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.

![EUTERPE synchrotron](image)

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 mm² 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 dipole 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 × 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 relatively 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.](image)

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.](image)

### 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 \( i'_1, i'_2, \ldots \) are shown. The total current is given by:

\[
i = I_0 + i_n,
\]

where \( I_0 \) is the common excitation current.

![Figure 4: Schematic using the dipoles in series with the power supplies and individual correction.](image)

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:

\[
i'_1 = i'_1,
\]

\[
i'_2 = i'_1 + i'_2,
\]

\[
i'_n = i'_1 + i'_2 + \ldots + i'_n,
\]

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:

\[
i = Ai'_n,
\]

with the vectors and the coefficient matrix given by:

\[
i = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_n \end{bmatrix}, \quad i'_n = \begin{bmatrix} i'_1 \\ i'_2 \\ \vdots \\ i'_n \end{bmatrix}, \quad A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & 1 & 1 \end{bmatrix}
\]

Suppose that:

\[
i'_n = Bu_n,
\]

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

Following from (1) and (2):

\[
i = ABu_n.
\]

As \( u_k \) may only influence \( i_k \) (with \( 1 \leq k \leq n \)), the following equations must be realized:

\[
i = \alpha ^I u, \quad \text{with } I \text{ the } n \times n \text{ unit matrix and } \alpha \text{ a scalar to be defined later.}
\]

Hence:
\[ B = \alpha A^{-1} \]

This results in:
\[ i' = \alpha A^{-1} u. \]

The inverse of \( A \) is:
\[
A^{-1} = \begin{pmatrix}
1 & 0 & . & . & . & . & . & 0 \\
-1 & 1 & 0 & . & . & . & . & 0 \\
0 & -1 & 1 & 0 & . & . & . & 0 \\
\end{pmatrix}
\]

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 \( \alpha \) 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.

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

with the time constant \( \tau_1 = L/R \). Measurements on a dipole prototype showed \( \tau_1 = 0.62 \text{ s} \).

A second time constant \( \tau_2 \) 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 oscillation can be avoided. By choosing the integration time constant of the PI-controller the same as the time constant of the dipoles (\( \tau_1 \)) (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, \( \beta = 1/\sqrt{2} \)).

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.