M-2 A REVIEW OF THE CRITICAL ASPECTS OF SUPERCONDUCTING A.C. GENERATORS

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SUMMARY

This paper reviews the development of superconducting generators undertaken by IRD on behalf of C.A. Parsons and Company Ltd. An outline design of a machine concept is presented with a discussion of the more critical development problems. An account is given of the manner in which performance is influenced by machine geometry, in particular by inter-winding coupling factors on substransient reactance. The principal mechanisms causing machine losses are reviewed and the techniques used for their prediction and minimisation are outlined.

1. INTRODUCTION

The conventional alternating current generator has grown from the first 500 candle-power Ferranti-Thomson machine of 1882, *Fig. 1*, to the 800 - 1300 MW machines of today. This represents a growth in size by a factor of about 5×10^6 in 90 years. The rate of growth of size of the generators has been, of course, a direct result of the increasing demand for energy; the trend to larger and larger unit ratings is likely to continue until either the limits of manufacturing techniques are reached or the benefits of increasing size are offset by a reduction in reliable operation. These two factors are of course related and the question to be answered is the limit of reliability of existing conventional manufacturing techniques.

Fig. 1 FERRANTI - THOMSON ALTERNATOR SMITHSONIAN INSTITUTE

1300 MW represents the largest machine that can be made at present with a single piece rotor forging; above this it becomes difficult to transport the heaviest portion of the machine, namely the stator core. Extrapolation of existing designs may well require that some of the manufacturing procedures be carried out at site. A consensus of different manufacturers would probably yield different limiting ratings based upon conventional designs but this is likely to be in the region of 2000 MW.

Superconductivity provides the means for an extension of manufacturing techniques and studies have indicated that the limit of the ratings of superconducting a.c. generators is far in excess of 2000 MW. Thus, if it can be shown that the superconducting machines may be produced and operated reliably and that their capital and operating costs are at least no higher than conventional generators, then a case exists for their development. *Fig. 2* shows the growth of sizes of a.c. generators and the possible future requirements subject to satisfactory reliability.

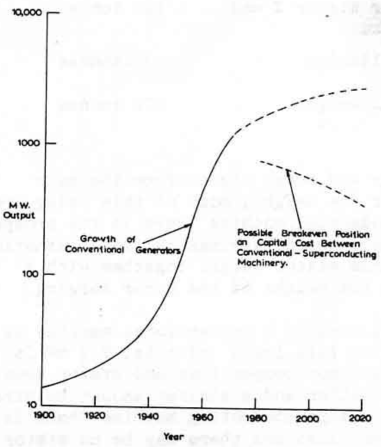


Fig. 2 GROWTH OF CONVENTIONAL TURBOGENERATORS AGAINST TIME PROJECTED TO 2020 A.D.

Studies have indicated that the breakdown point on capital cost between conventional and superconducting generators is around 500 MW and the advantage in favour of the superconducting machines increases as the size of the generators increases. It is also expected that the superconducting machines will show a slight advantage in respect of efficiency. The question of the reliability of superconducting generators may be assessed to some extent by a careful consideration of the solutions to the major design problems but can only be proved by demonstration. A consideration of all of these factors leads to the conclusion that a good case exists for the development of superconducting a.c. generators, at least to the point where their reliability and costs may be properly assessed. A further factor of interest is that as superconducting generators are developed, the break even costs with conventional machines may be expected to occur at lower ratings; a possible trend of this effect is also shown on *Fig. 2.*

This paper reviews the critical aspects of superconducting a.c. generators and, for a basis of comparison with conventional machines, a rating of 500 MW is selected. This is appropriate because the parameters of the latter for existing machines are well known and because it is a convenient base upon which to develop superconducting generators of larger ratings. To focus our minds on the 500 MW machine we consider some of the parameters of the conventional machine; a breakdown of the approximate weights is shown in *Table 1.*

Table 1 WEIGHT OF A CONVENTIONAL 500 MW A.C. GENERATOR

Rotor	68 tonnes
Stator core	195 tonnes
Outer stator & end covers	110 tonnes
Auxiliaries	35 tonnes
Total weight	408 tonnes

The inner and outer stator form the main components of the weight, most of this being iron. In a superconducting machine there is the prospect of considerable weight savings by the elimination of much of this stator weight together with a reduction in the weight of the rotor forging.

