A RECTIFIER-INVERTER VARIABLE SPEED DRIVE FOR A SYNCHRONOUS MACHINE

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ABSTRACT

Many inverter-controlled, a.c. motor, variable-speed drives have been described in the last 15 years, and it was widely expected that they would replace d.c. drives in many applications. That they have not done so is due mainly to the high cost of the inverter. However, substantial cost reductions can be made by utilizing an over-excited synchronous machine to commutate the inverter thyristors, thus saving on expensive commutation components.

In this project, a controlled rectifier/naturally commutated inverter/synchronous machine system employing rotor position detectors to control inverter frequency was designed and built, and tests results compared to results gained from a computer simulation of the system.

Novel features in the system include the use of feedback diodes across the inverter thyristors to permit sinusoidal currents to flow in the machine thus reducing machine iron losses, and the design of a thyristor-conduction detection system, which both allows more efficient operation during starting, and gives protection against d.c. link short-circuits at all speeds.

DECLARATION

I declare that this thesis has been composed by myself, and that the work contained within it is my own.

signed

D E Macpherson

ACKNOWLEDGEMENTS

In completing this work I would like to acknowledge the contributions made by others to the project. Foremost, I wish to express my thanks to Dr. H.W. Whittington and Mr. J. Shepherd of the Department of Electrical Engineering at Edinburgh University for their guidance and encouragement throughout the course of the project. Mr. Shepherd should also take the credit for the development of the computer model of the system.

Much valuable information concerning particularly the pumped-storage application of the system, was obtained from the North of Scotland Hydro-Electric Board, and I would like to mention Mr. R.M. Gove, the late Mr. A. Cochran and Mr. A. Marshall, who all gave freely of their time and expertise towards the project.

Credit for the cubicle construction and the inter-circuit board wiring should go to Mr. C. Taylor, who put many hours and much effort into the work.

Finally, I would like to thank Mrs Linda Halstead, who has transformed an untidy manuscript into the present form.

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SYMBOLS

δ	machine load angle
I_F	field current
E_F	back E.M.F. induced by I_F
I_D	current in the direct field winding
E_D	back E.M.F. induced by I_D
I_Q	current in the quadrature field winding
E_Q	back E.M.F. induced by I_Q
e_R	instantaneous value of E_F in the red phase
e_Y	instantaneous value of E_F in the yellow phase
e_B	instantaneous value of E_F in the blue phase
$V_{D.C.}$	d.c. link voltage
$I_{D.C.}$	d.c. link current
θ	phase angle between machine phase current and phase voltage
μ	commutation overlap angle
X_L	machine magnetising reactance
R	effective machine winding resistance
T	machine output torque
TPR	positive thyristor in the red phase
TPY	positive thyristor in the yellow phase
TPB	positive thyristor in the blue phase
TNR	negative thyristor in the red phase
TNY	negative thyristor in the yellow phase
TNB	negative thyristor in the blue phase
B_S	magnetic flux density set up by the stator currents
B_R	magnetic flux density set up by the rotor currents
α	angle in space between B_S and B_R

B_{red}	magnetic flux density set up by the current in the red phase
B_{yellow}	magnetic flux density set up by the current in the yellow phase
B_{blue}	magnetic flux density set up by the current in the blue phase
A	output from transducer A (after the buffer stage)
B	output from transducer B (after the buffer stage)
C	output from transducer C (after the buffer stage)
D	output from transducer D (after the buffer stage)
L	signal from thyristor state detection circuit around TPR
M	signal from thyristor state detection circuit around TPY
N	signal from thyristor state detection circuit around TPB
P	signal from thyristor state detection circuit around TNR
Q	signal from thyristor state detection circuit around TNY
S	signal from thyristor state detection circuit around TNB
X, Y, Z	signals from the comparator circuit, a measure of machine speed

CHAPTER 1 : INTRODUCTION

Ever since Gramme built the first industrial synchronous machine in 1878[1], generators in power systems have, almost exclusively, been of this type. Features of a 3-phase output with frequency proportional to rotational speed, a rugged, inexpensive design, a large power handling capability, and control over power factor make the synchronous machine an attractive choice as the generator in almost all power stations, regardless of scale or the energy source.

The characteristic of frequency proportional to rotational speed has severely restricted the use of synchronous machines as motors. The problems associated with accelerating the motor to its operating speed have resulted in other types of motor - normally either induction motors or d.c. motors - being used for all but the few drive applications where it is desired to hold the speed steady at one precise value.

The recent rapid progress in the power handling capabilities of thyristors, together with their reduced cost, has led to the development of static frequency converter systems which have a variable frequency output suitable for the control of synchronous motors.

1.1 SYNCHRONOUS MOTORS IN PUMPED-STORAGE SCHEMES

The growing interest in hydro-electric pumped-storage schemes has prompted much interest in methods of starting synchronous motors. To avoid redundancy of equipment, and to reduce civil works and thereby costs, it is desirable to use the same machines both for pumping and generating, and since synchronous machines are generally used for power generation, a system is necessary to accelerate this type of machine to synchronous speed when commencing operation in the pumping mode.

There are four main methods in use today for the starting of synchronous motors in pumped-storage schemes[2,3,4] :

1. 'back-to-back' starting ;
2. auxiliary 'pony' motor starting ;
3. asynchronous starting ;
4. static frequency converter starting.

Back-to-Back Starting

The use of an adjacent set for 'back-to-back' starting is achieved by connecting the two machines via their stators, so that one acts as a generator and the other as a motor. The fields of both are excited, and water is admitted to the turbine of the generating machine. After a few hunting cycles the motor synchronises with the generator and the two machines accelerate smoothly together. This system is inexpensive as no extra equipment is required, but it does have two disadvantages. The last set in the station must be started by an alternative method, and also stored water is being used at a time when the reservoir level may be low, so care must be taken that the level does not fall below the point where there is insufficient water to start the machines.

Pony Motor Starting

This is the method adopted for the four sets at the North of Scotland Hydro-Electric Board pumped-storage scheme at Cruachan. Here the machines are started by induction motors situated above the main motor/generator sets and mounted on the same rotor shaft. Each pony motor is wound such that its synchronous speed is greater than that of the motor/generator set, so that the motor/generator set can be accelerated to a speed fractionally above synchronous speed, at which point the pony motor is electrically disconnected and the motor/generator set synchronized with the mains. A typical pony motor power rating is 5% that of the motor/generator set that it is driving. Pony motor starting is expensive, not just because of the cost of the extra machine per set, but also because of the increased machine hall size[3] - a not inconsiderable factor in an underground station such as Cruachan - and the increased bearing load. A further disadvantage is that the pony motor must be removed before maintenance work can be carried out on the motor/generator set[5,6].

