View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by CERN Document Server

LHC POWER CONVERTERS
Performance requirements

F. Bordry, CERN, Geneva, Switzerland

Abstract

A description will be given of how the power converters are able to provide current to give the required field at any moment of the operating cycle.

All precision terms will be defined (accuracy, reproducibility, resolution…).

The digital current loop principle and the algorithm will be presented. This will include how to deal with overshoots and undershoots limitations, the performance (closed-loop bandwidth, small signal amplitude) according to the load time constant.

1 INTRODUCTION

The LHC machine is divided in eight independent sectors. In each sector, individual power converters will power the main dipole and quadrupole (focussing and defocussing) magnets; a total of 24 power converters are needed. The superconducting magnets require the use of a number of field correction methods. Additional time dependent effects also occur [1]. As a consequence, very careful control of the magnet currents will be required in order to minimise these effects. The accelerator physics requirements translate into an overall high precision [2].

An overview of the power converter performance to meet the accelerator physics requirements is presented, along with precision term definition, voltage and current ripple, control loop strategy and bandwidth. Finally some new results are presented.

2 PRECISION

The term **Precision** should not be used for "accuracy". It is only a generic term covering the following terms: accuracy, reproducibility and stability.

Before to define these terms, it is useful to recall several basic definitions:

a) **PPM**: Part Per Million = $10^{-6} = 2^{-20}$ (20 bits)

b) Nominal current ($I_{Nominal}$): Normal maximum value.

It 's a choice. For LHC, the nominal current for the power converter is chosen equal to the ultimate current

LHC: $I_{Nominal}$ = ultimate current

E.g. Main dipole converter: $I_{Nominal}$ = 13 '000 A (≡ 9 T)

c) **ppm of nominal**: 10^{-6} x $I_{Nominal}$ (Amp)

Examples:

For $I_{Nominal}$ = 13 kA, 1 ppm of nominal = 13 mA

For $I_{Nominal}$ = 600 A, 10 ppm of nominal = 6 mA

2.1 Accuracy

The accuracy is defined as the:

long term setting or measuring uncertainty taking into consideration the full range of permissible changes of operating and environmental conditions.

The permissible changes are mainly defined in LHC Engineering Specifications:

- General parameters for equipment installed in the LHC [1] (E.g. ΔT = ±2°C in UAs) [3]
- Main parameters of the LHC 400/230 V distribution system [4]

The accuracy is defined by default for a period of one year and the accuracy is expressed in ppm of $I_{Nominal}$.

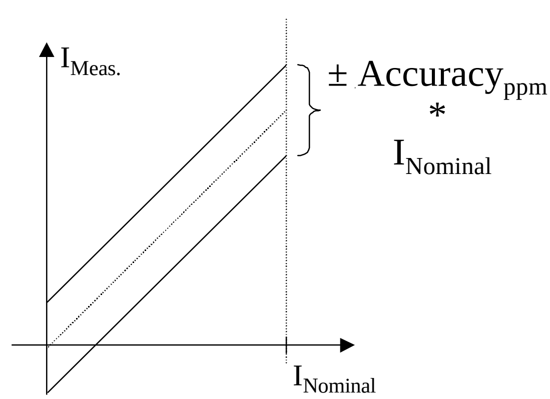

Figure 1: Accuracy illustration

If the one year accuracy is too large, a calibration process should be executed more often (e.g. every month). An in-situ quasi-on-line calibration system is developed for that purpose [5]. These systems will be installed for the 24 main circuits (main bends and main quadrupoles) and it is foreseen to install 8 systems for the inner triplets.

2.2 *Reproducibility*

The reproducibility is defined as the:
uncertainty in returning to a set of previous working values from cycle to cycle of the machine.

The reproducibility is defined by default for a period of one day without any intervention affecting the calibrated parts (e.g. DCCT, ADC). The reproducibility is expressed in ppm of $I_{Nominal}$.