The total loss in a conventional machine is about 7.7 MW on full load; of this, 2.2 MW is attributed to rotor copper loss and stator iron loss taken together and a similar amount to stray losses. In a superconducting machine there is no rotor copper loss and there may be no stator iron loss; furthermore, that portion of the stray losses associated with eddy currents in the ends of the core and screening rings caused by axial flux are eliminated. Superconducting machines will have losses in an environmental screen and a small loss due to the necessary helium refrigerator. The prospects for an overall improvement in the efficiency of superconducting generators are reasonable.

Let us now consider the design of a 500 MW superconducting a.c. generator.

2. A 500 MW SUPERCONDUCTING GENERATOR

Consider a 500 MW superconducting generator which is required to meet all the conditions laid down by the British Central Electricity Generating Board for conventional machines. Most of the problems associated with the design of even bigger generators are likely to appear at this rating, but this will not be true for relatively small machines because of scaling effects.

The machine output is governed by

$$S = kBAND^2L \text{ volt amperes}$$

where k = constant

B = average flux density at the armature winding (Tesla)

A = specific electrical loading of the stator winding (A/m)

L = active length of the machine (m)

D = armature winding diameter (m)

N = speed (rev/min)

In a conventional machine D is closely tied to the rotor diameter which in turn is controlled by the maximum permissible centrifugal loading. A is limited by the cross section of copper that can be placed in the slots. Hence increased output has to be obtained by increasing L, and, if necessary, running the rotor above its first critical speed. In a superconducting machine the restriction upon the rotor diameter remains. However the restriction upon the diameter of the armature winding is removed and D may be selected from other considerations. Thus the machine may have a large effective airgap and this is made possible by the large number of ampere turns available on the rotor. One design possibility is a machine in which the flux density at the stator winding and the electric loading are similar to a conventional machine. Thus in spite of similar rotor diameters on both conventional and superconducting machines, the stator winding diameter is greater on the superconducting machine, allowing L, the active length, to be greatly reduced for the same output. Hence the superconducting machine will be shorter than its conventional counterpart.

Fig. 3 **shows an outline drawing of one design which has been considered at IRD. It has two poles, with a rotating superconducting field winding and a stationary armature winding at ambient temperature. The machine has a double rotor structure consisting of an inner low temperature member which supports the field winding and an outer rotor at ambient temperature which is designed to withstand the short circuit torque and to screen the field winding from negative sequence and rapidly changing fluxes. Associated with the inner rotor structure is an intermediate temperature radiation screen and liquid and gaseous helium cooling ducts. Helium is led onto the rotor through a rotating seal and is taken to the winding through a radial duct and heat shunt. After cooling the winding, the helium is used to cool the cone end support structure before being led back into the refrigerator.**

Alternative design concepts in which all the windings are superconducting or which have a stationary superconducting field have been considered and rejected because (i) there is no superconductor capable of operating with the required performance at power frequencies and, even if there were, it is doubtful whether the additional cost would be worth the improvement in efficiency obtained; and (ii) a stationary field winding would mean that 500 MW of power would have to be removed from the rotor through sliprings and there would therefore be a very great risk of short circuits occurring at the machine terminals. Other workers[1] have reached the same conclusions and this is not the only objection to this approach.

3. ELECTRICAL BEHAVIOUR

Electrically the machine consists of: an inner field winding, a low resistance damper winding outside the field winding and concentric with it, a three phase stator winding and an outer environmental screen (enviroscreen) designed to screen the environment from field and armature reaction fluxes.

The number of ampere turns on the field winding is about two orders of magnitude greater than for a conventional machine and the field winding has zero resistance.