Asynchronous Starting

Asynchronous starting involves starting the synchronous machine as an induction motor using its damper windings, and connecting the stator directly to the grid system[2]. This method is cheap and simple, but it may draw very high currents and cause unacceptable local voltage drops on the grid system. Methods of reducing the starting current include the use of a series reactor, transformer tappings, or an autotransformer. These modifications, however, reduce the cost advantage of asynchronous starting without completely solving the problem of high currents and the resultant heating effect in the rotor and stator windings[3,7].

Static Frequency Converter Starting

Recently several electricity authorities have installed static frequency conversion equipment for starting the motor/generator sets, normally with the facilities for a 'back-to-back' start included as a reserve. A controlled rectifier feeds a constant d.c. current to a variable frequency, naturally commutated inverter which feeds the machine[8,9,10]. The inverter frequency starts either at zero or at a very low value, and is increased as the machine accelerates. A smooth, synchronous run-up to full speed is thus achieved, at which point the rectifier/inverter system is disconnected and the motor/generator set is synchronized directly to the mains.

The static conversion equipment is expensive, but only one set of compact equipment is necessary for a sequential start up of all the motor/generator sets. The disturbance to the grid system is low, and reliability has proved to be very good[8,3].

General Comments

Where the size of the individual sets is below about 100 MW, asynchronous starting is generally used, sometimes at a reduced voltage or with a series reactor to keep the starting currents low. Either pony motor or 'back-to-back' starting was invariably used for larger sets until 1974, when the first pumped-storage scheme to employ static converter synchronous starting was commissioned at Foyers on Loch Ness. Since then two schemes in the United States[4], Raccoon Mountain in the Tennessee Valley and Mount Elbert in Colorado, have been built which use static converter starting, and a similar starting system to that at Foyers is at present being installed at Dinorwic in North Wales[8].

1.2 VARIABLE SPEED DRIVES

Static frequency converter/a.c. motor systems are becoming increasingly competitive in variable speed drive applications; an area in which, until a few years ago, the d.c. motor was mostly used. The d.c. motor has characteristics of speed proportional to armature voltage and inversely proportional to field current, and torque proportional to armature voltage and field current, which make it flexible and easily controllable. The advent of the thyristor bridge rectifier has greatly facilitated the armature voltage control, and, if two anti-parallel bridges are used, the system is capable of four quadrant operation.

The d.c. motor has three main drawbacks :

1. The cost of the machine is high in comparison to its a.c. counterparts, due to the mechanical commutator.

2. The d.c. machine has high maintenance requirements.

3. There is a relatively low upper speed limit (typically about 3000 rpm) set by the current switching capability of the mechanical commutator.

Despite the expensive mechanical commutator, the cost of a complete d.c. motor drive system is generally less than the cost of an a.c. motor system[11], due to the high cost of the frequency conversion equipment. However, a.c. drive systems have been preferred in a number of instances, such as in the chemical industry[12] where the chemically laden atmosphere would necessitate much commutator maintenance in a d.c. motor system.

1.3 STATIC FREQUENCY CONVERTERS

There are two main types of 3-phase frequency converters :

1. The 18 thyristor cycloconverter which converts 3-phase fixed frequency to 3-phase variable frequency.

2. The 6 thyristor bridge inverter which converts d.c. to 3-phase variable frequency. If it is to operate from the 3-phase mains supply another 6 thyristor bridge is used to convert the mains to d.c.

1.3.1 The Cycloconverter

The cycloconverter has attracted a lot of attention as a variable speed motor drive, particularly where the maximum required output frequency is small relative to the supply frequency. The system (figure 1.1) consists of six phase-controlled rectifiers connected to the a.c. supply, two controlling the current to each phase. The firing of the rectifiers is controlled to produce the output voltage waveform shown in figure 1.2.

The principle limitation to the cycloconverter is that the harmonic distortion of the output waveform increases as the output frequency rises, due to the fewer number of segments of supply voltage which form one cycle of output voltage[42]. In practise, the output frequency should be limited to about one-third of the supply frequency to prevent the resulting losses becoming excessive. This can be a very serious restriction when operating from a 50 or 60 Hz supply. A further drawback to the

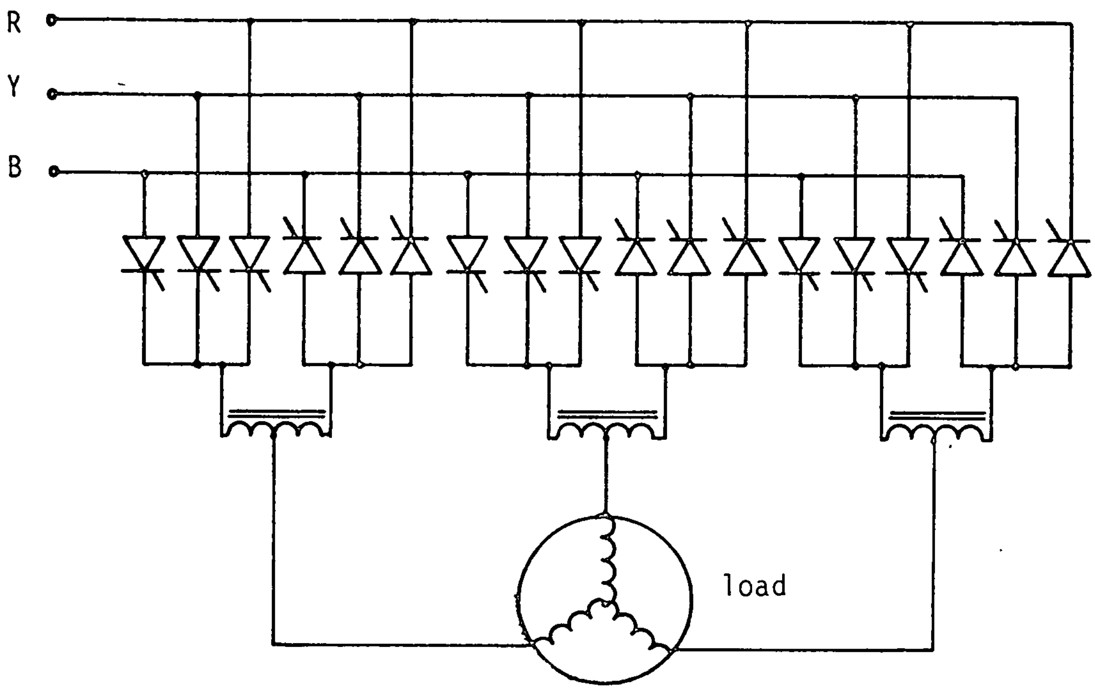


Figure 1.1 A Cycloconverter

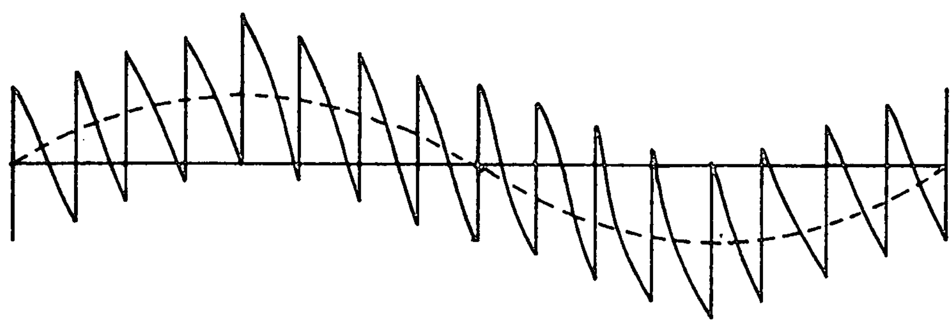


Figure 1.2 Typical Cycloconverter Phase Output Voltage

cycloconverter is the need for 18 power thyristors, as compared to 12 for the controlled rectifier/d.c. link/inverter system.

