EP-RR 8

NOTES ON SPEED BALANCE CONTROLS ON THE CANBERRA HOMOPOLAR GENERATOR

T. W. BRADY

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SUMMARY

The two 40-ton rotors of the Canberra Homopolar Generator, which are independently mounted, tend to run at different speeds for various reasons.

Satisfactory operation of the generator demands that the speed of the two rotors be synchronized, or balanced. This paper shows how this aim was achieved by a simple but effective servo of the "ON-OFF" type. This servo employs a contactor-clutch arrangement of simple design, which has an unusual phase advance characteristic.

1. INTRODUCTION

This paper describes a method of ensuring that the rotors of the Canberra Homopolar Generator run at equal or near equal speeds. This is referred to as speed balancing.

To understand the mechanism of the control it is necessary to be familiar to some extent with the Homopolar Generator itself. A list of references to the machine is given at the end of this paper, and a brief description follows.

2. DESCRIPTION OF THE MACHINE

Reference is made to Figure 1, which is a photograph of the machine, and to Figure 2 which is a basic electrical diagram.

Briefly, the machine is an energy storage device. Two large rotors supported by oil and air bearings are poised in a magnetic field which is produced by a large cyclotron-type magnet. These rotors are run up to speed in opposite directions by a motoring current supplied from a grid-controlled mercury arc rectifier set. Brushes are then pneumatically applied, and a pulse of current is drawn from the generator, the rotors of which slow down as energy is taken. Each rotor is 140 in. in diameter, and consists of two discs fastened together as shown in the diagram; such a rotor weighs about 40 tons. Maximum speed is set at about 900 rpm, and at this speed the energy stored in the system is 500 megajoules. Peak current which may be drawn from the generator is about 1.6 megamps. This last limitation is determined mainly by the brushes[6] which are applied to take a pulse.

Although the machine is based on a simple principle, its construction has posed many problems which are of great interest. This paper, however, is not concerned with the homopolar generator as such; nevertheless it might be mentioned that this machine is by far the largest of its type in the world, and it forms a unique form of energy storage. Originally designed[1, 2] for a proton synchrotron magnet drive, it is at present being used to supply current for a number of experiments, including a high field (Bitter) magnet for work on solid state physics.

A user of the homopolar generator may enjoy a wide variety of current pulses even for a fixed load, by adjusting the strength of the generator field, by choosing the speed at which to take the pulse, and by programming the electrolytic switch; this switch can absorb an appreciable part, or even the whole, of the machine energy. Pulses taken for useful work are rarely taken below 100 rpm, at least in experiments carried out so far.

It takes some time to achieve rotor speeds of several hundred rpm, since the maximum current which may be taken from the mercury arc rectifier set is limited to a maximum of 3,300 amps. At full field strength (17,000 gauss) this means an acceleration of about 70 rpm/minute.