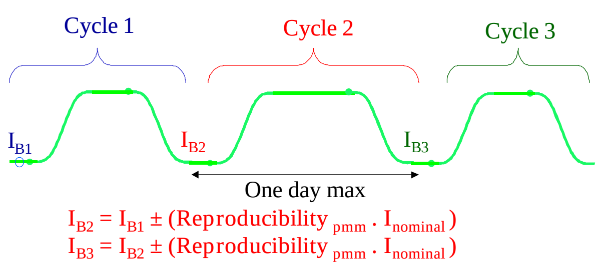

Figure 2: Reproducibility illustration

2.3 *Stability*

The stability is defined as the:
maximum deviation over a period with no changes in operating conditions.

The stability is defined by default for a period of half an hour. The stability is expressed in ppm of $I_{Nominal}$

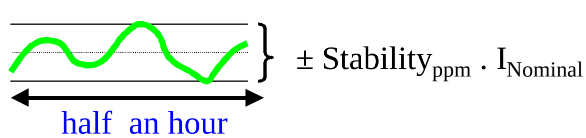

Figure 3: Stability illustration

Figure 4 shows an experimental example of ±1 ppm stability over 4 hours: [20kA, 6V] converter feeding a resistive load at 16kA [6].

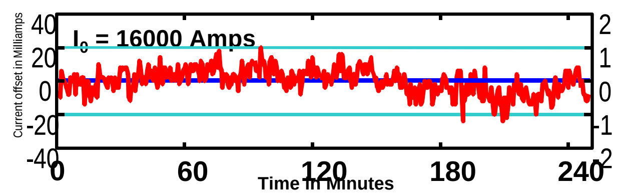

Figure 4: 16kA converter stability during 4 hours

2.4 *Resolution*

The resolution is defined as the:
smallest increment that can be induced or discerned.

The resolution is expressed in ppm of $I_{Nominal}$. Resolution is directly linked to A/D system.

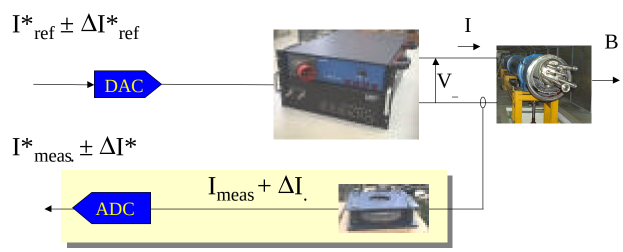

Figure 5: Resolution illustration

Figure 6 shows an experimental example of 1ppm control resolution: current steps of 1ppm are applied to the current reference.

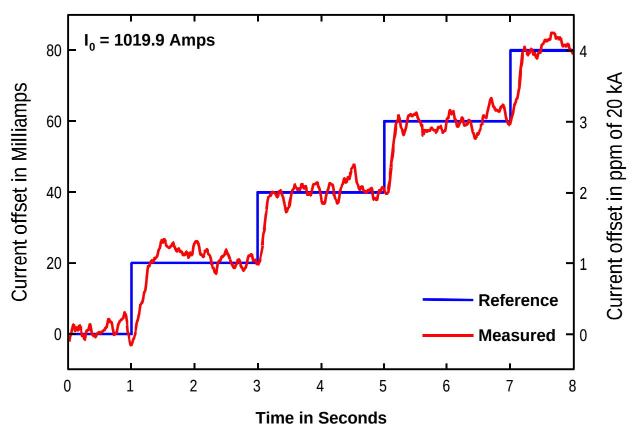

Figure 6: Results of Resolution Test with the Prototype Digital Controller

The Table 1 gives a summary of the precision performance of the LHC power converters.

Table 1: Power Converter Tolerances for LHC

Circuit Type	Nominal Current (A)	Current Polarity	One Year Accuracy (ppm of Inominal)	One day Reproducibility (ppm of Inominal)	1/2 hour Stability (ppm of Inominal)	Resolution (ppm of Inominal)
Main Bends, Main Quads	13000	Unipolar	± 50 ± 20 with calibration	± 5	± 3	1
Inner triplet	8000/ 6000	Unipolar	± 100 ± 20 with calibration	± 20	± 10	15
Dispersion suppressor	6000	Unipolar	± 70	± 10	± 5	15
Insertion quadrupoles	6000	Unipolar	± 70	± 10	± 5	15
Separators (D1,D2,D3,D4)	6000	Unipolar	± 70	± 10	± 5	15
Trim quadrupoles	600	Bipolar	± 200	± 50	± 10	30
SSS correctors	600	Bipolar	± 200	± 50	± 10	30
Spool pieces	600	Bipolar	± 200	± 50	± 10	30
Orbit correctors	120/60	Bipolar	± 1000	± 100	± 50	30

