GSI Helmholtzzentrum für Schwerionenforschung GmbH

Document Title

Common Specification on Power Converters

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Abstract

The document describes Common Specifications for the Power Converters for the FAIR Accelerator Project.

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1. Purpose and classification of the document

This document describes the general technical requirements of all parts and components for power converters for the FAIR Project. Detailed technical information concerning the power converters of the different accelerators and beam lines is given in the dedicated detailed specifications. General legal and technical requirements which are valid for all technical systems of FAIR are described in the general specifications [1] and technical guidelines which are referred in this document.
However, statements given in this document override the statements given in the general specifications and the technical guidelines. Statements given in the detailed specifications override the statements given in this document.

2. Scope of the technical System

2.1. System Overview

Both, for transportation and focussing of the beam, magnetic fields are needed. These magnetic fields are generated by magnets which are distributed along the accelerators and beam lines. The required magnet currents will be controlled by power converters with common characteristics described in this document.

In FAIR, power converters are needed for different machines and operation modes:

Linear accelerator:	The new proton linear accelerator needs power converters for DC operation or pulsed operation.
Synchrotrons:	The synchrotrons SIS100 and SIS300 need ramped power converters with repetition frequencies up to 0.5 Hz.
Super Fragment Separator:	The SFRS needs DC power converters which must be able to operate in a slowly pulsed mode.
Storage rings:	There are the storage rings NESR, RESR, CR, HESR, which need basically DC power converters with ramping capability for special cases.
Beam Transport System:	There are beam lines with different magnetic rigidities:

13Tm, 18Tm, 90Tm, 300Tm. Operation modes of power converters can be DC, pulsed or fast pulsed.

2.2. Limits of the System

Not in the scope of this technical system are the power converters for the RF-systems, for injection and extraction kickers and for experiments. The ACU system (see chapter 7.3.1), which is integrated in every power converter, is described in this document but its specification is not in the scope of this document.

2.3. Basis of Concept

To allow an unrestricted accessibility and to increase the lifespan of the electrical components all power electronics and control electronics are placed outside hot radiated areas. Therefore the power converters are placed in dedicated supply buildings beside the accelerator tunnels.
For standardisation reasons it is mandatory for all power converters to use the ACU system and the digital DCCTs which will be provided by the Company (see chapter 7.3.1 and 7.4). All power converters described in this document are current regulated or field regulated systems.

3. Engineering Standards and Design Principles

3.1. Standards

The design and the construction of a power converter have to comply with the standards and principles given in the technical guideline “Electrical Design Rules and Regulations” [2] in chapter 1.1.

3.2. Safety

The safety requirements are described in chapter 1.2 of [2]

The language for all operating panels must be English (preferred) or German. Warning signs and other safety-critical notes must be both, in German and in English.

3.3. Design Principles

Beside the definitions in chapter 1.3 of [2], in chapter 7.5 of this document, further design principles for the main components and functionalities of a power converter are given.

4. Environmental Electrical Conditions

4.1. The 20kV AC Supply System

The FAIR facility has two main 20kV AC supply systems (Figure 1):

- The common supply system with three in normal operation independent 20kV three phase feeding lines C1, C2, C3.
- The pulsed power supply system with two in normal operation paralleled 20kV three phase feeding lines PP1 and PP2.

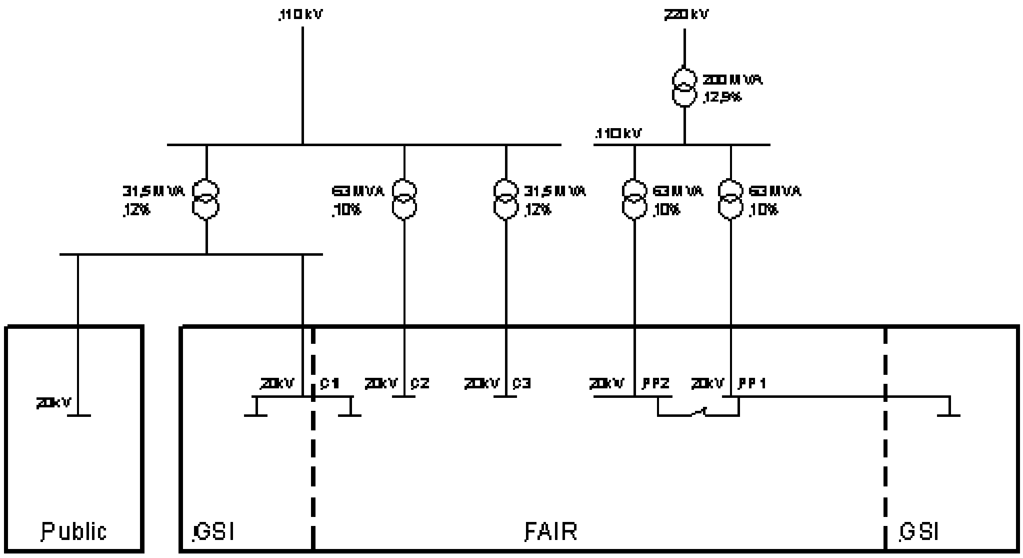


Figure 1 20kV AC supply system with feeding lines and feeding transformers

The 20kV feeding lines C1, C2, C3 are connected via 110kV/20kV transformers to the public 110kV-grid. While the feeding transformers of C2 and C3 are exclusively reserved for FAIR the feeding transformer of C1 also feeds GSI and a local public 20kV-grid.

The feeding lines PP1 and PP2 are exclusively reserved for FAIR and GSI. They are connected via two 110kV/20kV transformers and a common 220kV/110kV transformer to the public 220kV-grid. This feeding system is exclusively reserved for FAIR and GSI.

4.1.1. Characteristics of the electrical 20kV supply systems

The characteristics of the 20kV supply systems C1...C3, PP1 and PP2 are given in [2] in chapter 2.2.1.

4.1.2. Characteristics of the 400V AC supply system (common/pulsed)

There are 400V low voltage distributions for the common supply systems C1, C2 and C3 and the pulsed power supply system PP1/PP2. Their main characteristics are defined by the feeding 20kV systems. Common to all of them are the characteristics given below:

- line voltage : 400V
- System : TN-S (three phases + neutral + PE)
- 20kV/400V-transformer : rated power as given below
- Short time over voltage : 1.5kV_{rms}, phase to phase or phase to ground
- Transient voltage surge : 2.5kV_{peak}

The 400V secondary star mid-point of the transformer is earthed at the low voltage distribution and the neutral is directly distributed to the loads. Thus, the neutral **must not** be earthed at any other point.
Depending on the connected loads there are three power ratings for the low voltage distributions:

Power Rating	**1 MVA**	**2 MVA**	**4 MVA**
Transformer (20kV/400kV)	1 MVA	2 MVA	2 x 2 MVA parallel
u_k	6%	6%	6% // 6%
short circuit capacity	< 17 MVA	< 33 MVA	< 67 MVA

Table 4.1.2.1 Data of low voltage distribution

Note: With the 4 MVA configuration, the maximum shortcut current of most standard industrial switch gear components of 50 kA may be exceeded (total system impedance is to be considered).

5. Other Environmental Conditions

5.1. Cooling Arrangements

5.1.1. Ambient conditions

The following conditions must be considered:

- altitude :< 200m
- temperature variation for interim storage : -25°C to +50°C
- temperature variation to consider for the design of the converter : +10°C to +40°C
- temperature variation for power transformers located in transformer boxes : +5°C to +40°C
- ambient temperature for operation of the converter : +18°C to +28°C
- relative humidity : max. 80%

5.1.2. Water cooling

Water cooling is mandatory for cooling electronic power components (IGBTs, thyristors, power diodes, power transistors, see also chapter 6.2) taking advantage of the demineralised water system available as described in the technical guideline “Supply with cooled water” [3]:

- Max. operating pressure : 13 bar
- Peak pressure : 15 bar
- Inlet temperature : 25°C ± 2°C
- Difference pressure : 10 bar
- Max allowed outlet temperature : 55°C
- Conductivity : < 1 µS/cm

The materials in the cooling circuit shall be compatible with the use of demineralised water. Any material other than stainless steel and copper must be identified in the design report and need formal acceptance of the Company.