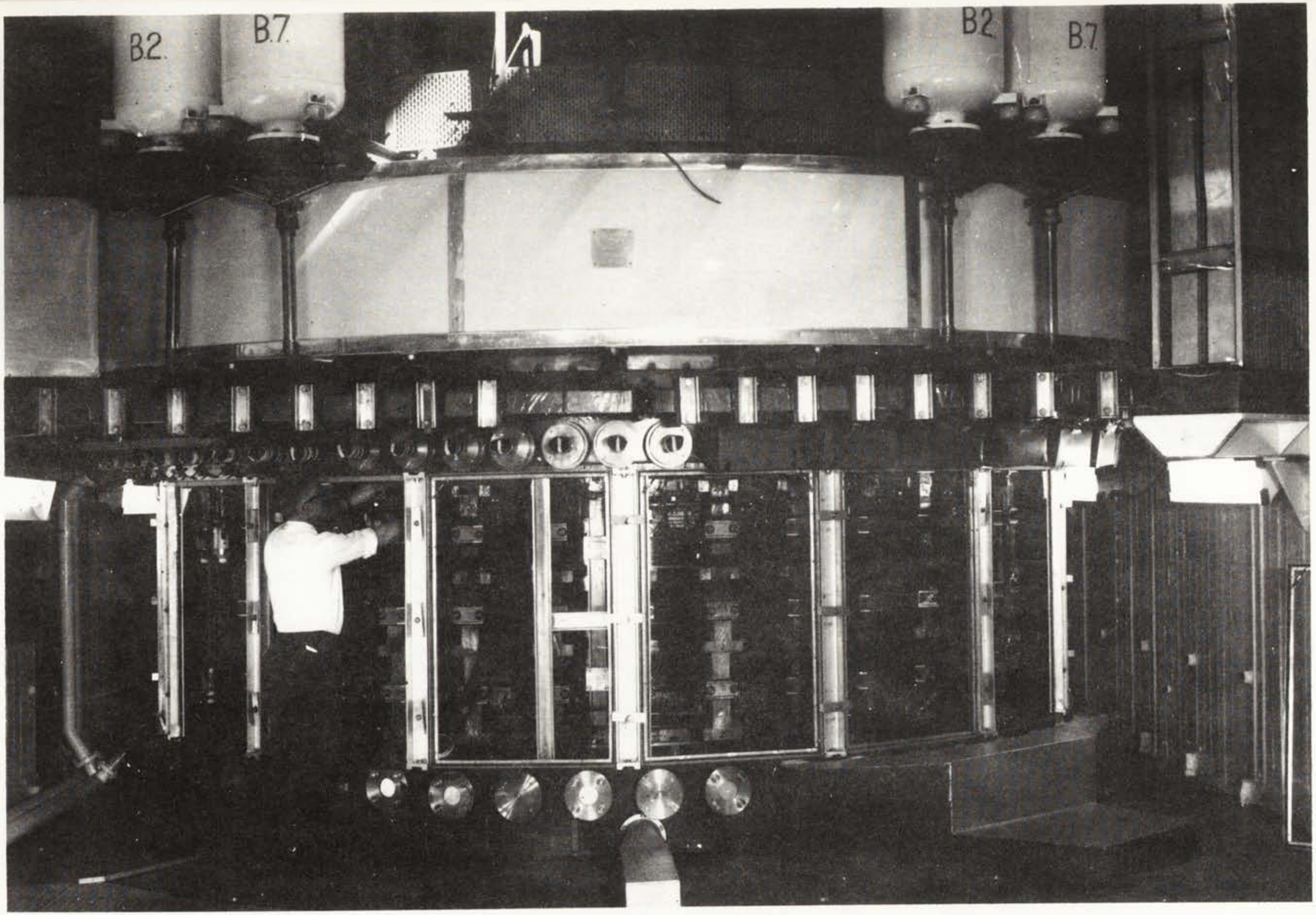


Figure 1. General view of the Homopolar Generator. The rotors can be seen behind the busbar risers. The tanks at the top of the picture (B2, B7) supply air to the pulse brushes.

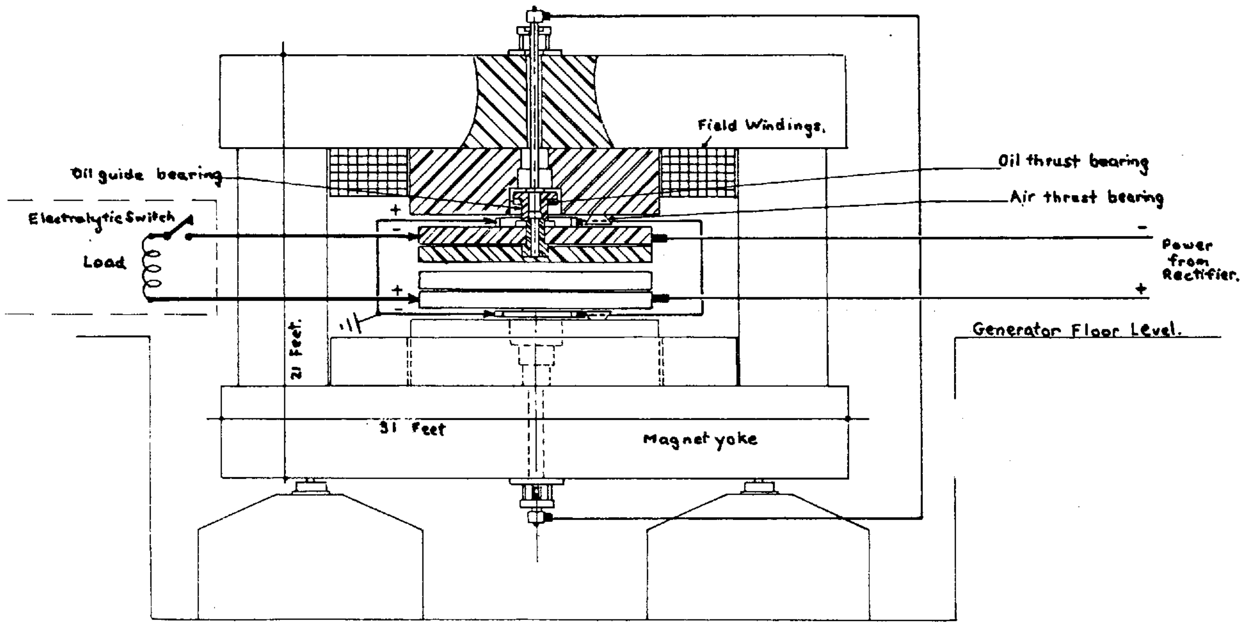


Figure 2. Basic electrical diagram of the Homopolar Generator. Pulse brushes are shown by arrows. The field of the generator is reversible.

It is relevant to mention one other fact which has some application to the text which follows. The mercury arc rectifier can accept regenerative braking current from the generator; this current is formed by the usual means of reversing the generator field at speed and adjusting the phase control of the rectifier. This is a powerful form of braking if a pulse cannot be taken for some reason. It is of course important that speed balance be maintained on decrease of speed as well as increase, as the logic of an experiment may dictate a sequence of pulses at various speeds.

During running, differences in friction, windage, local field strength all cause the rotors to run at a slightly different speed when pulse speed is attained. Then, as the pulse current is the same for both rotors, this speed difference will be perpetuated at the speed existing at the end of the pulse. As the rotors are run up to speed again, the speed difference becomes larger, because a new increment is added.

Figures may perhaps make the situation a little clearer. If in a sequence of pulses the top rotor is running 10 rpm fast at a pulse speed of 600 rpm, then, after the pulse is taken and the bottom rotor is say at 220 rpm, the top rotor will still be running fast at about 230 rpm. As the rotors are run up to speed again the factors which caused the top rotor to gain still exist, and at pulse speed the top rotor will now be about 20 rpm faster. The process is cumulative, and the speed difference would soon become so large that successful operation would become impossible; it is obvious that some mechanism must be provided to keep the rotor speeds as near equal as possible.

It must be mentioned that the specifications for such a mechanism can be markedly different from accepted speed controls. Pulses are rarely taken below 100 rpm as mentioned previously, and as it usually takes many minutes to run up from standstill, the control may act in a fairly leisurely manner. This is assuming that the speed difference will have disappeared before it is desired to take a pulse. In other words, synchronism at all times is not essential, and in fact if so desired, would consume large amounts of power.

