MULTI-STAGE ENERGY TRANSFER SCHEMES

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Abstract

An extension of the superconducting energy transfer principle is described with particular reference to its possible applications to synchrotron power supplies. By successively switching in a number of superconducting transformers a considerable reduction in the size of the rotating transfer coils can be achieved for a given final energy. Advantages and disadvantages are summarised, and possible switching methods are discussed. In addition an alternative hybrid scheme is noted, in which the superconducting transformers are driven by a conventional power supply.

1. Introduction

In previous papers[1,2] we considered the possibility of synchrotron magnet power supplies based on superconducting energy storage. In particular, a system was proposed consisting essentially of three concentric superconducting coils linked to the synchrotron magnet via a superconducting transformer; by rotation of one coil through approximately 180° energy could be reversibly transferred to the magnet in a single operation.

In this paper we present an extension of this principle, in which the energy transfer device oscillates several times through 180°, each time being switched to a different transformer. For N operations, the synchrotron current would be increased by a factor N and the energy transferred by a factor N^2.

Thus, for a given magnet stored energy, the energy transfer device itself might be made much smaller at the expense of a larger (but static) transformer system and the necessity for repeated switching.

In the following sections we outline briefly the basic principles of this arrangement, together with some of its practical and economic consequences.

In addition, using the same idea, we note the possibility of a hybrid scheme in which superconducting transformers are used to extend the energy transfer capability of a conventional power supply.

2. Basic Principle

A reminder of the single-transformer arrangement is shown in fig. 1. $L_1L_2L_3$ are arranged concentrically, and by rotation of L_1 relative to L_2L_3 through approximately 180°, the current in the transformer primary is reversed while the synchrotron current increases from zero to its maximum value. By reversing the direction of rotation the current can again be reduced to zero.

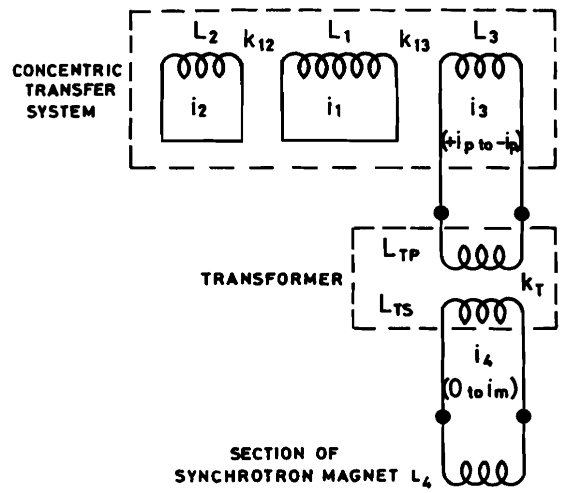

Fig. 1 Single-stage energy transfer

Although potentially feasible and economic, the idea in this form does require the construction of rather large rotating magnet systems. A 1,000 GeV synchrotron, for example, might be powered by, say, 6 such units, each capable of transferring about 10^8 Joules; with an internal peak magnetic field of 50 kG, each unit would require a coil system about 3 metres diameter. This size can, of course, be reduced by having more units, the diameter being inversely proportional to (no. of units)$^{1/3}$, but a simple calculation[2] shows that the total cost must increase by about the same factor. Thus to reduce the diameter of a unit to, say, 1 metre we would have to have over 160 units at perhaps three times the cost of the six 3 metre units.

We are thus led to consider the possibility of devising schemes which allow a device of smaller capacity to cycle several times during one machine cycle. Elementary schemes using 'flux pump' devices to transfer flux in increments from a single storage magnet to the synchrotron do not satisfy the requirement of constant total energy, and therefore involve external work. We can, however, achieve constant energy multi-stage operation by using a succession of transformers as indicated in fig. 2.

For this example we have arbitrarily assumed four stages, using four separate transformers (T1, 2,3 and 4) each of which can be either switched into the synchrotron and energy transfer circuits, or else isolated in the persistent current mode. With the initial currents as shown the sequence of operations is as follows:-

