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ALLEGATO 06 - AVAILABILITY REQUEST

Object:

Technical Specification of the Magnetic Energy Storage and Transfer System (MEST) Prototype

Abstract

This document contains the Technical Specification for the detailed design, manufacturing and testing of a prototype of a new Magnetic Energy Storage and Transfer System (MEST). The contract for will be articulated in two phases.

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TERMS AND DEFINITIONS

C	Capacitor bank of the MEST
CRFX	Consorzio RFX
CS	Central Solenoid
DEMO	European demonstration reactor
IGBT	Insulated Gate Bipolar Transistor
ITER	"The Way" in Latin, toward the production of net fusion energy
HMI	Human Machine Interface
KC	Sink Coil
LC	Load Coil
MEST	Magnetic Energy Storage and Transfer system
PF	Poloidal Field (coil)
PS	Power Supply
SITE	Consorzio RFX premises
SMES	Superconducting Magnetic Energy Storage

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1 INTRODUCTION

In all the tokamaks, high peaks of active power (P) are requested by the magnet system necessary for the plasma current formation, sustainment and control. The amount of power increases with the machine size and in fact, for DEMO, it is significantly higher than for ITER; the present estimation is of several hundreds of MW, which should be provided by the DEMO generator or should be still required from the electrical grid.

In all the present tokamaks the power supplies of the main coils are based on thyristor rectifiers; in DEMO, they should be rated for several tens of kA and several kV. One of the main drawbacks of this technology is the large reactive power absorbed when high currents and low voltage are required by the loads, as occurs during a great part of the plasma pulse.

In order to satisfy the power needs for the DEMO operation, minimizing the request of contribution from the electrical grid, and in particular high peaks of active power and reactive power, R&D has been launched to explore suitable electrical energy storage systems and advanced power converter topologies to maximize the energy exchange within the plant sub-systems, instead of demanding it to the generator or to the grid.

Among the available technologies for energy storage, the Superconducting Magnetic Energy Storage (SMES) is particularly suitable for large fusion devices, because of its large power density and adequate release time for these applications. Moreover, DEMO is provided with superconducting magnets, thus the plant is already equipped with the necessary cryogenic systems for superconducting coils.

Based on the SMES technology, a new system has been conceived, called MEST: Magnetic Energy Storage and Transfer system. It can represent an alternative solution to supply the main poloidal coils, providing a significant degree of decoupling between the grid/generator and the coils.

For a first step to explore the industrial feasibility of such a scheme, the development of a small scale prototype is proposed. It is pointed out that even in case of positive outcomes, much further work will be necessary to confirm the feasibility of this design approach for DEMO. In fact, the gap from the power level of the MEST prototype to that of the DEMO circuit is quite wide; moreover, this MEST prototype will be connected to copper coils, thus the operation is not the same as it would be with superconducting coils.

2 REFERENCE DESIGN OF THE MEST

A first conceptual design of the MEST circuit and relevant control can be found in [1]; a first application study for the EU DEMO Central Solenoid circuit can be found in [2], [3].

The reference scheme of the MEST is shown in Figure 2-1.

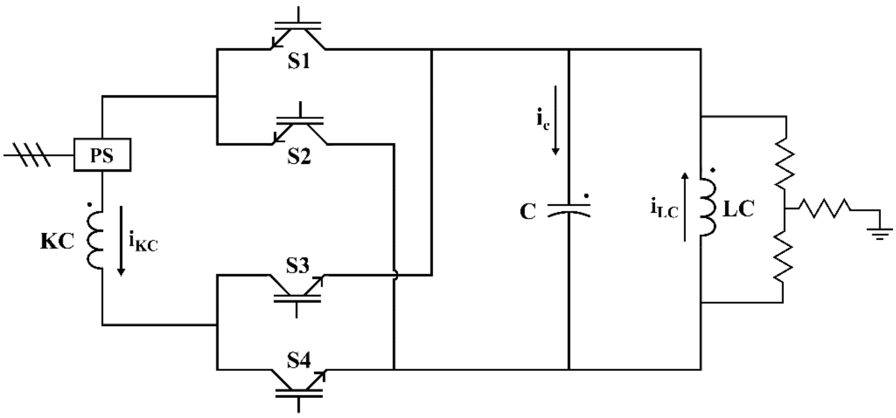

Figure 2-1 – Conceptual reference scheme of the MEST prototype

The basic principle is to charge a sink coil (KC) up to the total energy required in the circuit and then to transfer the energy from KC to the Load Coil (LC) and vice versa during the different phases of the plasma pulse, via switched capacitor. The Power Supply (PS) shown in Figure 2-1 has the only duty to provide the active power required by the load and to compensate for the circuit losses. The energy transfer process between the two coils is performed step by step through a suitable hysteresis control of the voltage across the capacitor bank, thus across the coil to be supplied, realized by acting on the fully controllable static switches S1, …, S4.

An example of the ideal sequence of operation is shown in Figure 2-2: the KC coil is charged by the PS to the desired energy value, which is at least twice the maximum energy to be stored in the load coil during the pulse. Then, if necessary, part of the energy stored in KC is transferred to LC before the pulse, as shown in the example of Figure 2-2. During the pulse, the load current is controlled as required by transferring the energy from the KC to the LC and viceversa.

The PS provides maintaining constant the total circuit energy; moreover the PS has to assure that the KC current is always higher than the LC one.

During the time between two consecutive pulses, the initial conditions have to be re-established.

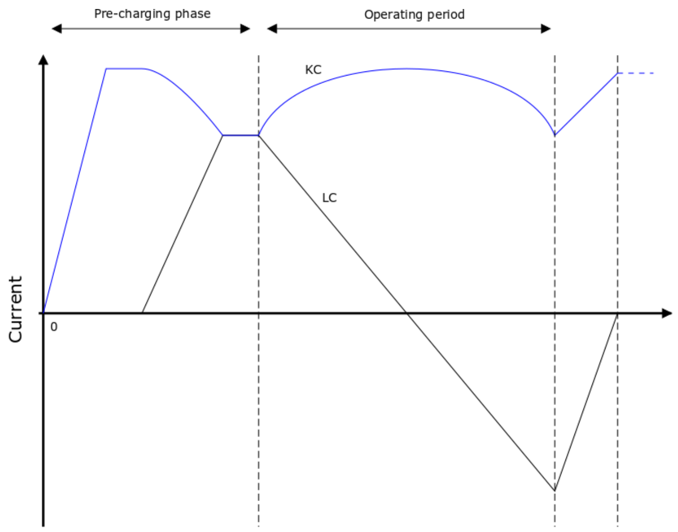

Figure 2-2 – example of the conceptual operation sequence of the MEST

The reference scheme for the control is shown in Figure 2-3. The variable to be controlled is the load current, thus the main reference signal is the desired load current. On the basis of the knowledge of the maximum current value desired in the load coil, the total energy required for the circuit to operate can be calculated (a certain margin is to be considered to assure that the KC current is always higher than the LC one) and the reference current to be reached in KC derived. The calculated KC reference current is used for the current control loop of the PS.

LC is charged via a closed loop control of the load current which generates a reference waveform for the load voltage (almost equal to the capacitor bank voltage), which is in turn regulated via a hysteresis control. During the plasma pulse the two nested loops continue operating to assure the desired current waveform in the load. In this phase, the PS current reference is the desired KC current necessary to maintain constant the total circuit energy.

