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The Potential for High Temperature Superconducting AC and DC Motors

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1. Introduction

The prospect of using superconductivity (SC) to power electrical machines has been a tantalizing but elusive goal ever since its discovery by Onnes in 1911. However, recent developments which have raised the critical temperature above liquid nitrogen (77K) has removed the major obstacle to practical application of SC to rotating machinery, namely the liquid helium refrigerant system. This paper addresses the potential for utilizing high temperature superconductivity (HTSC) in rotating (as opposed to linear) electrical motors and discusses several approaches to their implementation. Although SC at liquid nitrogen temperature is assumed, the implications of SC at room temperature is not considered in this paper.

2. Motivation for Development of HTSC Electric Motors

It is well known that electrical machinery comprises the greatest portion of the electrical load in this country. In particular, of the total U.S. electrical consumption of $1{,}683 \cdot 10^9$ kW.hrs, motors consume $1{,}081 \cdot 10^9$ kW.hrs or 64% of the total [1:p.27]. In the industrial sector alone, motors account for a whopping 76% [1:p26]. While the efficiency of electrical machinery has been on the rise, the efficiency of squirrel cage induction motors range roughly from 78 to 92% for machines rated between 1 and 100 HP suggesting that substantial energy savings remain to be achieved.

The challenges of utilizing the newly discovered high temperature superconductors in motors rather than generators are, however, complicated by their relatively small size when compared to turbo-generators which number only in the thousands. There are estimated to be over 50 million motors in use in the industry and commerce sector of the U.S. of which 1 million is greater than 5 HP [1:p1,2:p3-14]. There are also estimated to be over 7500 classifications of induction motors in the size range between 5 and 500 HP [2:p3-15]. Since cost is such an important driver in the end use market, the first motor application of superconductivity will almost certainly come from the family of motors rated above 500 HP which are normally classified as the form wound family of machines (as opposed to the random wound family which predominates below 500 HP).

In support of this observation, the present status of the permanent magnet (PM) motor can be recalled. The PM motor is a close cousin of the superconducting motor since it shares the same major attributes of a HTSC machine, namely zero input excitation power. However, the high cost of permanent magnet materials have kept PM machines out of the low horsepower motor market and the same market forces will probably occur for HTSC machines until the machine is of sufficient size such that the benefits of economy of scale for the cooling system can be attained.

Motors rated above 500 HP are dominated by three types; squirrel cage induction (27,000 machines installed in the industrial and commercial sector, [1:p29]) and synchronous (roughly 10,000 machines [1:p29]), with a relatively small number of dc motors (6,000) used for variable speed applications [1:p28]. The average rating of these machines is 1500 HP having an average efficiency of about 95%. While the numbers of ac machines above 500 HP are numerically small, these machines account for a large portion of the energy consumed by all electrical motors. For example, in 1977 the total energy consumption of ac motors in industry and commerce was estimated to be $540 \cdot 10^9$ kW.hr. Of this total, $61 \cdot 10^9$ kW hr or 3.6% of all electrical energy produced in the U.S. was consumed by machines in the I&C sector above 500 HP (7.4% by machines rated above 125 HP) [1:p38].

The losses in induction machines are typically divided into a) stator copper losses, b) rotor copper losses c) iron loss d) stray loss and e) friction and windage. The stator copper, rotor copper, and iron plus stray losses are roughly equal and total about 90% of the total motor losses, with e) accounting for the remaining 10%. It is estimated that replacement of a typical 1500 HP squirrel cage induction machine by a superconducting machine which retains the same basic laminated iron stator structure would result in a reduction of losses of 40% (30% by elimination of rotor copper losses, 5% by reduction in stator kVA requirements and thus reduction in stator copper losses, and 5% by an increase in air gap and thus reduction in stray losses). At a cost of energy of $0.05/kW-hr, this reduction of losses represents an annual savings of about $10,000 for the 1500 HP machine.

