THE CONTROL LOOPS OF THE HIGH POWER D.C. POWER CONVERTERS OF LEP

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Abstract

The overall control loop of a magnet power converter is a very sensitive element of the chain constituting the magnetic system of an accelerator. After reviewing the various sources of perturbations and errors, the Power Converter Control loop system is described. This consists of the realisation of an almost perfect voltage source built around the Power Converter and practically independent of network fluctuations. The voltage source, with its magnet load, is then converted into a current source having the particularity to present a zero steady state error during beam coasting and acceleration. To achieve field matching, the dynamic set-up of the current sources takes into account the vacuum chamber eddy current effects.

Introduction

As far as the regulation is concerned, the structure of the power converter is always the same, be it a conventional thyristor unit or the more modern switch-mode types. The principle elements (Fig. 1) are :
- a controllable power source
- a filter
- a load
- a current transducer.

For LEP, we have to consider the additional effects of the eddy current in the vacuum chamber.

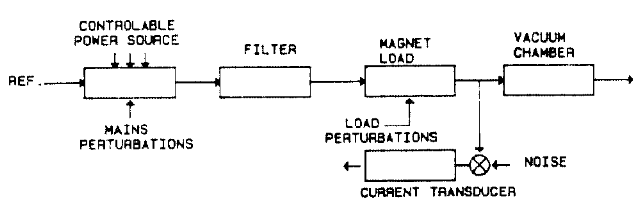


Fig. 1 Block diagram of a power converter

The controllable power source can be one of the following [1] :
- a 6-pulse thyristor bridge system (th 6P)
- a 12-pulse thyristor bridge system connected either in series or in parallel (th 12P/S or th 12P/P)
- a double 6-pulse thyristor bridge system assembled in the dual converter mode giving the true four-quadrant operation (4 quad)
- a switch-mode converter (chopper)
- a resonant converter (resonant).

All these sources are subjected to the random perturbations of the supply network and have greater or lesser abilities to reject them.

The filter must reduce the residual ripple to an acceptable level for the user. As the performance of a damped passive LC filter with a second C or of an undamped passive LC filter have been sufficient, no active filter has been required for LEP.

The load is the most important element of the system since it dominates the specification. It is made up of one or several magnets connected in series. Together with its supply cables, it can be represented as a simple resistor in series with an inductor having a time constant between 0.5 second and 1200 seconds. However, the vacuum chamber effect can modify this requiring consideration of a higher order model. The perturbations are of thermal nature which change the above characteristics and in some cases can be caused by coupling with other magnets, cables, etc. A non linear characteristic can result from the saturation of the magnetic circuit.

The current transducer (DCCT) is of the zero flux type. Seeing that its precision and dynamic performance are particularly remarkable, it can practically be treated as a perfect element as far as the regulation is concerned. However, in certain cases where a high gain is necessary, some precautions are needed to avoid noise injection into the system.

The various combinations of magnets, type of power source and filter are summarised in Table 1.

Magnet circuit		Power converter			
Name	Time constant L/R (s)	Output power (kW)	Power element	Filter characteristics	
				fc(Hz)	damping
Main dipoles	.6	6960	th 12P/S	27	.2
Inject. dipole	.5	255	th 12P/S	35	.2
Quad. QD QF	1	715	th 12P/S	30	.15
Quad. QS QL	.9-1.2	53-90	th 6P	22	.2
Quad. QS QL	.9-1.2	51	th 12P/P	35	.2
Quad. QS QL	.4-1.2	37.5	resonant	2	.08
Tilted Quad.	1	4	4 quad	27	.01
Sext. SF SD	.3-1	120	th 12P/S	35	.2
Sext. SF SD	.3-1	37.5	resonant	2	.08
Wiggler	1.3	210	th 12P/S	35	.2
Quad. QSC	1200	20	chopper	500	.15

Table 1 Magnet circuit with associated power elements

Compensation system [2]

Having briefly described the principle elements of the control process and the perturbations likely to create a fluctuation of the output current (Fig. 1), we have now to define how to generate the control signal to the power element.

The rejection of the mains perturbations can be achieved in two ways :
- measure the current and correct at the input;
- measure the voltage on the output and correct at the input.

If we consider a load time constant L/R greater than 0.3 seconds, it is evident that the information contained in the voltage is much richer than that of the current for bandwidth above the magnet break point. Hence, the second method consisting of generating a correction signal from the output voltage is much more interesting particularly when we take into consideration the signal to noise ratio.