5.2. Locations of Power Converters

All power converters are foreseen for indoor installation. The cabinets of the power converters will be placed on a metal base structure which is part of the false floor of the converter hall or converter room.

5.2.1. False floor

- The false floor has typically a height of 0.5 m
- A local peak load of 5000N and a distributed load of 30000N/m² can be carried.

5.2.2. Separate installation rooms

There are separate rooms for the 20kV transformers or other components like SCRs and inductors of converters of high power. The rooms are located close to the converter hall or converter room. All components in the separate rooms for transformers and power parts are placed on the metal structure of a false floor.

6. Interactions of Power Converters with the Environment

6.1. Electrical Power

6.1.1. Interactions of power converters with the supply systems C1, C2, C3, PP1 and PP2

The allowed interactions of the power converters with the above referred supply systems are given in chapter 3.1 of [2]

6.1.2. Electromagnetic Compatibility EMC

Every power converter has to fulfil the levels given in the following EMC standards:

- IEC 61000-2-4 (Environment – Compatibility levels in industrial plants for low frequency conducted disturbances)
- IEC 61000-6-4 (Generic Standards, Emission standard for industrial environments)

- EN 55011 Class A / Group 1 (Industrial, scientific and medical radio frequency equipment. Electromagnetic disturbance characteristics. Limits and methods of measurement).

Therefore the following measurements are defined (refer to IEC 61000-6-4):
- Voltage measurement at maximum DC load current with voltage probe in the frequency range of 150kHz to 30MHz in steps of 10kHz interval:
  - All AC power terminals to ground
  - Both output terminals (to the load) to ground.

6.2. Power Dissipation

6.2.1. Power Dissipation (Air Cooling)

Components like power electronics with a total power dissipation during operation <200W are allowed to be air cooled. Also transformers, inductors, capacitors and control electronics are allowed to be air cooled. For electronic units assembled in 19” racks, maximum power dissipation to air of 1.5 kW is allowed.
The power dissipation to air has to be calculated and documented.

6.2.2. Power Dissipation (Water Cooling)

Water cooling is mandatory for cooling of electronic power components (IGBTs, thyristors, power diodes, power transistors) having a power dissipation during operation >200W as well as electronic units assembled in 19” racks dissipating more than 1.5 kW.

Additionally the following terms apply:

- The maximum allowable outlet temperature is 55°C.
- Power dissipation to water has to be calculated and documented.
- Water flow q in l/minute has to be documented.
- Provisions must be taken to control the water flow according to the requirements of the electrical load (Flow-meters, control valves).
- To indicate insufficient flow of water an indication (flow switch) must be installed to create an interlock and alarms.
- The difference pressure required must be specified in the design report.

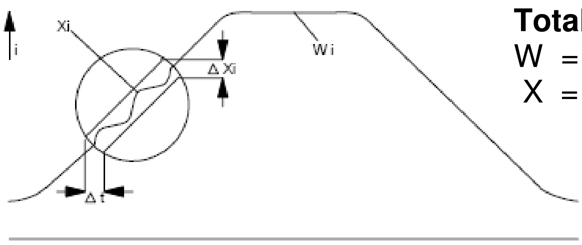
7. General Descriptions of Power Converters

7.1. Definitions

7.1.1. Total Deviation

A performance criterion for power converter is the "total deviation". The total deviation is a measure for the difference of the actual value (x_i) of the controlled quantity to an ideal set value (w_i). It summarizes data for

- ripple
- accuracy
- stability.



Total deviation
W = set value
X = actual value

Figure 2 Definition of total deviation

For power converters powering magnets the controlled quantity is the magnet current (in special cases the magnetic field), and the total deviation is given to **ΔI**. Commonly the total deviation is given as a per unit value. In the technical part of the specification of the power converters for

- converters with one current polarity and defined minimum current there is the per unit total deviation defined as **$\delta 1I = \Delta I / I$**,
  with I being the actual current,
- converters with bipolar currents there is the per unit total deviation defined as **$\delta 2I = \Delta I / I_N$**,
  with I_N being the nominal current (rated current).

The δI-criterion must be fulfilled for

- Ramped power converters at any time of a machine cycle
- Pulsed power converters in flattop after a given delay time to the start signal.
- DC power converters at any time of normal operation

In case of field regulation the definitions above apply to the magnetic field.
In special cases variations of these terms are given in the relevant technical specification.

7.1.2. Resolution of the Set Value

If not stated otherwise in the detailed specifications the requested resolution is given by the total deviation

$\delta 2I$ or by $\delta 1I \times I_{min} / I_{max}$

depending on the converter topology as described in chapter 7.1.1.

7.1.3. Modes of operation

There are three basic modes of operation.

Type A : Ramping mode

The actual value of the magnet current has to follow the set value at any time of the machine cycle without exceeding the given limits of the total deviation. In Figure 3 the definitions for operation mode A are shown.

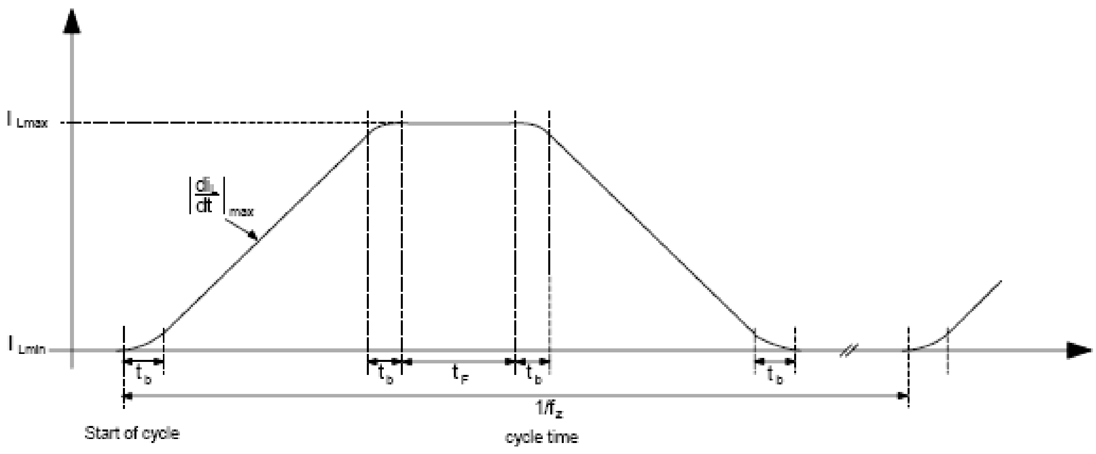


Figure 3 Definitions for operation mode type A

I_{Lmax}	maximum of the magnet current
I_{Lmin}	minimum of the magnet current
t_b	bending time
t_F	time during flattop
f_Z	cycle frequency

Type B : Pulsed mode

The actual value of the magnet current has to correspond with the set value only during flattop time without exceeding the given limits of the total deviation.
In Figure 4 the definitions for operation mode B are shown.

