could be modified during the FDR, also following the Contractor assessments and suggestions. In any case, suitable systems for monitoring earth faults and/or star point overvoltages shall be included.

The transformer shall be designed, manufactured and tested in accordance with the IEC 60076 and IEC 61378 standards (see also Section 12.6).

5.4 AC/DC converters

The topology in Figure 2 with 2 AC/DC converters and 2 DC-links is not the only possible but it is considered the best one.

The input converters can be separated for each DC-link or consisting of several units operating in parallel. This choice belongs to the Contractor that shall adequately motivate it in the FDR.

The AC/DC converters and the related components shall be able to completely charge the DC-link up to the nominal voltage starting from any initial condition between two successive pulses.

The AC/DC converters shall be able to adapt the power absorption to the specific conditions of the DC-links, considering the input power assumed in Section 5.1.

The AC/DC converters shall include all devices assuring their correct working in all normal and fault conditions, including the necessary turn-off snubbers and/or voltage clamping circuits to limit the over-voltage and/or voltage/current derivatives. In principle, each basic bridge arm shall be protected by fuses. In case of power switch fault (internal fault) the corresponding fuse shall operate to prevent the explosion of the component and other system damages.

The AC/DC converters shall be able to protect themselves and to request the opening of the AC breaker if necessary. In particular, it shall be able to protect itself in case of short circuit at the output terminals (i.e., across the DC-link).

5.5 Auxiliary power

DTT can provide the OL auxiliary power and the UPS auxiliary power summarized in Table 4.

In principle, only one connection point for the OL auxiliary power and only one connection point for the UPS auxiliary power will be provided by DTT for the entire PS system. The internal electrical distribution inside the PS system is under the Contractor responsibility.

The possibility of deriving the auxiliary input power from the same input cables of the transformer is not excluded. However, this shall be compatible with installation and maintenance operations.

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6 DC-Link

6.1 DC-link design

The output converters (H-bridges) are supplied by a DC-link, able to provide a sufficiently stable voltage during the operations.

The DC-link shall be designed also to meet the requirements on power demand from the grid in Section 5, also considering the possibility to recover part of the energy stored in the coils.

The DC-link shall be based on supercapacitor (ultracapacitor) technology. The use of other capacitor technologies is allowed to support the supercapacitor operations. The use of batteries in the DC-link is not allowed.

As introduced in Section 5.4, the topology in Figure 2 with 2 DC-links is considered the best one to balance the power demands of the output converters and to optimize the DC-link size. The Contractor could modify the amount and sharing strategy of the DC-links, but it shall be carefully analyzed and adequately described to be approved by ENEA.

The Contractor can determine the DC-link voltages and capacitances according to its considerations and design choices in order to comply with the general specifications.

The DC-link voltage or its capacitor voltage rating can be oversized to handle plasma disruption (see Section 8) and/or energy recovery from the load.

Within the limits of the maximum voltage and the other safety ranges established by the Contractor, the initial voltage of the DC-link shall be adjustable by the operators before each pulse.

The DC-link banks shall be designed for a continuous operation, namely assuming that the nominal voltage and charge are kept on the bank even outside the DTT pulses. For longer pauses (night hours, weekends, etc.), a command to discharge the DC-link shall be provided (even partial, if useful for preserving the component lifetime).

6.2 DC-link protections

Even though it is not explicitly reported in the scheme in Figure 2, the DC-links shall include filters, capacitances to support the output converters, monitoring and protection systems and everything else that is necessary for the correct operation of the PS system (for example, protections against overcurrents, overvoltages and unbalances). In order to avoid overvoltages or overtemperatures, the components shall be selected and balanced, also introducing active or passive balancing circuits and optimizing the layout and the connections.

In case of dielectric breakdown in one element of the DC-link, the faulted element (or group of elements) shall be isolated from the remaining healthy elements by fuses. The fuses are not required if self-healing capacitor elements are used.

This Contractor shall propose a scheme to limit the DC-link voltage to ground and to detect ground faults and unbalancing. This is subject to ENEA approval.

The PS control system shall always verify that the DC-link voltages do not exceed the rated values. The DC-links shall be equipped with adequate overvoltage protection mechanisms. These can functionally consist in a switch that discharge the DC-link on a suitable resistor (dump load schematized in Figure 2).

The DC-link and its protections shall absorb the energy coming from the load coil and coupled circuits when the crowbar is not closed (see Section 8).

In principle, it is not allowed to deliver the electrical energy of the DC-links back into the external distribution grid. Therefore, such energy shall be dissipated in a proper way.

Functionally, two different mechanisms shall be implemented to discharge the DC-link:

1. Fast emergency discharge until the DC-Link returns to nominal voltage.
2. Complete discharge of the DC-link for pauses or maintenance operations.

The Contractor can integrate the two previous functions in the same physical components, considering the thermal stresses in the different cases.

A visible indication is required to confirm that the DC-link is discharged.

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7 Output converters

In principle, the output converters are implemented by IGBT or MOSFET H-bridges. In the reference diagram in Figure 2, they are functionally represented as a single device, but they can physically consist of several H-bridges in series and/or parallel. The Contractor can decide the number of H-bridges or modules in parallel adequately justifying the choice and sizing of the components in the FDR.

The H-bridge design shall include any snubber circuit, protection, limiting resistors and inductances, capacitances and filter necessary for efficient and safe operation of the system.

Each output converter shall be protected at the input (at DC-link side) by at least a fuse and shall be separable from the rest of the system by a disconnector. Moreover, it shall be protected against possible overvoltages caused by the load.

Proper current sharing shall be assured among power switches and/or bridges connected in parallel, both statically and dynamically.

Paralleling several H-bridges may require the introduction of coupling (symmetry) reactors between output branches. The Contractor with adequate description in the FDR, considering all the technical issues, as thermal and space issues, can decide the characteristics of these reactors. The chokes shall be located far enough from metal parts to avoid EMC problems. The inductance values and their tolerances shall be estimated and verified at the actual working frequencies. The design, construction and testing of the reactors shall consider the applicable IEC standards, for example IEC 60076-6.

Even though it is not explicitly sketched in the diagram in Figure 2, it may be advisable to insert a filter at the output of the output converters. The possible presence and characteristics of this filter shall be decided by the Contractor and properly described in the FDR.

The issues related to the H-bridges, the reactors and the filters shall be evaluated with a holistic approach considering the mutual interactions and the implications at a general level.

The behavior of the output converters shall be as far as possible independent on the actual value of the DC-link voltage and on the drops on the power switches and on other elements in the circuit.

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8 Effect of plasma disruptions and protection techniques

8.1 Crowbar definition

The crowbar is a system able to bypass the output converters in case of fault. The crowbar can be only a switch (also consisting of several components) or can include a dissipative element in series (resistor or varistor).

The Contractor shall evaluate the necessity and the characteristics of the crowbar, by analyzing all the possible faults and by reporting the actions to cope with these faults. In particular, the Contractor shall verify that the configurations and the related actions are able to make faults not critical for the PS system, for the output cables and for the load coils.

The discharge by crowbar is not a standard mode to discharge the coils and to complete a pulse. The crowbar operates only in case of fault.

A simplified model of the phenomena to be protected by the crowbar is reported in the following.

8.2 Model of plasma effects

Unexpected plasma instabilities, as plasma disruptions or other events, can produce several fault situations in the VS circuit.

The situation sketched in Figure 7 is valid for each of the 2 VS coils when their circuits are separated and there is not the imbalance branch. Besides the auto-inductance, each coil has also a mutual inductance with the plasma (and with the other coils and with the passive structures). Therefore, a strong variation in the plasma current induces an equivalent voltage in the coil. Normally, when a plasma instability affects a VS coil, it affects also the other one, but with different magnitude and dynamics (see for example Figure 8 that is a worst case).

The voltage induced in the coils does not depend on the connection cable/busbar and on the PS configuration and characteristics. The induced voltages in 3 critical cases of disruption are shown in Figure 8. These voltages are calculated assuming that the coil circuits are completely open and no current can flow. The induced voltage is high, but it is not totally seen by the PS in the real cases because of the impedances of the circuit in Figure 7. The coil and cable impedances are reported in Table 2.

If the output converter is assumed to be bypassed by the crowbar (ideal crowbar), the overcurrent in the coil circuit is given by the equation:

$$v_{\text{induced}} \cong (L_{\text{coil}} + L_{\text{cable}})\frac{di}{dt} + (R_{\text{coil}} + R_{\text{cable}})i$$

where the inductances and resistances are those of the load coils and connection cables/busbars, respectively.

The equation only refers to the overcurrent added to the current flowing in the coil at the start of the instability. Therefore, the total current will be the sum of these two contributions. In this situation, the induced voltage could result in a very high current that will be better defined in the following.

8.3 Effect of imbalance branch

The presence of the imbalance branch complicates the disruption and crowbar modelling, but leading to similar levels of fault currents.

The presented simple circuital model clarifies the reason for the insertion of an inductance and of a resistance in the imbalance branch: without them, in case of disruptions or similar events, the current flowing in the circuit would be excessive.

The inductance and the resistance in the imbalance branch were established by ENEA (see Table 2), but the Contractor and ENEA will discuss successive optimizations of them also compensating the final characteristics of the connection cables/busbars.

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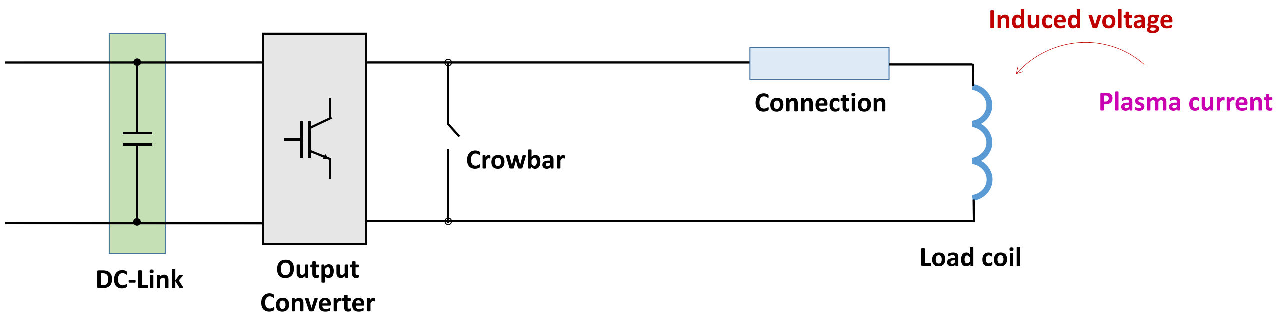

Figure 7. Simplified model of the plasma effect on the circuit of a single VS coil in case it is independently supplied.