In terms of the two-axis generalised machine theory the machine can be represented by seven windings; three on the rotor and four on the stator, *Fig. 4*. In the practical machine, end effects play an important part and the windings cannot be said to be sinusoidally distributed. Nevertheless the generalised machine equations can still be used to draw broad conclusions as to the nature and behaviour of the machine.

In the case of sinusoidally distributed windings it can be shown, provided end effects are ignored, that the coupling factor between two concentric windings of radii r_s and r_o (where r_s is greater than r_o) is equal to r_o/r_s. The mutal inductance between two concentric and sinusoidally distributed windings is

$$\mu_o \frac{\pi}{2} C_s C_o (r_o/r_s) \text{ Henries/m}$$

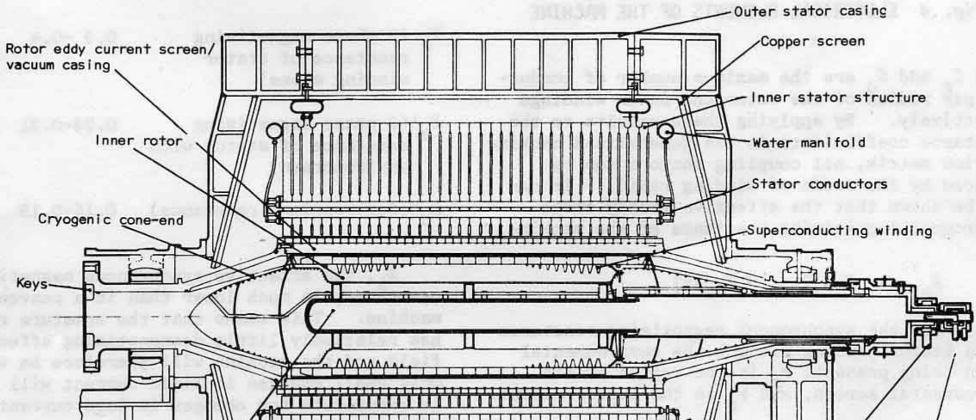
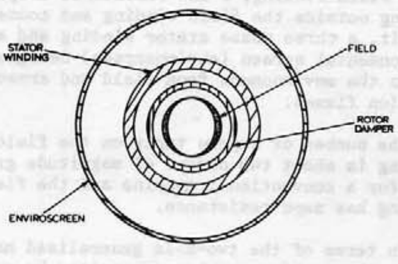
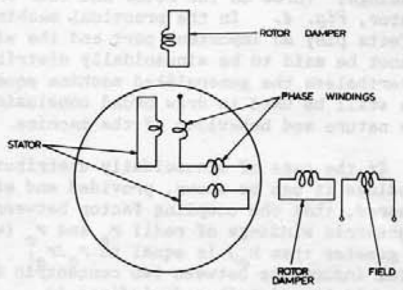


Fig. 3 500 MW SUPERCONDUCTING A.C. GENERATOR



BASIC ELECTRICAL ELEMENTS OF MACHINE



AXIS REPRESENTATION OF MACHINE

Fig. 4 ELECTRICAL ELEMENTS OF THE MACHINE

where C_s and C_o are the maximum number of conductors per radian of the outer and inner windings respectively. By applying these results to the inductance coefficients in the generalised machine equation matrix, all coupling factors can be replaced by the ratio of winding radii. It can then be shown that the effective steady state synchronous magnetising reactance of the machine is:

$$X_s{}' = X_s \left[1 - (r_s/r_x)^2\right]$$

where X_s is the synchronous magnetising reactance of the stator winding without the environmental screen being present, r_x is the radius of the environmental screen, and r_s is the stator radius.

