DYNAMIC BEHAVIOUR OF THE LEP POWER CONVERTERS

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Abstract

In order to ensure very close tracking of the various magnetic fields in the LEP machine during beam acceleration, a special effort has been made to understand the source of errors. These errors include mains pertubations, eddy-current effects in the vacuum chamber, delay-line effects and dynamic performance of the power converters. This paper describes briefly these errors and concentrates on solutions which can be implemented in the power converters. An overview is given of closed-loop converter performance for the classic method using proportional-integral compensation as well as the double proportional-integral compensation, where the following error reduces to zero. Optimised mains rejection will be achieved using proportional-integral compensation with partial state variable feedback. A novel method is proposed to introduce quasi-exponential starting and stopping of the acceleration reference waveform. These methods, coupled with adjustable time displaced reference waveforms for the various converter families, allows dynamic errors during acceleration to be reduced to the order of 10 parts per million (ppm).

Introduction

The various magnets which make up the LEP machine are powered by about 760 power converters. Each power converter contains regulation circuitry to maintain the output current at precisely the value demanded. This value is set by a digital to analogue converter (DAC) which receives data via the remote control system. Under static conditions, such as injection or flat-top, the flux in the magnet is proportional to the DAC setting. However, during periods when the demanded value is changing, such as "ramping", the magnetic flux inside the vacuum chamber deviates considerably from the input demanded. The principal causes of these deviations are :

a) the dynamic response of the power converter
b) the eddy current effects in the vacuum chamber
c) the "delay line" effect of series connected magnets

The main dipoles and the two main quadrupole chains require the tightest tolerances to be maintained both statically and dynamically. In particular, the ratio between all three magnetic fluxes inside the vacuum chamber must be maintained precisely if synchro betatron resonances are to be avoided. A power converter tolerance (short term) of ± 50 ppm was calculated while hoping that an improvement of about 3 times could be achieved at injection such that synchro-betatron resonances would not be crossed. This calculation assumed some correlation between converter errors.

The Closed-Loop Performance of Power converters

Power converters and their associated magnets form a closed-loop current-controlled system as shown in figure 1. The electrical time-constant L/R of the magnet is contained within the closed-loop and, as is normal with feedback systems, the small signal bandwidth, measured from DAC to output current (or magnet flux), is increased. The overall bandwidth of the power converter and magnet can easily be set higher in frequency than the natural bandwidth of the magnet alone. For example, for the main dipoles L/R = 0.44 s, therefore f(-3 dB) = 0.37 Hz for the magnet alone, whereas for the magnet and power converter combination the closed-loop bandwidth can readily be set to 3.2 Hz. This corresponds to an effective time-constant of 50 ms.

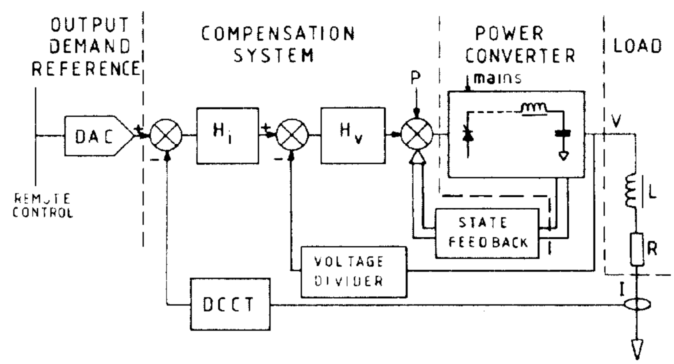

Fig. 1 - Closed-loop system for a power converter and magnet

The frequency characteristic shows a flat response up to the -3 dB point and then falls at 20dB/decade. This also means that the dynamic response, measured from the DAC output to the magnet flux, will behave as a time-constant of 50 ms. If the DAC produces a linear ramp output, then the flux will lag behind the demand by the power converter time-constant, i.e. in the above case by 50 ms.

Variations in the three-phase mains supply are compensated by closed-loop actions. Slow variations are completely eliminated and are not observable on the output current. Fast changes of 2 % will produce small current transients of approximately 40 ppm for some 30 ms. Unfortunately, virtually no correlation between power converters can be expected during such mains changes. It is important to realise that, due to the use of an appropriate corrector in the feedback loop, the current always returns to the original value after a disturbance.

