REGULATION OF GEOGRAPHICALLY SEPARATED MASTER/SLAVE POWER CONVERTERS WITHOUT EXTERNAL COMMUNICATION

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Abstract

The excitation of the quadrupole chains of LEP is achieved by several distributed power converters connected in series with the magnets. The regulation of the total system must not only give high D.C. precision, but give excellent dynamic qualities particularly at the start and finish of the acceleration cycle. We present a regulation system using the excitation current of the magnets as the means of communication between the units. At very little cost the desired performance is achieved while giving performance identical to that of a single power converter.

Introduction

In order to distribute the power and to limit the voltage to earth, the excitation of a magnet chain is often made by several power converters placed in series via their load around the circumference of the machine. Considering the following modes of operation :

- transient at the beginning and the end of the ramp,
- static during beam filling and coasting,
- ramping during beam acceleration,

as well as the extremely high precision required on the current in any of the above modes, it becomes very important for the resulting regulation process to be continuous and linear in order to avoid current transients resulting from switching the compensation system.

It is evident from the most elementary rules that the regulation of each unit in current is prohibited. We are therefore obliged to consider the type of structure shown in figure 1.

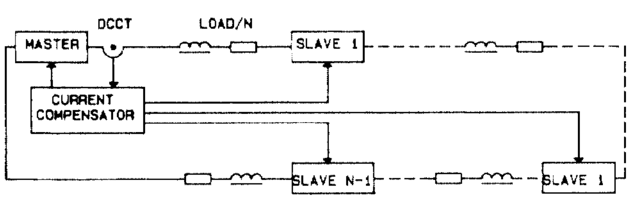


Fig. 1 Block diagram of master-slave with liaison element

The current compensator drives in parallel the slave voltage sources, which we consider to be ideal, via a liaison element (cable, communication system, etc). If the latter is ideal, then the resulting system seen by the current compensator is the same as a single system.

In fact, only the gain is modified by the number of power converters.

Once the distances between the master and slave converters becomes large (e.g. 14 km in LEP), then the choice of liaison element becomes critical from both a technical and economic point of view. The solution of digital transmission of references to the slave elements generally results in a non-linear system. We can eliminate the liaison element by taking the necessary information where it exists naturally. That is to say the current in the series-connected magnet. This leads us to a block diagram as shown in figure 2 from which we will derive the necessary compensation needed for each slave power converter.

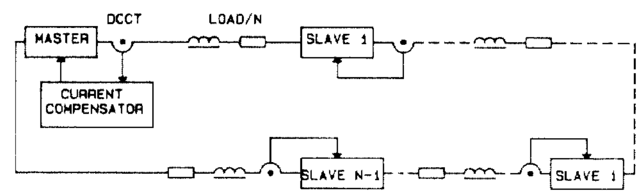


Fig. 2 Block diagram of master slave without liaison element

Determination of the required compensation

The system composed of 'n' power converters in a configuration of master-slave without liaison element is represented by the functional diagram of figure 3.

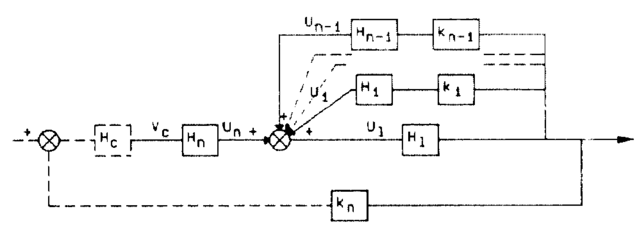


Fig. 3 Function diagram of 'n' power converters

H_l : transfer function of the load
k_i [1 - n] : current transducer gain
H_i [1, .. n - 1] : transfer function of slave voltage sources
H_n : transfer function of the voltage source of the master
H_c : transfer function of the current loop compensator.

The problem we have to resolve is whether we can compensate the slave converters in such a way that the input to the master converter shares the static and dynamic characteristics between all converters.

In other words, if we have for the load :

$$H_l = \frac{1}{R(1 + L/R\,s)} \qquad (1)$$

We should see from the input of the master converter :

$$\frac{I(s)}{V_C(s)} = \frac{H_n}{\frac{R}{n}\left(1 + \frac{L}{R \cdot n}\,s\right)} \qquad (2)$$

That is to say that the resistance and the time-constant must be divided by n in order to meet our criterion. From the functional diagram we obtain :

$$\frac{I(s)}{V_C(s)} = \frac{H_l(s) \cdot H_n(s)}{1 - H_l(s)\sum_{i=1}^{n-1} H_i(s)\,k_i} \qquad (3)$$