3 RIPPLE

The power converter topology and the performance of the inner control loops define the voltage ripple. The current ripple is defined by the load transfer function (cables, magnet inductance…). To get a good current ripple estimation, a good identification of the converter load is required. This is particularly important for the main dipole and quadrupole magnet strings. A good model identification of single magnet should allow determining all the resonance, especially in the range of 1 Hz to 1 kHz.

The field ripple is defined by the magnet transfer function (Figure 8). A determination of the transfer function B(s)/I(s) must be done for all magnet types.

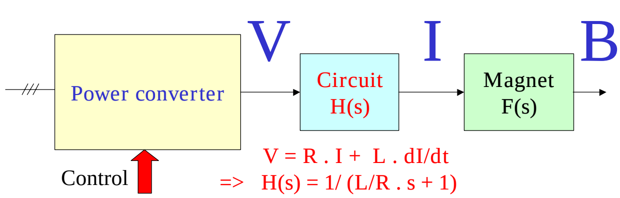

Figure 7: Power converter magnet transfer function

To get a specification for the voltage ripple, the following current ripple specification was taken:

$$\Delta I = 5\ \% * \text{Min (stability, resolution)} * I_{Nominal}\ \text{(Amp)}$$

then:

$$\Delta V \cong L(\omega)\ \omega\ \Delta I$$

where $L(\omega)$ is the circuit inductance.

Example:

Main quadrupole circuit: $I_{Nominal} = 13000$ A;

Min (stability, resolution) = Min (3 ppm ,1 ppm) = 1 ppm

$$\Delta I = 5\ \% * 10^{-6} * 13000 = 0.7\ \text{mA}$$

$$\Delta V_{50Hz} \cong (L\ \omega)\ \Delta I = 0.28\ \text{H} * 2 * \text{PI} * 50 * 0.7\ \text{mA} \cong 60\ \text{mV}_{50Hz}$$

$$\Delta V_{300Hz} \cong (L\ \omega)\ \Delta I = 0.28\ \text{H} * 2 * \text{PI} * 300 * 0.7\ \text{mA} \cong 350\ \text{mV}_{50Hz}$$

The voltage ripple specifications for the LHC power converters are presented in Table 2.

Table 2: Power converter voltage ripple specification

Power converter type	50 HzRipple pk-pk (mV)	300 HzRipple pk-pk (mV)
[13kA, ±180V]	60	350
[13kA, 18V]	60	350
[8kA,8V]	5	30
[6kA,8V]	5	30
[4kA,8V]	5	30
[±600A,±10V]	5	20
[±600A,±40V]	5	20
[±120A,±10V]	5	20
[±60A,±8V]	20	120
[900A, 550V]	40	250
[900A,1000V]	80	450

4 CONTROL LOOPS

4.1 Control loop description

To achieve the required performance defined in the section 2, a digital current loop control was chosen [7]. Then, the accuracy depends “only” upon current transducer and ADC

Switch-mode techniques are used for the converters [8]. Due to this technology, the voltage loop of the converters will have a high bandwidth (>500 kHz). When switch-mode technology is not suitable, classical thyristor converters are used with a lower voltage loop bandwidth (≅70 Hz)

The basic structure of a digital loop is shown in Figure8. The general structure of a digital controller can be described by a tri-branched structure known as R-S-T structure.

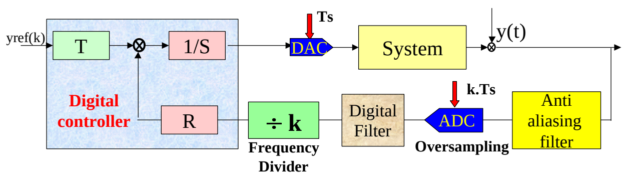

Figure 8: RST digital control loop

The RST controller makes it possible to obtain the desired tracking behaviour (following the reference) independent of the desired regulation behaviour (rejection of a disturbance). The RST control can be evaluated by the *"Tracking and Regulation with Independent Objectives"* method (R and S give the regulation behaviour and T gives the tracking behaviour) [9].