3. THE SPEED BALANCE MECHANISM

As a measure of the correction required to maintain synchronism or speed balance, a resistor was inserted into the main generator circuit as shown in Figure 3. This resistance could be switched by contactor across either rotor as desired. The rule is that for both motoring and regenerating the resistance must be switched across the rotor that is running fast.

For some time after a suitable value of resistance was found, speed balance was obtained by the tedious process of manually switching the resistance. Balance, or lack of it, was detected by fitting a synchro to each rotor and connecting each to a differential synchro ("hunter"). It is possible to detect lack of balance by observing the digital speed indicator for each rotor, but these are complex instruments, and in accordance

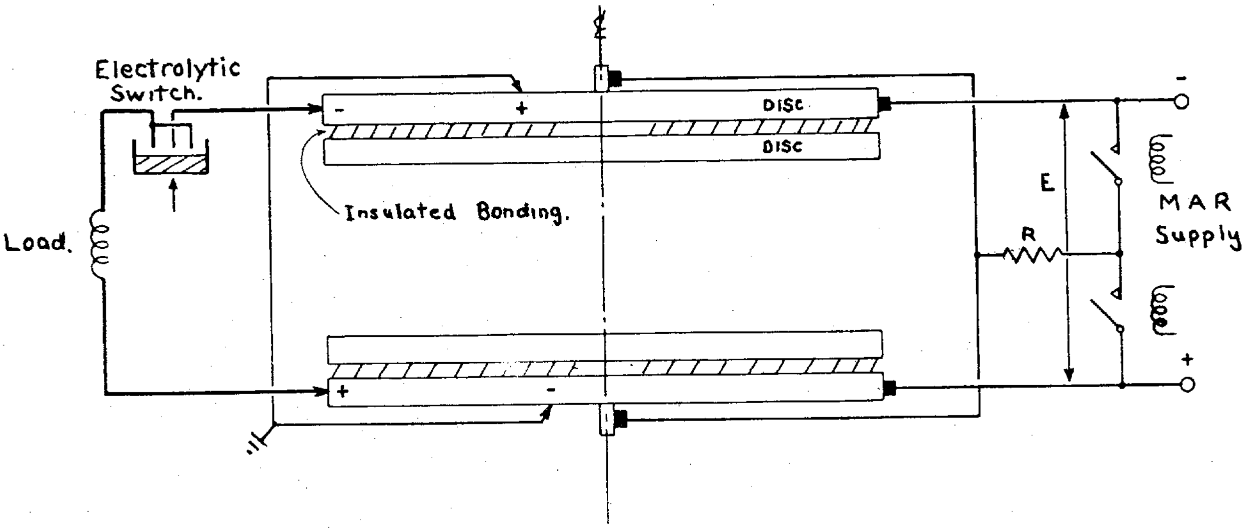


Figure 3. Simplified electrical diagram showing method of connecting and switching resistor.

with accepted control technique it was felt that the system ought to have its own detection system. It would also be difficult to extract the required information from a digital system, compared with the hunter synchro.

After some time on manual switching it was decided to make the control automatic, and this paper now describes how this was achieved.

Figure 4 is a simplified version of Figure 3. It can be shown quite easily that the braking torque exerted on a rotor when the resistance is thrown across it is approximately

$$K \, . \, \frac{E}{R.}$$

where K. is a constant. For a machine with the parameters of the homopolar generator

$$T = 1.\frac{1\,E}{R} \qquad \text{ft. lbs.} \qquad (1)$$

These figures are given for full generator field conditions. It should be noted that this torque T is a deviation of torque from the steady state value. In other words deviations of the machine from steady state torques and speeds are treated in the arguments which follow.

A block diagram of the complete servo loop is shown in Figure 5 with the correction applied to the bottom rotor. It is a mathematical convenience to include one rotor only in the loop. Drawings of the contactor-clutch device are shown in Figure 6.

In Figure 5 for mathematical convenience, the contactor-clutch device is divided into two parts, namely the converter and contactor-clutch proper, device. The converter is in fact the pointer attached to the hunter shaft; the contactor-clutch proper represents the rest of the device and warrants some description.

When the pointer attached to the hunter synchro shaft reaches a limit, it exerts pressure on the contact. This contact closes and pilots the contactor (Figure 3 or 4) applying appropriate correcting action. The resistance of the contact however causes the so-called free wheeling mechanism to slip at a low value of torque. This continues until correction of this type is no longer needed. Pressure then ceases on the contact, the free wheel--or clutch--becomes in effect solid and the pointer reverses into the deadband.

It was surprising at first--at least to the author--that this device has the unexpected property of giving a phase advance which theoretically can be as large as 90°.