If, for simplicity, it is assumed that the same improvement can be obtained in all machines above 500 HP, including synchronous and dc, and, using the same 95% efficiency for all three machines, the energy that could be saved by using HTSC machines is $1.22 \cdot 10^9$ kW-hrs or a dollar savings of $61,000,000 per year. It is important to note that these calculations do not include electrical machine in the electric utilities, government laboratories or municipal water works where the use of high horsepower machines is very substantial. Hence, this number could probably be safely inflated by at least 50%.

Other advantages in addition to energy savings are, of course, possible. In particular, the absence of laminated iron in the rotor would make the overall machine lighter in weight. And, since losses are substantially reduced, the power density could be increased accordingly making for a more compact machine. However, while these considerations are important for special applications such as land transportation or marine power, they would be of lesser importance to the general industrial market.

3. Application Considerations for HTSC Machines

While motoring is not, in principle, substantially different than the generating mode, numerous applications considerations make the motoring case a difficult constructional problem. Of particular concern is the starting performance of any new machine. As contrasted to a generator which is brought to synchronous speed by the prime mover, a motor must generally be started with power from the ac line. A reduced voltage start is usually used to bring the motor up to speed over a several second interval. Often the motor must accelerate a connected load which greatly increases the acceleration period. Large forces are experienced by the windings in the machine and heat builds up rapidly due to the high inrush current. Since the high temperature superconductors have been categorized as "brittle", these forces could cause breakage of the coils upon repeated starts. In addition, the high starting currents could cause substantial ac losses in the superconductors which could prevent the material from entering the superconducting mode when desired.

The characteristics of the load also greatly affect the feasibility of using a HTSC machine, again due to the brittle nature of the ceramic material. For example, servo type applications (steel mill drives, dynamometers, machine tools) place severe stresses on the windings of machines used for such purposes and the rotor windings must normally be strongly braced. It is uncertain whether the TSC rotors required for an ac machine implementation could stand up to the abuse. Also, these applications, including many others as well, experience modes in which the load torque connected to the motor shaft varies rapidly in almost stepwise fashion. These sudden load changes would cause rapid speed changes, which would, in turn, induce rapid changes of current if the SC field coil. Such sudden changes could bring the coil continuously out of superconductivity, causing extra losses and a severe heat transfer problem.

4. HTSC DC Motors

Probably the most highly researched SC machine is the dc homopolar machine. The machine employs a rotating disc inside a SC coil (Faraday Disc). The disc cuts the flux created by the coils and the resulting dc voltage induced between the inside and outside edges of the disc are picked up by brushes. Since the machine has, effectively, one turn, the voltage induced is inherently low. The situation can be improved by using a segmented rotor but the number of brushes increase in proportion to the number of segments [3].

While construction of the SC portion of the dc homopolar machine is relatively straightforward, the design of the armature is more difficult particularly with regard to the brush pickup problem which requires many brushes supporting a high current density.. NaK and Hg liquid metal have been used in some prototypes but with not with complete success due to contamination problems [4].

One of the important advantages of a SC homopolar motor is the fact that the machine can be scaled up to very large sizes and high speeds (up to 200 MW at 2000 RPM) while the conventional dc machine is limited to much smaller values (10 MW at 150 RPM) [3]. Such applications, however, are very specialized (such as ship drives). In general, most conventional dc machines are employed in variable speed applications such as in steel mills where the speed of response is often an important criterion. Since the Faraday Disc develops voltage by either rotating the disc at a high speed or, conversely, making the disc have as large a radius as possible, the geometrical shape of this machine is somewhat at odds with the normal requirements which tend to favor a machine with a relatively small diameter. Nonetheless, the inertia is lower than a normal commutator type dc machine due to the absence of an iron core and has low armature inductance and zero armature reaction. These characteristics are ideal for high performance mill type applications.

While the opportunities for replacing large, conventional dc machines appear to be bright, the future for dc machines in general is not as promising due to the nagging problems of brush maintenance. As a result, variable speed ac drives using solid state power converters to change the frequency from a fixed 60 Hz value to a variable frequency supply to an ac motor, has made continuous inroads on the dc motor market for the past 20 years. This trend is expected to continue until dc motor drives constitute a very small, special purpose market. Since the problems of brush maintenance are only aggravated with homopolar machines, the long term opportunities for homopolar machines for anything more than for special purpose machines is not promising.

