SYNCHROTRON POWER SUPPLIES USING SUPERCONDUCTING ENERGY STORAGE

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I. INTRODUCTION

The possibility of using energy storage in superconducting coils as the basis of a synchrotron power supply was discussed in a previous paper.[1] The present report reintroduces the idea for comment and discussion, with comments on one or two relatively minor additions to the theory. No significant improvements on the original version of the idea have been achieved, and no assessment has yet been made of its practical feasibility.

This line of thought arises immediately from work on superconducting synchrotron magnets. The energy stored in the latter would be typically at least four times that of conventional magnets (i.e., probably $\sim$ 1 MJ/GeV or more). This not only leads to an undesirably high power supply cost, but also, for very high energy accelerators requiring 10^8-10^9 joules, may pose basic problems of feasibility and reliability. (Some authoritative comments on the feasibility of conventional supplies in this energy range would be of value.)

On the other hand, the problem is simplified by the fact that the energy lost per cycle will be very small, and there will be no dc power requirements for "flat top" operation. Under these circumstances there arises the obvious concept of using a superconducting coil storing the same energy as the synchrotron magnet, with some means of transferring the energy from one to the other. Favorable economics results basically from the fact that a single large coil can store energy much more efficiently and cheaply than the large number of small magnets which constitute the synchrotron magnet ring. Nevertheless, over-all economics will obviously depend very much on the efficiency and cost of the energy transfer scheme. In the conventional motor-alternator-rectifier schemes, for example, only about 10% of the flywheel energy is utilized, and the rectifier conversion equipment represents typically half the total cost. The cost of the conventional system is indicated by curve (d) of Fig. 1, as a function of energy transferred. Curve (a) shows the present cost of superconducting coils, which, at the optimum field $\sim$ 50 kG, is about £1 to £1.5 $\times$ (stored energy in joules)$^{2/3}$. Comparison of the two curves in the 10^8-10^9 joule region, suggests that we have at least a factor of 10 available to turn the basic superconducting coil into a synchrotron power supply.

II. ENERGY TRANSFER

Several elementary ways of transferring energy between inductances were discussed in Ref. 1. Most of these involved either appreciable losses or a second energy storage system of a different type (capacitor bank, mechanical system, etc.). The exception was the system of coupled coils shown in Fig. 2. All coils are assumed superconducting, and by appropriate variation of the two coupling coefficients k_a and k_b, not only can energy be transferred to and from L_S (which represents the synchrotron magnet), but in addition the total energy of the system can be kept constant. The process is then completely reversible, and no external work is necessary during any part of the cycle.

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1. P.F. Smith, in Proc. 2nd Magnet Technology Conference, Oxford, 1967, p. 589.

The simplest solution is when $L_2 = L_3$, $L_4 = L_S$, and I_1 is constant. The condition for constant total energy is then

$$k_a^2 + k_b^2 = \text{constant} \quad , \tag{1}$$

where the coupling coefficients are defined in the usual way by $M_{xy} = k_{xy} (L_x L_y)^{\frac{1}{2}}$. Zero coupling between L_2 and L_3 is assumed.

For this solution, $I_2 \propto k_a$ and $I_3 \propto k_b$, so that the net effect is simply a reversible interchange of energy between L_4 and L_S. But although L_1 appears to have a completely passive role in the circuit, it is in fact the largest coil; its stored energy is minimized when $L_2 = L_3 = L_4 = L_S$, and is given by

$$\frac{L_1 \; I_1^2}{L_S \; I_2^2 \; (\text{max})} = \frac{4}{k_m^2} \quad , \tag{2}$$

where k_m is the maximum value of k_a or k_b, and, of course, k_m must be < 1.

The stored energy in all the coils can, in principle, be halved by using a synchrotron magnet with a dc bias, and allowing both positive and negative currents in the ac coils. However, the use of separate dc and ac magnets, Fig. 3a, is probably ruled out by the particle dynamics, and the use of superimposed dc and ac windings, with a scheme such as that shown in Fig. 3b, alters Eq. (1) to $(k_a - k_o)^2 + k_b^2 = \text{const.}$, which seems to be more difficult to achieve in practice. Nevertheless something along these lines might well be devised.

III. PRACTICAL SYSTEMS

From Eq. (1), by analogy with the geometric relationship $\cos^2 \theta + \sin^2 \theta = 1$, one is led immediately to a simple practical representation of the above circuit, shown in Fig. 4. L_2 and L_3 are mutually perpendicular, rigidly connected, and rotate on a common shaft in the field produced by L_1. They constitute a mechanically coupled motor and dynamo; provided k_a and k_b remain exactly proportional to $\sin \theta$ and $\cos \theta$ the forces on L_2 and L_3 are always equal and opposite, and no force is necessary to rotate the system except that required to overcome inertia and friction. Alternatively, of course, L_2 and L_3 may remain fixed while L_1 rotates.

