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Estimation of the electrical power needed for LHC magnets and radiofrequency at 7 TeV

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Summary

The purpose of this paper is to provide the electrical power needed from the grid for the power converters feeding the magnets (superconducting, warm and experiments) and the radiofrequency of the LHC. At 4 TeV, the active power required for the magnets is 17.6MW and the estimation is 25.5MW at 7 TeV. The active power needed for the radiofrequency depends on the beam intensity and on the bunch spacing. It will grow from 7MW to 10MW with 25ns bunch spacing operation. This does not include the power needed for the cryogenic and magnet auxiliary systems. This paper gives also the instantaneous profile of the power needed from the grid during the ramp and the reactive power which needs to be compensated by the static VAR compensators.

1. Introduction

The purpose of this note is to provide the electrical power needed from the electrical grid for the power converters feeding the magnets and the radiofrequency of the LHC. It concerns all the circuits powered by power converters under TE-EPC responsibility, which corresponds to all magnet circuits (superconducting, warm and experiments) and the klystron modulators for the radiofrequency. This note describes the methodology to estimate the power consumption at 4 TeV and 7 TeV. A campaign of measurements was done in April 2012 at 4 TeV to validate the methodology.

2. Methodology to estimate the power needed from the grid

The power needed from the electrical grid is the sum of the losses in the power converters and the losses in the circuits which includes DC cables and magnets. The efficiency of the power converters gives the losses dissipated in the power converters. All the parameters of the circuits come from the CERN layout database (as of 1st March 2012). The parameters R_total and L_total correspond to the resistance and inductance of the whole circuit connected on each power converter, which means magnets and DC cables. These parameters were checked and updated in the layout database during the hardware commissioning of the LHC in 2007. The main difficulty to evaluate the power needed is linked to the fact that the currents of many circuits aren't proportional to the beam energy.

Here are the hypotheses taken to evaluate the power needed from the grid at 7 TeV:

➢ **Type of Circuit**

- For all high-current superconducting circuits (> 1kA), all warm magnets and experiment magnets, the calculation is done with the nominal current (7 TeV) of each circuit.
- For the 600A corrector circuits, the estimation is made at 50% of their nominal current. The correctors are designed to correct imperfections of the machine and their operating points vary between 0 and 100% of the nominal current. A value of 50% is more realistic than a value of 100%.
- For 60A and 120A corrector circuits, they will not be taken into account. Most of them operate below 50% of their nominal current and their electrical consumption is negligible compared to the others circuits.

➢ **Power converter losses**

The power converter losses were measured during reception tests at CERN and they depend strongly on the power converter topology.

For switch-mode converters, the losses can be directly evaluated from the efficiency, which can be found below:

- For converters RPHE [13kA/18V] and RPHK [20kA/18V] (ATLAS Toroid), the efficiency is 80%. This efficiency seems low for a switch-mode converter, but it must be taken into account that these converters are very high current and low voltage. Moreover, they do not operate at nominal power while they deliver the nominal current.
- For converters RPHF/RPHG/RPHH [4-6-8kA/8V], the efficiency is 70% for the same reasons.
- For 4-quadrant converters RPMB [± 600A/± 10V] and RPMC [± 600A/± 40V], the efficiency is 70%. This relatively low efficiency is due to the high number of conversion stages needed to operate in the 4-quadrants.

For thyristor converters (RPTE type), the estimation of the losses is obtained by summation of its main losses, which are:

- The transformer losses, rated at 1% of their nominal power. These losses can be split into 50% of iron losses (independent of the output current of the converter) and into 50% of copper losses (proportional to the square output current of the converter).
- The thyristor losses which can be approximated by two thyristors in series with the load, giving power losses of 2 * Thyristor_voltage_drop * Iout (A), with Iout the output current of the power converter and the voltage drop of the thyristor can be estimated at 1V.
- The copper losses in the converters which are located mainly in the choke of the output filter and are defined in the technical specifications of the converters.

➢ **Apparent power**

The apparent power depends strongly on the power converter topology.

For switch-mode converters, the apparent power (S_in) is proportional to the active power (P_in). These power converters are equipped with a 3-phases diode rectifier on the AC side and have a fixed power factor (PF) of 0.95 [2].