5. HTSC Synchronous Motors

From Section 2 it is clear that AC machines form the greater part of the market for motors above 500 HP and, since ac motor drives are in the process of replacing, to a large extent, dc motor drives, the application opportunities for HTSC ac machines appear more widespread. Probably the most apparent application of HTSC is in the synchronous motor where a rotating superconducting coil is used to replace the usual wound field excitation.

As mentioned previously, an important difference between motors and generators is that motors must develop adequate torque to self start themselves as well as their connected load. Hence, operation directly from an ac supply will require a squirrel cage for starting since a shorted field winding is incapable of supplying adequate starting torque. Excitation of the field coil would then commence upon synchronization in much the same manner as for conventional synchronous machines. Starting could possibly be accomplished by means of a room temperature copper shell wrapped around the superconducting cylinder in much the same manner as used in SC synchronous generators [5]. The shell would also serve to shield the magnet from forces due to ac flux variations during starting. Forces are also exerted on the shell during starting and would make the design of this structure for motoring a more demanding exercise. It appears, however, that an iron core rotor would probably still be necessary to create the large forces necessary for adequate starting torque, severely restricting the maximum excitation achievable with the SC field coil and making the overall approach less attractive than for HTSC synchronous generators. Thus, it appears that more conventional stator and rotor structures having conductors embedded in a slotted iron cylinders may be the preferred approach for motoring applications, at least when the machine is started off the line.

The problems associated with starting the machine could be eliminated if the machine were brought up to speed with a solid state frequency changer as shown in Fig. 1. In this case the superconducting field could be energized with the rotor stationary. With the field then shorted, the field current would remain constant (assuming a constant load) and slip rings or other exciting means could be eliminated completely. Since the rotor always remains in synchronism with the rotating stator field, the starting cage could also be eliminated or substantially reduced since the shield may still be needed to short circuit the harmonic currents flowing in the stator due to the power converter. Finally, since the starting torque is obtained by synchronous rather than induction motor action, the slotted iron structure could be dispensed with and the excitation of the SC field increased to levels comparable with the SC generator.

If a power converter is engaged for the starting process, the same power converter could also be used in a continuously variable speed mode to optimize the process (for example a compressor). However, if continuous variable speed is not required, then upon reaching synchronous speed the machine could be transferred to the line and the converter bypassed. If the rotor cage were not used, system

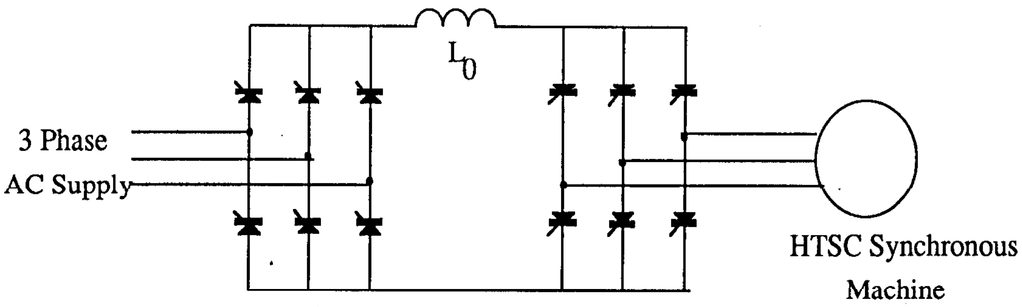

Fig. 1 Solid State Frequency Changer for Accelerating a HTSC Synchronous Machine from Rest.

damping could then become a problem. The problem may, however, be eliminated by providing damping from the stator side. One possible method of providing active damping is by inserting back-to-back thyristors in series with one, two or all three of the stator lines as shown in Fig. 2. System damping comes about by measuring the fluctuation in stator input power or input kVA due to rotor oscillations and controlling the thyristors to reduce these fluctuations.