The effective mutual inductance between the field winding and one phase of the stator when their axes are aligned is:

$$L_{ad}{}' = L_{ad} \cdot \left[1 - (r_s/r_x)^2\right]$$

where L_{ad} is the field armature mutual inductance without the environmental screen being present. Hence the effect of the environmental screen, as represented by the factor $(r_s/r_x)^2$, on X_s and L_{ad} is to reduce them by $\left[1 - (r_s/r_x)^2\right]$. The screen lowers the effective synchronous magnetising reactance and hence provides a demagnetising effect. If for instance the screen is at twice the diameter of the armature winding, the net demagnetising effect will be 25% at the stator armature winding. Hence, in order to limit the number of field winding ampere turns, the screen radius should be at least twice the stator armature winding radius. Similarly, the subtransient reactance, that is the value of reactance looking into the stator terminals at the instant of short circuit before currents have had time to start decaying, will be:

$$x_d'' = X_s \frac{\left\{1 - \left(\frac{r_s}{r_F}\right)^2\right\}\left\{1 - \left(\frac{r_D}{r_s}\right)^2\right\}}{\left\{1 - \left(\frac{r_D}{r_x}\right)^2\right\}}$$

where r_D is the field winding radius.

x_d'' depends on the relative positions of the stator winding, the stator enviroscreen and the rotor damper screen.

Table 2 represents the spread of reactance values that might be expected for a 500 MW superconducting machine and compares them with typical values for conventional machines.

Table 2 COMPARISON OF REACTANCES FOR SUPERCONDUCTING AND CONVENTIONAL MACHINES

	S/C	Conv. Machine
X_s (3 phase magnetising reactance of stator winding alone)	0.3 -0.4	2-2.7
$X_s{}'$(3 phase magnetising reactance of stator with enviroscreen)	0.23-0.31	2-2.7
x_d''(Subtransient reactance)	0.15-0.19	0.23-0.25

X_s, the effective synchronous magnetising reactance, is much lower than in a conventional machine. This means that the armature reaction has relatively little demagnetising effect on the field and the machine will therefore be very stiff. Only small changes in field current will be needed to compensate for changes in load current.

The subtransient reactances are much closer to one another. Hence the initial short circuit currents and torques will be similar. The equivalent value of transient reactance must lie between $X_s{}'$ and x_d'' but, because of the effect of the transient resistance of the eddy current screens, the exact value is difficult to estimate.

From the above, it is clear that the machine reactances and the transient performance are greatly influenced by the positions of both the rotor damper screen and the stator environmental screen.

With higher pole numbers the coupling factors between the windings depend upon factors of r^{p+1}. With the higher powers of r it is difficult to get such good coupling between windings as in the two-pole case. *Fig. 5* compares the flux patterns produced by a two-pole and a four-pole winding which illustrates the effect of pole number on coupling in an ironless machine. Since higher harmonics of flux density distribution fall off more rapidly with radius than the fundamental, it is possible for a non sinusoidal distribution of ampere conductors to produce a winding near sinusoidal flux density distribution except close to itself.