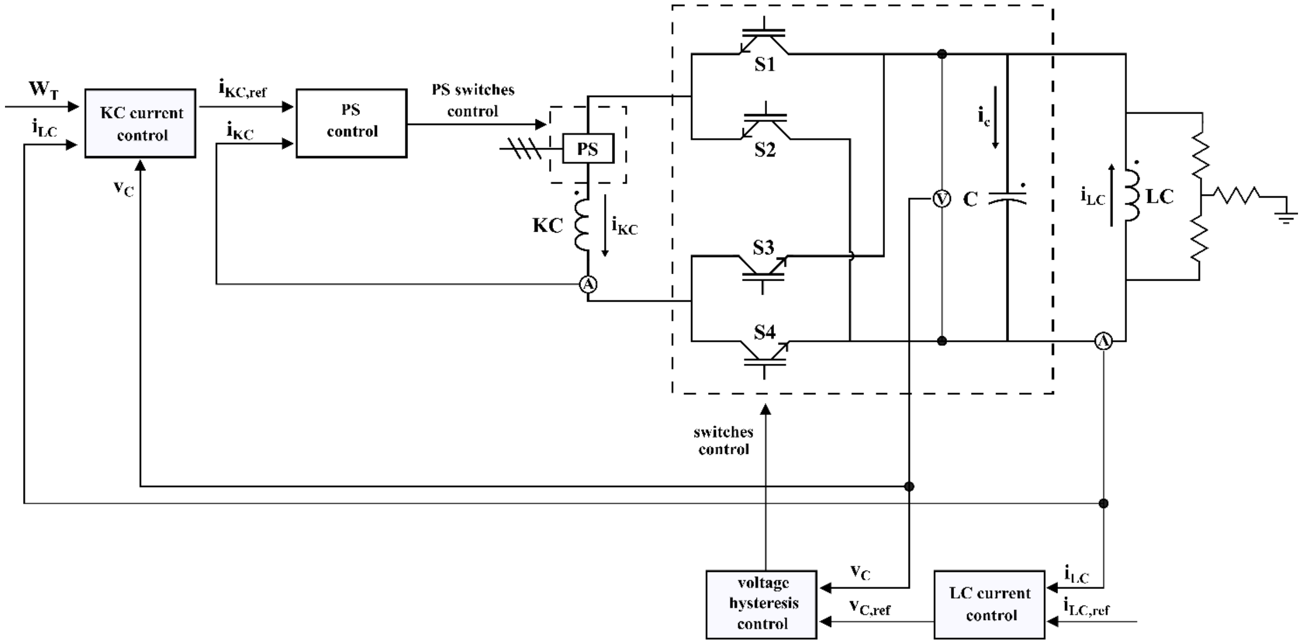

Figure 2-3– Block scheme of the reference control of the MEST

3 SCOPE OF THE CONTRACT

The scope of this contract is the development of a small scale prototype of the MEST to characterize its operation. It is pointed out that this prototype will be connected to copper coils, with no negligible stray resistance; this means that the temporal evolution of the waveform is very different with respect to that expected in DEMO.

It is highlighted that in the application for DEMO the energy stored in the LC (which can be CS or PF) and in the KC is orders of magnitude higher than in the capacitor bank, while in the MEST prototype the energy stored in the capacitor bank is not negligible with respect to that stored in the inductors. It is important to have in mind these aspects to correctly interpret the results more significant for DEMO.

The Supplier can propose in the offer a design solution different from the reference one (section 2), both for the power and control section, proving the compliance with the requirements and the advantages with respect to the reference one.

The contract will be articulated in two phases.

The aim of the first phase is the detailed design, manufacturing and test of the simplest circuit configuration with only one switch per branch; this is an important step to characterize the basic MEST operation since it is a new scheme: no similar examples have been found either in the field of fusion or in other fields.

The aim of the second phase of the contract is to select the most suitable circuit topology to increase the power identifying basic cell/module to be connected in series and in parallel; then, to realize and test a prototype with up to two modules to be connected both in series or in parallel. To approach, even if at low power, a realistic representation of the MEST implementation in DEMO, both the LC and KC cannot be divided in sectors each supplied by a single cell. Therefore, a single LC and a single KC has to be assumed (even if both composed of more than one inductor) for the design of the MEST prototype. The Supplier shall provide the circuit with the proper devices to ensure a reasonable current and voltage sharing between the parallel or series connected modules.

So, the contract is divided in two phases, but the detailed design of the MEST prototype shall be done considering both phase 1 and phase 2, such that the components and the control realized for the first phase can be already arranged to be upgraded to the second phase.

<u>First phase of the contract:</u>

With reference to the Figure 3-1, the contract shall include at least the following items:

- the detailed design and manufacturing of the components inside the dotted lines in Figure 3-1 (following the requirements described in Section 5). The power supply (PS) shall be rated to be suitable also for the second phase of the contract or to be easily upgraded to the necessary performance;
- the detailed design and manufacturing of the overall control, monitoring, data acquisition and protection system (section 5.3.4)
- the Human Machine Interface (HMI) for the control of the circuit operation to be installed on an external PC (section 5.3.4.5);
- the detailed design and manufacturing of the necessary protection devices
- the necessary provisions to safely discharge the energy stored in the circuit
- the assembly of the whole circuit, including the procurement of all the necessary cables and including fixing provisions against electrodynamic stress, for the proper insulation, the grounding system and any devices for the circuit safe operation
- the tests (following the requirements described in Section 6);
- the documentation as described in detail in Section 10.
- any other component and activity necessary for the correct and safe operation of the circuit, apart from those expressly cited in the list “Not included items: section 3.2”.
- the packaging and transportation of the KC and LC coils from CRFX to the Supplier premises. This requirement does not apply if the Supplier does not need these coils for the tests.

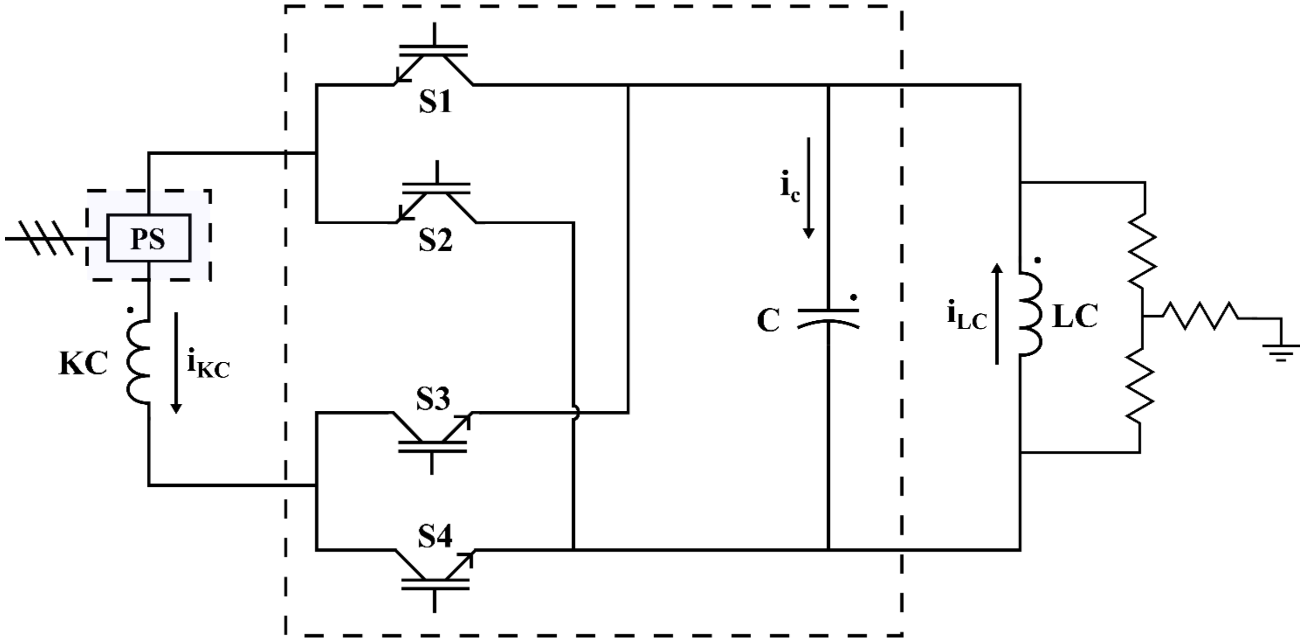

Figure 3-1 – reference MEST circuit for the first phase of the contract

Second phase of the contract:

A possible reference topology for the series or parallel connection of basic modules is shown in Figure 3-2; the contract shall include at least the following items:

- the components inside the dotted lines in Figure 3-2 not already provided during the first phase of the contract (following the requirements described in Section 5.1, 5.2,5.3);
- the upgrade of the PS for the operation of the modules in series or in parallel, if not already provided during the first phase of the contract
- the upgrade of the overall control, monitoring, data acquisition and protection system to manage the additional operation of the power modules in series or in parallel (section 5.3.4)
- the upgrade of the Human Machine Interface (HMI) for the control of the circuit operation to be installed on an external PC (section 5.3.4.5);
- the necessary additional protection devices
- the necessary additional provisions to safely discharge the energy stored in the circuit
- the assembly of the new circuit, including the procurement of all the necessary cables and including fixing provisions against electrodynamic stress, for the proper insulation, the grounding system and any devices for the circuit safe operation
- the tools for an easy reconfiguration of the modules in series and in parallel
- the tests (following the requirements described in Section 6);
- the packaging and transportation of the prototype to CRFX and of the KC and LC coils if the Supplier decided to utilize these coils for the tests (Section *8*);
- the installation of the prototype at CRFX (Section 9);
- the documentation as described in detail in Section 10.

