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MAGNET SYSTEMS - POWER SUPPLIES - COST OPTIMIZATION

Charles G. Dols

September 1, 1965
MAGNET SYSTEMS - POWER SUPPLIES - COST OPTIMIZATION

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Summary

As the number of auxiliary magnets for particle accelerators increases, it becomes increasingly important that some of the designs be standardized. More attention will therefore be paid to cost optimization of the standard magnet designs. In this paper we present significant concepts and elements that enter into such cost optimization.

A typical auxiliary-magnet system is first described. Then the factors that enter into cost optimization are discussed, with some examples given. These factors include power duty factors; incremental costs; and present value, including interest rate and useful life. Finally an expression for optimum current density in magnet conductors is derived.

Introduction

The coils of electromagnets used in auxiliary magnet systems of particle accelerators have been cooled by various methods: convection air, forced air, oil or water circulating over bare conductors (separated by spaced insulators), air or water flowing past fins imbedded in the coils, and water flowing in hollow conductors. The electromagnets are powered by storage batteries, motor-generator sets, and various rectifier power supplies in which selenium rectifiers, silicon rectifiers, vacuum-tube amplifiers, vacuum diodes, thyatrons, magnetic amplifiers, and silicon controlled rectifiers (SCR) are used.

Although many of the above elements continue to be used there is a trend toward the following system of magnet and power supply:

In this system, iron-core magnets with coils made of hollow water-cooled copper conductors are powered by supplies in which SCR’s rectify and control ac power. See Fig. 1.

While some users are finding it convenient to assemble power supplies and auxiliary magnets into a compact package, the Lawrence Radiation Laboratory and other laboratories are exploiting the flexibility of separate magnets and modular supplies. Since auxiliary magnets frequently operate at less than design power, it is often desirable that a "large" magnet be powered from a "small" supply. Under such conditions the use of SCR supplies becomes advantageous; they are readily adaptable to operation in multiple-in series, in parallel, or in series-parallel.

When power supplies are located at some distance from the magnets, they are typically connected to the magnets with flexible cables. These cables may be made up of AWG 4/0 or 500 000 CM conductors with as many conductors in parallel as are required for the magnitude of current. The cable between a magnet and its power supply is usually about 100 feet long.

Comments on Magnet Design

Shape of Magnet

Auxiliary magnets for particle accelerators are often mounted in shielding walls, which are usually built up of rectangular concrete prisms. Unless the magnets have rectangular cross sections, it is difficult to seal them into the walls. Although magnetic-field considerations permit cutting off the corners of some magnets, it is seldom advisable to do so.

Impedance of Coils

The design of hollow-conductor water-cooled coils is strongly influenced by the following: A coil design with an electrical impedance high enough to keep the connecting-bus currents conveniently low tends to have an impractically high predicted hydraulic impedance. Thus, in general, coil conductors are connected electrically in series and hydraulically in parallel. However, an inconveniently large number of parallel hydraulic paths are often required in order to achieve an "ideal" electrical impedance.

At present, difficulties in the hydraulic design of water-cooled coils are partly responsible for our having an unusually wide assortment of power-supply voltage and current ratings. Although the impedance levels of SCR-controlled power supplies are quite flexible, it will be very advantageous to standardize some power-supply voltage and power ratings.

Cost Optimization

Problems in engineering economy frequently reduce to minimizing the total of construction costs and capitalized operating costs, i.e., the present value of the operating cost. The significant operating cost of conventional magnet systems is the cost of the electric power consumed during the life of the magnets.

The present value of the electric-power cost for a magnet is a function of its full-load power consumption, the duty factor, the predicted useful life, and the "cost of money," i.e., the rate of interest.

Costs other than the present value of the electric-power consumption of the magnet during its entire life also vary with its power rating.
The addition of each new magnet increases the burdens on existing power supplies, cables, and water-cooling systems. In general, the cost-optimization study for a new magnet design should include allocated costs of the power and cooling system. These costs should be included even though no new system capacity is needed. Although some magnets require a one-to-one correspondence between the rating of magnet load and the rating of their power and cooling systems, in large laboratories where many of several types of general-purpose magnets are used, only a fraction of the load rating of each new magnet should be used in allocating costs of the power and cooling system.

