ELECTRICAL GENERATION SYSTEMS
SUITABLE FOR USE
IN WAVE POWER SCHEMES

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ABSTRACT

This note describes studies made on electrical generation systems which may be suitable for wave power stations. Two complementary systems are described and the results of testing are presented. Computer simulations of each system which were used both at the design stage and during testing are also described.

ELECTRICAL GENERATION SYSTEMS SUITABLE FOR USE IN WAVE POWER SCHEMES

1. INTRODUCTION

There are currently five devices under study for extracting power from waves, namely the Cockerell pontoon, the Salter duck, the Masuda bell, the Russell rectifier and the French inflatable membrane. Although this project has been specifically concerned with the Salter duck, the electric system designed is applicable to all methods of wave power extraction.

One major problem in wave power development is the design of an electrical system for extracting power from a rotating shaft whose speed and torque is determined by the time-varying energy spectrum of the sea in which incident energy levels can range over a factor of roughly six times.

Conventional synchronous generation is unlikely to be viable under these conditions and use of d.c. machines is limited to approximately 1 kV because of the commutator. Such voltages are not attractive for large power generation. Asynchronous systems have thus been considered:

(i) Induction generators feeding a common bus bar with local provision of magnetising current.

(ii) Synchronous machines each with a controlled rectifier feeding a common bus bar.

2. BACKGROUND

The Salter concept consists of a tubular backbone some 500 metres long, around which can rotate a number of shaped segments known as ducks. The combination of ducks and backbone is called a string. It

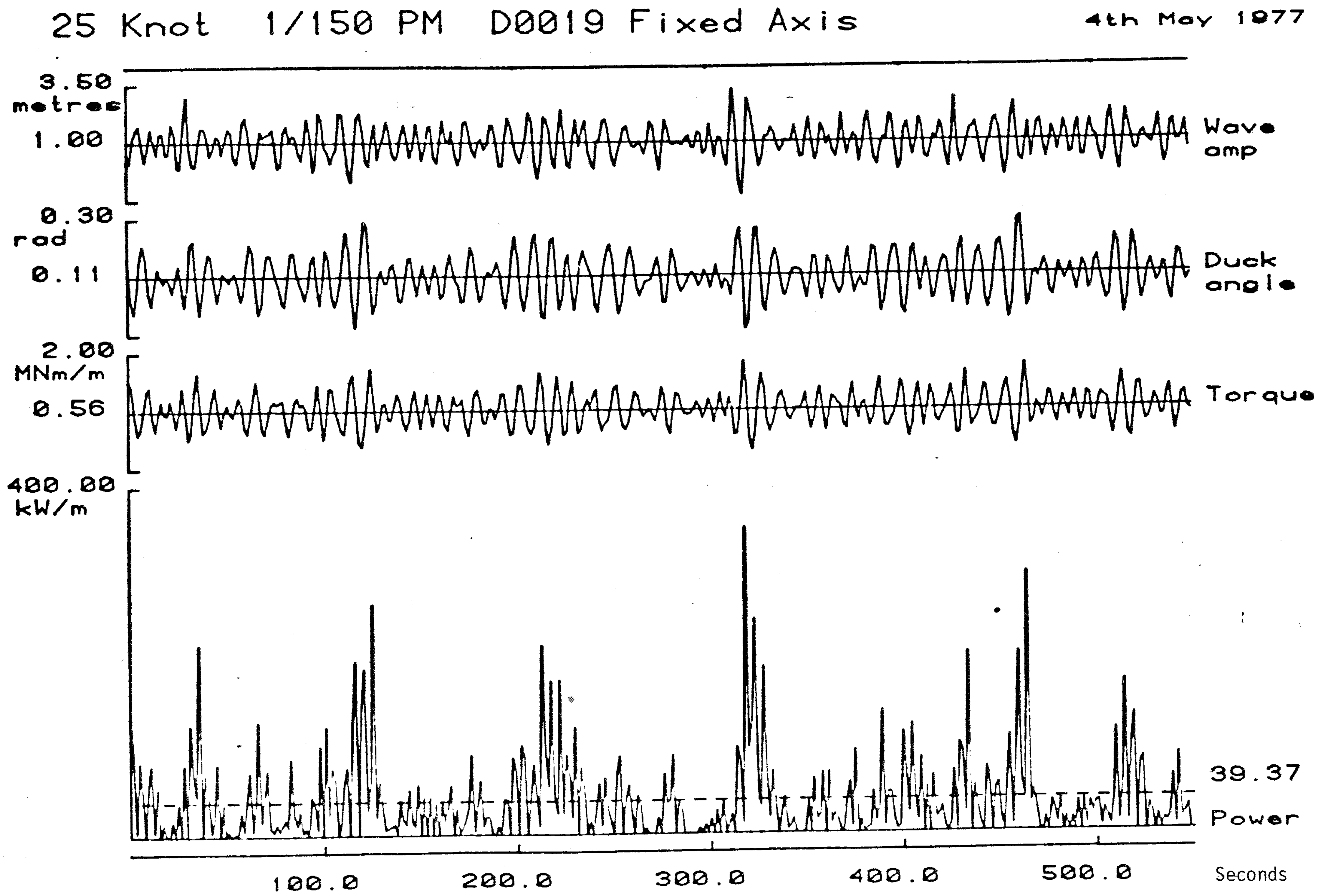
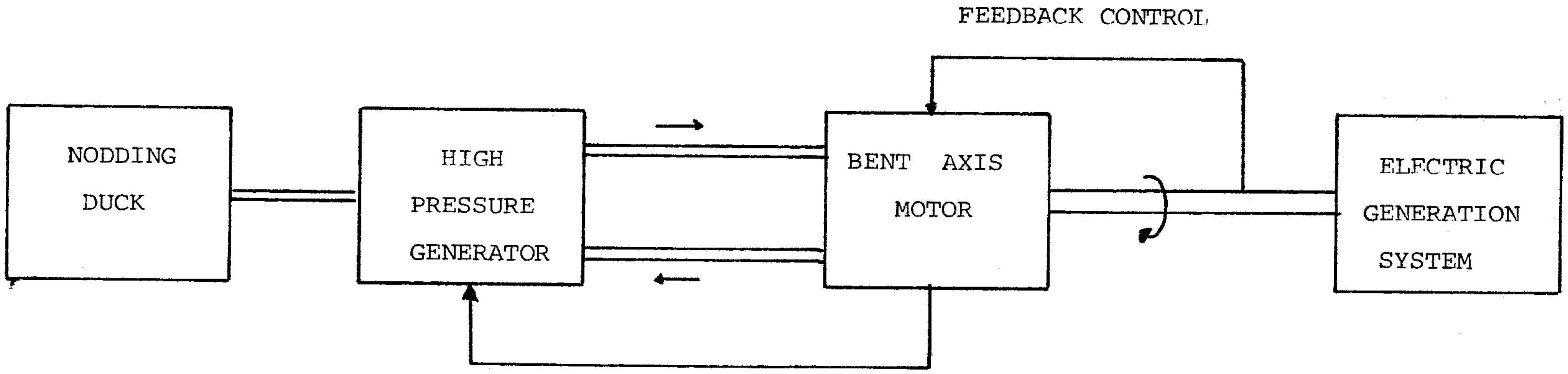


Figure 1. Typical Sea Energy Spectrum With Duct Response

FIGURE 2 Power Take-Off from the Duck



will generally lie parallel to the crests of the waves.

The nodding of the duck about its axis will produce useful work. It will usually have an angular displacement of less than half a radian. The peripheral velocities between duck and backbone are too slow by two orders of magnitude for conventional electricity generation but there are commercially available a rich variety of hydrostatic rotary components which are very efficient as both motors and pumps. These can be used to drive hydraulic motors at conventional speeds for electrical generation. The bent-axis hydraulic motor combines suitable variable speed and variable torque characteristics. Control of the bent-axis angle would allow the generator to run at an approximately constant speed for a variable input power from the duck motion.

A typical response of a duck in a simulated practical sea is shown in Fig.1. These show the typical variation in height of the waves and the corresponding angular displacement, torque and instantaneous power produced by a duck. It can be seen that the instantaneous power is very erratic which makes special requirements for any electric generation scheme used in conjunction with a duck.

The power take-off from a duck currently visualised is shown in Fig.2. The angular movement of the duck is converted to high pressure oil by a hydraulic pump on the duck. The oil is fed into a bent-axis motor which produces a unidirectional rotating shaft at an angular velocity compatible with an electric generation system. Feedback systems from the high pressure oil pump and the rotating shaft can regulate the speed-torque characteristics of the bent-axis motor.

3. THEORY

The two generation systems studied should be considered as complementary not competitive. Each requires a synchronous machine and a rectifier, either controlled or uncontrolled. In addition, the asynchronous a.c. system uses induction machines. There is given below a brief description of the main features of these machines.

3.1 The Induction Machine

The induction machine comprises a static metal casing, the stator, which carries a three-phase winding and a cylindrical rotating centre, the rotor (Figure 3). There are two main types of rotor:

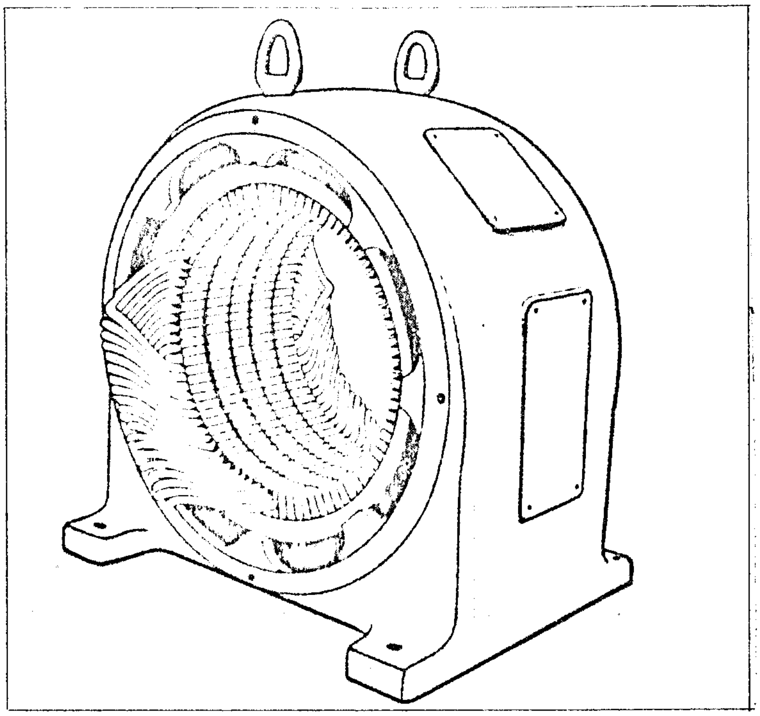
(i) the wound rotor

(ii) the squirrel-cage rotor

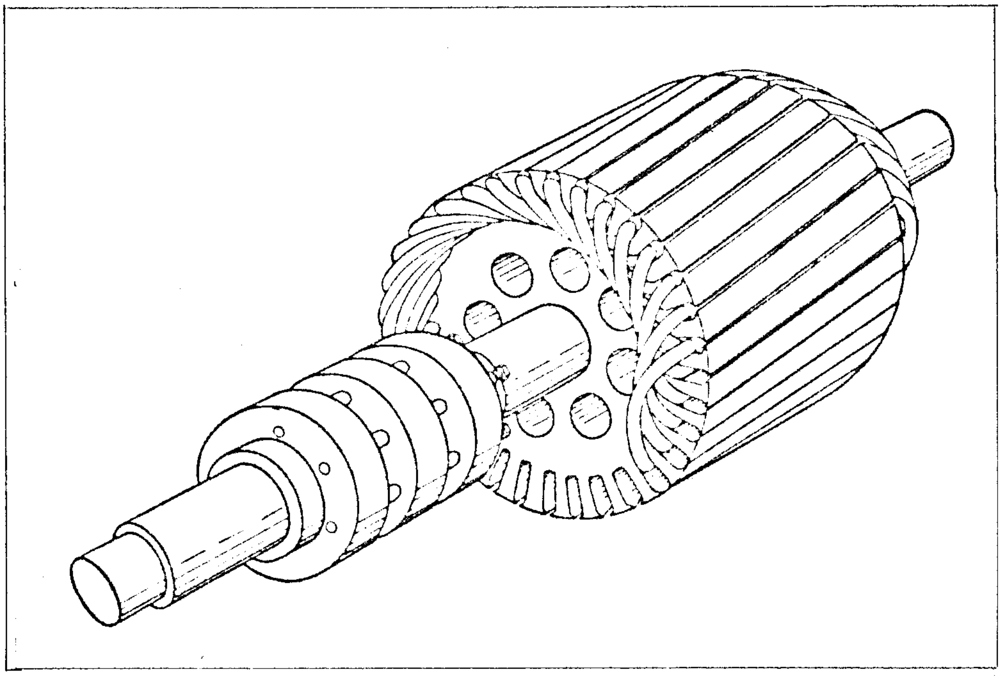
The wound rotor has a three-phase winding with the same number of poles as the stator. The ends are brought out onto three slip rings and may be connected together or to a variable, external resistor. The advantage of the wound rotor machine is that, with an external resistor, it can give a large starting torque the external resistance can be reduced to zero as the machine runs up to operating speed.

The squirrel-cage rotor consists of solid conducting copper bars inserted into closed slots in a solid metal cylinder and short-circuited by a heavy metal ring at their ends. This forms a very robust permanently short-circuited winding. The cage rotor is cheap but has the disadvantage of a low starting torque.

Draper (1971)[1] gives an excellent treatment of induction machine theory. The machine may be represented by an equivalent circuit with all parameters referred to the stator, Fig.4.



Induction Motor Stator with Double-Layer
Winding partly wound.



Wound Rotor for Induction Motor.