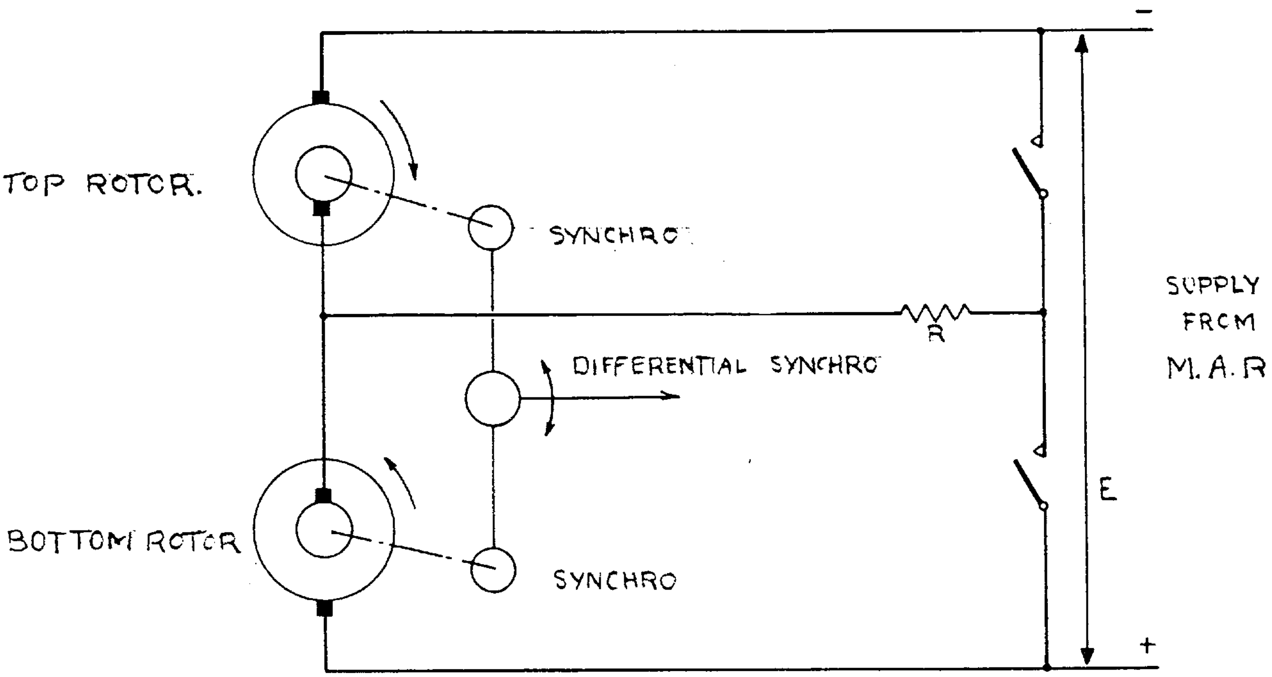


Figure 4. Diagram illustrating connection of synchros to rotors.