In simpler terms it appears evident that one should correct the influences of the perturbations as soon as they can be measured rather than correct a secondary effect. In particular, a simple voltage divider can be used to return the required information.

However, the current being the main control parameter, it is from the current transducer that we shall establish the low-frequency command of the system as well as the rejection of the load perturbations.

Together this leads to the principle diagram shown in figure 2 where we control the output voltage (voltage loop) and the output current (current loop).

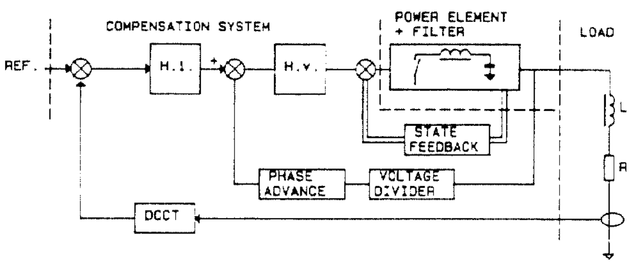


Fig. 2 Closed-loop system for a converter with a magnet

The voltage loop

To minimize mains perturbations, the performance of the inner voltage loop and ripple filter must be optimised. Since the load inductance insures 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 may be optimised since it does not need 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 (Hv).

If the implementation of the above is straight forward for small signal operation, it is not always the case for large signals amplitude. Particularly in the case of a thyristor bridge when we fall on the limit of linear operation.

As shown by the simulation (Fig. 3) using the SCRIPT program [3], we can see that the voltage source is temporarily lost when we apply a large step down reference to the bridge producing an absence of conduction of the thyristor.

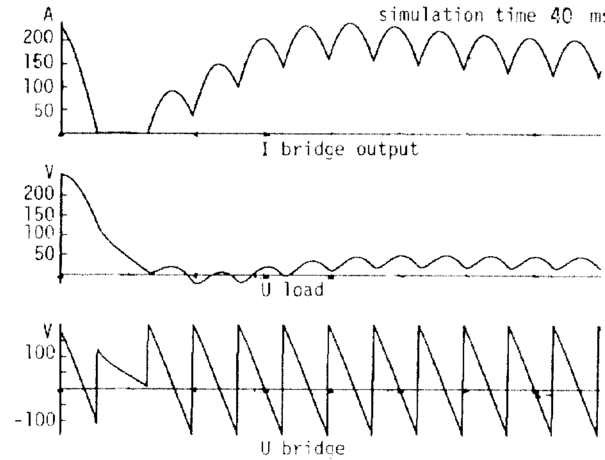
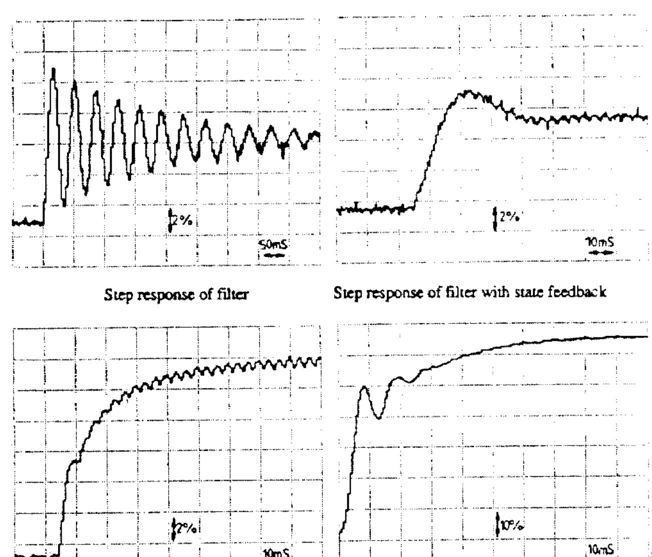


Fig. 3 Lost of conduction of a thyristor bridge

In order to remedy this situation we have introduce a slowing down of the system. Since we do not wish to deteriorate the dynamics of the system, we have chosen to introduce a small phase advance compensator in the feedback which gives a filtering effect seen from the voltage loop input.

The successive dynamics progress of the voltage source can be evaluated from the various step responses shown in figure 4.



