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Superconducting reciprocating machines

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[Plate 9]

The superconducting reciprocating generator/motor has several advantages over the machines with rotating superconducting field windings on which most existing work is concentrated. It consists essentially of a number of armature conductors oscillating within a superconducting solenoid of rectangular cross-section, the conductors being parallel to the long side of the rectangle and at right angles to the directions of both the field and the movement. In the three-phase version the solenoid is wrapped into a toroidal shape, each armature phase being situated at an angle of 120° to its neighbour. The electrical phase relation is maintained by linking each phase-set of conductors through a connecting rod to a crank on the drive shaft. Electrical contact between the armatures and fixed terminals is made through flexible connectors.

The chief advantages of the new machine are:

1. The superconducting field winding is stationary, while the armature does not require sliding contacts to carry the large output current.

2. The field flux is completely contained within the toroid without the need for iron or copper screens.

3. Because the armature conductors do not rotate, but reciprocate in the uniform toroidal field, it is possible to make them of superconductor since the a.c. losses, being due only to the self-field of the armature current, are tolerable. Even with normal conductors, eddy-current losses are greatly reduced.

Among other points, the paper discusses optimization of the design, the problem of fatigue, seals and bearings, losses, and reactances. As the main disadvantage of this machine lies in the linkage converting rotary to linear motion, the prospect of an all-reciprocating system will be touched upon.

1. INTRODUCTION

The cardinal advantage offered by superconductors as substitutes for normal conductors in alternators and other electrical machines is their ability to carry very large direct currents without an I^2R loss. This means that not only can the flux densities produced by present iron-cored field windings be achieved with an air-cored winding, but also that far greater flux densities may be produced, which could result in machines with much larger power densities than those in existing generators. Three practical benefits derive from this state of affairs:

1. The elimination or reduction of field-winding losses can be represented as a saving on the lifetime capital cost of the generator.

2. A superconducting machine would not have to depend on iron to achieve its working flux density, thus promising a significant reduction in mass.

3. The higher power density means that a superconducting machine of a given power would be smaller than its conventional counterpart.

It is not possible to extend these advantages by also using superconductors in the armature of a rotating machine. This is because the (type II) superconductors that remain superconducting at the working flux densities of large alternators have prohibitive power losses in alternating fields.

The pros and cons of superconducting rotating machines having the armature either stationary or rotating have been discussed elsewhere (Harrowell 1972). The main electromagnetic and cryogenic difficulties are as follows:

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1. With a stator armature, as at present, the rotating superconducting field winding requires a spinning cryostat, with attendant problems of rotating cryogenic seals.

2. With a stator field winding, superconducting, the rotor output has to be fed through slip rings and brushes with alternating currents of more than four times present d.c. values, which are already reaching the upper limit for existing brush/slip-ring systems.

3. If full advantage is to be taken of the high flux densities available from a superconducting field winding, in either version, the normal armature conductors will have to be finely stranded and transposed to reduce eddy-current losses. In a 500 MW machine about 2000 strands, each 1 mm square, per conductor would be required to keep eddy current losses at their present level.

4. Again in either version, large stray fields will be produced and these will almost certainly have to be contained by iron or copper screens, with consequent mass or loss penalties.

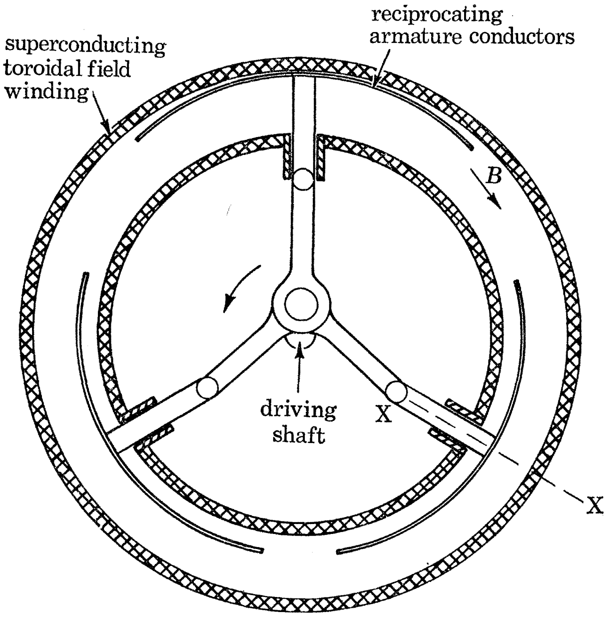

Figure 1. Transverse cross-section of three-phase machine.