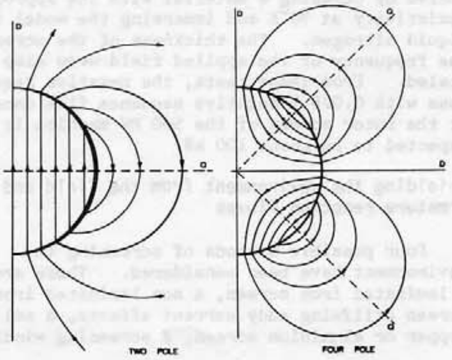


Fig. 5 FLUX DISTRIBUTION PRODUCED BY A SINUSOIDALLY DISTRIBUTED CURRENT SHEET

4 MECHANICAL BEHAVIOUR

Mechanically the rotor consist of two inertias, namely the inner and outer rotors, coupled together via the cone ends and the turbine generator coupling, *Fig. 6*. Ideally the rotor damper screen would screen the inner field winding from rapid flux changes and, under short circuit conditions, the damper would take the short circuit torque. The steady state torque would be taken by the inner field winding and support structure. In practice it is difficult to couple the inner and outer rotor members closely because of the need to provide a long thermal path between the cold field winding and the warm damper screen. Hence under short circuit conditions the torque applied to the damper screen will partly be applied to the turbine but will, in the main, be applied to the inner winding support structure. Therefore it will be necessary to design the inner rotor to take most of the short circuit torque. Alternative designs of rotor will behave in a similar manner unless the damper screen and field windings are very closely coupled. (In the conventional machine the problem does not really arise, because both the damper winding and the field winding share the same slots.) The damper screen will try to move relative to the field winding because short circuit torque is applied to it and the movement is only opposed by the weak compliance of the coupling between the damper screen and the field. Therefore the damper screen moves relative to the field flux. This will result in an eddy current damping torque between the inner and outer rotor members caused by eddy currents springing up on the <u>inside</u> of the damper screen. Hence the mechanical representation of the rotor must not only include inertias and shaft stiffnesses but also a large eddy current damping torque, which will be of the same order of magnitude as the full load torque.

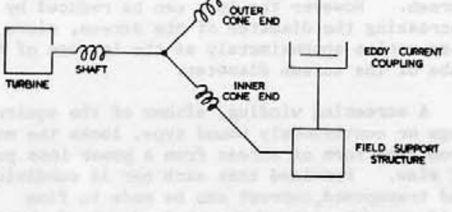


Fig. 6 MECHANICAL REPRESENTATION OF MACHINE

5. CRITICAL ASPECTS OF THE MACHINE DESIGN

Certain aspects of the machine design raise considerable difficulties, but seem to require little more than available knowledge and techniques for their solution. These areas are outlined in *Appendix A*.

There are, however, four aspects of the machine design which are felt to merit special attention. These are considered below.

Support of the stator winding

The support of the stator winding is perhaps the most critical aspect of the design of large superconducting machines. The resin type materials that will be quite suitable for the construction of small machines may well be unsuitable for very large machines because of the effects of hysteretic heating on the life of the material.

In the conventional machine most of the torque appears on the iron teeth and is thus directly transferred to the stator outer casing. Only about 20% of the torque appears on the winding and therefore the winding insulation is subject to relatively low stresses.

In the superconducting machine all the torque appears on the winding. Consequently each conductor (and, in turn, the winding insulation) is subject to forces about five times greater than in a conventional generator. Hence the support structure and the winding insulation are subject to higher stresses than is usual for insulating materials.

The stator is subject to a 3000 rev/min four pole force wave which gives 100 Hz cyclic stresses. Unfortunately the resin bonding materials which are required in such a structure are subject to a hysteretic heating loss when rapid cyclic stresses are applied. Because such materials are of low thermal conductivity it is difficult to remove the heat and a rise in temperature results. The loss increases with rise in temperature and consequently, if adequate cooling is not provided throughout the structure, there is a danger of runaway heating and degradation of the material. If a compressed wood composite such as densified plywood is used, then under full load conditions a hysteretic loss of 100 kW is expected in the stator. However, the fatigue life of the material under such conditions would not permit a service life as long as the necessary 30 years. It is reasonable to hope that materials which give a better performance will be developed, but they are not available at the moment. Such materials must have low hysteretic heat loss and good fatigue properties. They must also be cheap.

The protection of the field winding from negative sequence and stray fluxes

The superconducting winding must be protected against rapid variation of flux for two reasons. Firstly, rapid changes in flux give losses in the superconductor which could lead to the superconductor going normal. Secondly, rapid flux changes produce eddy currents in the surrounding heat shield and support structure and consequent energy dissipation. Because most materials have a very low specific heat at low temperature, very small amounts of heat energy input can lead to a large temperature rise. This means that the winding support structure might rise to an unacceptably high temperature under conditions of changing armature or field currents. The function of the rotor eddy current screen is therefore twofold; first it must completely exclude negative sequence flux from the rotor, and second it must slow down the rate of flux change seen by the rotor winding under transient conditions to an acceptable level, where the eddy current heating caused by the changing flux can be removed by the refrigerant without undue temperature rise. Therefore the screen must have sufficient thickness to attenuate negative sequence fluxes and slow down flux changes in the rotor under transient conditions, yet it must not be so thick that it makes the field flux time constant too long for control purposes.