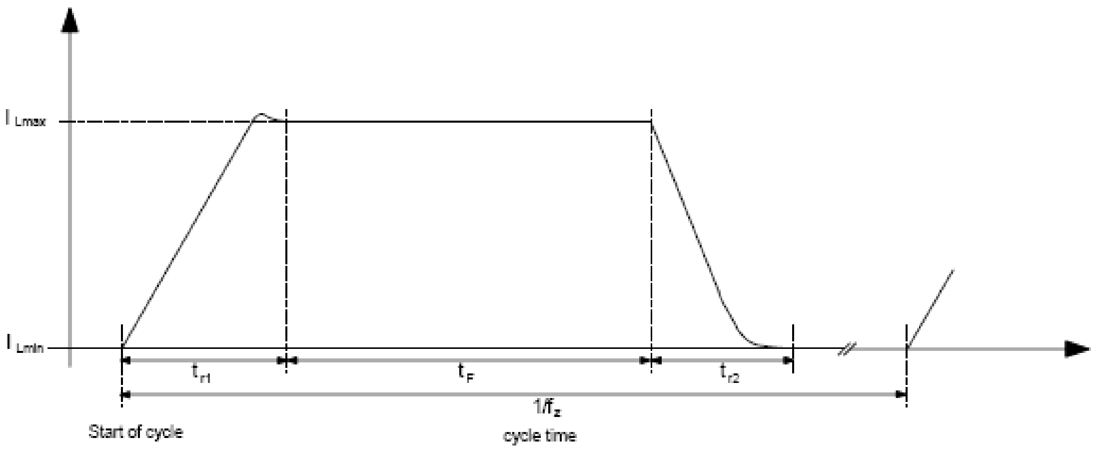


Figure 4 Definitions for operation mode type A

I_{Lmax}	maximum of the magnet current
I_{Lmin}	minimum of the magnet current
t_{r1}	rise time
t_{r2}	fall time
t_F	time during flattop
f_Z	cycle frequency

Type C : DC mode

The actual value of the magnet current has to correspond with the set value during flattop time without exceeding the given limits of the total deviation. Flattop time can be weeks.

7.2. Voltage ripples

The voltage ripple due to normal pulse modulated operation excluding the high frequency transients at the output of the power converter (ΔU in Figure 5) has to be

- smaller than 1% of the full scale value of the output voltage,
- however its value has not to be forced smaller than 1V, if the total deviation as defined in chapter 7.1.1 is not violated.

These values are also valid for the voltage ripple to ground.

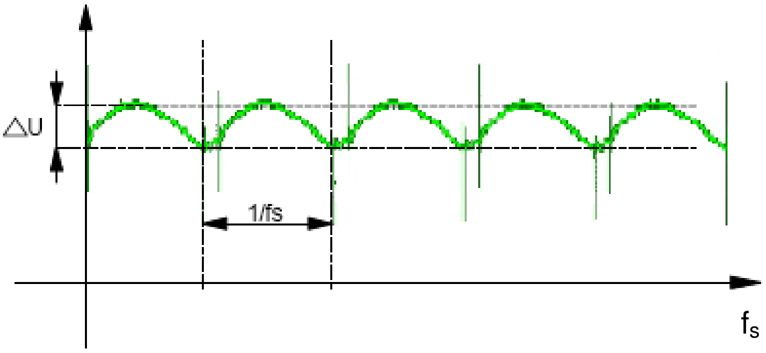


Figure 5 Voltage Ripple

The high frequency transients are determined by the levels defined in the EMC Standards EN 61000-6-4 (Generic Standards, Emission standard for industrial environments) and EN 55011 Class A / Group 1 (Industrial, scientific and medical radio frequency equipment. Electromagnetic disturbance characteristics. Limits and methods of measurement)
(see also chapter 6.1.2).

7.3. Converter Control

7.3.1. Adaptive Control Unit (ACU)

Because of standardisation it was decided that the ACU system has to be used in every power converter of the FAIR project. The Company will provide the components of the ACU system, and the manufacturer of the power converter has to integrate these components.
The ACU system is a modular digital control system for power converters. Figure 6 give a brief overview on the system and its application in a power converter.

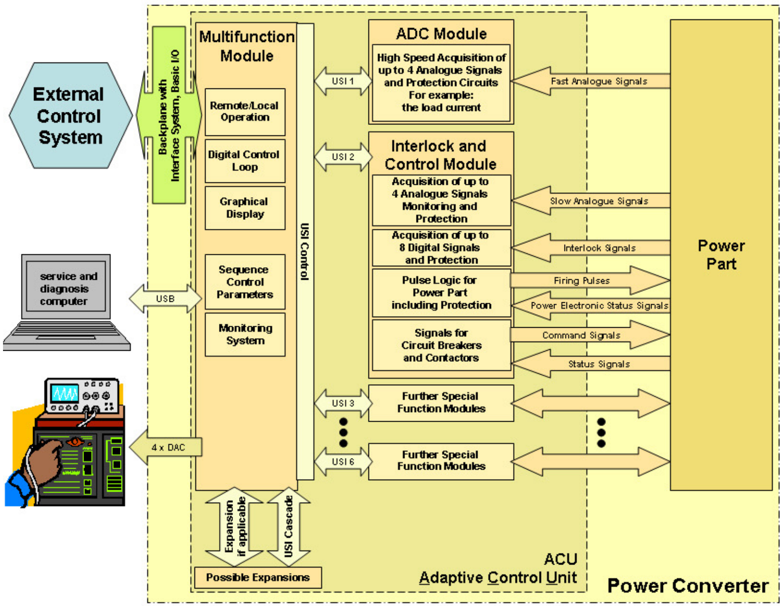


Figure 6 The use of the ACU system in a power converter

The ACU system consists of a set of electronic modules. There are three basic units:

- The multifunctional module (MFU) which contains the digital control algorithms, the link to the external control system of FAIR and the user interface for manual operation and measurement purposes.
- The Interlock and Control module contains the PWM (pulse width modulation) which produces the firing pulses for the power part. Additionally it handles status and interlock signals and slow analogue signals for protection purposes.
- Further the ADC module for a high speed acquisition of analogue signals, for example the actual magnet current.

The modules of the ACU system communicate by a serial protocol, the universal serial interface (USI). In the communication scheme the MFU acts as a master which can supply up to 10 chains of modules from its USI-ports. Each chain can consist of up to 8 cascaded modules. The maximal number of modules which can be cascaded at one USI-port depends of the module bandwidth. The USI hardware provides also a galvanic isolation of the connected modules.
The main performance data of the USI protocol is listed below:

- max. bandwidth 20 MBaud/USI
- Full duplex operating
- Transmission medium: standard network cable

- RS485 interface standard
- ASCII based protocol

Except for the Interlock and control module which will be placed close to the power part of the power converter all parts of the ACU system will be mounted inside a 19'' frame which is shown in Figure 7. This frame will be equipped with the following parts:

- Backplane 1
- Backplane 2
- Power Supply Module 1
- Power Supply Module 2
- Multifunction Module (MFU)
- First ADC Module for actual value (e.g. current signal)
- Second ADC Module for actual value (e.g. field value or voltage signal, if needed)
- DCCT Card (if needed/required)