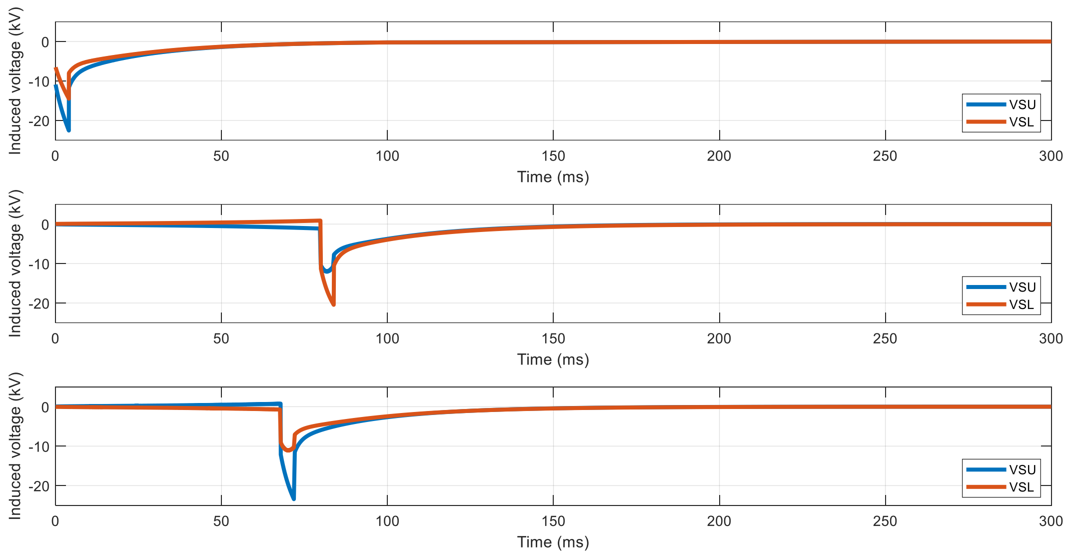

Figure 8. Voltage induced on the VS coils in 3 cases of plasma disruption assuming that the coil circuit is open.

8.4 Protection requirements

Figure 9 and Figure 10 show different significant situations of disruptions with consequent induced overcurrents after the intervention of the crowbars. In all these cases, the crowbars downstream the output converters are assumed ideal (immediately closing and zero impedance).

The worst-case peak current in the circuit is reached when the current before the disruption was flowing at its maximum value in the same direction of the induced overcurrent (see Figure 9 for the coils and for the imbalance branch).

Since the coils and the connection busbars/cables are designed to sustain the overcurrents, also the crowbar shall sustain them, while the output converters and the upstream systems can be designed for a lower current because they shall be protected by the crowbar.

Another critical situation to be considered is shown in Figure 10 where the current flowing in the closed crowbar can change its direction. In Figure 10, the curves refer to overcurrents, therefore the currents flowing in the circuit before the disruption event shall be summed.

When the overcurrent can be managed by the PS system exploiting the control of the output converter, the crowbar intervention is not necessary. Even without (or before) a crowbar intervention, the PS control shall include an operation mode (protection mode) that does not follow the external scenario because the only target is to drive the current to zero.

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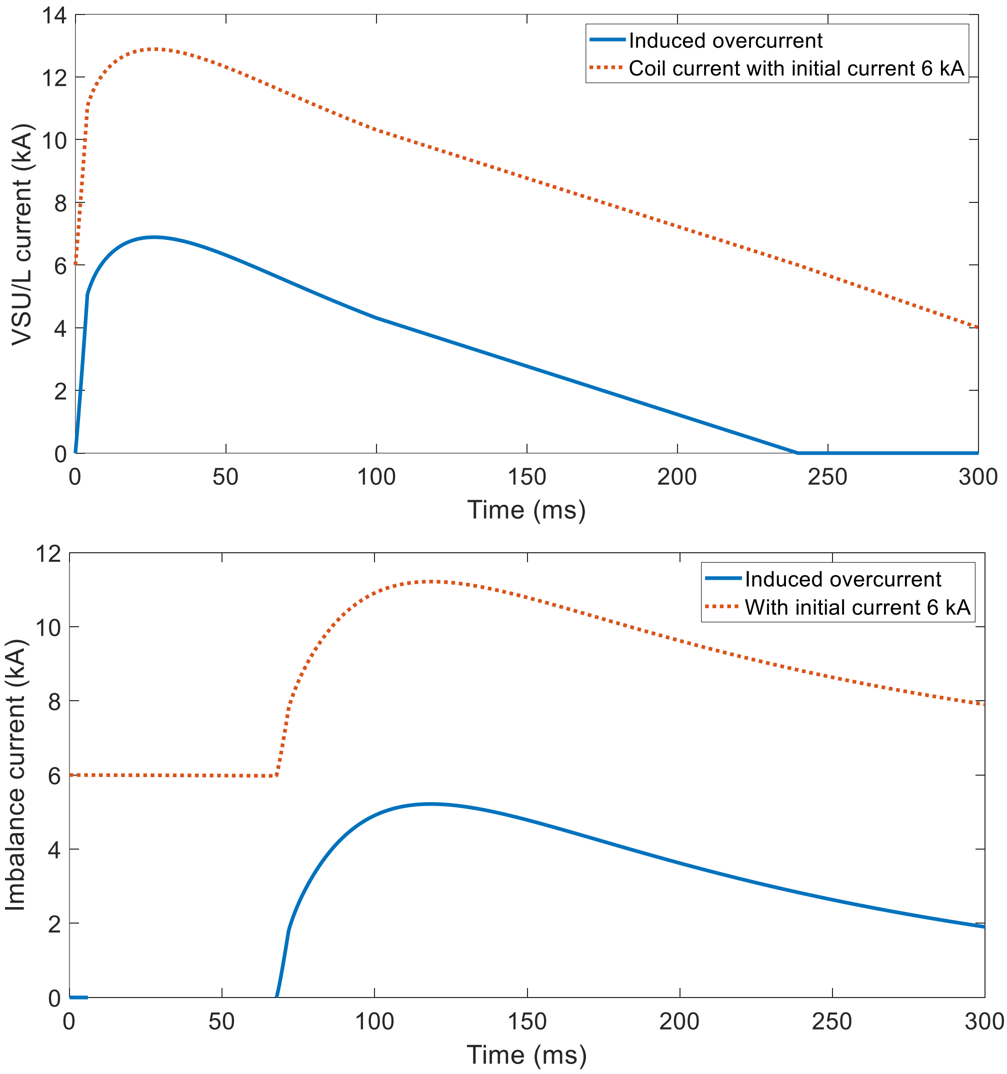

Figure 9. Effect of plasma disruption (assuming ideal crowbars) in the worst cases for the reached peak current for the coils and for the imbalance branch.

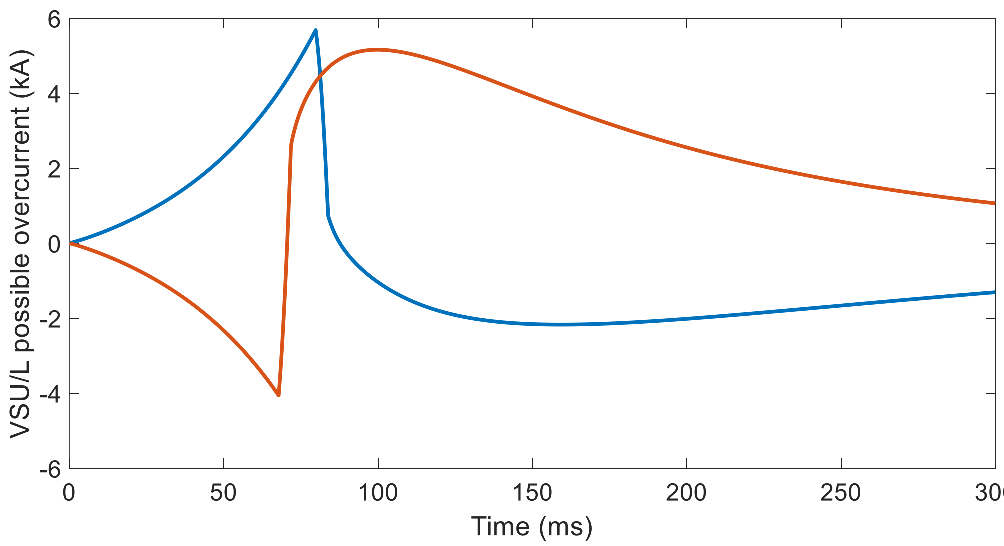

Figure 10. Effect of plasma disruption (assuming ideal crowbars) in two situations where the current direction can change.

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8.5 Crowbar scheme

The reliability of the crowbar is essential to preserve the power system and the loads connected to it. For this reason, the choice and the layout of the crowbar shall identify the right compromise between redundancy and simplicity.

The Contractor is responsible for the crowbar design and intervention thresholds. The Contractor shall present in the FDR all the considerations and calculations leading to the adopted choices.

The crowbar shall be bidirectional, i.e., it shall be able to flow currents in both directions. The curves in Figure 9 can occur in both directions. Moreover, the direction of the current in the crowbar could change during a disruption, as exemplified in Figure 9.

The crowbar can be activated in the following situations:

1. Automatically for self-protection, for example after detecting an overcurrent in the circuit or an overvoltage between the terminals to the ground.
2. By a command internal to the PS system for its needs.
3. By an external command sent by the CODAS (for example, because another DTT system is faulted or because the diagnostics predicted a disruption).

In the first two cases, the LCC shall send an external alarm to the CODAS. In the third case, the LCC receives an alarm from the CODAS.

The thresholds for the automatic or internal crowbar activation shall be compliant with the needs of the PS system. In any case, such thresholds shall be easily adjustable, possibly also via hardware, by the operators.

In general, after a crowbar intervention, the experiment will be stopped. There is not a requirement to reopen the crowbar with flowing current, the crowbar can be opened after the complete discharge of the current.

The basic scheme of the crowbar can include the following elements:

- Static electronic switch (bidirectional).
- Electromechanical switch.
- BOD to activate the static switch.
- Non-linear resistors (varistors) to protect against overvoltages before the BOD trips.
- Overvoltage detection system via voltage transducers.

The presence of all elements is not necessarily required. The Contractor shall evaluate and justify its usefulness in the FDR.

In principle, resistors (or varistors) in series with the crowbar switch are not foreseen, but the contractor in the FDR may propose design improvements. Without the resistors, the current drops exponentially.

The crowbar, after its intervention, shall be able to support the induced current and the related I2t and energy. The curve in Figure 9 can be assumed as worst-case for the design.

The numerical data for the plots in Figure 8 and Figure 9 will be provided by ENEA upon request.

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9 Control system

The PS system shall include a control system, that is in practice a programmable system, suitable for industrial environments, performing the functions of control, regulation, communication and protection.

9.1 Local Control Cubicle (LCC)

The whole PS system and in particular the output converters shall be managed by a Local Control Cubicle (LCC). In general, only one LCC for all the PS system should be provided, but for convenience, some functions can be replicated on smaller units or on single converters, for example for single item protection, testing or debugging functions.

The LCC shall be able to communicate with both the DTT general control system (referred to as CODAS) and with the local operators via control panels and an HMI.

There is no requirement for the architecture of the LCC and of the internal SCADA of the PS system. However, the implementation of choices common to the rest of the DTT system would be desirable. For example, DTT should adopt systems based on WINCC-OA and the same choice would be desirable for the PSs. The Contractor should discuss with ENEA before making any choice, even concerning its internal part.

In principle, all functions of the LCC shall be accessible remotely, also because this is the normal operating mode, apart during testing, commissioning and maintenance.

The LCC shall be able to operate in LSM for the tests, commissioning or debugging functions of each single converter. For these purposes, the HMI shall include the possibility of defining programmed typical or arbitrary waveforms to be generated by the output converters. Even the management of a single output converter shall be selectable by the LCC and HMI.

Local saving of all system measurements is not required, although it could be useful to locally record the main system states for trouble-shooting activities.

The Contractor shall provide access to the reprogrammable parts of the system via standardized interfaces, for example, Ethernet.

One or more password-protected administrator access levels shall be available (safeguarding IT security) that allow changing some system parameters, such as thresholds, gains, etc.