The proposed screen design is likely to be considerably longer than the field winding in order to prevent the negative sequence flux from getting in at the end of the winding. It would be supported against centrifugal forces by a set of multiple shrink rings of high tensile material on the outside of the screen. These would each be short compared with the screen length in order to ensure that the eddy currents flowed in the damper winding and not in the high resistivity strength rings.

A large number of tests have been carried out on a 1/10th scale model of the screen to ascertain the power loss with 10% negative sequence current flowing in the stator. The resistivity was scaled by choosing a material with the appropriate resistivity at 70°K and immersing the model in liquid nitrogen. The thickness of the screen and the frequency of the applied field were also scaled. From these tests, the negative sequence loss with 0.026 T negative sequence flux density at the rotor screen of the 500 MW machine is expected to be about 100 kW.

Shielding the environment from the field and armature reaction fluxes

Four possible methods of screening the environment have been considered. These are: a laminated iron screen, a non laminated iron screen utilising eddy current effects, a solid copper or aluminium screen, a screening winding.

The laminated iron screen has been rejected on grounds of weight. The dimensions are determined not only by the flux to be carried but, more significantly, by the need for the screen to have a high natural resonant frequency. The flux could be carried by a screen weighing 100 tons, but natural frequency requirements dictate a screen weight of 400 tons. This is only a little less than the weight of a conventional generator. The total loss would be about 450 kW. Hence a low loss screen can only be obtained at the expense of enormous weight.

A non laminated screen would certainly be capable of reducing the external field to an acceptable level, but the loss would be at least 80 MW.

A solid conducting screen of copper or aluminium would adequately screen the environment. A copper screen of approx. 4 m diameter and 40 mm thick would have a no load loss of 5 MW. This loss would rise to 12 MW under conditions of full load at 0.85 P.F. These losses cannot be reduced by making the screen thicker, since the screen is already several skin depths thick, unless some artificial means is found to force the eddy currents to flow deeper and more uniformly in the screen. However the loss can be reduced by increasing the diameter of the screen, since the loss varies approximately as the inverse of the cube of the screen diameter.

A screening winding, either of the squirrel cage or continuously wound type, looks the most promising form of screen from a power loss point of view. Provided that each bar is subdivided and transposed, current can be made to flow uniformly throughout the whole depth of the winding. Losses can therefore be kept to a chosen level by the use of a sufficient depth of copper. If a screen loss of 1.5 MW is acceptable, then a 4 m diameter screen should not need to be more than 100 mm thick.

Dynamic performance of the machine

The acceptability of the machine to the user depends upon the dynamic performance of the machine being compatible with the system to which it is connected. It is therefore important to have an adequate picture of transient performance before the machine is built.

General conclusions can be reached about the machine performance by the use of the generalised machine theory. However, it should be remembered that the generalised machine theory applies to ideal rather than real machines and must be used cautiously. In an iron cored machine, in spite of the presence of saturation the theory can be used satisfactorily because end effects can to a large extent be ignored. This is not the case in an ironless machine in which axial fluxes are present and end windings cannot be ignored. This means that the winding inductances appropriate for use in the machine theory are not necessarily the same as the measured machine inductances. It is therefore necessary to establish which machine inductances correspond in the real and two-axis model machines and to derive what, for want of a better name, can be called 'first harmonic' inductances for the remainder. In the two-axis model, sinusoidal ampere conductor distributions are assumed and therefore the inductance values chosen must reflect this. A particular example of this concerns the relationship between the synchronous magnetising reactance and the armature phase inductance and the phase to phase mutual inductance. The relation:

$$L_s = L - M$$

must hold. In practice when L and M are measured M is found to be about $-0.3L$ and hence L_s is $1.3L$. However the assumptions of the generalised theory demand that M be equal to $-0.5L$ and that L_s is equal to $1.5L$. Hence, whilst it is correct to use the measured value of L_s in the machine equations, it would be incorrect to use the measured value of L. The correct value to use is:

$$L = \frac{2}{3} L_s$$

Because of the low per unit synchronous reactance, only small changes in field current will be needed to compensate for armature reaction. Typically the field current need only rise to 1.4 p.u. at full load and zero P.F. lag to provide full terminal volts. In a conventional generator the field current would have to rise to 3.5 p.u. under the same conditions.