1.3.2 3-Phase Bridge Inverters

The 3-phase bridge inverter, shown in figure 1.3, employs 6 thyristors (or power transistors) to switch the inverter d.c. input from one phase to the next to produce a 3-phase, quasi-square output waveform. The order of firing of the thyristors is 1-6-2-4-3-5-1 ... : the period of conduction and the method of thyristor commutation depends on the system.

The d.c. supply to the inverter is usually either a battery eg, in battery driven vehicles[11,13,14], or a bridge rectifier fed from the mains. If a battery source is chosen a d.c. chopper is inserted in the d.c. link between the battery and the inverter to provide voltage control of the inverter output. If the power source is a controlled rectifier, voltage control may be achieved by varying the rectifier delay angle. However, in the latter case, operation with a large delay angle leads to a poor power factor on the a.c. side of the rectifier, so some designers prefer an uncontrolled rectifier with voltage control by a chopper in the d.c. link.

3-phase, bridge inverters can be sub-divided into three groups : forced commutated inverters, transistor inverters and naturally commutated inverters.

Forced Commutated Inverters

The forced commutated inverter is the type of inverter at present most commonly used. Several different commutation circuits have been described by various authors[12,15,19], most of which depend on the triggering of one thyristor allowing current to flow in an L-C circuit, temporarily putting a reverse voltage across the thyristor which is to be commutated. The thyristor which instigates the commutation may be one of the other main inverter thyristors, or it may be an auxiliary thyristor. A typical circuit employing auxiliary thyristors is shown in figure 1.4 [15,20].

There are three distinct methods of operating a forced commutated inverter : with 120^o conduction, with 180^o conduction or with pulse width modulation (p.w.m.). In the first case each thyristor only conducts for 120^o, after which the thyristor is forced commutated. Hence at any one instant only two thyristors are conducting. A feedback diode across each thyristor protects the thyristor from the large voltage spike which would occur through suddently switching off the phase current. An advantage of 120^o conduction is that the commutation of one thyristor may be started by the firing of another main thyristor, without the need for any auxiliary thyristors. The phase currents, however, are zero for 120^o per cycle and the phase voltage waveform is very irregular.