- any other component and activity necessary for the correct and safe operation of the circuit, apart from those expressly cited in the list “Not included items: section 3.2”.
- an estimation of the cost of a power supply system based on the MEST for a DEMO coil, against the cost of a solution based on Voltage Source Converter and of the solution adopted so far based on thyristor converter.

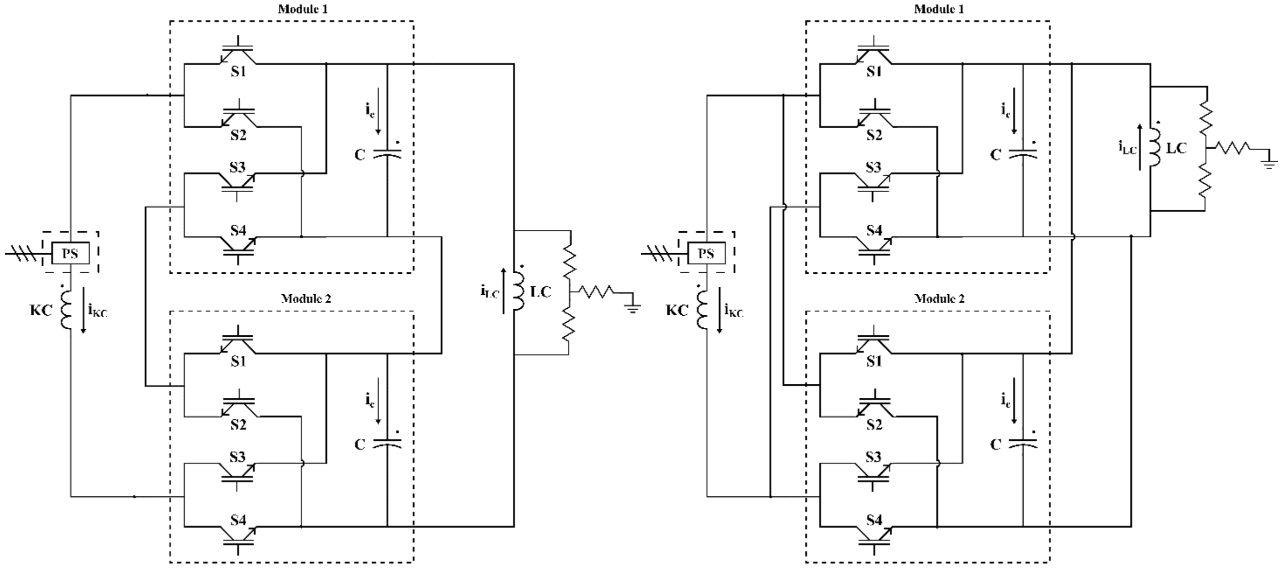

Figure 3-2 – reference MEST circuit for the second phase of the contract

The MEST prototype shall be operated by the HMI installed on an external PC. This mode of operation will be used in factory and will be also used during the tests at CRFX. In addition, it is required that the supplied system can operate at CRFX, under a remote control; details of the interface and control in this operating condition are given in 5.2 and 5.3.4.

3.1 Warranty

The system components shall be subject to standard EU commercial warranty.

3.2 Items not included in the Contract

The following items are not included in the Contract:

- the load coil (LC) and the sink coil (KC) that can be made available by the Contractor;
- the external PC, to communicate with the prototype control section; (however the Supplier shall made available one for the factory tests)
- the scopes and any other instruments / probes necessary for the tests; however the Supplier shall made available the own ones necessary for the tests execution in factory.

4 LOAD CHARACTERIZATION

The inductors that can be made available by the CRFX for the load and sink coils have the following characteristics: L=6.16 mH R=28.82 mΩ. These inductors can sustain a current of 6.25 kA with a duty cycle of 0.5 s/600 s (corresponding to a maximum i^2t of 19.5 MA^2s), with natural air cooling.

Eight of these inductors could be made available for the tests. The reference design for the MEST prototype has been studied for the case of one of these inductors for KC and one for LC. To explore different operating ranges, series/parallel connections of the inductors can be considered by the Supplier for the load and sink coils, provided that, the MEST prototype operation remains compatible with the requirements of Table 5-1 and Table 5-2, apart from the PS rating that could require being adapted.

Figure 4-1 **– plate data of the inductors that can be made available by the CRFX**

The Supplier can propose the use of own inductors, if available and more suitable for this application; this option will be discussed and agreed in case during the design phase. However, the correct operation of the MEST prototype also with the inductors described in this section shall be assured.

5 TECHNICAL REQUIREMENTS

5.1 Main requirements

Phase 1 of the contract – MEST prototype (1)

The minimum requirements which shall be satisfied by the MEST prototype (1) object of the first phase of the contract are summarized in Table 5-1.

Table 5-1 – Minimum requirements of the reference MEST circuit for the first phase of the contract

Nominal load voltage	± 2 kV

Maximum load current	± 2 kA
Maximum current in the sink coils / PS	2.8 kA[1]
Nominal PS voltage	≥ 150 V[2]
PS ac input voltage	380 V rms three phase
Max switching frequency	≥ 500 Hz
Max percentage hysteresis voltage band	± 20% of the nominal voltage[3]
Min. absolute hysteresis voltage band	The value corresponding to the maximum switching frequency
Duty cycle	1 / 300 s

[1] this value is in the case the load and sink coils have the same inductance value; should the sink coils have an higher inductance value with respect to the load one, the peak current could be reduced

[2] the PS voltage can be negative in case its design foresees the possibility to store internally the energy from the circuit, otherwise just one quadrant operation is specified

[3] the amplitude of the hysteresis band can be varied during the pulse. It is a parameter to be set in terms of percentage value of the voltage reference; moreover a minimum absolute value has to be set

Phase 2 of the contract - MEST prototype (2)

The minimum requirement for the second phase of the contract modified with respect to those of Table 5-1, are listed in Table 5-2. The others requirements of Table 5-1 remain valid also for the second phase of the contract.

Table 5-2 – Minimum requirements of the reference MEST circuit for the second phase of the contract

Maximum voltage at the load with modules connected in series	4 kV
Maximum load current with modules connected in parallel	4 kA
Maximum current in the sink coil / PS [1]	5.6 kA
Nominal PS voltage	≥ 300 V[2]

[1] see corresponding note in Table 5-1

[2] see corresponding note in Table 5-1

5.2 Interface requirements

The main interfaces of the MEST prototypes (1) and (2) are summarized in Figure 5-1

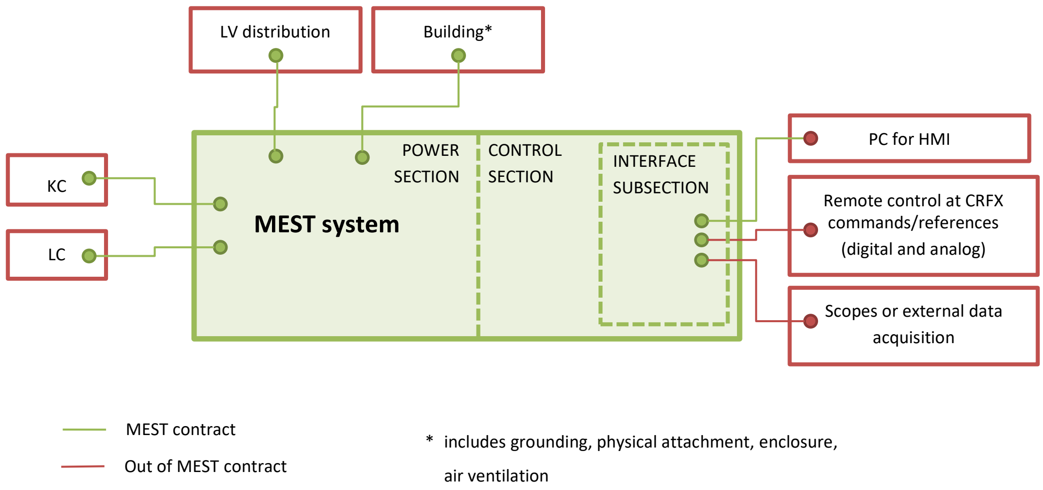

Figure 5-1 – Interface diagram of the MEST prototypes (1) and (2)

The MEST prototype shall be able to operate at CRFX under a remote control; thus, a dedicated interface subsection shall be arranged by the Supplier at this purpose. The interface subsection for the remote control shall be grouped in a single panel, collecting all the digital input/output ports, analog input /output ports, emergency push button, local/remote selector, etc.