S_in = P_in * PF

For thyristor converters, the apparent power is proportional to the output current of the converter and not to the output power. The apparent power can be calculated using an estimation of the AC line current.

S_in = SQRT (3) * U_line * I_line

The line current can be calculated using the RMS secondary current of the transformer.

I_line = SQRT (7/12) * Transformer Ratio * I_out

SQRT (7/12) is the ratio between the output current versus RMS current for 12-pulse thyristor converters (see annex B).

3. Examples

3.1 Example of circuit RQD.A12

This circuit is powered by a switch-mode power converter type RPHE. Here are the parameters extracted from the layout database for the circuit RQD.A12.

The total inductance of the circuit is: L_TOTAL = 0.263 H
The total resistance of the circuit is: R_TOTAL = 0.001 Ω
The di/dt_max of the circuit is: MAX_DIDT = 10 A /s
The nominal current of the circuit is: I_NOMINAL = 11870 A

At 7 TeV during the flat top

- the output voltage of the converter is:

  U_COLL = R_TOTAL * I_NOMINAL = 11.87 V

- the output power of the converter is:

  P_out = U_COLL * I_NOMINAL = 141 kW

- the input power needed from the grid is:

  P_in = P_out / efficiency = 176 kW

- the average apparent power is, using a power factor (PF) of 0.95:

  S_in = P_in / PF = 185 kVA

At 7 TeV at the end of the ramp

- At the end of ramp, the peak output voltage of the converter is:

  U_PEAK_CIRC = U_COLL + U_BOOST

  = U_COLL + L_TOTAL * MAX_DIDT = 14.5 V

- the peak output power supplied by the converter is:

  P_out_Peak = U_PEAK_CIRC * I_NOMINAL = 172 kW

- the peak input power needed from the grid is:

  P_in_Peak = P_out_PEAK / efficiency = 215 kW

- Using a power factor (PF) of 0.95, the peak apparent power is:

  S_in_Peak = P_in_Peak / PF = 226 kVA

PC NAME	L TO [H]	R TOTAL [Ohm]	MAX DI DT [A/s]	U BOOST [V]	U COLL [V]	U PEAK CIRC [V]	I NOMINAL [A]	P_out [kW]	P_out PEAK [kW]	efficiency	P_in [kW]	P_in PEAK [kW]	P.F.	S_in [kVA]	S_in PEAK [kVA]
RPHE.UA23.RQD.A12	0.263	0.001	10	2.6300	11.8700	14.5000	11870	140.90	172.12	0.80	176.12	215.14	0.95	185.39	226.47

Table 1: summary of all the calculations for circuit RQD.A12

3.2 Example of circuit RB.A12

This circuit is powered by a thyristor converter type RPTE supplied with 18kV. Here are the parameters extracted from the layout database:

The total inductance of the circuit is: L_TOTAL = 15.7 H
The total resistance of the circuit is: R_TOTAL = 0.00989 Ω
The di/dt_max of the circuit is: MAX_DIDT = 10 A /s
The nominal current of the circuit is: I_NOMINAL = 11850 A

At 7 TeV

- During the flat top, the active power needed from the grid is:

  P_in = P_out + losses = 154 kW + 105 kW =259 kW (see Annex A)

- At the end of ramp, the peak active power needed from the grid is:

  P_in_Peak = P_out_Peak + losses = 2120 kW

- At the end of ramp, the apparent power on the grid is:

  S_in_Peak = SQRT (3) * U_line * I_line

  = SQRT (3) * 18000 * I_NOMINAL * SQRT (7/12) * 190 / 18000

  = 2978 kVA

  Where 190/18000 is the transformer ratio.

