CHAPTER 25

TRANSFER LINE POWERING

25.1 INTRODUCTION

The magnets that guide and focus the beams during their transfer from the SPS to the LHC will be powered by 144 new power converters. These range in power from 250 W to 9.7 MW. Several power converter technologies and topologies will be used, based not only on the circuit electrical characteristics and the required performance, but also on the topology of the re-used power converters. To reduce the global cost, it was decided:

- To maximise the re-use of the available equipment retrieved from LEP and SPS.
  This equipment will be refurbished and adapted to ensure compatibility with the SPS system as the transfer lines will be part of the SPS machine from an operation point of view. Consequently, the SPS remote control system (MUGEF) and the SPS interlock system will be used.
- To minimise the length of the cables.
  The power converters will be installed at the both ends of each tunnel.
- To install the power converters in existing surface buildings.
  For TI 2, the power converters will be installed in BA7 and SR2; for TI 8, the power converters will be installed in BA4 and SR8.

Nevertheless in some cases, it is necessary to buy new power converters. Because of the different equipment origins, all equipment will undergo a standardisation process in order to facilitate operation and maintenance of the power converters.

25.2 GENERAL RUNNING

All large power converters will operate in a pulsed mode for economical reasons (electrical power and thermal design). The small power converters for the correctors will run in DC as their losses are negligible.

For the transfer lines, the only important operating characteristic is the flat top current, with the global cycle similar to that used for the SPS. However, the transfer line cycle has been optimised to reduce the rms current value that in turn reduces the overall electrical consumption. Thus the rms current value of the proposed reference cycle (see below) is 0.36 I nominal whereas the rms current value in the magnets is about 0.45 I nominal due to the current decay in the free-wheel diodes.

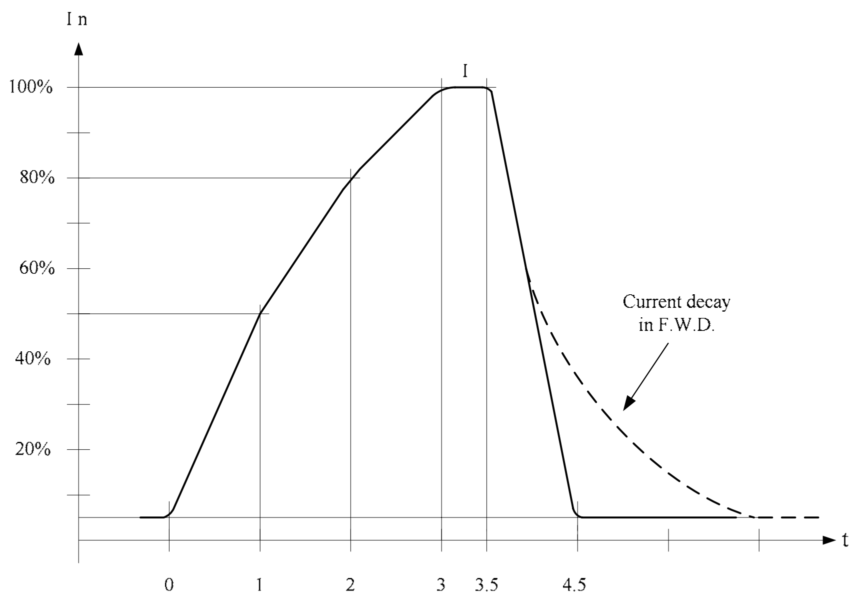

Figure 25.1: Proposed transfer line cycle

25.3 POWER CONVERTER REFURBISHMENT

All re-used power converters will be refurbished before re-installation to assure a good reliability. Refurbishment principally involves:

- Changing the main circuit breaker
- Installing a new electronics crate (identical to the SPS electronics crate)
- Installing new DCCTs (Direct Current Current Transformers)
- Re-cabling the control part to be compatible with the new electronics.

