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PIGGY-BACK POWER SUPPLIES FOR MAGNET SYSTEMS*

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Summary

In accelerator facilities, particularly beam switchyards, it is common to have two or more related magnets which require nearly the same dc current. Presently the magnets are energized from separate sources, or from a single current-regulated source, with the magnets connected in series, and current-sink shunts across one or more of the magnets to obtain the difference. This article describes the advantages of economy, efficiency, reliability, and flexibility which accrue if auxiliary power supplies are used to trim the currents by the addition of more current to one or more magnets.

Introduction

In this article the name "piggy-back" power supply is applied to an auxiliary power supply which adds a fraction of current to one magnet electrically connected in series with another magnet. The two magnets are energized from one master power supply. This arrangement of power supplies is feasible only in current-regulated systems because current-disparate supplies can work in parallel without modification, providing there is voltage compliance. In Figs. 1, 2, and 3, the connections of power supplies are shown for three different systems in which two magnets require nearly the same current. In particular, one magnet requires 90% of the current of the other magnet. Fig. 1 shows the conventional hook-up of two magnet loads each energized from a separate but identical master power supply. In Fig. 2, the two magnets are energized by a single master power supply having twice the voltage, but the same current capacity. Superimposed on the second magnet is the current of a piggy-back supply having a current capability of 10% and a voltage capability of 50% of the master supply. In Fig. 3 the same two magnets are energized from a power supply identical to that of Fig. 2. In this case the current in the first magnet is shunted by a current sink. In all these arrangements the magnets are operating at the same current and voltage levels.

In the systems of Figs. 2 and 3, the auxiliary units (piggy-back or current sink) require current regulation and stability that need be only a fraction as good as that of the master supply. The fraction is the same as the current ratio; in this example, one-tenth.

The arrangements can be expanded to several magnets in series with individual auxiliary units. Fig. 4 shows a typical four magnet arrangement with piggy-back units. In a further extension of the principle, small auxiliary units can be superimposed on larger auxiliary units. Further, two auxiliary units in parallel could be used to accommodate a larger fraction of the current. Cost, mainly, determines the limits to the arrangement. The relative costs for typical systems having two, three and four magnets indicate that cost savings of up to 30% can be realized by using the piggy-back arrangement over the individual power supply arrangement. The piggy-back connection runs 5 to 10% less than the current sink arrangement. The procedure used for arriving at these results will now be described.

Cost Study

System Design Parameters

The following assumptions are made to simplify cost calculations:

1. The resistance of each magnet is identical.
2. The master power supply for two magnets in series has the same current capacity as the master supplies energizing individual magnets. (The operational differences in the current requirements for each magnet is not known at the time of the purchase and installation. The differences can be determined only after tests in which the variations in the performances of the magnets and their misalignment come into effect.)
3. The master power supply cables cannot be readily transferred from one magnet to another after the completion of the installation. The connections of the auxiliary supplies (piggy-back or sink) can be easily changed from one magnet to another.
4. The auxiliary power supply has a current capacity of 10% of the master and a compliant voltage.
5. All supplies are continuously adjustable from zero to full current.
6. The master power supplies are large special units and are not available as catalogue items.
7. The regulation and stability of the master unit is 10^{-3} or better.
8. Standard piggy-back units, having 10% of the current capacity, can be found as catalogue items with a regulation and stability one-tenth as good as that of the master. (Catalogue units are readily available in sizes up to 2 kw, with regulation of ± 0.1% and better, and in sizes up to 10 kw, with regulation of ± 1% and better.)
9. Current sinks are not available as catalogue items in any size.

Unit Cost Relations

The following cost relations have been developed from experience and discussions. In practice they may vary considerably. Nevertheless, they are reasonable assumptions in calculations in which trends rather than precision in results is acceptable.

1. The relation of unit price versus quantity for large special current regulated power supplies is shown in Fig. 6. The relation is a function of several variables. The slope is due mainly to labor charges. As more units are constructed, labor efficiency rises rapidly in the early stages. The initial slope will be greater if a considerable amount of new engineering is required. The slope will be less if the cost of the components represent a large percentage of the price. Many variables are dependent on the cost accounting system of the manufacturer.
2. In the range of one to four special units in which this study is made:

$$\text{Power Supply Cost} = K\sqrt{\text{Power}}$$

3. The price of a standard piggy-back unit with one-tenth the current capacity of the master is 20% of that of a master unit for a single magnet. No quantity discount applies.