PC NAME	L TO [H]	R TOTAL [Ohm]	MAX DI DT [A/s]	U BOOST [V]	U COLL [V]	U PEAK CIRC [V]	I NOMINAL [A]	P_out [kW]	P_out PEAK [kW]	Losses [kW]	P_in [kW]	P_in PEAK [kW]	transformer ratio	S_in [kVA]	S_in PEAK [kVA]
RPTE.UA23.RB.A12	15.708	0.0011	10	157.08	13.035	170.115	11850	154.46	2015.86	105	259.46	2120.86	94.74	2978.45	2978.45

Table 2: summary of all the calculations for circuit RB.A12

3.3 Example of IPQ circuits

The IPQ circuits (Individually Powered Quadrupole) are coupled circuits (B1 and B2). The converters B1 and B2 have a common return cable. If the currents are balanced between B1 and B2 converters, no current flows in the common return cable. In this case, the losses in DC cables can be divided by two compared to standalone powering. Therefore R_TOTAL must be replaced by (0.5 * R_TOTAL) in U_COLL calculations.

In the example of RQ4.L2B1 and RQ4.L2B2 circuits, at 7 TeV during the flat top, the output voltage is:

U_COLL = 0.5 * R_TOTAL * I_NOMINAL = 1.63V

PC NAME	L TOT [H]	R TOTAL [Ohm]	MAX DI DT [A/s]	U BOOST [V]	U COLL [V]	U PEAK CIRC [V]	I NOMINAL [A]	P_out [kW]	P_out PEAK [kW]	efficiency	P_in [kW]	P_in PEAK [kW]	P.F.	S_in [kVA]	S_in PEAK [kVA]
RPHH.UA23.RQ4.L2B1	0.148	0.000904	10.833	1.6033	1.6317	3.2350	3610	5.89	11.68	0.70	8.42	16.68	0.95	8.86	17.56
RPHH.UA23.RQ4.L2B2	0.148	0.000904	10.833	1.6033	1.6317	3.2350	3610	5.89	11.68	0.70	8.42	16.68	0.95	8.86	17.56

Table 3: summary of all the calculations for circuit RQ4.L2

3 Total power needed at 7 TeV

3.1 Power converters for the LHC Experiments

The power converters for the experiments (Atlas, Alice, CMS and LHCb) and their magnetic compensators for Alice and LHCb, are powered continuously at their nominal current, independently of the beam energy.

PC NAME	RACK LOCATION	U COLL [V]	I NOMINAL [A]	P_out [kW]	P_in [kW]	S_in [kVA]
RPHK.USA15.RXTOR.ATLAS	USA15	8.404	21010	176.57	220.71	232.33
RPHFA.USA15.RXSOL.ATLAS	USA15	4.8	8000	38.40	54.86	57.74
Total Atlas					**275.57**	**290.07**
RPTH.SX2.RXSOL.ALICE	SX2	136.4	31000	4228.40	4450.95	5434.53
RPTI.SR2.RBAWV.R2	SR2	630	6000	3780.00	3978.95	7143.53
RPTL.SR2.RBWMDV.L2	SR2	104.5	550	57.48	71.84	119.74
RPTL.SR2.RBXWTV.L2	SR2	36	600	21.60	27.00	45.00
RPTL.SR2.RBXWTV.R2	SR2	30	600	18.00	22.50	37.50
Total Alice					**8551.24**	**12780.30**
RPTJ.USC55.RXSOL.CMS	USC55	1.816	18160	32.98	109.93	816.80
Total CMS					**109.93**	**816.80**
RPTI.SR8.RBLWH.R8	SR8	748.8	5850	4380.48	4611.03	6964.94
RPTN.SR8.RBXWH.L8	SR8	63.75	750	47.81	59.77	99.61
RPTN.SR8.RBXWSH.L8	SR8	32.76	780	25.55	31.94	53.24
RPTN.SR8.RBXWSH.R8	SR8	32.76	780	25.55	31.94	53.24
Total LHCb					**4734.68**	**7171.02**

Table 4: Power needed for the magnet experiments

3.2 Klystron modulators for the radiofrequency cavities

Four klystron modulators, type RPTK [100kV/40A] supplied with 18kV, provide the continuous DC voltage to the klystrons used by the LHC radiofrequency cavities. All are located at point 4.

