WINDINGS FOR SUPERCONDUCTING MACHINES

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Abstract

Superconducting electrical machines may be homopolar, for d.c. applications, or heteropolar, for a.c. generators. In the former the superconducting field windings are large solenoids, whilst in the latter they are similar to beam handling dipoles or quadrupoles. Machine windings are discussed with particular regard to the specification of the superconductor, and compared with magnets for other applications. The discussion is illustrated by machines being designed or built at IRD.

I Introduction

Throughout the past decade of development of the technically useful superconductors there has been interest in their application in the electrical power industry. For many reasons it is probable that the most significant industrial application will be in rotating machinery, at least until power production from nuclear fusion becomes a reality, and developments in this field are now well documented[1,2]. Despite the importance of these developments, at present the major use of superconducting materials is in high energy and plasma physics. It is thus of interest to consider the extent to which the requirements of the various applications are compatible.

The problems of using superconductors in high energy physics have been discussed elsewhere, for example by Smith[3]. Here only the machine applications will be outlined, and the design of suitable conductors discussed.

II Superconductors in machines

In electromagnetic machines the conductors carrying the armature current are arranged to cut the magnetic flux produced by the field winding, the resultant interaction giving rise to the machine torque. The power output is given essentially by the product of the speed of cutting, the total armature current, and the total magnetic flux. In conventional machines the flux is confined to a yoke of high permeability steel. The air gap is so small that excitation of perhaps 10^4 ampere-turns is sufficient, but at the same time the available flux is limited by saturation in the steel, and in places the fact that the armature conductors and the steel yoke are competing for the same space limits both the flux and the armature current in a machine of given size. If the steel is omitted these disadvantages are overcome, but the excitation then needed is of the order 10^6 - 10^7 ampere-turns. This can only be provided economically by the use of superconducting windings. Then, because of the need for deep low temperature refrigeration and the high cost of superconductors, the benefits, in smaller, lighter, and possibly cheaper machines, can only be realised for suitably large ratings, when they may be substantial. In these large ratings further benefits become apparent, because some of the limitations on the maximum possible ratings for which conventional machines can be built are avoided.

As is well known, two types of superconducting machine are being developed; for d.c. motors and generators, homopolar machines, the principle of which is illustrated by *Fig. 1*, show great promise, whilst for large a.c. power generators (500 MW rating and above) the heteropolar configuration shown in *Fig. 2* is appropriate.

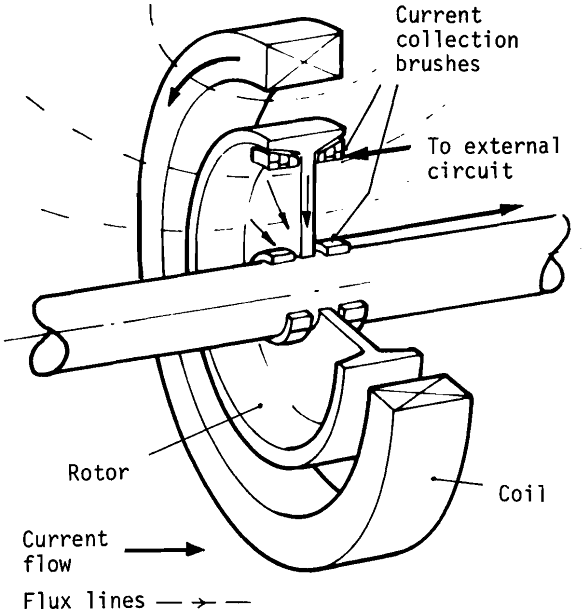

Fig. 1 Principle of homopolar machine

III D.C. machines

The feature of homopolar machines which was particularly attractive when superconducting machines were first developed was the lack of armature reaction, since it allowed relatively unstable superconductors to be used in the field winding whilst remaining unaffected by the armature current. Other advantages have now become more important; in particular, the size limitation on