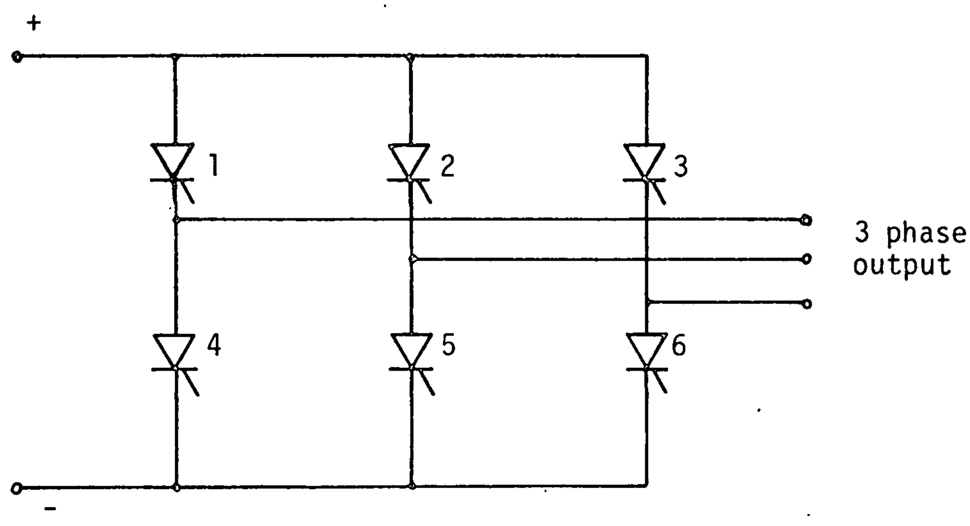


Figure 1.3 Basic 3-Phase Thyristor Bridge Inverter

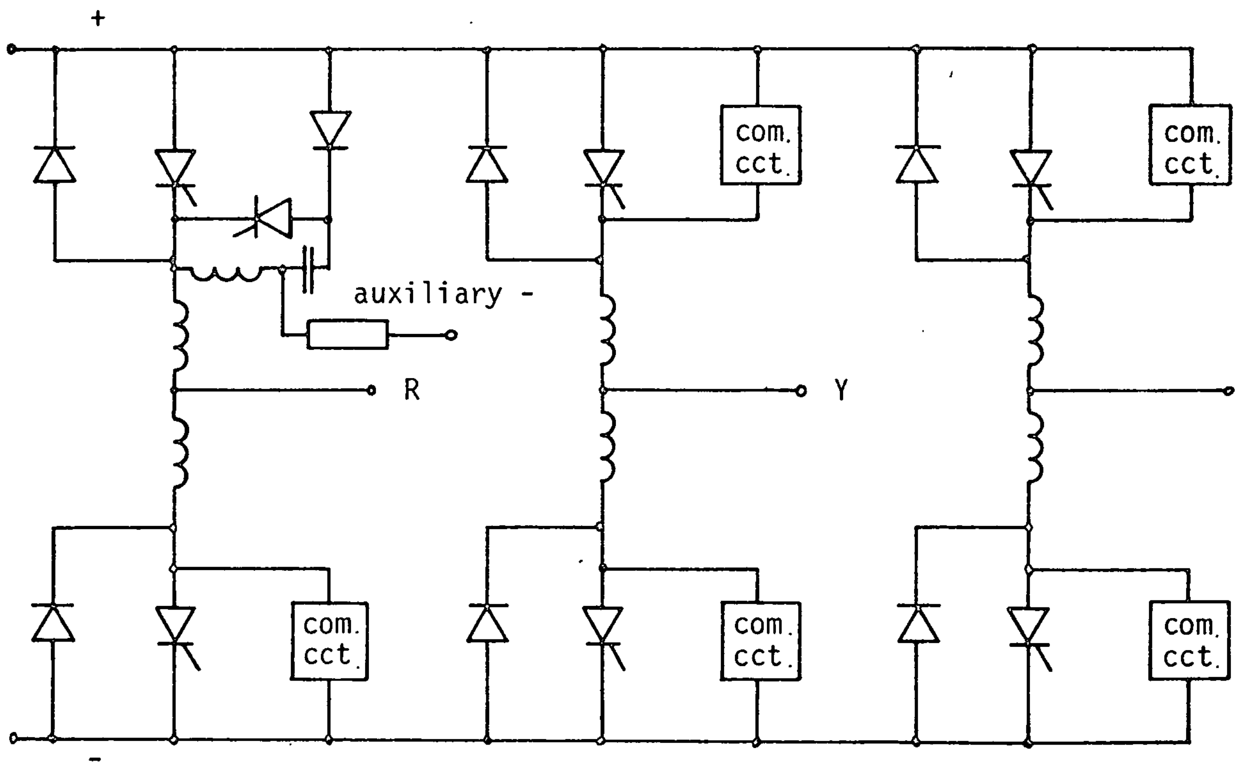


Figure 1.4 Typical Forced Commutated Inverter

If the inverter is operating with 180^{o} conduction, there are three thyristors conducting at any given instant, and there are no periods of zero phase current. In practice, the inverter will only operate with 180^{o} conduction if the machine has a unity power factor. If, say, the phase voltage leads the phase current by 20^{o}, each thyristor will conduct for 160^{o}, and the appropriate feedback diode for the remaining 20^{o}.

Lipo and Turnbull[21] studied both 180^{o} inverters and 120^{o} inverters, and found that motors supplied from a 120^{o} inverter have a maximum developed torque about 20% less than when supplied by a 180^{o} inverter, due to the reduction in effective a.c. voltage caused by the open circuiting of the stator phases for 60^{o} out of every 180^{o}. A further disadvantage of the 120^{o} conduction inverter is that the instantaneous phase current at commutation is substantially higher than with 180^{o} conduction inverters, implying the need for larger capacity commutating components and indicating higher commutation losses.

A pulse width modulation inverter offers the attractive feature of including voltage control as well as frequency control within the inverter unit, making it a suitable system for operation from a battery source, as a d.c. chopper is not required. The inverter thyristors are switched at a much higher frequency than the inverter operating frequency, so that the output voltage is controlled by the mark : space ratio of the thyristor conduction. A typical p.w.m. output waveform is shown in figure 1.5.

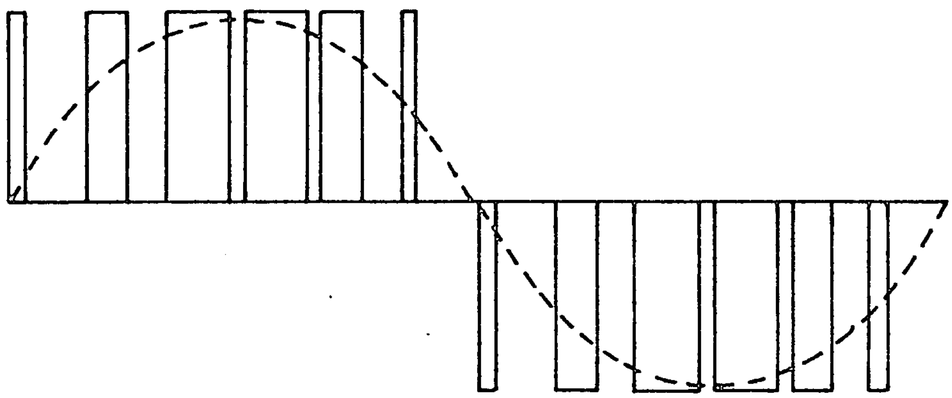


Figure 1.5 Typical Output Voltage from a P.W.M. Inverter

p.w.m. has advantages when operating at low speeds, as the resulting output voltage waveform can be controlled to be nearly sinusoidal, eliminating the pulsating torques of the 180^{o} and 120^{o} conduction inverters. At operating frequencies greater than about 100 Hz[22], however, the switching losses become prohibitive, and a 120^{o} or 180^{o} conduction inverter with a quasi-square output is used.

A variation of the p.w.m. inverter called pulse angle modulation is described by Blumenthal[23], where the stator current vector is switched at a high frequency between two or more positions, so that its average angle can be smoothly changed. This system is only suitable for low frequency operation, as it involves rapid switching of the phase currents.

Transistor Inverters

The recent improvements in the power handling capabilities of transistors have made them an attractive alternative to thyristors for use in bridge inverters up to about 50 kVA[24]. Bulky and expensive commutation circuits are not required in transistor inverters, as commutation is achieved simply by the removal of the signal to the base, a characteristic which makes them very suitable for pulse width modulation techniques.

Power transistors have two main disadvantages :

(i) As yet no power transistors have been produced with power ratings comparable to that of thyristors, although Stokes[24] anticipates the feasibility of a 200 kVA transistor inverter working from an 850Vd.c. rail with one device/limb in the very near future. Also the overcurrent capability of transistors is much smaller than that of thyristors.

(ii) Power transistors require considerably more power to drive them than thyristors. Associated with this problem is the need to de-couple electrically the control electronics from the power transistors. This is a more complex problem with transistor inverters than with thyristor inverters, as the base signal is normally a square wave at the inverter operating frequency, compared to the high frequency pulse train normally used to trigger thyristors. Most designers[24,25] use optical couplers to control the base drive, but this requires six floating power supplies to provide the base drive current.

Although the power transistor has only recently become a serious contender to the thyristor for use in inverters, its possible successor can already be seen in the form of the gate-controlled thyristor[26]. The device is switched on in the same manner as ordinary thyristors by a positive pulse to the gate relative to the cathode. However, it can also be switched off by a negative pulse to the gate. Gate controlled thyristors with a forward blocking voltage of 1400 V and capable of interrupting a current of 100 A have been built and incorporated in a 35 kVA, p.w.m. inverter to drive an induction motor. A serious drawback to the device is that high losses are incurred due to the forward voltage drop of about 3 V.

Naturally Commutated Inverters

Forced commutated inverters cease to be practical at about 500 kVA, due to the very high cost and large bulk of the commutation capacitors required,so for greater powers naturally commutated inverters are used where the thyristors are commutated by the back E.M.F. of the machine.

If the machine is operating with a leading power factor, then the current through any thyristor will have reduced to zero before the complementary thyristor is fired at the 180° point (figure 1.6). Forced commutation is then unnecessary to prevent the condition where two thyristors in the same phase leg conduct simultaneously, creating a short circuit across the d.c. link, as the thyristor will have commutated naturally.

Induction motors always operate with a lagging power factor, so it is not possible to use them in such a system. However, either a permanent magnet or a separately excited synchronous motor may be used.