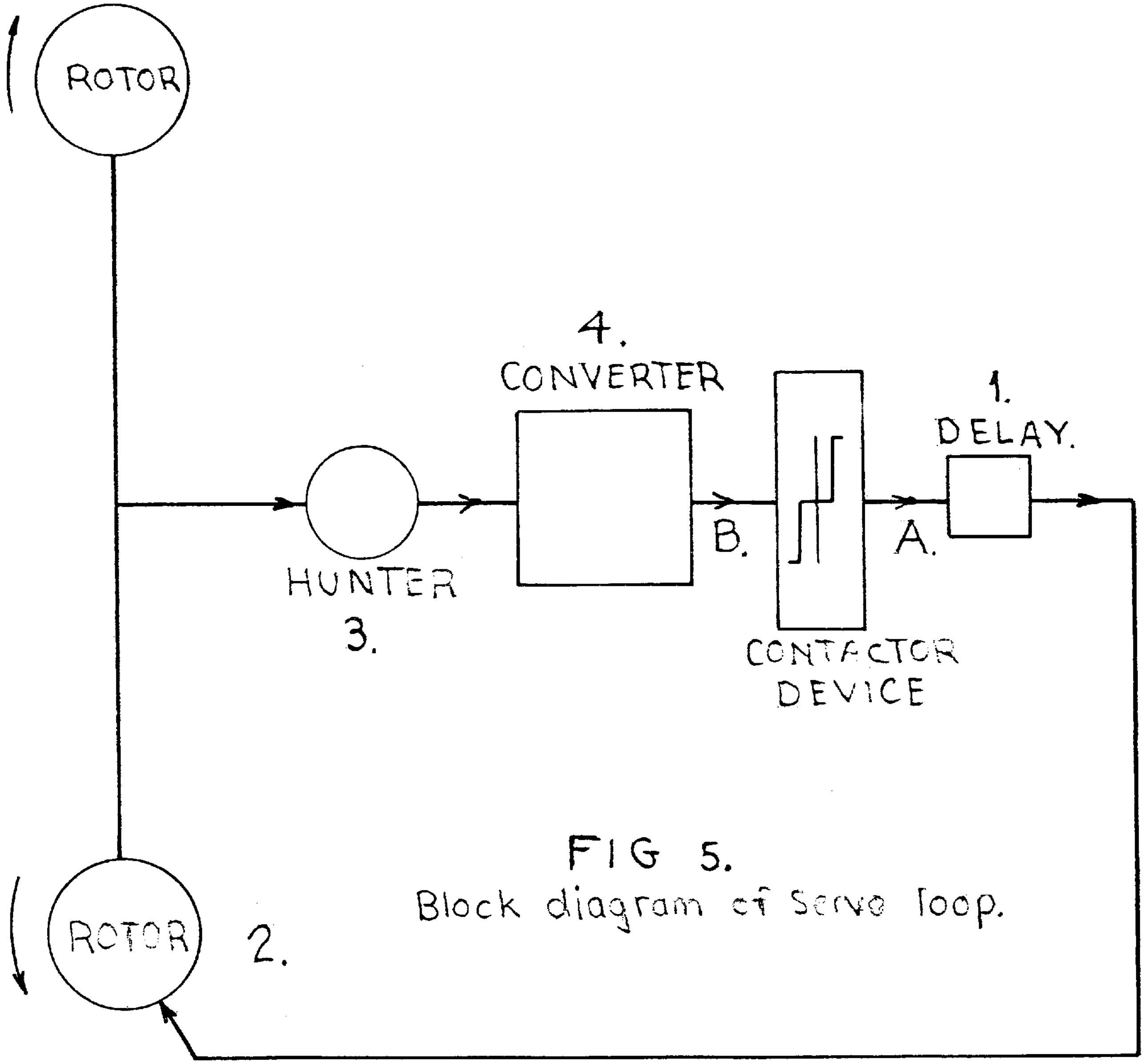
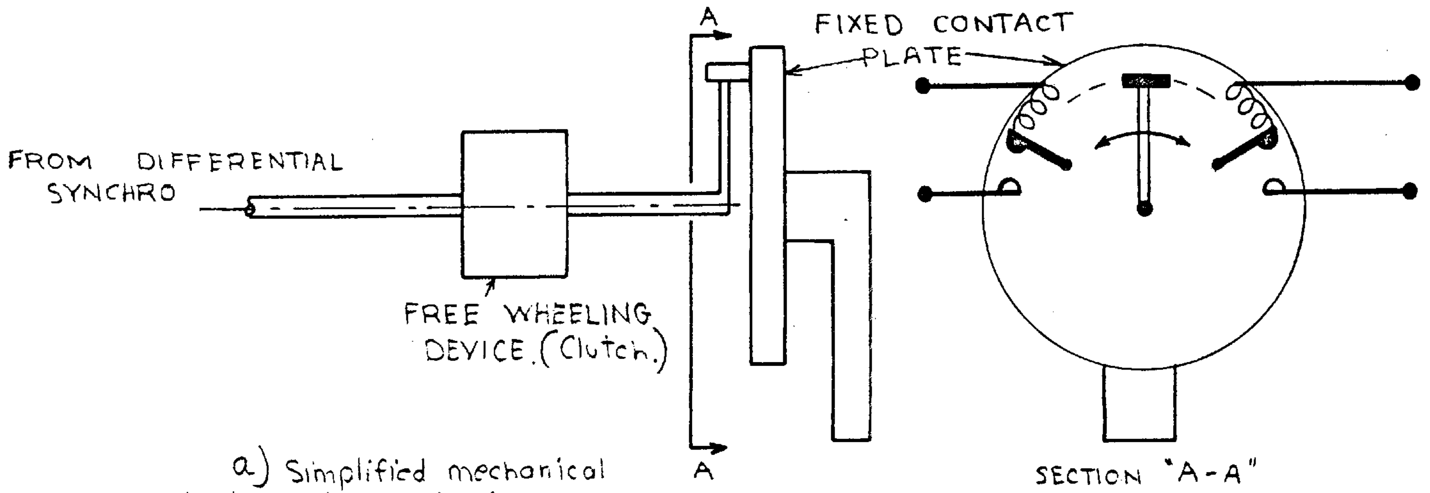
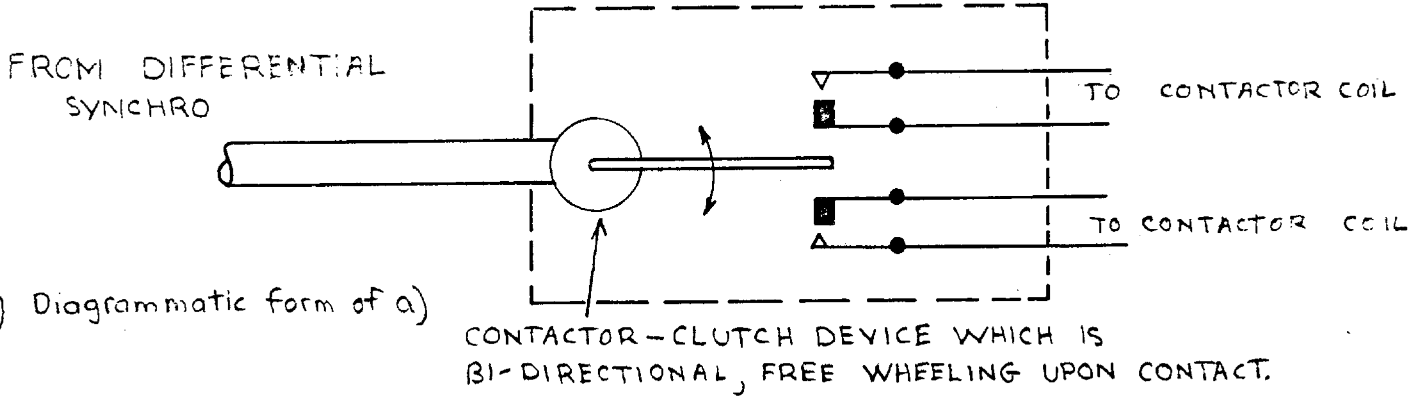


Figure 5. Block diagram of servo loop.



a) Simplified mechanical contactor-clutch device.



b) Diagrammatic form of a)

Figure 6. (a) Simplified mechanical contactor-clutch device.
(b) Diagrammatic form of (a).

This is easily seen if large ratios of driving wave amplitude to deadband are considered (Figure 7a Case Three). The amplitude and phase plot of the contactor is shown in Figure 7b. It will be seen later how this property of phase advance stabilizes the closed loop.

First, the loop from A to B in that direction will be examined. The treatment is, of course, the usual one which appears in books on servo-mechanisms.[8] All units are British.