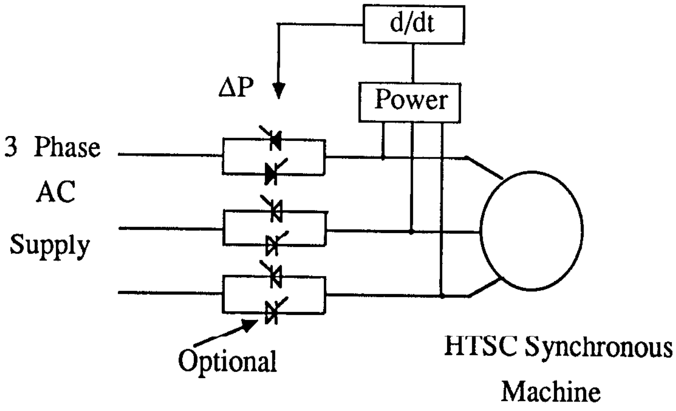

Fig. 2 Method for Stabilizing the Speed Oscillations of a HTSC Synchronous Generator Not Having a Rotor Shell for Damping.

Because power need not be fed to the field coil continuously, elimination of the slip rings and rotating exciters would be an important advantage of an HTSC synchronous machine. However, since the field remains short-circuited, it cannot be adjusted with load and hence, the power factor can not be controlled. When the field becomes superconducting and is short circuited, flux is trapped in the coil and, by the law of constant flux linkages, cannot change thereafter. In effect, when the load changes, field current is induced in the SC coil so as to exactly cancel any change in stator flux linking the field coil due to the load change. The machine behaves continuously, even in the steady state, according to the "constant voltage behind transient reactance" model.[6]

The problem of induced field current affecting the power factor is probably not of concern with a HTSC synchronous machine operating from a converter supply. In this case the machine could be continuously controlled with the frequency converter such that only the component of stator MMF orthogonal to the field axis (q-axis) were allowed to change while the stator MMF in the field axis (d-axis) would remain constant.

Since control of power factor is often an important application issue for the case where the machine operates off the grid, it would be useful to develop a means for adjusting the excitation of a machine without recourse to a separate rotating exciter. In the approach of Fig. 3, phase back of the same thyristors as used for damping in Fig. 2 are used to create a small negative sequence current component which rotates backward in the air gap of machine resulting in a 120 Hz field component as seen from the rotor. Rather than being short circuited, the SC field coil is connected to a simple diode bridge. The bridge is excited by a smaller coil operating at room temperature. The rectified induced voltage, in turn, is used to adjust (increase) the field current. The presence of the diode and extra coil, of course, introduces losses so that the field current will now decay slowly by free-wheeling through the diodes if the winding is not "pulsed" repeatedly. However, the losses incurred can be made very small since the conductor of the additional coil can be made with a few turns of large cross section while the conductor of the SC coil has a much larger number of turns.

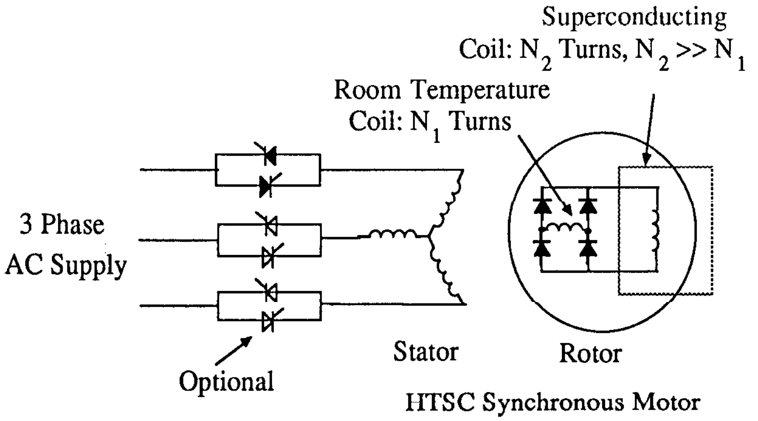

Fig. 3 Illustrating Method for Inducing Excitation in a SC Field Coil Without a Rotating Exciter.