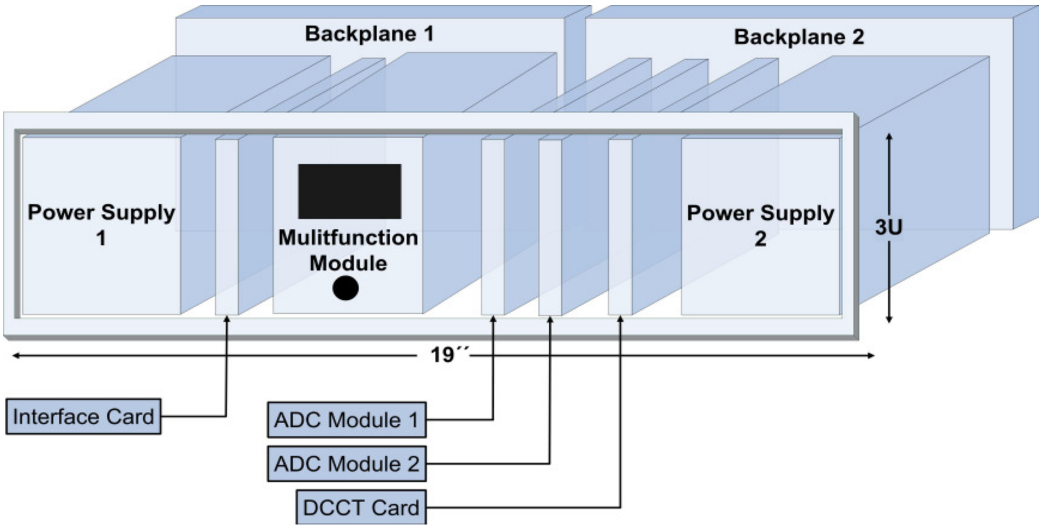


Figure 7 19'' frame of the ACU system

In addition to the delivered hardware modules the firmware will be provided to run the modules, and also the software for parameterization will be available.

The internal PWM of the Interlock and Control module supports the following hard switching topologies:

- 1 quadrant (chopper)
- 2 quadrant (half bridge)
- 4 quadrant (full bridge).

Each of the given topologies can have one DC-link[1] or a low voltage DC-link for flat-top operation and a high voltage DC-link for pulsed operation. Figure 8 shows the typical set up of the ACU system inside a switch mode power converter.

12 pulse SCR converters with parallel active filter will be supported by the ACU system, too.

There will also be the possibility to supply up to four power converters of low power and little requirements for accuracy with one MFU. In this case the MFU contains no control loops but provides the digital set value of the magnet current. In this set up the Interlock and Control module will be replaced by a DAC/ADC control unit, and the power converter control will be analogue. Figure 9 shows the according scheme.

If one contractor wants to use other power converter topologies as stated above there will be no support from the existing ACU system. However, there will be the possibility to use the hardware components of the ACU system with a contractor specific firmware or contractor specific hardware modules connected via the USI interface. Therefore the contractor will have full access to the detailed ACU documentation with training support by the Company.
Nevertheless, the contractor is responsible for the functionality of the power converter including the ACU system, its integration into the power converter and its parameterisation.

In any case the MFU has to be used in every power converter.

[1] Every DC-link is supplied by a 50Hz transformer and a diode rectifier.

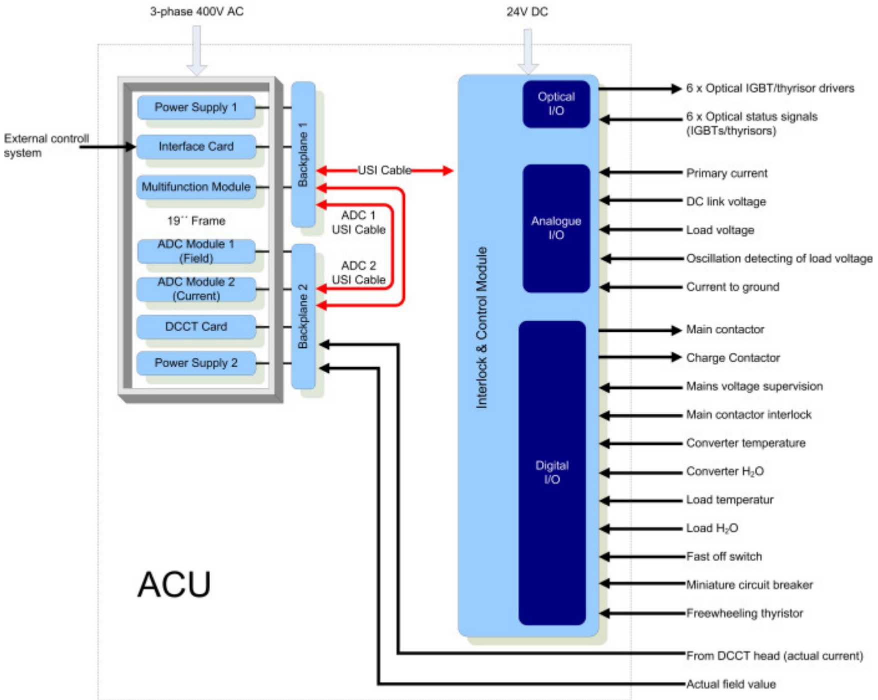


Figure 8 Typical application of the ACU system inside a power converter

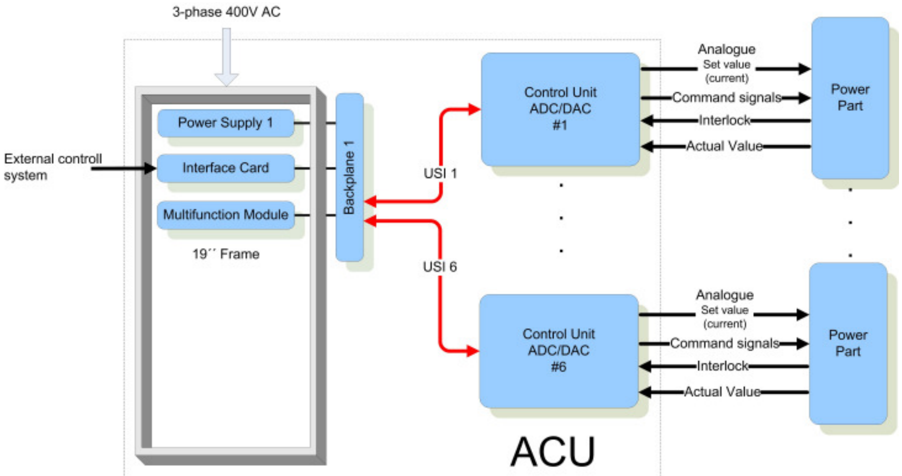


Figure 9 One Multifunction Module can supply up to six power converters with analogue current regulation.

Detailed information on the ACU system is given in [4] and [5].

7.3.2. Control circuits and set values

The ACU provides two independent control loops with proportional and double integral characteristics. These control loops can be cascaded. Therefore a current loop with a subordinate voltage control loop is possible. The used control algorithms are based on analogue control strategies enhanced by the possibilities of digital signal processing like limiters and the adaption of control parameters.

The FAIR control system will provide one or two set values:

- set value for the load current. This value is mandatory.
- set value for the load voltage. This value will be provided if technically needed.

The signal of the current set value will have time segments (bending time) which are described by 2rd or 3rd order polynomials. Hence the first and second derivation of the 3rd order polynomial will have no discontinuities.
The set value for the load voltage can be used directly for the voltage control (if needed) or as a feed forward signal as a part of the control voltage (if needed). The ACU system can internally calculate an additional control voltage from the set value of the load voltage. It considers a damped LC-filter and the load parameters. This signal can also be used as a feed forward as an additional part of the control voltage.

7.3.3. Control panel

On the front panel of the Multifunction Module (MFU) there are a Local/Remote Mode selection switch and three buttons for ON / OFF / RESET. The manufacturer of the power converter has to provide a Fast Shut Down Button (on the outside of the front door) which acts independent from software.