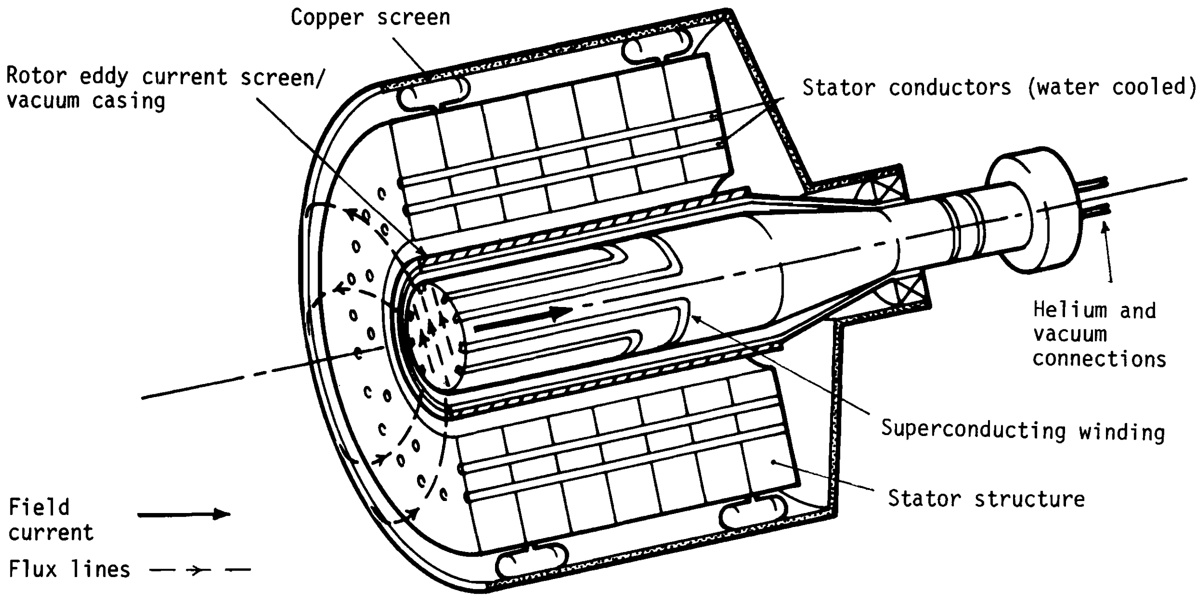

Fig. 2 Principle of heteropolar machine

conventional machines (which is determined largely by problems of commutation) can be exceeded[1] and thus the wider application of d.c. drives can be considered. This is illustrated by *Fig. 3*.

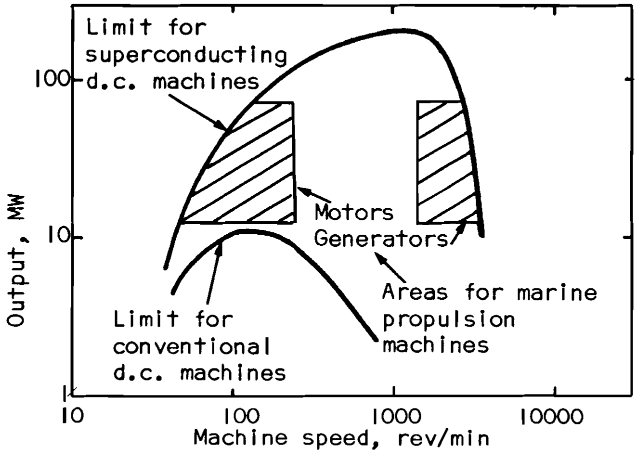

Fig. 3 Output parameters of conventional and superconducting d.c. machines

Windings of d.c. machines

As is apparent from *Fig. 1*, the field windings of homopolar machines are, at the simplest, a solenoid, and more generally, an assembly of solenoids. The power rating, W, of the machine is given by an expression of the form:

$$W = \frac{f\pi^2 \, q \, D^3 \, B_{av}}{4}$$

where f is the rotational speed, D the diameter of the outer slipring (in practice this is as close to the coil bore as possible and will be treated as equal in this discussion), B_{av} the mean flux density, and q the current loading of the outer slipring per unit of circumference. It is immediately obvious that a wide range of power ratings is possible for a relatively small range of coil bores. Moreover, there is in general little incentive to use high values of flux density, for though the specific power rating of the machine is increased, so too are the mechanical problems, and also the costs (since less superconductor is needed to produce a given amount of flux in coils of greater bore). Thus, for most purposes coils will lie within the range of about 1 to 3 m diameter with flux densities of up to 5 T, and corresponding stored energies between 4 and 40 MJ. The current density can often be chosen on grounds of cost, for with such large diameter coils the cross-sectional dimensions are relatively quite small. Thus the field near the windings is large (in a 2500 kW motor built by IRD it varies from 1.5 T on the axis to 3.7 T at the winding) and it is important to choose the dimensions so as to minimise the peak field and hence the associated degradation of the superconductor. For designs studied at IRD the costs have been a minimum at, or have only decreased very slightly with current density above, overall current densities of about 5000 A/cm^2. At these levels stresses in the coil can be contained without too much difficulty (a simple expression for stress, BJr, gives a considerable overestimate, but even with r = 2 m, B = 5 T and J = 5×10^7 A/m^2 the stress is 5×10^8 N/m^2, or about 10^5 lbf/in.^{2}).

Finally, the method adopted for controlling the machine has an important bearing on winding design. For many applications control will be by variation of the field strength, in some cases a complete reversal being needed. The rate of change demanded is determined by the response time of the system being driven, and thus the shortest reversal times that can be envisaged are 2 and 10 seconds for rolling mill drives and ship drives respectively. In any case, even with these times the exciter is already becoming large, and alternative control systems thus of interest. The repetition period is also relevant, and could be as little as ten times the quoted charge times in extreme cases such as reversing mills.

IV A.C. machines

The configuration of the windings in a.c. machines is as shown in *Fig. 2* for the case of superconducting machines. Large power generators are usually 2-pole (as shown), running at 3000 or 3600 rev/min to suit steam turbines, though 4-pole machines running at half these speeds are built. The diameter of the machine is limited by centrifugal forces, and thus the only means available for increasing the power output of conventional machines are (i) increasing the active length, and (ii) increasing the stator current loading by improved cooling. The former brings mechanical problems whilst the latter gives a machine with such large armature reaction that stability of the power network becomes a problem[4]. The use of superconducting field windings allows these difficulties to be postponed until unit ratings of 5000-10,000 MVA are needed, which is not likely to occur before the turn of the century.

Although some of the problems of conventional generators are avoided by using superconductors, new problems arise, especially in connection with mechanical stresses on both rotor and stator. Thus again, there is no great incentive at present to use flux densities above 4 to 5 T at the winding. In a typical rotor of 1 m diameter by 2 m long, the stored magnetic energy is thus around 30 MJ. High current densities are of greater interest than in homopolar machines, but even so 10,000 A/cm^2 is a useful overall value.

Rate of change of field is more difficult to define, for variations in field level can arise in a number of ways. The excitation will be subject to changes to compensate for variations in load, but these are of small amplitude and relatively slow (say<5%/s). The rotor is also subject to some fields, at harmonics of the power frequency, which are produced by the armature (stator) currents; these are only present if the load is electrically unbalanced, so the amplitude is large only under fault conditions.

In practice there are good reasons for incorporating screens into the machine, between the field winding and the stator, which effectively make the ripple field at the winding negligible under normal conditions. Thus fault conditions which are severe enough to cause an a.c. loss problem in the rotor are unlikely, and in such an event it will probably be acceptable to quench the field and remove the machine temporarily from service.

V Superconductor requirements

As well as the broad technical requirements for superconducting windings outlined above, two further considerations are important. These are reliability, and the cost of the finished windings - reliability because equipment which cannot work for at least several years with a minimum twelve month major servicing interval has little chance of finding an industrial market, and cost because, as up to 25% of superconducting machine is accounted for by windings, and in many instances alternatives to superconducting systems exist, the size of the potential market is very sensitive to this factor. In these respects the constraints on windings for machines are probably more severe than those for nuclear of plasma physics. In technical specifications, on the other hand, the requirements are in many ways similar, though less exacting in the industrial field. These points will be illustrated by considering various aspects of the coil and conductor design.