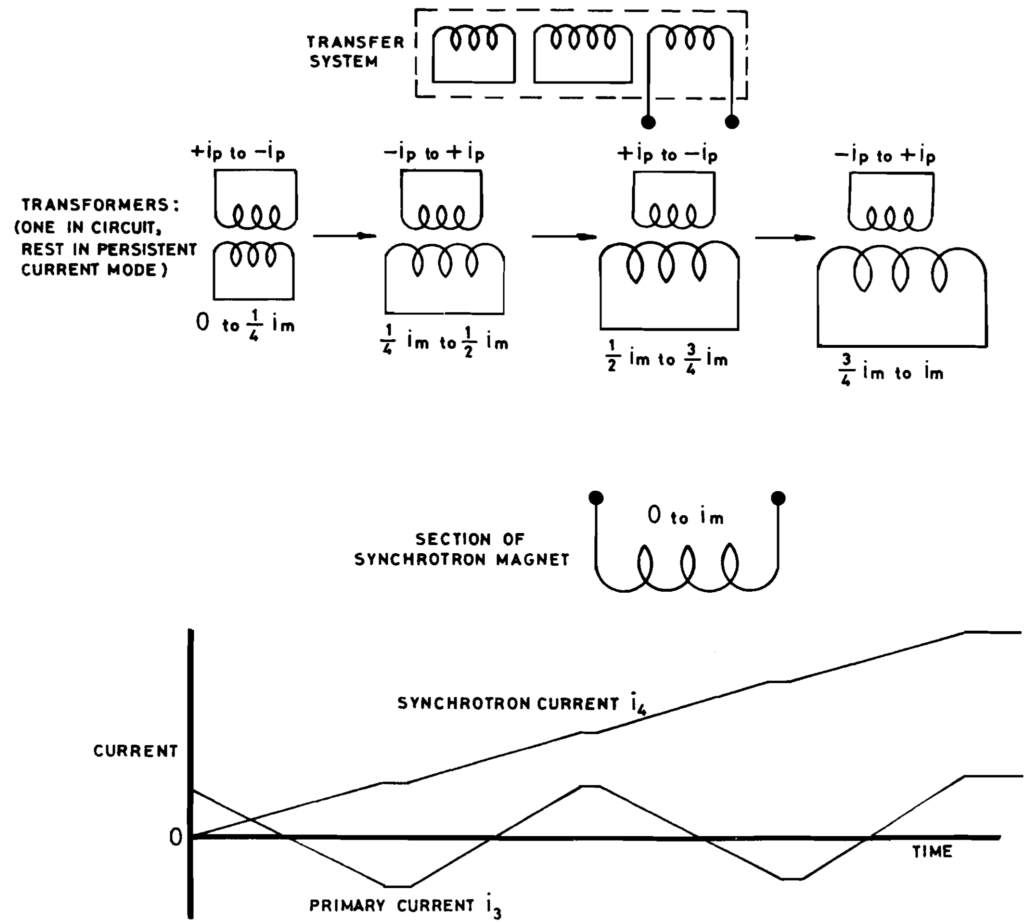

Fig. 2   Multi-stage energy transfer

(1) T1 switched in; 180° rotation of L_1 increases synchrotron current i_4 from 0 to $\frac{1}{4}i_m$.

(2) T2 switched in, T1 re-isolated; minus 180° rotation of L_1 increases i_4 from $\frac{1}{4}i_m$ to $\frac{1}{2}i_m$.

(3) T3 switched in, T2 re-isolated; 180° rotation of L_1 increases i_4 from $\frac{1}{2}i_m$ to $\frac{3}{4}i_m$.

(4) T4 switched in, T3 re-isolated; minus 180° rotation of L_1 increases i_4 from $\frac{3}{4}i_m$ to i_m.

(5) Rotation of L_1 stopped to produce 'flat top' at i_m.

(6) Operations (4), (3), (2) (1) reversed to decrease i_4 from i_m to zero in four stages.

The significant point is that at each changeover the currents in the two transformers are exactly matched in value, so that no disturbance occurs; but in the outgoing transformer primary and secondary currents are opposed (giving minimum internal stored energy) whereas in the incoming transformer the primary and secondary currents are aiding (giving maximum internal stored energy.)

Thus the effect of each transformer substitution is to change the sign of the primary current, so that each successive 180° rotation of L_1 will produce an increment of i_4 in the same direction.

In the example given, for the case in which secondary and load inductance are equal, the current ratings of the transformer secondaries are in the ratio 1:2:3:4 and their energy storage capacities in the ratio of 1:4:9:16. Thus, for a given peak energy in the synchrotron magnet, the required capacity of the transfer device is reduced by a factor 16 compared with the single-stage circuit of fig. 2.

This type of scheme thus offers two possible advantages:

(a) The lower cost of the energy transfer device more than offsets the extra transformer cost, giving lower total cost.

