A DISTRIBUTED DIPOLE POWER SUPPLY SYSTEM FOR THE EUTERPE ELECTRON RING

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A distributed power supply system is described for the bending magnets of the 400 MeV electron synchrotron and storage ring EUTERPE. The system consists of a series connection of alternately power supplies and dipoles. In this concept the leakage current of internally cooled coils of dipoles is minimized. The advantages of one big power supply with equal current through all coils and of separated power supplies with a low voltage hence low leakage currents, are combined. Individual correction of dipoles and current stabilization can be provided. As the individual power supplies have extra power capacity, failure of a single unit will be corrected by the others, which implies a large overall reliability of the system.

I. INTRODUCTION.

At the Eindhoven University of Technology the 400 MeV electron storage ring EUTERPE (see figure 1) is under construction [1]. The purpose of this project is twofold, studies are made and experience is gained in the field of beam dynamics and accelerator techniques, applications of synchrotron radiation are pursued.

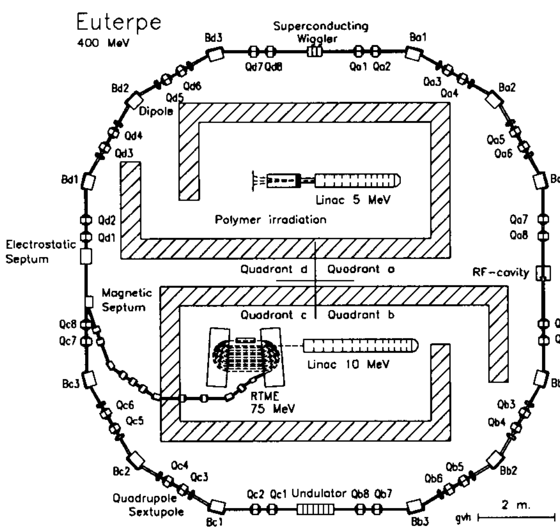

Figure 1: EUTERPE synchrotron

The circumference of the ring is 40 meters. The RaceTrack Microtron Eindhoven (RTME) injects electrons at 75 MeV (2). The ring has 12 identical dipole magnets of unconventional design and construction (3). They have a weight of 600 kg each, and consist of 5 blocks of laminated iron which are glued together. The gap width is 2.5 cm, the pole size is 12 cm by 48 cm. The coils are placed above and below the air gap. Each coil consists of 84 turns of hollow copper conductor, 6 x 6 mm^2 with a bore of 3.5 mm diameter for water cooling. The total inductance (L) of the two coils in series is 102.8 mH, the resistance (R) of the circuit is 167 mΩ. The magnetic field varies between 0.25 T and 1.35 T, corresponding to electron energies of 75 MeV and 400 MeV. For this an excitation current per turn between 30 A and 170 A is required.

This paper describes the power supply and its driving circuit for the twelve dippole magnets. For this system we have the following set of demands.

* The current has to be adjustable from 20 A to 200 A.
* For each dipole a supply voltage of at least 30 V must be available.
* The relative drift of the current should be less than 10^{-5}, measured over a period of 8 hours.
* The difference between the supply currents of any two dipoles related to the average supply current must be less than 10^{-5}.

An obvious solution is to connect all dipoles in series. Then a supply voltage of at least $12 \cdot 30$ V = 360 V is needed. This solution has the disadvantage, that the voltage of the connections of several dipoles is dangerously high, requiring shielding of these connections. Moreover the isolation between the inductors and the iron dipole core, which is grounded, has to meet high requirements. Furthermore as the coils are internally cooled by water, differences in the individual magnet supply current may exist, caused by leakage currents through the cooling water.

Another solution is to provide each dipole with its own 30 V / 200 A power supply. However in this way it becomes difficult to get all the supply currents precisely the same, because separate control circuits are needed, which also makes the system more complex. In the next section an alternative solution is proposed, which combines the advantage of one big power supply with equal current through all coils with that of separate power supplies with low voltage.

II. DISTRIBUTED POWER SUPPLY SYSTEM.

Here we propose to take n identical 30 V / 200 A power supplies in series. Connect a dipole between every power supply (see figure 2). Then at any point the supply voltage is low, the current through the dipole magnets is the same (the dipoles are in series), apart from the leakage current. The difference in leakage current is n times smaller than using a single power supply. Moreover, only one control circuit is needed. This is a major advantage with regard to using n supplies. The repair after a failure of a single unit is easy. The defect power supply can easily be replaced by a stand-by unit. This stand-by unit is relative cheap. Because standard power supplies can be used, we emphasize that this method provides a low cost solution.