Since the subtransient reactance has been shown to be similar to that of a conventional machine (*Table 2*), the initial short circuit torque will be similar. However, the overall behaviour after short circuit will be greatly influenced by the time that it takes for the flux to penetrate the rotor damper screen, by the time that it takes to penetrate the enviroscreen, and also by the exact behaviour of the inner and outer rotor members. The whole dynamic problem is therefore much more complex than in the conventional machine.

If, for example, a very simple estimate of the available eddy current damping between the inner and outer rotors is made, and the relative angular velocity between the two members is 0.1 radians per second, then the torque available would be equal to the full load torque. Hence the eddy currents that can arise on the inside of the damper screen are of equal importance to those that can arise on the outside and must be taken into account when analysing the machine performance.

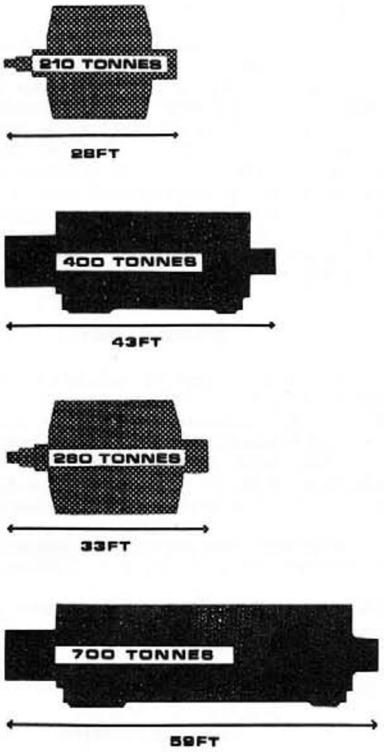


Fig. 7 COMPARISON OF THE WEIGHTS AND LENGTHS OF SUPERCONDUCTING AND CONVENTIONAL A.C. GENERATORS

(a) 500 MW superconducting
(b) 500 MW conventional
(c) 1300 MW superconducting
(d) 1300 MW conventional

SUMMARY OF THE MACHINE DESIGN

The main dimensions of the machine are outlined in *Appendix B*. *Fig. 7* shows what these figures mean in terms of overall dimensions for superconducting machines. 500 MW and 1300 MW superconducting machines are compared with conventional machines of the same output. Considerable weight and length reductions can be achieved.

CONCLUSIONS

The development of superconducting a.c. generators has reached a most interesting stage; subject to a successful outcome of engineering development work on some critical areas, the feasibility of the new machines has been established reasonably well and the economics appear to be attractive. When this is taken with the other advantages of size, weight and efficiency, it is seen that there is a good case for further development of the machines.

An essential feature of the work carried out at IRD is the very close co-operation with C.A. Parsons & Company Ltd. to ensure that maximum benefit is derived from the very considerable experience of the latter with large conventional a.c. generators. It is considered that the most satisfactory approach to the problem is to undertake the essential development work on test rigs and to follow this with a test machine of moderate rating. It is possible that a test machine with a rating of about 60 MW will emerge as the optimum before the full size prototype is constructed.

ACKNOWLEDGEMENTS

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The authors are grateful to IRD and C.A. Parsons for permission to publish this paper.

NOTE: IRD & C.A. Parsons are members of the Reyrolle-Parsons Group.