Currently with the LHC at 4 TeV with bunch spacing at 50ηs, these converters provide a current of 30A at 50kV, corresponding to 1.5MW of active power by modulator. The losses can be estimated to 0.25MW by modulator at this level. The active power taken on the grid is then 1.75MW per modulator. The total power consumption for the radiofrequency is rated to 7MW. These modulators are thyristor type converters which generate a lot of reactive power. The apparent power is then much higher than the active power and it can be estimated to:

S_in = SQRT (3) * U_Line * I_ Line
= SQRT (3) * 18,000 * 30 * SQRT (7/12) * (100000/18000)
= 3.97 MVA

The total apparent power is closed to 16MVA for all the 4 klystron modulators.

PC Name	LOCATION	Udc Klstron [V]	I NOMINAL [A]	P_out [kW]	P_in [kW]	S_in [kVA]
RPTK.SR4.RA43U2.L4	SR4	50000.00	30.00	1500.00	1750.00	3969
RPTK.SR4.RA43U3.L4	SR4	50000.00	30.00	1500.00	1750.00	3969
RPTK.SR4.RA47U2.R4	SR4	50000.00	30.00	1500.00	1750.00	3969
RPTK.SR4.RA47U3.R4	SR4	50000.00	30.00	1500.00	1750.00	3969
Total RF				**6000**	**7000**	**15875**

Table 5: Power needed for the radiofrequency at 4 TeV

The power needed by the RF does not depend on the beam energy but it depends on the beam intensity and on the bunch spacing. With the foreseen increase of beam intensity associated with the operation at 25ηs of bunch spacing, the klystron could operate up to 58kV at 9A each. A modulator is powering 4 klystrons, which gives 36A at the output of the modulator. The total power will be closed to 10MW, and the apparent power closed to 19MVA.

PC Name	LOCATION	Udc Klystron [V]	I NOMINAL [A]	P_out [kW]	P_in [kW]	S_in [kVA]
RPTK.SR4.RA43U2.L4	SR4	58000.00	36.00	2088.00	2438.00	4762
RPTK.SR4.RA43U3.L4	SR4	58000.00	36.00	2088.00	2438.00	4762
RPTK.SR4.RA47U2.R4	SR4	58000.00	36.00	2088.00	2438.00	4762
RPTK.SR4.RA47U3.R4	SR4	58000.00	36.00	2088.00	2438.00	4762
Total RF				**8352**	**9752**	**19049**

Table 6: Power needed for the radiofrequency at 7 TeV with high intensity beams and operation at 25ηs of bunch spacing

3.3 Power converters for the LHC magnets

Apart the experiments, the power for all circuits depends on the beam energy of the machine. The estimation of the power needed at 7 TeV is shown in the table below, where the power converters are grouped by family in different locations of the machine as described below:

WM Power converters of the warm magnets
SC Power converters of the superconducting magnets
RPTE Power converters of the main dipoles circuits

PC Type	LOCATION	P_out [kW]	P_out PEAK [kW]	P_in [kW]	P_in PEAK [kW]	S_in [kVA]	S_in PEAK [kVA]
WM	SR1	438.75	441.38	453.75	456.38	892.94	892.94
SC	UJ14/RR13	151.17	196.40	215.97	280.57	227.34	295.34
SC	UJ16/RR17	145.16	191.00	208.26	272.86	219.22	287.22
Total LHC-1				**877.98**	**1009.81**	**1339.50**	**1475.50**
RPTE	UA23	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA23/UJ23	554.58	690.20	738.79	921.38	777.67	969.87
RPTE	UA27	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA27/UJ27	545.06	677.91	721.83	899.49	759.82	946.83
Total LHC-2				**1979.54**	**6062.59**	**7494.39**	**7873.60**
WM	SR3	929.19	933.58	972.19	976.59	1664.96	1664.96
WM	UJ33	171.78	172.49	245.39	246.41	258.31	259.38
SC	UJ33	30.01	38.63	42.87	55.18	45.13	58.08
Total LHC-3				**1260.45**	**1278.18**	**1968.39**	**1982.42**
RPTE	UA43	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA43/UJ43	379.19	491.23	499.63	647.57	525.93	681.65
RPTE	UA47	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA47/UJ47	385.61	492.19	507.63	648.73	534.35	682.87
Total LHC-4				**1526.18**	**5538.02**	**7017.18**	**7321.42**
WM	SR5	438.75	441.38	453.75	456.38	892.94	892.94
SC	USC55/RR53	191.68	236.91	273.84	338.44	288.25	356.25
SC	UJ56/RR57	174.06	219.28	248.65	313.26	261.74	329.75
Total LHC-5				**976.24**	**1108.08**	**1442.93**	**1578.94**
WM	SR6	851.84	864.25	877.84	890.26	1327.10	1327.10
RPTE	UA63	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA63/UJ63	326.11	418.60	430.89	551.87	453.57	580.92
RPTE	UA67	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA67/UJ67	344.01	441.96	448.62	576.43	472.23	606.77
Total LHC-6				**2276.27**	**6260.28**	**8209.80**	**8471.69**
WM	SR7	702.81	706.04	745.80	749.03	1664.96	1664.96
WM	UJ76	133.11	133.57	190.15	190.81	200.16	200.85
SC	RR73	4.34	8.10	6.21	11.57	6.54	12.18
SC	RR77	4.65	8.40	6.64	12.00	6.99	12.63
Total LHC-7				**948.80**	**963.41**	**1878.64**	**1890.62**
RPTE	UA83	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA83/UJ83	549.89	682.76	729.65	907.35	768.05	955.11
RPTE	UA87	154.46	2015.86	259.46	2120.86	2978.45	2978.45
SC	UA87/UJ87	527.29	662.92	700.47	883.06	737.34	929.54
Total LHC-8				**1949.04**	**6032.13**	**7462.29**	**7841.55**