9.2 Regulation modes

Each output converters shall include a regulation system. The regulation shall consider (if necessary, modifying its actions) the appropriate protection actions following internal or external faults and alarms.

The output converters shall be able to operate in one of the following alternative ways of regulation:

1. CRM, that consists in following in real time a current profile coming from the DTT CODAS.
2. VRM, that consists in following in real time a voltage profile coming from the DTT CODAS.

CRM is the normal mode during testing and commissioning, but VCR is the expected to be the standard approach during the DTT experiments.

9.3 General concepts of DTT CODAS

The CODAS consists of different parts and sub-networks depending on the functionality and criticality of the information to be managed.

The following subsections present some general concepts of DTT CODAS and the general guidelines for interfacing the PS systems to the central CODAS (or to an intermediate system, normally an industrial PC, between the CODAS and the PS LCC).

The CODAS control is based on the state machine principle. Same principle should be the basis for the operations of the LCC. Basic operations include a set of states that are propagated by the CODAS state machine. When CODAS enters in a new state, all other systems, including the PS system, shall update their states accordingly. The PS LCC shall pass to the expected state according to the command coming from CODAS, returning an appropriate acknowledgement signal, and perform all the actions necessary for the state transition.

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9.4 Communication interfaces

The CODAS communicates with the other DTT systems in a variety of modes, as specified below, depending on the implemented function and on the timing constraints:

1. Slow Interface, used to exchange status information and commands between the LCC (normally carried out by a PLC) and the CODAS. This interface shall be used to synchronize the PS system to CODAS via a state machine (see next subsections), to read status information from the PS system, to write configuration parameters and to send commands to the PS system. OPC-UA shall be used for communication. It is expected that the PS LCC will implement the OPC-UA server functionality for exporting the OPC-UA variables, but this is not mandatory (in this case, an intermediate system will host an OPC-UA server for handling communication).
2. Fast Interface, used to read signal whose dynamic requires a sampling rate >10-100 Hz. Ethernet-based communication shall be used also for sending reference signals to the PS system. This will typically happen during DTT operations, when the PS system output is under the CODAS direct control.
3. Very Fast Interface. In case higher sampling rates are required, either ad-hoc digital transmission shall be used (protocol to be agreed) or analog signals. In this case, the CODAS will provide analog-to-digital channels for fast data acquisition with electrical insulation from PS ground.
4. Machine Protection Interface, used to exchange fast protection signals, to request fast recovery actions to the PS system and to communicate anomalous conditions that may require global actions from the CODAS central machine protection system. in this case, based communication shall be based on fiber optic.
5. Safety Interface, used to exchange (slow and/or fast) signals required for personnel safety. Safety architecture is not yet defined for DTT.

Table 5 summarizes the interfaces and the type of networks that shall be present between the LCC of the PS system and the DTT CODAS. They can be used for control and/or monitoring.

Table 5. Summary of the interfaces available between PS LCC and CODAS (see also next subsections).

Interface type	Use case, functions and notes	Applicable protocol	Speed	Latency
Slow	CODAS sends references and commands to LCC and obtains information form it	OPC-UA	10 Hz (up to 100 Hz)	$\frac{1}{f}$
Fast	To share commands, reference or data. Transmission time synchronous to DTT time. Packets from LCC typically exchanged in response to a fast control packet from CODAS.	Ethernet (1-10 Gbit) and agreed UDP multicast	1÷10 kHz	100 µs
Very fast	Point to point signals replace analog wires where there are isolation or immunity concerns	Custom	≈ MHz	<10 µs
Interlock	Point to point fibers (1 per signal) to exchange interlock bits of information (see Sections 11.3 and in Section 11.13)	Optical pulse train with f>>1/latency	Single event	µs to ms
Safety	Point to point wire pairs (1 per signal) Exchange safety bits of information	Dry contacts (with fail-safe logic)	Single event	ms
Slow time	Distribute time information to PLCs	NTP and PTP or optical PPS		
High-performance time	Distribute time information to fast controllers	IEEE 1588 (if supported)		
Simple time	Square waveform with raising edges synchronized with DTT official clock to distribute high-precision time information. Bit to be acquired and sent back to CODAS via either Fast or Very Fast interfaces and to reconstruct signal time-bases.	Fiber optics 1 Hz		<1 µs
Local HMI	Supplier-specific interface between PS system and local panels/monitors	Any based on Ethernet		

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9.4.1 Segregation modes

A PS system can be in only one of the following control modes:

1. Under Local Segregation Mode (LSM), i.e., operated locally and disconnected from CODAS.
2. Under Remote Segregation Mode (RSM), i.e., only operated by CODAS.

During DTT operation, all involved systems shall be exclusively under RSM. When in RSM, no local operation shall be allowed.

In order to better describe how a system is moved to/from RSM, the following segregation states are recommended (see also Figure 11):

1. RELEASED. The PS system is not controlled by anybody but accepts requests to change its segregation mode to either LOCAL or REMOTE. Commands sent from CODAS can only change to REMOTE. Commands sent from local panels can only change to LOCAL. This is the state into which a plant enters just after having been switched on.
2. LOCAL. The plant is controlled by commands selected in the LCC. If more local panels or local screens can manage commands, the Contractor software logic shall arbitrate these. The segregation mode can only be affected via the local control panels/screens. Status information can be sent to CODAS in local state, but no commands shall be issued by CODAS.
3. REMOTE. The system is controlled by commands issued by CODAS via the OPC-UA interface. The segregation mode can only be affected by commands sent from CODAS.

An additional segregation state may be meaningful for systems involving power, such as PSs:

4. LOCAL WITH POWER. Same as LOCAL mode but to perform activities that normally requiring a higher-level coordination as they imply some risks. The transition to this mode is only possible from LOCAL and requires both a specific command and a set of system pre-conditions. For instance, this implies the PS being connected to a dummy load rather than a tokamak coil. Since this has human safety implications, an appropriate interlock mechanism must be established.

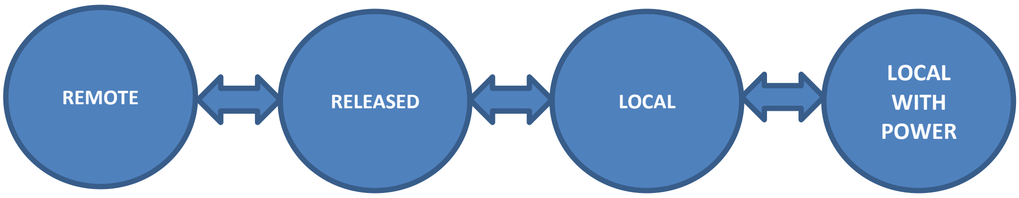

Figure 11. Overview of the segregation modes recommended for the PS system.

9.4.2 States and state machines

States are steps within the operation history of a system. A state is defined in practice by a set of conditions met by the system process variables (measurement of the system status). The specific conditions may depend on the current system mode.

The transition between states is not an instantaneous operation as it typically implies changes on the system physical parameters. A state machine shall drive state transitions.

A specific state machine shall be defined for the PS LCC. As an example, the state machine in Figure 12 may be defined for the LCC of a PS system.

Substates are also shown in Figure 12. Substates are introduced to better describe the evolution of the system when a state transition is requested by CODAS. When a state transition is requested, the system will immediately enter in TRANSITION substate, while still remaining in the original state. This condition means that the internal operations associated with the state transition are being carried out by the system. When these operations terminate, the system can either enter the STABLE or ALARM substate. In the former case the system has successfully terminated the actions associated with the state transition. In the latter, an error condition has been reached. In both cases, the system enters in the new state. The error condition shall

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prevent CODAS from further advancing the state machine, requiring some sort of actions in order to drive the substate to STABLE. In addition to the state transition management, the system can also communicate to the central CODAS that any of the following two conditions occurred:

1. Pulse Inhibit, indicating that the internal condition does not prevent advancing the state machine, but preventing the repetition of the state machine sequence from its initial state (i.e., performing a new DTT pulse after the current one).
2. Abort request, indicating the internal condition requires aborting the current state machine sequence and moving to an abort state.

State and substate information shall be made available by the PS LCC via OPC-UA variables as well as state transition requests and asynchronous requests. Detailed naming convention and protocol are defined in the general CODAS architecture document that will be provided after the Contract assignment.

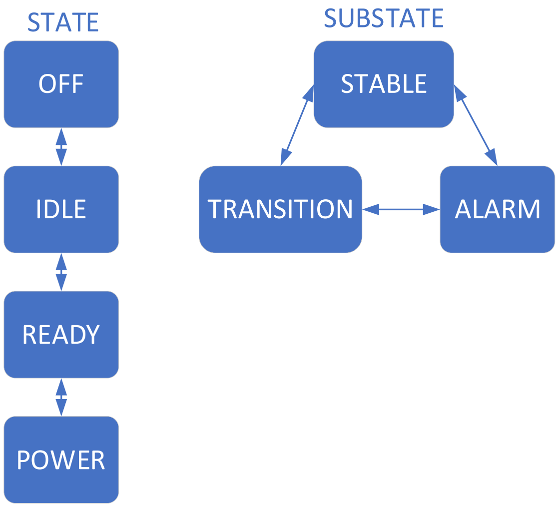

Figure 12. Possible states and substates for a state machine.

9.4.3 Synchronous and asynchronous modes and commands

The system can operate in either synchronous or asynchronous mode. When in synchronous mode, the only commands that will be issued by CODAS via the plant system are the state transactions, as described before. This is the typical operation mode during DTT plasma operations.

In asynchronous mode, it is possible to issue individual commands to the machine, while remaining in the same state. Both state transitions and individual commands shall be issued via OPC-UA process variables. Switches between synchronous and synchronous operation modes shall be communicated by CODAS to the plant via OPC-UA variables.

When in asynchronous mode, commands can be issued to the PS system to trigger a specific operation while remaining in the same state of the state machine.

Individual commands shall be issued via OPC-UA variables, requiring however a handshaking protocol, involving another OPC-UA variable used to acknowledge the command as shown in Figure 13.

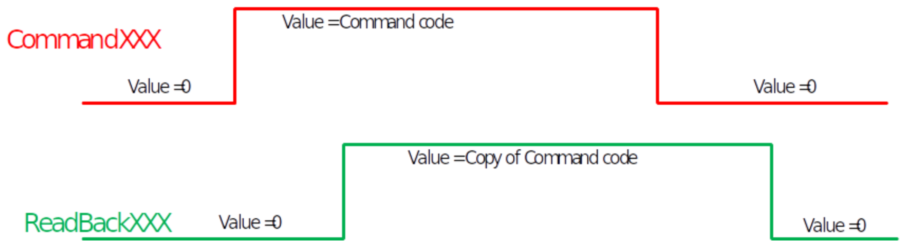

Figure 13. Schematic of command protocol.

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9.4.4 Status visualization and parameter setting

A set of OPC-UA process variables shall be defined to export plant status information to CODAS. One or more HMI mimics shall be defined in central CODAS to display in central control room the information and date related to PS system. Another set of OPC-UA variables shall be defined to provide the required configuration parameters for the PS system. The setting of configuration parameters shall be carried out as a single transaction (namely, changing the configuration variables shall not affect the plant configuration until a specific command, changing all the affected configuration parameters at the same time will be provided). When in synchronous operation mode, configuration parameters shall be entered upon specific state transitions. When in asynchronous operation mode, a specific command shall be defined to enter the configuration parameters.

9.4.5 Ethernet-based fast interface

The characteristics of the interface are summarized in Table 5.