On the Power converter control panel, above the ACU frame, indication instruments have to be provided for:

- 400V supply voltage of the electronics frame U_{L1-L2} (moving-vane instrument, app. 50mm x 50mm)
- 400V supply voltage of the power part (moving-vane instrument, app. 50mm x 50mm)
- secondary transformer voltage in case of 20kV supply (moving-vane instrument, app. 50mm x 50mm)
- Voltage selector switch for 400V supply voltage or secondary transformer voltage of power part

- DC link voltage (if available) (moving-coil instrument, app. 50mm x 50mm)
- load voltage (moving-coil instrument, app. 50mm x 50mm)
- primary current (moving-vane instrument, app. 50mm x 50mm)
- secondary current in case of 20kV supply (moving-vane instrument, app. 50mm x 50mm)

On the front panel of the MFU there is an incremental encoder to apply set values for DC currents. There are also available four to case isolated DAC output terminals (LEMO connectors) showing the current measurement (±10V), for example. The graphical TFT-display shows the magnet current and status and fault messages, such as

- Local, Remote
- ON, OFF
- internal and external interlocks.

7.3.4. Installation of ACU system

The connection of the ACU to the electrical supply system must be independent from the power part of the power converter (see chapter 7.5.12). A three phase disconnector (miniature circuit breaker, manually operated switch...) is mandatory.
All cables which connect the Interlock and Control module with the power part have to be shielded. The cable shielding has to be grounded very close to the Interlock and Control module on a metal mounting plate. The Interlock and Control module has to be mounted easy accessible inside the power converter.
For further information see [5].

7.3.5. Interface to the control system of FAIR

The Interface to the control system of FAIR is part of the ACU system and will be not treated by the manufacturer of the power converter.

7.4. Digital DCCT

Because of standardisation it was decided that digital DCCTs have to be used in every power converter of the FAIR project. The Company will provide the components of the DCCT and the manufacturer of the power converter has to integrate these components.

For power converters with a resolution up to 16 bit a classical analogue DCCT system together with an ADC card mentioned in 7.3.1 can be used.
Power converters which have a demand for 18 or 20 bits will use a DCCT with a direct digital output. The electronics of these DCCT will be situated in a temperature controlled rack close to the power converter. The rack will be provided by the company.

7.5. Design Principles

Beside the definitions in chapter 1.3 of [2], further design principles for the main components and functionalities of a power converter are given in this chapter.

7.5.1. Over-Voltage and Voltage transients on the feeding line

- The power part and its components must withstand or must be protected against over-voltage and voltage transients as listed in chapter 2.3 of [2].

7.5.2. Inrush current at turning on

- The inrush current has to be as small as possible, taking into account that the charging time of the DC-link capacitor has to be smaller than 8s.The inrush current should never exceed the rated input current of the power converter.

7.5.3. Choice of voltage level in the power part

- At worst specified load conditions the power converter has to fulfil the criteria of total deviation 7.1.1 taking into account
  - 10% under-voltage of the supply system
  - a spare of 5% in the control signal.

7.5.4. Transformers and inductors

- All transformers and inductors are of dry type to be built for indoor installation. Oil insulated transformers are not allowed to be installed.
- Transformers and inductors > 1 kVA shall have **isolation class F**, **but** temperature sensors must provide an interlock in case of **T > 120°C**.
- The test voltage for transformers and inductors with rated voltages below 1000V is at least 2.5 kV.
- If there is a number n ≥ 2 of power converters of the same rating and the same type, then halve of the converters must be equipped with input

transformers which are phase shifted by 30° in respect to the transformers of the second halve of the converters. Two power converters with phase shifted transformers connected to the same distribution bus bar behave like a 12-pulse load to the supply system.

- Transformers and inductors have to be designed for a permanent load of 110% of nominal current I_n (I_n at nominal supply voltage U_n).
- All transformers must have an electrical shield between primary and secondary winding, with the shield connected by a low impedance to ground.

7.5.5. Filter capacitors (DC-link)

- The rated voltage of a capacitor has to be 1.1....1.25 times the value of the maximum DC-link voltage U_{max} at over voltage of the supply system.
- The lifetime of a capacitor must be greater than 100.000 h. This has to be achieved by the correct selection of the pulsed current in one single capacitor.
- Forced air cooling for capacitors must be avoided.
- The DC-link capacitor bank shall be discharged to a voltage less than 50V in less than 30 seconds after normal turn off, Fast-Shutdown or actuating the door-switch.
- The DC-link capacitor bank and its conductors to switching elements have to be constructed for low impedance to avoid excessive transient voltage spikes at semiconductors and to avoid additional EMI as well as an unbalance of pulsed current in different capacitors of the bank. Hence instead of wires and copper bars for building the bank, copper plates are preferred.

7.5.6. Semiconductors

- The rated voltage of a semiconductor must be more than c_D times the maximum voltage $U_{Devicemax}$ which can stress the device. $U_{Devicemax}$ is known by calculation or by measurements or given by voltage limiting measures like active clamping or other snubber circuits.
  c_D = 1.5 for IGBTs
  c_D = 2.3 for thyristors and diodes
- All semiconductors have to be designed for a permanent load current of 110% of the nominal load current I_n .
- The current in a single device must not exceed 80% of its rated current values (data sheet of device).
- The junction temperature must be smaller than 90% of the maximum allowed junction temperature (data sheet of device).

- All semiconductors with losses more than 200W have to be water cooled.
- Over temperature of the heat sink of semiconductors must cause an interlock. The location of the temperature sensor must be correctly chosen.

7.5.7. Cabinet properties

- The standard size of one cabinet is:
  Width = 0.8m...1.2m
  Depth = 0.8m
  Height = 2.2m
- All electrical connections and water connections are bottom up (Except the interconnecting power cabling of components of a large power converter. In dedicated rooms it is allowed to come top down if losses are reduced).
- Warm air has to be let out at the top of the cabinet; therefore the roof of the cabinet has to be lifted up. Air outlets at the side of the cabinet are not allowed.
- If fans for the power part are necessary, it is preferred to mount them on top of the cabinet.
- All necessary fans and air filters must be easily exchangeable.
- All cabinets and housings for power electronics have to be designed for a protection degree of IP22 (exceeds [2]).
- The access to the front panel must be possible without opening the front door. Therefore the 19'' frame of the ACU system has to be integrated in the front door.
- All cabinets have front and back doors and are interlocked by door switches except the front door with the control panel of the ACU system.
- The front door with the control panel of the ACU system must have a *fast shut down* button (chapter 1.2 of [2]).
- The doors have to be equipped with door locks for double-bit keys.
- The noise level of any cabinet or rack must not exceed 60 dBA at any point 1 meter away from it.
- The converters should be vibrations free. If any, it must be eliminated or damped.
- Cabinets must be constructed for transportation by a hand pallet truck (without using pallets). The access for the hand pallet truck must be possible from each side of the cabinet.
- Cabinet colour shall be RAL 7032 (stove enamel).

7.5.8. Mechanical layout

The mechanical layout depends on the size of the power converter. There are four different layouts:

- **Small power converters**
  Several small power converters can be installed into one standard size cabinet (0.8m x 0.8m x 2.2m).
  There is one electric input for the power parts, one electric input for control electronics and one input for water cooling common to all converters within the cabinet. The distribution of electric power and water within the cabinet belongs to the power converter design and must allow for individual maintenance of the converters. Parts have to be quickly exchangeable.

- **Medium power converters**:
  The power converter consists of one or several adjacent standard size cabinets (0.8…1.2m x 0.8m x 2.2m).

- **Large power converters**
  The transformers of large power converters, which operate directly at the 20kV supply system, are located in separate transformer rooms close to the converter hall (it is possible to place transformers of two large power converters in one transformer room). Usually all other components (inductors, SCRs, IGBTs, capacitors) are mounted in standard size cabinets (0.8..1.2m x 0.8..1m x 2.0..2.2m) in the converter hall. In one front door of these cabinets space has to be foreseen to integrate the ACU frame.
  All interconnecting cabling is part of the power converter.

