ELECTRICAL POWERING STRATEGY OF LHC FIRST DESIGN STUDY

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Abstract

Superconducting accelerators, and in particular the LHC, require detailed analysis of the electrical powering due to the integrated nature of these machines. The situation is made more difficult in LHC where the maximum use needs to be made of the existing infrastructure, notably the AC electrical distribution and the underground excavations of LEP. This, coupled with the dynamic performance of the main dipole magnets, the quench protection requirements and the needs of the accelerator physics, have meant that new powering techniques, as well as tighter power converter performance specifications, will be required. A description of the powering system of LHC is given along with the reasons for adopting certain solutions. The static and dynamic requirements of the machine are also discussed and the first ideas for solving some of these problems are presented. In all the LHC will use about 1500 power converters able to supply approximately 1750 kA in total. Some of the on-going studies to achieve a better optimisation of the powering system are also discussed.

1 INTRODUCTION

Recent studies have been directed towards the optimum use of the existing infrastructure of LEP, which is concentrated in the even points. This has become known as the "four feed point" version [1]. By engineering all the cryogenic plant into the even points, the existing 66 kV (38MVA) supplies and cooling towers of LEP can be re-used. For the same reasons, it is equally desirable that the DC feed of the machine is concentrated at the even points. While LEP requires high voltage and low current for its loads, LHC will require very large currents and rather small voltages for its superconducting magnets. Although it was relatively easy and inexpensive to install the power converters for LEP on the surface and cable them to their underground loads, such an approach would be prohibitive for LHC because of the high DC currents. Fortunately, LHC will not need the large RF complex used for LEP2 at the even points, nor will any future electron machine installed with LHC. Thus the large RF galleries, parallel to the tunnel, can be vacated to allow the underground installation of high current power converters very close to the current feedthroughs.

2 GENERAL POWERING PHILOSOPHY

In the new powering scheme all the main lattice elements (Main Dipoles, Quadrupoles, Sextupoles, Octupoles and Spool Pieces) are fed from the even points, left and right, using superconducting bus-bars running through the machine cryostat and the magnet cold masses. This segmentation of the machine into eight, rather than 16, eliminates the need for any lattice power converters in the odd points where little infrastructure exists. Further, the main quadrupoles, QD and QF, have been separated from the dipole circuit so as to give maximum tune flexibility to the machine. This also minimises the installation in the odd points, since the bus-bars of the main quadrupoles (QD and QF) continue into the insertion regions and are used to power the quadrupoles of the dispersion suppressor and, where appropriate, other quadrupoles of the insertion. Low current trim quadrupoles, placed next to the quadrupoles, adjust the necessary overall field gradient. The associated small power converters can be located in the existing but restricted underground areas in the odd points. In the cleaning insertions of points 3 and 7, the FODO cells and separators use warm magnets which can be powered from the surface using the existing surface buildings and cabling of LEP.

3 THE LATTICE CIRCUITS

3.1 Main Dipole Circuits

The quench protection system uses cold by-pass diodes across each magnet with energy extraction to decrease rapidly the current should a magnet quench [2]. The total inductance of all 1232 dipole magnets in LHC is 148 H which has a stored energy of 11.6 GJ at the ultimate current of 12.5 kA. If all magnets were connected in series then a voltage of about 18 kV would be needed in order to extract this energy. This is the main reason for electrically segmenting the machine in eight. There are however other advantages:

- only 1/8 of the machine (a sector) needs to be rapidly discharged if a magnet quenches,
- no risk, in principle, of a complete machine avalanche quench or voltage build-up,
- eight galvanically isolated and earthed systems,
- saves on heavy current connection across the eight 500 m straight sections,
- eight sub-sections for installation, commissioning and fault finding,
- allows sector-to-sector correction of the field and field errors, both static and dynamic, due to different cable and magnet manufacturers. (A sector will contain magnets from the same manufacturer, batch and having the same cable.)

The disadvantage is an increase in the complexity of power converter control, resolution and short term stability.