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4. The price of a special current sink with one-tenth the current capacity is 30% of that of a master for a single magnet. The price-quantity relation of Fig. 6 applies.

5. The cost of installation and cabling for a single magnet and power supply is 10% of the purchase price of the power supply. The price-quantity relation for the installation is similar to that of Fig. 6. The multiplier is 0.75 for a quantity of four. (The magnets are located 150 feet from the group of power supplies. One output terminal from the auxiliary unit is connected to the output terminal of the master and the other output terminal is connected to the magnet.)

6. The cost of installation of an auxiliary unit is 10% of that for the installation of the master unit for a single magnet. No quantity discount applies.

Cost Comparison-Systems

Using the assumptions of the preceding two sections, the results of the cost study for power supplies plus installation are shown in Fig. 7. The prices are normalized, with the cost of a single power supply for energizing one magnet considered unity. In Fig. 8, the savings are shown as a percentage of the cost of the corresponding arrangement using individual supplies. With four magnets connected in series, the piggy-back power supply system saves 27%. By extrapolation a peak of about 30% is reached somewhere between six and eight magnets and then declines. The reason is that the effect of price reduction for the master power supplies and their installation becomes appreciable as the number of magnets increases. The piggy-back supplies have no price reduction for quantity.

The percentage savings favor the piggy-back system over the current sink system in the order of 5% to 7% (Fig. 8).

Cost Of Power

Based on one power supply using 10% less current than the other for a two magnet system, the power output of all three systems are nearly equal (Figs. 1, 2, 3). Those of the individual power supplies and the piggy-back system are identical. That of the current sink system is 5% greater than the piggy-back system. This just about equals the losses of the transformer and rectifier in the piggy-back supply. However, the power into the system depends largely upon the respective efficiencies of the master power supplies. The systems using auxiliary power supplies require higher voltage master units. Higher voltage units are appreciably more efficient in the region of 10 to 150 volts output. A 100-volt unit will run about 70% efficient and a 50-volt unit about 50%. As an example, two magnets, each of 25 kw, operate at 50 volts and 50 amps. Electricity costs 3¢ per kwh and the systems are operated 50% of the time. The cost of operation is $1300 approximately, for the individual power supply system as against $900 for the other two systems. If the total cost of the two power supplies is $15,000, then the savings in the cost of power is 2.5% approximately. The percentage savings increase at a slower rate as the number of magnets and auxiliary units is increased.

Reliability

The reliability of the piggy-back system will greatly exceed that of the other two systems. For simplification, the reliability of a master power supply may be considered unity. That of a unit having twice the voltage and the same current may be 0.8. The higher number indicates greater reliability. A standard piggy-back supply will have a reliability several fold better than a master unit mainly because the weaknesses of a standard unit will have been eliminated with experience. A value of 5 may be applicable. Hence a piggy-back system with two magnets would be more reliable by a factor of 1.4. (The reliability of the individual power supply system is $\frac{1}{1+1} = 0.5$. The reliability of the piggy-back system is $\frac{1}{\frac{1}{0.8}+\frac{1}{5}} = 0.7$.) Three and four magnet systems using piggy-back units will be more reliable by a factor of 1.9 and 2.2 respectively. The reliability figures are not authentic and the method lacks elegance, but a trend is definitely indicated.

The reliability of a current sink system in which all power supplies are special will have about the same reliability as the individual power supply system.

Flexibility

Flexibility, as the word is applied herein, is used very generally and is also a "catch-all" for several minor advantages. A piggy-back supply, being a catalogue item in most instances, can be easily replaced with a smaller or larger unit if the current differences turn out to be less or more than the worst possible case anticipated. Should a piggy-back unit fail, an identical or equivalent substitute should be easily available. Engineering time required for drawing purchase specifications are eliminated in the piggy-back unit procurement. The preceding arguments do not apply to a current sink. The delivery of one master supply in a piggy-back system should in most cases be faster than the delivery of a master unit and current sink, or multiple master units.

