A STRATEGY FOR CONTROLLING THE LHC MAGNET CURRENTS

I. Barnett, G. Fernqvist, D. Hundzinger, J-C Perréard, J.G.Pett, CERN, Geneva, Switzerland

Abstract

The LHC will require an unprecedented precision of a few ppm in the control of the current in the major magnetic circuits. As a result of the optimisation of the machine design, the machine will be powered in eight sectors with separate power converters. This scheme, along with other operational constraints, has led to a re-evaluation of the methods needed to ensure adequate performance. An overview of the strategy envisaged to meet this new challenge is presented, along with details of digital control and correction methods, new techniques for analogue to digital conversion and improvements in DC current transducers above 10 kA.

1 INTRODUCTION

The present design of the LHC requires the magnet structure to be powered in a non-conventional manner. Earlier accelerators normally powered all the principal dipole and quadrupole magnets as either a single electrical circuit or as three separate circuits. Due to optimisation of the overall machine, separate powering of each of the eight sectors of the machine has become necessary [1], where each sector will be powered by three individual power converters.

The superconducting magnets do not have a current-to-field characteristic similar to conventional steel-cored magnets and require the use of a number of field correction methods. Additional time dependent effects also occur. As a consequence, very careful control of the magnet currents will be required in order to minimise these effects.

The LHC will need very precise and stable fields (and therefore magnet currents) in order to set and maintain the orbit and tune. These accelerator physics requirements translate into an overall precision requirement of 3 parts per million (ppm) of maximum field for the main circuits. During injection and transition to the nominal acceleration ramp, the power converter performance requirements are the most severe and dictate an 'essentially infinite' resolution in the setting of current. Any deviations from ideal performance between the 24 principal power converter currents will result in beam errors and must be reduced to the minimum possible.

Analysis of techniques employed for present accelerators, which are based on analogue methods, have shown that it is highly unlikely that the above performance can be achieved reliably with the same methods. Therefore, a considerable effort has been made to evaluate the known limitations of our present methods and to propose an overall strategy for the low-power electronics which can meet the LHC requirements. The high-power aspects are dealt with in another paper to this conference [2].

2 TECHNICAL LIMITATIONS

The technologies used today for power converter low power electronics are typically based on an analogue regulation loop, using a proportional/integral/derivative (PID) control. The reference input to this loop is from a precision digital to analogue converter (DAC), which is set from a digital function generator (FG). The FG normally accepts a series of current/time vectors, from which it calculates intermediate values using a straight line approximation. The output current of the power converter is measured by a precision current transducer, usually a Direct-Current Current-Transformer (DCCT), which provides the feedback signal for the control loop. The interface to the accelerator control system (ACS) is purely digital and consists of the current vectors as input and the digitised value of the DCCT output (via a precision analogue to digital converter or ADC). A typical structure is shown in Fig 1.

Today a practical system can provide setting and reading of output currents to an overall accuracy of about 15 ppm of Imax., although the short term stability can be about five times better. This performance limit includes errors due to drift, overall linearity, temperature effects (controlled environment) and the basic resolution of the analogue/digital converters. Measurement and analysis of all error sources shows that it is improbable that analogue technology will advance sufficiently to overcome the major errors and therefore the power converters could become a significant source of error in the LHC machine. However, many errors remain stable over time and are therefore termed "reproducible errors". Such errors can in theory be removed by suitable means. In addition to the above problems with traditional methods, the LHC magnets operate at a current level above 11 kA and their electrical circuits have large time-constants (the dipole time-constant = 23000 seconds). Unfortunately, DCCT's above a few kA have additional sources of error, and control-loops for very large time-constants are difficult to realise using analogue electronics.

It was therefore evident that if the power converter system was not to become a limitation, improved methods would be needed in a number of areas.