25.4 OVERVIEW OF TI 2

The power converters for both the extraction system of the west area and the TT60 line of TI 2 have been retained. However to prolong their useful life, each converter has been refurbished and reinstalled. The additional power converters required for TI 2 are installed in the BA7 (SPS) and SR2 (LHC) surface buildings. The list of power converters with their main characteristics is given in Tab. 25.1.

Table 25.1: TI 2 power converters

TI 2													
Converter name	Magnet Type	Number of Magnets in Series	Inom [A]	I max DCCT [A]	Cable total length (estimated) m	Cable section mm2	Reproducibility 24h ± ppm of I max	Reproducibility 1/2h ± ppm of I max	P.C. Loc.	Converter type	Origin	Source	Umax Conv. [V]
MBI 2213M	MBI	112	5150	5400	4000	1500	50	20	SR2	RA3/A	LEP	18000	1800
MQIF 2580M	MQI	26	490	600	5880	630	100	40	SR2	RA1/S	LEP	18000	1300
MQIF 2840M	MQI	13	490	600	2500	630	100	40	SR2	RB9/H	LEP	400	350
MQID 2850M	MQI	40	490	600	5996	630	100	40	SR2	RA1/S	LEP	18000	1300
MBB 2015M	MBB	2	3690	4400	620	1920	100	40	BA7	R21	SPS	18000	160
MBIBH 2931M	B280	6	725	800	1272	1000	50	20	SR2	N10	New	400	450
MBIAV 2063M	B340	17	925	1000	814	480	50	20	BA7	RA1/MG	LEP	18000	1300
MBIAV 2685M	B340	12	900	1000	3034	1260	100	40	SR2	RA1/S	LEP	18000	1300
MBIAV 2911M	B340	4	565	800	1616	630	100	40	SR2	RB9/O	LEP	400	350
MQID 2010	MQI	1	370	500	760	240	100	40	BA7	RB4	LEP	400	105
MQIF 2020	MQI	1	290	400	696	240	100	40	BA7	RB15	LEP	400	100
MQID 2030	MQI	1	270	400	636	240	100	40	BA7	RB15	LEP	400	100
MQIF 2040	MQI	1	330	500	576	240	100	40	BA7	RB4	LEP	400	105
MQID 2050	MQI	1	460	600	484	240	100	40	BA7	RB8	LEP	400	210
MQIF 2060	MQI	1	470	600	544	240	100	40	BA7	RB6	LEP	400	200
MQIF 2860	MQI	1	500	600	1658	500	100	40	SR2	RB6	LEP	400	200
MQID 2870	MQI	1	510	600	1598	500	100	40	SR2	RB6	LEP	400	200
MQIF 2880	MQI	1	410	600	1538	500	100	40	SR2	RB6	LEP	400	200
MQID 2890	MQI	1	460	600	1478	500	100	40	SR2	RB6	LEP	400	200
MQIF 2900	MQI	1	390	600	1416	500	100	40	SR2	RB6	LEP	400	200
MQID 2910	MQI	1	220	400	1356	500	100	40	SR2	RB15	LEP	400	100
MQIF 2920	MQI	1	320	500	1270	500	100	40	SR2	RB4	LEP	400	105
MQIF 2930	MQI	1	380	500	1246	500	100	40	SR2	RB4	LEP	400	105
MQIF 2940	MQI	1	150	300	1146	500	100	40	SR2	RB2	LEP	400	200
MQID 2950	MQI	1	280	500	1076	500	100	40	SR2	RB4	LEP	400	105

25.5 OVERVIEW OF TI 8

For TI 8 a new extraction system has been installed at point 4 of the SPS. This involves 9 additional power converters, four for vertical bumpers, four for horizontal bumpers and one for the MSE magnets. These converters are part of the SPS machine and are described in Chap. 18. The additional power converters for TI 8 are installed in the BA4 (SPS) and SR8 (LHC) surface buildings. The list of power converters together with their main characteristics is given in Tab 25.2.