Bates Accelerator Application

At the 400 MeV Linear Electron Accelerator of the Massachusetts Institute of Technology, the piggy-back system was applied to a series of four quadrupoles. The quadrupoles rotate the beam ninety degrees just before reaching the target and "energy loss" spectrometer. The arrangement of the four magnets and systems with current and voltage requirements is shown in Fig. 5. All magnets have the same resistance. Two magnets were required to have a current capability 10% greater than the other two. In each pair one magnet would require current within 5% of the other. Thus the system has a 5% piggy-back unit superimposed on a 10% piggy-back unit. Since the master unit, having a stability of ± 0.01%, was already in house as surplus equipment, no cost analysis is available. The piggy-back supplies were well within the power, voltage and current range of standard items having a stability of ± 0.1%.

Conclusion

The advantages of cost economy, power efficiency, reliability and flexibility realized by the application of a piggy-back power system for energizing magnets requiring nearly the same value of current can be extended from the models described. If a standard unit is readily available for piggy-back application, the fraction of current it supplies can be greater than the 10% used in the model for analysis. The resistance of the magnets need not be equal, but can vary considerably. Piggy-back units may be superimposed on other piggy-back units. The merits of each application will have to be determined on the requirements of the system.

Acknowledgement

It is always a pleasure to work with Dr. S. B. Kowalski, the designer of the quadrupoles for beam rotation.