Every sample for one or more channels shall be packed into a UDP datagram and sent/received. The datagram payload shall include a header whose layout will be defined in the FDR preparation.

CODAS will provide heartbeat UDP packets on a regular frequency. These packets shall be used to detect whether the plant is connected to CODAS.

9.4.6 Timing

All the signals acquired from the plant shall be timestamped. Internal clocks without synchronization for timestamping are not allowed, because the unavoidable clock drift may make the time information useless.

For slow signals, i.e., signals acquired via OPC-UA variables, Network-based Time Protocol (NTP) synchronization, normally available on board the PLCs will be sufficient. Faster signals require a more precise synchronization. IEEE 1588 synchronization will be used in DTT CODAS. The PS system could either:

1. Implement internally an IEEE 1588 synchronization and use the synchronized time to timestamp signals (in the UDP packet header). In this case, CODAS will provide the grand master clock over Ethernet for IEEE 1588 internal synchronization.
2. Use external gate, trigger and clock signals provided by CODAS in order to achieve internal synchronization.

If for a valid reason it is not possible to achieve internal synchronization either via IEEE 1588 or external timing signals, the clock internally used for analog-to-digital conversion sampling shall be provided as an analog output signal in order to allow CODAS properly timestamp signal samples.

9.5 Fault management and alarms

Alarms can be grouped in 3 types:

1. Severe fault (SF).
2. Light fault (LF).
3. Warning, when there is no dangerous failure, but the event still needs to be notified and kept under control.

If several faults occur, it is sufficient to send the type of alarm of the most worrying type, but the coding adopted shall allow all the occurred faults to be described.

In case of an internal fault in the power supplies, the following actions shall be implemented:

1. Carry out all the internal protection operations and adjustments (on one or more PS component) according to what was agreed with ENEA in the FDR. Consider if the protection requires interventions on other external systems.
2. Transmit the LF or SF alarm (interrupting the signal on one of the two fibers).
3. Transmit the presence of the LF or SF alarm on the Fast Interface according to the agreed coding.
4. Transmit the agreed complete coding of the alarm on the Slow Interface to allow the identification of the affected component without accessing the LCC. The alarms shall be encoded

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according to a standard agreed in the FDR. In case of multiple faults, all fault codes shall be available.

5. Once triggered, the alarm shall remain activated (with the relative status of the machine) until a reset signal is given by the CODAS or from the panel in the case of LSM.

In some cases, the problem may not be so dangerous as to require an emergency alarm. However, this situation requires a "warning". This can be accomplished by limiting the communication to the appropriate coding on the Fast and Slow Interfaces.

The generation of an alarm or a warning does not exempt the Contractor from the obligation to implement all the measures, redundancies and protections dictated by the applicable standards and good industrial practice to prevent and deal with problems. In particular, the analysis of faults and protection interventions is one of the main purposes of the FDR.

The fault detection systems and the most important protections shall be redundant and have a back-up system (for example, based on a different physical principle).

All fault detection, alarm communication and protection systems shall be implemented according to a fail-safe logic.

If the alarm comes from outside, the controller shall carry out all the internal protection actions and adjustments (for example, rapid switching-off of the power supplies) according to what was agreed with ENEA. Furthermore, it shall send an acknowledgment signal to confirm receipt of the alarm (option to be confirmed, for this purpose it may be sufficient to signal the alarm in output). Please note that there may be two types of external alarms (LF or SF) as presented above.

The acknowledgments shall be accompanied (or replaced) by appropriate independent systems, based on the monitoring of specific physical quantities (with respect to a threshold) to provide evidence that the alarm has been implemented. The same principle shall apply to give evidence of the states and positions of Interlock and Safety Interfaces.

A particular type of alarm that shall be managed is that coming from the emergency mushroom buttons that the Contractor shall provide in various points of the system or from the micro-switches of the doors or fences.

9.6 Mini-CODAS

During the tests, ENEA will provide a "Mini-CODAS", that is a system that emulates all the functions and communication interfaces with the final DTT CODAS.

To facilitate the procedures, the Contractor can ask ENEA for technical support to purchase the hardware and internally develop one or more Mini-CODAS.

9.7 Measurements and transducers

The list of the internal measurements will be agreed in the FDR, but it should be updated and integrated in any phase of the Procurement.

The sensors and measuring transducers shall comply with the applicable IEC standards.

The LCC shall be able to receive (directly or indirectly) the measurements of the various transducers present in the power systems, verifying the status and operation of the transducers themselves. In particular, the most important measurements, such as those of the global current and voltage of the power supplies shall be redundant (possibly through a less accurate system) to continuously verify their reliability.

The measurements acquired internally to the system shall be transmitted by the LCC with the characteristics shown in Table 6. The acquired measurements shall be transmitted as fast as possible, introducing a maximum delay equal to the inverse of the transmission band specified in Table 6.

The measurement transmission messages shall be independent for each power supply to be able to operate even in the absence (in case of failure) of one or more of the other power supplies.

All measurements shall be transmitted to CODAS according to the principles summarized in Table 5. Some measurements may be omitted, if deemed irrelevant to the general operation of the plant but shall be available for testing or trouble-shooting purposes. However, as a general principle, it is suggested to transmit

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all available information to CODAS, especially those useful for system diagnostics and for monitoring pre-alarm situations.

The analog outputs of all transducers shall be easily accessible for test or trouble-shooting operations. The main measurements useful for testing or verifying operation shall be shown on the terminal block or standard connectors with isolated low-impedance or 4-20 mA current outputs.

Table 6. Measures characteristics (calculated on the signals transmitted by the LCC).

Measures	Minimum accuracy	Bandwidth
Current through each output converter	±0.5%	≥ 30 kHz
Current through the imbalance branch	±0.5%	≥ 30 kHz
Voltage (differential) of each output converter	±0.5%	≥ 30 kHz
Voltage of DC-link(s)	±1%	≥ 30 kHz
Other fast measures	±1%	≥ 5 kHz
Other measures	±1%	≥ 10 Hz

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10 Water cooling system

To cool down the PS system, DTT can provide raw (technical) cooling water with the characteristics reported in Table 7.

For specific needs, the Contractor may request, justifying it, to modify the characteristics of the cooling water. ENEA will evaluate whether the requested change can be accepted.

Table 7. Characteristics of the raw water provided by DTT for the VS PS system.

Characteristic	Value
Maximum thermal power dissipated in the complete PS system	700 kW
Duration of operation at the maximum power	≈100 s
Distance between dissipations at the maximum power	≈3600 s
Inlet temperature of the raw water	15÷25 °C
Maximum temperature variation of the raw water at the heat exchanger outlet	15 °C
Input pressure	400 kPa
Allowed pressure drop	≤200 kPa
Water hardness	7÷15 °f

Table 8. Characteristics of the demineralized water supplied by DTT only for periodic replacement.

Characteristic	Value
Input pressure	550 kPa
Conductivity at the time of delivery	<0.1 µS/cm at 25 °C
Maximum frequency allowed for water replacement	Once a month

If the PS cooling needs demineralized water, since it cannot be provided directly by DTT, the Contractor shall implement an internal closed circuit with demineralized water, that is cooled by the DTT raw water through suitable heat exchangers at the Contractor's expense. This closed circuit shall be isolated from the DTT hydraulic system and shall be equipped with internal pumps of suitable characteristics and reliability.

To keep the proper characteristics of the demineralized water in the internal circuit, the Contractor has 2 options:

1. DTT will provide a circuit for the periodic replacement of the demineralized water in the PS internal closed circuit. The replacement water will have the characteristics in Table 8. The internal cooling system shall be able to determine, through appropriate measurements, the need to replace the demineralized water.
2. The Contractor can insert an own local water treatment system, designed according to the PS needs. The selection of this option and the related dimensions shall be communicated to ENEA in the FDR.

A single connection point (for water input and output) will be available, in the position decided by the Contractor. The type of interface flanges/connectors will be agreed between ENEA and the Contractor among the most common ones. The water distribution between the elements of the Procurement and inside the panels is under the responsibility of the Contractor.

All the pipes and accessories shall be made of materials compliant with the used water. Aluminum is preferred for the water heatsinks. Materials suitable for ultrapure water, as "food grade" pipes, should be used. Materials in contact with the water, in particular with that distributed by DTT, shall be reported in the FDR for ENEA approval.

Both the raw and the demineralized water lines shall include an outlet line that can be used to drain/purge the systems.

The Contractor shall insert at its own expense all transducers, indicators, fault detection systems, valves, flow switches, faucets, drains (in particular, at the lowest points), purge valves, and filters (replaceable) necessary for the proper operations of the cooling system. A sufficient amount of shut-off and isolation valves, at least at the entrance to each panel, shall be inserted to allow maintenance operations. Hydraulic

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system controls, guards, pumps and diagnostics shall be concentrated in specific cabinets, located where it is most convenient for the final layout. The main plumbing measures shall be visible on these cabinets.

The LCC shall collect at least the following measurements for each exchanger block:

1. Input and/or output flow, also to identify any possible leak.
2. Temperature of the inlet and outlet water.
3. Inlet and outlet water pressure.
4. Water conductivity (in case of demineralized water).

All these measurements shall be associated with any alarms with modifiable thresholds.

The whole system shall be realized following the state-of-the-art technologies and solutions and according to the applicable standards, with particular regard to safety issues. Pipes, flanges and connections in all the parts of the cooling system shall prevent leaks and ensure a high level of reliability over the life of the system. Connections made with hose clamps or plastic connectors are forbidden.

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11 General requirements and conditions

11.1 Construction

The fabrication of the system shall comply with the best engineering practice, the applicable IEC standards and the typical standards of the individual components. The principles of simplicity, reliability, availability and low maintenance shall be favored. Modularity should also be exploited as much as possible. All these aspects shall be adequately assessed in the FDR, in the construction and in the tests.

In the case of redundant components, the failure of a component shall lead to the exclusion/by-pass of the redundant component without affecting the global operations, nevertheless launching an appropriate alarm or warning (see Section 9.5).

The assembly of components and cables shall take into account the mechanical stresses during transport and during operations, including expected failures.

11.2 Component identification

All the components shall be identifiable by appropriate codes with the relative correspondences on the electrical and mechanical diagrams and on the attached documentation, according to the practices of this kind of systems.

The larger components shall be identifiable by appropriate external plates (in metal or plastic).

The adopted nomenclature and codes shall comply with the specifications in PQMS [1] and shall be approved by ENEA.

11.3 Cabinet arrangement

As a general principle, all components shall be contained in closed structures, enclosures or, in limited cases, fences.

The Contractor is fully responsible for implementing all the protections for safety of people, such as mushroom buttons and interlocks.

Panels, cabinets and switchboards shall be manufactured in accordance with applicable IEC standards and good industrial practice. In particular, all safety precautions shall be taken into account. The enclosures and metal structures shall be grounded using suitable low resistance connections (see Section 11.12)

Closed panels shall have approximately IP 5 (dust protected) 2 (dripping, 15° tilted) D (protected against access with a wire) H (high voltage apparatus) according to the IEC 60529 standard. In case of open doors, the IP3 level shall be guaranteed to avoid risks of direct or indirect contact with live parts. Enclosures shall have at least IP 2XBH. Different solutions shall be approved by ENEA.

The electrical panels shall guarantee sufficient space for maneuvers and maintenance, also considering the opening of the doors, including a "spare" space of at least 20%. In particular, appropriate and optimized test points for maintenance and troubleshooting shall be highlighted and made easily accessible.