The eight current source power converters each power ring 1 and 2 in series and are placed in the RF galleries in points 2, 4, 6 and 8 (see Figure 1). One sector (1/8 of the machine) of the main dipole circuit is shown in Figure 2. The total inductance (18.5 H) is divided equally between the go and return lines by using two types of dipole magnet having connections to either the go or return bus. This allows two sets of extraction resistors and shorting switches to be located at each end of the circuit to minimise the voltage to earth during energy extraction. The centre point of the far end resistors is connected to earth to give a symmetrical electrical circuit during both energy extraction and normal operation. This configuration has been shown to minimise common mode noise. On flat top, the current source power converters will need about 10 V at 12.5 kA to feed the resistive part of the connections and a voltage of ±185 V to achieve a normal ramp of ±10 A/s. The electrical time constant of the circuit is about 23’000 seconds.

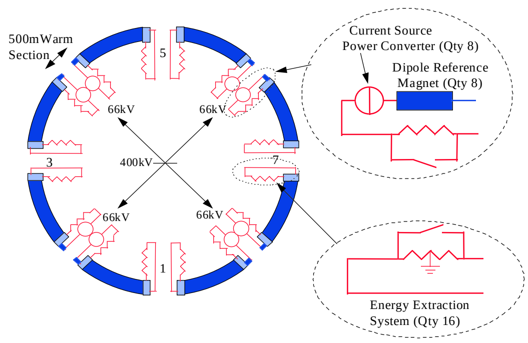

Figure 1 Segmentation of Main Dipoles

3.1 *Main Quadrupole Circuits*

The QD and QF circuits (ring 1 and 2 in series) are separately powered to allow different vertical and horizontal phase advances and, in conformity with the dipole circuits, are segmented into eight, giving a total of 16 circuits. Small tune shift quadrupoles in the arcs are used to correct the b2 differences between rings 1 and 2 and give the possibility of fast tune adjustments. The relatively low inductance of the main quadrupole circuit means that only one energy extraction system is needed per circuit and one current source power converter of 15V/12.5 kA per circuit is sufficient. The time constant of the circuit is about 350 seconds.

3.2 *Auxiliary Circuits*

In each sector it is proposed to have:

- four or eight families of lattice sextupoles,
- several families of arc tuning quadrupoles, octupoles and skew quadrupoles,
- two families each of b3 and b5 main dipole spool piece correctors.

This gives full flexibility for correction on a sector-to-sector basis and again sub-divides the circuits into manageable portions for quench protection. It is proposed not to use by-pass diodes on these circuits but to rely on rapid energy extraction (~1 sec) to protect a quenching magnet. The power converters can be placed near to the current feedboxes and need only low voltage (12 V) and 600 A. Some will need to be fully bipolar. There will be about 400 in all, the majority being placed in the vacated RF galleries along with the power converters of the main circuits.

3.3 *Closed Orbit Correctors*

Recently the estimated radiation levels in the arc tunnels have been revised and lowered (<100 Gy per 10 years) making it possible to consider placing the power converters for the locally fed dipole orbit correctors in the tunnel next to the current feedthroughs. This reduces