Table 25.2: TI 8 power converters

Converter name	Magnet Type	Number of Magnets in Series	Inom [A]	I max DCCT [A]	Cable total length (estimated) m	Cable section mm2	Reproducibility 24h ± ppm of I max	Reproducibility 1/2h ± ppm of I max	P.C. Loc.	Converter type	Origin	Source	Umax Conv. [V]
TI 8													
TT 40													
MBHC 4001M	BHC	3	900	1000	652	750	100	40	BA4	RB13	LEP	400	300
MDSV 4002	MDS	1	0	400	714	240	100	40	BA4	N08	New	400	125
MBHA 4003M	B340	4	1000	1100	761	800	100	40	BA4	RA2	LEP	18000	550
QTMD 4001	MQI	1	470	500	606	240	100	40	BA4	RB6	LEP	400	200
QTRF 4002	QTR	1	100	400	652	240	100	40	BA4	RB10	LEP	400	250
QTRD 4003	QTR	1	70	300	714	185	100	40	BA4	RB2	LEP	400	200
QTLF 4004	QTL	1	250	400	782	185	100	40	BA4	RB10	LEP	400	250
TI 8													
MBI 8160M	MBI	236	5250	5400	2000	1500	50	20	BA4	2xRA3/T	LEP	2x18kV	3600
MQIF 8700M	MQI	34	500	600	5508	630	100	40	SR8	RA1/MG	LEP	18000	1300
MQID 8710M	MQI	34	500	600	5700	630	100	40	SR8	RA1/MG	LEP	18000	1300
MCICH 8040	MDS	1	240	400	1094	185	100	40	BA4	RB10	LEP	400	250
MBIAH 8788M	B340	7	900	1000	1210	1260	100	40	SR8	N11	New	18000	600
MBIAV 8110M	B340	12	800	1000	1883	400	100	40	BA4	RA1/MG	LEP	18000	1300
MBIBV 8774M	B280	5	730	800	1325	1260	100	40	SR8	RB9/H	LEP	400	350
MQID 8010	MQI	1	400	500	892	240	100	40	BA4	RB6	LEP	400	200
MQIF 8020	MQI	1	410	500	952	240	100	40	BA4	RB6	LEP	400	200
MQID 8030	MQI	1	600	600	1012	240	100	40	BA4	RB6	LEP	400	200
MQIF 8720	MQI	1	500	600	1614	500	100	40	SR8	RB6	LEP	400	200
MQID 8730	MQI	1	600	600	1554	500	100	40	SR8	RB6	LEP	400	200
MQIF 8740M	MQI	2	300	400	1490	500	100	40	SR8	RB15	LEP	400	100
MQID 8750	MQI	1	490	600	1434	500	100	40	SR8	RB6	LEP	400	200
MQIF 8760	MQI	1	500	600	1374	500	100	40	SR8	RB6	LEP	400	200
MQID 8770	MQI	1	360	500	1314	500	100	40	SR8	RB4	LEP	400	105
MQIF 8780	MQI	1	320	500	1254	500	100	40	SR8	RB4	LEP	400	105
MQID 8790	MQI	1	290	400	1126	500	100	40	SR8	RB15	LEP	400	100
MQIF 8800	MQI	1	360	500	1066	500	100	40	SR8	RB4	LEP	400	105
MQID 8810	MQI	1	290	400	1006	500	100	40	SR8	RB15	LEP	400	100

25.6 GENERAL PERFORMANCE

The cycle to cycle reproducibility, given in the Tab. 25.1 and Tab. 25.2, is defined as the maximum deviation of the average value of the flat top current, I, over a period of half an hour. The precision is expressed in ppm of I_{max}. The environmental conditions are assumed to not change and are defined in [1].

The cycle to cycle reproducibility for 24 h is defined as the maximum deviation of the average value of the flat top current over a period of one day, taking into consideration the full range of permissible changes of operating and environmental conditions. The precision is again expressed in ppm of I_{max}.

In all cases a constant current ripple contribution from the converter itself is added to the drifts described above. The current ripple is dependant on the converter voltage ripple (given in each topology description – see below) and also on the magnet characteristics. The current ripple can be derived from the following transfer function:

- $I_{ripple}/U_{ripple} = 1/(R * (1 + jL\omega/R))$
- With R and L resistance and inductance of the load (cables + magnets).