1. Delay

This is the transport delay[8] of the contactors switching the correcting resistor and is given by

$$e^{-s\tau}$$

where τ is estimated to be about 0.1 second: the delay is therefore

$$e^{-0.1s.} \qquad \left[\text{no units}\right.$$

2. Rotor

This transfer function is given by

$$\frac{\omega\,(s)}{T\ (s)} = \frac{g}{Ps}$$

where ω = angular velocity of deviation from steady state
T = torque deviation
g = accel. due to gravity
P = polar moment of inertia of rotor

Inserting values,

$$\frac{\omega\,(s)}{T\ (s)} = \frac{32.2}{1,540,000s}$$

$$= \frac{.0000209}{s.} \qquad \left[\text{units } \frac{\text{radians}}{\text{ft. lbs. secs}}\right.$$

3. Hunter

Transfer function is 1 say $\qquad \left[\text{no units}\right.$

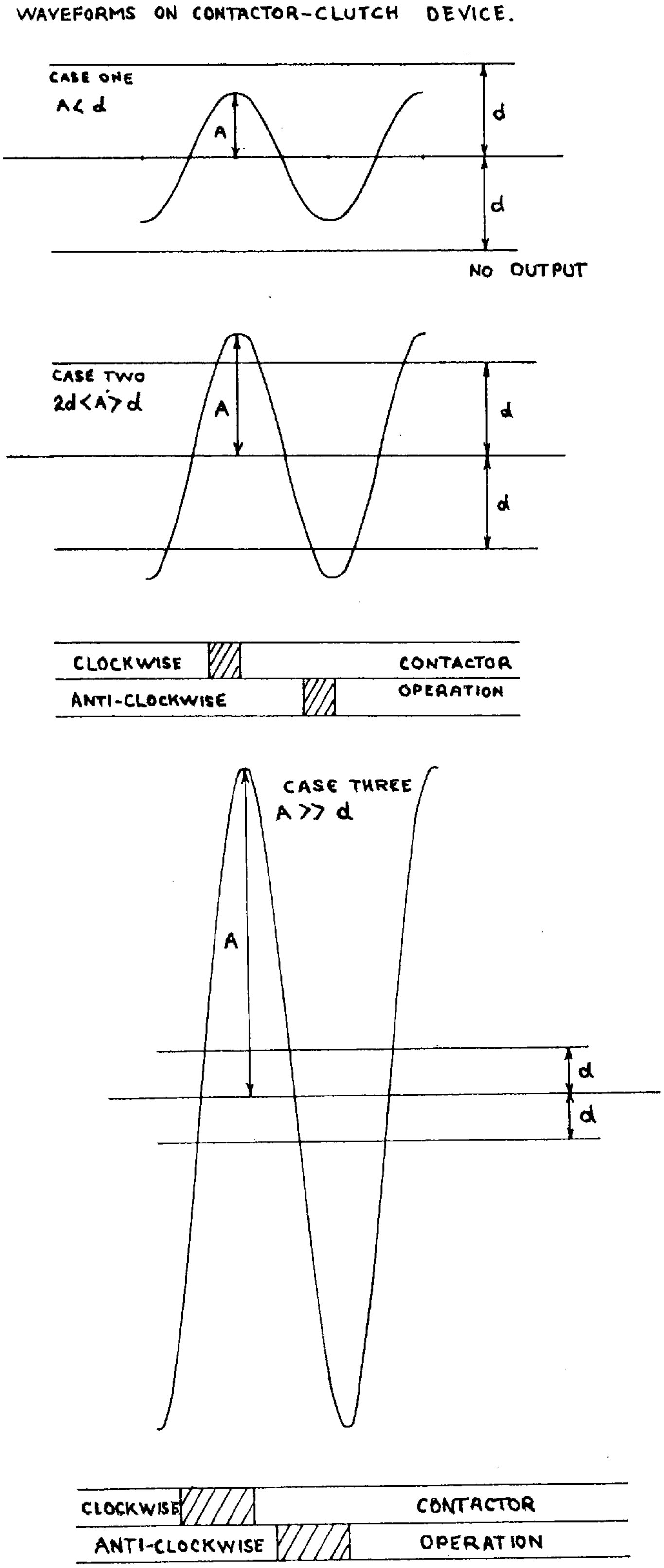
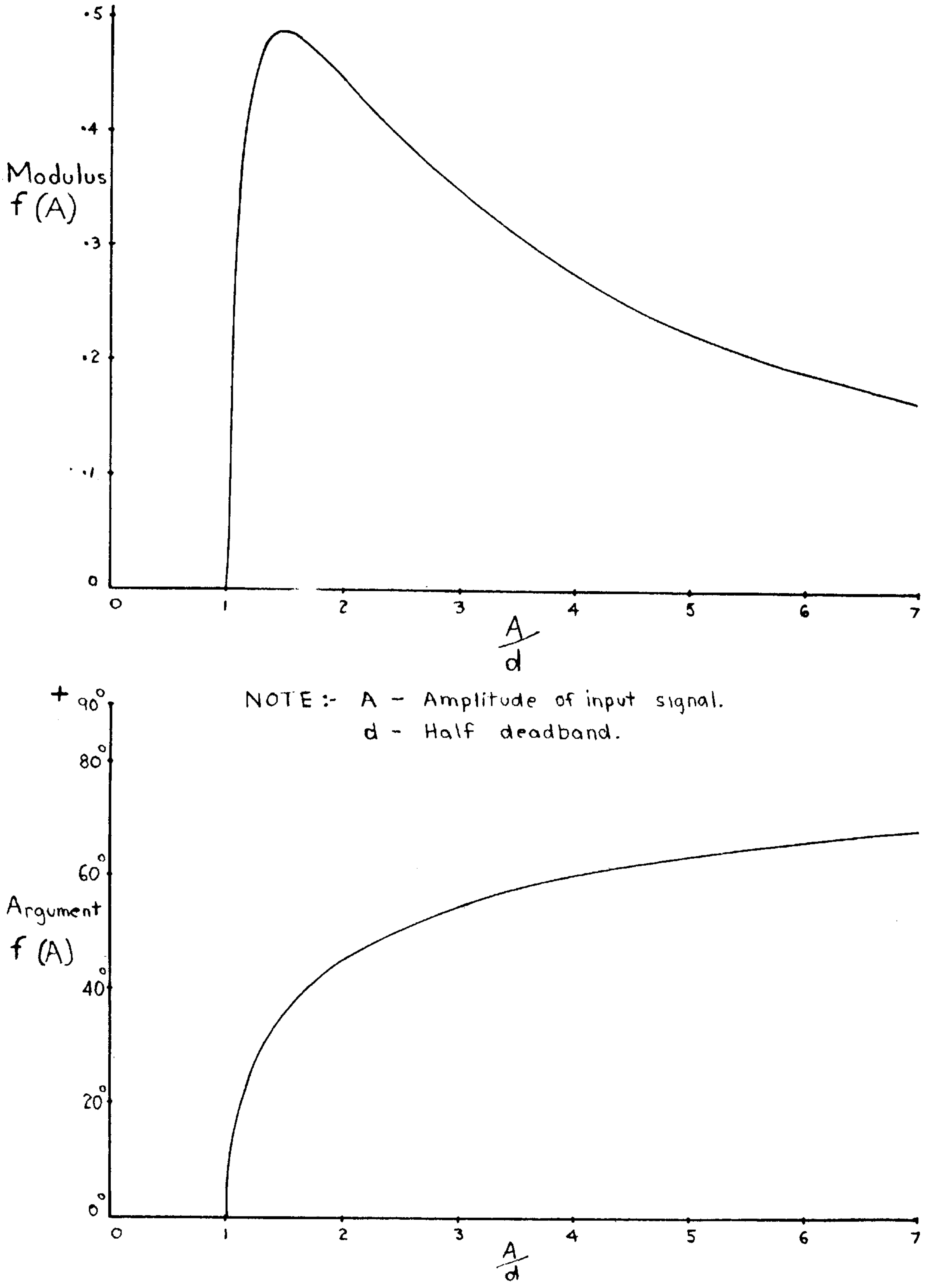