A new type of machine, which does not suffer from these difficulties and, in addition, would allow the use of a superconducting armature, has been proposed (Harrowell 1969). It consists essentially of an armature that reciprocates (instead of rotating) in a uniform magnetic field produced by a stationary superconducting solenoid. This scheme does not require slip rings and brushes, connexion to the armature now being made through positively connected flexible leads, an arrangement that is inadmissible in principle with a rotating armature. As the armature does not undergo reversals of magnetic field, it may use superconductors or normal conductors that are not finely stranded. There will be some a.c. losses in both types of conductor, due to the armature current, but these are much smaller than the losses that would occur in a strong alternating field.

If the field solenoid has a rectangular cross-section and is wrapped round to form a toroid, a new form of three-phase alternator emerges (see figure 1). Essentially, three sets of armature conductors, situated 120° apart around the toroid, reciprocate radially in the annular field space. If they are operated by the crank and connecting rods, as shown in the diagram, they will generate a three-phase alternating e.m.f. The strong magnetic field is confined to the toroidal tunnel; the question of large stray fields therefore does not arise. Figure 2 is a longitudinal cross-section through X–X. The machine can also be operated as a synchronous motor.

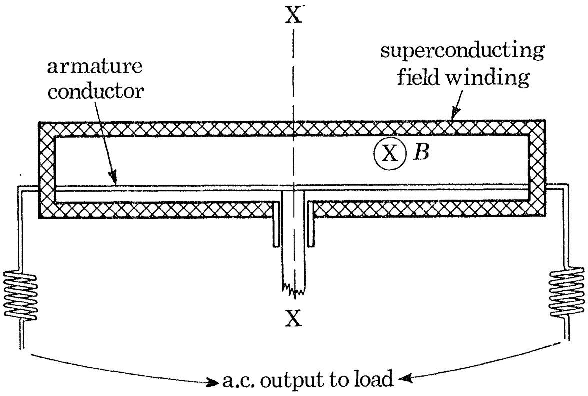

Figure 2. Longitudinal cross-section of one phase of the machine.

'Retrograde step'

The first response to the idea of a reciprocating machine is that it is somehow retrogressive: the turbine was an advance on the piston steam engine; *ipso facto*, a reversion to a reciprocating machine must be a step backwards. This reaction contains a double confusion. First, the present proposal is not necessarily to make the prime mover reciprocating; the main idea is that the electrical generator would have reciprocating motion, which is not a reversion to a discarded mode, since generators (and motors) have virtually always been rotary. Secondly, there is thought to be an inherent inefficiency in reciprocating motion and that this was the reason for the turbine ousting the old steam engine. As Sir Alfred Ewing wrote (1914), when discussing rotary alternatives to the reciprocating steam engine, it is a 'fallacious idea that a distinct mechanical advantage in respect of power [is] to be secured by avoiding the reciprocating motion of a piston'. The principal advantages of rotary machines, from the turbine to the Wankel engine, lie in the realm of thermodynamics rather than mechanics.

2. Electrical and mechanical design

The central feature of both the electrical and the mechanical design of a reciprocating electrical machine is the stroke of the armature. For a very small crank throw r ($= \frac{1}{2}$ stroke) the work forces are too great to be transmitted through the linkage; for a very large value of r, the work forces are small but the inertial forces become excessive. These effects are illustrated by the graphs in figure 3, which are derived by equating the maximum permissible force in the linkage to the sum of the work and inertial forces:

$$a\beta T = 2P/\omega r + r\omega^2 m_a + \tfrac{1}{2}r^2 a l \rho, \qquad (1)$$

where a is the cross-sectional area of the connecting rod driving one phase, β is the reciprocal of the factor of safety, T is the tensile strength of the connecting rod, P is the mean power of the machine, ω is the angular frequency, m_a is the mass of the armature, l is the length of the connecting rod, and ρ is the density of the connecting rod.