Table 7: Power needed for the magnets

3.4 Overall power needed for LHC magnets and radiofrequency

The table below shows the estimated overall power of the LHC power converters at 7 TeV. The power converters in TI2 and TI8 are not directly associated with the LHC, and therefore are not included in this estimate.

	P_in [MW]	P_in PEAK [MW]	S_in [MVA]	S_in PEAK [MVA]
Expériments	13.70	13.70	21.00	21.00
RF	9.75	9.75	19.05	19.05
Machine	11.80	28.30	36.80	38.40
Total	**35.25**	**51.75**	**76.85**	**78.45**

Table 8: Power needed for all the LHC magnets and radiofrequency at 7 TeV

The graph below shows the profile of the instantaneous power during the ramp in energy from 450 GeV to 7 TeV, assuming that the beam energy increases linearly with time and that the ramp is done in 20 minutes.

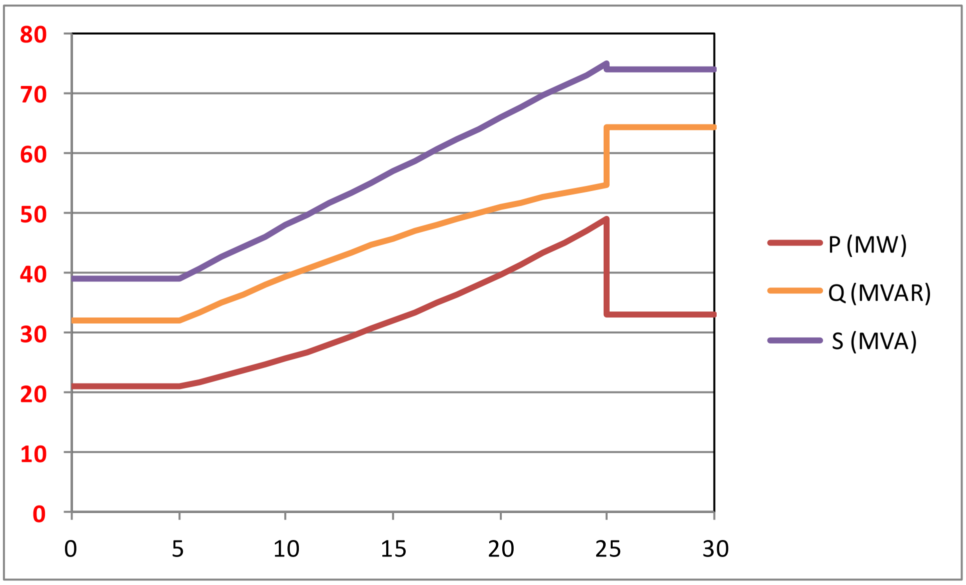

Figure 1: LHC power cycle

The vertical axis represents the active, reactive and apparent power, respectively in MW, MVAR and MVA.