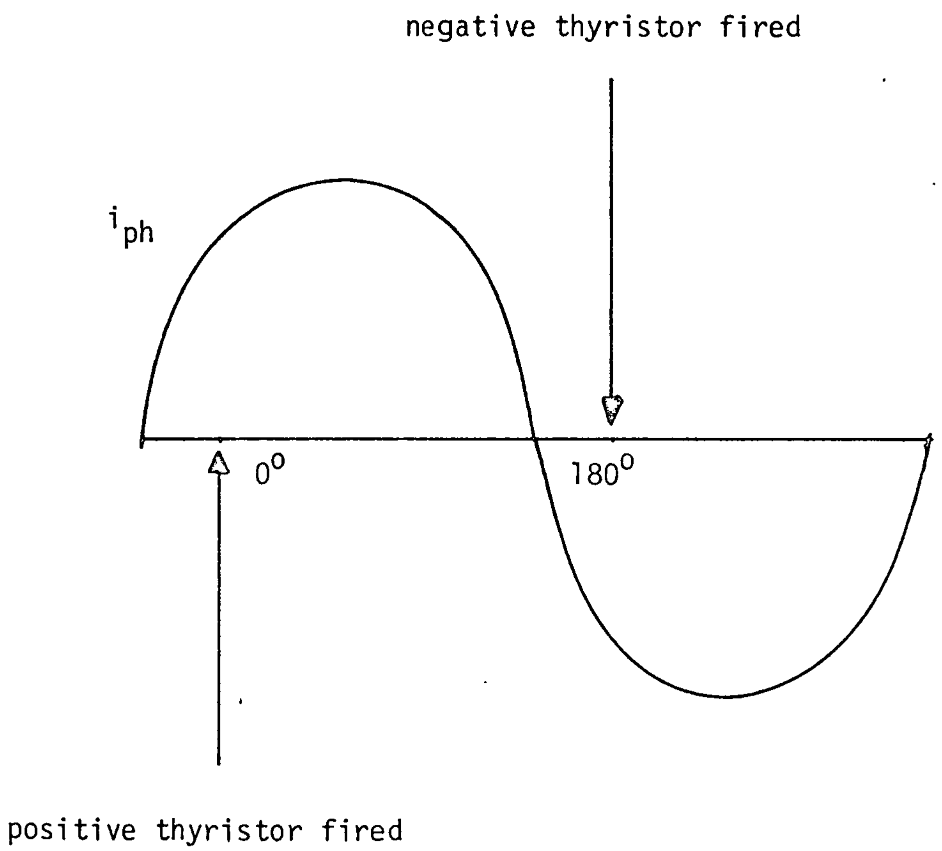


Figure 1.6 When Operating with a Leading Power Factor, Each Inverter Thyristor is Commutated before the Complementary Thyristor is Triggered

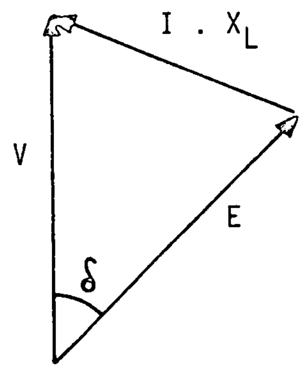
CHAPTER 2 : NATURALLY COMMUTATED INVERTER/SYNCHRONOUS MACHINE SYSTEMS

2.1 INVERTER FREQUENCY CONTROL

If the output frequency of the inverter is controlled by an external frequency reference generator, there is always the possibility that the synchronous motor will fall out of synchronism during non-steady-state conditions. Therefore, a speed change must be effected by a smooth change in inverter output frequency, gradual enough for the machine to remain in synchronism, yet not so slow that unnecessary time is wasted.

An alternative technique developed in the 1930's [27] is to control the firing of the inverter thyristors, and thus the output frequency, with signals from transducers detecting the rotor angular position. The system then ceases to have the characteristics of a synchronous machine, as an increase in load will result in a reduction in rotational speed and a corresponding fall in inverter frequency; a characteristic similar to that of the d.c. machine, to which it is often compared[28-30].

The load angle of the machine, δ (figure 2.1), becomes independent of load when the inverter firing is controlled by signals from rotor position transducers. δ may be adjusted by inserting a time delay in the transducer signals, however the resulting change in δ is dependent on speed as well as the time delay. A superior method of controlling δ is to rotate



V = applied voltage

E = machine back E.M.F.

I = phase current

X_L = machine reactance

Figure 2.1 Phasor Diagram of a Synchronous Machine the transducers around the rotor shaft, a rotation of angle θ corresponding to a change in δ of $\theta.P$. It is unsatisfactory physically to rotate the transducers to change δ, so extra transducers[28] are normally included in the system, and their output signals combined to produce the same effect (Section 3.3.1).

Several authors[31,32] have examined systems where the inverter firing is controlled by the machine voltages rather than by rotor position transducers, and ASEA[9] have installed such a system in the North of Scotland Hydro Electric Board pumped storage scheme at Foyers. Here, there is the clear advantage that the transducers may be dispensed with; however, at low speeds misfiring may occur due to the high harmonic content in the voltage waveform. At Foyers ASEA have avoided this problem by controlling the inverter frequency with a frequency reference generator at very low speeds, with the field excitation at a reduced value until the machine has synchronized with the inverter. In the pumped storage scheme under construction at Dinorwic ASEA appear to have adopted the system of using rotor position detectors at low speeds, then dispensing with them and referring to the machine voltages at higher speeds.

Miyari and Tsunehiro[29] have analysed the brushless d.c. motor by treating it as a d.c. machine, whereas Chalmers, Pacey and Gibson[33] and Williamson, Issa and Makky[32] have developed their theory based on the characteristics of the synchronous machine, extending their results to take into account the effects of saturation.

2.2 MATCHING THE INVERTER TO THE MACHINE

An inverter feeding an a.c. machine may be designed to have one of two possible output characteristics :

1. sinusoidal voltages and square current waveforms;
2. sinusoidal currents and square voltage waveforms.

The former characteristics are more suitable for a machine with damper windings on the rotor, while the latter are more suitable for a machine without damper windings.

2.2.1 An Inverter for a Machine with Damper Windings

The impedance of a synchronous machine to transient currents is reduced by the presence of damper windings on the rotor. Driving a machine with damper windings from an inverter with a square output voltage waveform, therefore, would result in very uneven stator currents.

A controlled rectifier has a constant voltage d.c. output (disregarding the 300 Hz ripple from the mains), so a choke is included in the d.c. link to prevent the rectifier from impressing a square voltage waveform onto the machine. The choke keeps the d.c. link current at a constant value, with the result that square blocks of current are delivered to the machine; however, it does allow the machine to control the voltage waveform.

A typical phase current waveform is shown in figure 2.2. The positive thyristor in the red phase, TPR, is fired at point A, and the red phase starts to conduct some of the d.c. link current, until at point B all the d.c. link current is flowing through TPR and the blue phase is open circuit.