Stability

For stability, and also low losses, twisted filamentary conductors of niobium-titanium are adopted almost without question. The twist pitch needed to maintain stability with a copper matrix at the highest rates of change of field is rather short, but three component conductors, with a thin sheath of CuNi around each NbTi filament and a twist pitch of around 1 cm, are suitable for almost all machine applications. Epoxy impregnation of the coils is also adopted, for up to the sizes in question the benefits of robustness outweigh any marginally better guarantee of performance afforded by cryostatic stabilisation. IRD experience is that performance very close to short sample can be achieved (in 1 m bore coils), though how far this is due to the low current density in the coils so far made (the large proportion of copper giving additional enthalpy and dynamic stabilisation) is not known.

Robustness and reliability

The advantages of epoxy impregnation for robustness have been mentioned. This is probably most important in coils which may be subject to long term vibration (e.g. on board a ship) or to repeated pulsing, though there is as yet little data on the fatigue life of impregnated coils.

Reliability must be considered in terms of the complete winding, cryostat and refrigerator system, and a number of points remain unresolved. From the point of view of cooling effectiveness and simplicity of coil construction it is preferable to immerse the coils in liquid, though the refrigerator engineer would prefer the helium to be confined to relatively small pipes. The latter approach involves making thermal connections between coils and pipes which are both durable and have the low thermal resistance necessitated by the use of niobium titanium conductors. Satisfactory methods have yet to be developed.

Protection

At present, protection of the winding and extraction of energy after a quench are major aspects of coil design, if only because prototype coils are likely to be driven normal during testing. In the longer term a machine winding which quenches under any but the most severe fault conditions will hardly be acceptable, and thus the design criteria should be for the coil to be capable of surviving one or two such events during its whole lifetime. With the current densities used in machine windings - say 12000 A/cm^2 in the conductor - discharge time constants of 5 and 10 s correspond to final maximum temperatures after a quench of about 100°K and 300°K respectively (the theory is as discussed by Maddock and James[5]). With the usual dump resistor circuit, these times correspond, for typical stored energies, to feasible values of current and voltage (e.g. 4 kV and 2500 A is equivalent to 20 MJ discharged in 4 s).

With potted coils, however, the speed of propagation of the normal region is such that large sections of winding become resistive in a fraction of the discharge time (the speed may be of the order of 500 cm/s along and 20 cm/s perpendicular to the conductor); thus the final temperature reached is fairly uniform throughout sections of the size now impregnated as a single unit, and quite high temperatures may be acceptable without fear of damage due to differential expansion. If at the same time so much of the coil becomes resistive that the natural discharge time constant is suitably short, no external dump resistor and the associated d.c. circuit breaker will be needed. Such a condition is easily achieved in systems so small that one coil section alone can absorb all the stored energy without damage, and it seems that in fact most machine windings could be designed on this basis.

Losses

For most industrial applications, in contrast to those in high energy physics, the losses occurring in the superconductor on charging or discharging the windings are too small to affect significantly the refrigerator rating. Even in the worst case the mean loss rate may be around 10 W (200 J every 20 s) compared with a typical refrigerator rating equivalent to 50 W at 4°K, and thus the increase in cost should be quite small. The situation is made a little worse by the effects of the high transient loading on the stability of the refrigerator controls, which is thus a development problem currently being studied.

Perhaps more important are detail considerations of heat flow in the coil. The specific heats near 4°K are so low that virtually steady state temperature distributions are set up, and it is important to minimise thermal impedances in order to avoid degrading the niobium titanium conductors (obviously most of these problems would disappear if filamentary niobium-tin conductors became available). The impedance of the epoxy/conductor system is by itself tolerable; however substantial additional impedance, either in the form of long thermal paths between coil and cooling pipes, or as spreading resistance if the cooling medium makes contact with the coil at a limited number of points, cannot be allowed.