APPENDIX A

COOLING PROBLEMS

The total requirement for refrigeration at $5^{\circ}K$ will be about 30 W. The main problem is to design suitable seals so that liquid helium can be led onto the rotor and one or more gas streams be removed from the rotor. Provided that the sealing is done at ambient temperature and that the liquid helium is kept well away from the seal, there should be no undue difficulty in using magnetic fluid seals. Other alternatives are available, but require development.

Transfer of helium from the centre of the rotor to the field winding

The helium liquid will undergo work of compression in moving from the axis of the machine out to the winding because of the centrifugal force upon it. Since this process should take place isothermally, it will be necessary to surround the radial heat transfer duct with a thermal shunt from the outer radius to the machine axis.

Provision of vacuum insulation on the rotor

It is necessary to provide pumping facilities to maintain a vacuum between the inner and outer rotors in order to provide a high degree of thermal insulation. It will be necessary to use a stationary pump coupled to the space to be evacuated via a rotating vacuum seal, because if the pump were to be on the rotor it would be subject to large out-of-balance forces. The pumping capacity is dependent more upon the size of the vacuum seal than upon the size of the pump, because of the distance between the pump and the space to be evacuated. Hence, leakage of helium into the vacuum space must be kept to a minimum. Air leaks can be taken care of by cryopumping. The conventional face seal has speed limitations, but both the labyrinth pump seal and the ferromagnetic seal look reasonably promising. Alternatively, both the rotor and the gap between rotor and stator could be evacuated. A simpler seal could then be used in conjunction with a much larger pump. However, it would not then be possible to test the rotor independently of the stator; a feature which seems necessary in a new type of machine.

Allowance of thermal contraction between inner and outer rotors

It is estimated that the overall differential contraction between the inner and outer rotors would be approximately 1.2 cm. Two methods of accommodating this contraction are possible. Firstly by means of a sliding joint at one end of the machine, or secondly by supporting the inner and outer rotors on separate bearings in such a way that they can move independently. The relative movement takes place during cool-down and warm-up and hence there is no need to provide for movement during operation of the machine.

Design of the field winding

The shape of the winding and the number of ampere turns are influenced by the following considerations. Firstly by the required field form at the stator winding. Secondly by the need to leave enough space between field and armature windings to accommodate a radiation shield, a damper screen and an adequate distance between rotating and stationary parts. Thirdly by the desired flux density at the stator. Fourthly by the cost of superconductor. A reasonable choice is a field winding of about 1 m diameter and a stator diameter of 2 m, giving a field at the stator of about 0.8 Tesla and a field at the rotor winding of 3.2 Tesla. A saddle type winding would be used with 5×10^6 ampere turns and a stored energy of 20 MJ.

Considerable use has been made of both the computer and inductance models to establish the coupling coefficients and winding inductances for the full sized machine. It has been found in practice that of the two methods the use of models gives the greater insight into machine design.

The final method chosen for constructing the winding and the choice of cooling technique will depend upon experience gained from the tests on the large d.c. machines at present under construction and upon experience gained from the design of static quadropole magnets.

REFERENCE

1 HARROWELL, R.V. Preliminary studies of superconducting alternators. Cryogenics,April 1972, pp.109-115

APPENDIX B

PARAMETERS OF 500 MW SUPERCONDUCTING A.C. GENERATOR

Max. rotor magnetic field	3.2T
Max. field at stator	0.8T
Rotor ampere turns	5×10^6
Stored field energy	20 MJ
Overall machine length	8.5 m
Length between bearings	6.4 m
Length of stator winding	3.7 m
Stator nominal dia.	2.1 m
Rotor nominal dia.	1.05m
Screen nominal dia.	4.2 m
Total machine weight	210 tonnes
Rotor weight	29 tonnes
Inner stator weight	40 tonnes
Outer stator weight	120 tonnes
Max. lift (outer stator bottom)	50 tonnes
Copper joule loss	1.8 MW
Eddy current loss	0.5 MW
Outer shield loss	1.5 MW
Stray and refrigerator loss	1.0 MW
Windage and friction loss	1.0 MW
	5.8 MW
Overall efficiency	98.8%