5.2.1 Building

5.2.1.1 Ambient temperature

The ambient temperature to be considered for the thermal design of the equipment is in the range 0 ÷ +40°C.

5.2.1.2 Available space for the MEST prototype

The space available at CRFX for the MEST prototype is 2.00 m x 2.70 m, as shown in

Figure 5-2. The maximum height available on site is 3.10 m. During the design phase the verification of the area available on Site shall be performed taking into account the actual size of the MEST prototype.

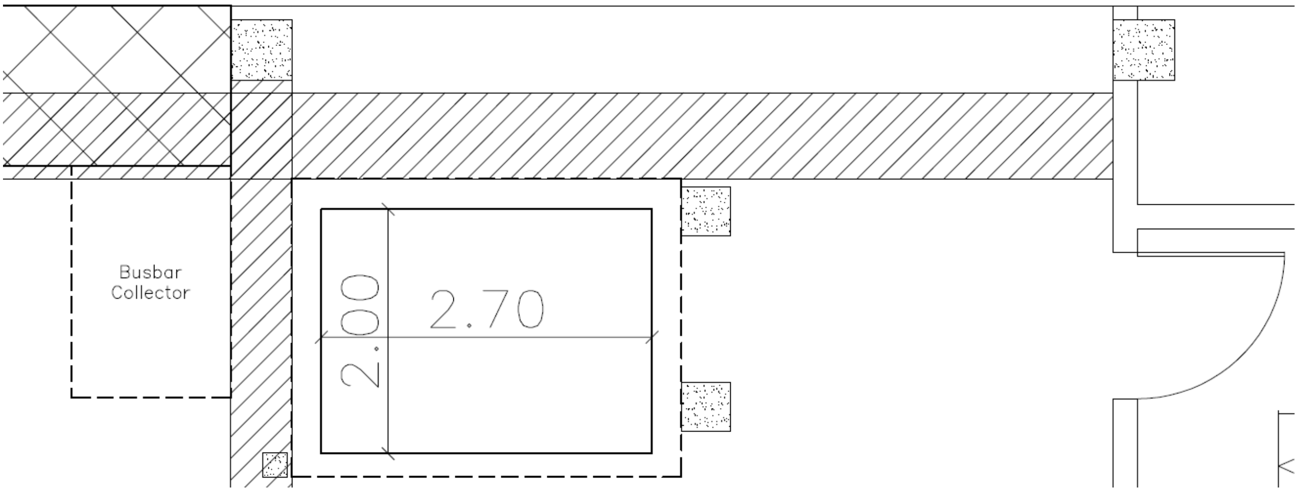

Figure 5-2 – Available space for the MEST prototype

5.2.1.3 Grounding

A grounding point for the power section is made available in the space dedicated to the MEST prototype.

5.2.1.4 LV distribution

The PS for the MEST shall be fed by the LV distribution (380 V64 A).

5.2.2 Coils KC and LC

The KC and LC coils on Site will be located 20 m far from the Supply.

5.2.3 Interface with the external PC

The MEST control section shall include an Ethernet interface (TCP/IP), safely insulated from the power section, through which an external PC (not included in the contract) will be connected.

In Table 5-3 and Table 5-4, a tentative list of signals to be exchanged via Ethernet link is shown.

Table 5-3 – List of slow commands from the external PC to the Ethernet interface

Name	Type	Full scale	Description
Reset	Slow, digital	ON/OFF	Reset after a fault. Ignored during a pulse
Control parameters	Slow, digitalised		control parameters *
Enable	Slow, digital	ON/OFF	Enable signal such that the MEST is ready to start
Start	Slow, digital	ON/OFF	To start the MEST operation

* values of KC and LC inductances, value of C capacitance, max. I_{LC} value for total energy calculation and initial charge of KC, configuration of the modules in series or in parallel, max percentage value and minimum absolute value of the hysteresis band, local / remote control, parameter of the current control loops, control

loop selection, enable / disable, selection of internal or external reference, HMI or remote control, max. pulse duration, etc.

Table 5-4 – List of status, alarm and monitoring signals from the Ethernet interface and clean contacts of the prototype to the external PC

Name	Type	Full scale	Description
MEST ready	Slow, digital	ON/OFF	MEST ready to start
MEST enabled	Slow, digital	ON/OFF	Enable feedback
MEST auxiliary voltage ok	Slow, digital	ON/OFF	Auxiliary voltage ok
Control parameters	Slow, digitalised		control parameters *
Alarms: fault code	Slow, digital	Encoded (4 bytes)	A fault code identifies the kind of fault and the component involved

* same control parameters listed in the note of Table 5-3

5.2.4 Digital input/output signals

It shall be possible to command the MEST such that it can operate with an external power supply.

Table 5-5 – Digital inputs and output to the MEST

Name	Type *	Full scale	Description
Enable	Fast, digital input	ON/OFF	Enable signal such that the MEST is ready to start
Start signal for the MEST prototype	Fast, digital input	ON/OFF	Start the switching operation of the MEST
Emergency stop	Fast, digital input	ON/OFF	To quickly stop the MEST operation
Ready	Fast, digital output	ON/OFF	Ready to receive the enable
Enabled	Fast, digital output	ON/OFF	Enable feedback
Fault	Fast, digital output	ON/OFF	internal fault which requires to stop the external power supply
LOCAL/REMOTE	output	ON/OFF	Communicate the source of commands, selectable by switch on board

* to be agreed during the design phase (optic fiber, clean contact..)

5.2.5 Analog input/output signals

The analog inputs are listed in Table 5-9 while the analog outputs are listed in Table 5-7 and Table 5-8. The inputs and outputs shall be in the range -10 / +10 V corresponding to the full scale.

5.3 Requirements of the main components

5.3.1 Switching section

The choice to design the MEST modules as indicated in the reference scheme or to use power switches directly connected in series or parallel will be specified in the offer and discussed during the design phase.

The inductance of the internal and output power connections of the switches shall be minimized in order to minimize the voltage drop across these connections.

The selection of the type of power switches is left to the Supplier; but it is recommended to use switches that can be suitable in perspective for higher power ratings.

Proper design of the gate circuits and wiring has to be implemented to assure safe operation of the devices and a safe start-up, to limit the jitter between commands and to minimise the leakage inductance and resistance. For the IGBTs, a de-saturation protection circuit shall be included.

The prototype shall be completed with all the devices needed to assure the proper working and the protection against faults.

Fault conditions (power switch and misfiring faults, overvoltage, overcurrent, overtemperature, etc.) and relevant protection actions shall be analyzed and reported in the Design Report. If the “Enable” signal is removed, the switch-off of the circuit operation has to be realized with all the necessary provisions (including crowbars or other protection systems) to safely discharge the energy stored in the circuit.

5.3.1.1 Solid state devices

The voltage safety factor for the power switches shall assure proper margin in any operating conditions; it shall not be lower than 1.6. In the MEST module all the four switches have to withstand the same direct and reverse voltage.

In any operating conditions, the peak junction temperature shall never exceed 90% of the semiconductor manufacturer specification, with the maximum ambient temperature specified in Section 5.2.1.

In case of parallel connection of power switches or cells, adequate current sharing has to be assured, both statically and dynamically, and in any case, it has to be assured the above prescription on the peak junction temperature of switches.

The solid state devices selected for the MEST shall be available on the market at the time of the tendering; the power module shall be designed to be able to host most powerful switches expected to be available the next years.

5.3.1.2 Cooling system

Pulsed operation of the MEST is assumed with a duty cycle that can avoid the need of cooling water system, both for the switching section and the PS.

5.3.2 Capacitor Bank

The capacitor bank shall comply with IEC 61071 and be designed for the duty cycle of the MEST prototype.

Assuming the capacitor bank is provided for each cell, as in the reference scheme, the nominal dc-link voltage is 2 kV, as indicated in Table 5-1. The capacitance value shall be selected such to assure the compliance with requirements in Table 5-1.

If, for the phase II, the Supplier will propose a concentrated capacitor bank, the relevant rating shall be selected to assure the correct operation of the two cells in series and in parallel.