3 THE OVERALL STRATEGY

Having quantified the existing error sources, alternative methods were investigated both via simulation and limited laboratory tests. The resulting strategy has emerged, namely :

- For the 24 (or more) major magnetic circuits, obtain the best possible transfer function between demand and output current by using digital, rather than analogue techniques. This approach minimises the number of critical (analogue) components and allows use of more advanced control loop methods.
- Employ on-line correction methods to reduce known residual errors in the control electronics and the local environment as well as feedback of field and beam related errors.
- Incorporate extensive calibration methods both for on-line and off-line use.
- For the (>1600) less demanding magnetic circuits, employ simplified (and therefore cheaper) circuitry, but using essentially the same basic electronics.

4 DIGITAL CONTROL LOOPS

The basic structure of a digital control loop is shown in Fig 2. It can be seen that the feedback loop uses the output of the ADC, i.e. in digital form, rather than the analogue signal shown in Fig 1. All the functions shown inside the dotted box of Fig 1 are realised by a digital signal processor (DSP), which removes the errors of the comparator and the DAC. By comparison, the DAC shown in Fig 2 can be a less precise device, since it is inside the feedback loop (a cheap audio DAC, as used in CD players, is adequate). For ultra-high performance, the ADC becomes the limiting factor and must be able to deliver an essentially perfect digitisation of the output voltage of the DCCT. However, the performance of the DCCT is equally important in both types of control loop.

The advantages of the digital approach, apart from those mentioned above, are that the algorithm defining the closed loop corrector can more easily handle large time-constant loads and can be made to automatically adapt to follow variations in the time-constant. This will be essential, as the loop response must be non-overshooting and identical for each magnetic circuit, otherwise dynamic errors will add to the static errors of the system. To minimise dynamic and tracking errors, a predictive (or feed-forward) loop will be needed, again benefiting from the auto-adaptive characteristics of the digital approach.

A major advantage of the digital control loop is that the resolution available is, in theory, limited only by the mathematical precision of the DSP algorithm. In practice the noise from the ADC degrades this somewhat but it remains possible to operate well below the rms noise of the ADC, since filtering is provided by the current-loop cut-off frequency. This means that very smooth and extremely high resolution output functions can be generated (< 1ppm of Imax). Clearly, the ADC performance must be monotonic and linear to the required precision (see below).

Using a DSP as the function generator (FG) allows more complex functions to be realised as well as simple straight line vectors. Since the desired output value is calculated on each iteration of the loop algorithm, it is easy to evaluate a mathematical function, thus giving smoother and more progressive changes of slope. Tables of correction coefficients for "reproducible errors", (e.g. linearity of the ADC and DCCT), can also be included in the loop algorithm. This can considerably improve the basic precision of the output current.

In addition, the on-line corrections, derived externally from field and beam errors, can be incorporated on each iteration. This mechanism will be essential to keep the machine tune within the desired limits. The accelerator control system must of course be able to supply data to each power converter at the desired rate and within an acceptable delay.

5 ANALOGUE TO DIGITAL CONVERTERS

This key component is not yet available from industry with the desired performance but it is likely to become so in a few years time. As a consequence, some effort has been invested in evaluation of possible ADC methods. The charge balance or Sigma-Delta conversion methods as well as multi-slope systems are capable of providing the required precision in theory but are too slow or inaccurate at the present state of development. One manufacturer of precision digital voltmeters has an expensive product which can almost be considered adequate but has a number of interfacing problems. Practical investigations have resulted in a prototype ADC which has demonstrated that the Sigma-Delta method can deliver the required performance. In the present state of development it has a small non-linearity for positive input signals. This reproducible error of some 5 ppm, (which can be corrected by the DSP), is the only major source of error which exceeds the desired 1 ppm objectives.

6 SIMULATIONS AND LAB. TESTS

A number of simulations of digital control loops and ADC's have been performed and practical laboratory demonstrations have confirmed that the entire system can perform as predicted. Tests with a small power converter have also been made. These practical, proof of principle investigations have served a very useful purpose since, at this level of performance, considerable uncertainty exists and a great deal of relevant knowledge has been acquired. In particular, the feed-forward and adaptive loops show great promise.