(b) Most of the cost is now in the static transformers - which should be relatively simple to construct; the energy transfer device is now much smaller, and thus should constitute a less difficult development problem.

3. Theory and Economics

Mathematical details are omitted in this paper for reasons of space, but are given in a separate report[3)]

The principal conclusions are as follows:

3.1 A succession of transformers of increasing size can be inserted between a given energy transfer device and a given load L_4, without upsetting the constant energy condition, provided that the quantity $L_{TP}L_4/(L_4 + L_{TS})$ is the same for each (and equal to L3 for maximum energy transfer).

3.2 For a given final energy in the load, the size and cost of the transfer device decreases rapidly with increasing number N of transformers; there is no clear optimum system, but typical examples indicate an approximum cost optimum at about 3 or 4 transformers, and suggest an overall cost gain of up to a factor 2 over the original single stage system.

3.3 Accompanying practical advantages are (i) since the energy transfer unit is now a relatively small percentage of the total cost it can be subdivided into several still-smaller parallel units without significantly increasing the overall cost; and (ii) the largest components are now the transformers which, being simple optimised bifilar coils with few practical constraints, would be much simpler to construct than the coils required in a large energy transfer device.

4. Some Practical Aspects

4.1 Switching

In the above discussion we have assumed the ability to switch rapidly and reliably from one transformer to the next without significant losses or disturbance of the synchrotron current waveform. We now consider what this means in practice.

Fig. 3 shows the switches required for the 4-transformer example. One side of each primary is connected to a common line, and two switches enable the coil to be either shorted or connected to the return line; the secondaries are connected similarly. The changeovers are then achieved by means of an appropriate 'make before break' sequence (1st change: close P_{11} P_{22} S_{11} S_{12} then open P_{12} P_{21} S_{12} S_{21}; 2nd change: close P_{21} P_{32} S_{21} S_{32} then open P_{22} P_{32} S_{22} S_{31}; and so on). These changeovers are initiated when the currents in the two coils are exactly equal, so that no voltage is developed during the opening of a switch. During the cycle the switches have to carry up to typically 5000A when closed, and withstand typically 5000V when open. Assuming that we must limit the total energy dissipated in the switches to, say, 10% of the synchrotron magnet losses (i.e. about 10% x $10^{-4} = 10^{-5}$ of the transferred energy) this implies a closed resistance of less than 10^{-6} ohms and an open resistance of greater than 10^{6} ohms - and preferably an order of magnitude better than this.