The tolerance of the overall capacitance shall be within -10% / +30% with respect to the nominal value.

A visible indication placed close to the capacitor bank is required to confirm that it is charged or discharged.

The switches of the capacitor discharge circuit shall be able to withstand the short-circuit current level at their point of connection when closed.

The capacitor bank / banks shall be provided with safe discharge and earthing system /systems that shall be capable to operate also in case of lack of auxiliary voltage, either manually or automatically. The discharging devices shall reduce the residual voltage of the fully charged capacitor bank to less than 50 V within few tens of seconds (exact time value to be agreed).

A time sufficient for the full discharge to occur shall be allowed between the closure of the discharging and the short-circuiting switches.

The Supplier shall declare the minimum time which has to be waited between repetitive discharges to avoid overheating of discharge devices. This time shall be in any case not higher than 15 minutes. The resistor temperature shall be monitored and the capacitor bank charge inhibited if it exceeds critical values.

The discharge, short-circuiting and earthing system shall be designed and manufactured for at least 10,000 open/close cycles during its lifetime.

Both the impregnating agent and the dielectric of the power capacitors shall be not flammable and shall not support combustion or release hazardous fumes in the event of a fire. Mineral oil is not accepted. The capacitor bank shall be suitable for indoor installation.

The capacitor bank shall be provided with internal or external fuses associated to one element or group of elements. In case of dielectric breakdown in one element, the fuse shall be capable to isolate the faulty element (or group of elements) from the remaining healthy elements. The other fuses shall not be damaged. The fuse intervention shall be indicated. The internal fuses shall not intervene in case of short-circuit at the terminals of the capacitor bank. The fuses are not required if self-healing capacitor elements are used.

5.3.3 Power Supply - ac/dc converter

The ac/dc converter shall comply with the applicable IEC standards, in particular with IEC 60146.

The ac/dc conversion system shall provide for the initial charge of the sink coil and then for the power to compensate for the circuit losses so as to maintain the total energy in the circuit.

The ac/dc conversion system shall be designed in order to satisfy the requirements given in Sections 5.1.

The number of paralleled power switches of the PS shall be such to permit to operate in the rated conditions assuring at least the safety margin on the junction temperature of static components specified in Section 5.3.1.1. The Supplier shall indicate this margin in the Design Report.

The ac/dc converter shall include all devices assuring its correct working in all the operating conditions and shall be able to protect itself in case of faults.

5.3.4 MEST prototype control section

5.3.4.1 Functions of the MEST control section

The MEST prototype shall be provided with a digital control section; the main functions are:

- to operate the MEST in order to meet the requirements and to assure its full control and monitoring;
- to protect the components in case of fault and to generate proper fault signals;
- to provide the interface as described in paragraphs 5.2.3, 5.2.4 and 5.2.5.

5.3.4.2 Real-time control

The real time control shall assure that the MEST operates as described in section 5.1.

The real time control shall perform at least the following functions:

- to receive the reference waveforms from the analog input ports or from the HMI;
- to receive the Enable and the Start signal from the HMI or from the digital input port;
- to control the switches in order to follow in real-time the references, such to produce the desired load current;
- to make available the voltage and current measurements;
- to activate the protections of the MEST in case of fault;
- to communicate the internal fault;

PHASE 1 - MEST prototype (1)

The reference scheme for the real-time control is shown in Figure 5-3. It operates as described in section 2 some more details are given below.

The MEST operation can start when the system is ready and enabled. After the enable signal and before the start signal, the real-time control shall assure that both the inductors (KC; LC) and capacitor (C) remain discharged.

After the receiving of the start signal, the charge of the KC coil, starts. The total energy to be stored in the KC coil can be calculated on the basis of the knowledge of the maximum current value desired in the load. From the calculation of the total energy, the reference current to be reached in KC can be derived. The calculated KC reference current is used as reference signal for the PS current control loop, as shown in Figure 5-3.

LC is charged via a closed loop control of the load current which generates a reference waveform for the capacitor bank voltage, which is in turn regulated via a hysteresis control. During the plasma pulse the two nested loops continue operating to assure the desired current waveform in the load. In this phase, the PS provides maintaining constant the total circuit energy; the required energy in KC can be calculated by subtracting to the total energy the energy stored in the LC and in the capacitor bank (in the application for DEMO it will be negligible but in this prototype it is not).

It is required that the MEST can also be operated in voltage control during the pulse, as shown in Figure 5-3; in that case, the reference voltage for the hysteresis control will be pre-programmed.

The Supplier can propose a different type of control for the MEST prototype, provided the compliance with the described performance and requirements reported in this section.

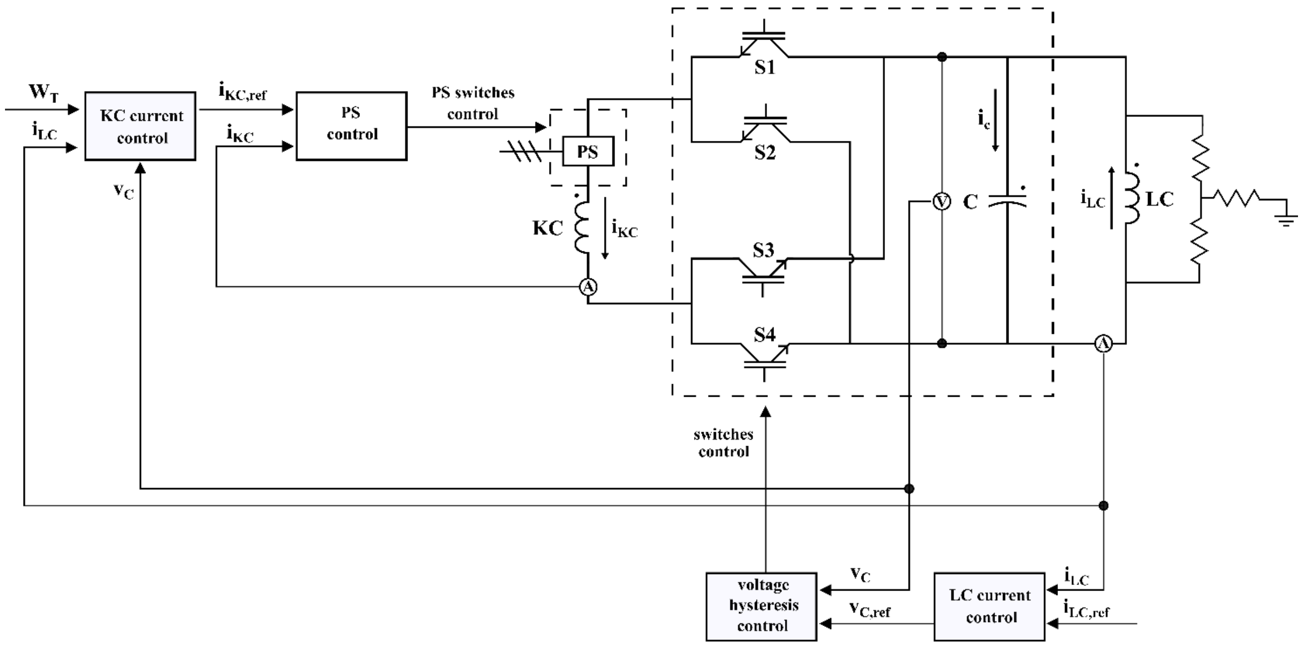

Figure 5-3 – Block scheme of the reference control of the MEST prototype (1)

PHASE 1 - MEST prototype (2)

The feedback control of the MEST prototype (2) requires all the functions above described for feedback control of the MEST prototype (1). The provisions for the current sharing between the two modules connected in parallel and voltage sharing between the two modules connected in series will be discussed and agreed during the design phase.

In addition to the requirements of Table 5-1, the control of the MEST prototype shall satisfy the requirements of Table 5-6.

Table 5-6 – Requirements for the real-time control of the MEST prototype

Description	Value
Range of operation of the voltage reference (1)	±100%
Latency(2) between the reference voltage variation and the variation of the output voltage	< 2 ms*
Maximum error between load current (averaged in the switching period) and reference current (3)	< ±4%

[1] With respect to the full scale of the reference (Table 5-9).

[2] The time interval between the variation of the reference of the capacitor voltage and the consequent modification of the state of the switches by the control.

[3] In steady state condition; it is referred to the full scale of the reference. Switching period will not be constant and means the time between two subsequent turn-on of the switches.