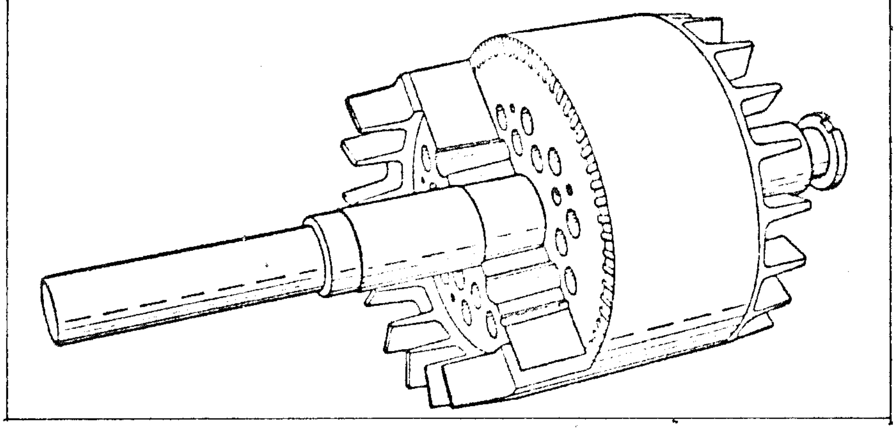
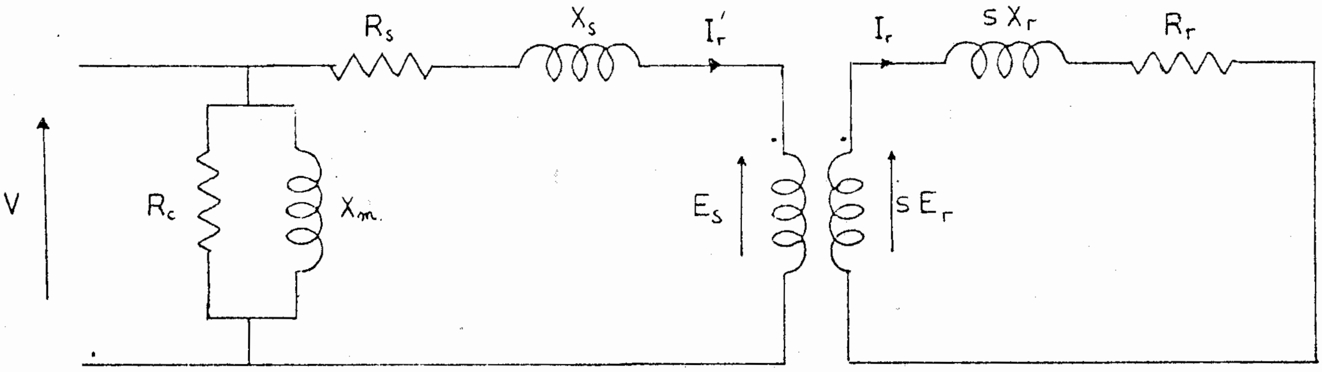
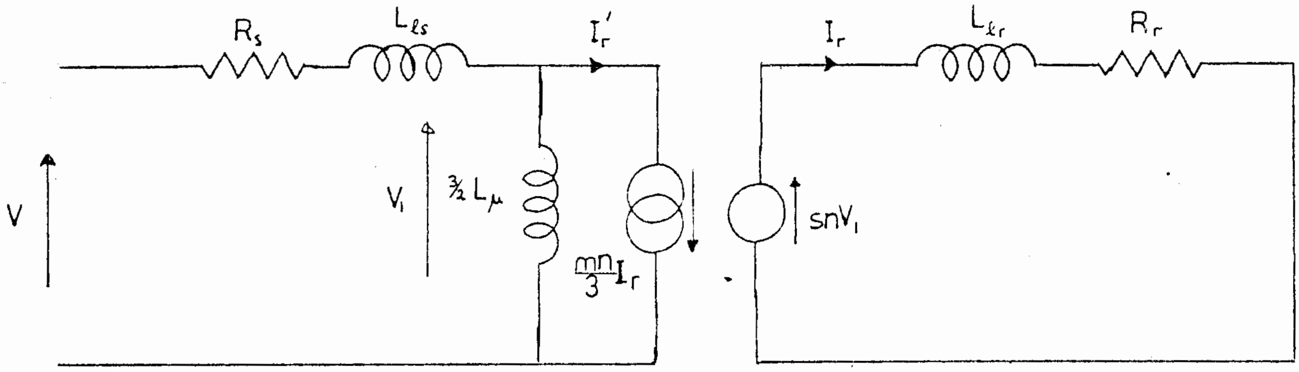


Figure 3

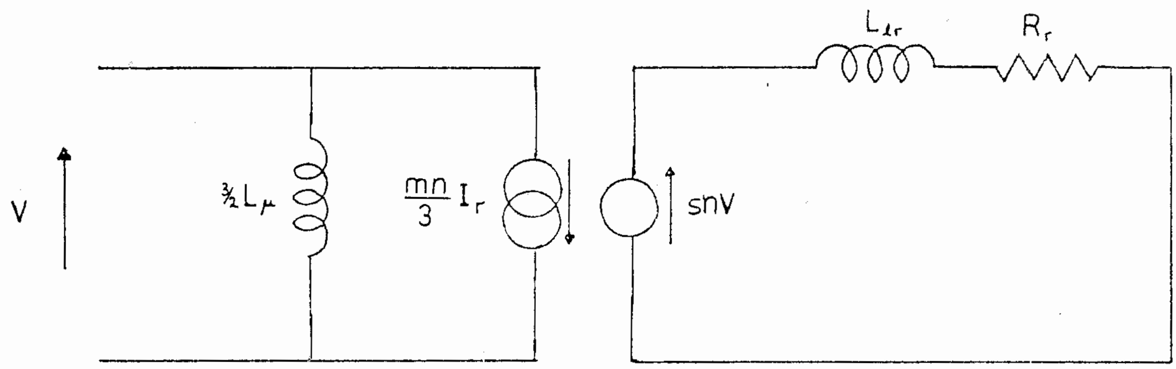
Cage type Rotor in part section showing
Cast Aluminium Bars and Rings.



Approximate Equivalent Circuit for the Induction Machine.



Simplified Equivalent Circuit for the Induction Machine.



Simplified Equivalent Circuit Neglecting the Effect of Stator Leakage Resistance and Stator Leakage Inductance.

Figure 4

R_r = rotor resistance,

m = number of phases

$n = \frac{N_{er}}{N_{es}} = \frac{\text{effective number of rotor turns}}{\text{effective number of stator turns}}$

R_r' = referred rotor resistance

$= R_r \frac{3}{mn^2}$

L_{1r} = rotor leakage inductance

L_{1r}' = referred rotor inductance

$= L_{1r} \frac{3}{mn^2}$

ω_o = synchronous speed of stator flux pattern

$= \omega/p$

ω = angular speed of supply and

p = number of pole pairs

ω_r = angular speed of rotor

$$s = \frac{\omega_o - \omega_r}{\omega_o} = \frac{\omega/p - \omega_r}{\omega/p}$$

$$= \text{slip.}$$

When the rotor is stationary $\omega_r = 0$ and $s = 1$; with the rotor at synchronous speed $\omega_r = \omega_o$ and $s = 0$; for rotor speeds where $\omega_r > \omega_o$, s is negative. In the latter case, an external drive is applied to the rotor shaft and the machine operates as a generator.

3.1.1 The Circle Diagram for the Induction Machine

In the simplified equivalent circuit of Fig.5, a constant

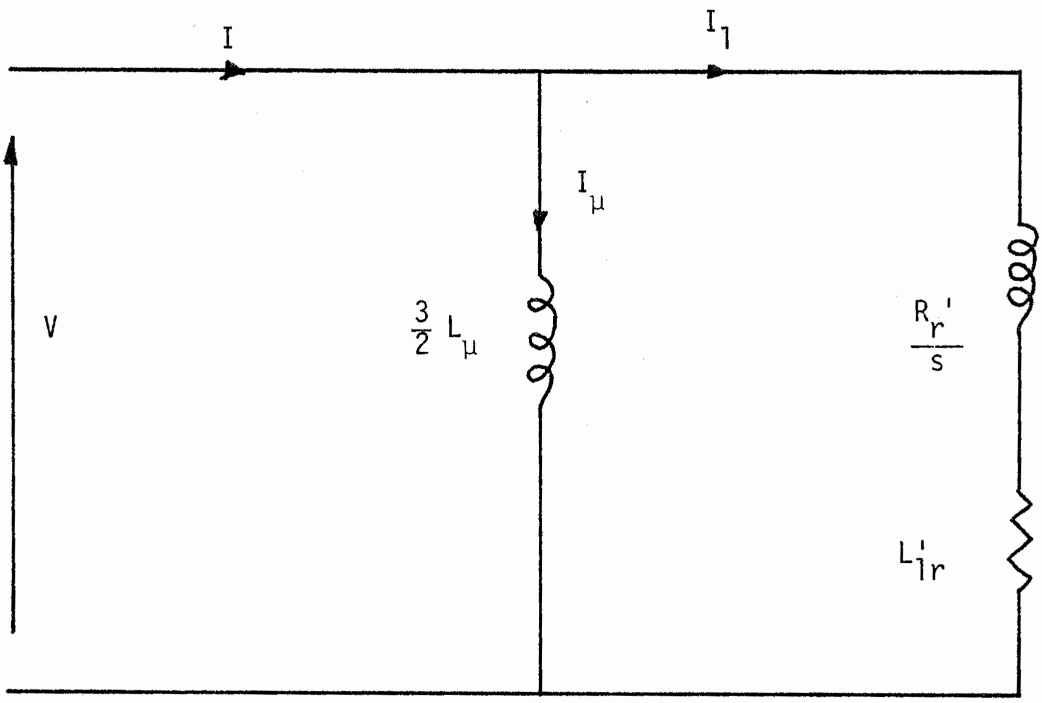


Figure 5. Equivalent circuit of the induction machine with the rotor parameters referred to the stator.

magnetising current, $I\mu$, given by:

$$I\mu = \frac{V}{3/2\ \omega\ L\mu}$$

flows in the first branch, while a variable current dependent on s, and therefore the machine speed, flows in the second branch. For this branch, the constant phasor voltage must be the sum of two mutually perpendicular phasor components, see Fig.6.

(i) that due to the voltage drop across the variable resistor R_r'/s, and

(ii) that across the impedance $\omega L_{1r}'$.

By geometry these phasors must fall within the arc of a circle with V as the diameter as shown in Fig.6.

The phasor current I_1 is proportional to $I_1 \omega L_{1r}'$ and therefore the locus of current phasors is a circle of diameter $V/\omega L_{1r}'$ as shown in Fig.7. The overall stator phasor current is the vector sum of the currents in the two branches and is thus as shown in Fig.8.

Fig.9 shows the complete circle diagram; the upper half corresponds to speeds less than synchronous, i.e. s positive and the machine motoring, while the lower half corresponds to supersynchronous speeds with s negative and the machine generating.

3.1.2 General Characteristics of the Induction Generator

An induction generator does not differ in its construction from an induction motor. Whether an induction machine acts as generator or motor depends solely upon its slip. Below synchronous speed, it can operate only as motor; above synchronous speed, it operates as generator.

The power factor at which an induction generator operates is fixed by its slip and its constants and not by the load. The quadrature

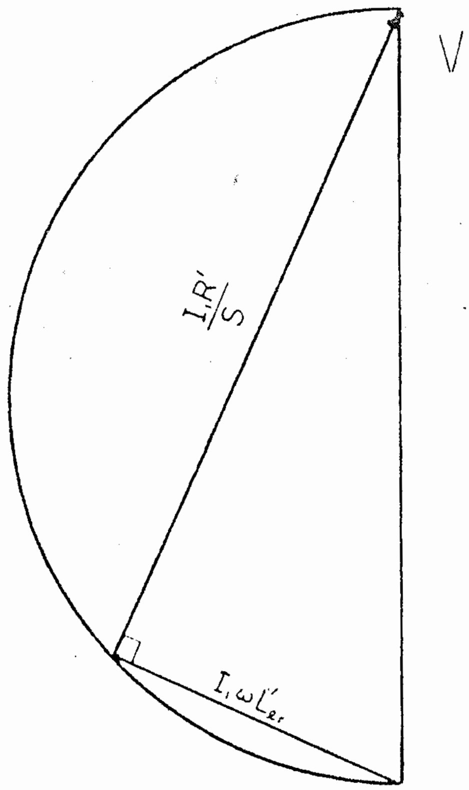


Figure 6: Locus of Voltage Phasors for Second Branch of Equivalent Circuit in Figure 5.

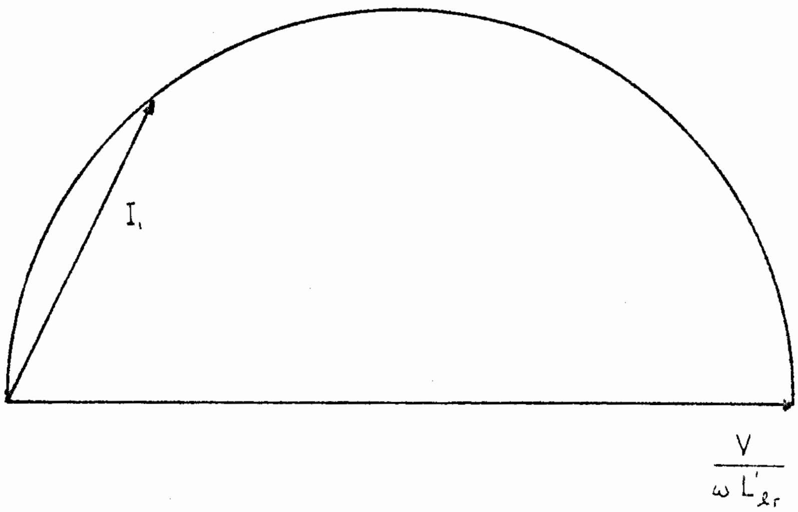


Figure 7: Locus of Current Phasors for Second Branch of Equivalent Branch of Equivalent Circuit in Figure 5.

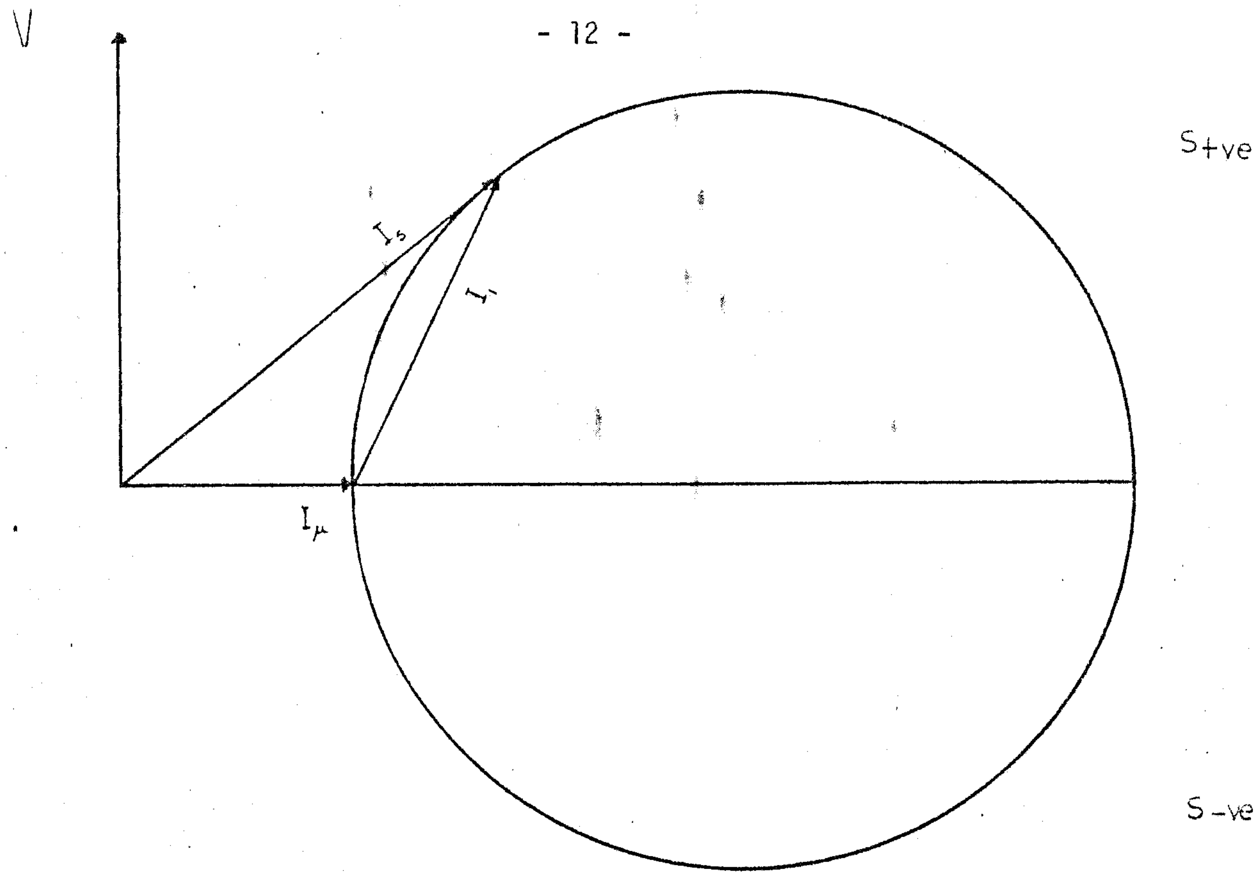


Figure 8: Complete Circle Diagram for Induction Machine.