We must determine $\sum_{i=1}^{n-1} H_i k_i$ such that :

$$\frac{H_l(s)}{1 - H_l(s)\sum_{i=1}^{n-1} H_i(s)\,k_i} = \frac{1}{\frac{R}{n}\left(1 + \frac{L}{R \cdot n}\,s\right)} \qquad (4)$$

Since the contribution of each slave converter is supposed to be identical, we have :

$$\sum_{i=1}^{n-1} H_i(s)\,k_i = (n-1)\,H_i(s)\,k_i \qquad (5)$$

and the solution is given by :

$$H_i(s) = \frac{R}{n}\left(1 + \frac{n+1}{n}\,\frac{L}{R}\,s\right) \quad n \geq 2 \qquad (6)$$

This implies that each slave converter has a static gain of R/n and presents a zero at $\frac{n+1}{n}\,\frac{L}{R}$ sec.

The solution to our problem is therefore very simple and easy to realize. However, we must not forget that we have assumed perfect voltage sources which is not always the case. Also, in practice we know that a differentiator will amplify the existing noise in the system and therefore we must add a pole to limit the system gain at higher frequencies. For each application, it is necessary to quantify the effect of these imperfections as well as those due to parasitic elements of the magnet chains.

The static compensation [1]

In a first application we are only interested in a static compensation used on the main power converters of LEP. In fact the slow ramp rate only requires a small boost voltage of the order 0.5% of nominal. The master can therefore perform the dynamic role for the entire load. In this case the transfer function (3) becomes :

$$\frac{I(s)}{V_C(s)} = \frac{n \cdot H_n}{R\left(1 + n\,\frac{L}{R}\,s\right)} \qquad (7)$$

where the gain and the time constant of the load is multiplied by the number of converters.

Instead of ideal converters, the use of a second order model in a two-converter system as been simulated. In particular, the root locus analysis has shown the following :

- the position of the pole of the load is modified in conformity with the basic theory;
- the pair of imaginary poles of the slave are hidden by a pair or zeros with a precision on the real and imaginary part better than 1% for :

$$200 < \omega < 500 \text{ and } 0.1 < \zeta < 0.9.$$

This confirms that the slave modes could be ignored in the resulting system for this particular application.

The straight forward implementation of the above in the LEP power converters has demonstrated a complete conformity between simulation and practical results. No other phenomena was observed.

The dynamic compensation

For the simulation we have used the following model for each slave converter :

$$H_i = \frac{(1 + 2.5\,s)}{(1 + 0.005\,s)}\,\frac{1}{(1 + 0.004\,s + 1.6 \cdot 10^{-5}\,s^2)} \qquad (8)$$

In complement to the second order model of the power converter we have introduced the zero of the dynamic compensation with its associated pole in order to limit noise injection.

The root locus analysis of the resulting system seen by t he output of the master converter, in function of the number of slave converters as led to the following :

- as n increase, the poles and zeros due to the slave modes move to the right. For n = 6, two unstable modes are obtained;
- the dominant resulting system instead of giving a real pole at w = nR/L gives two real poles and a real zero at higher frequencies. This modification of the ideal system is due to the pole which as been introduced for noise limitation.

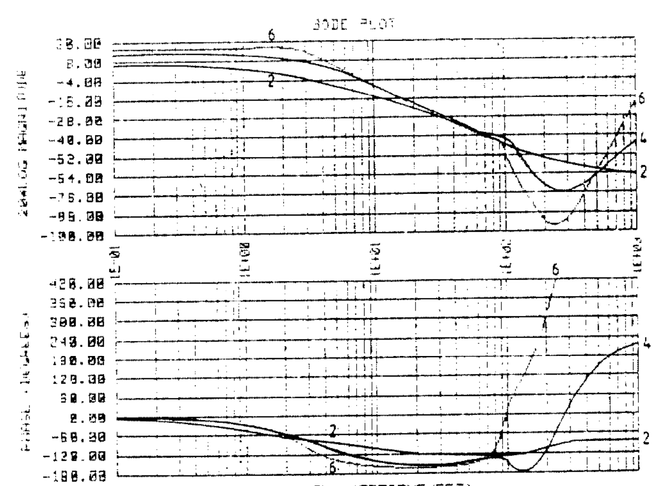


Fig. 4 Bode plot of resulting systems

The system evolution can be evaluated as well from the Bode plot of figure 4. We can observe for $\omega < 100$ that the resulting system tends to the basic theoretical results. However, the slope is higher than 20 dB/dec and increases with the number of converters.

For $\omega > 100$ the rapid positive slope of the phase when n increases associated with the negative amplitude slope characterizes the evolution of the poles of the system towards the unstable zone.