Transposing a refined version of this equation to give a explicitly

$$a = \frac{\dfrac{2P}{\omega r} + \dfrac{\omega^2 ri}{j}\left\{\dfrac{\sqrt{2}\rho_1 j}{J_c} + \dfrac{\sqrt{2}\rho_2}{\sqrt{(\omega\sigma\mu\mu_0)}} + \rho_3 d\right\}\left\{\dfrac{\sqrt{2}V}{B\omega r} + 2(n-1)\ (r+4t)\right\}\left\{1+\dfrac{1}{x}\right\}}{\alpha\beta T - \frac{1}{2}r^2\omega^2\rho(4p+x)\ (1+1/x)}, \tag{2}$$

where i is the rated r.m.s. phase current, j is the r.m.s. superficial current density in the armature superconductor, in which J_c is the critical current density in flux density B, ρ_1, ρ_2, ρ_3 are respectively the densities of the superconductor, the normal conductor, and the supporting material of the composite armature, σ is the electrical conductivity of the normal conductor in the armature, μ is the relative permeability of the normal conductor, μ_0 is the permeability of free space, d is the thickness of the armature supporting material, E is the r.m.s. phase voltage of the machine, B is the flux density at the armature conductors, n is the number of armature conductors, t is the radial thickness of the field winding, x $(= l/r)$ is the ratio of the connecting rod length to the crank throw, α is a number between 1 and $\sqrt{2}$, p is the number of toroids.

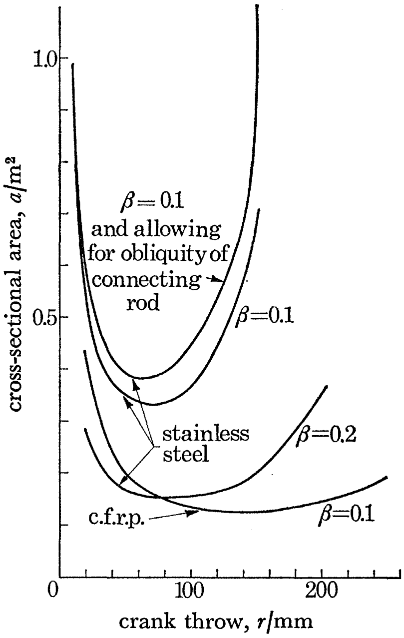

FIGURE 3. Connecting-rod cross-sectional area as a function of crank throw: one phase of a 500 MW machine.

Equation (2) is generalized to include both super- and normal conductors. Superconductors generally require a substrate of normal conductor to give electrothermal stability and overload protection. Where the armature uses only a normal conductor, the first term in the first brackets in the numerator is zero.

Equation (2) is plotted in figure 3, with r as the independent variable. For a given tensile strength, the linkage force will be proportional to the ordinates of these curves.

For an acceptable size of connecting rod it is clear that the crank throw cannot vary much from its optimum value, although some parameters allow more latitude than others. It can be seen that this would be a desirable use for a carbon-fibre reinforced plastic (c.f.r.p.).

Once the linkage material has been chosen and a factor of safety decided upon, the resultant optimum crank throw then allows the design to proceed.

The total length (L) of armature conductor is determined by the flux-cutting equation:

$$L = E/Bv, \tag{3}$$

where v is the r.m.s. velocity of the conductors relative to B ($= \omega r/\surd 2$).

The machine length is governed by the number of conductors that can be accommodated circumferentially. This number is determined by the allowable current density and the inner circumference of the toroid, which is decided by the armature stroke. The number of conductors can be increased, and the length of the machine therefore reduced, by winding a second toroid on top of the first. If the flux density is in the opposite direction to that in the first toroid, this arrangement also allows easy series connexion of the armature conductors. Figure 4 shows the essentials of a machine of this type.