7 CURRENT TRANSDUCERS

The measurement of magnet current is the most important process in the entire system since any error sources are unobservable. The use of DCCT's to measure the magnet currents is universal but a number of errors are associated with their use in power converters. As a consequence, an extensive series of evaluations was launched, in close collaboration with industry, to quantify and ultimately improve the performance of these vital components. Above 6 kA little experience exists and measurement accuracy decreases, since Standards Laboratories do not have methods of measurement suited to such current levels. In parallel with our evaluations it has therefore been necessary to develop improved techniques for such measurements. A program was started to upgrade the CERN Standards Laboratory, providing increased accuracy in basic voltage and resistance measurements. Current measurement capability is also being pushed to the ppm level at 15 to 20 kA, through a collaboration between CERN, National Standards Laboratories and industry.

The main sources of error in the DCCT's needed for LHC are due to the non-linearity of the burden resistor and the magnetic fields existing in the volume occupied by the DCCT coils. These fields, which can be both external and self induced, result in severe non-linearities at high output values. In particular, it has been demonstrated that it is essential to place the DCCT coils outside the main power converter cubicle (in which many strong AC and DC fields exist), and also in a busbar structure which reduces the effects of self induced field. These measures have resulted in prototype transducers which have a non-linearity error of about 5 ppm of maximum output. Both stability and noise are below the 1 ppm level. It is hoped that improvements can still be made to the basic performance but use of correction methods, as outlined above, can be employed successfully at this level of error.

8 OUTSTANDING PROBLEMS AND FUTURE PLANS

The foregoing has shown that the major sources of error in the power converter low-power electronics have been identified and quantified. Any improvements which can be made in reducing the remaining errors will be of value in ensuring that the power converter system as a whole is not a major source of error in the LHC machine. Clearly, every attempt must be made to reduce these remaining uncertainties and we expect that our external collaborations will be of considerable benefit in this area. This initial work will now be used as input to the detailed design of full-scale prototypes which will be tested on superconducting magnets in an operational test environment. These tests aim to demonstrate that tracking between power converters and closed-loop control via external inputs can be achieved reliably. Design and tests of the global calibration structure for the power converter system will also be made

9 CONCLUDING REMARKS

As a result of the work completed to date, we believe that a strategy based on optimisation of power converter performance, regular system re-calibration and field plus beam related feedback mechanisms will permit a successful operation of the LHC machine. As far as the power converter system is concerned, these stringent performance requirements now need to be proven in a series of full-scale tests.

10 ACKNOWLEDGEMENTS

The authors wish to thank the many CERN, academic and industrial colleagues without whom this work could not have been made.

REFERENCES

[1] Electrical Powering Strategy of LHC. First Design Study by P. Proudlock, CERN. EPAC'96 Contribution.
[2] High Current, Low Voltage Power Converters for LHC. Present Development Directions by F. Bordry, CERN. EPAC'96 contribution.
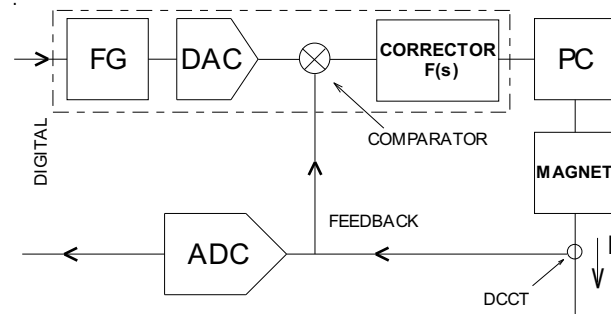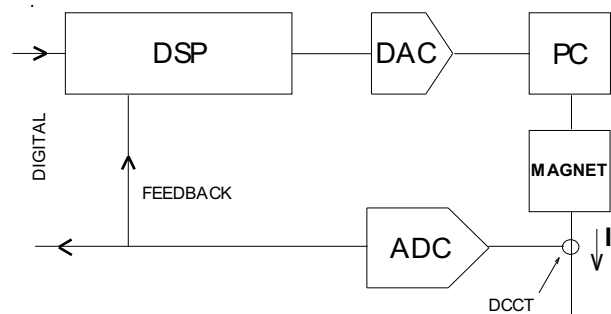
Fig 1 Typical Analogue Control Loop

Fig 2 Basic Digital Control Loop