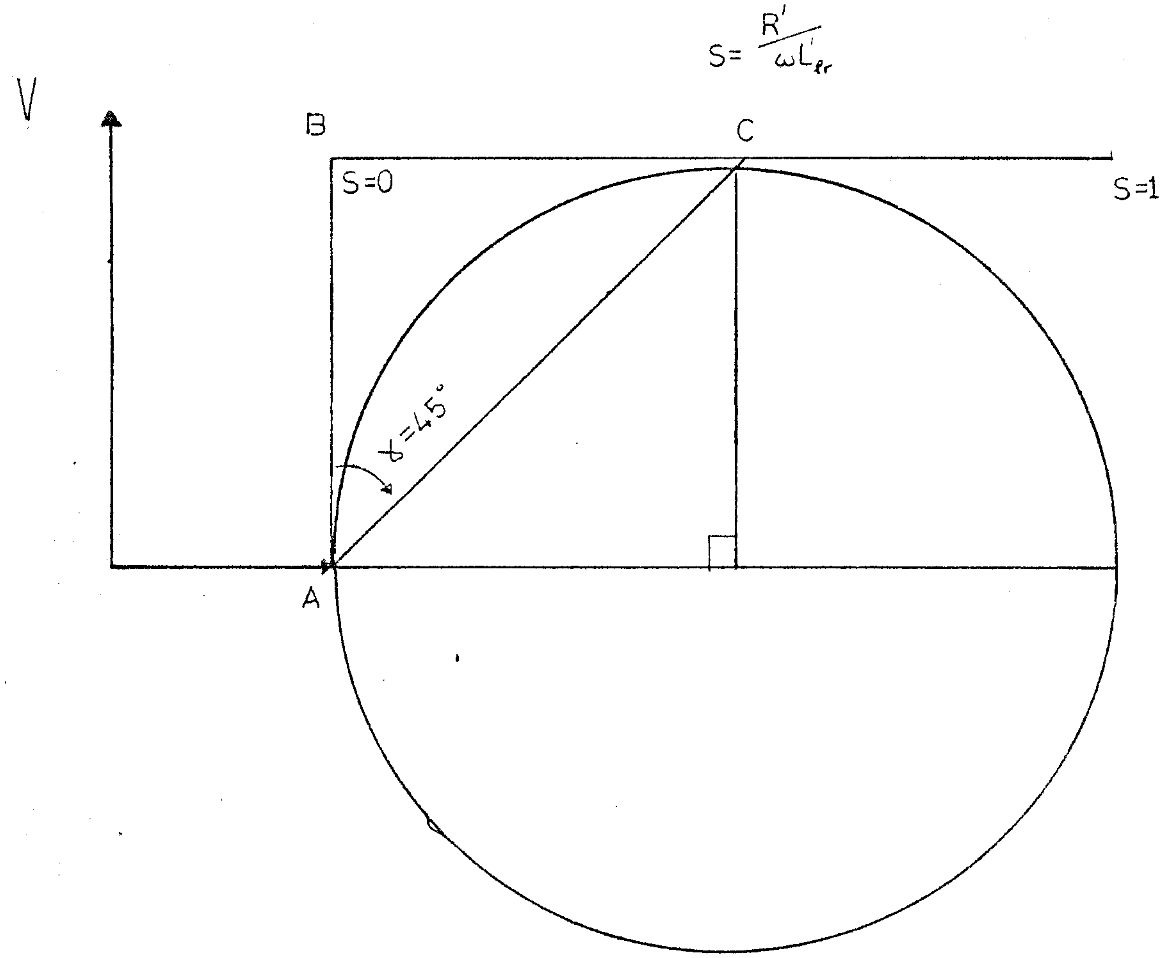


Figure 9: Circle Diagram with Slip Scale Included.

component of the current output is nearly constant for any fixed terminal voltage and frequency and leads the voltage. The power factor of the induction generator is fixed by the machine and not by the load, and it is necessary therefore to operate such generators in parallel with synchronous machines. These synchronous machines not only supply the quadrature lagging current demanded by the load but also supply sufficient quadrature lagging current to neutralize the quadrature leading component of the current delivered by the induction generator. The induction generator depends upon its quadrature leading current for excitation and unless the combined connected load calls for this leading component, the induction generator loses its excitation and voltage. The synchronous machines in parallel with an induction generator determine its voltage and frequency. Its slip fixes its output.

3.1.3 Circle Diagram of the Induction Generator

The circle diagram can be applied to the induction generator merely by completing the circle. All currents which lie below the base line represent generator action.

Changes in Power Produced by a Change in Slip

The following changes in power occur as the slip of an induction machine changes.

1. At synchronous speed the rotor current is zero. The current in the stator comes entirely from the synchronous machines and is the exciting current of the induction machine. The core loss is supplied by the synchronous machine. The mechanical power required to drive the rotor at synchronous speed is equal to the friction and windage loss.

2. Below synchronous speed there is rotor current. To balance the demagnetizing action of this current there must be an equivalent component current in the stator circuit. Under this condition only motor power can be developed.

3. Above synchronous speed the current in the rotor reverses in direction as does also the component current in the stator required to balance the demagnetizing action of the rotor current. At a speed above synchronism generator action occurs, but power is not delivered to the external circuit until the current in the stator, which balances the demagnetizing effect of the rotor current, has a component equal and opposite to the current required to supply the core loss. At the slip at which this particular condition occurs, the generator supplies its own core loss. Its external output is zero. At larger slip, power is delivered to the load.

3.1.4 Power Factor of the Induction Generator

The only current to produce generator power in an induction generator is that component of the primary current which is equal and opposite to the rotor current. A 1:1 ratio of transformation between the rotor and stator is assumed. The power factor of this component current with respect to the primary induced voltage is fixed by the rotor constants and by the slip.

$$pf = \frac{R_r}{\sqrt{R_r^2 + (\omega L_{1r})^2 s^2}}$$

Since the slip is small $(\omega L_{1r})^2 s^2$ is small compared with R_r^2 and the power factor is nearly unity. The load component of the primary current is therefore nearly in phase with the primary induced voltage. Neglecting the magnetizing current and the phase displacement of the terminal voltage due to the resistance and reactance drops in the primary windings, the primary current is very nearly in phase with the terminal voltage. This is the basis of the common but incorrect statement that an induction generator can deliver power only at unity power factor. The magnetizing current is not negligible and the power factor in consequence of this may differ considerably from unity. The correct statement is that an induction generator can deliver power only at leading power factor. The power factor, in large machines, usually is over 90 per cent at full load, but at no load or at small loads it may be very low. The quadrature component of the current, mainly magnetizing changes little with the load.

3.1.5 Phase Relationship Between Rotor Current Referred to the Stator and the Rotor Induced Voltage

The rotor current in an induction machine is given by

$$I_1 = \frac{V}{R'/s + j\omega L'_{1r}} = \frac{Vs}{R' + j\omega L'_{1r}s}$$

Rationalising this gives

$$I_1 = V\left(\frac{R's}{(R')^2 + (\omega L'_{1r}s)^2} - \frac{j\,\omega L'_{1r}s^2}{(R')^2 + (\omega L'_{1r}s)^2}\right)$$

Below synchronous speed, s is positive and the expression for I_1 takes the form

$$I_1 = A - jB$$

which represents a lagging current with respect to V. Above synchronous speed, s is negative; the real part of the equation reverses its sign, but the sign of the quadrature part remains unchanged.

$$\text{i.e.} \quad I_1 = -A - jB$$

This [illegible]ts a leading current w[illegible]ct to -V.

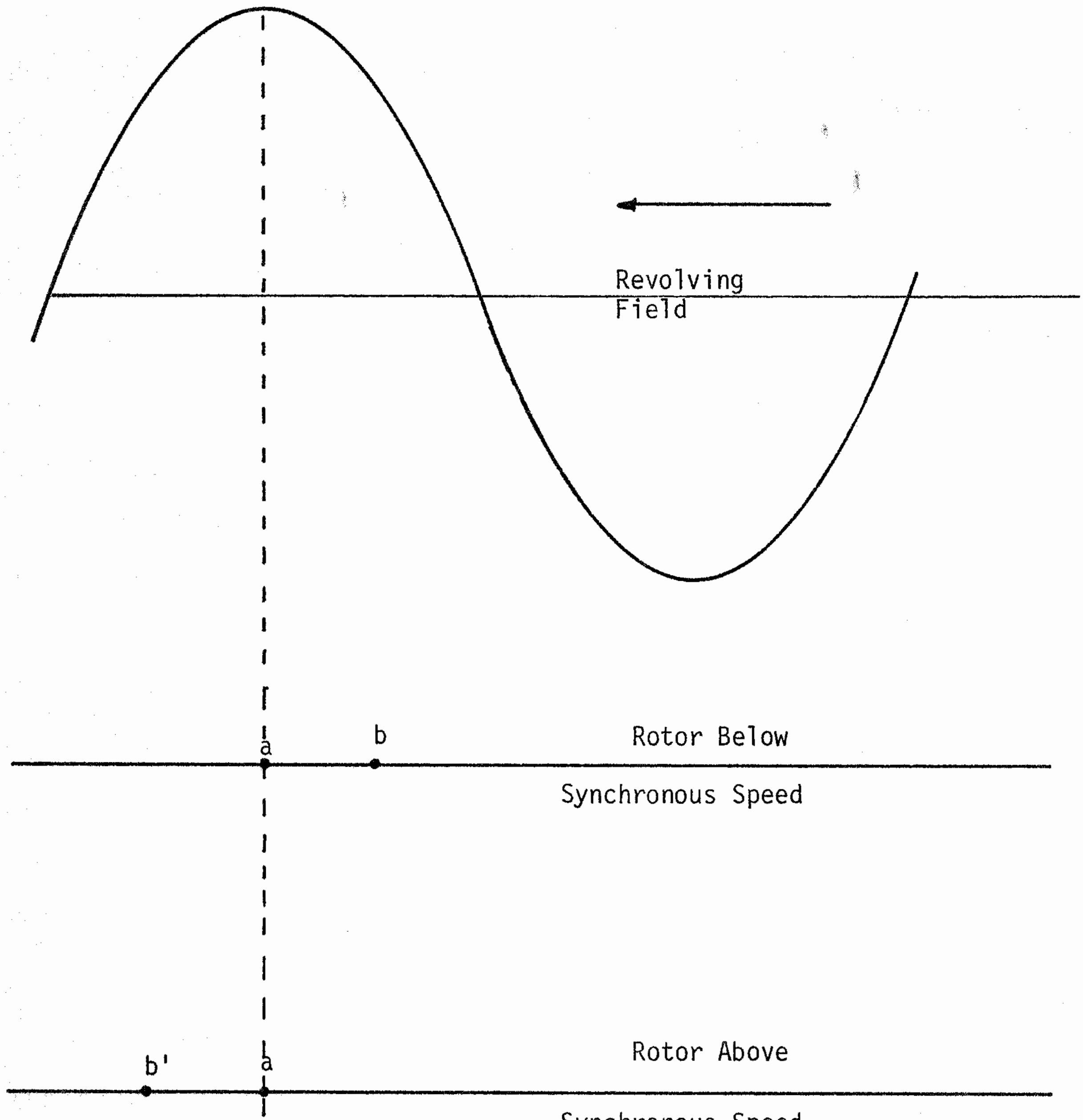

Revolving
Field
a
b
Rotor Below
Synchronous Speed
b'
a
Rotor Above
Synchronous Speed

Figure 10

The current I_1 in the rotor cannot actually lead the voltage in the rotor which causes it, since the rotor circuit is inductive. It is only when this current is considered with respect to the stator that it has this apparent phase relation. The reason for the apparent phase relation is the reversal of the relative direction of motion of the revolving magnetic field and the rotor when the slip changes sign. This can be seen by referring to Fig.10. Let the magnetic field move to the left, as shown by the arrow. Consider the voltage induced in an inductor a on the rotor. This voltage has its maximum value when the inductor is at the point of maximum flux density of the stator field, in position a.

Below synchronous speed the rotor moves to the right relatively to the field, and since the rotor circuit is inductive, the inductor moves to some position such as b before the current in it reaches its maximum value. Above synchronous speed, the rotor moves faster than the field and moves to the left with respect to the field. In this case the inductor a moves to some such position as b' before the current in it reaches its maximum value. In both cases the rotor when considered with respect to the stator moves in the same direction as the field, i.e. from right to left. Therefore if the voltage and current in the rotor are observed from any fixed point on the stator, the voltage is seen to pass through its maximum value before the current passes through its maximum value when the rotor is below synchronous speed and after the current passes through its maximum value when the rotor is above synchronous speed.

3.2 The Synchronous Machine

A synchronous machine, schematically shown in Fig.11, is an a.c. machine in which the rotor moves at a speed which bears a constant relationship to the frequency of the supply to the armature winding. As a motor, the shaft speed must remain constant, irrespective of the load, providing that the supply frequency remains constant. As a generator, the speed must remain constant if the frequency of the output is not to vary. In the synchronous machine a direct current, termed the field current, is steady. In most cases the field is excited by a direct current obtained from an auxiliary generator which is mechanically coupled to the shaft of the main machine.

3.2.1 Construction

The stator of a three phase synchronous machine is not essentially different from that of an induction machine (see Fig.3). Connected to a three-phase supply both give an air-gap field pattern rotating at synchronous speed, ω/p. Under steady-state conditions the rotor rotates at synchronous speed, i.e. in synchronism with the stator pattern. Consequently, paths within the rotor iron link constant magnetic flux, there are no voltages induced in the rotor iron paths or rotor windings.

In steady-state operation there are no induced currents in the rotor winding and the injected direct current produces a sinusoidal air-gap flux density in the absence of stator currents. The rotor

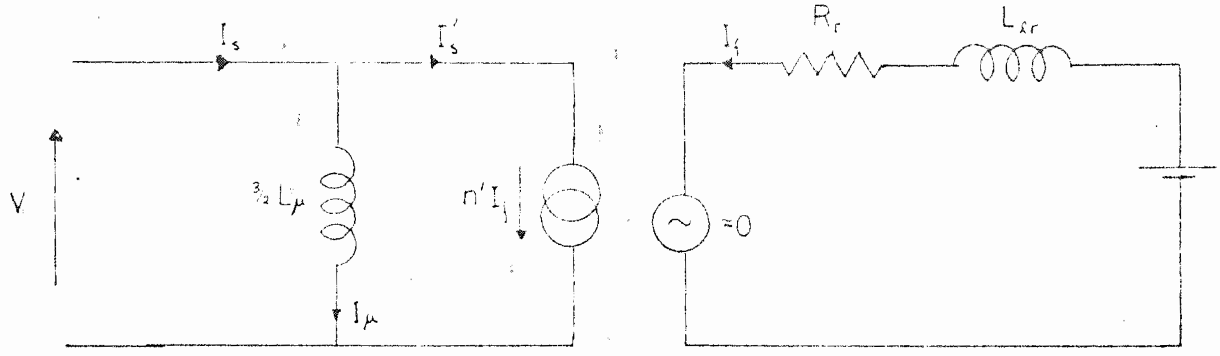


FIGURE 11: Simplified Equivalent Circuit for the Synchronous Machine.

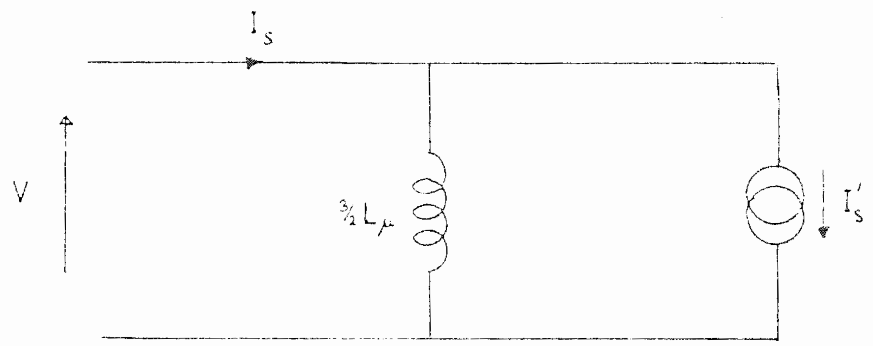


FIGURE 12: Equivalent Circuit for Synchronous Machine neglecting the rotor branch.