Notice that in the absence of resistance the equations do not contain the time variable. If the rotation is stopped the currents simply remain constant. By programmed rotation or oscillation of the shaft, therefore, any desired current waveform can be fed into L_S. The initial currents in L_1, L_3, and L_4, are established by means of dc supplies and superconducting switches.

In the previous paper it was pessimistically assumed that the maximum value of k^2 likely to be achieved was ~ 0.5. This is true for a configuration of the shape indicated in Fig. 3, but further work has shown that much better coupling could be achieved by using approximations to ideal spherical coils, i.e., with a $\sin \theta$ distribution of current producing a uniform internal field. For two such concentric windings, of mean radii R_1 and R_2, the maximum coupling is $(R_2/R_1)^{3/2}$, so that for very large coils values of k^2 in the region 0.7 to 0.8 can be envisaged.

As an example, consider a power supply for a 200 GeV superconducting synchrotron magnet storing 2×10^8 joules. Assuming a maximum k^2 of 0.7, and no dc bias scheme, the stored energy of L_1 would be $\sim 1.2 \times 10^9$ joules. At 50 kG, this would be a coil of radius 240 cm (for a spherical coil $E = H^2 a^3/3 \times 10^7$) costing perhaps £1.5 x 10^6. L_2, L_3 and L_4 are 2 x 10^8 joule coils and would bring the total cost up to about £3 x 10^6, plus control and ancillary equipment. It is, however, not clear whether required topological arrangement of L_2 and L_3 can be achieved without significantly decreasing the coupling to L_1. It may also prove desirable to split the system into several smaller units, which would further increase the cost. Nevertheless these figures suggest that the system may still be competitive with a conventional power supply, which, for 2 x 10^8 joules, might cost about £8 x 10^6.

The ac loss in the superconductor presents much less of a problem than in the synchrotron itself; since it is relatively small in the largest coil L_1, through which the total flux and current remain constant and only local field variations occur. The loss is sufficient to rule out the use of existing conductors in L_2, L_3, and L_4, but reduction of the filament size to ~ 1 mil should be sufficient, compared with the 0.2 to 0.4 mil needed for the synchrotron magnet.

Apart from this, very few of the practical aspects of the system have been considered. One major problem, for example, is likely to be the internal stresses, since the forces on L_2 and L_3, although equal and opposite, are extremely large. Other problems arise from the small losses present in any real system, and from the usual need to subdivide the magnet ring and ensure equality of the parallel currents.

It was originally hoped that a substantial reduction in the size of the L_1 L_2 L_3 energy transfer system would be possible by devising a multiply-cycled arrangement in which the energy was transferred in smaller increments. So far, no such system has been discovered. The basic reason for this is that the circuit equations require that certain sums of flux terms (of the form $L_x I_y$, $M_{xy} I_y$) remain constant; at the same time we require that the total energy (i.e., the sum of terms of the form $L_x I_y^2$, $M_{xy} I_x I_y$) also remains constant. It is clearly impossible to satisfy these two requirements if the circuit contains only L_4, L_S, and an arbitrarily small energy transfer device, but a rigorous proof of the minimum size of the latter has not been obtained.

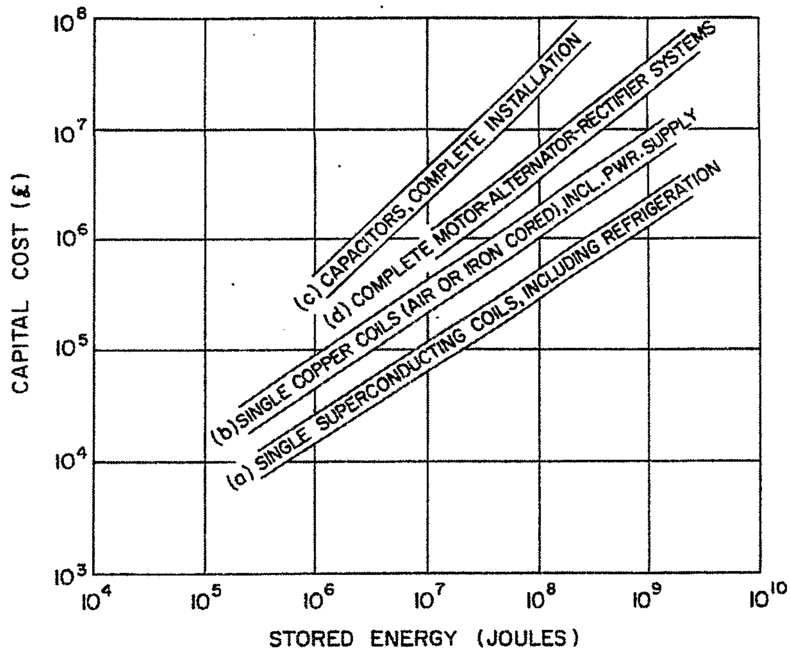

Fig. 1. (a), (b) and (c). Approximate cost of energy storage systems. (d). Cost of conventional synchrotron power supplies as a function of energy transferred.