Table I is a very rough summary of power and cooling requirements reflecting current experience at the BNL AGS, the LRL Bevatron, and the LRL 184-inch synchrotron. It gives approximate percentages of magnet ratings required for power and cooling.

### Power Duty Factor

Of all the general-purpose magnets (e.g., bending and quadrupole) owned by a laboratory, some fraction, $f_i$, will be in position for an experiment and connected to power supplies. Of these, some fraction, $f_e$, will be energized. The average currents will be $f_c$ times the rated currents. Because power varies as the square of the current, the power duty factor, $f_{pe}$, of the energized magnets is $f_{pe} = (f_i f_c f_e)^2$, when $f_i$ is the average current fraction to the average current fraction. When statistics of power consumption are available, the power duty, $f_{pe}$, is taken as the average fractional power of the energized magnets; thus the problem of estimating $f_i$ is avoided. If all magnets are de-energized at a significant fraction of the time, the factor $f_{pe}$ could correspond to averages during operation only. Then the factor, $f_i$, defined as the ratio of active time to total time, should be used.

### Table I. Examples of power and cooling requirements.

<table>
<thead>
<tr>
<th>Power supplies</th>
<th>Total load capacity</th>
<th>50% of the total dissipation ratings of all magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supplies in</td>
<td>Total load capacity</td>
<td>90% of all power supplies</td>
</tr>
<tr>
<td>Service</td>
<td>Average load</td>
<td>60% of the total rating of the connected supplies</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Capacity required</td>
<td>40% of the total dissipation ratings of all magnets</td>
</tr>
</tbody>
</table>

The power duty factor for all magnets is

$$f_p = f_i f_e f_c f_{pe} f_t$$

Table II gives some approximate magnitudes of duty factors, summarizing experience at LRL and BNL.

### Table II. Examples of magnet duty factors.

<table>
<thead>
<tr>
<th>Duty Factor</th>
<th>Symbol</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average fraction installed</td>
<td>$f_i$</td>
<td>60% of all magnets</td>
</tr>
<tr>
<td>Average fraction under power</td>
<td>$f_e$</td>
<td>60% of those installed</td>
</tr>
<tr>
<td>Average current</td>
<td>$f_c$</td>
<td>60% of magnet ratings</td>
</tr>
<tr>
<td>Average power</td>
<td>$f_{pe}$</td>
<td>45% of the total dissipation ratings of the energized magnets</td>
</tr>
<tr>
<td>Fraction of operating time over which the above factors are averaged</td>
<td>$f_t$</td>
<td>100%</td>
</tr>
<tr>
<td>Power duty factor</td>
<td>$f_p$</td>
<td>16% of the total of the dissipation ratings of all magnets</td>
</tr>
</tbody>
</table>

### Useful Life

In the planning of the design and construction of magnets, some assumption about the length of time the magnets will be useful is implied. Although the lifetime of laboratories is measured in decades (at least), the expected lifetime of magnet designs is significantly less. Magnets become obsolete and obsolete because the requirements of experimenters change and because technology advances. A useful life of about 15 years seems reasonable.

### Interest Rate

Interest rate varies with the risk associated with the use of money. Since investment in highways, for example, is considered a low-risk venture, the cost of money for highways is low. Highways have been essential to civilization for centuries; neither substitutes for them nor dramatic cost reductions are probable.

In contrast, the allocation of money for general-purpose magnets for a high-energy physics laboratory is a medium-risk investment. The magnets may not actually be used as much as was expected when construction was planned; the coils may be damaged -- by electrical, mechanical or radiation accidents; design or fabrication errors
may contribute to early failures; or a direct substitution of a more economical device, such as a superconducting magnet, may occur before the end of the magnet's estimated useful life. Because of these risks, an interest rate of about 8% seems appropriate.

Present Value

When the rate of interest is 8%, $8.56 will purchase an annuity of $1.00 for 15 years. Thus with interest at 8%, the present value of 15 years of operating cost is determined by multiplying the yearly cost by 8.56.

Incremental Costs

As the size of a magnet or the size of (for example) the core or the coil increases, the corresponding cost increases in the manner illustrated in Fig. 2. A curved band is shown to suggest the uncertainties in cost estimations, the fluctuations of cost with time, and the discrete jumps in cost that correspond to (necessary) discrete changes in design. The actual cost function is well represented, as shown in the figure, by approximating it as the sum of a fixed cost plus the product of an incremental cost and a size number (usually weight).