Figure 7 (a). Waveforms in contactor-clutch operation.



NOTE :- A - Amplitude of input signal.
d - Half deadband.

Figure 7 (b). Amplitude and phase plot of contactor-clutch operation.

4. Converter

This is just a pointer on a shaft and therefore if d is the distance the tip moves, $d = r\Theta$, or in transfer function form,

$$d(s) = r \frac{\omega(s)}{s.}$$

If $r = 2$ in. (Figure 6)

$$\frac{d(s)}{\omega(s)} = \frac{2}{s} \qquad \left[\text{units}\ \frac{\text{ins. secs}}{\text{radians}}\right.$$

The complete transfer function A-B can now be written

$$e^{-0.1s} \times \frac{.0000209}{s} \times \frac{2}{s} \qquad \left[\text{units}\ \frac{\text{ins.}}{\text{ft. lbs.}}\right.$$

writing $j\omega$ for s (for steady state frequency response)

$$= -e^{-0.1j\omega} \times \frac{.0000418}{\omega^2}$$

inverting this $= \dfrac{-\omega^2 e^{0.1j\omega}}{.0000418}$ (2)

The modulus of (2)

$$= \frac{\omega^2}{.0000418} \qquad (3)$$

the argument of (2) $= \pi + 0.1\omega$ (4)

The contactor B-A is now considered:

this characteristic is given by

$$\frac{T}{d} f(a) \qquad \left[\text{units}\ \frac{\text{ft. lbs.}}{\text{ins.}}\right.$$

where T = runaway (deviation) torque given in equation (1), page 6.
d = half deadband on contactor-clutch
f (A) = complex function of amplitude for contactor-clutch[1]

substituting expression for T from (1) and if d = 1/2 in. say, the expression now is

$$960\ f\ (A) \tag{5}$$

The characteristics of both (2) and (5) above are plotted on polar graph paper, Figure 8. It appears that for the conditions stated the closed loop is stable, as the describing function of the contactor is on the left as the other plot is traversed in the direction of increasing frequency. This criterion is well known.[9]

It is possible however that the system could be underdamped.