The reactive power, mainly generated by the thyristor power converters, is calculated by the following equation: $Q = SQRT(S^2 – P^2)$.

The reactive power is compensated by the static VAR compensators (SVC) which are located at points 2, 4, 6 and 8 of the LHC. In this case, only the active power is taken on the 400kV/66kV main transformers. Unfortunately, this is not the case in point 1 where no SVC is installed.

4 Measurements done at 4 TeV

To validate the estimation of power consumption at 7 TeV, measurements were done at 4 TeV in April 2012. To obtain the power consumption at 4 TeV from data at 7 TeV the following rules were applied:

- For switch-mode converters, the estimations at 7 TeV are multiplied by a factor 16/49 ($4^2/7^2$), the power being proportional to the square of the beam energy.

- For thyristor converters, except RPTE converters, the active power is multiplied by a factor 16/49, but a factor of 4/7 is used for the apparent power. In fact, for thyristor converters, the apparent power is proportional to the beam energy.

- For the main dipole (RPTE type) power converters, the active power has to be calculated taking into account the copper losses, iron losses and thyristor losses. At 4 TeV, the active power is 104kW (see annex A).

The LHC is composed of eight sectors which are almost identical. The measurements were done only on relevant circuits, which are: the experiments, RF, RB.A12, UA23, RR13, UJ33, RD1.LR1, RD34.LR3, SR3 (RQ4.LR3 and RQ5.LR3) and RPTM at point 6.

The table 9 summarizes the measurements and compares measurements and estimations at 4 TeV.

The active power (P_meas) and reactive power (Q_meas) were measured from the 18kV switchgears. The apparent power (S_Meas) is calculated with the equation: $S^2 = P^2 + Q^2$ (The harmonics are then not taken into account).

P_cal and S_cal represent the estimations of active power and apparent power at 4 TeV.

In most cases, the measurements correspond to the estimated values. In total, the difference between the estimations and measurements is less than 5%. Therefore the estimation for the LHC power converters at 7 TeV can be considered as accurate.

The table 10 gives the detailed estimates of power needed for the power converters at 4 TeV (except the RF and the experiment power converters).

18kV cell	Power converter	Date	Time	Energy [TeV]		P_meas [kW]	P_cal [kW]	Err [%]		Q_meas [kVAR]		S_meas [kVA]	S_cal [kVA]	Err [%]
EMD405/1E	Atlas (EXD3 et EXD4)	2012/04/11	20H-23H	4.00		319.00	275.57	13.61		40.00		321.50	290.07	9.78
EMD407/2E	Alice Solenoide	2012/04/12	14:10	4.00		4162.00	4168.42	-0.15		3564.00		5479.45	5259.22	4.02
EMD410/2E	Alice Dipole	2012/04/12	14:10	4.00		3922.00	3978.95	-1.45		6407.00		7512.11	7143.53	4.91
EMD210/5E	CMS	2012/04/12	14:10	4.00		138.00	109.93	20.34		823.00		834.49	816.00	2.22
EMD411/8E	LHCb Dipole	2012/04/12	14:10	4.00		4644.00	4611.03	0.71		5717.00		7365.52	6964.94	5.44
EMD207/4E	Total RF	2012/04/12	14:10	4.00		6736.00	7000.00	-3.92		14374.00		15874.05	15874.52	0.00
EMD203/1E	RD1.LR1	2012/04/11	20H-23H	4.00		125.00	148.16	-18.53		400.00		419.08	510.25	-21.76
EMD402/1E	RR13	2012/04/11	20H-23H	4.00		72.00	51.41	28.59		0.00		72.00	54.12	24.83
EMD602/2E	RB.A12	2012/04/11	20H-23H	4.00		120.00	104.00	13.33		1750.00		1754.11	1701.97	2.97
		2012/04/12	15:30	4.00	(*)	1089.00	1211.92	-11.29		1300.00		1695.85	1701.97	-0.36
EMD601/2E	UA23	2012/04/11	20H-23H	4.00		220.00	241.24	-9.65		0.00		220.00	253.93	-15.42
EMD304/3E	RD34.LR3	2012/04/11	20H-23H	4.00		120.00	143.70	-19.75		386.00		404.22	489.84	-21.18
EMD303/3E	SR3	2012/04/11	20H-23H	4.00		127.00	173.75	-36.81		453.00		470.47	461.57	1.89
EMD305/3E	UJ33	2012/04/11	20H-23H	4.00		75.00	94.13	-25.50		57.00		94.20	99.08	-5.18
EMD406/6E	RPTM	2012/04/11	20H-23H	4.00		127.00	143.32	-12.85		328.00		351.73	379.17	-7.80
EMD408/6E	RPTM	2012/04/11	20H-23H	4.00		127.00	143.32	-12.85		328.00		351.73	379.17	-7.80
Total						**21034.00**	**21386.93**	**-1.68**				**41524.64**	**40677.38**	**2.04**