It is important to distinguish between average costs and incremental costs because (a) there is usually a significant difference in magnitude (incremental costs are often about two thirds of the average) and (b) the relative magnitudes of incremental costs determine the design balance for minimum overall cost.

Table III lists some examples of incremental costs that were derived from experience at LRL.

Table III. Some approximate incremental costs.

<table>
<thead>
<tr>
<th>Description</th>
<th>Incremental Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-kW SCR-controlled power supplies</td>
<td>$50/kW</td>
</tr>
<tr>
<td>48 by 36-in. bending magnet, 8 in. gap</td>
<td>$0.40/lb</td>
</tr>
<tr>
<td>Core of solid iron</td>
<td></td>
</tr>
<tr>
<td>Coils of hollow copper conductors</td>
<td>$3.00/lb</td>
</tr>
<tr>
<td>Total weight</td>
<td>26 tons</td>
</tr>
<tr>
<td>8 in. i.d. by 30 in. long quadrupole</td>
<td></td>
</tr>
<tr>
<td>Core of laminated iron</td>
<td>$0.85/lb</td>
</tr>
<tr>
<td>Coils of hollow copper conductors</td>
<td>$2.00/lb</td>
</tr>
<tr>
<td>Total weight</td>
<td>4 tons</td>
</tr>
</tbody>
</table>

Optimum Current Density

The designs of some magnets (septum, for example) are strongly influenced by requirements for fitting the magnet and/or the conductors in a small space. Such magnets may operate economically at very high current densities in the conductors. However, the need for small size does not dominate the design of most magnets. It is of interest, therefore, to examine the influence of other factors on the magnitude of economical current density.

The costs of producing a magnetic field for n years include:

- Installed cost of the magnet iron, \( C_i \);
- Installed cost of the magnet conductor, \( C_c \);
- Installed cost of the power supply and switch gear (including building space) \( C_p \);
- Installed cost of the cooling system, \( C_h \);
- Capitalized cost of energy, \( C_e \), (the present value of the energy for n years of operation);

and the Capitalized maintenance cost of the power supply and cooling system, \( C_m \).

The total of these costs, \( C_t \), is then

\[
C_t = C_i + C_c + C_p + C_h + C_e + C_m
\]

The last four terms can be approximated as a simple function of the magnet power, \( P \). Call the combination, \( C_p \), the cost of power:

\[
C_p = C_p + C_h + C_e + C_m
\]

Cost \( C_p \) is approximated in terms of incremental costs as

\[
C_p = K_1 + \left( \frac{\partial C_p}{\partial P} \right) P + \left( \frac{\partial C_h}{\partial P} \right) P + \left( \frac{\partial C_e}{\partial P} \right) P + \left( \frac{\partial C_m}{\partial P} \right) P = K_1 + \frac{\partial C_p}{\partial P}
\]

where \( K \) is a constant.

The cost of the iron plus the conductor is (similarly) approximated as

\[
C_i + C_c = K_2 + \left( \frac{\partial C_i}{\partial W_i} \right) W_i + \left( \frac{\partial C_c}{\partial W_c} \right) W_c
\]

where \( W_i \) and \( W_c \) are the total weight of the iron and the conductor, respectively. The terms \( \partial C_i/\partial W_i \) and \( \partial C_c/\partial W_c \) represent the incremental unit costs of the iron and of the conductor.

The iron cost varies with conductor weight because a larger coil requires a longer flux-return path through the iron. The factor \( \partial W_i/\partial W_c \), which is a measure of the magnitude of this effect, is the ratio between the weight of iron required to allow for an increase in coil size and the corresponding increase in conductor weight. The factor \( \partial W_i/\partial W_c \) can be estimated to a useful precision from the dimensions of a very rough design for a particular magnet. Its magnitude should, of course, be checked and if necessary revised as the magnet design is refined.