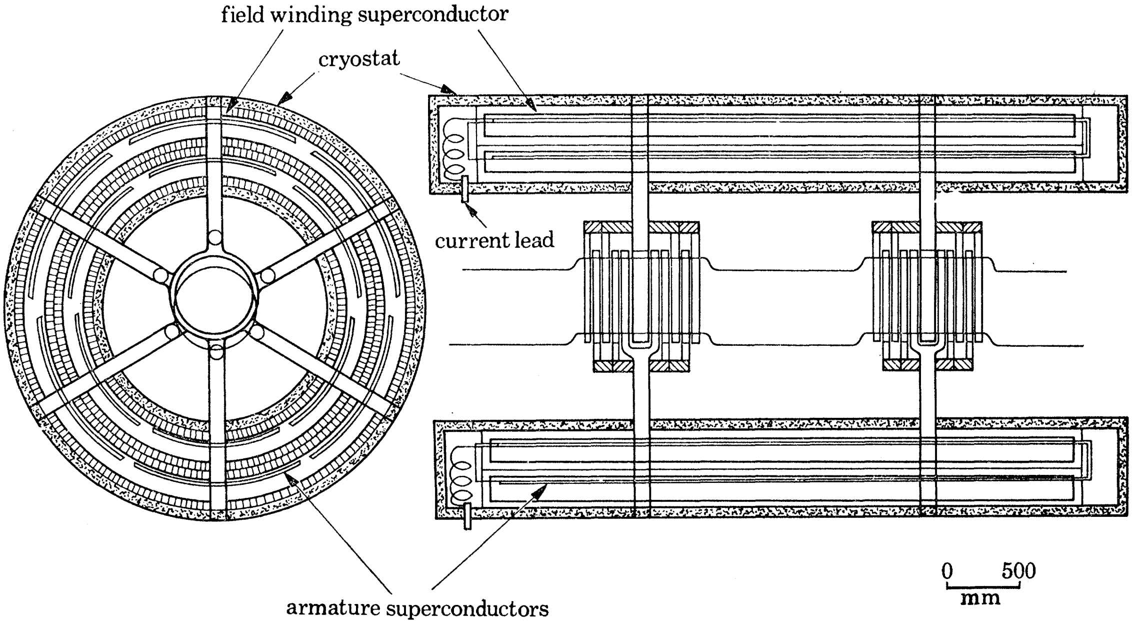

FIGURE 4. Possible arrangement of the major components in a large machine.

The six sets of armature conductors give greater rigidity than the rudimentary arrangement shown in figure 1. They also provide theoretically perfect mechanical balance and cancellation of electrical harmonics due to connecting rod obliquity. The series links joining armature conductors reside in the space outside the field winding but inside the cryostat, as do the flexible helical end connectors.

3. THE MAJOR PROBLEMS

The bulk of the problems that arise in the design of a practical superconducting reciprocating machine are mechanical. The major electrical problem is the inherently low reactance, which this machine shares with other superconducting machines.

(a) *Bearings*

Probably the most serious mechanical problem is the necessity for several additional bearings. As well as producing frictional losses, they are sources of increased unreliability. Even if the reliability of individual big-end and little-end bearings were as high as that of a journal bearing in a conventional alternator, the overall reliability of the new machine would be significantly reduced by the addition of some two dozen reciprocating bearings. At a time when reliability is a justifiably fashionable concept in central power generation, any suggestion of a lack of this quality naturally saddles a new device with a weighty handicap. But for many other applications there is no reason why the reliability of the bearings should be any more of a problem than it is in reciprocating machines generally.

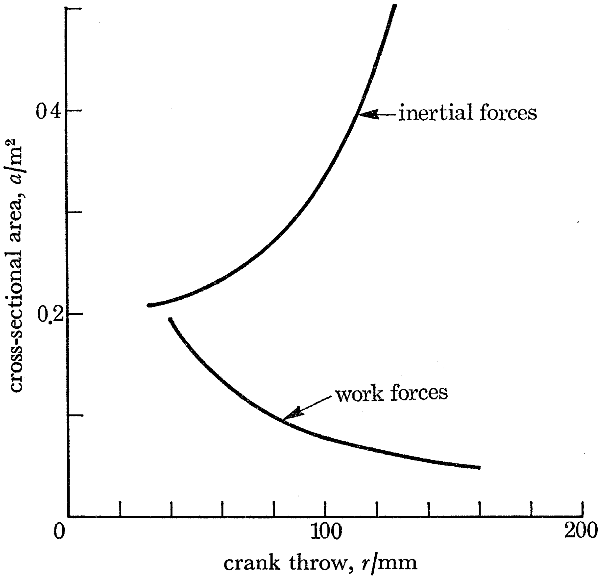

Figure 5. Connecting-rod cross-sectional area as a function of crank throw, showing separate effects of work and inertial forces: one phase of a 500 MW machine.