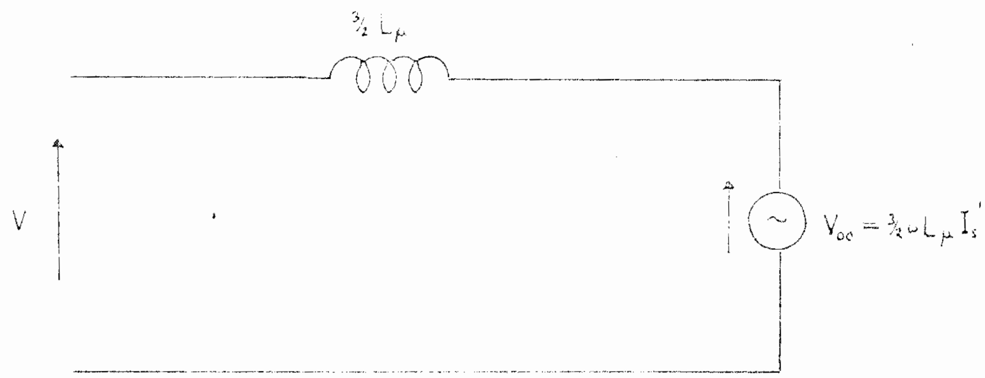


FIGURE 13: Thevenin Equivalent Circuit for the Synchronous Machine.

winding therefore resembles a one-phase winding through which the current passes to produce fixed polarities on the rotor surface.

The basic operation of a synchronous machine does not depend on induced currents. However, if there is a transient disturbance to the electrical or mechanical systems which are coupled to the machine, induced currents must flow in the rotor to damp out mechanical oscillations by induction machine action. In a solid, cylindrical rotor machine the induction machine action relies on induced currents in the solid rotor.

3.2.2 Simplified Equivalent Circuit of a Synchronous Machine

Discussion is limited to the case of a three-phase synchronous machine which has the stator three-phase winding connected to a large constant-voltage balanced supply, and also with the rotor maintained at synchronous speed ω/p by a large constant-speed mechanical system while the rotor winding carries an injected d.c. field current, I_f. The stator supply gives rise to three pulsating fields which taken together have a constant amplitude rotating pattern form. There is no induced voltage in the rotor winding as it moves at synchronous speed, with slip $s = 0$, but there is the externally injected rotor direct current reacting in the stator winding in the same way as the rotor current of an induction machine reacts on the stator. Thus the equivalent circuit will resemble that of the induction machine as shown in Fig.4. The turns ratio, n, for rotor induced voltage is given by

$$n = \frac{Ner}{Nes}$$

as in the induction machine but as $s = 0$ the induced voltage is zero. The ratio, n', which relates to the stator balance current per phase, I_s', to the rotor current, I_f, may be found from comparison of the rotating pattern amplitude which would be set up by these currents in the stator and rotor respectively. For an r.m.s. current I_s' in each of three stator phases the total pattern amplitude is proportional to:

$$2\ Nes \times 3/2 \times I_s'$$

whereas for the direct current in the rotating rotor, the pattern amplitude is proportional to:

$$Ner \times I_f$$

Thus to balance these amplitudes n' is given by

$$n' = \frac{I_s'}{I_f} = \frac{Ner}{2\ (3/2)\ Nes}$$

The phase of the stator balance current, I_s', will depend on the position of the rotor coils relative to the rotating pattern as these both rotate at synchronous speed. There will be maximum torque and maximum power transfer through the machine when the rotor coil slides lie at the maxima of the rotating pattern. There will be zero torque and power transfer when the rotor coil sides correspond with the zeros of the rotating pattern. Maximum torque and power transfer therefore occur when the stator balance current, I_s', is in quadrature with the stator magnetising current, $I\mu s$, and zero torque and power transfer when I_s' and $I\mu s$ are in phase with one another.

From Fig.11 the equivalent circuit for a synchronous machine can be shown simply as Fig.12. The circuit of Fig.12 can be represented by a Thevenin equivalent as shown in Fig.13.

3.3 Controlled Rectifier System

Theory

3.3.1 Controlled Rectifier Bridge

The most common circuit arrangement used with thyristors is the 3-phase thyristor bridge circuit as shown in Fig.14. If there is no firing delay (i.e. each thyristor is equivalent to a diode), the

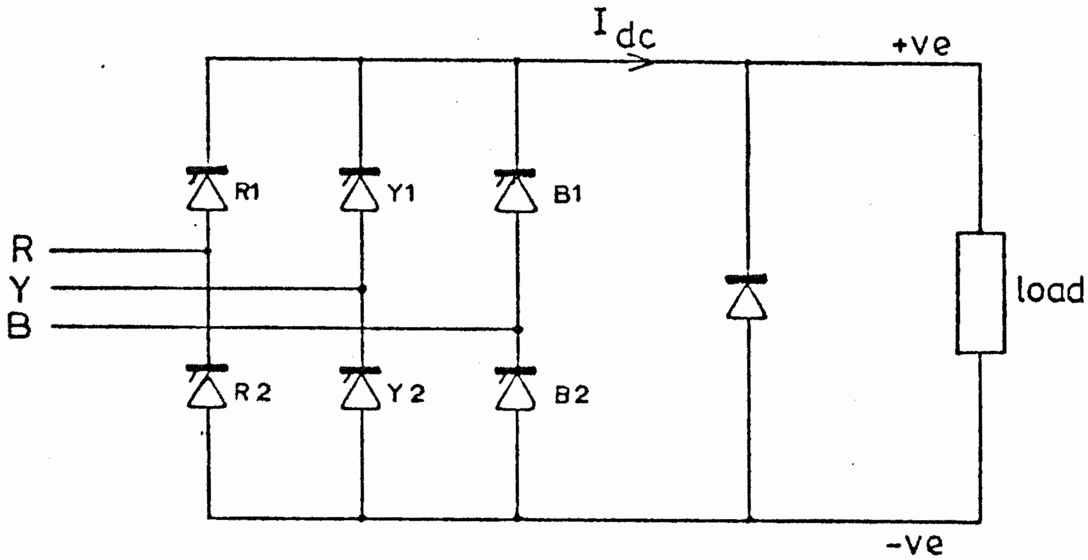


Figure 14: : Rectifier Bridge

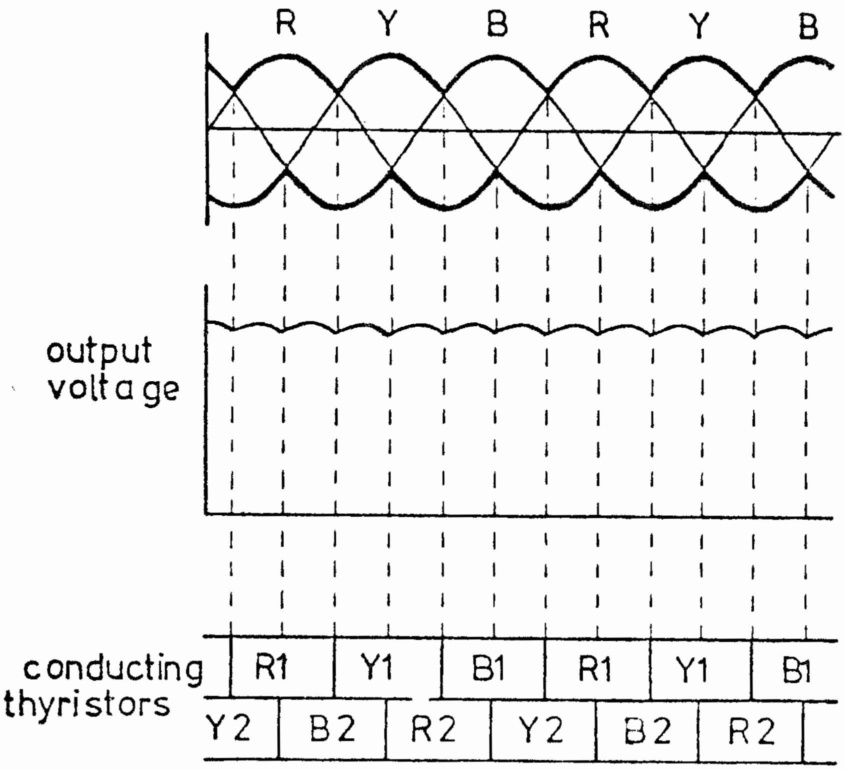


Figure 15: Voltage Waveforms

thyristor in the top row with the most positive anode conducts and the thyristor in the bottom row with the most negative cathode conducts. The voltage appearing across the load is therefore the difference between the phase voltages applied to the two thyristors. Fig.15 shows the voltage waveforms on the two rails and the resulting output voltage waveform. The voltage on the d.c. rails has a six-phase ripple for one a.c. cycle as shown.

Each thyristor carries the full direct current I_{dc} for 120^o in each cycle. Two thyristors always conduct simultaneously in order to complete the circuit, but the conduction periods of thyristors in the upper and lower rows do not coincide in time. The conduction sequence of the thyristors is indicated in Fig.15.

The average d.c. output voltage can be controlled by delaying the instant at which a thyristor is fired relative to the a.c. supply.

The firing angle α is measured in electrical degrees from the equivalent diode state. The average d.c. voltage from a 3-phase thyristor bridge is given by

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} E_m \sin wt \, dwt$$

$$= \frac{3E_m}{\pi} \cos \alpha \text{ volt}$$

where E_m is the peak line voltage of a.c. supply.

When firing pulses are removed, the bridge should cease to conduct. However, if the load is inductive, there is an associated stored energy of magnitude $\frac{1}{2}$ LI^2. To provide a discharge path a "flywheel" diode may be incorporated between the d.c. rails as shown in Fig.14. Without this diode, serious overvoltages could occur which might damage the thyristors.

3.3.2 Firing Techniques for Thyristor Bridges

Since commercially designed firing circuits were readily available (Westinghouse Co.), and were ideally suited for the present purposes, it was decided to design the system using these units. The circuit chosen gave output trains of pulses with a variable delay angle in synchronism with an a.c. supply. The pulses have an amplitude of about 6 V and a frequency of 2.5 KHz with a mark/space ratio of the order of 1/10. Thus, the pulse width is very large compared with the turn-on response of a thyristor. The circuit chosen gave full range of control for an input variation in voltage of 0 - 3 V.

Output pulses are delivered via pulse transformers so that the printed circuit card is not electrically coupled to the thyristor bridge.

4. SYSTEMS DESIGN AND TESTING

Both systems described in the introduction were designed and constructed at about 1/200th scale, such ratings being suitable for use in the present laboratory. The basic features of each system are described below together with the results of testing.

4.1 Induction Generator System

Both the induction machine and the synchronous machine used in this study were coupled mechanically to d.c. machines forming two motor-generator units. The induction machine was of four poles and rated at 200 volt, 6.4 amp and 1460 rpm. The stator was delta connected and the wound rotor was brought out via slip rings to a star connected external resistor.

The synchronous machine was of four poles and rated at 200 V, 6 A 1500 rpm. The stator was star connected and the rotor separately excited using slip rings with an external supply.

4.1.1 Induction Machine Characteristics

Standard locked-rotor and open-circuit tests carried out on the induction machine yielded the circle diagram shown in figure 16 and the equivalent circuit in figure 17.

The stator of the induction machine was then connected to the three-phase supply and the machine run as a motor up to almost synchronous speed. The d.c. machine, which was mechanically connected to the induction machine, was switched on to drive the induction machine to super-synchronous speed and the following readings taken:

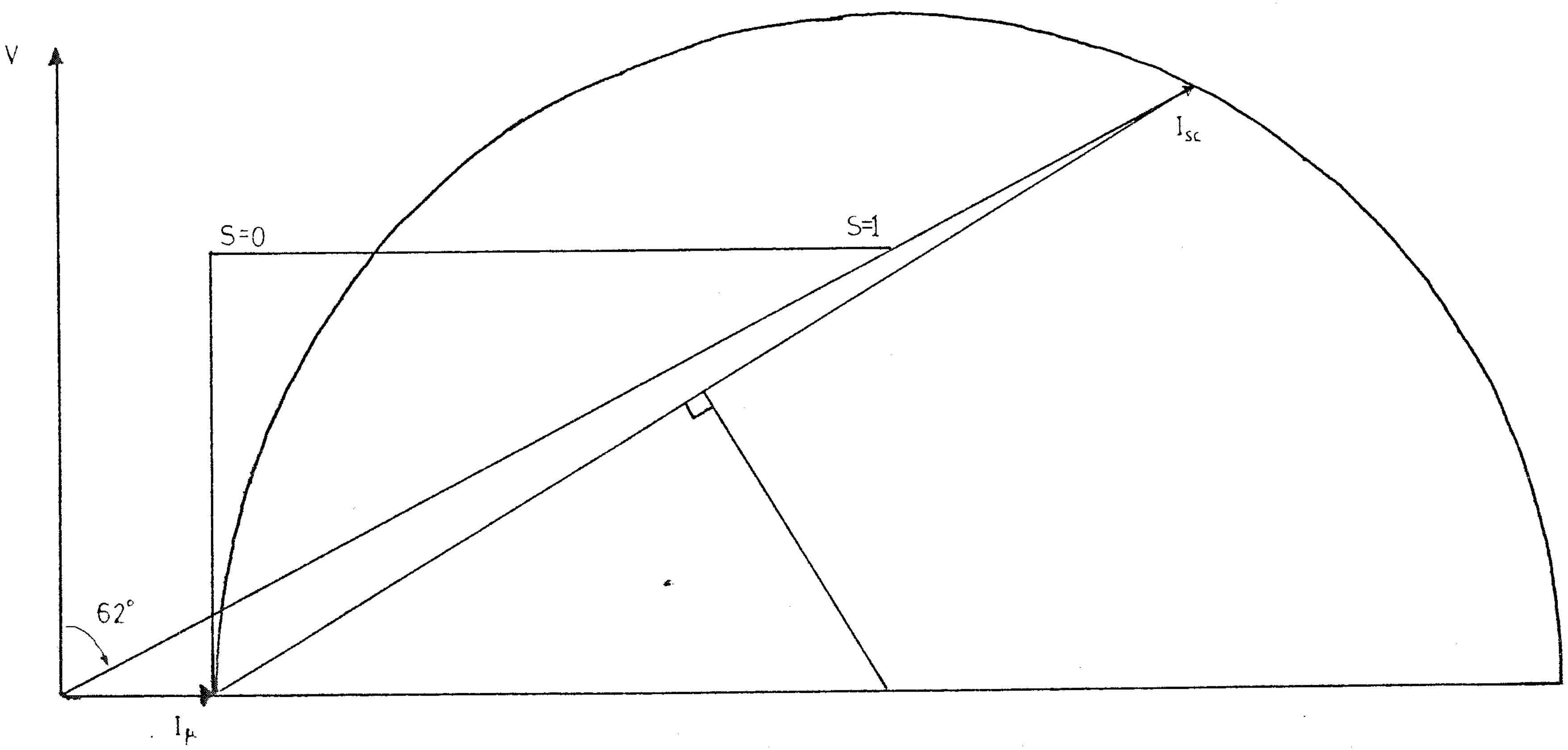
D.C. Machine		Induction Machine			D.C. Power In	Windage & Friction	D.C. Power In - W & F
V Volts	I Amps	V1 Volts	V1 Amps	ω rpm	Watts	Watts	Watts
0	0	212	3.8	1460	0	235	- 235
240	2	212	3.7	1490	480	242	238
240	4	215	4.0	1500	960	245	714
235	6	215	4.8	1520	1410	250	1160
235	8	215	5.5	1530	1880	251	1629
235	10	215	6.3	1540	2350	252	2098
335	12	217	7.2	1550	2820	253	2567

TABLE 1

It should be noted that under the above conditions, the induction machine was operating as a generator.