Table 9: Power estimations and power measurements

PC Type	LOCATION	P_out [kW]	P_in [kW]	S_in [kVA]
WM	SR1	143.27	148.16	510.25
SC	UJ14/RR13	49.36	70.52	74.23
SC	UJ16/RR17	47.40	68.00	71.58
Total LHC-1			**286.69**	**656.07**
RPTE	UA23	50.44	95.00	1701.97
SC	UA23/UJ23	181.09	241.24	253.93
RPTE	UA27	50.44	95.00	1701.97
SC	UA27/UJ27	177.98	235.70	248.10
Total LHC-2			**666.94**	**3905.98**
WM	SR3	303.41	317.45	951.41
WM	UJ33	56.09	80.13	84.34
SC	UJ33	9.80	14.00	14.74
Total LHC-3			**411.58**	**1050.49**
RPTE	UA43	50.44	95.00	1701.97
SC	UA43/UJ43	123.82	163.14	171.73
RPTE	UA47	50.44	95.00	1701.97
SC	UA47/UJ47	125.91	165.76	174.48
Total LHC-4			**518.90**	**3750.16**
WM	SR5	143.27	148.16	510.25
SC	USC55/RR53	62.59	89.42	94.12
SC	UJ56/RR57	56.84	81.19	85.47
Total LHC-5			**318.77**	**689.84**
WM	SR6	278.15	286.64	758.34
RPTE	UA63	50.44	95.00	1701.97
SC	UA63/UJ63	106.48	140.70	148.10
RPTE	UA67	50.44	95.00	1701.97
SC	UA67/UJ67	112.33	146.49	154.20
Total LHC-6			**763.83**	**4464.59**
WM	SR7	229.49	243.53	951.41
WM	UJ76	43.46	62.09	65.36
SC	RR73	1.42	2.03	2.13
SC	RR77	1.52	2.17	2.28
Total LHC-7			**309.81**	**1021.18**
RPTE	UA83	50.44	95.00	1701.97
SC	UA83/UJ83	179.56	238.25	250.79
RPTE	UA87	50.44	95.00	1701.97
SC	UA87/UJ87	172.18	228.72	240.76
Total LHC-8			**656.98**	**3895.50**

Table 10: Power needed for the magnets at 4 TeV

The total power needed at 4 TeV for the magnets and radiofrequency can be found in the table 11:

	P_in [MW]	S_in [MVA]
Expériences	13.70	21.00
RF	7.00	15.90
Machine	3.90	19.40
Total	**24.60**	**56.30**

Table 11: Power needed for the magnets and radiofrequency at 4 TeV

Annex A –Losses in RPTE converter (powering the dipole circuit)

This power converter is composed of two interleaved 6-pulse thyristor bridges in parallel.
The nominal current at 7 TeV is 11.85kA.

The following table gives the calculation of the losses of the main dipole power converter at 7 TeV and 4 TeV.