Eddy-Current Effects in the Vacuum Chamber

Studies have shown that, during ramping at 0.5 GeV/s, eddy-currents in the LEP vacuum chamber introduce an additional lag between magnet current and flux inside the vacuum chamber. This lag can be considered to be an additional time-constant Tf in series with the power converter time-constant. Measurements have shown this time-constant to be 53 ms for the main dipoles and 8.7 ms for the main quadrupoles. Figure 2 shows the effects of this additional lag, which is outside the feedback loop of the power converter. The constant slope region shows that the flux inside the vacuum chamber now lags behind the demand by Tpc + Tf. As stated earlier, it is vital to maintain the ratio of the main dipole and main quadrupole fluxes at precisely the same value. It is relatively simple to align the constant slope regions, but this is not so for the initial and final curves. The transfer functions of two sets of series connected time-constants (eg. for the dipoles and the quadrupoles) can only be identical if both the sums and the products of the time-constants are identical.

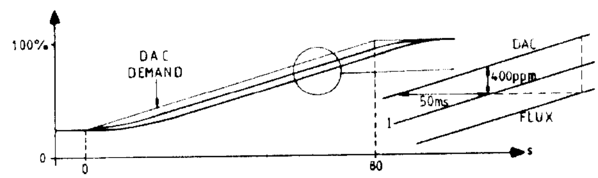

Fig. 2 - Additional time-constant due to eddy currents in the vacuum chamber

Delay-Line Effects

The series connection of magnets around the LEP ring generates an electrical circuit equivalent to a lumped-parameter delay-line. When a current ramp is applied to one end of the line, the disturbance travels along it and is reflected back. These wavefronts produce differing excitation levels in the magnets around the ring during the start and stop of the ramp. These effects have been studied in detail[1]. The solution needed to reduce these effects to less than a few ppm is to start and stop the ramp gradually.

Converter Performance Improvements

Among the previously mentioned sources of error only mains pertubations and dynamic performance are associated with the power converter and must be minimised.

The regulation system finally chosen is shown in figure 1. To minimise mains pertubations, the performance of the inner voltage loop and ripple filter must be optimised. Since the load inductance ensures minimum interaction between converter and load modes, it is possible to introduce a STATE compensation on the converter independent of the load. This type of compensation has a number of advantages compared to the classic approach, namely minimum interaction between setting the bandwidth and damping function as well as giving better rejection. Practically it is also simpler, needing only a gain adjustment rather than setting time-constants.

The voltage source produced by this method has a mains rejection, for higher frequencies, given by the passive LC filter which will be optimised since it has no additional resistive damping.

The damping however will be achieved by the STATE feedback compensation and the low-frequency rejection will be given by the proportional-integral action of the voltage loop. Figure 3 compares the state feedback method with the classic approach.

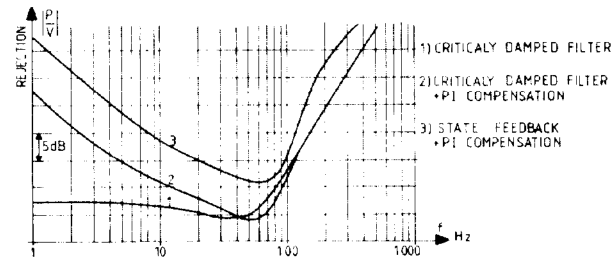

Fig. 3 - Rejection curves of voltage source

Considering the voltage source to be perfect, the current regulation of the converter and load can be described by the simplified model shown in figure 4. Where A is the open loop gain of the entire system including the voltage source, the load and the current transducer (DCCT).

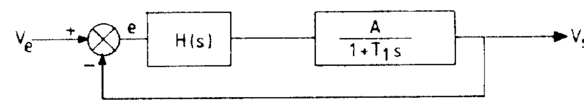

Fig. 4 - Simplified model for current regulation

Classic methods using proportional - integral compensation give an open loop transfer function :

$$H_1(s) = H(s)\frac{A}{1 + T_1 s} = \frac{K(1 + T_2 s)}{s}\frac{A}{1 + T_1 s} \qquad (1)$$

T_1 is the L/R time constant of the load, T_2 the corrector time-constant and K the corrector gain. The steady-state error to a unit ramp input, given by the "final value theorum"[2], is :

$$e = \lim_{s \to o} \frac{s(1/s^2)}{1 + H_1(s)} = \frac{1}{A\,K} \qquad (2)$$

and gives typical values as described earlier. This error is inversely proportional to the total open loop gain A·K and hence its precision depends directly on these coefficients. The following error therefore will not be known to better than ± 20% due to uncertainty in component values and load resistances variations. Should these uncertainties prove to be problematic an improved method has been envisaged, using a correcter with double proportional-integral $(PI)^2$ compensation. This method leads to an open loop transfer function :

$$H_2(s) = H(s)\frac{A}{1 + T_1 s} = \frac{K(1 + T_2 s)(1 + T_3 s)}{s^2}\frac{A}{1 + T_1 s} \qquad (3)$$

where T_3 is the additional time-constant of the corrector. In this case, the steady-state error to a ramp input becomes zero. This double integration therefore allows the following error, and hence the uncertainty in its value, to be made equal to zero. Apart from some error "bumps" at the start and stop of the ramp input other sources of error due to the power converter will not exceed a few ppm.