- **Large power converters in distributed systems**
  This power converter system consists of several power converter groups, which are electrically interconnected but may be localized in different buildings and operate directly at the 20 kV supply system.
  In every relevant building the transformers and the power parts (inductors, SCRs, DC circuit breakers…) are placed in separate dedicated rooms close to the converter hall. There the standard size cabinets (0.8m x 0.8m x 2.2m) are located, which are housing the ACU system and, for example, an active filter. However, there is only one ACU system for the distributed converter system. All interconnecting cabling within one building is part of the installation of the power converter.
  The additional signal cabling between different buildings is part of the converter design. Cable lists have to be given to the Company to install the cables. However, connecting the cables is part of the installation of the converter system.

Independent from the individual layout it has to be guaranteed that all components have to be easy accessible and easy to exchange in case of a fault. Every power converter must have a type plate showing the following information:

- Type-name
- Serial number
- Effective apparent power
- Fuse rating of power input (fuse is located in low voltage distribution)
- Max. output current
- Max. output voltage
- Max. water flow and differential pressure
- Manufacturer and year of construction.

7.5.9. Cooling arrangements

- All water circuits in a converter are limited to a maximum flow rate of 16 l/min. If a higher amount of water is needed an additional water circuit has to be implemented. Each of the water circuits of medium and large power converters has its own water inlet and water outlet (stainless steel, ¾”).
- Each of these water circuits has to have a flow meter with an electrical output to monitor the water flow. The flow meter has to be mounted at the outlet, the electrical output pulses of the flow meter will be handled by the ACU system which give an interlock in case of lack of water.
  The electrical output of the flow meter is a pulse train, and the pulse rate in pulses per second is linearly depended on the flow rate in l/min.
- The water circuits inside a power converter have to be equipped with a valve to exhaust the air during the filling procedures. This valve has to be mounted at the highest point of the water circuit. The design of the water cooling system of the power converter has to avoid trapped air.
- Cooling air for air cooled components can be guided from the bottom of the cabinet to the top. Cooling air for high precision control electronics is sucked in through an inlet in the front door and specially guided to avoid mixing with already heated air.

7.5.10. Interlocks

As described in 7.6 a power converter has to be self-protecting. Therefore it must be designed to handle the minimum set of internal and external faults as listed below. The interlocks are displayed by the ACU system.

However, there is no special demand for internal interlocks of small power converters (see 7.5.12). It is sufficient that such a power converter gives one status signal for internal faults to the ACU system.

The interlock list for medium and large power converters is:

- Load over-current
- DC Filter capacitor over-voltage (for converters with energy recovery)
- Coils over-temperature of transformers and inductors
- Semiconductors heat sink over-temperature
- Primary over-current
- Earth fault
- Fuse fault
- Driver fault
- Water fault, power converter
- Fast Shut Down button
- Doors open (when open, the door switch can be manually set to a closed position)
- AC Phase fault
- Oscillation of the output voltage
- Fan fault
- Quench protection (In case of super conducting magnets).

Beside the internal interlocks listed before, the following external interlocks will be handled and displayed by the ACU System:

- Load over-temperature
- Load water fault.

In case of super conducting magnets

- Fault cryogenic supply
- Quench

Any of these interlocks shall force the converter to the FAULT state. The manufacturer may add to this list any safety interlock that is considered as necessary. Further information will be given in the detailed specifications.

As already defined by the external interlocks, the power converter has to protect the load.
Each normal conducting magnet will have an interlock for water flow and for temperature. As the ACU is designed to control also the water flow rate of the

magnet, a 10 pin plug (type to be defined by the Company at contract) has to be built into the power converter cabinet.
The wiring is described in chapter 5.3.5 of [10].

In the case of super conducting magnets no water flow control is needed. To protect the magnet, the power converter receives a single optical signal of the external quench detection system.

7.5.11. Beam interlock system

In [6] two different versions of a beam interlock system are described.
The manufacturer of a power converter has to provide all needed relays and connectors to realize the version defined in the detailed specification of the power converter. The functionality will be handled by the ACU system.

Version A:
In most cases version A (see Figure 10) will be used, which indicates the status of the power converter to the control system.
The Interlock and Control module controls a relay with a 24V signal, which will be switched to 0 V in case of an interlock. At 0V the contacts of the relay are open.
Additionally an auxiliary contact of the main-contactor is connected in series with the relay contact. The auxiliary contact is open, when the main-contactor is off.
The principle wiring is shown in Figure 10.

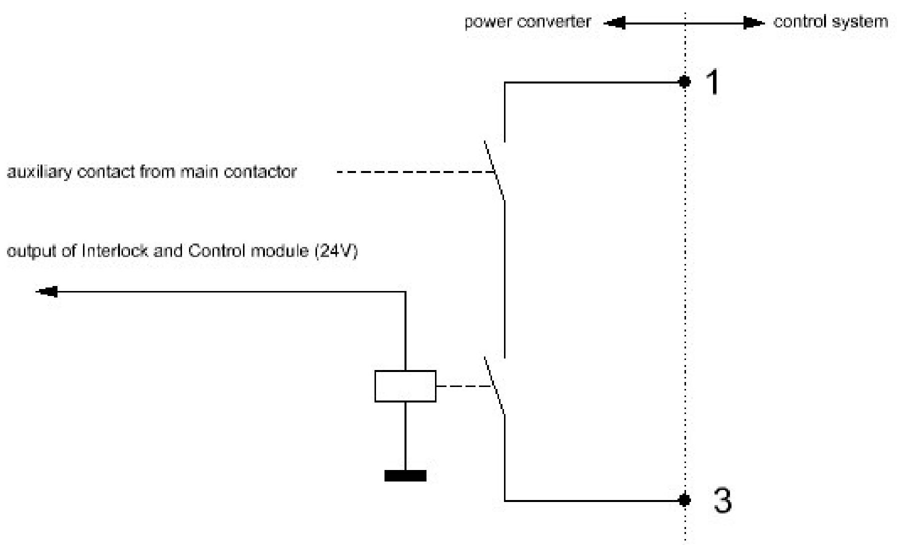


Figure 10 Beam Interlock System Version A

Version B:
For some dipole power converters version B will be used (see Figure 11). As in version A the status of the power converter is indicated to the control system. In addition the power converter has to react to the setting of an external contact. An open contact will shut down the power converter. The Interlock and Control module returns the status of the external contact to the control system by a second contact. This contact must have the same setting as the external contact. The principle wiring is shown in Figure 11.