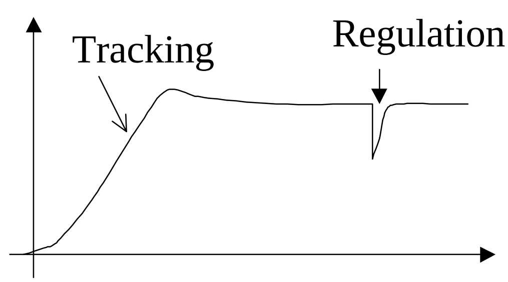

Figure 9: Tracking and Regulation

This method allows obtaining a good tracking of the reference: no lagging error, no overshoot.

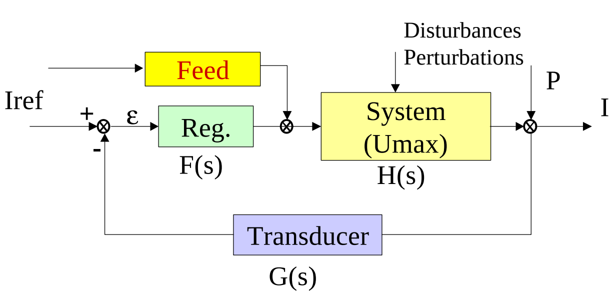

Figure 10: Current control loop

The choice of desired performance in terms of the response time (bandwidth) is linked to the dynamics of the open-loop system H(s) and to the power availability of the power converter during the transient. The acceleration of the natural response requires control peaks that are greater than the steady-state values

Umax/Ustat $\cong$desired speed/natural speed
$\cong$ desired bandwidth / natural bandwidth
$\cong f^{CL}_B / f^{OL}_B$
with
- Umax : maximum output voltage of the power converter
- Ustat : maximum steady-state voltage
(Ustat = R . $I_{Nominal}$)
- f^{CL}_B closed-loop bandwidth; f^{OL}_B open-loop bandwidth

The robustness of the closed-loop system is linked to the ratio f^{CL}_B / f^{OL}_B. A huge ratio leads to a lack of robustness of the control loop.

Example: arc orbit corrector circuit
Magnet: L=7 H; R = 30 mΩ (cable: 60m of 35 mm^2)
Time constant: T = L/R = 300 s => $f^{OL}_B \cong 0.5$ mHz

U_{stat} = R.I = 1.8V
Large signal bandwidth: $u_{max}/u_{stat} \cong 4$ => $f^{CL}_B \cong 2$ mHz
=> t_R = 175 s (dI/dtmax $\cong$ 0.9 A/s)

Small signal bandwidth:
With the choice of $f^{CL}_B \cong 1$ Hz
=> $u_{max}/u_{stat} \cong 1/ 0.5\ 10^{-3} = 2000$!
Then u_{stat} = 6 / 2000 = 3mV
=> ΔI = 3mV/30 mΩ = 0.1 A = 0.15 % Imax

For the arc orbit corrector, due to the large time constant of the circuit, a choice of 1Hz for the closed-loop bandwidth leads to 0.15% current range of the maximum current. If a larger range is necessary, the only solution is either to reduce the closed-loop bandwidth or to increase the output voltage of the converter (cost implication).

The Table 3 presents the choices for voltage and current loop bandwidth for all LHC electrical circuits.