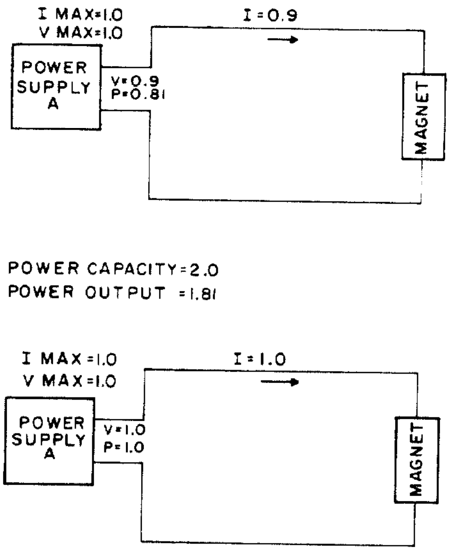

Fig. 1 TWO MAGNET SYSTEM MAGNETS INDIVIDUALLY ENERGIZED

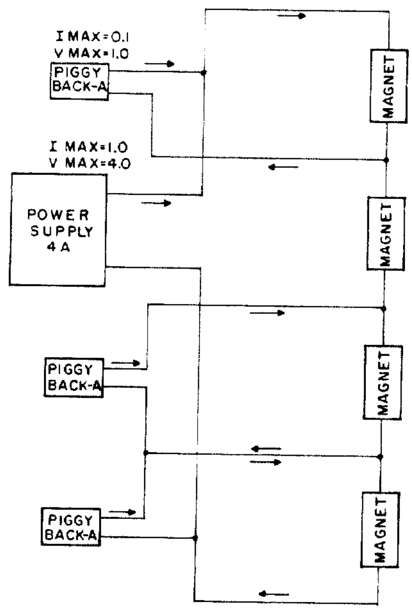

Fig. 4 FOUR MAGNET SYSTEM WITH PIGGYBACK SUPPLIES

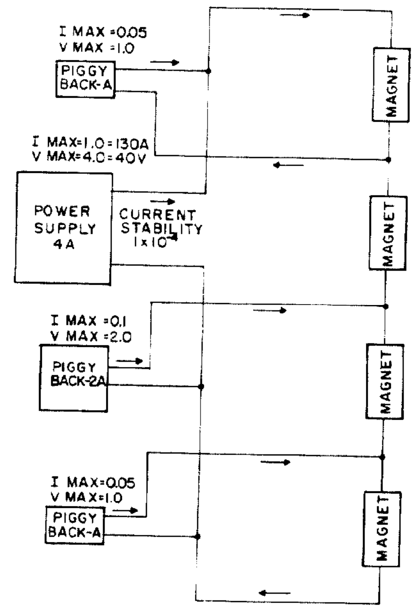

Fig. 5 FOUR MAGNET SYSTEM FOR ROTATING ELECTRON BEAM WITH PIGGYBACK SUPPLY SUPERIMPOSED ON PIGGYBACK SUPPLY

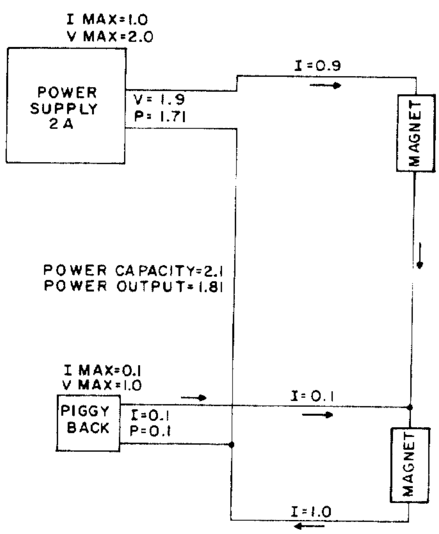

Fig. 2 TWO MAGNET SYSTEM WITH PIGGYBACK SUPPLY

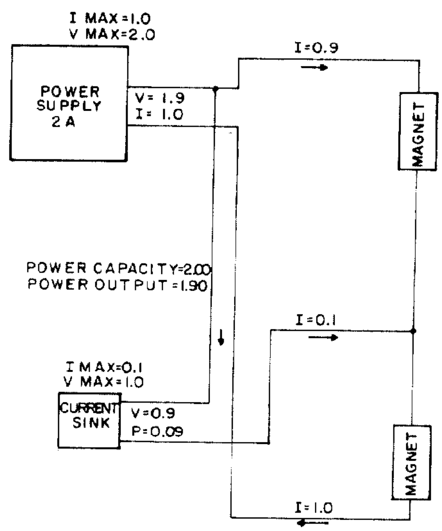

Fig. 3 TWO MAGNET SYSTEM WITH CURRENT SINK

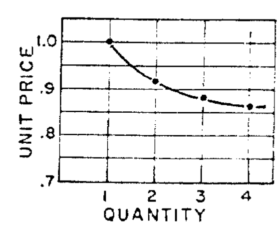

Fig. 6 RELATIVE COST OF SPECIAL POWER SUPPLY vs QUANTITY

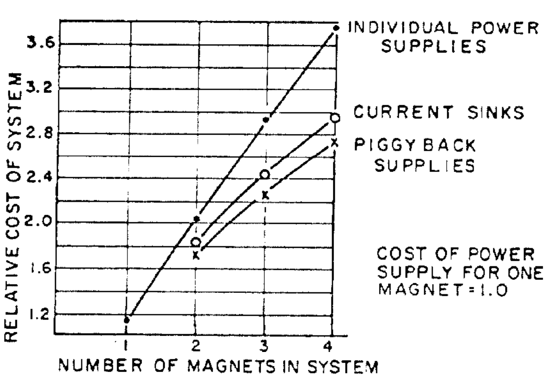

Fig. 7 RELATIVE COST OF SYSTEMS: EQUIPMENT & INSTALLATION

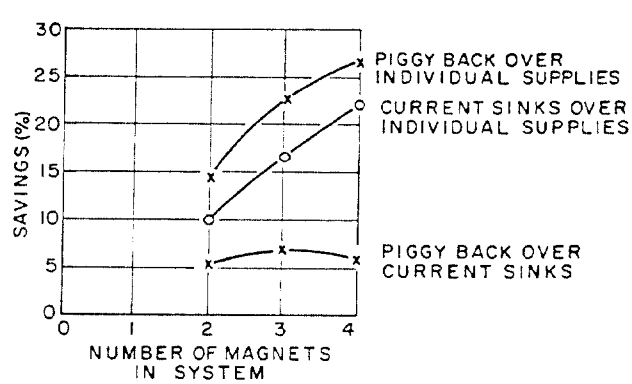

Fig. 8 % SAVINGS FOR SYSTEMS: EQUIPMENT & INSTALLATION