25.7 POWER CONVERTER TOPOLOGIES

25.7.1 Six-pulse Power Converters

The main characteristics of the 6-pulse power converters are:

- Working range: I min 5% of I max, I max 100% of DCCT range,
- Voltage ripple of V max: 2×10^{-3} at 50 Hz; 1×10^{-2} at 300 Hz,
- Typical small-signal current loop bandwidth: 10 Hz.

In order to handle the magnet current ramp-down under the worst fault condition, e.g. a power cut, the converters are equipped with a free-wheel diode. The 6-pulse power converters are made of one thyristor full bridge or two thyristor half bridges.

Full bridge topology

This topology concerns the RB2, RB10 and RB15 types. The complete converter is composed of a circuit breaker, a 50 Hz transformer, a thyristor bridge and passive filter assembled in one cubicle. The complete converter is air-cooled. A schematic circuit diagram is shown in Fig 25.2.

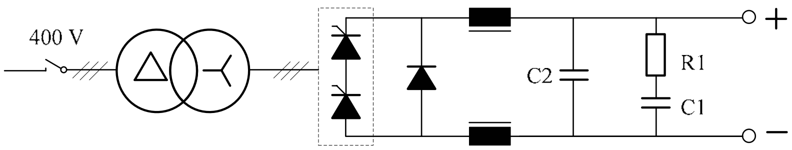

Figure 25.2: A full-bridge thyristor converter 6 P topology

Two half bridges topology

This topology concerns the R21 type. The complete converter is composed of a circuit breaker, together with a 50 Hz transformer which has two secondary windings that are phase shifted by 180º. Two half thyristor bridges and a passive filter make up the remainder of the active elements which are all installed in one cubicle. The complete converter is air-cooled.

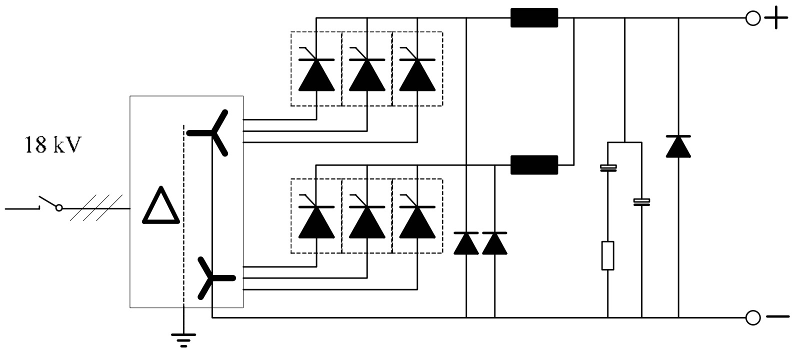

Fig. 25.3: A Two half-bridge thyristor converter, 6 P topology

25.7.2 T welve-pulse Power Converters

The main characteristics of this type of converter are:

- Working range: I min 5% of I max, I max 100% of DCCT range,
- Voltage ripple of V max: 2×10^{-3} at 50 Hz; 5×10^{-3} at 600 Hz,
- Typical small-signal current loop bandwidth: 10 Hz.

In order to handle the magnet current ramp-down under the worst fault condition, e.g. power cut, the converters are equipped with free-wheel diodes. The 12-pulse power converters are made of series, parallel or series-parallel combinations of full bridge thyristors.

12–pulse parallel power converter

This topology concerns the N10, N11, RB4, RB6, RB8, RB9, RB13 and RA2 converter types. The complete converter is composed of a circuit breaker together with two sub-converters phase-shifted by 30º and connected in parallel, resulting in a 12 pulse configuration. The complete converter is air-cooled. A schematic circuit diagram is shown in Fig 25.4.