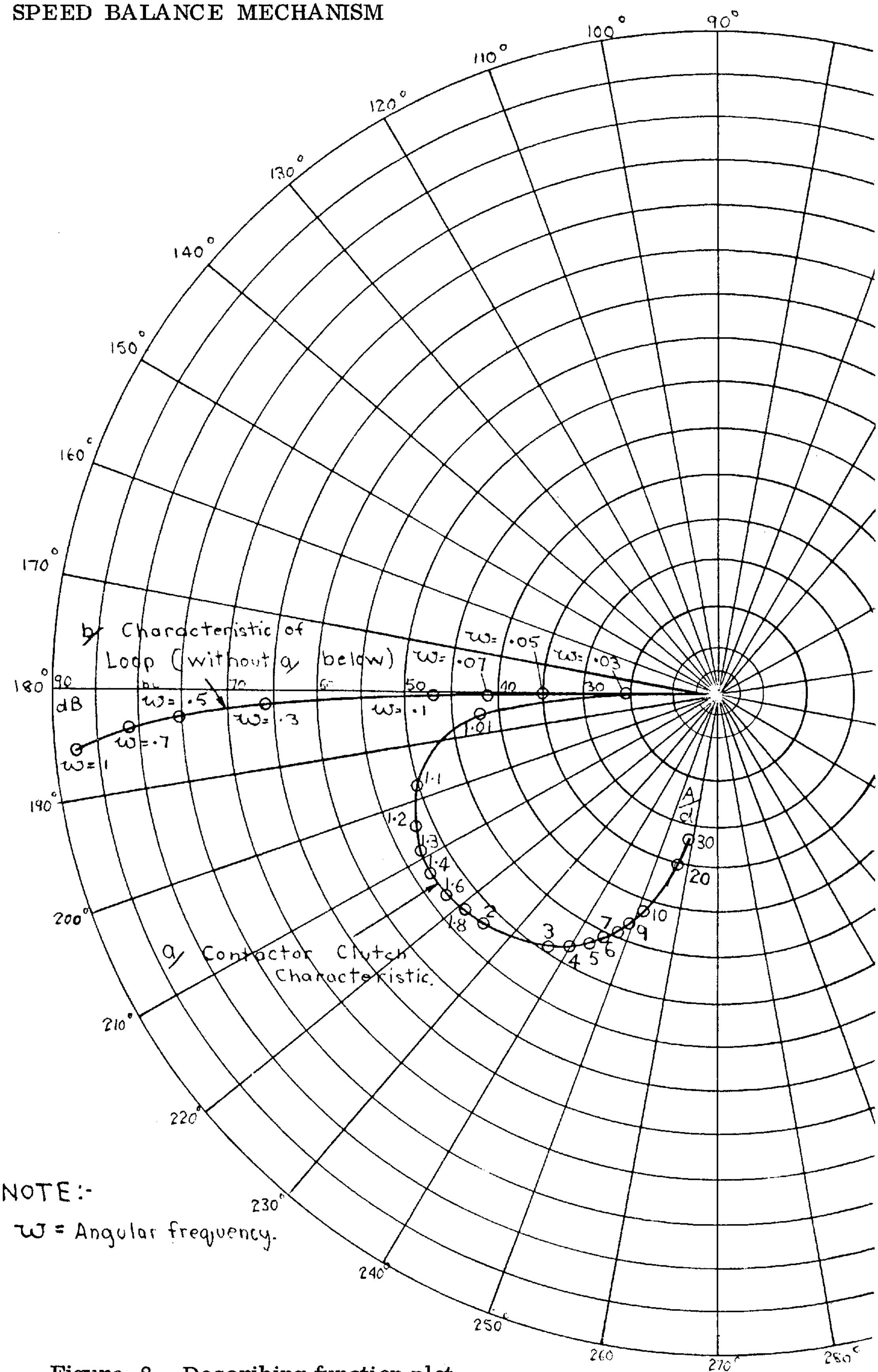
In all the previous mathematical arguments several simplifications have been made. For example, the transfer characteristic of the hunter synchro has been simplified, and dynamic lag in the contactors has been ignored. There are other simplifications, but they can safely be accepted when generator parameters are considered.

4. PERFORMANCE

The automatic control described has been installed and has worked very well over a period of months. In practice, a speed difference soon develops when the rotors depart from standstill. This will persist for some time on run up, until the control starts to "bite", when both rotors are gradually brought into synchronism. Once synchronism has been achieved, speed difference will not generally exceed 0.6 rpm even for a prolonged programme of pulses; this is so even for a wide variety of speeds and field strengths. The only time a prolonged speed difference can occur at speeds over 100 rpm say, is when for some reason the generator field is turned off and the machine coasts. Different friction and windage soon cause the speeds to diverge, but once field is restored the control will gradually regain command.

The describing function plot of the contactor in Figure 8 was calculated for maximum field and speed conditions. Any diminution of these quantities would cause the describing function to move to the right. Fears that in fact the system may be underdamped have not been sustained, in that excessive operation of the main contactors does not occur. While the theory undoubtedly shows underdamping, contactor operation occurs only about once every three minutes or so; this is not a very arduous duty.

It has been suggested that a resistance could be permanently fixed across one rotor causing an unbalance. Correction would then have to be applied to the other rotor only. While this is feasible, the fixed resistance would have to exert a considerable and probably intolerable drag. This is because in the uncorrected condition it is impossible to say which rotor will run fast on a particular day. Cross-over sometimes occurs on run up; one rotor may run fast up to say 75 rpm and then the other rotor will overtake it. On another day this situation may be reversed.



NOTE:-
ω = Angular frequency.

Figure 8. Describing function plot.

One other practical point may be of interest. In practice it was found that a small hysteresis was necessary in the contactor-clutch to prevent the large contactors chattering when the correction signal hovered about the edge of the deadband. This is not unusual in servos of the "ON-OFF" type. Hysteresis affects the characteristics of Figure 7b and the describing function plot in Figure 8, but the alteration is not shown plotted.

5. IMPROVEMENTS, FUTURE WORK

Some alternative schemes have been suggested for speed balancing, including among other things, injection of d.c. currents into the rotors. The aim of these schemes is mainly to produce a contactor-less servo.

While this aim is attractive, the present scheme has the great advantage of being extremely simple, and so maintenance presents almost no problem. It appears though, that it would be useful to vary the controlling resistance throughout the speed range so that it changes from one value to a higher value as the speed is increased. This change need not be smooth, and it could be a simple change from one value to another.

By this means speed balance could be achieved at lower speeds; this is desirable if these speeds are ever to be used. Signals are made to appear when rotor speeds reach 100 rpm; these were introduced for other reasons than the servo, but could well be used to switch the resistance to a higher value as the machine speeds up.

This improvement could easily be made without detracting from the simplicity of the servo as it now stands.

6. CONCLUSION

The speed balance control described in this paper is very simple for the task it performs. The nature and scale of the problem seemed at the beginning to indicate that some powerful means would be needed to achieve balance and maintain it under a wide range of conditions, and it still seems remarkable to those concerned with the problem that it can be done so simply.

It is interesting to spend a little time on trying to devise a contactor or deadband mechanism which would duplicate the performance of the contactor-clutch described in this paper, but accept electrical instead of position signals. First thoughts indicate that any circuit which is likely to do this seems more complicated than the usual simple and widely used phase-advance circuit, and so would not be worth constructing, but this may not be so. It is, of course, possible that the contactor-clutch device as it stands may be of some use in other servos. Some time may well be spent on profitable speculation.

7. ACKNOWLEDGEMENTS

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