Acceleration Requirements

It can be seen from the foregoing that if all power converters were ramped with the theoretically calculated ramp waveform applied to their DAC's, then the resulting magnetic fields inside the vacuum chamber would be far from ideal. Variations in the closed-loop bandwidth of the power converters, the difference in the eddy-current effects of the vacuum chamber, the non-alignment of the starting and stopping regions plus the delay-line effect could combine to produce large tune deviations and hence excite synchro-betatron resonances. It is clearly necessary to align the flux waveforms as precisely as possible by minimising the differences between each family of power converters and magnets. Since it is not possible to make the eddy-current effects equal it was decided to delay the start of the "faster" system such that the constant slope regions were aligned. Simulations of such an approach were performed using typical time constants and the resulting difference between two power converter plus magnet types, are plotted in Figure 5.

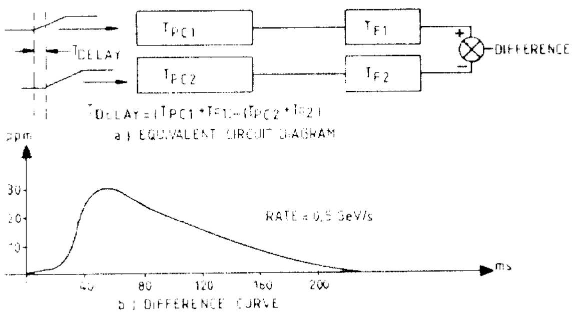

Fig. 5 - Simulation of delayed ramp starting

Prior to the 80 s acceleration period, the vectors defining the ramp functions will be down-loaded from the control room and stored locally in each power converter. Approximately 30 vectors per power converter was considered adequate to define the "curve" to the required precision.

Earlier sections have explained that gradual starting and stopping regions are needed. This requires that, upon receipt of a start or stop pulse, the hardware of the ramp generator would automatically produce the gradual transition regions in a totally reproducible way.

Upon receipt of a start pulse, transmitted by the LEP timing system, all power converters will start to generate their particular ramp functions, including necessary delays. The start time precision achievable will be a small fraction of 1 ms. Since unscheduled stops could arrive via the timing system at any time, the ramp generator hardware must automatically derive the gradual transition region data from the ramp data previously stored.

The Hardware Ramp Generator

The DAC is set by a micro-processor based controller. This programmable device generates, from the down-loaded vectors, a series of short vectors each being 256 ms long. The starting and stopping of this process can be delayed in steps of 1 ms if required, using pulses sent via the LEP timing system. This delay period can be easily adjusted from the control room for fine trimming.

By controlling the internal short-vector generation, gradual transition regions can be incorporated. Sub-dividing a normal short-vector into four regions, each 256 ms long, allows a quasi-exponential to be generated. The resulting magnetic flux inside the vacuum chamber is considerably smoothed by the low-pass filtering action of Tpc + Tf. No extra hardware is therefore needed to generate the time displaced ramps or for creating the gradual transition regions.

Simulation

An interactive computer program was written to simulate the complete system[3].

Results confirmed that no delay-line effects would occur and that the overall system would behave as predicted. The use of the gradual transition regions considerably reduced the difference curve because of the effectively slower ramp transitions. However, the remaining problem was that the shape of the curves produced by Tpc1 + Tf1 was not equal to that produced by Tpc2 + Tf2, particularly if the individual time constants were widely different (their sums being equal). A solution was found whereby an additional time-constant was introduced (between the DAC and power converter control loop amplifier) so as to better balance the time constants. The compensating time delay was also reduced to the 0 to 10 ms range.

These modifications enabled the peak amplitude of the error, during ramp starting or stopping, to be reduced to less than 10 ppm.

General Conclusions

A number of improvements have been suggested to provide more precise alignment of the magnetic fields inside the vacuum chamber during the process of acceleration. These improvements can all be incorporated in the presently designed power converters. In terms of operation, there should no longer exist any substantial difference between static and dynamic settings for the power converters, resulting in considerably improved performance and ease of use.

References

(1) H.W. Isch, Dynamic Behaviour of the Main Bending Magnet System, LEP Note N°508,CERN, June 1984.

(2) Fundamentals of Automatic Control, Gupta, Hasdorff, John Wiley & Son, 1970.

(3) J.G. Pett, Dynamic Behaviour of Power Converters during LEP Acceleration, LEP Note N° 560, CERN, 10 April, 1986.