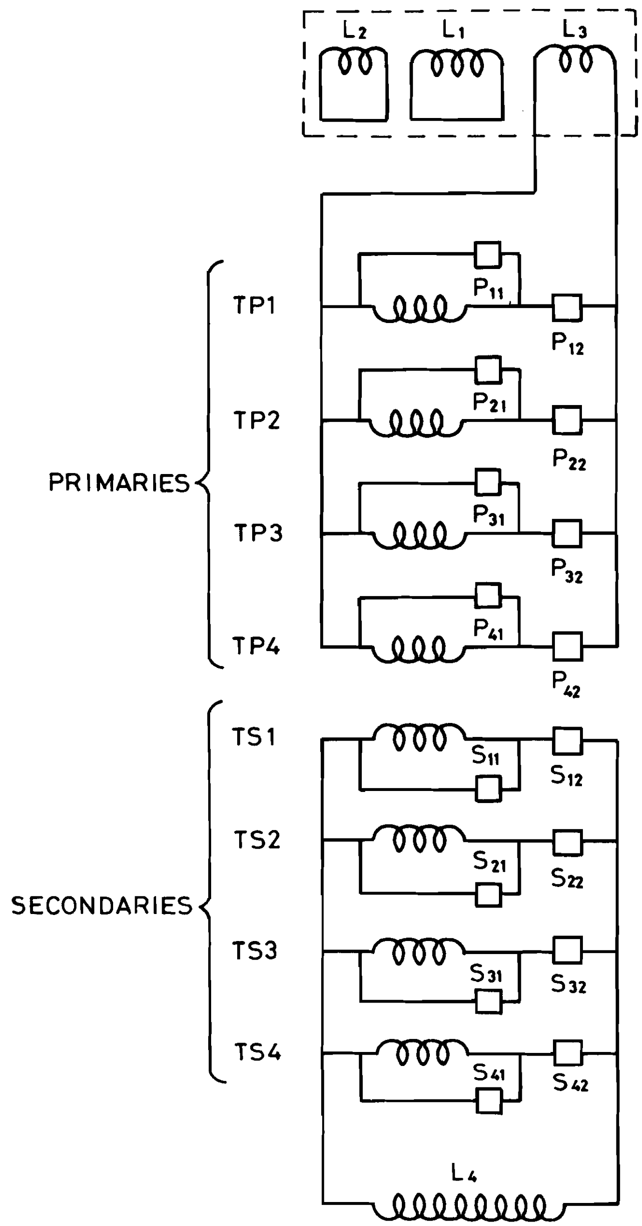

Fig. 3 Typical switching arrangement

So this seems immediately to rule out superconducting switches, because of the prohibitive cost of obtaining the high normal state resistance. A range of conventional techniques - low pressure, solid state, or mechanical switches - are available but have the practical and economic disadvantage that a large number of current leads have to be brought out to room temperature. The best solution suggested so far appears to be the mechanical switch operating in liquid helium; contact resistance measurements carried out by Wilson[4)] and Zar[5)] indicate that resistances better than 10^{-6} ohms can certainly be achieved with reasonable pressures, and this can probably be improved to $\sim 10^{-7}$ ohms with further development.

4.2 Matching

There are at least two obvious alternative ways of ensuring equality of currents at changeover: (a) one may simply operate the switches (and programme the rotation of L_1) from a logical control unit in response to accurate measurements of currents in the various circuits - or (b) one may attempt automatic operation by means of, for example, double-wound superconducting relays designed to change over as soon as the currents in the two windings become equal and opposite.

In choosing between these and other alternatives, it is evident that a vital consideration will be the overall reliability of the system - involving, for a large synchrotron, perhaps 100-200 individual switches, each operating $\sim 10^7$ times per year.

Another question relating to the changeover problem is: what happens if the secondary circuits are not matched at exactly the same moment as the primary currents? There are, for example, small losses in each circuit (superconductor ac losses, joint resistances, etc); these can be made up by means of continuously operating flux pumps, so that we can arrange that there are no progressive changes in the current levels, but there may be nevertheless slight short term fluctuations about the ideal theoretical current values.

Thus equality of currents could occur in the primaries slightly earlier than in the secondaries or vice versa. What happens in these two cases is shown in fig. 4. in which the time difference between primary and secondary changeovers has been exaggerated.

(1) If the secondary currents become equal first, at t_1, the load is switched to the secondary of the second transformer and thus, between t_1 and t_2, i_4 is unaffected by changes in i_3 and remains constant. At t_2 the primary currents become equal, the changeover is completed, the rotation of L_1 is reversed, and i_4 again begins to increase.

(2) If the primary currents meet first, at t_1, the changeover of the primaries again isolates the load from any further changes, but the continuing increase of $|i_3|$ causes the new secondary to decrease its current until at t_2 it equals the load current. The changeover is then completed, the rotation of L_1 is reversed, and i_4 again begins to increase.