* the specified latency could be achieved allowing a limited number of commutations at a frequency higher than the maximum specified

5.3.4.3 Measurements

The measurements indicated in Table 5-7, shall be available; thus, the relevant transducers as shown in Figure 5-4 shall be provided. These measurements shall be in analog form (low impedance signals) and safely insulated from the power section. These measurements shall be used by the MEST control for both protection and regulation purposes. The bandwidth of these measurements shall be chosen in order to satisfy the functional requirements requested in this TS.

Phase 1 of the contract – MEST prototype (1)

Table 5-7 – measurements of the MEST prototype (1)

Description	Full scale	Precision *
Load current	-2 kA / 2 kA	< 2%
Load voltage	-2.4 kV / 2.4 kV	< 2%
Voltage across the capacitor bank	-2.4 kV / 2.4 kV	< 2%
Current in the capacitor bank	-2.8kA / 2.8 kA	< 2%
Sink coil current	0 / 2.8 kA	< 2%
PS voltage	-150 V / 150 V	< 2%
Current in each switch	0 / 2.8 kA	< 5%

* Referred to the full scale. It takes into account the entire measuring chain from the transducer to the analog output port.

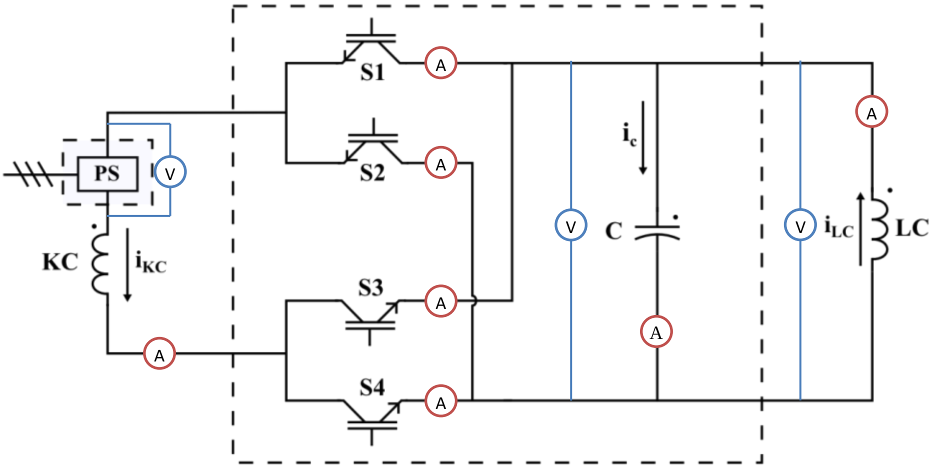

Figure 5-4 – Probes arrangement for the MEST prototype (1)

Phase 2 of the contract – MEST prototype (2)

In the second phase of the contract, the following additional measurements shall be provided

Table 5-8 – measurements of the MEST prototype (2)

Description	Full scale	Precision *
Load voltage	-4.8 kV / 4.8 kV	< 2%
Load current	-4 kA / 4 kA	< 2%
Voltage across the capacitor bank of the additional module	-2.4 kV / 2.4 kV	< 2%
Current in the capacitor bank of the additional module	-2.8 kA / 2.8 kA	< 2%
Input current in each module	-2.8 kA / 2.8 kA	< 2%
Output current in each module	-2 kA / 2 kA	< 2%
Current in each switch of the additional module	0 / 2.8 kA	< 5%
Sink coil current	0 / 5.6 kA	< 2%
PS voltage	-300 V / 300 V	< 2%

* see corresponding note in Table 5-7.

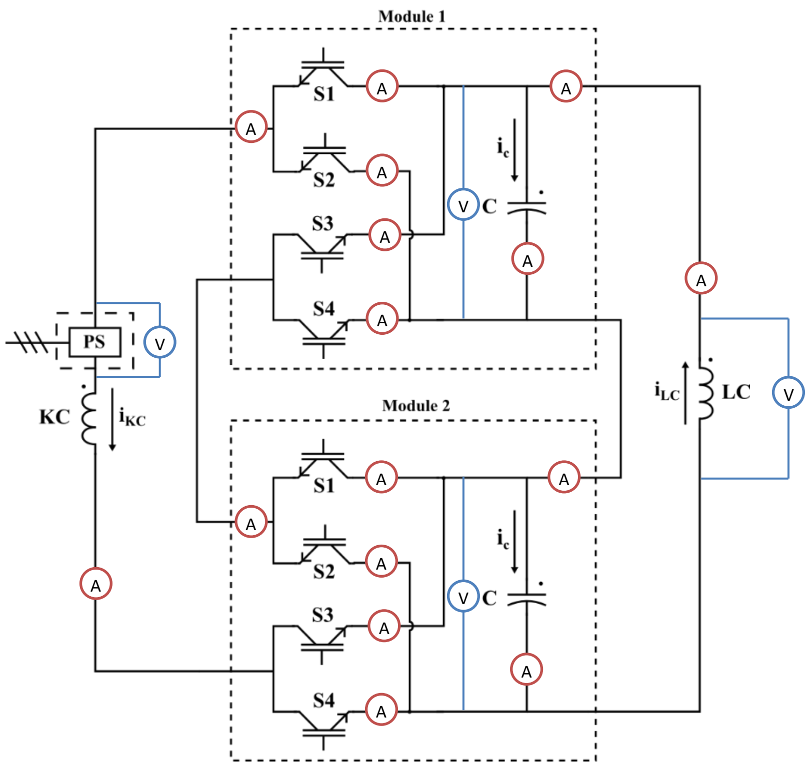

Figure 5-5 – Probes arrangement for the MEST prototype (2)

For the purpose of testing, trouble-shooting and commissioning, all the measurements of Table 5-7 and Table 5-8 shall be made available, as analog signals ±10 V, in a panel for the acquisition with scopes or by the remote control at CRFX. Some additional analog outputs shall be provided to address some internal key signals of the real–time control; the selection of the internal signals to be addressed to the analog outputs shall be made by the HMI.

5.3.4.4 Generation of internal references

The control section of the MEST prototype shall be able to generate internally the load reference current and the load reference voltage.

Moreover, it shall be possible to also receive the reference waveforms from an external generator, via the analog input ports, with the characteristics indicated in Table 5-9.

Table 5-9 – References at analog input port

Description	Type	Full scale
Load current reference	Fast, analog, ±10 V	-2 kA / 2 kA*
Voltage, reference	Fast, analog, ±10 V	-2 kV / 2 kV*

* the values refer to phase 1 of the contract, they will be doubled for phase 2

It shall be possible to choose from the HMI of the external PC via Ethernet link (with the software provided) at least among these types of references for the load current and the load voltage:

- square reference;
- trapezoidal waveform reference;
- arbitrary reference waveforms by setting at least ten points.

For each type of reference, it shall be possible to set from the external PC the relevant parameters, such as the amplitude, the frequency, the duty-cycle etc. The values of these parameters shall be bounded by the rated values of the MEST prototypes (Table 5-1): the MEST prototype shall safely operate within the specified ratings, for any allowed duration of the pulse. The MEST prototypes (1) and (2) shall also reproduce waveforms of current in the load like those shown in the Figure 5-6 and Figure 5-7. Figure 5-6 mimics the reference waveform of a DEMO CS circuit; it is derived from one of the DEMO reference scenario.

With a similar approach, examples of reference waveform are provided to mimic the operation of one DEMO PF circuits; they are shown in Figure 5-7.