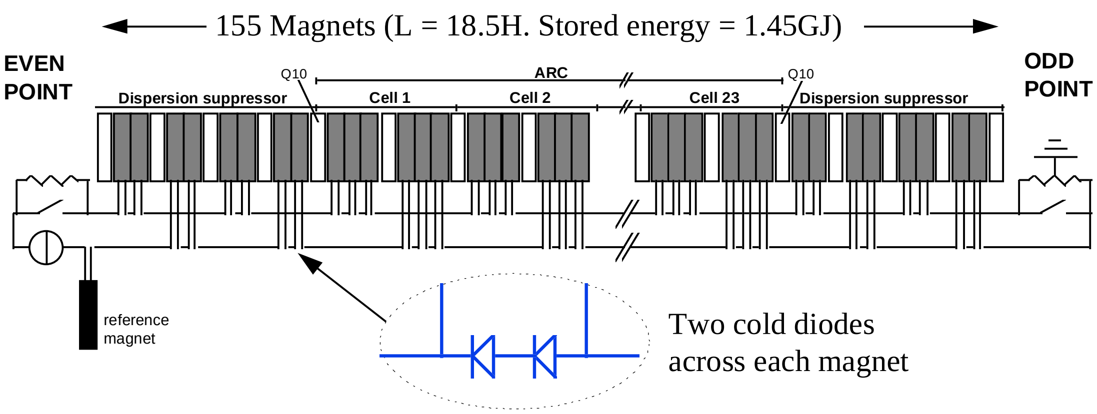

Figure 2 Main Dipole Circuit for One Sector (1/8) of LHC

drastically the DC cabling and means that cheaper, better optimised, magnets of higher current can be used. The power converters, about 1000 in all, can be rated 50A/8V instead of 32 A/120 V. However, issues of reliability, radiation hardness, and control need to be addressed.

4 INSERTIONS

The LHC insertions use many high current low voltage power converters (6 to 12.5 kA at 8V), placed as close as possible to the current feedthroughs using, in general, the RF galleries. The outer triplets are separately powered, left and right, ring 1 and 2. The recombination magnets are powered in series but separated left and right of the intersection because of the distance involved. The same is true for the low Beta inner triplet which also uses trim quadrupoles and several correctors.

5 PERFORMANCE

The performance of the powering system is dominated by the tune tolerance which ultimately should reach 0.003. This is made more complex by the segmentation of the machine and the fact that the field-to-current relationship in a superconducting magnet is a complex function of many parameters, both static and dynamic. It is particularly delicate at the low currents of injection where great care must be taken to precisely cycle and set the magnets to take into account the effects of DC and AC magnetisation and snap-back of the persistent currents. Initial studies have shown that the overall performance of the main circuits, in order to bootstrap the machine, needs to attain about 1.5 10^{-5} of maximum. However, a resolution and short term stability of the power converters in the order of 10^{-6} will be needed to allow precise cycling and fine adjustment. Past experience with accelerators, and in particular those using superconducting magnets, has demonstrated the importance of reference magnets. For this reason one set of reference magnets (Dipole and Quadrupole) is associated with each sector of the machine to provide field and field error information. Studies are continuing on the usefulness of these reference magnets, how to choose and instrument them, and what information can be extracted from them. Other possibilities of field feed-back are being investigated and more reliance will need to be placed on beam feedback for ultimate performance.

Because the sectors are basically optically autonomous the sector-to-sector tracking tolerance is of the same order as that of the global requirements.

Much progress has been made in performance with the development of new Analogue-to-Digital Conversion techniques and a greater understanding of high current DC Current Transformers. These developments, along with the progress in Digital Signal Processing techniques, mean that adaptive digital control technologies can be used to meet these challenges [3].

6 POWER CONVERTERS

In all, there will be about 1500 power converters having a total steady state input power of 20 MW and a peak power of 51 MW. They will supply a total current of about 1750 kA and are, in general, characterised by having high current and low voltage. To meet these requirements, as well as the need for compact reliable high performance power converters, switch-mode techniques will be used [4].

They will also be used for the large quantity of auxiliary circuits such as the dipole correction elements where, above all, an economic and reliable design will be needed, taking into consideration the quantities.

7 DISTRIBUTION OF AC POWER

LHC will make extensive use of the existing power distribution of LEP. However, some modifications will be required in order to match the new requirements notably:

- modification to the surface distribution at the even points for the cryo-plants (~ 11 MVA per point),
- new installations for the experiments in points 1 and 5 (~ 15 MVA per experiment),
- new underground low voltage sub-stations and distribution for the power converters.

8 CONCLUSIONS

The Powering Strategy of LHC is based on:

- an electrical segmentation of the circuits into eight as dictated by the needs of the quench protection system. This also reduces DC cabling, power consumption and the size of the power converters while allowing sector-to-sector correction of field and field errors due to different magnet and cable manufacturers,
- the maximum use of existing infrastructure by using the LEP ac power distribution and underground galleries in the even points, and limiting the current and therefore size of the power converters in the odd points,
- the use of compact, high reliability switch-mode power converters for underground installation,
- high precision control of the power converters using predictive and adaptive digital control loops of 20 bit monotonic resolution aided by appropriate field and, eventually, beam feedback.

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