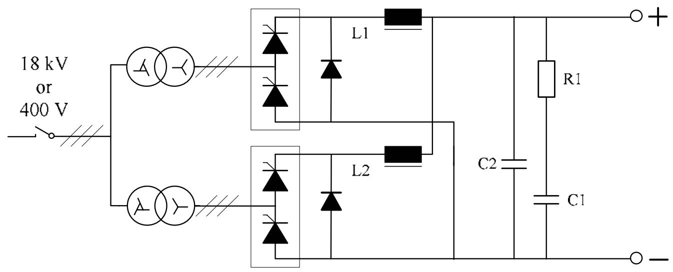

Figure 25.4: A 12–pulse parallel power converter

12 –pulse series power converter

This topology concerns the RA3 types. The complete converter is composed of a circuit breaker and two sub-converters phase-shifted by 30º and connected in series, resulting in a 12 pulse configuration. The thyristor bridges and the chokes of the passive filter are water-cooled.

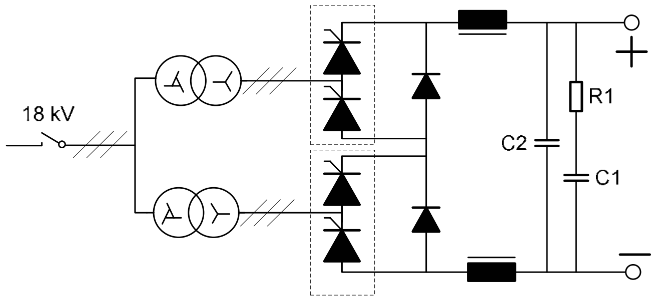

Figure 25.5: A 12–pulse series power converter

12–pulse series-parallel power converter

This topology concerns the RA1 types. The complete converter is composed of a circuit breaker and two series sub-converters phase-shifted by 30º and connected in parallel, resulting in a 12 pulse configuration. The complete converter is air-cooled.

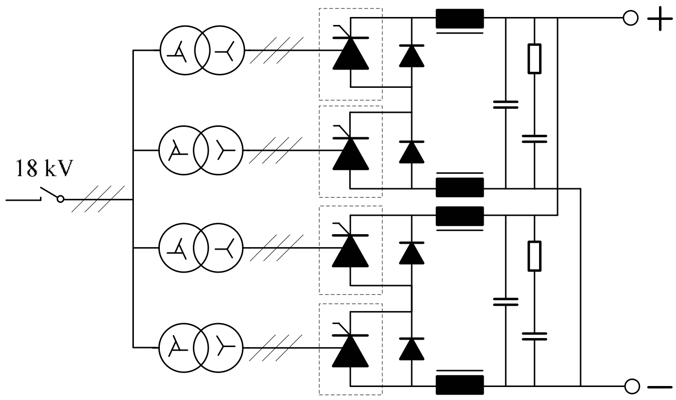

Figure 25.6: A 12–pulse series-parallel power converter

25.7.3 Bipolar Power Converters with Mechanical Polarity Changer

These bipolar power converters are made with 6-pulse or 12-pulse power converter which has a mechanical switch added at the output. The polarity can only be changed at zero current and does not occur during normal machine operation. Power converters using this topology are denoted by an "S" at the end of their type name.

25.7.4 Four-quadrant (4Q) Switch-mode Converter

This topology concerns the NO8 type. The MDSV 400293 magnet requires a 4-quadrant power converter, capable of regulating zero current. The main characteristics are:

- Voltage ripple of V max: 1×10^{-3} at 16 kHz,
- Typical small-signal current loop bandwidth: 10 Hz.

This 4-quadrant power converter is composed of: a main circuit breaker, a step-down transformer, a diode rectifier bridge, a DC passive filter, a brake chopper to dissipate the magnet energy in case of converter fault, a chopper bridge unit, a high frequency filter and a crowbar. Fig 25.7 shows the circuit.