It is important to note that this method can be used only to increase the field current since the process of decreasing the current relies solely on the the diode conduction drops. Fortunately, in many cases, relatively slow changes in excitation are all that is desired. While the problem of rapidly reducing the field current could be completely solved with light triggered devices, this case is , perhaps, awaiting a more practical solution. Also, the process of inducing a current in the field winding implies good coupling between the armature and the field winding which, in turn, implies a conventional laminated iron stator and rotor. Hence, the very high field strengths obtained by the SC synchronous generator can not be approached. At present, the rotating exciter approach (which has its own loss problems) appears to be the most practical method for exciting a machine in which continual adjustment of excitation is required.

6. HTSC Induction Motors

While superconducting dc and ac synchronous machines have been fairly well researched, other machines also hold promise for the future. Chief among these is the HTSC induction motor [7,8]. It is apparent that the rotor resistance of an induction motor must be non-zero to develop torque so that this concept appears to be a contradiction in terms. The principle of operation, however, is only to start the machine by induction motor torque. When the motor reaches the vicinity of synchronous speed, the current induced in the rotor drops rapidly. As the current drops, the rotor conductors cool rapidly to the point where they become superconducting. The rotor flux at this instant is "trapped" and the machine suddenly becomes an HTSC synchronous machine. Hence, the starting torque function and the excitation function are combined in the same winding. Contrary to superconducting synchronous machines which, due to the high field strength, do not require iron on the rotor or even the stator, the iron path of a SC induction motor would still be needed if starting is off the ac mains. Again, starting from a converter supply could alleviate the problem of high inrush currents, and, perhaps permit an ironless rotor construction. However, the machine then need never operate as an induction motor, and the desirability of this machine structure for such an application is questioned.

When the HTSC induction machine reaches the superconducting state, and the rotor resistance drops to zero, stability again raises its ugly head. As an example of the difficulty expected to be encountered, Figs. 4 and 5 show the acceleration of a 100 HP induction motor off the ac mains where, in Fig. 4 the rotor resistance remains constant while in Fig. 5 the rotor resistance drops to zero at 0.98 per unit speed. Continuous strong oscillations in the speed of the superconducting machine can be observed. Again damping of these oscillations could possibly be derived from thyristors in series with the ac line, as shown in Fig. 2.

Chief among the problems associated with this machine is the requirement to achieve the superconducting state at precisely the right moment during runup. If SC

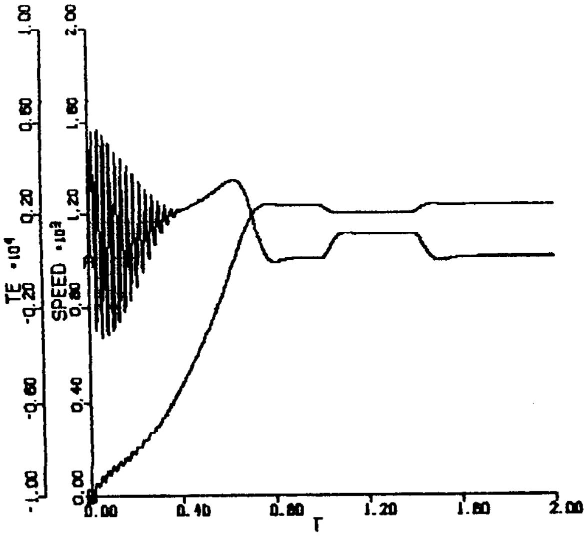

Fig. 4 Acceleration From Rest of a Conventional 100 HP Induction Motor. TE: Electromagnetic Torque (Nt-m), SPEED: Rotor Speed in RPM.