Switchboards, cabinets and panels shall be heated or cooled to ensure correct operation of all systems taking into account the environmental conditions (see Section 13.2).

The panels shall be equipped with low consumption lamps to facilitate inspections, operations and internal maintenance. For the same purpose, where possible, the panels shall be equipped with low voltage sockets protected by dedicated switches.

A document holder shall be available inside or outside the cabinets to allow the conservation of the documentation that could be useful for the operators.

Panel doors shall be equipped with safety micro-switches connected to control systems, according to safety standards and industrial practice. Even when the doors are opened, the risks of accidental (direct or indirect) contacts with live parts shall be limited (for example, via Plexiglas screens).

Dedicated protections (for example covers) and access procedures shall be implemented for the capacitors and, in case, of supercapacitors and for the panels that contain them. In particular, a mechanism shall always be available for their total discharge, also in case of lack of auxiliary voltage, and an indication of their charge shall always be visible.

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11.4 Semiconductor design

The Contractor shall select size and integrate the semiconductor devices and their auxiliary systems (fuses, snubbers, heatsinks, gate drivers, temperature sensing etc.) taking into account:

- Operating currents and voltages.
- Adequate safety margins.
- Datasheets, technical notes and recommendations from the device manufacturers, possibly asking the manufacturers themselves for confirmation of the choices made.
- Standards of the IEC 60146 series and other applicable IEC standards.
- Current practice and procedures adopted by the Contractor.
- Reliability throughout the useful life of the plant (see Table 1) shall be guaranteed through adequate safety margins and redundancies, not lower than the higher ones normally used in industrial practice. Reliability shall be estimated in the FDR according to algorithms commonly used in technical practice.

In particular, the following guidelines shall be met for semiconductors (unless different choices are properly justified by the Contractor and approved by ENEA):

- For the output converters, the safety margin on maximum (repetitive) blocking voltage shall be at least 1.5.
- For the AC/DC converters, the safety margin between peak repetitive reverse voltage rating and working level shall be determined taking into account the circuit requirements. In any case, the safety factor shall not be less than 2.4 with the AC input supply voltage at nominal value.
- Maximum junction temperature lower (with an adequate safety margin) than that recommended in the manufacturers' datasheets. This shall be verified under nominal operating conditions. Furthermore, the temperature limit shall be maintained even assuming that the device continues to operate during the most severe failure conceivable (for example, before crowbar intervention) starting from the maximum temperature under nominal conditions.
- Thermal cycles suitable for the useful life of the system.
- Imbalance between paralleled components or systems ≤10% (however, it should be kept as low as possible).

Proper design of the gate circuits and wiring shall be implemented to assure safe operation of the devices, to limit the jitter between commands and to minimize the leakage inductance and resistance. For the IGBTs, a desaturation protection circuit shall be included.

The Contractor in the FDR shall detail all these aspects. In particular, the Contractor shall clearly estimate in the FDR the voltage and temperature safety margins in the worst-case conditions.

11.5 Passive components: resistors, reactances, capacitances

The nominal values and tolerances of passive components (resistors, reactances, and capacitances) shall be selected in accordance with all applicable IEC standards, taking into account working conditions, environmental conditions (Section 13.2), parasitic parameters and useful life.

11.6 Cables, bars and terminals

All connections and layouts shall be taken care of in terms of clarity, labeling, segregation, shielding, EMC, bending radii, mechanical supports.

All cables and connectors shall be clearly identified by a visible label. The labeling criteria will be communicated by ENEA before assembling the systems.

The color of the cable external sheath of cables shall be:

- Black for low voltage cables (up to 0.6/1 kV).
- Red for medium voltage cables (above 0.6/1 kV).
- Yellow/green for earth wires.
- Black with an orange or red longitudinal band for fire resistant cables.

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The color of the individual sheaths in multicore cables shall comply with IEC 60445 and specified in the technical documentation.

The cables shall be made according to the applicable IEC standards, in particular according to the IEC 60502 and IEC 60332 series.

All cables shall comply with CPR UE 305/11 with reference to the medium risk level:

- Class CPR: C_{ca} – s1b, d1, a1.
- G16 type insulating compound based on high modulus ethylene propylene rubber with low acidity and fume development with a characteristic temperature of 90 °C for use in cables according to the fire reaction classes envisaged by the CPR.

The power conductors shall be separated from the measurement, control and auxiliary ones, with adequate distances and raceways.

The transmission of signals, especially between high voltage components or areas, between distant components or in cases where the signal may be disturbed, shall in principle be in optical fiber. Different choices shall be clearly justified.

Cable connections and bars should be made of copper. The capacities and the parallels shall be selected according to the applicable IEC standards, according to the IEC 60502 series. The capacities shall be derated in case of several conductors in parallel according to the applicable IEC standards.

Each multicore cable shall include at least 20% spare capacity. Spare conductors shall be terminated properly.

In principle, cables are subjected to insulation tests with the rest of the system, but ENEA can evaluate special situations on the proposal of the Contractor.

The connection bars inside the PS system (as will be those outside it) shall be sized and installed to support the electromechanical stresses due to the rated and maximum currents in the event of a fault. In addition, they shall possess the appropriate seismic qualifications, as described in Section 11.16.

11.7 Optical fibers

Alike the cables, the fibers shall be clearly identified by a visible label, shall be made according to the applicable IEC standards, in particular according to the IEC 60502 and IEC 60332 series, and shall comply with CPR UE 305/11 with reference to the medium risk level.

In principle, all communication with DTT CODAS shall be via optical fibers. In particular, high-speed data and Ethernet connections shall use OM3/OM4 standard fibers.

In principle, fibers are subjected to insulation tests with the rest of the system, but ENEA can evaluate special situations on the proposal of the Contractor.

Multi-core fiber optics shall include at least 10% spare capacity.

11.8 Fuses

The intervention of the fuses shall be properly monitored by the PS control system. The power fuses shall be equipped with a striker pin and a micro-switch in order to provide the remote monitoring of the fuse status.

11.9 Hazardous materials, fire and explosion protection

Materials exposed to combustion shall be LSOHFR.

PCB (polychlorinated biphenyl) and PCT (polychlorinated triphenyl) type materials are not allowed and shall not be used in any component. Oil filled equipment shall not be used.

Impregnating agents and dielectric materials used in power capacitors shall not be flammable and shall not release toxic fumes in the event of fire. The use of mineral oil is not permitted. The frames housing the capacitors shall be connected to earth.

All cabinets and containers shall be sized in such a way as to limit the possible explosion of each of the components located inside without any risk for the operator. In particular, the explosion risks of thyristors and other semiconductors shall be considered.

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11.10 Cleaning and painting

Before being coated or painted, all parts of the system shall be cleaned of corrosive materials or external agents. All interior and exterior surfaces shall receive a primary inhibitor treatment and two coats of varnish.

The external colors will have to be agreed with ENEA before the manufacturing, depending on the part completed in that phase.

11.11 Anti-condensation and anti-dust measures

All the components of the electrical system which may be subject to internal condensation shall be equipped with specific devices designed to prevent condensation in the worst environmental conditions. The operation of these devices shall be monitored and, an alarm shall be locally visible and sent to CODAS in the event of a failure.

The Contractor shall introduce every possible precaution to avoid the accumulation of dust on sensitive components. In particular, it shall take into account the positioning of the openings and fans with respect to these sensitive components.

11.12 Earthing/Grounding

All switchboards, cabinets, screens, enclosures, structures, grids and other metal parts shall be grounded in accordance with IEC standards and other applicable laws and regulations. The Contractor shall provide all internal grounding connections. All the power ground connections shall be designed according to IEC standards. The ground connections shall be distributed within the cabinets and subsystems using copper conductors having adequate sections to avoid dangerous or disturbing voltages.

The Contractor is responsible for connecting elements to the building ground network in any test or operation.

All ground connections shall be clearly visible and identifiable and easily accessible.

The grounding terminals of the power circuits and of the cubicles (switchboards, fences, doors, etc.) shall be independent. As the floor where the PS system will be installed may be referred to a ground different from the ground to be used for the PS, all the cubicles, fences and metallic parts could be electrically insulated from the floor. This will be defined by ENEA, also following the suggestions from Contractor before the system manufacturing.

The position of the points available for connection in the final installation will be communicated by ENEA. The Contractor may request further details on the DTT ground network during the preparation of the FDR. As far as possible, the Contractor will be able to make suggestions on the best positioning of these connection points.

Grounding scheme shall prevent closed current loops. The impedance of ground loops shall be minimized. All conductors shall be made of copper and shall be sized to withstand the maximum fault current (withstanding single short-circuit in accordance with the standards IEC 60204-11 and IEC 62271-200) without reaching voltages dangerous for safety.

The system must be equipped with an earth current detection system capable of measuring small earth fault currents. The detection of currents above a predetermined threshold shall produce an alarm and shall be sent to CODAS.

11.13 Disconnectors, breakers and interlocks

A disconnector is a device that can be opened and closed only without flowing current.

Power systems shall be equipped with all switches and disconnectors required by safety regulations and standards and good industrial practice. In particular, visible (extractable) and interlocked systems shall be available to provide evidence and safety of the disconnection and/or grounding of the functional or spatial macro-blocks of the systems, for example at the interfaces of the power supplies towards other systems.

Appropriate key interlocks shall be introduced to avoid improper actions.

All devices shall be able to withstand the worst overvoltage and overcurrent situations that are estimated to occur.

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11.14 Electromagnetic compatibility (EMC)

All systems supplied shall comply with IEC standards and electromagnetic interference and compatibility (EMI/EMC) regulations, especially IEC 61000-6-2 and IEC-61800-3. Furthermore, the Contractor shall introduce all possible measures to prevent problems that it has encountered in its experiences with similar installations. The systems shall be able to operate without problems considering all possible compatibility aspects, for example: emissions, immunity, perturbations, earth, masses, shielding, network filters, differential signals.

The environment in which the PS system will be installed (see Section 13) is to be considered industrial. The installation area will contain another PS system with characteristics similar to this Procurement.

The magnetic field in this building, due to the currents generated by the power supplies themselves, could require special precautions, but it is estimated that it will be less than 10 mT.

11.15 Vibrations and noises

The mechanical structures and supports shall withstand the most severe electromechanical stresses and the most critical conditions that can reasonably be assumed.

Noise and vibrations shall be evaluated under normal and stationary operating conditions, keeping the switchgear doors closed.

All systems shall operate without unnecessary vibrations and with the minimum level of audible noise in the environment, trying to limit any danger and/or discomfort for personnel.

In particular, the audible noise, measured at a distance of 2 m with an instrument compliant with the IEC 61672 standard and averaged over 8 hours of work, shall not exceed 65 dB(A).

11.16 Seismic design

The anti-seismic qualification is mandatory only for safety elements that are expected to act as protection even in case of a seismic event. In practice, a safe path for the current shall be ensured during or after a seismic event. This can be accomplished by qualifying at least the crowbar and its connections to the external connections (busbars or cables) to the load coil, to ensure the current flow in the closed crowbar.

Moreover, the Contractor shall identify and qualify all the other elements it evaluates critical from a seismic point of view.

The seismic qualification shall include all the auxiliary or support systems necessary for the operations of the elements to be qualified.

The other elements of the PS system are not subject to particular seismic qualifications or requirements, but, as a general, they shall maintain their state (switch position) during seismic events.

The qualification consists in the compliance with the industrial seismic guidelines and in the resistance to stresses according to the Standard IEC 60068-3-3. The response spectra for the application of the Standard IEC 60068-3-3 are reported in Table 9. The reported values do not consider any dynamic interactions with the building and structures that shall be assessed by the Contractor.