The frictional losses arise essentially because of the need to transmit the shaft torque to the reciprocating armature conductors. In addition, however, there are inessential forces produced by the armature accelerations. The reduction in bearing losses that complete absorption of this inertial energy would give can be seen from the curves in figure 5, where the losses would be proportional to the ordinates. This inertial energy absorption could be achieved in a number of ways, one of which would be by the use of cushioning cylinders like those used in the Willans steam engine.

(*b*) *Fatigue*

Although fatigue is a consideration in the design of rotary generators, its effects are more severe when the stresses are alternating, and so it has to be given especial attention in the design of a reciprocating machine. However, if the stresses can be kept below the endurance limit, then this problem is no worse than it is in conventional machines.

The stresses in the linkages will be of the same order as the connecting rod stress already calculated. The major stresses in the armature will be normal to sections at right angles to neutral axes. The former stresses can certainly, and the latter probably, be kept within the endurance limit.

(*c*) *Flexible armature connectors*

As mentioned earlier, the ends of the series connected armature conductors in the double toroid are taken through helical springs to fixed terminals outside the field winding but within the cryostat. Simple fatigue calculations for helical springs made from copper tube have shown in principle the feasibility of such connectors having the approximate size required for a 500 MW generator. These hollow elements could also be the flexible links for feeding helium coolant to the armature.

(*d*) *Seals*

Whether the armature employs a super- or normal conductor, it is necessary for the annular space to be evacuated to some degree in order to overcome drag losses. Sliding or flexible seals must then be provided for the push rods.

Most of the side thrust can be borne by a room temperature crosshead, thus allowing the bearing in the inner wall of the annular space to act mainly as a seal. The most promising material for the latter purpose at low temperatures is polytetrafluorethylene impregnated with carbon or a metal. Where no leakage is permissible, an artificial rubber bellows or rolling diaphragm seal can be fitted in the room temperature space. Lives of over 10000 h have been obtained from the latter type of seal by Rietdijk and his colleagues at Eindhoven (Rietdijk, van Beukering, van der Aa & Meijer 1965).

(*e*) *Machine reactance*

Because of their high field flux densities and their lack of iron magnetic circuits, superconducting a.c. machines in general tend to have low percentage reactances. The design of the reciprocating machine is such that its reactances are much lower than those of superconducting rotary machines.

The drawback of the low-reactance is the resultant poor short-circuit performance. A transient reactance of about 5% in a 500 MW machine would mean that, allowing for transformer reactance, initial fault currents would be roughly double those of an equivalent conventional machine, a situation that would certainly be intolerable with a superconducting armature. It seems therefore that a reciprocating machine would probably require the addition of external reactances or the development of a fast switch to divert the fault current.

4. LOSSES

The estimated losses in a 500 MW reciprocating alternator, together with those in an equivalent conventional machine, are set out in table 1.

TABLE 1. COMPARISON OF LOSSES

	conventional machine loss		reciprocating machine loss	
source	kW	%	kW	%
armature iron	490	6.5	0	0
armature I^2R	1325	17.6	500	15.7
eddy current	515	6.9	0	0
field	2735	36.3	100	3.1
stray	1000	13.3	0	0
windage and main bearings	1445	19.2	600	18.6
big end, etc.	0	0	1500	47.0
push rod	0	0	100	3.1
heat leak	0	0	85	2.7
field screen	0	0	300	9.4
	7510	1.5%	3185	0.6%†

† A further reduction in losses of about 700 kW could be achieved if it were possible to use c.f.r.p. in the linkage.

(*a*) *Losses due to self-field of armature*

Even in the reciprocating machine there will be losses due to the alternating current in the armature itself. As the maximum field strength that this will produce is likely to be only about 2 % of the main field strength and the losses are proportional to at least the second power of the field strength, it is evident that these losses will be very small compared with those that would be produced by rotation of the conductors within the main field. Although much less than the armature losses in a rotary machine, these self-losses are not negligible: the copper eddy-current loss or the room-temperature power required to pump the low-temperature superconductor loss comes to about 500 kW.