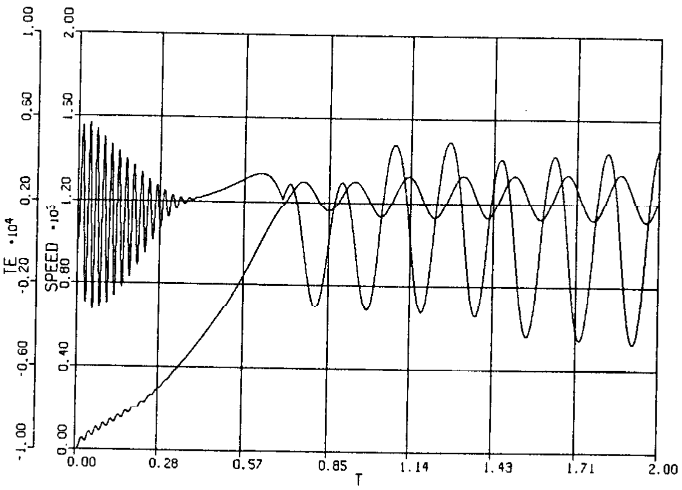

Fig. 5 Acceleration From Rest of a 100 HP HTSC Induction Motor. Rotor Resistance is Switched to Zero at 0.96 Per Unit Speed. TE: Electromagnetic Torque (Nt-m), SPEED: Rotor Speed in RPM.

is achieved to early, high pulsating torques will appear due to the machine slipping poles. If SC is achieved too late, very little current will be retained in the SC rotor winding and the machine may still require excitation power from the stator side as it continues to operate under load. Vagaries such as the degree of loading during the start, the line voltage amplitude during the start and even ambient temperature will affect the amount of heat generated in the rotor bars during a given start and thereby indirectly affect the instant of superconductivity. The prospect for success with this machine seems very problematical.

7. HTSC Induction/Synchronous Machine Hybrid

Another type of machine that has been proposed [9] is a true induction/ synchronous machine hybrid in which the synchronous rotor is located co-axially within the induction machine as shown in Fig. 6. The induction rotor is connected to the external load while the synchronous rotor rotates freely. The induction rotor becomes, in effect, a shell within which the synchronous rotor rotates. Each rotor rotates independently so that the induction machine rotor slips with respect to the synchronous machine rotor which rotates synchronously. Constructional problems associated with supporting the rotating induction motor shell are immediately apparent. Also, it should be noted that since the slip losses are still required if the machine is to drive the load, the rotating field excitation of this type of machine only serves to correct the power factor. While the stator current is reduced somewhat (from about 0.9 to 1.0 pf),the energy saved does not appear to be substantial.

8. HTSC Reluctance Motor

A cousin to the HTSC synchronous motor is the HTSC reluctance motor in much the same manner as their room temperature counterparts are relatives. In this

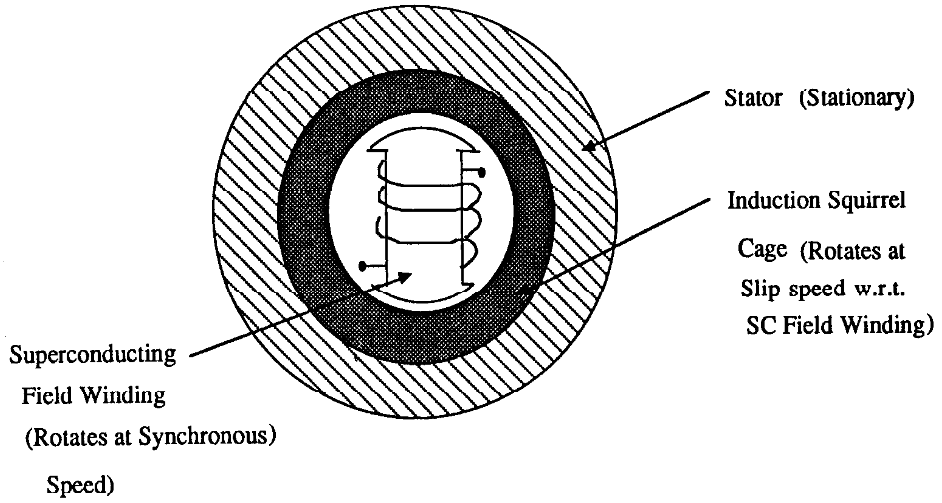

Fig. 6 Concantenated Induction and Synchronous Machine Rotors.