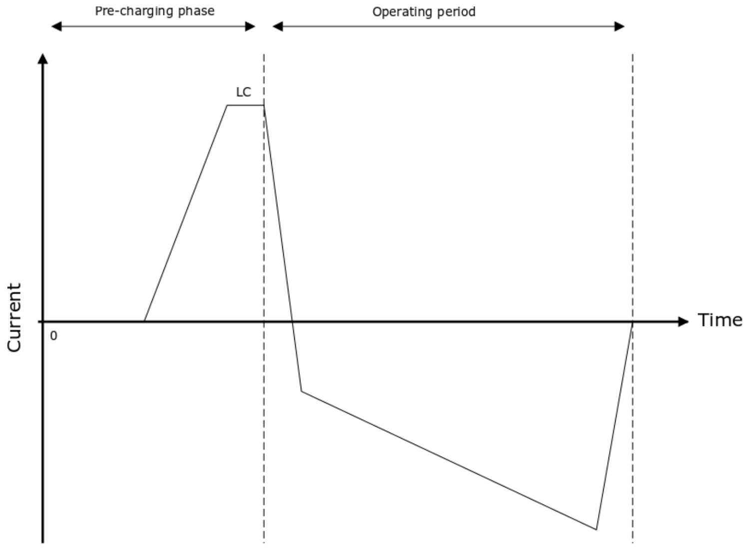

Figure 5-6 – reference waveform for the MEST prototype to mimic the operation of a DEMO CS circuit

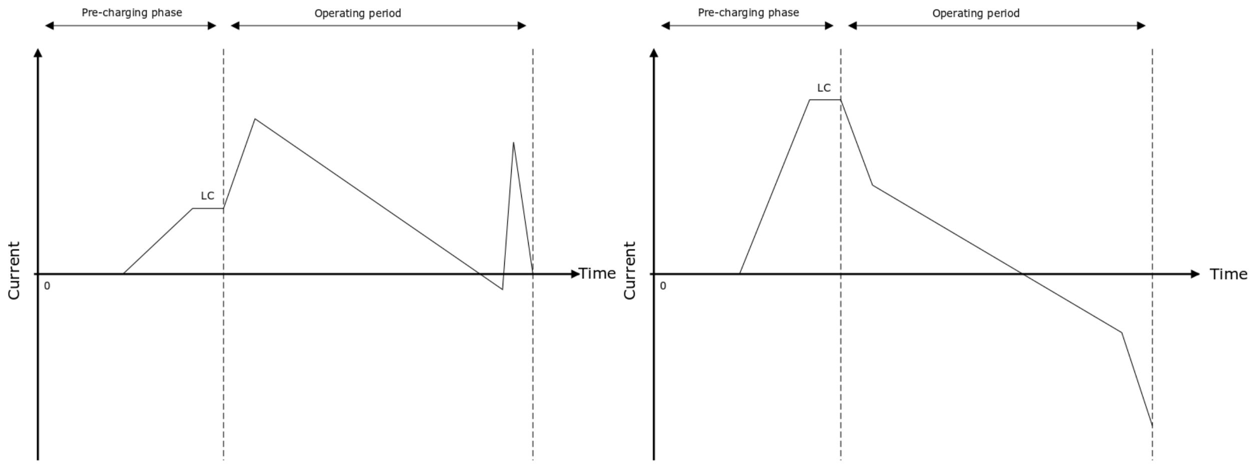

Figure 5-7 – reference waveforms for the MEST prototype to mimic the operation of DEMO PF circuits

It has to be pointed out that Figure 5-6 and Figure 5-7 are just typical waveforms, but the MEST prototype shall be able to reproduce on the load any arbitrary waveform, within the specified and acceptable operating space. The MEST prototype shall also be able to protect itself if the reference waveforms demand performance out of admissible operating space.

5.3.4.5 Human-Machine Interface

The HMI software to be installed on the external PC, to communicate with the MEST prototype control section via Ethernet link, is included in the contract. This software shall manage the control parameters, the list of alarms, the enable and reset signals, the start signal, the status of the MEST, the reference waveforms generation (5.3.4.4); further details will be agreed during the design phase

The software shall be sufficiently user-friendly, with adequate documentation.

The acquired measurements and the derived ones (like the total stored energy) shall be stored in the HMI after each pulse and made available as a csv file to be downloaded. Moreover, also key internal signals of the real-time control will be made available in the csv file; the precise list will be agreed during the design phase.

This software shall work under recent operative systems, preferably on recent versions of Microsoft Windows® or a GNU/Linux distribution. During the design phase, the Supplier shall indicate the minimum technical requirements for the PC.

5.3.4.6 Protection system

The protection system of the MEST prototype shall promptly detect the internal faults and anomalous conditions. As a consequence of these faults, it shall put in place all necessary protective actions, graded depending on the severity of the fault. The protection actions shall address, but not be limited to, the following faults:

- internal short-circuit or overvoltage;
- ground fault;
- misfiring of static components;
- overcurrents;
- KC current lower than LC current;
- thermal overload, I^2*t in KC and LC;
- overtemperature of components;
- feedback anomalous operation: feedback control loop not regulating the output voltage/current as desired (e.g. not following the reference signal);
- fault of the auxiliary voltage supply.

In general, the list of faults, the details of the fault detection and the protection actions shall be defined and agreed during the design. In any case, if applicable, the following general prescriptions shall be observed for protections:

- no single-device failure shall give rise to a dangerous situation;

- all protection circuits shall be implemented in a fail-safe manner.

On the HMI, with the software provided with the contract, it shall be possible to visualize the list of active alarms and the alarm history, with a sufficiently explicit description of each alarm, the origin and the time when it occurred. The first alarm which originated the others shall be clearly marked. It shall be possible to reset the alarms. The active alarms shall be latched until the reset signal is received from the HMI or a push-button is pressed.

The Supplier shall make an analysis of all the fault conditions and relevant protection actions during the design phase that shall be included in the design report.

5.4 General requirements

This Section provides general requirements which shall be fulfilled unless otherwise agreed between Contractor and Supplier.

5.4.1 Design and construction

The design and construction of the equipment shall conform to the best current engineering practice. All the components shall comply with the relevant IEC standards.

It is required to reserve the room for the installation of a 4U 19" rack, close to the control system, and the installation of a 220 V, 16 A plug.

5.4.2 Transmission and insulation of signals

The transmission of the signals between the MEST prototype live parts and the low voltage touchable devices (for example, devices connected to the analog or digital input ports, the external PC, instruments connected to the output measurement terminals) shall assure the insulation of the signals for human safety, as required by the applicable standards.

5.4.3 Cables and optical fibres

All power cables included in the contract (if any) shall be selected, sized and laid according to applicable IEC standards and shall be made of copper unless differently agreed with the Contractor.

Cable insulation shall be LSOHFR (Low Smoke Zero Halogen Fire Retardant). PVC should be avoided and may only be used, though not as a preferred solution, for low voltage wiring, after the written approval of the Contractor.

To reduce interference on control, protection and monitoring signals, twisted pair cables or shielded cables shall be used, if relevant. Analog signals shall be routed separately from digital signals, using different cables.

6 TESTING AND ACCEPTANCE REQUIREMENTS

6.1 General requirements

The provided equipment shall be subjected to inspection and test to prove the compliance with the Technical Specification at the Supplier's Facilities.

In this Section an outline of the tests to be performed and the relevant test conditions are described; the Supplier can propose modifications / integrations of the test outline and conditions which shall be agreed with the Contractor

The Supplier shall deliver the test procedures at least two weeks before the starting of the tests. The test procedures shall be approved by the Contractor.

The Contractor can witness all the tests at the Supplier's Facilities; the Contractor shall be informed about the relevant dates at least two weeks before their occurrence.

For each test a report shall be prepared by the Supplier.

Records, certificates and performance curves shall be supplied for all tests carried out, within one month from the respective tests, whether or not they have been witnessed by the Contractor.

The Supplier is responsible for the provision of all what will be necessary for the test execution, like for example the measuring and recording instrumentation and personnel. Measuring equipment shall be proven to be recently calibrated (since not more than two years).

Approval of any test by the Contractor does not relieve the Supplier from their obligation to meet the requirements of this TS.

Routine Tests of commercial components shall include all routine electrical, mechanical and hydraulic tests in accordance with the relevant IEC Standards. In particular, it is generally assumed that current/voltage transducers are routinely tested and calibrated as certified by the manufacturer, according to the relevant IEC Standards. If not, each transducer shall be subjected by the Supplier to tests to be agreed between the Supplier and Contractor aimed at demonstrating the calibration and the compliance of the transducer with the required performance specifications.

6.2 Acceptance Tests for the control section

6.2.1 Insulation Test

Insulation tests shall be performed on the control section as indicated in IEC 60439-1, section 8.2.2.

6.2.2 Functional Test

Unless otherwise agreed, the Functional Test shall be conducted at the normal test ambient temperature.

The Functional Test shall be performed on the control section and shall consist of a comprehensive series of measurements of the characteristics of the equipment to check that its performance is in accordance with the requirements of this specification and performs the operations for which it was designed.

The safe and correct operation of all protective functions and the generation of proper fault signals and alarm codes shall be checked.

No malfunction of the equipment shall occur as a result; the outputs of digital equipment shall be monitored throughout the test to ensure that no spurious operation occurs.