			7 TeV	4 TeV
Losses in the transformers				
Number of transformers	2	unit		
Nominal power per transformer	2	MVA		
Iron losses per transformer		kW	10.00	10.00
Copper losses per transformer		kW	10.00	3.27
Global losses		kW	40.00	26.53
Losses in the thyritor bridges				
Number of bridges	2	unit		
Thyristor voltage drop		V	1.00	1.00
Current per bridge		kA	6.00	3.43
Losses per bridge		kW	12.00	6.86
Global losses		kW	24.00	13.71
Losses in the filter inductances				
Number of inductances	2	unit		
Inductance voltage drop		V	3.50	2.00
Current per inductance		kA	6.00	3.43
Losses per bridge		kW	21.00	6.86
Global losses		kW	42.00	13.71
Global losses per converter		kW	106.00	53.96
Global output power per converter		kW	154.00	50.29
Global input power per converter		**kW**	**260.00**	**104.24**

Table 12: RPTE power converter

Annex B – Line current of thyristor converter

The line current waveform for a 12-pulse thyristor converter can be found in figure 2.

The rms line current can be calculated with : I_line_rms = sqrt (7/12) * I_load

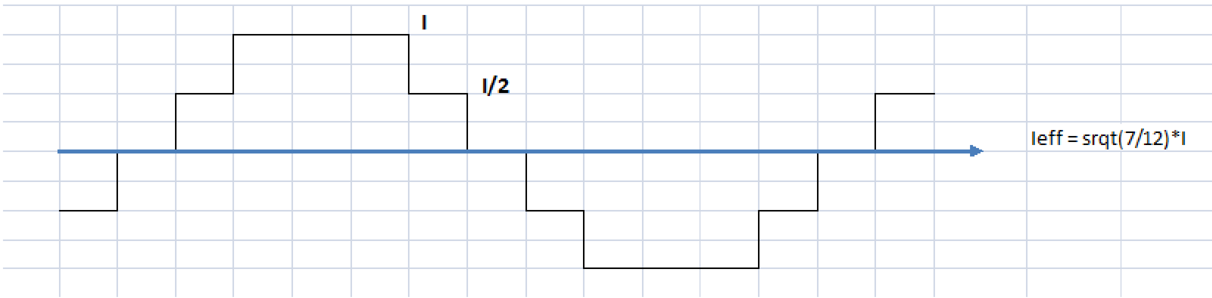

Figure 2: Line current waveform of 12-pulse thyristor converter

Glossary

P_in :	Active power needed from the grid during the flat top at 7 TeV
P_in_PEAK :	Maximum active power needed from the grid at the end of the ramp
S_in :	Apparent power needed from the grid during the flat top
S_in_PEAK :	Maximum apparent power needed from the grid at the end of the ramp
P :	Instantaneous active power from the grid
Q :	Instantaneous reactive power needed from the grid
S :	Instantaneous apparent power from the grid
PF :	Power factor
P_out :	power of a circuit during the flat top at 7 TeV
P_out_peak :	Maximum power of a circuit at the end of the ramp
U_line :	Voltage of the grid
I_Line :	Current of one phase of the grid
I_out :	Output current of the power converter
U_out :	Output voltage of the power converter
Udc_klystron:	DC voltage applied to the Klystron
I_Nominal :	Output current of the power converter at 7 TeV
L_TOTAL :	The total inductance of the circuit
R_TOTAL :	The total resistance of the circuit
MAX_DIDT :	Maximum di/dt of the circuit during the ramp
U_COLL :	Output voltage of the power converter at 7 TeV
U_BOOST :	Additional voltage needed for the ramp
U_PEAK_CIRC :	Maximum voltage of a circuit
WM :	Warm Magnet power converters
ERD :	400V electrical switchboard feeding the power converters
RPTE :	[13kA/180V], thyristor converter feeding the dipole circuit
RPHE :	[13kA/18V], Switch-mode converter feeding the quadrupole
RPHK :	[20kA/18V], Switch-mode converter feeding the Atlas toroid
RPMB :	[± 600A/± 10V], Switch-mode converter for 600A circuit
RPMC :	[± 600A/± 40V], Switch-mode converter for 600A circuit
RPHK :	[4kA/8V], Switch-mode converter for 4kA circuit
RPHG :	[6kA/8V], Switch-mode converter for 6kA circuit
RPHH :	[6kA/8V], Switch-mode converter for 6kA circuit
RPTK :	[100kV/40A], Klystron modulator
WM :	Power converters for the warm magnets
SC :	Power converters for the superconducting magnets
SVC :	Static VAR compensator

References

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