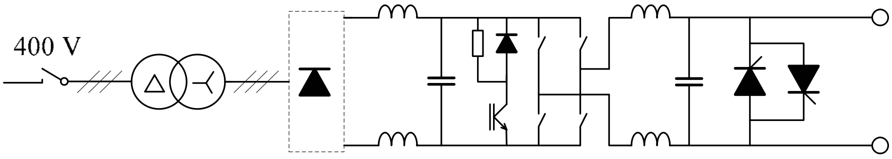

Figure 25.7: A 4-quadrant switch mode converter

25.7.5 Power Converters for the MCIAV and MCIAH Correctors

Ninety one NX type power converters (±70 V, ±3.5 A) are needed to feed the MCIAV and MCIAH corrector magnets. These are 4-quadrant power converters with zero current regulation and are identical to the existing SPS units. More details can be found in [2].

25.8 DISTINCTIVE FEATURES OF THE TI 8 MBI POWER CONVERTERS

The TI 8 MBI magnets will be fed by two series connected power converters 1800V/5400A, installed in BA4. These two power converters will run in Master/Slave mode. Only the Master will be seen by the control room. The slave converter will be fully controlled by the Master. For economic reasons, these two converters will also feed the MBG magnet chain of CNGS. A diagram of the general arrangement is given in Fig. 25.8.

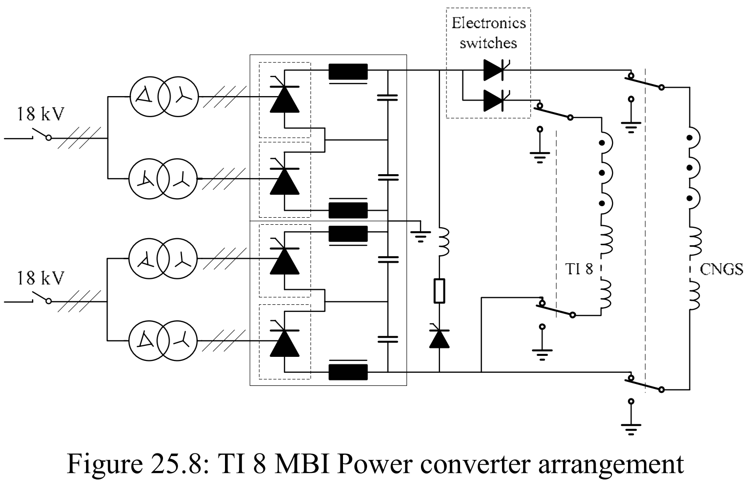

Figure 25.8: TI 8 MBI Power converter arrangement

Two mechanical switches per magnet chain permit an earth connection for safe intervention even while the converter is operating on the alternative chain. The mechanical switches are operated in four modes:

1) TI 8 without CNGS
2) CNGS without TI 8
3) TI 8 and CNGS
4) Neither TI 8 nor CNGS.

When functioning in mode 3 “TI 8 and CNGS”, all mechanical switches are in position to permit both magnet chains to be powered. In this case, the thyristor switches in series with each magnet chain can control which magnet chain is enabled on a cycle-by-cycle basis.

Two additional DCCTs (one in each circuit) are available for an independent interlock circuit that will prevent beam extraction if the magnet chains do not have the correct current.

Operation of this circuit requires a two-quadrant converter to assure the same current ramp rate independent of the TI 8 or CNGS system. In this way the current in the circuit is guaranteed to reach zero, permitting the turn off of the electronic thyristor switch before turning on the thyristor switch of the alternative circuit. Under normal operation, the magnet current is ramped down under closed loop regulation. In case of a power converter fault, the magnet current will decay with a natural time constant through the free-wheel thyristor.

25.9 POWER CONSUMPTION AND LOSSES

The additional power consumption and losses due to the transfer line power converters in the buildings BA7, SR2, BA4 and SR8 are indicated in the table 25.3.