Table 9. Seismic design response spectrum: pseudo-acceleration versus frequency and damping.

	Horizontal			Vertical		
	Damping			Damping		
Frequency (Hz)	**1%**	**2%**	**5%**	**1%**	**2%**	**5%**
0.1	0.272	0.23	0.17	Horizontal values multiplied by 2/3		
1.4	4	3.38	2.5			
3.3	9.6	8.10	6			
7	9.6	8.10	6			
20	2.1	2	1.9			
100	2.1	2	1.9			

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Furthermore, the Contractor shall demonstrate (for example, using a "hammer test") that the natural frequencies of the systems are far from the most critical ones predictable in the DTT area and in any case greater than 20 Hz.

11.17 Spare parts

The Contractor shall include in the Procurement without surcharge a basic set of spare parts according to its experience on similar systems.

The basic set of spare parts shall include at least:

- 1 complete basic system (H-bridge/thyristor module) to be connected in parallel to form an AC/DC converter, equipped with all the necessary accessories (for example, gate drivers).
- 3 complete basic systems (H-bridge module) to be connected in parallel to form an output converter, equipped with all the necessary accessories (for example, gate drivers).
- 1 semiconductor stack of the crowbar, equipped with all the necessary activation components (gate drivers and BOD).
- 2 supercapacitor modules identical to those adopted in the DC-link.
- 2 capacitor modules identical to those adopted in the DC-link.
- 2 gate driver boards for each semiconductor family.
- 2 signal conditioning and analog/digital/optical interfacing boards for each type used in the PS system and in the LCC.
- 2 electronic cards of each type (control, interface, commands, display, etc.) used in the PS system and in the LCC.
- A set of minor components such as fuses, capacitors, electronic components, etc.
- A set of fibers/cables proportional (for example, 10%) to the amount used in the PS system.
- A set of sacrificial contacts for each mechanism that requires them.

In addition to these, before the end of the Procurement, the Contractor shall issue a list of recommended spare parts that ENEA will be able to purchase at its discretion with an additional expense. In particular, the Contractor shall report which components require particularly long procurement or replacement times.

For non-standard components, the Contractor shall include the technical specifications prepared for their procurement and any other information useful for their procurement. The Contractor shall prepare a list of non-standard or critical components (for operation and for availability) that require special traceability. For them, the Contractor shall keep all the information for traceability and procurement for at least 10 years (or for the period required by law, if longer).

The Procurement of spare parts does not release the Contractor from the obligation to replace any part damaged during testing, transport or the warranty period.

11.18 Packaging and transportation

The Contractor will have to pack and transport the PS system complete with all the parts and accessories to the ENEA Research Center in Frascati.

The systems shall be suitably packaged so that they can be transported (by sea or by road) and loaded and unloaded, preventing risks of damage, contamination, humidity and guaranteeing the cleanliness of the components.

Packaging shall provide adequate supports and hooking systems for transport, unloading and handling and for anchoring in means of transport.

The materials used for packing shall comply with the health laws and regulations of the countries involved in the transport. For example, if wooden crates are used, they shall be accompanied by the phytosanitary certificates required by the regulations.

Any damage during packing, transport and unloading on DTT site is under the responsibility of the Contractor. The Contractor is required to take out insurance for any damages suffered during transport. In any case, the Contractor shall take every possible precaution to avoid damages and consequent delays in the

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Procurement. For example, every package shall include several stress sensors and/or shock recorders and possibly additional monitoring and event recording systems.

All crates and transport containers shall be properly identified on the outside and traceable. All the documentation and procedures necessary for transport, even between different countries, are under the responsibility of the Contractor.

ENEA will be able to assist in the packaging activities to verify its adequacy and inspect the packages before transport to verify their integrity. The Contractor may carry out a similar inspection upon arrival of the packages at the ENEA Research Center in Frascati. An official document may be issued by the parties at each inspection, reporting the list of packages and any problems.

The heavy elements shall be equipped with structures, supports and devices that facilitate their transport and handling. For example, you need bars and/or feet that allow for transportation by forklift or pallet truck. An overhead crane is not available in the final installation area, but the presence of eyebolts can be useful, also for temporary storage. The Contractor shall discuss all these aspects with ENEA before finalizing the definition of cabinets, boxes and macro-blocks.

ENEA assumes that the limits for standard transports will be respected and that exceptional transports will not be necessary.

The Contractor shall issue a Transportation Manual according to the guidelines in the PQMS [1] and in the Packing & Marking Procedure for Material and Equipment [2], that ENEA will provide to the selected Contractor.

11.19 Long-term storage

The area for the installation of the PS system (see Section 13) could be not available by the end of the Contract and even for a long time. Moreover, the PS system could start the ordinary operations a long time after the installation. Therefore, the Contractor shall develop the design, manufacturing and packaging to allow a long-term storage in another area before the installation and a long-term inactivity before starting the operations. In particular, the question of electrolytic capacitors shall be analyzed. For example, a configuration to facilitate the treatment of such capacitors should be arranged.

The Contractor shall issue a Long-Term Storage Manual where all these aspects are addressed also in compliance with the PQMS [1].

11.20 Required certifications

The Contractor is responsible to verify that all the delivered and used goods have the certifications, labels and authorizations required by the Italian legislation and by the applicable European directives and regulations (as CE marking).

11.21 Warranty

All elements of the procurement shall be covered by a warranty against defects in design, construction or installation for a period of 2 years from the end of Contract.

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12 Acceptance tests

12.1 Importance of tests

The approval of the FDR is not sufficient for the acceptance of the PS components or systems by ENEA. They shall pass all the acceptance tests.

The complete Test Plan containing the description of all the tests to be carried out on single components and on complete systems shall be presented by the Contractor as an attachment to the offer to participate to the Call for Tender selection process and will be subject to evaluation for the assignment of the Contact. This plan shall include at least all the tests listed in the following subsections, complying with all the principles illustrated below, as well as with all the requirements of the applicable regulations and standards.

The tests and procedures offered by the Contractor in the Call for Tender are mandatory in case of assignment of the Contract. However, they are not exclusive: ENEA may request further tests to meet the requirements in this Technical Specifications. The definitive Test Plan will be that approved by ENEA after the signing of the Contract.

12.2 General test requirements and criteria

There are 3 types of tests:

1. Factory acceptance tests (FATs): official tests in the Contractor facility (or in the facility one of a subcontractor of its). ENEA or its delegated representatives shall be able to attend the official tests. No components of the Procurement shall be delivered to ENEA without passing the FATs required for it and without the ENEA approval of the relevant Test Reports.
2. Site acceptance tests (SATs): official tests in the final location in the DTT site on dummy loads and/or, only if/when possible, on real DTT loads (not included in the scope of Procurement).
3. Internal tests: the Contractor can/shall carry out internally, without mandatory ENEA attendance, all the additional tests necessary for the development of the project and to guarantee compliance with the specifications.

The Contractor (or one of its subcontractors) shall provide the electrical power, instruments, materials, tools, supports, personnel, safety measures and any other ancillary service necessary to perform the FATs. The Contractor is responsible for their correct operations. In particular, the Contractor shall demonstrate that all the used instruments are calibrated according to its procedures and to the applicable standards and regulations (see also PQMS [1]).

The tests can be carried out on single components or on several components at the same time based on the specific convenience. The tests shall be carried out in conditions as similar as possible to the operating ones, but also introducing or simulating the possible worst cases of some parameters (for example: extreme temperature, minimum auxiliary voltage or power, disturbed environment, etc.). It would be desirable to carry out the tests in the most critical conditions (limit ambient temperature, cooling water at maximum temperature, minimum input voltage, etc.), but, if this is not possible, these conditions shall be verified through calculations or certifications.

In the Test Plan (see PQMS [1]) the Contractor shall propose the testing procedures to ENEA for approval. Some details of the procedure can be specified later, but at the latest at the time of the official communication of the dates and place of the tests and are always subject to ENEA approval.

In the testing procedure, the Contractor shall specify which elements will be subject to:

1. Type tests on a representative component. In principle, these will be the most severe tests. The Contractor shall be able to demonstrate that the component tested is actually representative of the others. In case of doubt, the tests shall be repeated as routine tests.
2. Routine tests to be repeated on each component.

In principle, all the tests required in this Technical Specifications shall be considered as routine tests, unless otherwise specified. The Contractor may ask ENEA to consider them as type tests and therefore to be exempted from repetition on other components. This request shall be explicitly approved by ENEA.

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In principle, to demonstrate the repeatability and reliability of systems, each functional test shall be repeated 10 times at intervals of 3600 s (or less). A lower number of repetitions can be authorized by ENEA. The Contractor may propose to ENEA to be exempt from certain tests, if it is able to produce detailed documentation demonstrating that equivalent or tests that are more stringent have been carried out on an identical component. This exemption is always subject to the approval of ENEA.

ENEA shall be invited to participate (at its discretion) in all the FATs. To this aim, ENEA shall be informed of the place and dates of the tests in accordance with the prescriptions of the PQMS [1].

For each performed test, regardless of the ENEA attendance, the Contractor shall send to ENEA a Test Report for approval as prescribed in the PQMS [1].

The Contractor shall repair or replace any item damaged or deteriorated during testing.

ENEA can request the replacement of any component or system that has not passed a test and the subsequent repetition of all the necessary tests at each stage of the project. The replacement and repetition of the tests will be charged to the Contractor.

The performed tests do not release the Contractor from its obligations on the Procurements, for example regarding compliance with specifications and guarantees.

12.3 Minimum set of FATs

The following tests shall be included in the FATs:

1) Ability to supply and regulate DC current in short-circuit, at nominal current and at various other current levels agreed in the Test Plan(s). These tests are particularly useful for verifying long-lasting thermal effects (temperature rise tests).
2) No-load voltage regulation capability on various voltage scenarios agreed with ENEA.
3) Load functional tests, for example on a dummy load. The conditions shall be as close as possible to the nominal ones, taking into account the limits of the dummy load. Minimum objectives of the tests are:
    a. Verification of the accuracy and repeatability of current and voltage regulation on various output levels.
    b. Checking the current ripple, possibly at rated current.
    c. Verification of the current harmonics in input and output to the H-bridges.
    d. Estimation of the effect of DC-link parasitic elements.
    e. Characteristics of sinusoids generated from very low frequency to the maximum expected frequency.
    f. Dynamic responses (as rise time) on transient waveforms.
4) Emulation of all faults and their protection.
5) Management of internal and external alarms.

In each test, the following aspects shall be verified:

1) Verification of the controls synchronism, including the verification of the synchronizations between converters (bridges) in parallel.
2) Check for static or mechanical imbalance between parallel devices or converters, including DC-link capacitors.
3) Speed and delays in the regulation control loop.
4) Overall power losses.
5) Thermal stresses at various locations using thermal imaging cameras and/or local sensors, including at least power semiconductors and their heatsinks, capacitors, supercapacitors and coupling reactances.
6) Characterization of semiconductors and their heatsinks. In particular, the direct or indirect measurement of the junction temperatures of the semiconductors and of the most critical heatsinks shall be carried out, including the estimation of the thermal resistances and the verification of the effect of the variations in the characteristics of the cooling water.
7) Verification of LCC functionality, including communications with individual converters and CODAS.