(*b*) *Losses in push rods*

As part of each push rod is alternately immersed in and withdrawn from the magnetic field, it will consequently suffer eddy-current losses. These losses can be reduced by laminating the push rod, although, with stainless steel, the thickness of the lamination would have to be 0.1 mm to give the loss shown in table 1. Fortunately, the laminations would have to be parallel to the plane of bending due to connecting rod forces, so that the mechanical strength would not be impaired.

C.f.r.p., having a high specific strength and Young modulus, is, in any case, an attractive material for use in the reciprocating linkage; it would also have a low eddy-current loss in the push rod situation.

(*c*) *Bearings and windage*

The bearing losses are twofold: there are the losses in the main journals, which are proportional to the crankshaft mass and can be scaled directly from those in a conventional machine; and the new losses due to the big ends, etc., which have already been discussed. The former have been estimated at 600 kW.

Windage loss in a machine with a superconducting armature would be due to oscillation in gaseous helium at a pressure of about 10 mPa and a temperature of the order of 10 K. The effective room-temperature loss would be about 1 kW. A loss of rather more than this would be produced by a normal-conductor armature oscillating in room temperature air at a pressure of about 1 kPa.

(*d*) *Field screen*

Because parts of the field winding lie in the a.c. and transient d.c. fields produced by the armature it is necessary to provide some screening around the field winding. The main fields to be excluded are the second harmonic due to asymmetrical running of the machine, and the d.c. and a.c. transients resulting from sudden short circuits.

In the case of the machine with a superconducting armature the screen, too, must be superconducting, since the annular space in which it resides is at, say, 10 K and the losses in a normal screen at this temperature would be too high for economic refrigeration. If a normal armature working at room temperature is used, the screen would probably be a normal conductor.

In either case, the screen also acts as a damper winding; and it suffers a steady loss due to flux reversals arising from the fundamental armature current. It turns out that the latter loss in a room-temperature copper screen is about the same as the effective room temperature loss in a superconducting screen having a critical current density of 10^{10} A m^{-2}.

(*e*) *Thermal leakage*

The heat due to thermal leakage that has to be pumped away at low temperature comes from three sources: heat transfer through the cryo-jacket, conduction along the mechanical supports, and conduction through the electrical leads, the latter being accompanied by heat generation in the leads themselves.

If the cryojacket can consist mainly of superinsulation, which can have an effective thermal conductivity as low as 10^{-4} W m^{-1} K^{-1} (Eigenbrod, Long & Notaro 1969), the heat loss from this cause in a 500 MW machine will be in the region of 50 W for 30 mm thick insulation without a radiation shield at intermediate temperature. Such a cryojacket cannot sustain compression, and so the field winding has to be supported by circular bands attached to thin, high-tensile tangential spokes that penetrate the superinsulation and are attached to external supports.

If the supporting spokes are well insulated, the thermal leakage through them will be very small over the practical lengths required.

Although the loss in an optimized current lead is only about 1.2 mW A^{-1}, such a figure is usually of interest in terms of liquid helium supply, generally under laboratory conditions. When the thermal cost of refrigeration is taken into account, this figure should be multiplied by about 2.3 (Colyer 1967), giving a loss of 2.8 mW A^{-1}. For the leads from the three-phase superconducting armature of a 500 MW machine a loss of about 165 W at 4.2 K would be incurred; but the loss due to the field-winding leads would be only about 15 W.

(*f*) *Total losses*

It is seen that, despite the peculiar losses introduced by the new machine, the net loss is only about half the total loss in an equivalent conventional alternator. The capitalized value of this saving represents a large fraction of the total cost of a conventional machine.

5. MASS

The savings in mass that might be achieved in a 500 MW reciprocating machine can be seen from table 2, which analyses the mass of a typical conventional alternator and the estimated mass of a reciprocator.

TABLE 2. COMPARISON OF MASSES OF 500 MW MACHINES

component	conventional machine tonnes	reciprocating machine tonnes
armature iron	180	0
armature copper	10	10
field iron	70	0
field copper	10	25†
frame, etc.	230	155
crankshaft	0	10
total	500	200

† Includes superconductor, support material and cryostat.