Express the total incremental cost of the conductor as
\[ \frac{\partial C_t}{\partial W_i} = \frac{\partial C_i}{\partial W_i} \frac{\partial C}{\partial W_i} + \frac{\partial C}{\partial W_i} \]

Then,

\[ C_t = C_i + C_c + C_p \]

\[ = K_1 + K_2 + \frac{\partial C_p}{\partial P} + \frac{\partial C}{\partial W} W_i. \]

\[ P = \frac{I^2 R}{A} \]

and \( W_i = \sigma N L_{mt} A, I = \text{current in conductor of cross section } A, \rho = \text{resistivity of conductor}, \sigma = \text{density of conductor}, N = \text{number of turns in magnet coil}, L_{mt} = \text{length of a mean turn of the magnet coil}. \]

\[ C_t = K_1 + K_2 + \frac{I^2 \rho N L_{mt}}{A} + \sigma N L_{mt} A \frac{\partial C}{\partial W}. \]

\[ \frac{dC_t}{dA} = \frac{I^2}{A} \frac{\rho N L_{mt}}{A} + \sigma N L_{mt} A \frac{\partial C}{\partial W}. \]

\[ dC_t = 0, \text{ when } A = A_{\text{optimum}}. \]

Then \( \left( \frac{I}{A} \right)_{\text{opt}} = \sqrt[\text{optimum}] \left( \frac{\sigma (\partial C_t/\partial W)}{\rho (\partial C_p/\partial P)} \right) \) is the optimum current density.

For copper, \( \sigma = 461 \times 10^{-6} \text{ tons/cu in.} \)
\[ \rho = 0.826 \times 10^{-6} \text{ ohm-inch at 75° C.} \]

With \( I/A \) in amperes per square inch, \( (\partial C_t/\partial W) \) in dollars per ton, and \( (\partial C_p/\partial P) \) in dollars per kW, the optimum current density for copper is

\[ \left( \frac{I}{A} \right)_{\text{opt}} = 442 \sqrt[\text{optimum}] \left( \frac{\partial C_t/\partial W}{\partial C_p/\partial P} \right) \text{ (copper)}. \]

The corresponding expression for aluminum of 61% conductivity is

\[ \left( \frac{I}{A} \right)_{\text{opt}} = 311 \sqrt[\text{optimum}] \left( \frac{\partial C_t/\partial W}{\partial C_p/\partial P} \right) \text{ (aluminum)}. \]

The magnitude of economical current density will be relatively large when power cost and duty factor are low and when the incremental costs of magnet steel and conductors are high. Table IV lists two sets of parameters for magnet systems. The corresponding magnitudes of optimum current densities span most auxiliary-magnet applications.

| Table IV. Two examples of economically optimum current density. |
|---------------------------------|-----------------|
| Cost of electrical power (c/kWh) | 0.5 1.5 |
| Power duty factor, \( f_p \) (numeric) | 0.07 0.7 |
| Incremental cost of power supply, \( \frac{\partial C_p}{\partial P} \) ($/kW) | 30 60 |
| Incremental cost of cooling system, \( \frac{\partial C}{\partial W} \) ($/kW) | 40 40 |
| Relative capacity of P.S. and cooling systems (per unit of magnet full rated load) | 0.4 1.0 |
| Incremental copper cost, \( \frac{\partial C_p}{\partial W} \) ($/lb) | 3.00 2.00 |
| Incremental steel cost, \( \frac{\partial C}{\partial W} \) ($/lb) | 0.85 0.40 |
| Steel weight increment \( \delta W_i \) (per unit of copper weight increment) | 4.0 4.0 |
| Interest rate (\%) | 8 8 |
| Useful life, n (yr) | 15 15 |
| Optimum current density \( (A/in.\)^2 \) | 6800 1250 |

As the number of auxiliary magnets in use increases, more attention will be paid to economic factors in their construction and operation. As experience in magnet applications accumulates, better economic data will become available. Some types and sizes of magnets will become standardized. Very probably some of the standard designs will provide the same field strength and gap dimensions in two different designs -- one operating at a relatively high current density, and the other at a significantly lower current density. An example of this pattern exists in the so called "low-power quads" and "high-power quads" in use at the LRL Bevatron. The Bevatron also has low- and high-power bending magnets.

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A Typical Magnet System

fig. 1

Modular SCR Controlled
Power Supply Units
connected singly, in series,
in parallel, or in series-parallel

solid or laminated
iron core

coils of hollow
copper conductors

about 100 feet
of flexible cable.

cooling
water

MUB-7748
How Cost Usually Varies With Size

fig. 2
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