Experimental results

The temporary availability of 4 power converters rated at 300 A, 200 V gave us the possibility of an actual test on loads having the following characteristics :

$$R = 0.75\ \Omega,\ L = 1.45\ H$$

The static compensation leads to a total gain for each slave

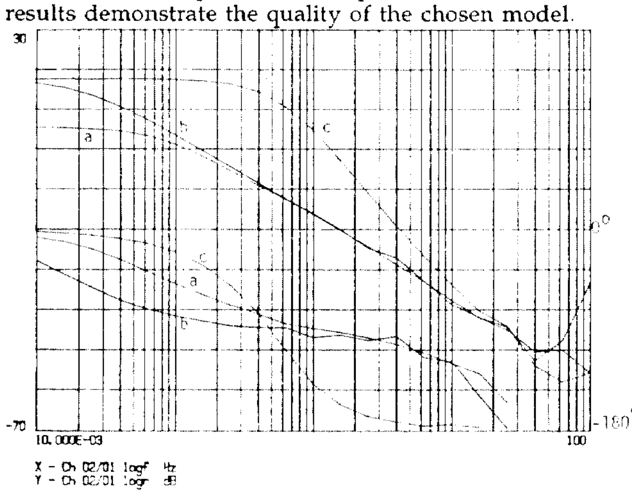
$$H_i\, k_i = R/n = 0.187$$

the time constant of the zero associated with the dynamic compensation is :

$$T = \frac{1 + n}{n}\,\frac{L}{R} = 2.4\ s$$

and the limiting pole is placed at 100 Hz.

From the bode plot of figure 5 we can see the successive evolutions of the system seen by the output of the master. Between curve a) and b) we find the expected factor four on the breakover frequencies and on the static gains. For the static and dynamic compensation (curve c) the expected double pole at 0.5 Hz was observed by the simulation while the ideal model gives a simple pole at 0.32 Hz. The equivalence of practical and simulation results demonstrate the quality of the chosen model.

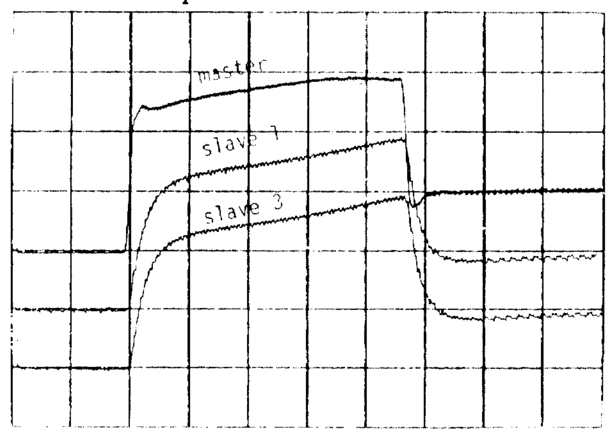


a) master only
b) master/slave with static compensation
c) master/slave with static and dynamic compensation

Fig. 5 Successive bode plots of a four-converter system

In order to verify the dynamic voltage sharing, we have established the current regulation of the system. The corrector Hc is the same as the one described in [3]. It is basically composed of a double integrator to achieve zero following error, and in this case a phase advance compensation has been necessary to compensate the double pole due to the slave converters.

The oscillogram Fig. 6 shows the voltages across the master and two of the three slaves when applying a current ramp of one second giving 70% of current change. It shows a reasonable dynamic and static voltage sharing. Also the faster response of the master illustrates its different role compared with the slaves.



Scale : 40 V/div., 200 ms/div.

Fig. 6 Master and slaves voltage during a current ramp

Conclusion

The proposed master slave system has been used successfully in its static form for the power converter of the main dipole and quadrupole chains. A demonstration has also been made to show that the technique can be extended to take into consideration the dynamic case. The system is very simple and give the great advantage that from the outside, and particularly from the control point of view, the power converters can be treated in the same way as an individual unit. While imperfections have a negligible effect when the quantity of power converter is small (typically < four) the errors they cause will propagate once this number is exceeded and special care will be needed. A more indepth study may also be necessary for such a case. In particular, the hypothesis of equation (2) leads to an under use of the master in the dynamic role. For perfect matching between master and slaves, the simple division of the resistance and the inductance by 'n' will result in the slaves having a static gain of R/n and a time constant for the zero of L/R seconds.

References

[1] A. Beuret, P. Proudlock, Commande de convertisseurs en série géographiquement éloignés et sans organes externes de communication auxiliaires, LEP Note N°608, April 1988.

[2] K. Dahlerup-Petersen, P. Proudlock, Design, Construction, Testing and Commissioning of the LEP Main Dipole Power Converter, CERN/LEP-PC/89-77, December 1989.

[3] A. Beuret, F. Bordry, The Control Loops of the High Power D.C. Power Converters of LEP, 2nd EPAC, Nice, 1990.