The equivalent circuit and the phasor diagrams of the fundamental waveforms are shown in figure 2.3. The rotor position transducers set the angles of the back E.M.F. and the current phasors, with the latter delayed by an angle μ, the commutation overlap angle. The voltage phasor is the resultant of $\tilde{E}_F$ and $X_L.\tilde{I}$.

An obvious requirement for successful commutation is that thyristor TPR must have ceased to conduct and be in the forward blocking state by point C. In practise, commutation will fail if TPR is not in the forward blocking state before the line voltage V_{RY} reverses polarity[32], ie, the fundamental of the phase current must lead the phase voltage for successful commutation.

The commutation overlap angle, μ, increases as the machine inductance, L, increases, so commutation may fail if an inverter of this type is used to drive a high impedance machine.

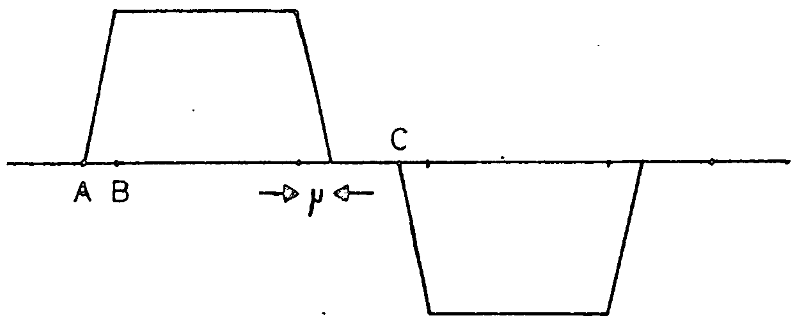


Figure 2.2 Typical Phase Current Waveform for an Inverter with a D.C. Link Choke

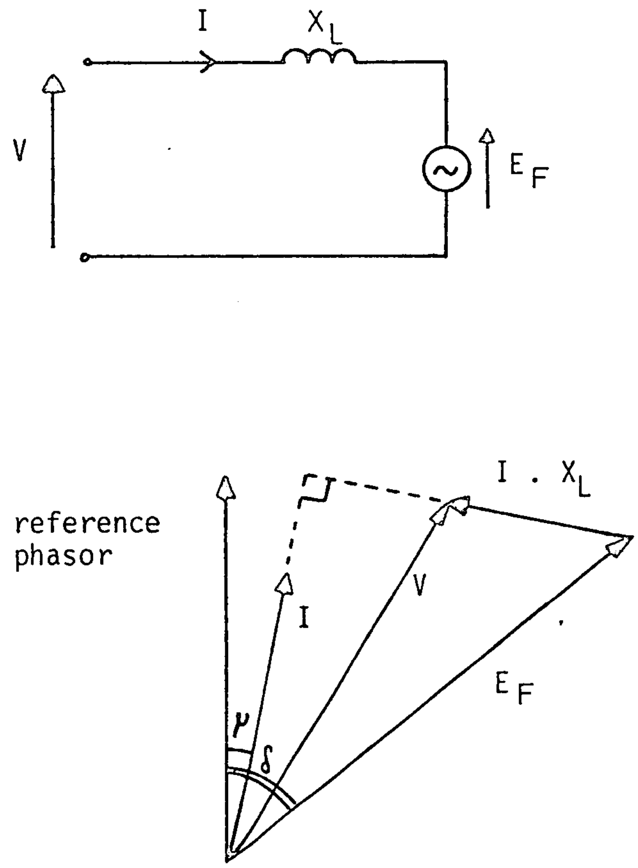


Figure 2.3 Equivalent Circuit and Phasor Diagram for a Synchronous Machine Driven by an Inverter with a D.C. Link Choke

The normal high impedance of the synchronous machine should be artificially reduced by placing damper windings on the rotor to ensure safe commutation.

2.2.2 An Inverter for a High Impedance Machine

A high impedance machine tends towards being a constant current source. Feedback diodes should then be included in the inverter (figure 2.4) to conduct the reactive component of current, and allow the machine currents to remain sinusoidal, independent of the operating power factor.

Typical phase voltage and current waveforms for the system operating with a commutation safety angle (defined as 180^o minus the angle for which each thyristor conducts per cycle) of 20^o are shown in figure 2.5. Thyristor TNR commutates at -20^o, and diode D4 conducts the positive phase current until TPR is fired 20^o later. The current immediately transfers to TPR and remains there until the phase current reverses at 160^o. D1 then conducts the negative phase current until TNR is fired at 180^o. The stepped phase voltage waveform is positive when either TPR or D1 connect the red phase of the machine to the positive rail of the d.c. link. The red phase voltage becomes positive when TPR is fired, so its phase is fixed by the rotor position transducers which control the inverter firing.

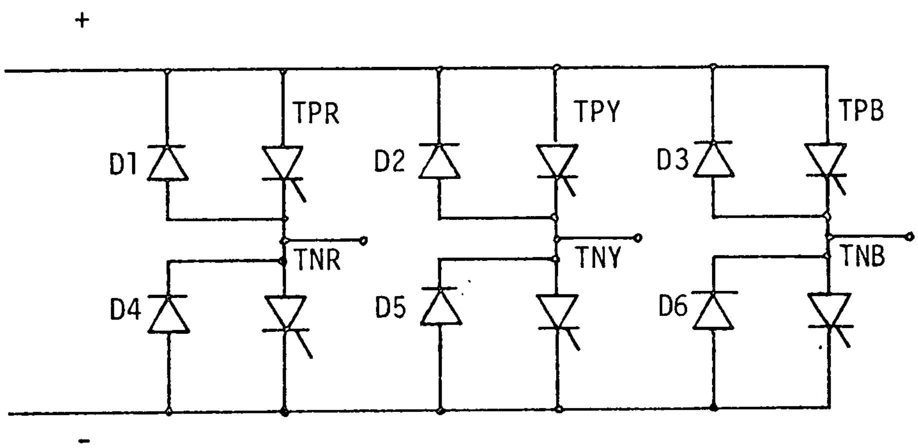


Figure 2.4 An Inverter with Feedback Diodes

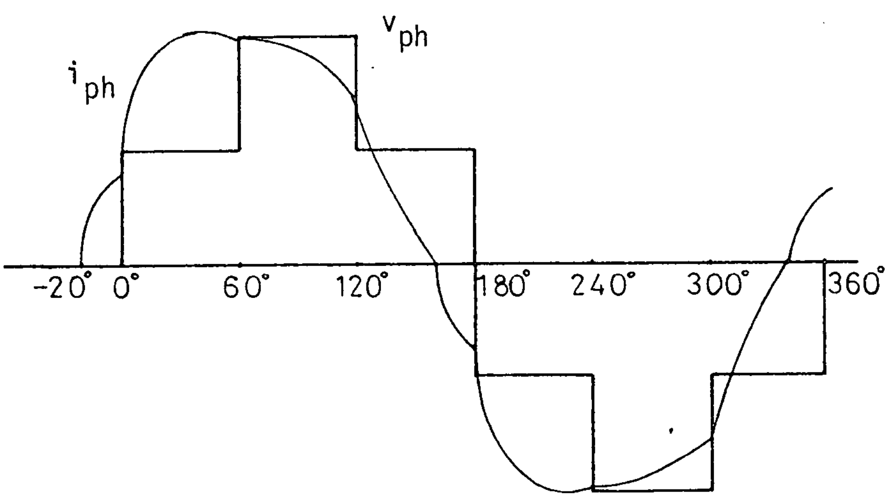


Figure 2.5 Typical Phase Current and Voltage Waveform for an Inverter with Feedback Diodes