From the equivalent circuit, figure 17, the induction machine magnetising current from a 50 Hz supply is 3.8 A. Using this value and the readings of line current in table 1, the in phase component of the induction machine current, I_{REAL}, may be found

FIGURE 16: Complete Circle Diagram for Induction Machine



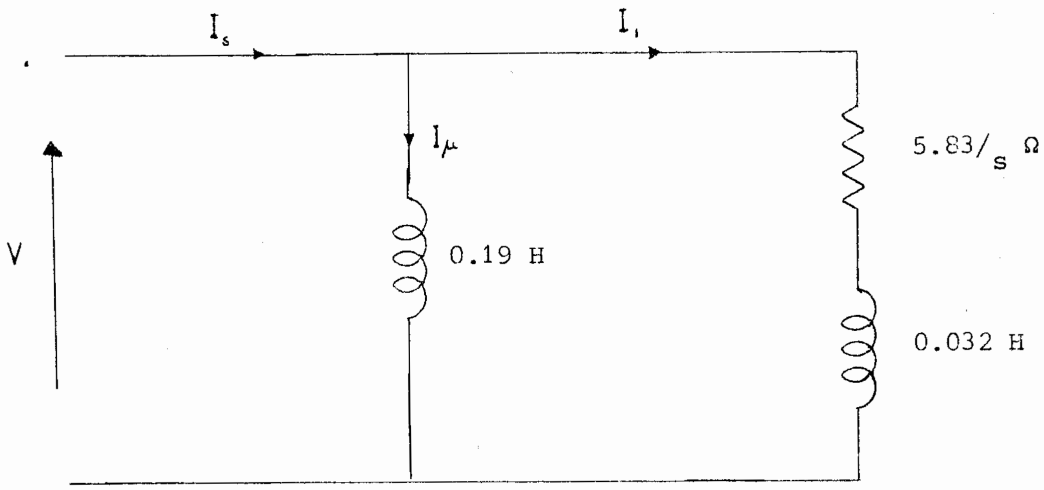


FIGURE 17: The Equivalent Circuit for the Induction Machine used in the Project.

i.e. $$I_{REAL} = \sqrt{I_L^2 - I_\mu^2}$$

and the induction machine electrical power output is given by

$$P = \sqrt{3}\, V_L\, I_{REAL}$$

The results are tabulated below.

ω	I_1	I_{REAL}	P	Power In - Windage & Friction
rpm	Amps	Amps	Watts	Watts
1460	3.8	-	-	235
1490	3.7	-	-	238
1500	4.0	1.25	465	714
1520	4.8	2.93	1091	1160
1530	5.5	3.98	1482	1629
1540	6.3	5.02	1869	2098
1550	7.2	6.12	2300	2567

TABLE 2

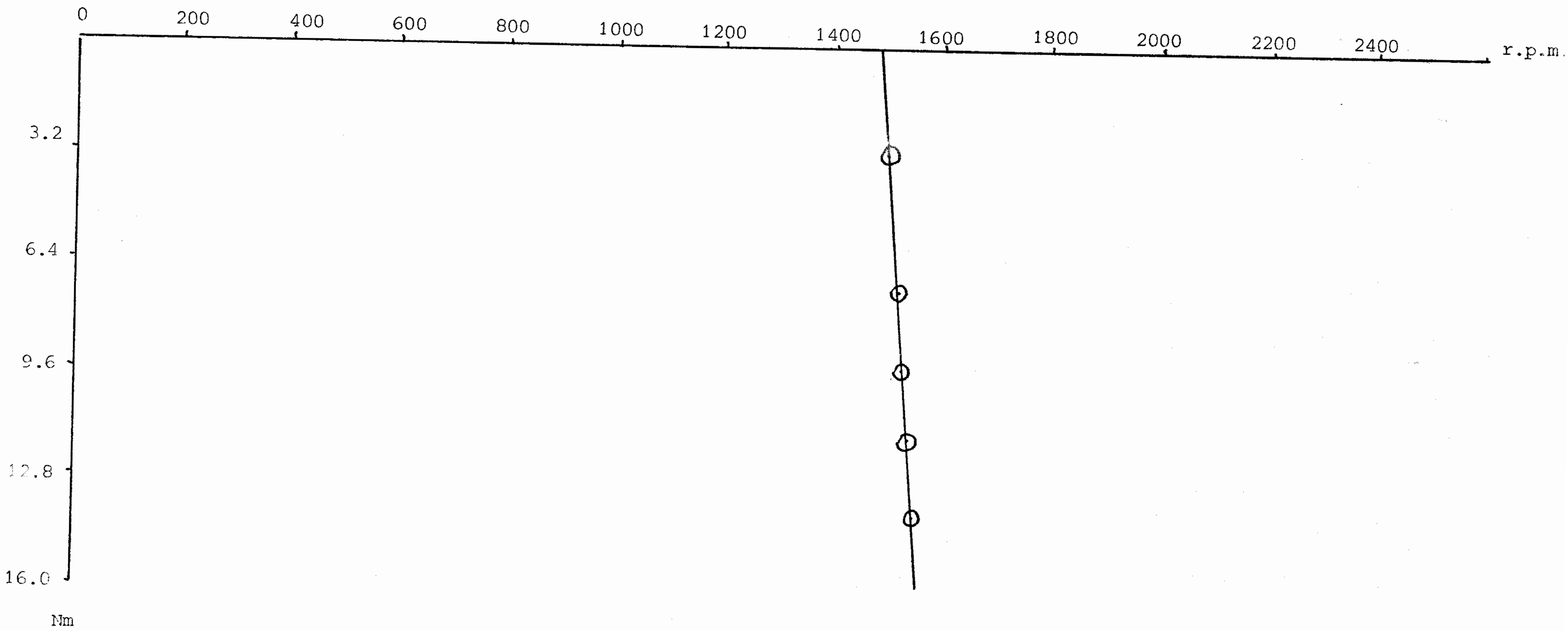
From table 2, part of the speed-torque curve for the induction generator can be drawn, figure 18.

4.1.2 Synchronous Machine Characteristics

Standard short-and open-circuit tests were made on the synchronous machine and the equivalent circuit shown in figure 19 was derived.

The windage and friction losses of the synchronous machine motor-generator set were found in the same way as those of the induction machine with the d.c. machine driving the synchronous machine on open circuit. The following results were obtained:

FIGURE 18: Speed-Torque Characteristics for the Induction Machine



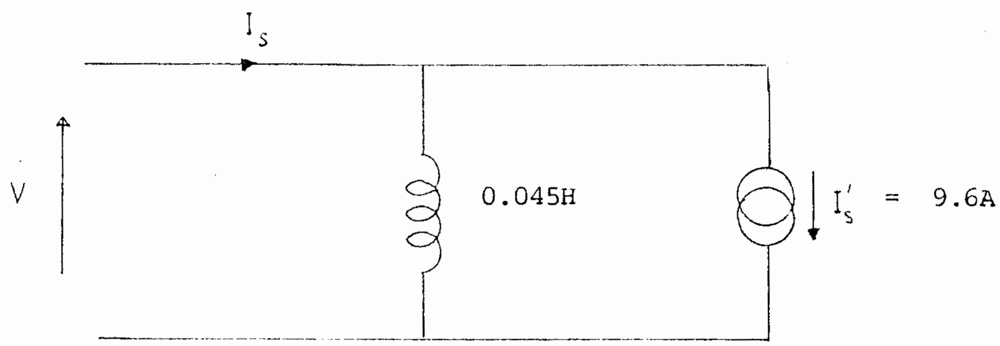


FIGURE 19: Approximate Equivalent Circuit for the Synchronous Machine Used.

V_{DC} (Volts)	I_{DC} (Amps)	ω (r.p.m.)	Windage & Friction (Watts)
72	3.4	900	245
90	3.2	1100	288
112	3.4	1270	381
125	3.75	1430	469
149	3.8	1640	566
165	3.8	1832	627

TABLE 3

4.1.3 System Testing

Induction Machine Coupled to Synchronous Machine

The four laboratory machines were connected as shown in figure 20, with the induction machine coupled electrically to the synchronous machine. For identification the induction machine, d.c. machine set is labelled I, while the synchronous machine, d.c. machine set is labelled II.

The synchronous machine was run up to 1500 r.p.m. with d.c. machine II and then the field excitation was switched on. This results in a three-phase supply being fed to the induction machine which starts motoring, reaching a speed of approximately 1460 r.p.m. D.C. machine I is then switched on and its field adjusted to bring the speed of the induction machine above 1500 r.p.m. The induction machine is then generating and d.c. machine II can be gradually turned off and left to freewheel.

The system ran with no apparent problems. Operating in this mode the synchronous machine is supplying the quadrature current for the induction generator while the induction generator supplies the windage and friction power required by the synchronous machine.

The field excitation of d.c. machine I can then be varied. This speeds up and slows down the induction generator which in turn results in

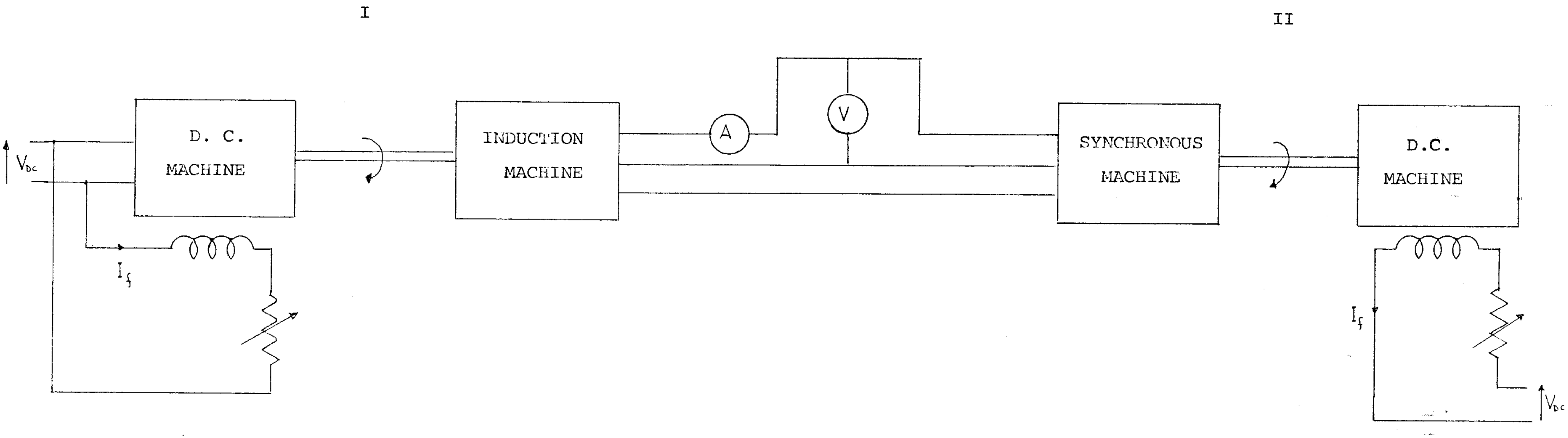


FIGURE 20: Induction Machine Motor-Generator Set electrically coupled to Synchronous Machine Motor-Generator Set.

the synchronous machine speeding up and slowing down in sympathy. The synchronous machine must always operate at a slightly lower speed than does the induction machine to maintain the generation mode.

4.1.4 Induction Machine, Synchronous Machine Set Operation with a Resistive Load

A delta connected, three-phase, variable resistive load was connected across the induction machine output as shown in figure 21.

Increasing the power drawn by the load slows both machines down. The decrease in speed of the induction machine can be compensated by varying the field excitation on d.c. machine I. The speed of the synchronous machine must drop relative to the speed of the induction machine to increase the fractional slip of the generator. The operating voltage of the system is determined by the synchronous machine, thus a drop in synchronous machine speed results in a drop in operating voltage. The drop of operating voltage can be compensated for by increased field excitation of the synchronous machine. A series of results taken is given in Table 4:

	D.C. m/c		I.M.			S.M.			LOAD	
	V (V)	I (A)	V (V)	I (A)	(rpm)	V (V)	I (A)	(rpm)	V (V)	I (A)
(1)	225	5.2	204	3.4	1600	200	3.4	1540	200	0
(2)	229	6.6	195	4.4	1600	190	3.7	1518	190	1.3
(3)	225	9.1	190	5.6	1600	184	4.0	1500	184	2.6
					change in S.M. excitation					
(4)	225	12	202	6.9	1600	192	4.8	1500	192	3.6
(5)	220	18.8	186	8.9	1600	180	5.5	1460	180	5.3

TABLE 4

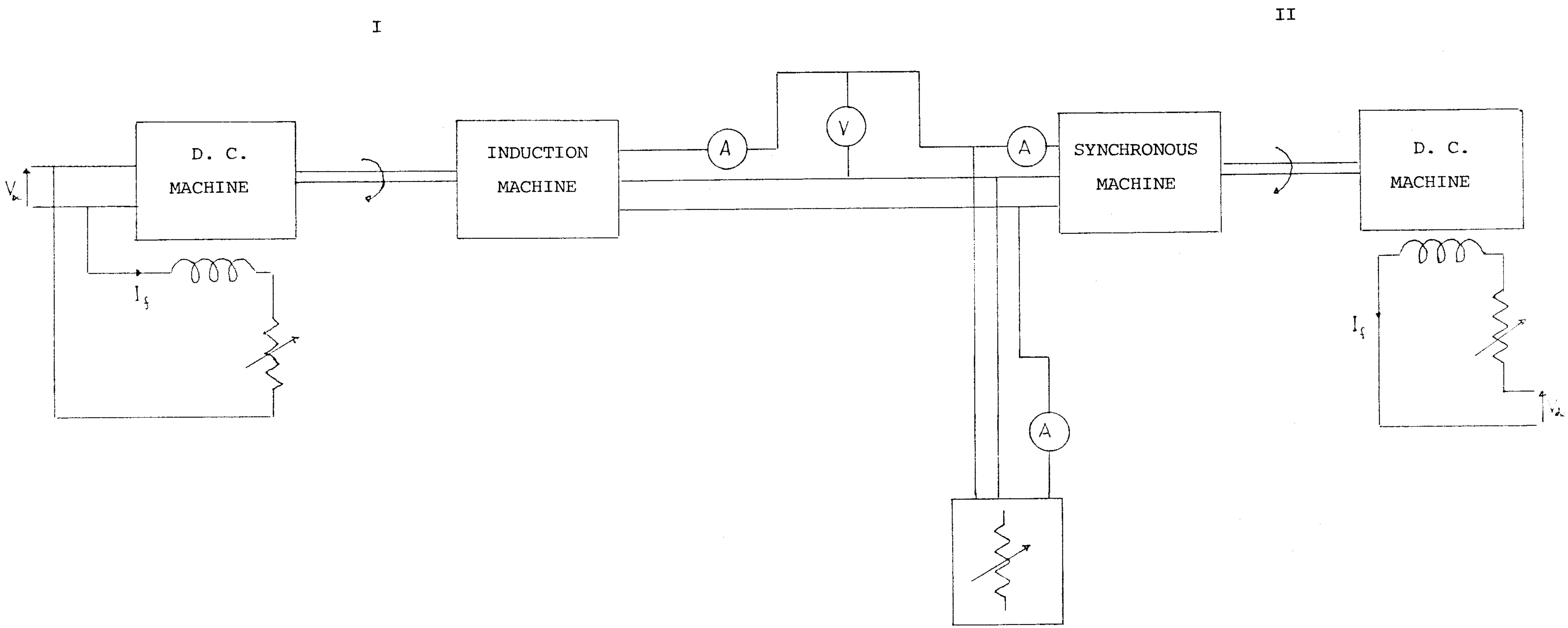


FIGURE 21: Induction Machine and Synchronous Machine Connection with Three-Phase Delta-Connected Resistive Load.

This experiment showed that it is possible to load electrically the induction generator-synchronous motor set. Detailed analysis of the readings in Table 4 is not carried out as both the operating voltage and frequency of the system are varying simultaneously. The speed-torque curve of an induction machine is both voltage and frequency sensitive so that detailed analysis would be of little value.

4.1.5 Induction Machine, Synchronous Machine set with Diode Load

The resistive load of Section 4.1.4 was replaced by a diode bridge feeding a d.c. rail as shown in Figure 21. The d.c. rail voltage is constant which imposes a constant maximum value of voltage on the a.c. side of the bridge as soon as the bridge conducts. This makes the system operation easier to control and considerably aids the analysis of results.

The voltage waveforms at different operating speeds are shown in figure 23 to 24. These illustrate the peak clipping effect of the diode bridge. Commutation overlap due to the diode bridge being fed from an inductive circuit can also be seen in the diagrams. A higher frequency ripple due to the effect of the diode bridge is seen on the peaks of the waveforms.