The communication with the external PC via Ethernet link shall be checked. The HMI operation shall be checked.

The proper working of the analog input reference port and of the analog output measurement ports shall be checked.

6.3 Acceptance Tests for the MEST prototype

The MEST prototype shall be tested according to the IEC 60146, where applicable.

Other components shall be tested according to the relevant IEC standards, where applicable. Different tests shall be agreed during the design phase and described in the procedures.

In particular, the power supply can be tested on the provided inductors (section 4).

6.3.1 Insulation Test

This test shall be carried out according to IEC 60146 on the supplied system.

Then, on the whole circuit, once completed the assembly, the nominal voltage shall be applied with respect to ground for 10 minutes.

6.3.2 Dynamic Tests

The MEST prototype circuit shall be assembled and connected as in the final configuration presented in the Design Report.

<u>Phase 1 of the contract</u>

The first part of all the dynamic tests described below will consists in charging the sink inductor by means of the power supply to the total circuit energy. Starting from this initial condition, the capability of the MEST prototype to control the load current shall be tested in voltage loop first by controlling the voltage across the capacitor bank with canonic waveforms to characterize its operation in these conditions. In particular, step voltage variation of the reference voltage from the minimum to the maximum values and viceversa shall be applied and it shall be verified the voltage control capability.

In voltage loop, the latency between the reference variation and the variation of the output voltage shall be measured; this test shall be repeated ten times. The measured value shall be always lower than the maximum latency specified in Table 5-6.

The capability of the MEST prototype to control the load current shall be tested in closed loop; i.e., a current reference will be given as input to the current loop which will generate the appropriate voltage reference across the capacitor bank. Again, canonic current waveforms will be given to characterize the MEST prototype operation in these conditions. The maximum error between the output current and the reference shall be checked and shall be compliant with Table 5-6.

The capability to reproduce the waveforms of Figure 5-6 will be verified in closed loop operation. A current reference like that one indicated in Figure 5-6 shall be generated and the MEST prototype shall reproduce it on the load with the precision indicated in Table 5-6. The tests shall be repeated tens of times setting similar waveforms but with different amplitude and di/dt values. The maximum error between the output current and the reference shall be checked and shall be compliant with Table 5-6.

The capability to reproduce the waveforms of Figure 5-7 will be verified in closed loop operation. A current reference like that one indicated in Figure 5-7 shall be generated and the MEST prototype shall reproduce it on the load with the precision indicated in Table 5-6. The tests shall be repeated at least ten times setting similar waveforms but with different amplitude and di/dt values. The maximum error between the output current and the reference shall be checked and shall be compliant with Table 5-6.

Phase 2 of the contract

The dynamic tests described for the phase 1 of the contract shall be repeated for the circuit realized during the phase 2, both for the configuration with the modules in series and for the configuration with the modules in parallel.

In the case of series configuration, the voltage sharing between the modules shall be measured and it shall be verified that it remain within the value determined by calculations and declared in the design report.

In the case of parallel configuration, the current sharing between the modules shall be measured and it shall be verified that it remain within the value determined by calculations and declared in the design report.

In case of configurations with direct connection of switches in series / parallel the voltage / current sharing between switches shall be measured and compared with that determined by calculations.

In all the tests, the repetition of the tests will be done according to the maximum operation duty foreseen and declared by the Supplier in the design report for the different current level.

In general, the MEST prototype shall prove to operate satisfactorily under all the specified test conditions, in line with this TS and the design calculations. No malfunction shall occur during the tests.

7 CODES AND STANDARDS

The Design, Manufacture and Testing of all equipment supplied shall be in accordance with the most recent issues of the relevant IEC Standards and Recommendations.

In particular the latest version in force of the following Standards and Recommendations shall apply:

IEC 60038 IEC standard voltages

IEC 60044 Current and voltage transformers

IEC 60146 Semiconductor convertors

IEC 60269 Low-voltage fuses

IEC 60300 Reliability and maintainability management

IEC 60332 Tests on electric and optical fibre cables under fire conditions

IEC 60439 Low-voltage switchgear and controlgear assemblies

IEC 60529 Degrees of protection provided by enclosures (IP Code)

IEC 60947 Low-voltage switchgear and controlgear

IEC 61010 Safety requirements for electrical equipment for measurement, control, and laboratory use

IEC 61071 Capacitors for power electronics

IEC 61140 Protection against electrical shock - Common aspects for installation and equipment

UNI EN ISO 5457 Technical drawings - Sizes and layout of drawing sheets

8 PACKING AND TRANSPORT REQUIREMENTS

If the Supplier will decide to utilize the components made available by CRFX, the Supplier shall be responsible for their transport from CRFX (Padova, Italy) to the Supplier premises and then back to CRFX.

After the completion of the factory tests, the prototype will be further tested at CRFX premises by CRFX personnel. The Supplier shall be responsible for the MEST prototype transportation from the Supplier premises to the CRFX premises.

Handling, packaging and transportation from / to CRFX of the components, have to be performed according to procedure insuring minimising the risk of damage to the components.

9 INSTALLATION

The Supplier shall provide for the assembly and installation of the prototype also at CRFX. Before the start of the installation, CRFX will make available the area where the MEST prototype will be installed, see paragraph 5.2.1.2 for reference.

10 DOCUMENTATION TO BE SUPPLIED

A final certificate of conformity of the prototype shall be issued.

The final documentation shall include all the documentation described below, corresponding to the as built configuration of the component and including all the revisions performed during the tests.

The documentation shall be provided in standard formats (Microsoft Word, Excel, pdf, Autocad) and shall be delivered both in electronic and one hard-copy version.

10.1 Technical documentation

10.1.1 First Design Report

The First Design Report shall demonstrate the full compliance with this Technical Specification.

The contents of the First Design Report shall include at least:

- a detailed design description of the power section and the selection of rating and type of the major components, including power switches, voltage and current transducers and passive components, their main data / data sheets (for standard components) and relevant tolerances; thermal design of the major power components;
- a detailed design description of the control section, with block diagrams showing the main functional blocks and the flow of the various signals, list of the main components used in the control, list and characteristics of signals exchanged through Ethernet link;
- analyses of the MEST prototype operation in anomalous condition; the Supplier shall provide a table of fault conditions, which lists the fault, detection, related protection (main and back-up), the related alarms and monitoring;
- the preliminary list of Factory Tests to be performed;
- a preliminary list of reference standards used for the design of the system.

10.1.2 Factory Test Plan, Procedures and Reports

The Supplier shall complete and update the list of Factory Tests included in the First Design Report at least two weeks before the execution of the respective tests. The Supplier shall provide a detailed description of the test procedures to be performed and the acceptance criteria for each test. The Supplier shall provide written records of all Factory and Acceptance Tests performed and relevant for the Contract. The Test Reports shall be provided no later than one month after the relevant tests have been performed. The Test Reports shall be added in the same document containing the test procedures that have to be updated according to the very final ones executed during the tests. The test results have to clearly reported, and the compliance with the requirements given in this Technical Specification clearly proved.

10.1.3 Certifications/specifications for components

For standard components the relevant certifications shall be provided where applicable.

For non-standard main power components the technical specification prepared for their procurement shall be provided.

10.1.4 Final Design Report

The Supplier shall issue a Final Design Report at completion of the contract, reviewing and updating all the information requested in the First Design Report and including detailed functional schemes.

10.1.5 Software for the external PC

The final version of the software to be installed on the external PC shall be provided. Sufficient documentation for the software shall be provided, to operate it easily without additional support.

10.1.6 Source code

The source code (sufficiently explained and preferably with high-level language) of any software used for FPGA, DSP, microprocessor, PLC or other programmable devices shall be provided within one month from the acceptance of the Supply, together with sufficient documentation. It is assumed that the relevant software tools for the programmable devices are available in the market; any deviation has to be agreed with the Contractor.

11 REFERENCES

[1] R. Piovan et al., “MEST: a new Magnetic Energy Storage and Transfer system for improving the power handling in fusion experiments", Fusion Engineering and Design, in press

[2] I. Spresian, Studies on a new Magnetic Energy Storage and Transfer system: application to the European DEMO Fusion Reactor, tesi di laurea magistrale, a.a. 2018 / 19, http://tesi.cab.unipd.it/62206/

[3] F Lunardon et al., The MEST, a new magnetic energy storage and transfer system: Application studies to the European DEMO, Fusion Engineering and Design 157, 111666