When TPR is fired and takes over the conduction of the red phase current, a step rise in d.c. link current occurs. The d.c. link should be able to supply this step rise, therefore a choke is not included in the d.c. link.

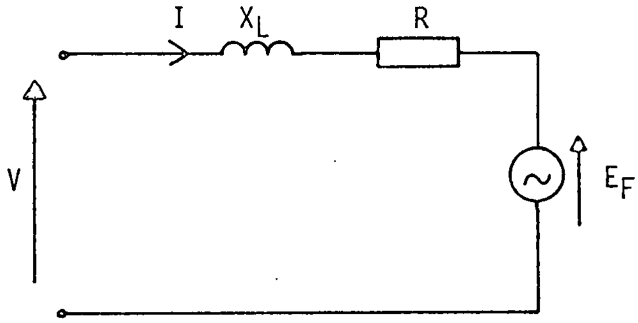
Feedback diodes are included in most forced commutated inverters[15,17-19,21,22,29,33-35] to provide a path for the phase current after a commutation and so avoid large transient rises in voltage which might cause serious damage. It appears that no authors have considered the advantages of including feedback diodes in naturally commutated inverters as a means of matching the inverter output characteristics with those of the machine.

2.3 INVERTER WITH FEEDBACK DIODES

In this project a naturally commutated inverter with feedback diodes was constructed, and its control requirements investigated.

2.3.1 Control Requirements

The Thévenin equivalent circuit of a synchronous motor and its associated phasor diagram is shown in figure 2.6. (For the purposes of the following approximate analysis, V is taken to be the fundamental component of the inverter output voltage.)



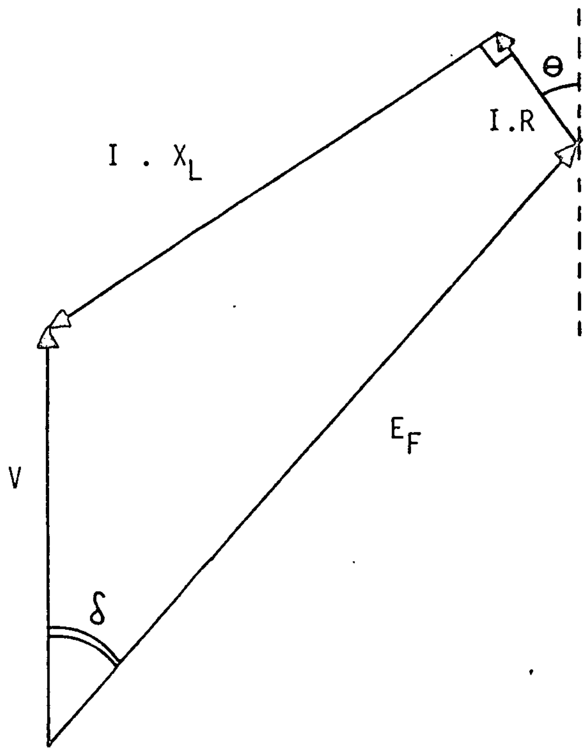


Figure 2.6 Equivalent Circuit and Phasor Diagram for a Synchronous Machine, Including the Winding Resistance

V is controlled to rise linearly with inverter frequency above a set threshold voltage to prevent saturation of the magnetic circuit (the threshold voltage is to take account of the voltage drop across the resistance R, which at low speeds becomes very noticeable). This may be achieved by controlling the firing angle of the controlled rectifier with a signal derived from a tachometer mounted on the machine (Section 3.1).

The output mechanical power from the machine is

$$3(V \cdot I \cdot \cos\theta - I^2R) \quad \text{watts} \qquad \ldots (1)$$

From the phasor diagram

$$E_F \sin\delta = I X_L \cos\theta + I R \sin\theta \qquad \ldots (2)$$

$$E_F \cos\delta - V = I X_L \sin\theta - I R \cos\theta \qquad \ldots (3)$$

$$(E_F \cos\delta - V)^2 + (E_F \sin\delta)^2 = I^2 X_L^2 + I^2R^2 \qquad \ldots (4)$$

From equations (2) and (3)

$$I \cos\theta = [X_L E_F \sin\delta - R(E_F \cos\delta - V)] \cdot \frac{1}{X_L^2 + R^2} \qquad \ldots (5)$$

So, substituting (4) and (5) into equation (1),

$$\text{Output power} = \frac{3}{X_L^2 + R^2} (V \cdot X_L \cdot E_F \sin\delta + V \cdot R \cdot E_F \cdot \cos\delta - R E_F^2) \text{ watts} \quad \ldots (6)$$

At very low speeds, $X_L << R$, so equation (6) becomes

$$\text{Output power} = \frac{3 \cdot E_F}{R} (V \cdot \cos\delta - E_F) \text{watts} \ldots (7)$$

and at high speeds, $R << X_L$, so equation (6) then becomes

$$\text{Output power} = 3 \cdot \frac{V \cdot E_F \sin\delta}{X_L} \text{ watts} \quad \ldots (8)$$

The angle, θ , between the applied phase voltage and the phase current is obtained by combining equations (2) and (3) to produce

$$\tan\theta = \frac{E_F \cdot \sin\delta \cdot R + X_L \cdot (E_F \cdot \cos\delta - V)}{E_F \cdot \sin\delta \cdot X_L + R \cdot (V - E_F \cdot \cos\delta)} \quad \ldots (9)$$

Therefore, at higher speeds, with $X_L >> R$, the machine will operate with a leading power factor only if $E_F \cos\delta > V$.

It can be seen from the above results that for operation at low speed ($X_L << R$), when commutation is carried out by pulsing the d.c. link, the optimum value for δ is zero.

At higher speeds ($X_L >> R$) the preferred value of δ to a large extent depends on the machine ratings. Operation with a large value of δ (eg, $\delta = 60^o$) severely limits the voltage which may be applied to the machine if a leading power factor is to be maintained, and gives rise to high operating currents. On the other hand, a low value of δ (eg, $\delta = 30^o$) allows operation with high voltages, and with much lower currents. Therefore, the value of δ is chosen to suit the per unit reactance of the machine.