Step response of filter

Step response of filter with state feedback

Step response of closed voltage loop (small signal)

Step response of closed voltage loop (large signal)

Fig. 4 Performances of the voltage source

The current loop

For the current loop, we consider two modes of operation :

- the static case, flat-top operation during beam coasting
- the ramping case during beam acceleration and squeezing.

In order to reduce beam losses, the transient times at both ends of the ramp have to be minimize and the dynamic behaviour of the power converters must be identical. Therefore, the bandwidth set up is a compromise between:

- the dynamic performance
- interference with the voltage source
- injection of current transducer noise.

The type of compensation is determined by the requirements for ramping. The fact that an acceleration of 0.5 GeV/s leads to a ramp duration of the order of one minute, while the 1% settling time of a power converter is typically about 300 ms, shows clearly that a zero following error becomes an important criteria and justifies a double integrator compensation. Compared with the simple integrator we obtain not only a zero following error, but an invariable error. Any parameter variation in a simple integrator system will result in a change of its steady state following error.

Further, during static operation, the double integrator assures a total rejection of deviations of the magnet load due to thermal effects of a ramp like nature. This is also true for simple component-drifts within the compensation circuit.

Interferences with the voltage loop is only a problem with thyristor line-commutated equipment which can only achieve a bandwidth of 40 Hz and 90 Hz for 6 P and 12 P respectively. Under these conditions, the bandwidth of the current source is limited between 10 Hz and 20 Hz.

When the controllable power source is a switch-mode converter having a large bandwidth, then the limiting factor for the current source having a comparable dynamic response is no longer the interference with the voltage source, but the noise of the system (particularly the DCCT).

This problem is amplified in supraconducting magnets (QSC), where a gain in the order of 10000 in the compensator becomes necessary if we are to obtain a closed loop response similar to the other magnets. In this case, a systematic filtering is necessary along the entire chain of action.

Compensation of vacuum chamber effects

Effects of eddy-current in the vacuum chamber introduce an additional lag between magnet current and flux inside the vacuum chamber. As the equivalent time constant of this effect is T1 = 53 ms for the dipoles and T2 = 8.3 ms for the quadrupole it has been necessary to introduce an analogue filter (Fig. 5) in order to get proper field matching during acceleration.

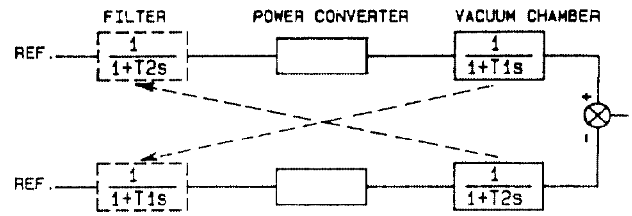


Fig. 5 Block diagram of dipole and quadrupole systems

Of course, this solution to give good results assumes an identical dynamic behaviour between the power converters. Unfortunately, this is not straight forward because the load transfer function of the dipole is modified by the vacuum chamber and required a higher order model.

However, the appropriate choice of the zero location of the compensator combined with a closed-loop bandwidth of 15 Hz, giving an equivalent time response of about 10 ms, has led to a good compromise. It should be noted that a fine adjustment of the ramp delays can be achieved by software. Until now an extra delay of only 4 ms has been required.

Conclusion

The regulation principle we have described is used in all LEP large power converters, whatever power element is concerned. The fundamental principle consisting of generating a current source for the magnet from an almost perfect voltage source has proved to give the best possible results while respecting the fundamental laws of cascading voltage and current sources. In addition to its very simple implementation, this approach leads to a simple step by step set up not requiring an expert. This is a non negligible aspect if one considers the large number of converters.

The special effort made on the current compensator assuring zero error during beam acceleration, squeezing and coasting, has proved its effectiveness on the operation side of the machine, since no doubt has arisen concerning errors and error variations from this source. The above combined with analog/digital compensation of the vacuum chamber effects has led to an almost perfect matching between magnet fields.

References

[1] H.W. Isch, Realization of the LEP Power Converters, EPAC CONF., Rome, June 7-11, 1988, Vol. 2, p. 1166.

[2] J.G. Pett, A. Beuret, Dynamic Behaviour of the LEP Power Converter, Proc. of the IEEE Part. Accel. Conf. Washington, March 1987, Vol. 3, p. 1440.

[3] F. Bordry, Synthèse des Méthodes de Simulation des Convertisseurs Statiques, Thèse de Docteur Es-Science, Toulouse, December 1985.