6. Prime mover

Although it is possible to drive the reciprocating generator from a turbine, by means of cranks and connecting rods, the concomitant bearing losses are appreciable; but with a reciprocating drive they would be negligible. To revert to a reciprocating steam engine would be to exchange one inefficiency for another. Recent work (Meijer 1970) on the Stirling gas engine, however, has shown that the efficiency of this reciprocating machine can be comparable with that of modern steam turbines, i.e. about 40 %. This is an area where there might be room for some long-term development work directed towards central power generation.

7. Model generator

The essential feasibility of the proposed machine has been practically demonstrated by the successful running of a small alternator producing a few hundred watts. This consisted of a pair of superconducting armatures oscillating in horizontal opposition in a pair of superconducting solenoids. The design was developed from the theory outlined in this paper and elsewhere. A photograph of a room-temperature model of this generator is shown in figure 6, plate 9.

8. Conclusions

The basic design principles for a superconducting reciprocating generator or motor have been established. Although this machine overcomes some of the key difficulties of rotary machines, its feasibility for large-scale generation is naturally at this stage still very much open to question. The major stumbling block, bearing reliability, could be eliminated if a reciprocating prime mover were to replace the steam turbine. Even with a rotary drive, however, the reduced mass, size and losses might well make these machines of interest in applications outside central power generation.

The work was carried out at Central Electricity Research Laboratories and is published by permission of the Central Electricity Generating Board.