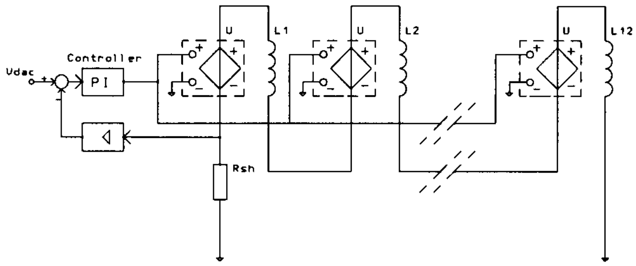

Figure 2: Schematic using dipoles and power supplies in series.

It is well known that the reliability for individual power supplies in series is less than the reliability of one big power supply. However, overrating the power supplies, the other $n-1$ power supplies are able to take over the function of a failing power supply. Then [4], the reliability of individual power supplies in series is higher than the reliability of one big power supply. However diodes, in parallel with the power supplies, are needed. In this way the current loop is not interrupted.

A simple improvement to this method can be made; one side of the inductor of the dipole magnets has a positive potential ($+^1/_2$U) with respect to earth, while the other side of the inductor has a negative potential ($-^1/_2$U). In this way the leakage currents through the cooling water are alternating positive and negative. This reduces the differences in excitation current in comparison with the method above (see figure 3).

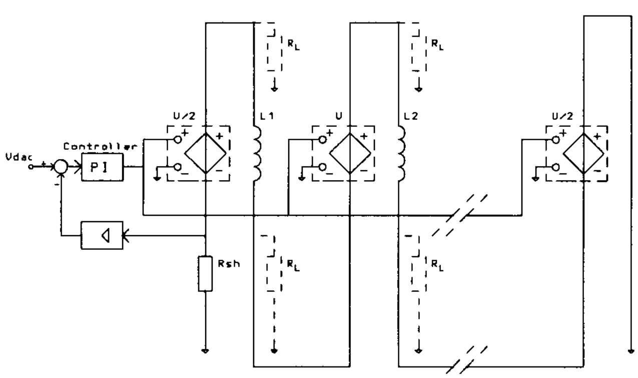

Figure 3: Distributed power supply system, symmetric with regard to ground. The dashed resistors denote the resistance of the cooling water.

III. INDIVIDUAL DIPOLE CORRECTION.

Because of temperature differences, leakage currents through the cooling water, mechanical tolerances, etc. the dipoles can differ. Moreover extra bending capacity may be required for closed orbit corrections. A method to correct the magnetic field in each dipole by means of a small separate current source is shown in Figure 4. Here all correction currents i'_1, i'_2, etc. are shown. The total current is given by: $I_n = I_0 + i_n$, where I_0 is the common excitation current.

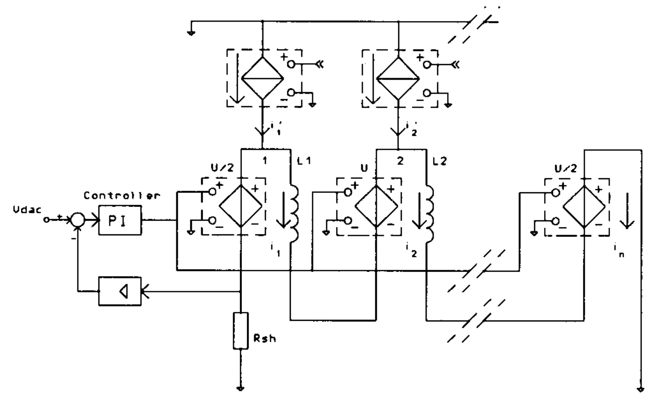

Figure 4: Schematic using the dipoles in series with the power supplies and individual correction.

However, this solution has the problem that when the current through one dipole is corrected, the current through the other dipoles also changes. It would be nice to control the current through a dipole separately from the other dipoles by a separate control variable. For this we make the following analysis. From Figure 4 follows:

$i' = i'_1$,

$i_2 = i'_1 + i'_2$,

.

$i_n = i'_1 + i'_2 + i'_3 + i'_n$,

with i'_n the correcting current for dipole n and i_n the total correcting current in this dipole.

In matrix notation this is written as:

$$i = A\underline{i'}, \tag{1}$$

with the vectors and the coefficient matrix given by:

$$i = \begin{pmatrix} i_1 \\ i_2 \\ . \\ i_n \end{pmatrix}, \quad \underline{i'} = \begin{pmatrix} i'_1 \\ i'_2 \\ . \\ i'_n \end{pmatrix}, \quad A = \begin{pmatrix} 1 & 0 & . & . & . & 0 \\ 1 & 1 & 0 & . & . & 0 \\ . & . & . & . & . & . \\ 1 & 1 & 1 & 1 & . & 1 \end{pmatrix}$$

Suppose that:

$$\underline{i'} = B\underline{u}, \tag{2}$$

with B the transformation matrix from $\underline{u}$ to $\underline{i'}$ and $\underline{u}$ as the wanted control vector (with elements u_1 up to and including u_n).