Table 3:Voltage and current loop bandwidth

Cold Circuits	Current (kA)	Converter	Inductance (mH)	Resistance (mohms)	TC max. (sec)	Ramp 0 to 100% (sec)	U max. (V)	Voltage loop (Hz)	Current loop (Hz)
Main Bend	13.00	[13kA,±180V]	16632	0.8	20790	1300	176.7	500	0.1 to 1.0
Main Quads	13.00	[13kA,18V]	263 to 285	0.8 to 0.97	356	1300	15.2	500	0.1 to 1.0
Inner Triplet	7.00	[8kA,8V]	220	0.33	667	1300	3.5	500	0.1 to 1.0
Inner Triplet Trim	4.40	[6kA,8V]	38	0.45	84	1300	2.1	500	0.1 to 1.0
Disper. Quads	5.82	[6kA,8V]	21 to 26	0.49 to 0.95	53	360	5.9	500	0.1 to 1.0
Insert. Quads	4.65 to 5.82	[6kA,8V]	15 to 30	0.49 to 0.9	61	360	5.7	500	0.1 to 1.0
Insert. Quads	3.90	[4kA,8V]	74 to 148	0.67 to 0.9	221	360	5.1	500	0.1 to 1.0
Separators	6.00	[6kA,8V]	28 to 50	0.52 to 0.68	96	360	4.9	500	0.1 to 1.0
Q6,pts 3 & 7	0.60	[±600A,±10V]	600	1.8 to 7.02	333	360	5.2	1000	0.1 to 1.0
Q6,pts 3 & 7	0.60	[±600A,±40V]	600	23	26	360	14.8	1000	1 to 2
Spool b3,b5	0.60	[±600A,±10V]	31 to 123	8.28	15	120	5.6	1000	1 to 2
Trim Quads	0.60	[±600A,±10V]	31 to 248	1.8 to 8.28	138	120	6.2	1000	0.1 to 1.0
Trim Quads	0.60	[±600A,±40V]	31 to 248	25	10	120	16.2	1000	1 to 2
SSS Correctors	0.60	[±600A,±10V]	72 to 432	2.34 to 8.28	185	120	7.1	1000	0.1 to 1.0
SSS Correctors	0.60	[±600A,±40V]	72 to 144	26 to 47	5.5	120	28.9	1000	1 to 2
Octupoles	0.60	[±600A,±10V]	13.5 to 18	1.8 to 8.28	10.0	120	5.1	1000	1 to 2
Octupoles	0.60	[±600A,±40V]	13.5 to 18	49	0.4	120	29.5	1000	1 to 2
Spool b4	0.12	[±120A,±10V]	31	35	0.9	120	4.2	1000	1 to 2
Orbit Correctors	0.12	[±120A,±10V]	2240 to 4100	11 to 49	373	120	8.0	1000	0.1 to 1.0
Low B Corr.	0.12	[±120A,±10V]	3.7 to 21	9.4 to 36	2	120	4.341	1000	1 to 2
Orbit Correctors	0.06	[±60A,±8V]	7000	31	226	120	5.4	2000	0.1 to 1.0

Warm Circuits	Current (kA)	Converter	Inductance (mH)	Resistance (mohms)	TC max. (sec)	Ramp (sec)	U max. (V)	Voltage loop (Hz)	Current loop (Hz)
Quads	0.81	[900A,550V]	640	410 to 534	1.6	120	436.9	70	5 to 10
Separators	0.81	[1000A,1000V]	1200 1800	1000	1.8	120	822.2	70	5 to 10
Dump Septum	0.88	[900A,550V]	1060	569	1.9	120	508.5	70	5 to 10
Warm Trim/Corr	0.60	[±600A,±40V]	25 64	26 59	2.5	120	35.7	1000	5 to 10

4.2 Results

Several tests we made using the new digital controller with a RST algorithm.

Figures 11 and 12 present the ramp from 200 A to 13000A with a dI/dt = 200 A/s. The converter is one of the [13kA, 16V] converter of String 2. The load is: 1mH inductance and 0.8 mΩ resistance (τ = 1.5 s).

The continuous line is the current reference, the step line is the ADC measure (measurement every 10 ms).

Figure 11 shows the start of the ramp from 200 A to 225 A. It is the zone where the snap-back effect is present. On Figure 11-b and 11-c (zoom), it can be seen that there is no lagging error.

Figure 12 shows the end of the ramp. The Figure 12-b presents the round off at the end of the ramp. It can be noted that the overshoot is almost equal to zero.