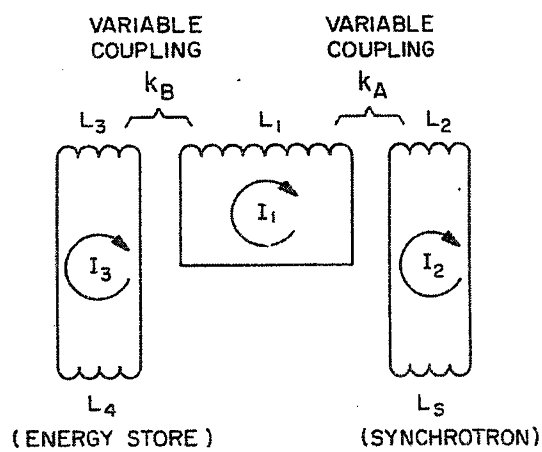

Fig. 2. Constant energy system.

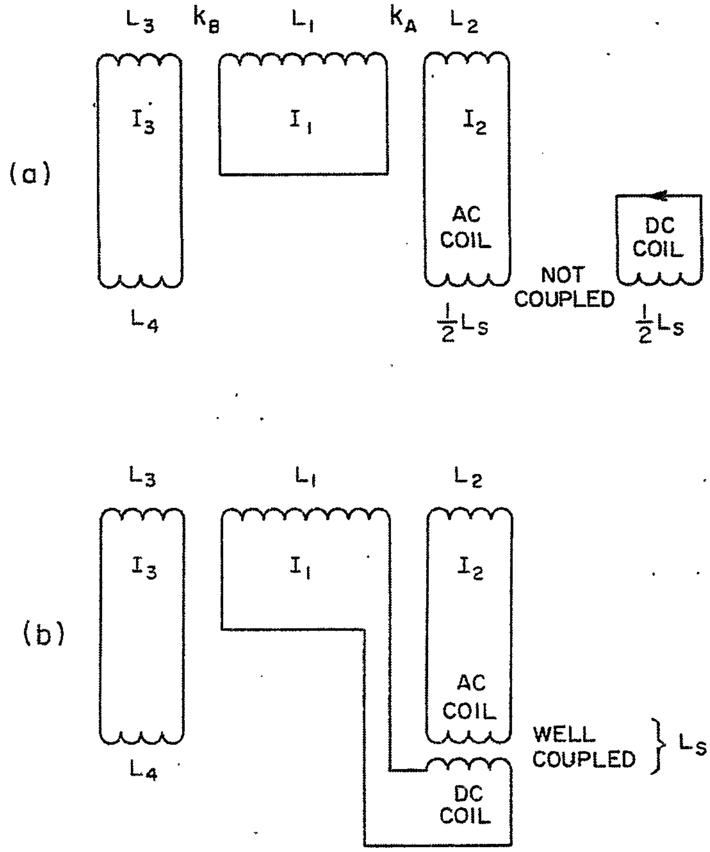

Fig. 3. Dc-biased systems.

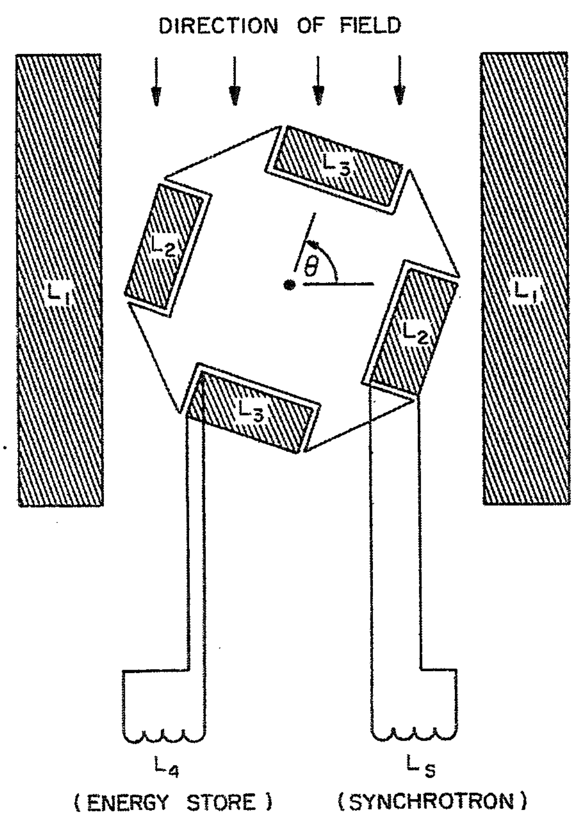

Fig. 4. Motor-dynamo representation.