These loss considerations dictate a filament size (say 10-20 μm) smaller than would be necessary for stability (about 50 μm); they also dictate that some consideration be given to minimising eddy current losses in the finished conductor. For example in the coils for the 1000 kW machines discussed in *Section VI*, for which 50 μm filaments were specified, the hysteresis loss is about 50* mJ/m, which could be reduced by a factor of 5 by adopting smaller filaments; the eddy loss in a solid conductor of 3 mm diameter is about 20* mJ/m, reducing to about 1.5* mJ/m in the equivalent 19-strand conductor adopted. At the rates of change of field encountered in machines it is not necessary to insulate completely the separate strands of a cabled conductor, though if solder is used to impregnate the cable (to ensure good thermal contact between strands and so increase the dynamic stabilisation), its resistivity should not be too low. Some measured values are tabulated below, and of these Sn5%In has been used in the machines now being constructed.

TABLE 1 Resistance ratio of solders

Solder	Resistance ratio $\rho_{300}/\rho_{4.2}$	Approximate resistivity at 300°K (μΩ-cm)
60Sn40Pb	40 (H > 3 kGs)	13
95Sn5In	5	15
95Sn5Ag	70	13
95Sn5Sb	6	17

Cabled conductors

From the foregoing discussion, cabled conductors appear to have many advantages. The superconductor is basically in the form of a standard composite, which can be processed in relatively large quantities and for which the manufacturing methods can be readily established. Suitable filament sizes and twist pitches for machine applications can be obtained without difficulty. The cabling process allows considerable freedom in choice of proportion of copper, or

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* *These figures are calculated using well known formulae quoted by, for example, Smith et al*[6].

of reinforcing materials, for little variation in manufacturing cost. Joints in individual strands can probably be tolerated, thus allowing optimum use of the manufacturer's lengths of superconductor, or even grading of the conductor to match the different magnetic field levels throughout a coil. The usual objections to cables, namely a poor space factor, the risk of strand breakage during compaction or drawing the finished cable, and the problems of insulation of strands, are not relevant, because of the modest current densities and rates of change of field.

VI Experimental machines

The IRD programme to date has included three large scale experimental homopolar machines. The first of these, the Fawley motor[7], was a low speed 2500 kW machine with a field coil 2.8 m diameter. Cryostatically stabilised conductor was used, and though this performed well the construction is now obsolete.

The last two machines, a motor and a generator each of 1000 kW rating, are to be used together in a prototype drive system for a ship. The field windings of the two machines are similar, each consisting of a number of epoxy impregnated coils 1 m or $1\frac{3}{4}$ m in diameter immersed in liquid helium.

At the time of writing, two 1 m coils have been tested in helium. Clamped together, but charged separately, each coil quenched at the short sample current, I_s, except for one 'training' quench at about 0.85 I_s. Charged as a pair, the coils remained superconducting up to 95% of short sample current, at which point testing was stopped as the design stress limit was reached. Preliminary tests on rapid charging (0.2 T/s) suggest that the design performance will be reached. Final assembly is now in progress, and further testing planned for next spring.

VII Conclusions

Windings for the superconducting machines now being developed are essentially d.c. magnets, which for some applications may be pulsed, or subject to small superimposed a.c. excitation. For d.c. machines the 'magnets' are solenoids, whilst for a.c. machines they are similar in form to beam handling dipoles or quadrupoles. The specifications of the conductor are less exacting than for high energy physics applications, and thus conductors of the types already developed are adequate for all immediately foreseeable machine applications.

References

1 A.D. APPLETON. 'Status of Superconducting Machines Spring 1972' presented at Applied Superconductivity Conference, Annapolis, May 1972, p. 16.

2 B.E. MULHALL. Review of Physics in Technology 3, (1972).

3 P.F. SMITH. Proc. VIII Int. Conf. on High Energy Accelerators, Geneva 1971, p. 213.

4 H.H. WOODSON, et al. Trans. IEEE PAS-90 620 (1971).

5 B.J. MADDOCK and G.B. JAMES. Proc. IEE 115 543, (1968).

6 P.F. SMITH, et al. J. Phys D: Appl. Phys. 3 1517 (1970).

7 A.D. APPLETON. Bull Int. Inst. Refrigeration, Annexe 1969-1 p 207, (1969).

Acknowledgement

The contents of this paper have been drawn from work undertaken in the Electrical Engineering Department at IRD under the direction of Mr. A.D. Appleton. The author is grateful for the assistance provided and to International Research & Development Co. Ltd. for permission to publish the paper.