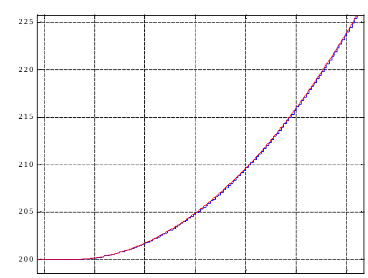

Figure 11-a: from 200 A to 225 A

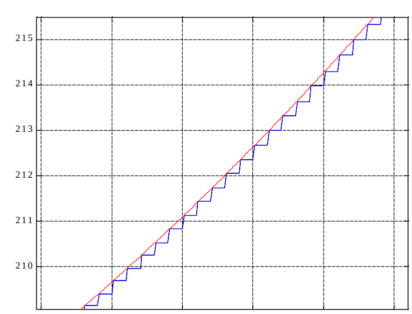

Figure 11-b: from 210 A to 215 A

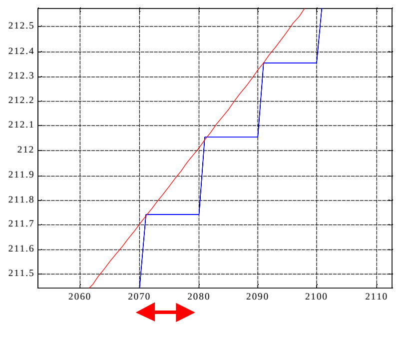

Figure 11-c: from 211.5 A to 212.5 A

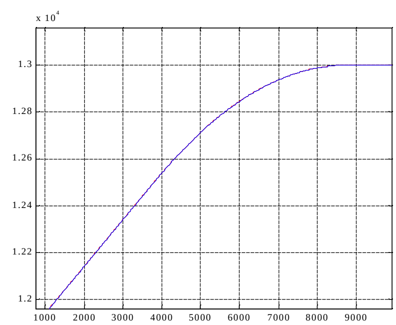

Figure 12-a: from 12'000 A to 13'000 A

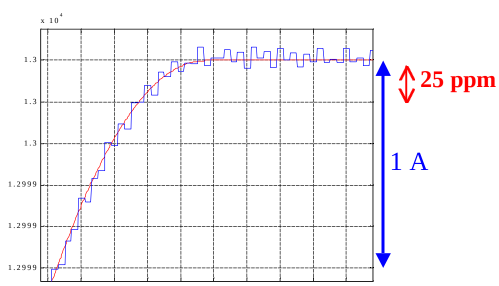

Figure 12-b: from 12'999 A to 13'000 A

5 CONCLUSION

As a result of the tests completed to date, the control of the magnet current seems to fulfil all the performance requirements of the LHC:

- high precision: accuracy, reproducibility, stability, resolution
- no overshoots and undershoots
- low voltage ripple and high perturbation rejection
- large current range (for 1-quadrant converter: from 1% to 100%)

6 ACKNOWLEDGMENTS

Thanks are due all members of the SL/PO group involved in the work described and for all the ideas and information they provided

REFERENCES

[1] L. Bottura, “From the LEP warm magnets to the LHC superconducting magnets”, Proceedings of the workshop on LEP-SPS performance, Chamonix X , January 2000

[2] O. Brüning, “ Accelerator physics requirements at commissioning”, Proceedings of the LHC, Chamonix XI, January 2001, (these proceedings).

[3] P. Cruikshank, P. Proudlock, G. Ridone, R. Saban, R. Schmidt, “General parameters for equipment installed in the LHC”, LHC-PM-ES-0002.00, April 1999

[4] G. Fernqvist, J. Petersen, “Main parameters of the LHC 400/230 V”, Engineering Specification, LHC-EM-ES-0001, August 2000

[5] G. Fernqvist, ”The measurement challenge of the LHC project”, CPEM’98 Conference, Washington, July 98.

[6] F. Bordry and al, “An LHC 20 kA, 6 V power converter prototype”, EPAC’98, Stockholm, June 1998

[7] I. Barnett, G. Fernqvist, D. Hundzinger, J-C Perrerard, J. Pett, “A Strategy for controlling the LHC magnet currents”, EPAC’96, Barcelona, June 96.

[8] F. Bordry, A.Dupaquier, “High Current, Low Voltage Power Converters for LHC. Present Development Directions”, EPAC’96, Barcelona, June 96.

[9] F Bordry, H. Thiesen, “RST Digital Algorithm for controlling the LHC magnet current”, Electrical Power Technology in European Physics Research EP2, Grenoble, October 1998