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8) Verification of communications of commands, references, alarms and measurements with CODAS, especially through the mini-CODAS supplied by ENEA.
9) Delays, jitter and settling time between the scenarios requested by the CODAS and the waveforms produced by the PS system (see also Section 12.11).
10) Verification of the nominal value and tolerance of passive components, including characterization of parasitic effects, including at least
    a. Inductance of coupling reactances. The test current and frequency shall be agreed with ENEA, also taking into account the IEC 60076-6 Standard.
    b. Capacity and ESR of (super)capacitor banks, also considering transient effects and the effects of unbalances and connections.
    c. Resistance of the grounding resistors and, if present, of crowbar resistors (or equivalent in the case of varistors), taking into account thermal effects and the recovery time between successive operations.
11) Verification of the accuracy of the complete chain with all measurements.
12) Verification of auxiliary systems, including at least the test of high-pressure tightness of the water cooling system, that shall withstand at least 1 MPa for 6 hours without leaking.
13) Verification of the efficiency of switches and mechanical disconnectors, even though repeated operations.
14) Noise levels.
15) Visual inspection before, during and after each test.

Other specific tests that shall be included in the FATs are described in the following subsections.

12.4 Preliminary tests

All components are subject to inspections at the premises of the Contractor (or subcontractors).

A visual and general inspection of all components and systems shall be included in the FATs and final installation, to verify at least the following aspects:

1) Compliance with the general Technical Specifications and specifications to sub-suppliers or subcontractors.
2) Compliance and validation of the layout and dimensions.
3) Verification of assembly and maintainability aspects.
4) Check earth connections.

12.5 Insulation tests

In the factory, all components shall first be subjected to electrical insulation tests according to Table 10 and according to the applicable standards, in particular to the IEC 60071 series, to the IEC 60146 series and to the IEC 60076-3 standard. The tests shall be accompanied by insulation resistance measurements as prescribed by IEC 60146-1-1.

Unless otherwise required, the insulation tests shall be carried out for 60 s either in AC 50 Hz with a rms value equal to the prescribed voltage or in DC with a value equal to the peak value corresponding (multiplied by square root of 2) to the prescribed voltage.

Table 10. Voltage levels for factory insulation tests.

Component	Test voltage (to ground)
Input transformers	According to standard IEC 60076-3
AC/DC converters	According to the voltage and the selected scheme
DC-links	≥10 kV rms (depending on the adopted DC-link maximum voltage)
Output converters	≥10 kV rms (depending on the adopted DC-link maximum voltage)
Crowbars	10 kV rms
Imbalance L_{im} and R_{im}	10 kV rms
Low voltage auxiliary systems	According to standard IEC 60146-1-1

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On DTT site, after installation and before proceeding with other testing and commissioning activities, the insulation tests shall be repeated at voltages lower than those used in the factory. These tests are not included in this Procurement. The methods of these tests will be redefined under a new Contract.

12.6 Specific tests for the power transformers

At least the following tests are required for the transformers, according to the standards IEC 60076-2, IEC 60076-3, IEC 60076-5:

- Measurement of winding resistance.
- Transformation ratio and phase shift measurement.
- Measurement of short-circuit impedance and load losses.
- Measurement of current and no-load losses.
- Induced voltage insulation test.
- Measurement of partial discharges.
- Temperature-rise test (type test).
- Short-circuit withstand capacity (type test).
- Dielectric type tests.
- Detection of the harmonic content in the no-load current (type test).
- Noise level measurement (type test).

12.7 Specific tests for the AC/DC converters

Specific tests shall include at least:

- Verification of the DC-link charge time starting from various conditions.
- Discharge rate (residual voltage) of the DC-link during several reference scenarios, as those described in Section 4. This test shall verify the correct sizing of the DC-link and the mutual support with the input stages.

12.8 Specific tests for the DC-links

Specific tests shall include at least:

- Checking the DC-link charge during operations.
- Verification of self-discharge phenomena.
- Emergency fast discharge activation test of the DC-link in case of overvoltage.
- Measurement of the current between the DC-link and the output converter.
- Verification of the effect and optimization of any filters or capacities between the DC-links and the output converters, with comparative measurements of the current upstream and downstream of them.

12.9 Specific tests on supercapacitors

The Contractor shall verify by type tests at nominal current that the supercapacitor cells employed in the DC-links have the parameters, in particular the ESR, assumed and modelled in the design. This test shall be performed at least on a single cell, on two cells in series and on two cells in parallel.

It is recommended to repeat the same tests on supercapacitor modules and banks employed in the DC-links.

12.10 Specific tests on the crowbar

Specific crowbar tests shall include at least:

- Activation of the crowbar on both external command and following automatic intervention (by the BOD, if present).
- Verification of the ability to withstand the peak current and the I2t.
- Verification of coordination between crowbar activations.

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12.11 Specific tests on control and regulation algorithms

The control, regulation and communication functions shall be first tested on individual subsystems, then on the overall system, even controlling several converters and functions simultaneously.

The most critical operations and functions of the LCC and of the converter controllers shall be verified before their applications to the power circuits by means of hardware-in-the-loop (HIL) or power hardware-in-the-loop (PHIL) simulations.

Specific tests shall be performed to verify the transfer function from requested to applied voltage, with particular reference to the delay and time constant (see Section 4.6 and Table 2).

12.12 Specific tests on control interfaces

For the integrated system tests (at the Contractor's premises), ENEA will provide a Mini-CODAS, as described in Section 9.6.

Tools developed in previous section could be initially exploited for these tests.

12.13 Specific tests for anti-seismic qualification

Tests shall be performed to verify the seismic qualification of the components and the natural frequencies of the systems as described in Section 11.16. The tests shall follow the industrial seismic guidelines and the Standard IEC 60068-3-3 (see Section 11.16).

After each qualification test, a visual inspection shall verify that there are no displacement or disconnections in the mechanical parts.

12.14 EMC test

Regarding EMC, the following tests shall be performed:

- Assessment of disturbances conducted on the external power grid (main and auxiliary) with a single input converter and with all input converters. In particular, the current THD shall be measured in different scenarios.
- Soak testing, i.e., emulation of the simultaneous operation of the systems for several hours in conditions as similar as possible to the operational ones.

The Contractor shall identify and provide all the needed certifications and program the appropriate tests to verify the compliance with the EMC requirements (see Section 11.14).

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13 Layout, requirements and conditions for installation

13.1 Location and layout

The installation of the PS system in the DTT site is not included in the scope of this Procurement Contract and will be performed under a future new contract, in case with a different contractor. Nevertheless, the Contractor shall consider all the installation requirements and conditions during the system design and manufacturing. Moreover, the Contractor shall issue an "Installation and Commissioning Manual" as reported in the PQMS [1].

The PS system will be installed inside DTT Building 191 in the ENEA Research Center in Frascati (see Figure 14).

The absolute altitude in the DTT site is about 185 m above sea level.

DTT Building 191 is still under construction. When ready, the Contractor will be able to inspect it. As far as possible, ENEA will welcome suggestions from Contractor on the project and on the preparation of the new area.

Figure 15, Figure 16 and Figure 17 show a preliminary layout of the PS system in the DTT Building 191. This is only a reference: the Contractor can adapt the layout not exceeding the reference dimensions, also taking into account the installation, operation and safety requirements. Different external shapes shall be proposed in advance to ENEA for approval. All the area colored in green in Figure 15, Figure 16 and Figure 17 is available for the PS system. the area in red will be occupied by another DTT PS system with similar characteristics, the area in yellow will be available for movements and installation. The columns (in gray) are part of the building.

The maximum height in Building 191 is 4.9 m. To avoid any possible interference with external ducts, busbars and other services, the height of the PS cabinets should not exceed 2.2 m. This limit could be exceeded in the positions properly agreed between the Contractor and ENEA.

It is preferred that the output terminals of the PS system to the load coils will be located on the top of the cabinets for easy connection of output cables. The exact position and characteristics of these terminals will be agreed between the Contractor and ENEA.

The PS components shall be laid and fixed on the building floor and shall be fixed (post-installed) with chemical or mechanical anchors during the future installation contract.

The Contractor could design a floating floor to simplify internal connections (cables, busbars, pipes, etc.) and personnel access.

The maximum average load of the PS system to the floor shall be less than 600 kg/m^2 or 5 kN concentrated. In case higher loads will be necessary, the Contractor shall identify adequate solutions, but it shall inform ENEA as soon as possible.

ENEA can provide more detailed drawings upon request.

13.2 Environmental conditions

The air in Building 191 is conditioned by DTT with the characteristics in Table 11.

All the PS components shall operate correctly and for the entire useful life of the system under the conditions reported in Table 11. The operations will be interrupted by the DTT CODAS if the limits in Table 11 are exceeded or in case of risk of condensation.

Table 11. Characteristics of the ventilation system in Building 191.

Characteristic	Value
Temperature range ensured by the building ventilation system	15÷30 °C
Maximum relative humidity in the building	70%
Air changes in the building	1 vol/h
Operating range of PS system	5÷40 °C

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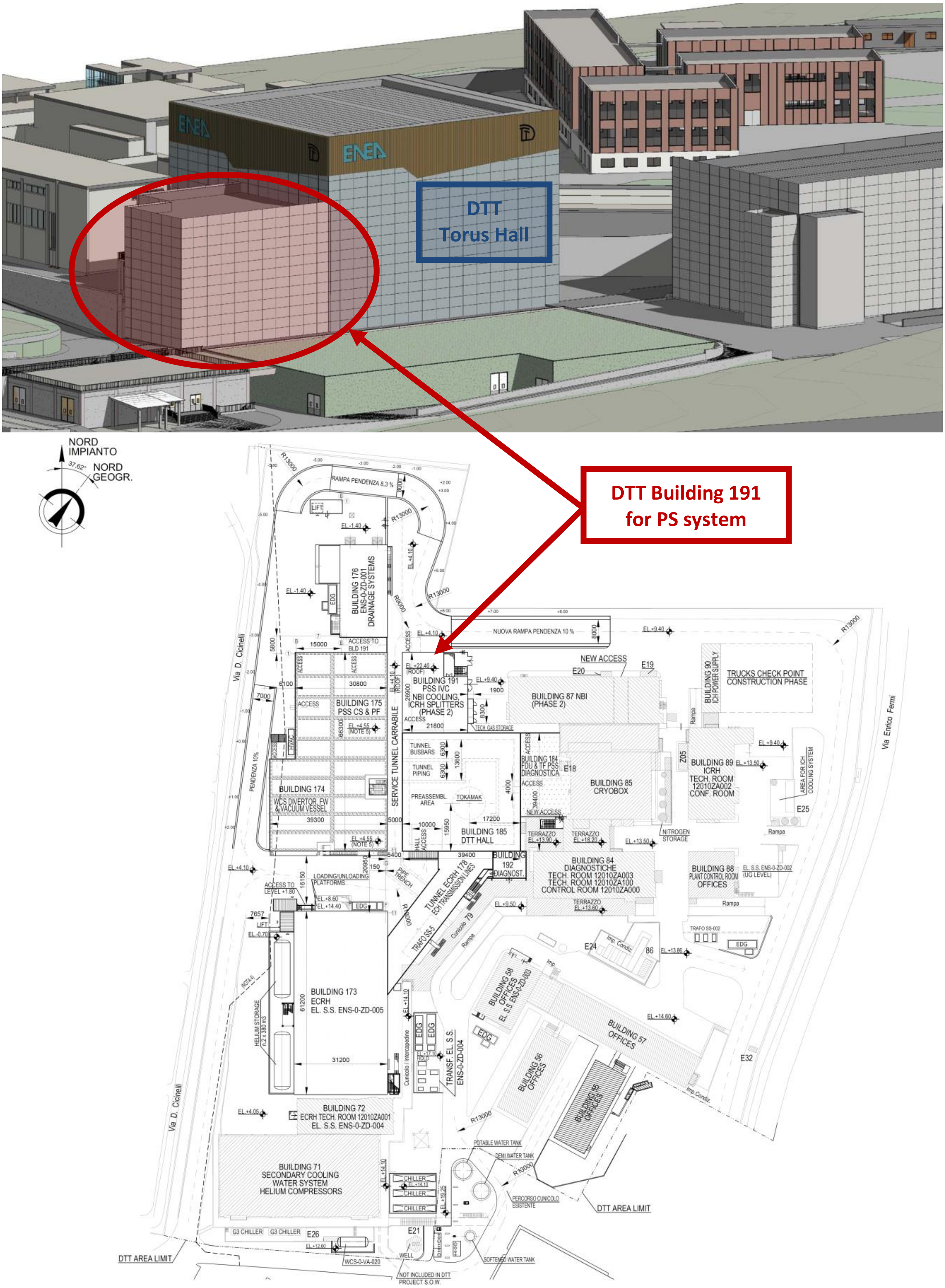

Figure 14. Map and 3D view of the DTT buildings in the ENEA Research Center in Frascati. The PS system will be installed in Building 191. The tokamak will be in Building 185 (Torus Hall).