Figure 25 shows the position of the current waveform with respect to the voltage waveform. It should be noted that the voltage waveform is the line voltage and is thus displaced by 30^{0} from the phase voltage. The effect of commutation overlap is very evident in the current waveform. The current and voltage waveforms are far from sinusoidal but the machines appeared to operate satisfactorily with the distorted waveforms.

Results taken at different speeds are given in Table 5.

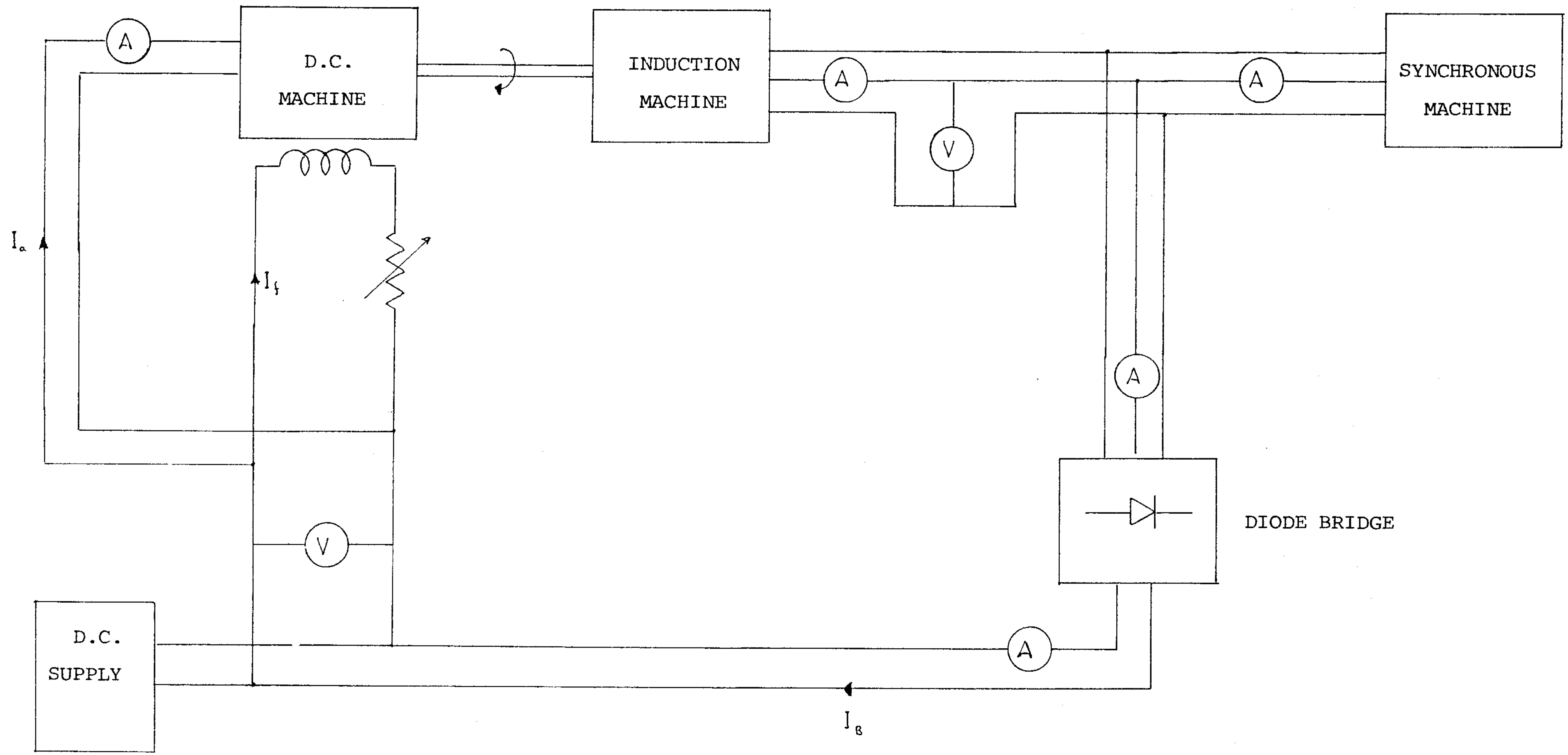


FIGURE 22: Induction Machine & Synchronous Machine Connection with Diode Load.

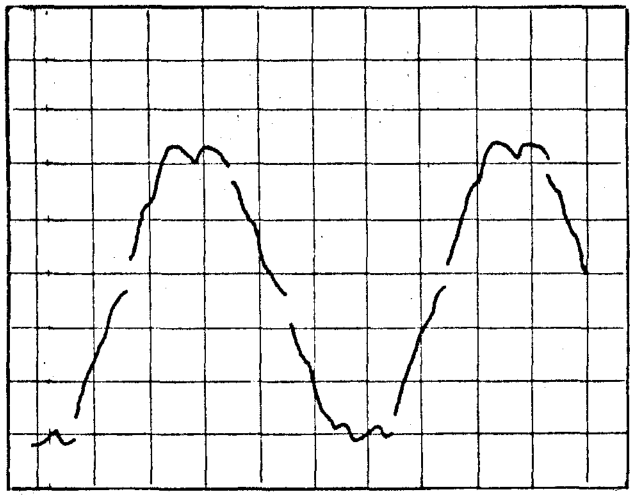


Figure 23: Voltage Waveform for Synchronous Machine speed of 1000 rpm.

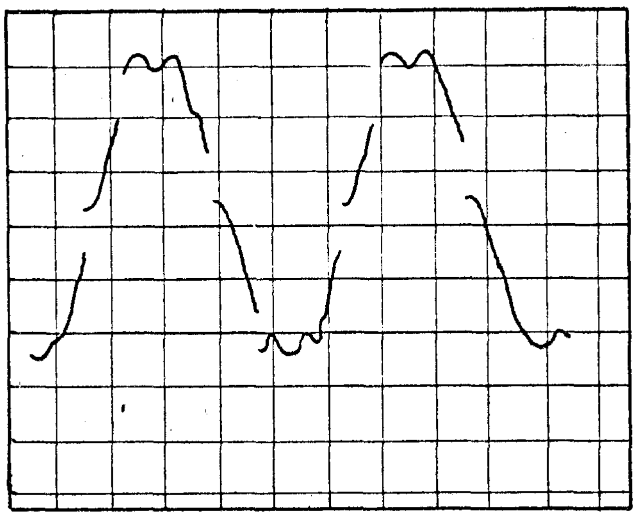


Figure 24: Voltage Waveform for Synchronous Machine speed of 1250 rpm.

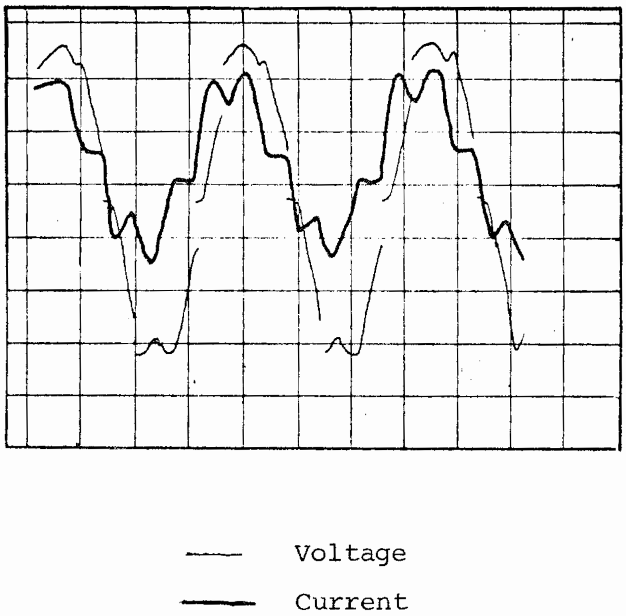


Figure 25: Voltage and Current Waveforms for Synchronous Machine speed of 1700 rpm.

	D.C. m/c			I.G.			S.M.				Bridge		
	I_f	V	I_a	V	I	ω_m	V	I	ω_m	I_f	V_{dc}	I_{ac}	I_{dc}
1	0.67	230	3.8	160	3.5	1500	165	3.4	1320	0.5	240	0.38	0.5
2	0.5	320	8.0	180	5.2	1736	175	4.2	1510	0.5	240	2.5	3.3
3	0.47	227	10.0	180	6.1	1872	175	4.6	1590	0.5	240	3.25	4.2
4	0.42	225	12.0	182	6.9	1990	175	5.0	1680	0.5	240	3.85	5.1
5	0.38	225	14.2	184	7.7	2184	175	5.6	1820	0.5	240	4.3	5.7

TABLE 5

The power flow through the system is tabulated below.

Power In	a.c. Bridge Power	d.c. Bridge Power	Total W + F	W + F + d.c. Bridge Power
(Watts)	(Watts)	(Watts)	(Watts)	(Watts)
874	-	120	645	765
1840	758	792	795	1587
2270	985	1008	855	1863
2700	1167	1224	940	2164
3195	1303	1368	1080	2448

TABLE 6

Analysis of current and power flows within the system requires a separate circle diagram for the induction machine for each result as operation is at different frequencies. The electrical operating frequencies and induction machine magnetising currents are tabulated below and circle diagrams for each result were drawn.

The real and quadrature currents of the induction machine were found from the circle diagrams. The current flowing through the diode bridge must be real. Thus the real and quadrature currents of the synchronous machine can be deduced. The real component of the synchronous machine current supplied electrical losses plus windage and friction. This allows for a second estimate for the real component to be found from

$$I_{REAL} = \frac{\text{Windage + Friction}}{\sqrt{3}\, V_1}$$

which gives a check on current deduced from circle diagram analysis. The current flows are given in Table 7.

I_R	I_Q	$\sqrt{I_R^2 + I_Q^2}$	I_{METER}	I_{AC}	I_R	I_Q	$\sqrt{I_R^2 + I_Q^2}$	I_{METER}	$\frac{W + F}{3V_1}$
(A)	(A)	(A)	(A)	(A)	(A)	(A)	(A)	(A)	(A)
-	3.5	3.5	3.5	-	-	3.5	3.5	3.4	1.3
3.5	3.8	5.2	5.2	2.5	1.0	3.8	3.9	4.2	1.6
4.7	4.0	6.2	6.1	3.3	1.4	4.0	4.2	4.6	1.7
5.4	4.2	6.8	6.9	3.9	1.5	4.2	4.5	5.0	1.9
6.2	4.6	7.7	7.7	4.3	1.9	4.6	5.0	5.6	2.1

TABLE 7

D.C. machine I must supply the power produced by the induction generator, the induction generator losses and the windage and friction losses of motor generator set I. This is shown in Table 8.

D.C. Power In	W & F I	Power of Ind. Gen.	W & F + P of Induct. Gen.	Losses
(Watts)	(Watts)	(Watts)	(Watts)	(Watts)
875	245	-	-	-
1840	295	1091	1386	454
2270	325	1465	1790	480
2700	360	1702	2062	638
3195	430	1976	2406	789

TABLE 8

The induction generator must supply the power flowing through the diode bridge, the windage and friction losses of motor-generator set II, and the electrical losses of the system. This is shown in Table 9.

Power of Induct. Gen.	W & F II	Bridge Power	Bridge Power + W & F
(Watts)	(Watts)	(Watts)	(Watts)
1185	400	120	520
1590	530	1008	1292
1954	580	1224	1804
2263	650	1368	2018

TABLE 9

Thus power flows through the system are shown to balance within the expected experimental accuracy of 10%.

As can be seen from Table 7 the currents flowing within the system can be accounted for within an accuracy expected using a circle diagram. It should be noted that the synchronous machine must supply all the quadrature current for the induction machine not just the magnetising current.

From Table 5 it is evident that the system is stable in steady state over a large range of operating speeds (1500 - 2184 r.p.m.). As the d.c. machine is driven faster, using field control, more power flows into the induction generator. The induction generator must rotate at the same speed as the d.c. machine as they are coupled together mechanically. This forces the speed of the synchronous machine to rise to a value determined by the speed of the induction machine and the fractional slip required to transmit the incoming power electrically. The system frequency is determined by the speed of the synchronous machine and therefore also increases with incoming power. As the frequency increases the magnetising current drawn by the induction machine decreases. However, this reduction in quadrature current is more than compensated by the increase due to the new operating points on the circle diagram. Thus the current flowing from the synchronous machine increases.

As more mechanical power flows into the induction generator, more electrical power is produced. Most of this power is transmitted by the diode bridge while the remainder is dissipated as windage and friction losses in the synchronous machine. Increased power flow through the diode bridge is directly proportional to increased current flow through it as the voltages are fixed at both sides of the bridge.

4.2 Synchronous Alternator/Rectifier System

4.2.1 Supply

Although the most suitable form of supply would have been a synchronous machine driven directly from a variable speed shaft due to machine unavailability, at this stage, it was necessary to use the 3-phase mains in conjunction with a 3-phase rheostat to provide a varying supply. This was indeed convenient as it provided opportunity to test the system under worst case conditions, i.e. step changes in voltage.

4.2.2 Controlled Bridge Rectifier

The thyristor bridge had an average current rating (d.c.) of 12 A with an r.m.s. rating (a.c.) of 18.5 A. For experimental purposes it was decided not to exceed the 12 A rating.

The thyristors were the 12RCM40 type manufactured by International Rectifier. The maximum repetitive reverse voltage of these devices was 400 V.

Incorporated in the bridge were three Westinghouse 3D82LED/321 driver circuits mounted on p.c. cards. Two terminals on the driving circuit were available for the connection of a d.c. control voltage in the 0 - 3 V range.

4.2.3 Feedback Control

From equation $V_{dc} = \frac{3E_m}{\pi} \cos \alpha$ volt, the control parameters for a steady d.c. output are the a.c. line voltage and the bridge firing angle. In the first part of the study, no attempt was made to control the a.c. line voltage; this simulated the condition of a constantly excited variable speed alternator. The control of the d.c. output was done by phase angle control only.

A nominal d.c. level of 100 V and output control over a range of two to one in alternator speed were decided upon. The closed loop system shown in figure 26 was designed and built.

The feedback unit was basically a d.c. inverting amplifier operating on an input range of 0 - 12 V and giving an output compatible with the thyristor firing circuits described above. Provision was made in the divider circuit for changing the nominal output voltage should this be required.

4.2.4 System Testing

Successful operation of the bridge and the control units on open loop were verified before closed-loop tests were made.