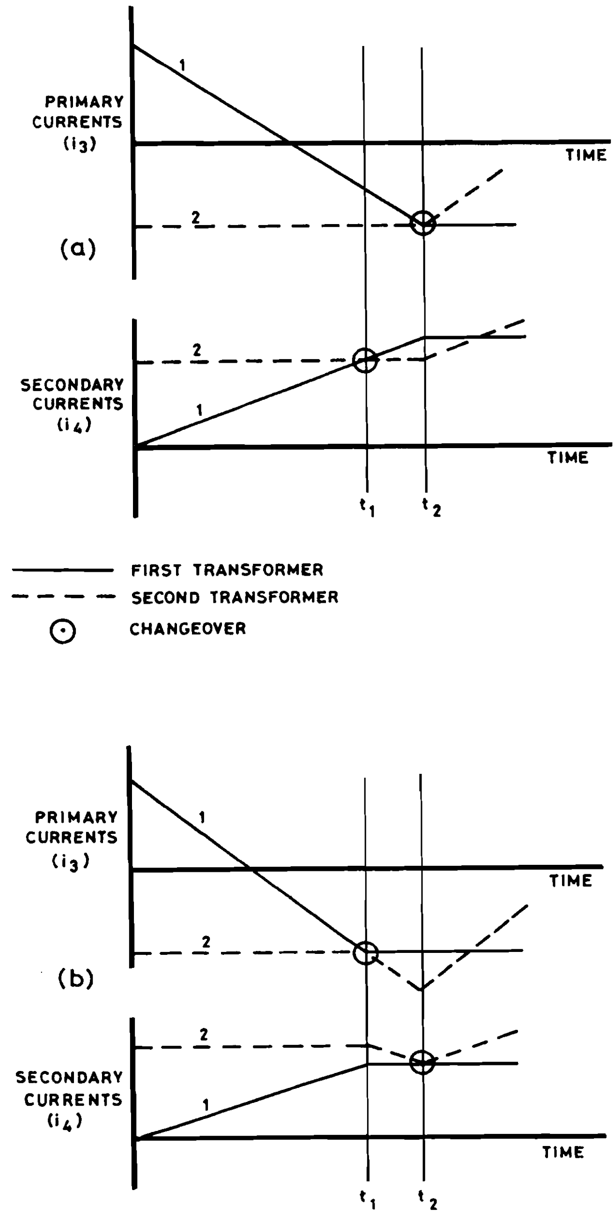

Fig. 4 Effect of non-simultaneous switching:
(a) secondary before primary
(b) primary before secondary

Thus in each case (provided the rotation of L_1 is not reversed until both primary and secondary changeovers are complete) the net effect is to introduce a small interval $(t_2 - t_1)$ in which i_4 remains constant, but the cycle is otherwise unaffected. By continuous control of flux pump power, the interval $(t_2 - t_1)$ could be prevented from increasing progressively, and probably held to a value less than the switching time (< 0.1 sec?)

4.3 Effect of synchrotron waveform

One possible objection to the multi-stage scheme is that it is necessary to reduce di/dt to zero at each changeover, giving possible difficulties in r.f. programming, passage through resonances, etc. In addition to being required for switching, such an interruption of the current rise is in any case an inevitable consequence of the reversal of rotation (or of the passage through 90° if it is suggested that L_1 should rotate continuously).

It is possible in principle, by using additional subsidiary energy transfer circuits (conventional or superconducting) to contrive arrangements in which the changeover occurs at non-zero di/dt, so that there is no significant interruption of the current rise. However this would involve an undesirable increase in complexity of the system, and it appears preferable to accept the small platforms in the current waveform.

4.4 Transformers

The turns ratio $n = (L_{TS}/L_{TP})^{\frac{1}{2}}$ is not a parameter which is related to the constant energy condition; it affects only the ratio of peak operating currents in primary and secondary. It is thus quite permissible to adopt n = 1, in an interleaved or bifilar construction in order to achieve a value of k_T close to 1.

Assuming the transformers have to be located in reasonably close promixity we have the problem of avoiding mutual coupling - this can be achieved by using a toroidal configuration (e.g. pancakes stacked in a circle) or perhaps sufficiently well by two adjacent opposing solenoidal transformers connected in series. It is shown in ref. 3 that the toroidal arrangement should not be significantly more expensive than the optimum sphere or solenoid.

Iron shielding might also be considered but would, of course, introduce significant non-linearity if located close to the windings.

5. A Hybrid Scheme - Conventional Power Supply plus Superconducting Transformers

The mathematical details of the above scheme show that, for each ∿ 180° rotation of the transfer device, the initial and final energies of the latter are the same. All the energy comes from the transformers in this arrangement; the rotating device is simply a means of transferring energy from the transformers to the load.

However, during each ∿ 180° rotation there is some passage of energy in and out of the transfer device: between 90° and 0° a quantity of energy $E_4/2N^2$ is absorbed into L_2 which is then returned to the transformer and load during rotation from 0 to -90°.

Thus we could equally well replace the rotating system by a conventional power supply of the same energy transfer capability.

Thus supposing there exists a conventional synchrotron power supply capable of mean energy transfer rate of up to E_c Joules in T seconds - then by N current reversals in N superconducting transformers, exactly as in fig. 2, an energy $2N^2 E_c$ can be transferred in 2NT seconds - so that the mean rate of energy transfer has been effectively increased by a factor N. The extra energy is simply the field energy initially stored in the transformers and is, of course, all returned to the transformers during the 2nd half of the cycle as the synchrotron current is reduced to zero.

Note that when a conventional power supply is used to effect the energy transfer, there are no particular 'constant energy' conditions to be satisfied and thus no restriction comparable to the constant $L_{TP}L_4/(L_4 + L_{TS})$ necessary in the all-superconducting case. However, it would presumably be most efficient in general to operate near to maximum rating at each stage of transfer.

Note also (by putting N=1 in the above expressions) that a single transformer will double the total energy transfer but not the rate of energy transfer.

Hybrid arrangements of this type might prove attractive as part of a progressive synchrotron conversion programme, as an alternative to providing a completely new power supply.

References

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