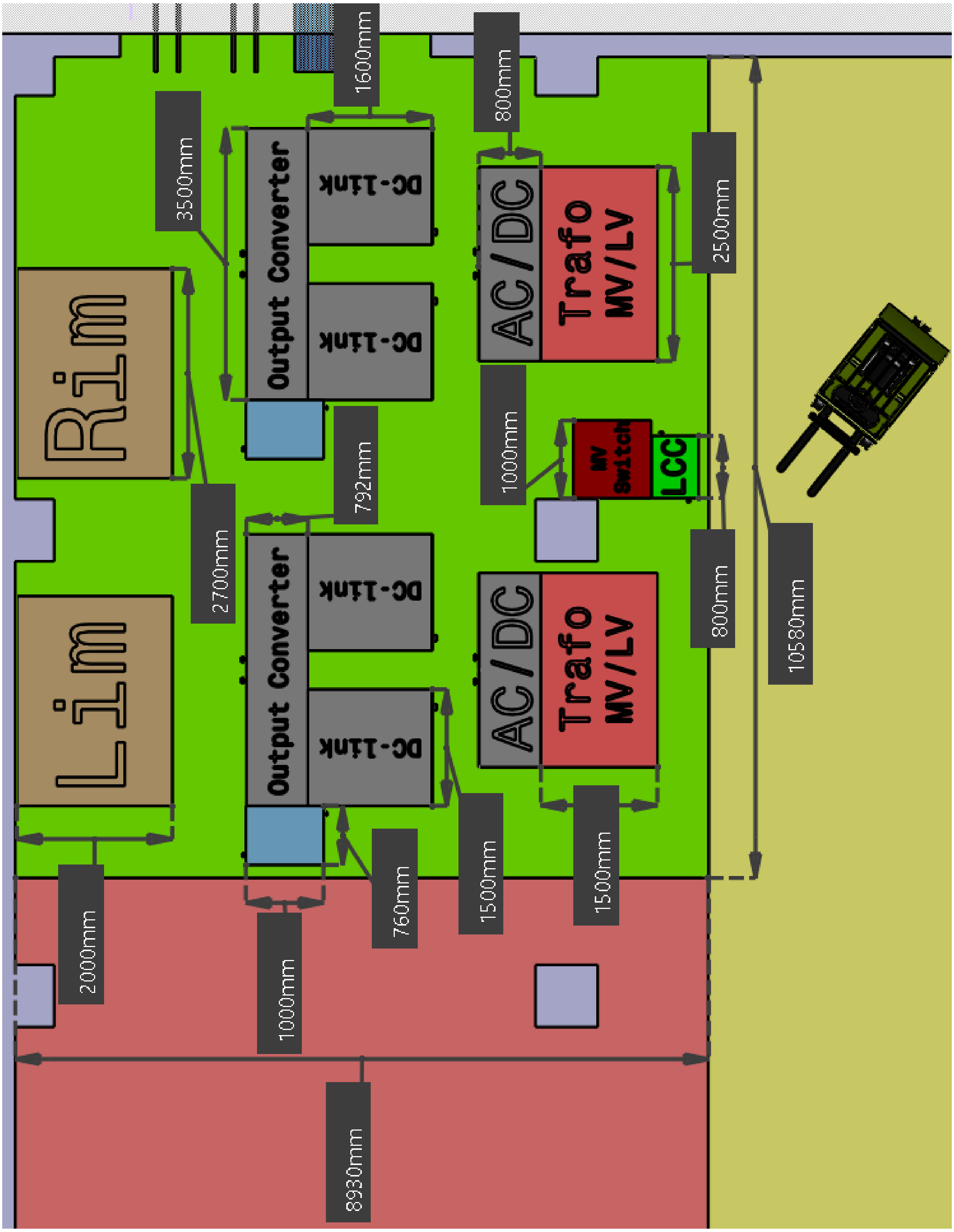

Figure 15. Preliminary layout with some relevant dimensions of the VS PS system in the DTT Building 191. The area colored in green is available for the VS PS system, the area in red will be occupied by another PS system, the area in yellow will be available for movements and installation.

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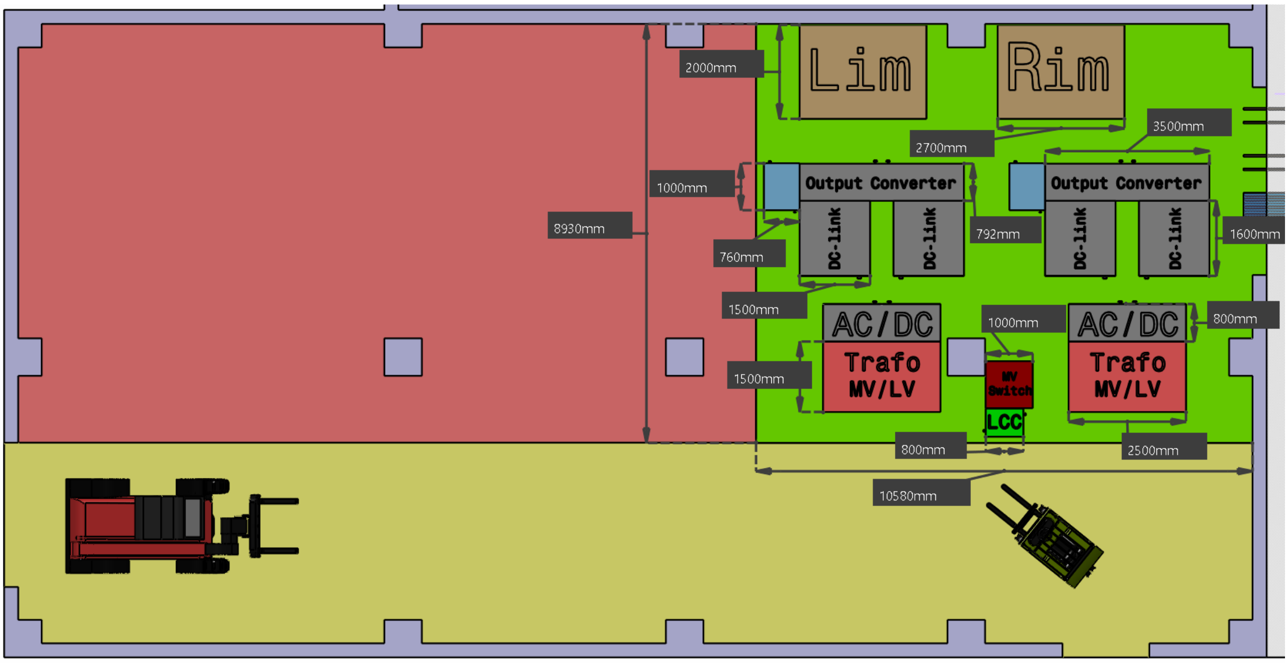

Figure 16. Preliminary layout in Figure 15 extended to show the entire DTT Building 191, also to show the entrance doors. The area colored in green is available for the VS PS system, the area in red will be occupied by another PS system, the area in yellow will be available for movements and installation.

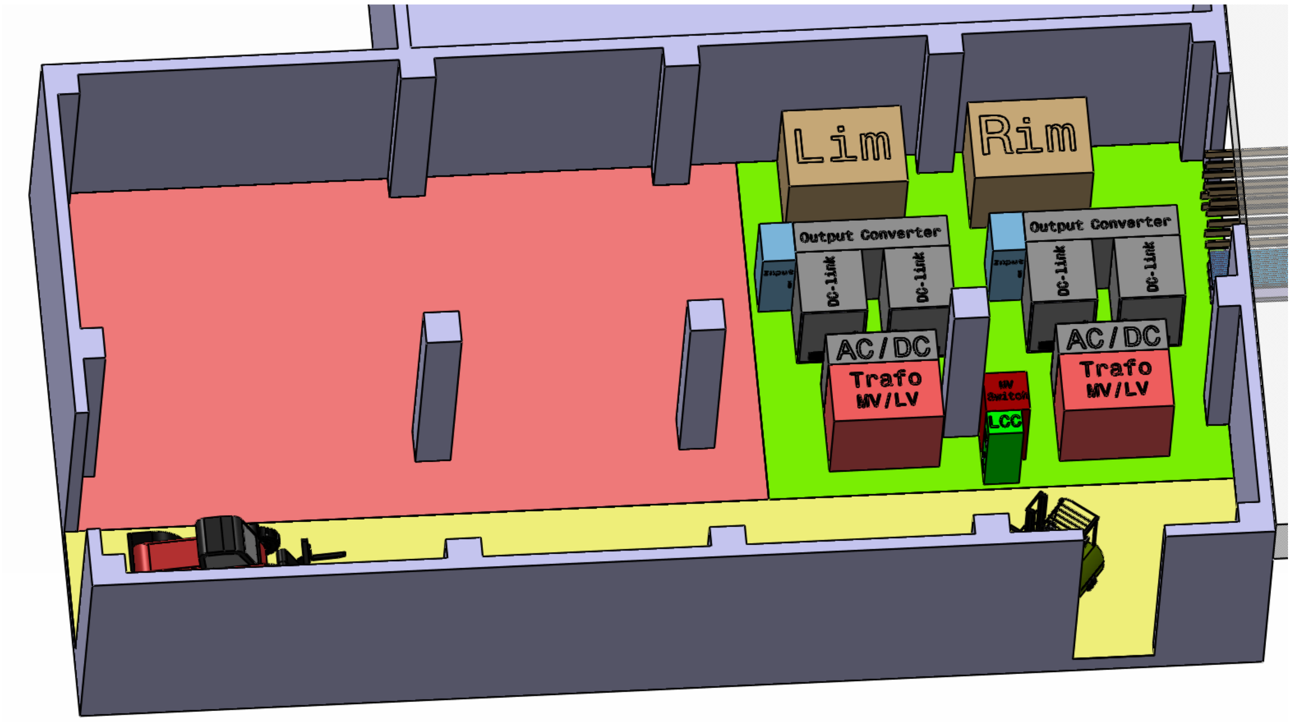

Figure 17. 3D view of the preliminary layout of the VS PS system in Figure 16.

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