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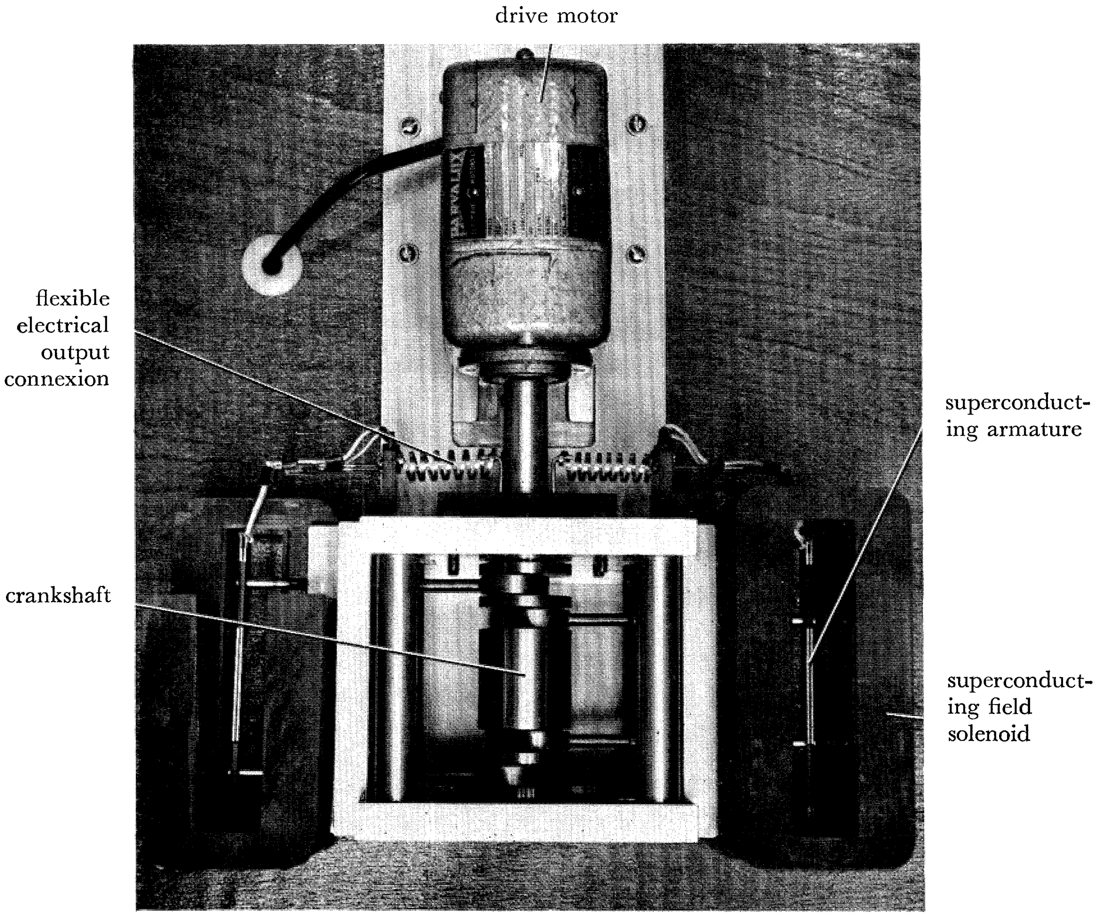
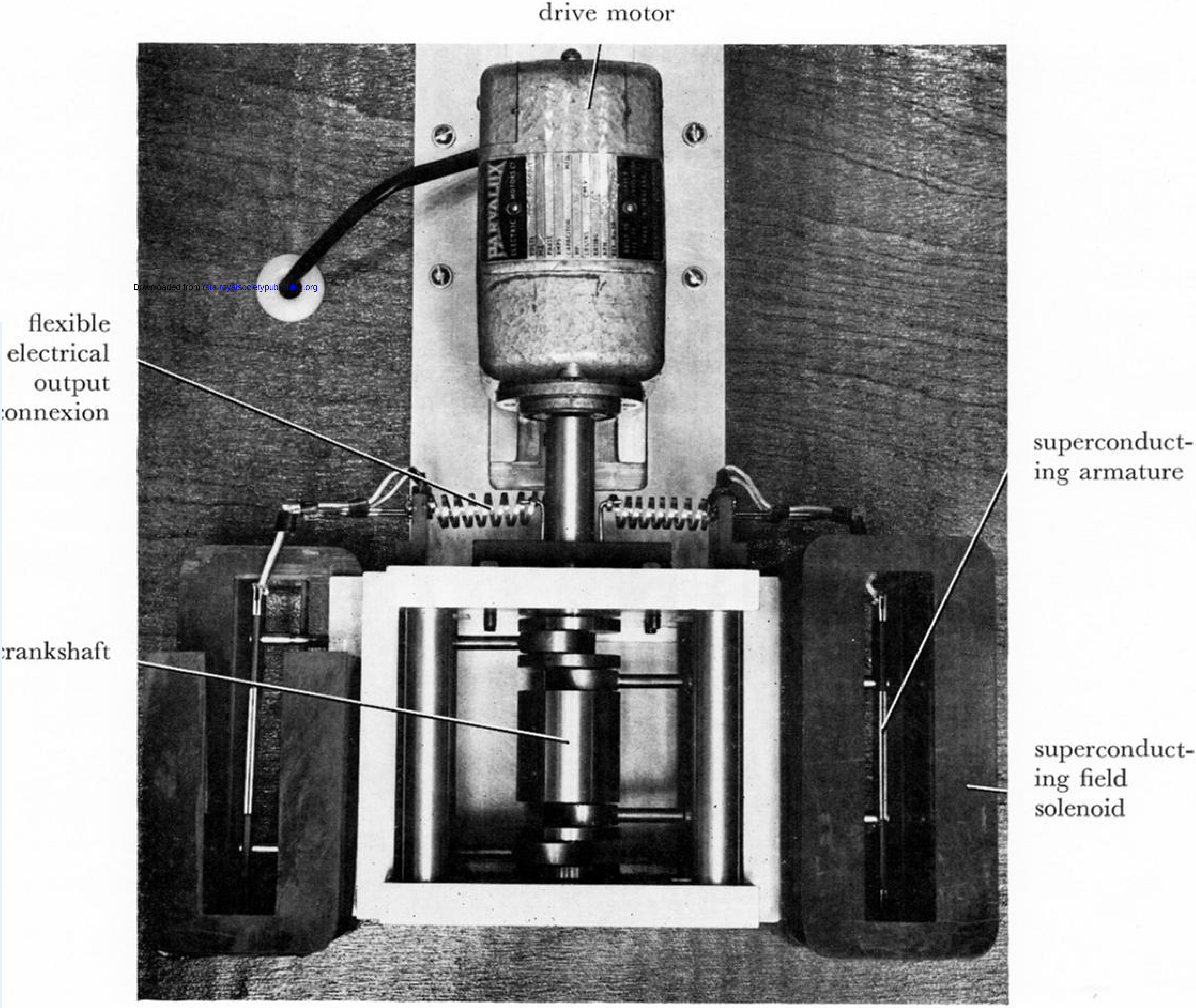


FIGURE 6. Model of the experimental generator.



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