case the superconducting coil is not energized from an external source and torque production is obtained by an "equivalent saliency" effect due to the SC coil. The principle can be explained by reference to Fig. 7. Note that the so-called q-axis is encircled with a superconducting coil. Assuming that the machine is operating at synchronous speed and no-load, the flux produced by the stator is located in the direct axis or maximum permeance axis. When the machine is loaded, the rotor is retarded and moves towards the q-axis. As it does so, current is induced in the SC coil such that the total flux linking the coil remains zero (the value of flux linkage at the instant of achieving superconductivity). Since no stator flux appears to link the rotor q-axis circuit, the machine appears to have a very small permeance or inductance in the q-axis. The current in the SC coil (q-axis) now reacts with the stator flux component remaining in the d-axis to produce torque. Conversely, it can be said that the d- and q-axis components of stator current react to produce torque due to the difference in "saliency" between the two axes (conventional reluctance motor theory).

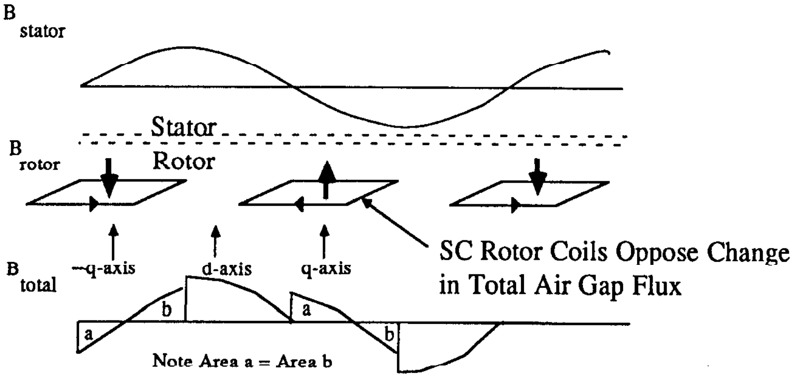

Fig. 7 Operating Principle of Superconducting Reluctance Motor.

The HTSC reluctance motor is an interesting concept since external excitation of the rotor windings is unnecessary. Unfortunately, the current which is induced in the rotor windings is necessarily demagnetizing, thereby ensuring lagging power factor operation. Good coupling is needed to induce a reasonable amount of SC coil current so that conventional stator and rotor iron structures are mandated. The motor cannot be started without an extra cage or without the help of a variable frequency converter. Finally, the instability problem, already cited in the case of the HTSC synchronous and induction machines is also a headache here. The problem must again be resolved by operating continuously from a frequency converter or inserting inverse/parallel thyristors in series with the ac line (Fig. 2). These problems seem to indicate that this machine, while conceptually interesting, is perhaps better suited to lower power applications in the 1-25 HP range. Further development should probably await the appearance of room temperature SC.

9. HTSC Homopolar Inductor Motors

Inductor type machines are another class of ac machines that have, over the years, been touted as a possible replacement for conventional synchronous machines, particularly in the generator mode [10]. The basic principle of a inductor type machine is to create a pulsating unidirectional field in the rotor. The ac component of this field couples with the ac armature winding field to produce torque. Both radial and axial air gap machines of this construction have been investigated, but not, apparently with a SC field coil in mind. Figure 8 shows an idealized representation of one possible geometry for an axial air gap machine. The machine is excited by a circular SC field coil inserted between protruding poles