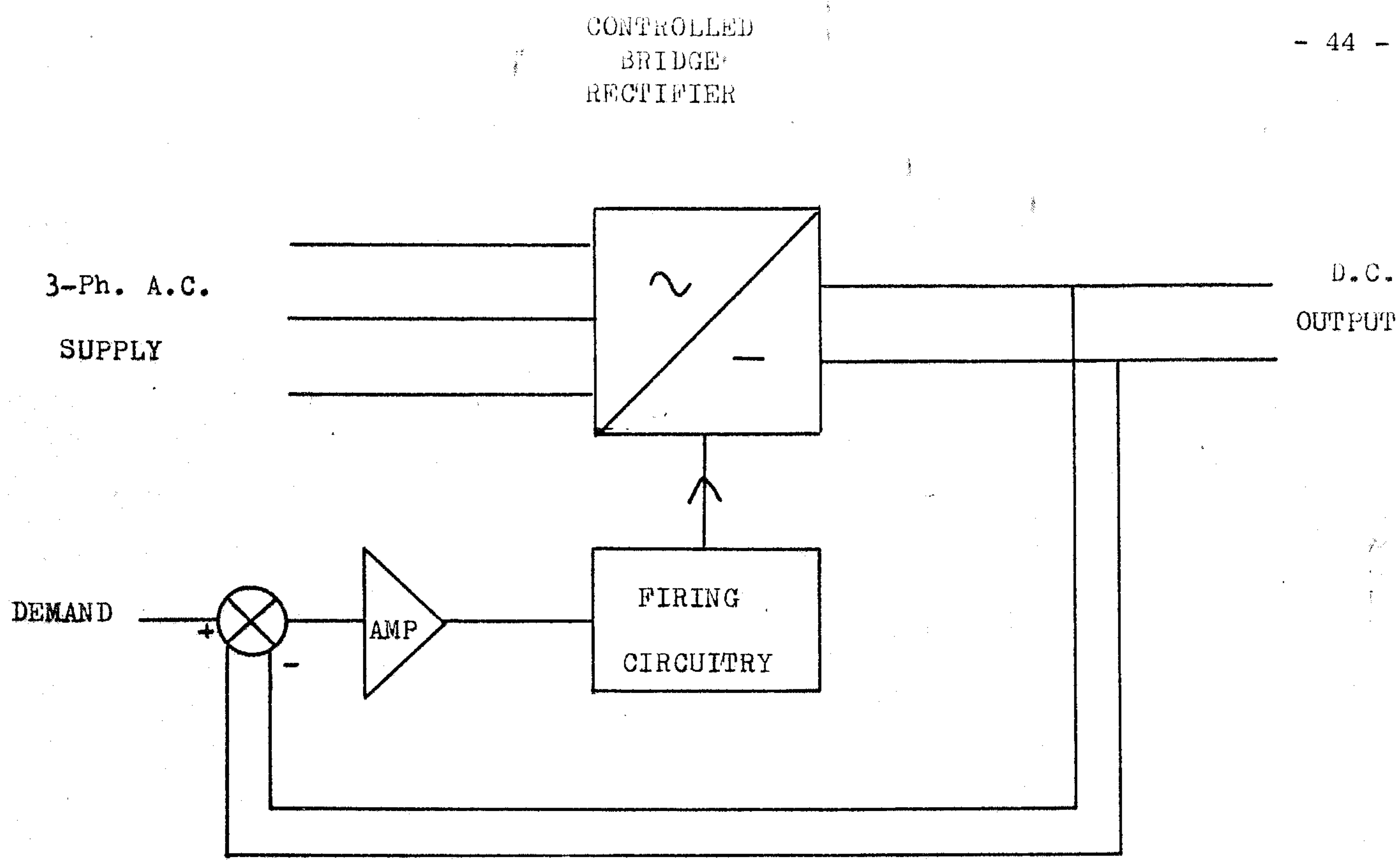


Figure 26: Negative Feedback Control System

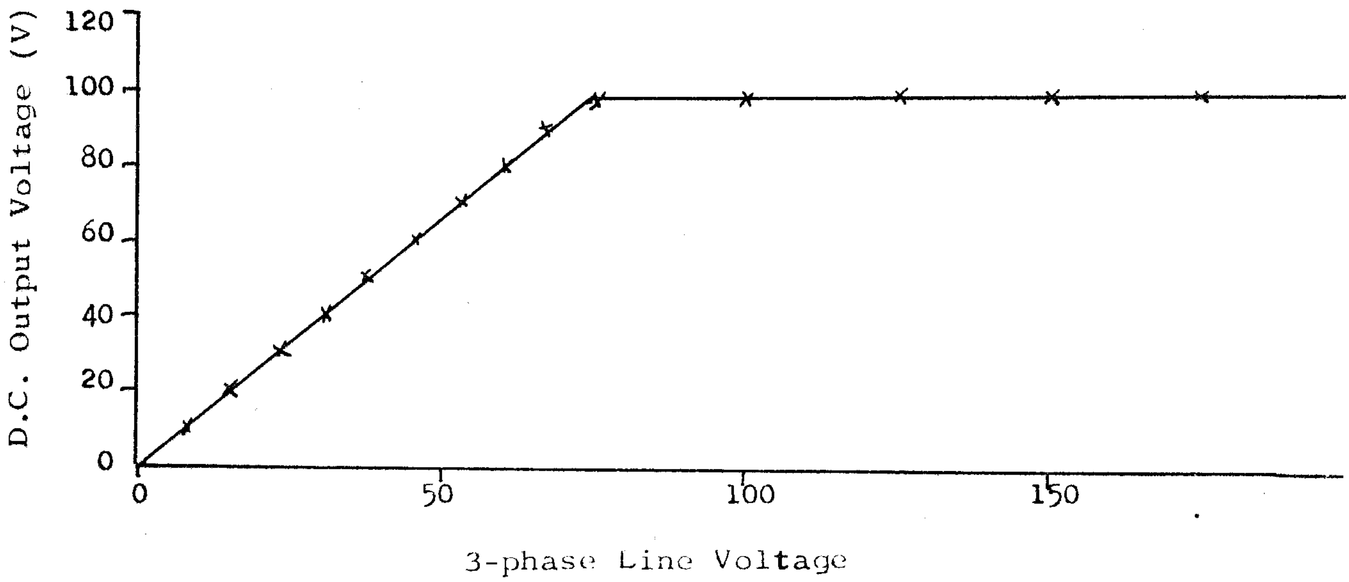


Figure 27: Controlled Rectifier System Input/Output Characteristics

4.2.4.1 Closed-Loop Testing

The a.c. line voltage was varied from 0 to 200 V r.m.s. and the resulting d.c. output voltage measured. The results are plotted in figure 27. Control can only be achieved when the input voltage reaches a value corresponding to 100 V or greater on the output, i.e. about 75 V r.m.s. Thereafter, a change in input of 150% i.e. 75 - 200 V resulted in an output controlled to within ±1% of nominal.

4.2.4.2 Settling-Time of the System

To test the effect of a step input, the rheostat was used to increase the a.c. input from 100 to 200 V in 0.5 seconds. A storage oscilloscope was used to monitor the d.c. output.

The effect of other alternator/bridge rectifier systems operating in parallel was simulated by smoothing the output with a large value capacitor.

It was found that the time for the system stabilisation at 100 V was set basically by the capacitor, not by the control electronics and was less than 0.8 seconds.

This was as expected and suggested that in a fully realised system where the parallel capacity of the other units would be much greater than that of the capacitor used in the present tests, the electronics would control successfully even the most arduous transient conditions.

4.2.5 Alternator and Diode Bridge

Because of the relatively high cost of the controlled rectifier, any system using this method of d.c. voltage stabilisation would be expensive. An alternative, and possibly cheaper method of d.c. voltage control is to control the alternator excitation and rectify this controlled a.c. voltage using a diode bridge.

Such a system, shown diagrammatically in figure 28, was built and tested.

4.2.5.1 System Design and Testing

The 3-phase output from the synchronous machine was connected to the 3-phase bridge rectifier. A voltmeter was placed between the red and yellow phase of this input to monitor the r.m.s. line voltage. The rectifier was loaded with a 100 Ω resistor. Suitable interfacing electronics was built for the feedback loop.

Having determined the alternator output voltage characteristics with speed and excitation and the transfer characteristic of the control circuit on open loop, the system was tested on closed loop. The d.c. output voltage was stabilised to ± 1.5% of nominal for a 16% change in alternator speed. This was considered unacceptable and was probably due to the large uncertainty of the value of h_{fe} of the power transistor over operating range. The system was abandoned for the present and plans are in hand for a more accurate power electronic controller.

5. DISCUSSION OF RESULTS

5.1 Induction Generator System

Although successful system operation was achieved using the resistively loaded system described in Section 4.1.4, this system was found to have the disadvantage of a varying generation voltage. An improvement was made using the laboratory d.c. supply and a diode bridge to set the a.c. system voltage. This scheme, which is described in Section 4.1.5, more accurately simulates generation into a large national grid system.

The power flow through the diode bridge was determined by the power generated less the system losses. Power flows through the bridge

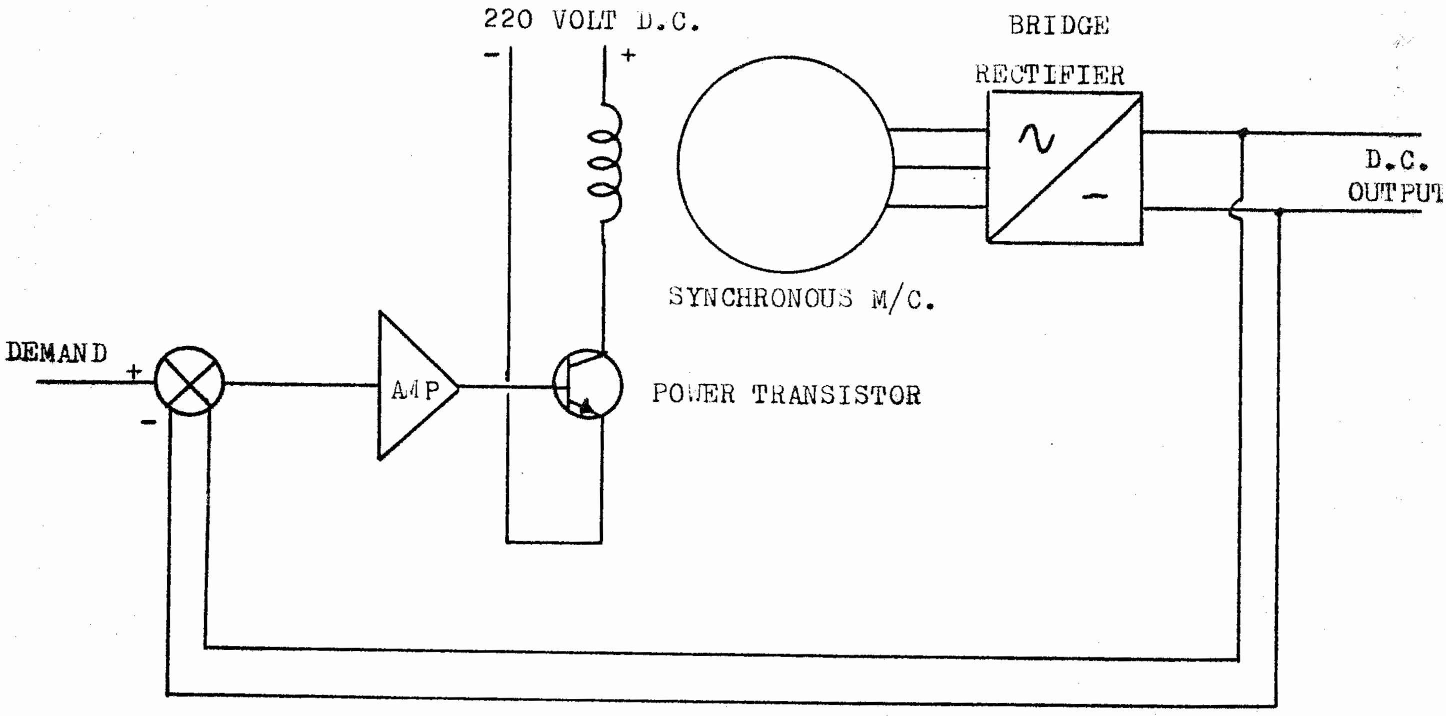


Figure 28 Negative Feedback System.

as soon as the a.c. voltage rises sufficiently to allow the bridge to conduct. The voltage at which this occurs depends on the d.c. voltage which the diode bridge feeds. The synchronous machine speed which corresponds to the threshold voltage of the bridge depends on the field excitation used. A higher field excitation results in the bridge conducting at a lower machine speed.

It was shown that the system was stable for a large range of operating speeds, 1000 - 2000 r.p.m. The induction machine speed was determined by the d.c. machine driving it and since this was shunt-connected, a higher speed meant a correspondingly larger power flow. The synchronous machine speed was determined by the induction machine speed and the operating slip corresponding to a given power output.

5.2 Controlled Rectifier System

Here, successful system operation was achieved with a transfer efficiency of about 95%. Voltage control was within ±1% for a large range of input voltage (150% change) and transient conditions appear to have presented no serious problems.

5.3 Field Control of Alternator

This system was considered not to have been successful; control was within ±1.5% for a 16% change in alternator speed. It was felt that the shortcomings were not inherent in the idea but in the design of the control circuit. Construction of testing of a different power electronic controller is being considered.

6. IMPLICATIONS TO WAVE POWER GENERATION

It is probably that each duck will be some 20 m long. Thus the average incident power level on the duck will be approximately 1 MW based on the average power density of 50 kW/m. However, the peak incident power level will be around 4 MW, assuming a torque cut-out at 200 kW/m. The electrical rating of the machines will therefore be very dependent on how much incident energy can be stored over short time intervals.

There are currently two possible generation philosophies:

(i) electrical generation on the duck itself

(ii) separate generation pods at the ends of each duck string

In the former, the generation system must fit between the backbone and the shell of the duck. This limits the diameter of the system to approximately 1 m^2. Machines with ratings in excess of 500 KVA are unlikely to be suitable because of their physical size. Each duck would therefore contain several 500 KVA induction machines; the exact number depending on the installed over capacity. (Over capacity is defined here to mean the installed capacity compared with the average power level experienced over the year). If the induction generator system were adopted alone, a synchronous machine for each three induction generators would probably be required. The bent-axis motor, the induction generator and the required control systems would probably be in a hermetically sealed box with high pressure oil flowing in at one end and three-phase electric power flowing out of the other. For transmission to the sea-bed, generation voltage would be as high as possible. This could be 415 V, 3.3 KV or possibly 11 KV. If the synchronous machine were itself also driven by the duck, its output could be fed via a rectifier onto the d.c. rail.

In the second generation system, hydraulic oil would be pumped along the length of a string of ducks to generation pods at each end. The advantages of this system are:

(a) reduced possibility of corrosion problems on the duck due to stray currents in steel which is in contact with sea-water

(b) more freedom in machine design.

In the generation pod system, the generator size is limited to around 2 MVA by the maximum economic size of bent-axis motors. For the induction generator system, the synchronous machine size will depend on how many induction generators it is desirable to have connected together.

Although further work is required on system dynamics when many generating units are connected together, it is possible to speculate at this stage about possible generation configurations. These are shown in figures 29 and 30. There are, of course, other possibilities.

7. CONCLUSIONS

The following conclusions are drawn from the work reported above.

(1) An asynchronous a.c. generation system using an induction machine coupled to a synchronous machine operates satisfactorily at a scale factor of about 1:200.

(2) An overall electrical generation efficiency for the induction generator system of 60% has been achieved in the laboratory. This is a pessimistic figure since the laboratory systems used inefficient teaching machines and also involved windage and friction losses of two d.c. machines which would not be included in a practical system. A fair estimate of electrical system efficiency from generator input to transmission link is probably about 85%.

(3) For the induction generator system machines of the same rating one synchronous machine is required for three induction machines, and speed ranges of 1000 - 2000 r.p.m. are possible for stable machine operation.

(4) A system using controlled rectification of a variable a.c. input operates successfully at a scale factor of about 1:200.

(5) Limited success was achieved with a.c. voltage control of an alternator/diode bridge arrangement.