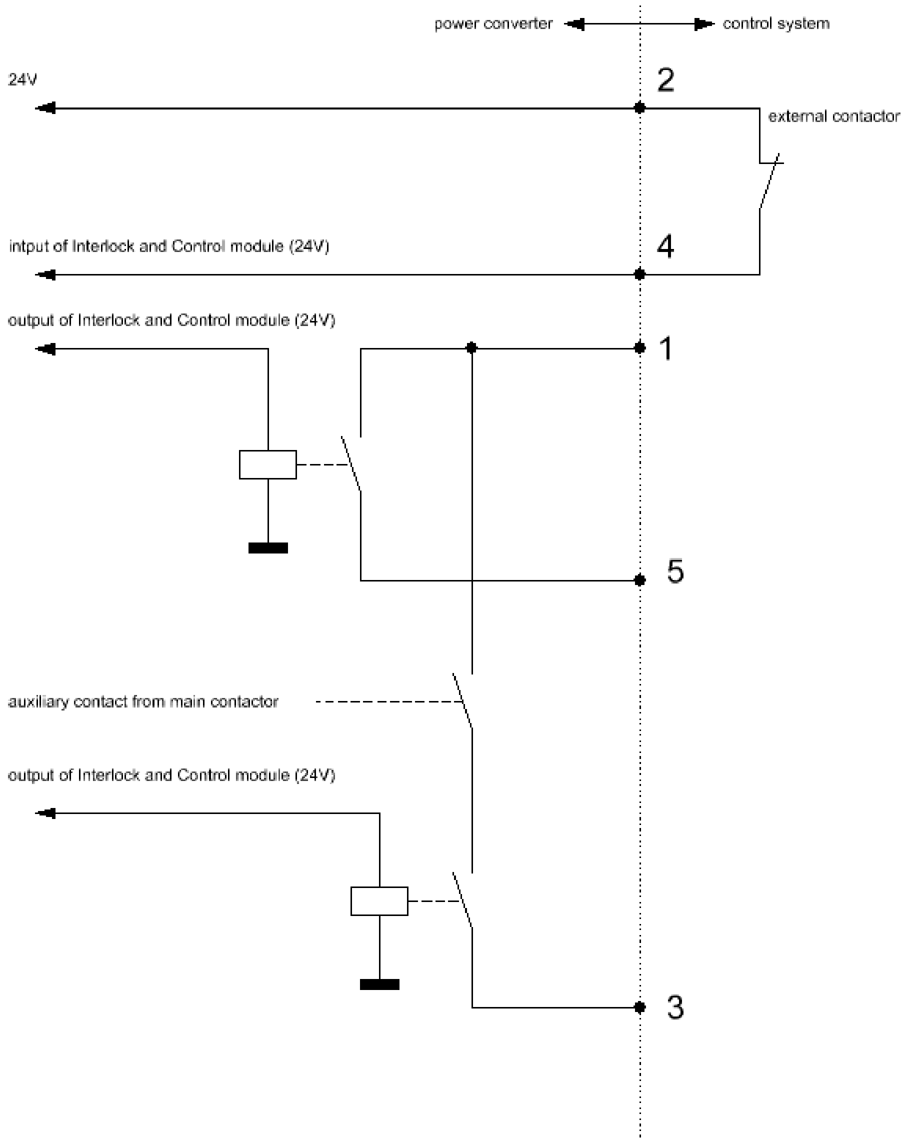


Figure 11 Beam Interlock System Version B

The connector to be used is a 5 pin female connector of type “Binder” with the pin assignment of Figure 10 and Figure 11.

7.5.12. Connecting power converters to electrical power

Note: Unless otherwise noted, all 3-phase AC voltages are given phase-to-phase, single phase AC voltages are given phase-to-neutral.
Power converters can be connected to the common power systems or to the pulsed power systems (see 4.1.2). The assignment to a power system depends on the rated power of the power converter, its working principle and according to this on the power exchanged with the power grid. Thus a large number of small power converters operating in a synchronized mode can be decided to be connected to the pulsed power systems. The assignment is given by the Company.

There is a second way to classify power converters in FAIR according to their rated power (S_n):

- small power converters < 10 kVA
- medium power converters 10 kVA < S_n < 500 kVA
- large power converters > 500 kVA

In special cases the assignment of power converters to a classification can be changed in agreement with the Company.

Small and medium power converters are connected to the 400V three phase supply system. All input terminals, switch gears and transformers are part of the power converters. The type of the supply net is TN-C. Take care for symmetrical loads to avoid currents on neutral line.

Large power converters of high power designed for 20 kV have to be delivered including transformers as part of the converter which is connected to the supply system via 20kV switch gear. The transformer is to be placed in a nearby transformer box of the building. The 20kV switch gear is scope of supply of the Company.

Generally every power converter has two independent supply inputs. One input is for the supply of the electronics of the power converter and is connected to the common 400V three phase supply system. The second input connects the power part with the appropriate supply system. The two electrical supply systems are ***not allowed to be coupled*** within the power converter.

7.5.13. Connecting power converters to ground

The cabinets of a power converter are connected to a low impedance grounding system. The output terminals of the power converter have to be symmetrically grounded. The connection to ground has to be done by resistors including an earth fault detection device and by capacitors with low ESR. The resistors and the earth fault detection device must allow for permanent operation even in case of an earth fault (one output terminal is short circuited to ground).

The shields of all power cables have to be grounded in the power converter using connections of very low impedance.

7.6. Failures and Reliability

The power converters must be self-protecting, and they also have to protect the load.
There are fault detecting devices and protection devices in the power converters to avoid damage in case of external or internal faults.
In particular the converters shall withstand the following fault situations without suffering any further damage:

- Output short circuit while at full power
- Output short circuit at ON command
- Output open circuit
- Internal faulty components
- Loss of one, two or three AC phases
- Malfunction of control.

All components must have an individual MTBF greater than 100.000 hours under the worst case operating conditions described in this specification.

8. Quality Assurance, Tests and Acceptance

Quality assurance, tests and acceptance are specified in the General Specification [1] and in the contracts. Only some additional points are specified here.

In general all power converter projects consist of the following phases:

- Concept phase
    - Design concept
    - Creation of manufacturing documents
- Realization of the first unit (prototype)
- Realization of the first series unit (pre-series prototype)

- Series production
- shipping
- Installation & commissioning.

During all phases, status reports are mandatory. contractor and the Company have to agree about the reporting intervals. The deliverables of each phase and corresponding rights will become property of the Company.

8.1. Quality Assurance system of the supplier

One important means to guarantee that the system fulfills the requirements is an intense document exchange during the concept phase.

The concept phase is divided into two sections. In the first section, a set of documents has to be delivered by the supplier which is denoted as "design concept". The design concept has to include the following information:

- Functional description of all components
- Explanation of design criteria according to chapter 7.5
- Technical data
- Block diagrams
- Manufacturer/type of all main components
- Interface description.

A conjoint agreement (between the contractor and the Company) about this design concept has to take place before the manufacturing documents are created.
In the second section of the concept phase, a set of documents has to be delivered by the contractor which is denoted as "manufacturing documents".

In addition to the updated design concept information, the manufacturing documents have to contain the following information:

- A description of the complete power converter
- Mechanical drawings of all main components: Cabinet, transformer, inductor, capacitor bank, arrangement of semiconductors, placement of DCCT-head
- Schematics of the control loops
- Complete schematics of all electrical circuits
- Detailed specification of all main components
- Complete specification of all interfaces (electrical, mechanical, building, media, software, etc.)
- List of recommended spare parts

- Transportation specification (dimensions and weights with and without packaging)

In general, the manufacturing documents contain all information which allows an immediate production without further R&D activities.
After the manufacturing documents are available, a formal acceptance of the Company is mandatory before the production can start.

8.2. FAT

The general procedure for test and acceptance is described in the chapters 9.1 to 9.5 of [1]. For power converters chapter 9.2.8 of [1] is to be excluded.

After manufacturing and before delivery, the power converters shall be tested at the factory site. The contractor shall provide the necessary testing equipment and personnel to perform the tests.
A test procedure shall be established for each unit of a series production and a protocol for each unit shall be delivered with the unit, in this case the power converter.
For a pre-series prototype, that is the power converter of the series to be tested before series production starts, there will be an extended test procedure.

8.2.1. FAT of a pre-series power converter

Specific power converter type related tests are described in the detailed specification of the power converter. The ACU system and the graphical user interface on the testing computer support the test procedure.