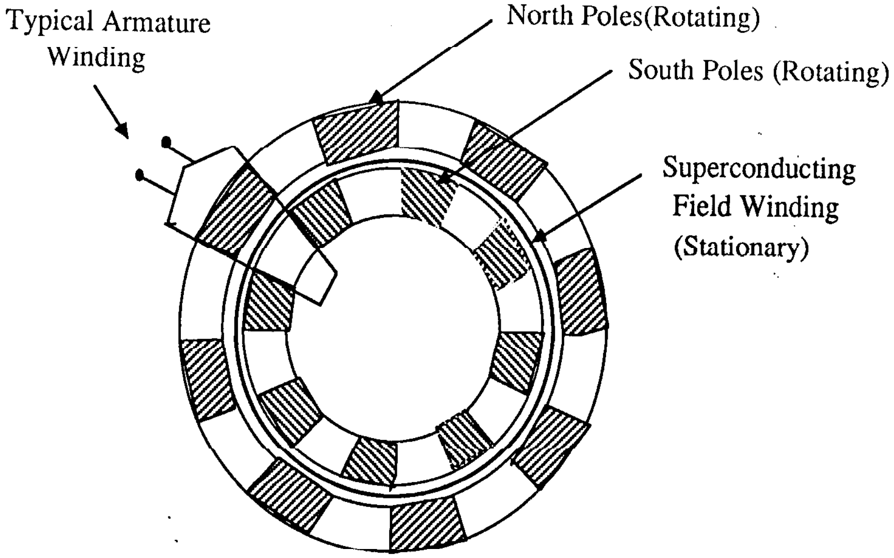

Fig. 8 Axial Air Gap HTSC Inductor Motor.

which are staggered on alternate sides of the coil. Pairs of protruding poles face each other across the air gap. The poles are fastened to the rotor and rotate while the SC field coil remains stationary. Also in the air gap are located ac armature windings which couple with the alternating component of the air gap flux produced by the field. This alternating flux induces currents in the armature windings which reacts with the field flux to produce torque. The armature windings are also stationary so that the only member that rotates is the member containing the protruding iron poles.

As an alternative, the armature coils could be placed in slots or fastened on the surface of a stationary iron member such that only one set of protruding poles rotate to form the rotor of the machine. In this case the saliency of the protruding poles is somewhat reduced but the assembly problem is probably simplified.

An obvious important advantage of this scheme over all other HVSC ac machine arrangements is the fact that the field coil remains stationary. Thus, SC coil cooling problems are simplified enormously. While the machine is not inherently self starting, starting could be readily accomplished by building a squirrel cage in the protruding poles. Assembly would be simplified and iron losses reduced since the rotor poles could be constructed in tape wound fashion. Since the coils need not be placed in slots, assembly of the armature could be simplified as well.

It is important to note that the principles of constructing a superconducting reluctance machine could also be used to synthesize the protruding poles by rotating SC coils which would, in effect, produce saliencies without the presence of any iron member. For example, the SC coils could be inserted between the protruding poles of the rotor to greatly improve the saliency of the structure and thereby its energy conversion ability. Also, the protruding iron poles could be dispensed with completely and the SC coil principle utilized to create an effective rotor saliency similar to the HTSC reluctance motor. It should finally be mentioned that similar principles could be used to also construct a more conventional radial air gap machine. Compared to the substantial problems facing the design of HTSC synchronous, induction or reluctance machines, the HTSC inductor machine has many useful features which makes the concept warrant investigation.

10. Conclusion

This paper has summarized the status and future prospects of high temperature superconductivity as applied to motor technology. It has focussed on the features of motor operation which make the design problems substantially different than for the generating case. Problems of developing adequate starting torque, inducing an adjustable field current, and speed instability have been identified and discussed. It has been suggested that the problems associated with HTSC induction machines will probably preclude its use while the hybrid, concantenated synchronous/-induction machine will apparently not provide sufficient benefits to pursue its development. Although the HTSC reluctance motor is, perhaps, viable; its inherent low power factor will limit its field of application to smaller machines where poor power factor is of less concern. The HTSC synchronous motor is more promising. However, the machine may be limited to operating with an auxiliary inverter for starting purposes unless the problems of designing a machine with adequate starting torque can be worked out. Of all the machines considered, the homopolar dc machine appears to be the most suitable for a motoring application and is also at a relatively advanced state of development. Unfortunately, the need for dc motors is small and diminishing. Finally, the potential of the HTSC homopolar inductor ac machine has been presented and discussed. It is suggested that the unique features of this ac machine make it a candidate for a more detailed investigation.

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