Following from (1) and (2):

$$\underline{i} = AB\underline{u} \ .$$

As u_k may only influence i_k (with $1 \le k \le n$), the following equations must be realized: $\underline{i} = \alpha \ \ I \ \ \underline{u}$, with I the n x n unit matrix and α a scalar to be defined later.

Hence:

$$B = \alpha A^{-1}$$

This results in:

$$\underline{i'} = \alpha A^{-1} \underline{u} .$$

The inverse of A is:

$$A^{-1} = \begin{pmatrix} 1 & 0 & . & . & . & . & . & 0 \\ -1 & 1 & 0 & . & . & . & . & 0 \\ 0 & -1 & 1 & 0 & . & . & . & 0 \\ . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & . & 0 & -1 & 1 \end{pmatrix} .$$

From this we obtain:

$i'_1 = \alpha u_1$,
$i'_2 = \alpha (u_2 - u_1)$,
.
$i'_n = \alpha (u_n - u_{n-1})$,

with α a constant which has to be specified according to the required correction current and the available control voltages.

Conclusion: Individual dipole correction is possible using different control voltages.

Figure 5 gives a possible realization for individual correction.

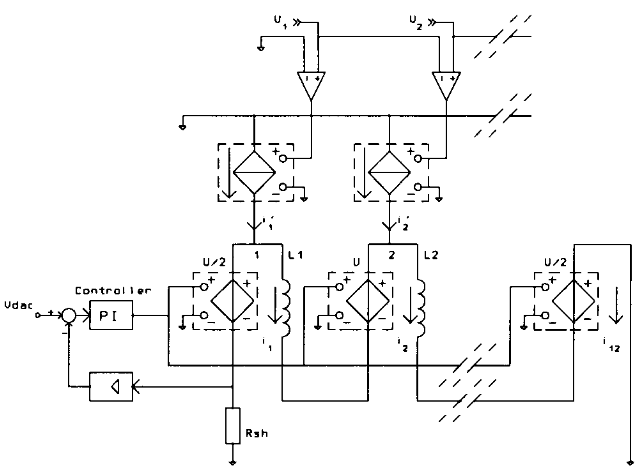

Figure 5: Possible realization to correct the current through each dipole.

IV. CURRENT MEASUREMENT AND STABILIZATION.

The required drift of the current source less than 10^{-5} over a period of 8 hr implies at least the same stability for the current measurement system. the current is measured via a curent shunt. the shunt we use, has an output voltage of 200 mV at a acurrent of 200 A. the stability of the shunt is $2 \cdot 10^{-5}$ /K. the measured output voltge is amplified by a factor of 25 using an instrumentation amplifier, which has an input drift of $\leq 10^{-6}$ V/K. From this the following can be concluded: the drift at the output of the amplifier is equivalent to an input current drift of:

$$(2 \cdot 10^{-5} \, I + 10^{-3}) \, A/K$$

Further it is desirable to place the current shunt and measuring equipment in an oven. The stability of the temperature in the oven must be within 0.4 K. This requirement is relatively simple to realize.

To stabilize the current it is desirable to know the dynamic behavior of the current loop. Neglecting the parasitic effects, we find with n power supplies and n coils (inductor and resistor) placed in series an admitance:

$$Y(\omega) = \frac{1}{nR} \cdot \frac{1}{1 + j\omega\tau_1} ,$$

with the time constant τ_1 = L/R. Measurements on a dipole prototype showed τ_1 = 0.62 s.

A second time constant τ_2 is introduced by the dynamic behavior between the output voltage of the n power supplies and the driver voltage. This time constant is about 3 ms. About the parasitic effects the following remarks can be made: Iron losses in the core are negligible because of the use of laminated iron. Crosstalk between the turns is only relevant at frequencies above 20 kHz. By placing a filter in the loop, this effect can be suppressed. In this way parasitic oscillaton can be avoided. By choosing the integration time constant of the PI-controller the same as the time constant of the dipoles (τ_1) (see Figure 5) and making the static open loop gain equal to $\tau_1/2\tau_2$, the closed loop behavior is similar to a second order critically damped process (damping ratio, ß = $1/_2\sqrt{2}$).

V. CONCLUDING REMARKS.

The use of a distributed power supply system combines the advantages of one big power supply with those of separate power supplies. The currents in all dipoles are the same, with low voltages at the electrical connections. The leakage current is low. The reliability is high (10% overdesign). The repair-time is short due to modular construction. The solution is economical and stabilization is relatively simple.

VI. REFERENCES.

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