8. REFERENCES

1. Draper, A. Electrical Machines, 2nd Edition (1971) Longmans, London.

2. Edinburgh University Wave Power Group, Private Communication (1977).

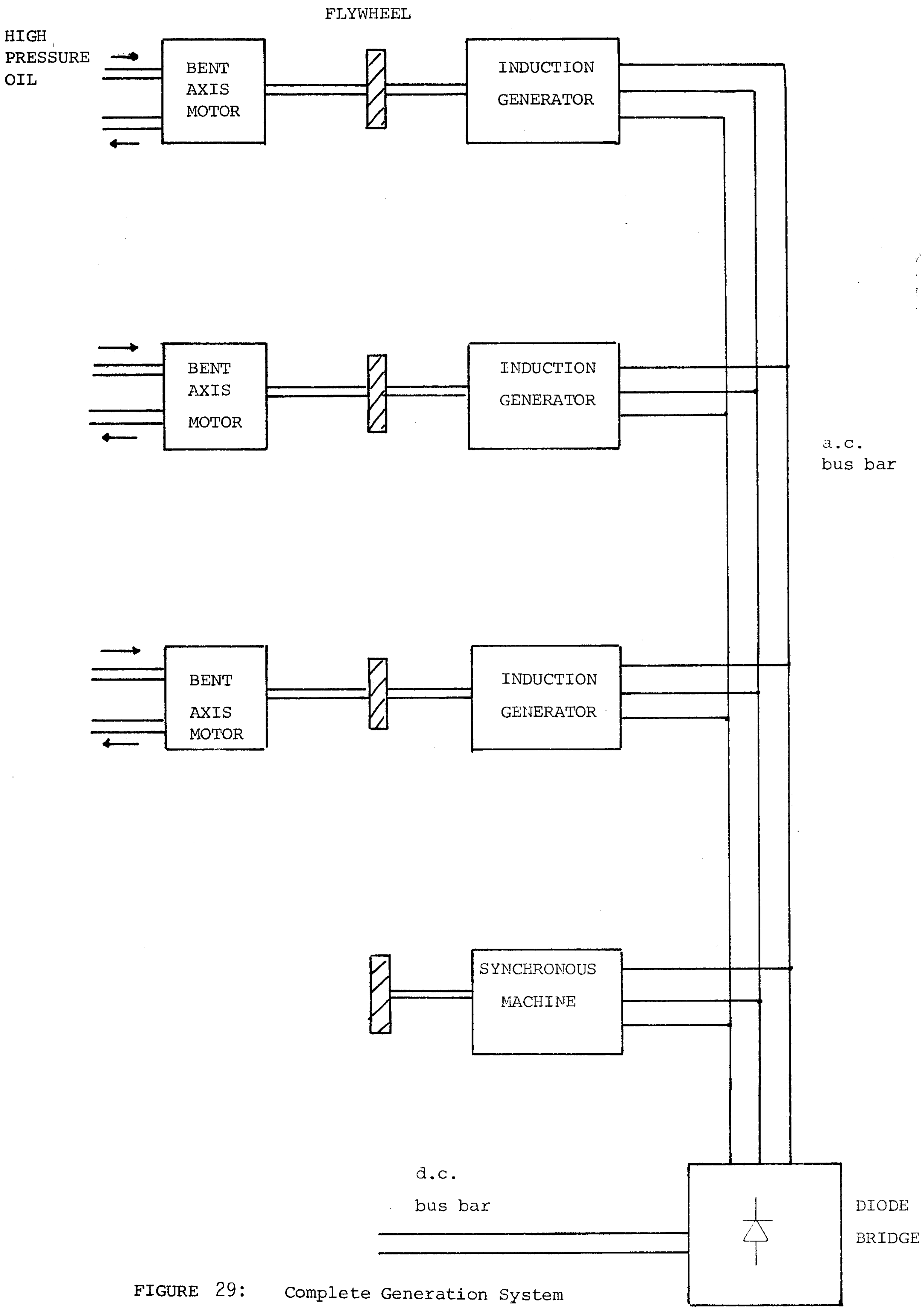


FIGURE 29: Complete Generation System

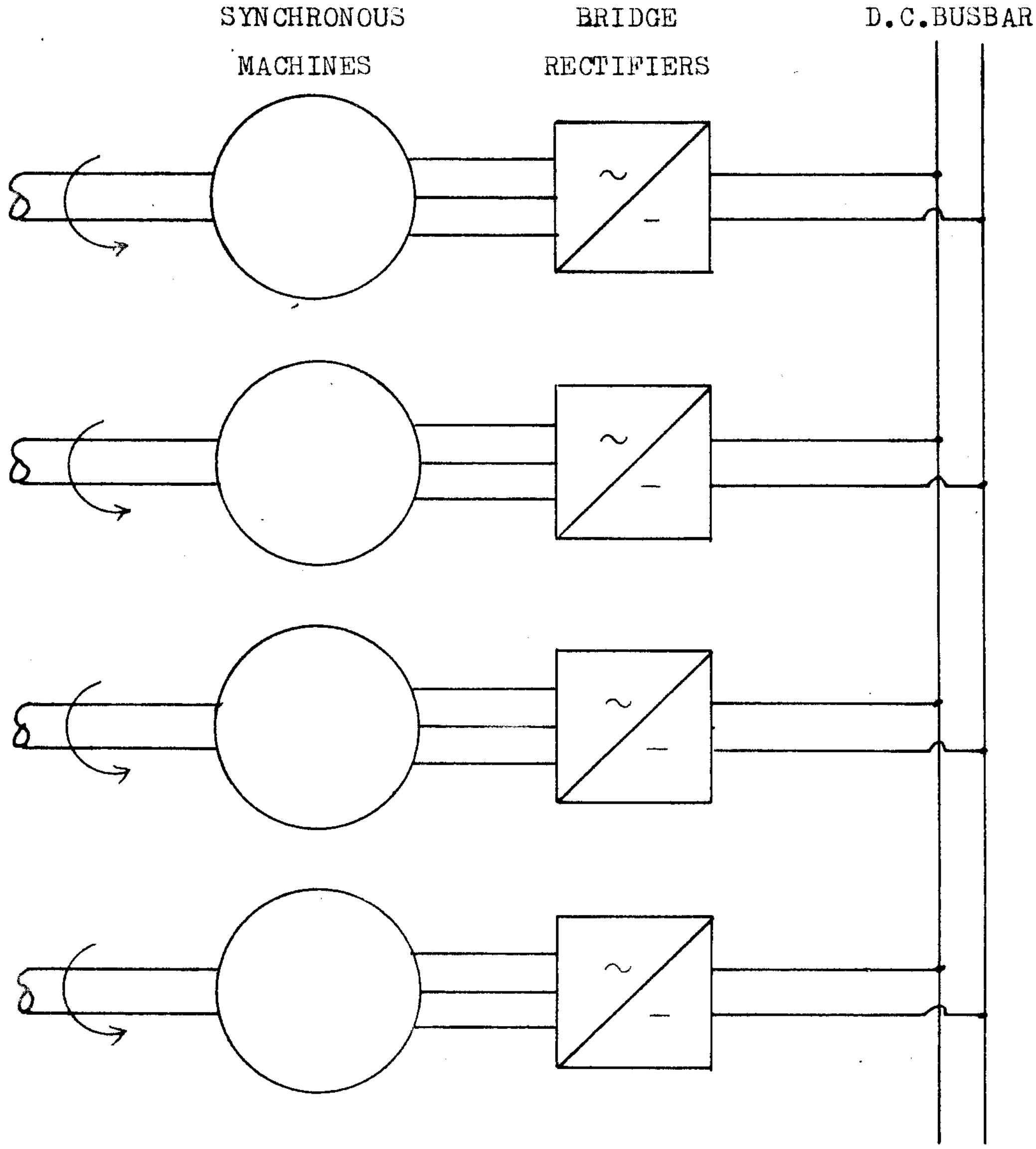


Figure 30: Alternator/Rectifier System

APPENDIX I

Computer Simulation

In parallel with the laboratory studies of each of the generation systems, computer simulations were undertaken.

Induction Generator System

Here the two-phase equivalent circuit model for induction and synchronous machines given below was required. These equivalent circuits are valid for both static and dynamic analysis. The two-phase equivalent circuit of the induction machine is given in Figure I.1 and that of the synchronous machine in Figure I.2.

Symbols used are defined:

R = stator resistance

RR = rotor resistance referred to the stator

LL = rotor leakage reactance referred to the stator

VGD = generation voltage in the D phase given by

$$VGD = WM \int_0^t VSQ - (WM \times IRQ \times LL)$$

WM = the mechanical speed of the machine

IRQ = rotor current in Q phase

VSD = voltage across the referred rotor circuit in D phase

VSQ = voltage across the referred rotor circuit in Q phase

VGQ = generation voltage in the Q phase given by

$$VGQ = WM \int_0^t VSD - (WM \times IRD \times LL)$$

VSDO, VSQO = applied voltage to D and Q phase respectively which have a phase difference of 90^0

IMD = the magnetising current in the D phase

IMQ = the magnetising current in the Q phase

Symbols for the synchronous machine are defined similarly but with an extra S to differentiate between the two machines.

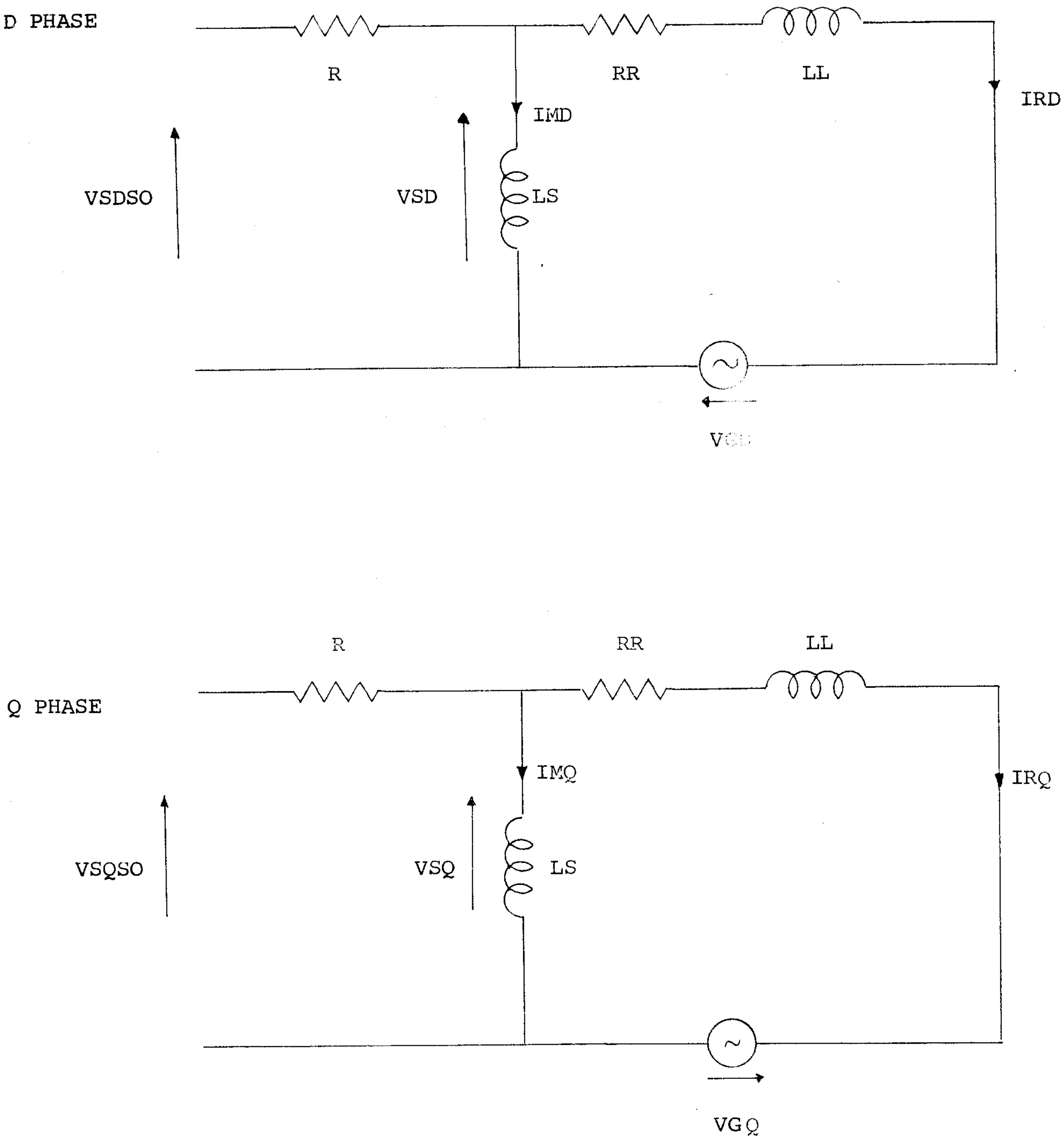


FIGURE I .1 Two-phase Equivalent Circuit for an Induction Machine.

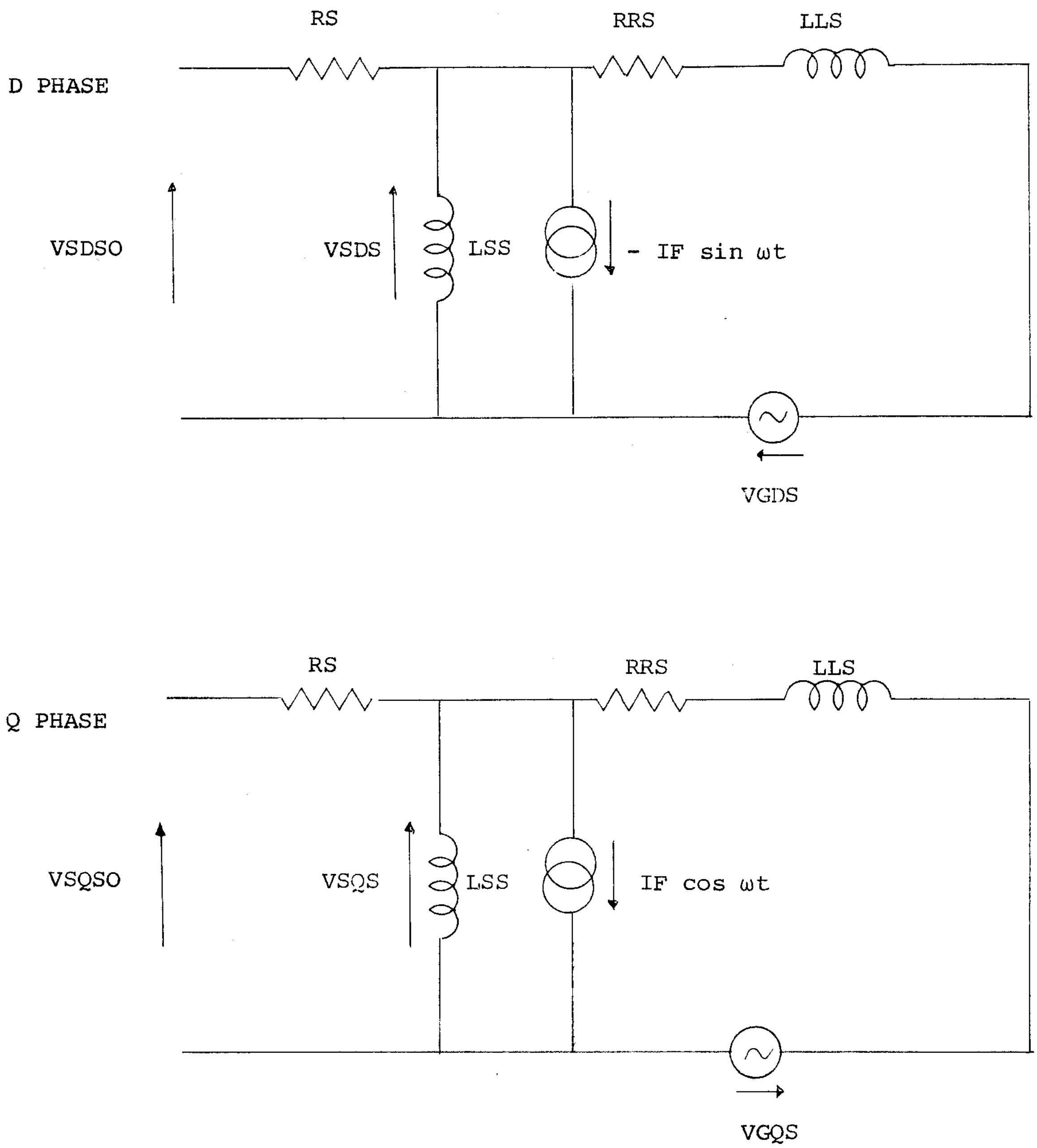


FIGURE I .2 Two-phase Equivalent Circuit for a Synchronous Machine.

Controlled Rectifier System

Here two programs were written; one to simulate the operation of a controlled bridge rectifier and one to simulate the operation of a rectifier feeding onto a d.c. busbar.

The first program was written to examine the output from a rectifier bridge. Written into this program is a routine to output on the graphplotter so that waveforms could be examined in detail.

The second program was written to simulate the effect of a bridge rectifier feeding into a d.c. busbar.

In both cases software studies were made to predict system performance before laboratory tests were made. In addition, simulations could be made of the effects on performance of altering system parameters. For example, the effect of different rotor inertias was studied in the case of the induction generator scheme. Further more detailed computing is planned.

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15 June 1977