In general the pre-series Factory acceptance test on the power converters shall include:

- Verification of the assembly and wiring, according to the technical documentation
- Checking of relevant signals like:
  - Actual load current
  - Actual load voltage
  - DC link voltage
  - Input current
  - Control voltage
  - Gate signals
- Checking the functionality of all protection and interlock circuits and the resulting actions and reactions
- Testing of Local and Remote operation with full functionality
- Insulation test of the power part

- Thermal test:
  - A test load may be used to run the converter up to thermal equilibrium under the worst case conditions at maximum possible power. Temperature measurements at the semiconductors, inductors and transformers shall be done.
  - The power converter has to be operated at 110% of the maximum output current I_n. Temperature measurements at the semiconductors, inductors and transformers shall be done.
- Functionality test:
  A test load may be used to run the converter under the worst case conditions at maximum possible power and with the maximum cycle frequency or ramp rate (if possible at the maximum output current I_n). During the test the following measurements have to be done:
  - Measurement of total deviation (only under test load conditions)
  - Measurements of the output voltage ripple
  - Measurements of turn on and turn off behaviour of the semiconductors (i.e. V_{CE} of IGBTs)
  - EMC measurements according to chapter 6.1.2
- All other test that the Company may consider important for the final operating conditions of the power converter.

On completion of the tests, the converter will be inspected visually and no damage must be evident. If the tests show that any part of the specification is not met, the contractor must correct the fault and repeat the tests at his cost. Tests will have to be repeated also if there is any modification during factory tests. The contractor shall fully test the equipment in the factory, but the Company reserves the right to repeat any test at the FAIR site.

The Company reserves the right to have a representative present to witness the factory tests of the equipment. This right shall also apply to any subcontractor. According to the period defined in the contract the contractor must give notice to the Company of the proposed date for factory tests in advance.
The test procedure has to be documented and provided to the Company.

8.2.2. FAT of power converters of the series

Specific power converter type related tests are described in the detailed specification of the power converter. The ACU system and the graphical user interface on the testing computer support the test procedure.

In general the series Factory acceptance test on the power converters shall include:

- Verification of the assembly and wiring, according to the technical documentation.
- Checking of relevant signals like:
    - Actual load current
    - Actual load voltage
    - DC link voltage
    - Input current
    - Control voltage
    - Gate signals
- Checking the functionality of all protection and interlock circuits and the resulting actions and reactions.
- Testing of Local and Remote operation with full functionality.
- Insulation test of the power part.
- Functionality test:
  A test load may be used to run the converter under the worst case conditions at maximum possible power and with the maximum cycle frequency or ramp rate (if possible at the maximum output current I_n). During the test the following measurements have to be done:
    - Measurement of total deviation (only under test load conditions)
    - Measurements of the output voltage ripple
    - Measurements of turn on and turn off behaviour of the semiconductors (i.e. V_{CE} of IGBTs)
    - EMC measurements according to chapter 6.1.2 , however restricted to voltage measurement at the output terminals and the ac-input terminal L1 to ground.
- All other test that the Company may consider important for the final operating conditions of the power converter.

On completion of the tests, the converter will be inspected visually and no damage must be evident. If the tests show that any part of the specification is not met, the contractor must correct the fault and repeat the tests at his cost. Tests will have to be repeated also if there is any modification during factory tests. The contractor shall fully test the equipment in the factory, but the Company reserves the right to repeat any test at the FAIR site.

The Company reserves the right to have a representative present to witness the factory tests of the equipment. This right shall also apply to any subcontractor. According to the period defined in the contract the contractor must give notice to the Company of the proposed date for factory tests in advance.
The test procedure has to be documented and provided to the Company.

8.3. SAT

The general system for site acceptance tests is described in chapter 5 of [1].

For power converters the site acceptance types SAT A and SAT Ba are mandatory.
Site acceptance tests are planned to take place as soon as possible when the facilities are available. The Company requests that the technical responsible person of the contractor (who will have participated in the manufacturing and factory tests of the power converter) is present at the FAIR site to participate in the site acceptance tests.
All parts of the test procedure have to be documented and provided to the Company.
In the event of any fault, the contractor must correct them immediately at his cost at FAIR site. Site acceptance will only be granted after successful tests and approval of the documentation.

8.3.1. SAT A

Site acceptance test SAT A is done in two steps:

- SAT Aa is the incoming good inspection after delivery to the FAIR site. It proves that no damage or changes have occurred during packing and transportation.
- SAT Ab involves the scouring of the cooling system of the power converter with demineralised water. This can be done in a specially equipped testing hall. The equipment is supplied by the Company. After completion of scouring the power converter is transported to and integrated in its final installation place. The contractor’s technical responsible person will supervise the integration.

8.3.2. SAT Ba

Site acceptance test SAT Ba will be carried out at the final installation place with the real load. Specific power converter type related tests are described in the detailed specification of the power converter. The ACU system and the graphical user interface on the testing computer support the test procedure.

In general the site acceptance test on the power converters shall include:

- Checking of relevant signals like:
    - Actual load current
    - Actual load voltage
    - DC link voltage
    - Input current
    - Control voltage
    - Gate signals
- Checking the functionality of all protection and interlock circuits and the resulting actions and reactions.

- Testing of Local and Remote operation with full functionality.
- Control tests. The specified current deviation has to be fulfilled within every specified operation mode.
- Stability test with the real load to run the converter up to thermal equilibrium under the worst case conditions at maximum power and with the maximum cycle frequency or ramp rate. During the test total deviation has to be measured at maximum output current I_n.
- EMC measurements according to chapter 6.1.2 , however restricted to voltage measurement at the output terminals and the ac-input terminal L1 to ground.

9. Transportation

Transportation of the power converters to the FAIR site and to their final installation places is part of the delivery.
For transportation and installation purposes the following technical guidelines are available: [7], [8] and [9].

10. Documentation

10.1. Documents of the Tendering process

The following documents have to be delivered during the tendering process It must be given in English, and optionally in German, printed on paper and as electronic documents (Microsoft Word and pdf-format)

- Mechanical dimensions and weight of the power converter
- Description of the power converter topology and the working principles
- Diagram of the power part (principle layout)
- Diagram of the control part (principle layout)
- Mechanical drawings of the power converter (alternatively photograph of similar power converters)
- Design data of the main components (transformers, inductors and power electronic components)
- Effective apparent power
- Losses of the main components to water and to air referred to nominal operation mode
- The needed water flow and the needed differential pressure.

10.2. Final Documentation

The final documentation must be given in English, and optionally in German, printed on paper and as electronic documents (Microsoft Word and pdf-format). It includes:

- service manuals
- final mechanical drawings
- circuit diagrams and schematics of control and power electronics
- list of components
- protocol of factory acceptance test
- protocol of site acceptance test.

Additionally all circuit diagrams and schematics have to be given in EPLAN P8 format and dxf-file format. Schematics and drawings included in other electronic documents must be also given as dxf-file format.

11. Warranty

The warranty period will start when the power converter has successfully passed the final acceptance tests.

I. Attached Documents

none

II. Related Documentation

[1] General Specifications v0.4 F-GS-B-01e

[2] Electrical Design Rules and Regulations F-TG-ET-02 01e

[3] Supply with cooled water v1.1 F-TG-F-03e

[4] Operating Manual Adaptive Control Unit (ACU)

[5] Module Description Adaptive Control Unit (ACU)

[6] F-TG-C-03e ACOS Interlock Interface

[7] F-TG-T-01e Transport

[8] F-TG-T-03e Installation

[9] F-TG-T-02e Existing Infrastructure

[10] Integration of Adaptive Control Unit (ACU) for Switch Mode Power Converters

III. Document Information

III.1. Document History

Version	Date	Description	Author	Review / Approval
0.1	2010 07 06	Draft version	H.Welker	
0.2	2011 05 25	Draft version	H.Welker	
1.0	2011 12 09	Draft version	H.Welker	
1.01	2012 05 30	Draft version	H.Welker	
1.02	2012 06 10	Draft version	H.Welker/H.Ramakers	
1.03	2012 06 13	First Version	H.Welker/H.Ramakers	