Table 25.3: Additional power consumption and losses due to the transfer lines

Building	Flat Top Real power	Flat top Apparent power	Water flow	Water losses	Air losses
BA7	1.1 MW	2.9 MVA	0	0	48 kW
SR2	11.8 MW	17.5 MVA	4 m^3/h	80 kW	108 kW
BA4	18.6 MW	28.6 MVA	8 m^3/h	200 kW	84 kW
SR8	1.7 MW	4.0 MVA	0	0	90 kW

25.10 CONTROLLING THE POWER SUPPLIES FOR TI 2 & TI 8

25.10.1 Control Equipment for the Transfer Line Power Supplies

The control of the transfer lines TI 2, TI 8 and TT40 will be made to be the same as the rest of the SPS. For this Mugef systems will be used. Mugef ROCS corresponds to a standard hardware and software, ROCS indicating the last important upgrade of this system in 1998 (based on VME, LYNXOS and many standardised modules). A MUGEF crate is capable of controlling up to 64 power supplies, with each Mugef being connected directly to the Ethernet and to the SPS Timing networks. Additionally, there are two special lines, "Remote Reset" and "Remote Terminal". A standard Mugef crate consists of:

CPU:	PowerPC603
System managing:	SAC = System Arbiter Controller
Non volatile memory:	MEM206
Timing:	TG8
Commands & status:	Statophone 1.0
Analog measurement:	MPV915
Function generator:	New Wave 3.1.

Specific cards or modules needed for the SPS main power supplies, the control of RF cavities and for the Transfer Lines, are added to this standard crate.

25.10.2 Specificities of the Mugef for the Transfer Lines TI 2 & TI 8

Fast Extraction Interlock

The addition of a fast extraction interlock function to the standard Mugef system requires the addition of a special hardware device. This will provide basic local diagnostics as well as the connection to the central Interlock crate in each building.

Very high precision Power Supplies

For the five most demanding precision power supplies, the standard Mugef crates are equipped with a different function generator card. On these cards, the general 16 bit DAC is replaced by a special 18 bit DAC that ensures 16 bit monotonicity over the full bipolar range in addition to improving other parameters.

25.10.3 Fast Extraction Interlock System (FEI)

In order to avoid damaging the vacuum chamber of the transfer lines when a power supply fails, a measurement of the current of all the power supplies concerned must be taken immediately before each extraction. If the current of one or more units is outside a preset tolerance, the extraction must be prevented. In order to be able to optimise the measurement speed compared to the expected error rate, it is possible to set the following parameters separately for each power supply:

1) The nominal value of the current at the time of extraction. To increase the reliability of the system, a second 'Extraction Current Reference' (in addition to the regulation current reference) is sent and compared with the measured value. If the measured value exceeds the accepted tolerance on the reference value, the fast extraction interlock is activated.
2) The tolerance of the permitted current without interlocking the system.
3) The sample number "N" for the measurement which defines the degree of measurement filtering. The precision (and thus the reliability) of measurement increases with "N".

How the F.E.I. works

Each Mugef crate has a centralised fast measurement system of all the currents. The functionality for the fast extraction interlock is created by the addition of some hardware and software enhancements to this measuring system.

The Mugef system measures the all of the power converter output currents each millisecond. For a full Mugef crate this means that 64 Power supplies × 2 channels = 128 measurements are made per millisecond. Just before extraction, the following sequence is carried out:

- The extraction system sends an extraction request signal (event) to all Mugefs,
- Each Mugef sets the "fast interlock" process to maximum priority. This process consists of building an average of "N" samples of the measured current for each measurement and comparing it with the instantaneous nominal value,
- For each power supply, the Mugef processor extracts the "out of tolerance" bit, and memorises it.
- The logical "OR" of all the "out of tolerance" bits controls the "extraction permitted" output of the Mugef crate.

As operation of the Transfer Lines shares some vacuum chambers with the CNGS, it is envisaged to implement a Fast Extraction Interlock that is localised to the relevant vacuum zone. This will be performed by means of programmable masks that will group subsets of the Mugef crate into several interlock signals dedicated to a particular zone.

REFERENCES

[1] J.P. Burnet, "*Technical Specification for the Renovation of a Series of Thyristor power Converters with rating from 5 kW to 10 MW*", IT/2353A/SL, December 1997.

[2] A. Dupaquier, "*Technical Specification for D.C. Power Converters rated ±3.5 A, ±70 V*", IT-2114/SL, November 1992.