If the angle θ in figure 2.6 is set at 30^o (a reasonable safety margin for natural commutation), then

$$\frac{V}{\text{Sin } (60 - \delta)} = \frac{I \cdot X_L}{\text{Sin } \delta}$$

This may be reduced to

$$\text{Tan } \delta = 0.866 \times \frac{1}{\left(\frac{V_{ph}}{X_L \times I_{ph}} \right) + 0.5}$$

$$= 0.866 \times \frac{1}{\left(\frac{1}{X_{p.u.}} \right) + 0.5} \qquad \dots (10)$$

Also, from figure 2.6, with $\theta = 30^o$,

$$\frac{E_F}{\text{Sin } 120^o} = \frac{V}{\text{Sin } (60 - \delta)}$$

ie, $$\frac{V}{E_F} = \frac{0.866}{\sin (60 - \delta)}$$

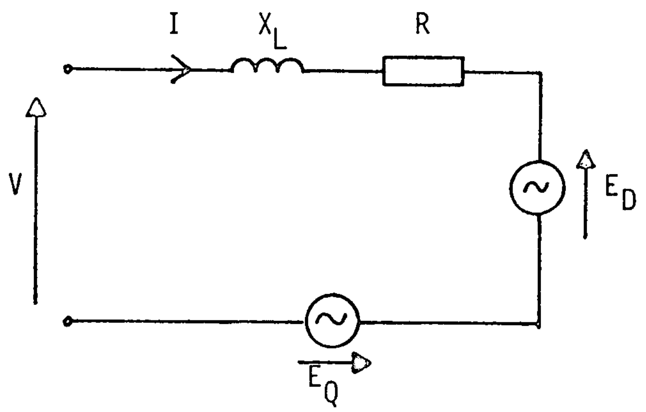
Values of δ and the corresponding ratios of $V : E_F$ are shown in Table2.1for different machine impedances.

$X_{p.u.}$	0.2	0.5	1	2	5	10
δ	9^o	19^o	30^o	41^o	51^o	55^o
$V : E_F$	0.91	0.76	0.58	0.38	0.18	0.09

Table 2.1

Optimum control at intermediate speeds ($X_L \triangleq R$) would require a smooth variation in δ from 0^o at zero speed to the chosen high speed value. However, this is difficult to implement, and most authors[11,28,32] have settled for operation with two different values of δ, typically 15^o for low speed operation and 45^o for high speed operation.

A convenient experimental method for varying δ is to use a machine with two orthogonal field windings. The inverter firing is timed such that one winding, the direct field, produces a back E.M.F. E_D in phase with the inverter output voltage, while the other, the quadrature field, produces an E.M.F. E_Q which lags E_D by 90^o. The equivalent circuit and phasor diagram for the two field machine are shown in figure 2.7. The load angle, δ,



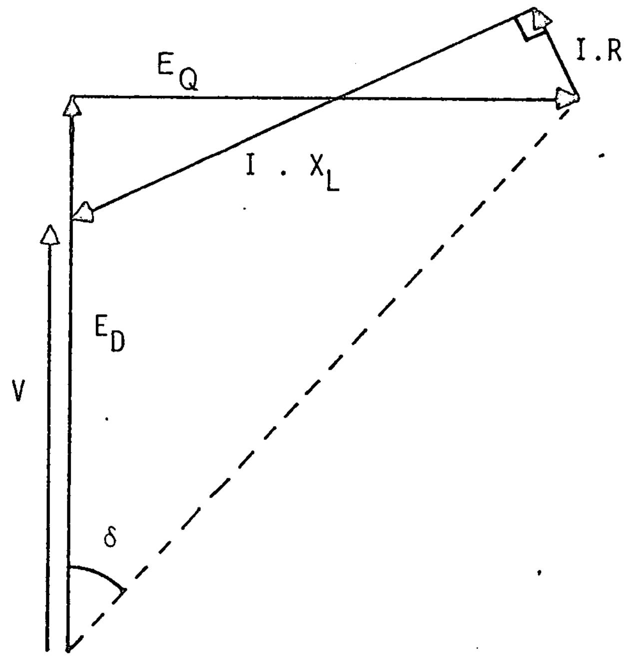


Figure 2.7 The Equivalent Circuit and Phasor Diagram of a Synchronous Machine with 2 Field Windings

may now be varied by adjusting the ratio, $E_D : E_Q$. The condition for operation with a leading power factor at high speeds ($X_L >> R$) now becomes $E_D > V$, and the machine output power

$$= 3 \cdot \frac{V \cdot E_Q}{X_L} \cdot \text{ watts}$$

At low speeds ($R >> X_L$), the output power

$$= \frac{3}{R} (V \cdot E_D - E_D^2 - E_Q^2) \text{ watts}$$

2.3.2 Low Speed Commutation

Some form of forced commutation is necessary for the inverter during operation at very low speeds when the machine impedance is mainly resistive, as the machine back E.M.F. is insufficient for natural commutation to take place. Conventional forced commutation circuits (Section 1.3.2) may be used : however, if the inverter is fed from a controlled rectifier, a simpler method[28] is to suppress the rectifier thyristor firing pulses whenever commutation of an inverter thyristor is due to take place. The d.c. current into the inverter will reduce to zero and the inverter thyristors will switch off. As soon as commutation has been achieved the appropriate rectifier and inverter thyristors are switched on and the system will operate as normal until the next commutation instant.

There are six thyristors in the inverter, so a commutation occurs every 1/6 of a cycle (electrical), the exact timing controlled by signals from the rotor position transducers.

In order to limit the number of rotor position transducers, it is convenient to set the commutation of a thyristor to occur either 120^{o} or 180^{o} after the initial triggering of that thyristor. Experimental results (Section 4.2) showed that faster commutation is achieved if 120^{o} conduction is chosen.

Consider the inverter thyristors feeding the Thevenin equivalent circuit of the synchronous machine in figure 2.8. Operation is at a low speed, 2 Hz, and the load angle, δ, is set at 0^{o}. If the rotor reference angle is set such that the positive thyristor (TPR) in the red phase is fired at a rotor angle of 0^{o}, at 120^{o} $e_R = 3.7$ V, $e_Y = 0$ V and $e_B = -3.7$ V (figure 2.9). The back E.M.F. e_R, although of insufficient magnitude to commutate fully TPR, assists in reducing the commutation time. In contrast, at a rotor angle of 180^{o} $e_R = 0$V, so commutation is not aided.

2.3.3 Starting Torque

The initial movement of the machine when starting from rest is identical to that of the d.c. machine. The field is excited and the rotor position transducers select the appropriate inverter thyristors to be fired, causing a d.c. current to flow in two of the 3-phase windings on the stator. The resulting starting torque T can be expressed as

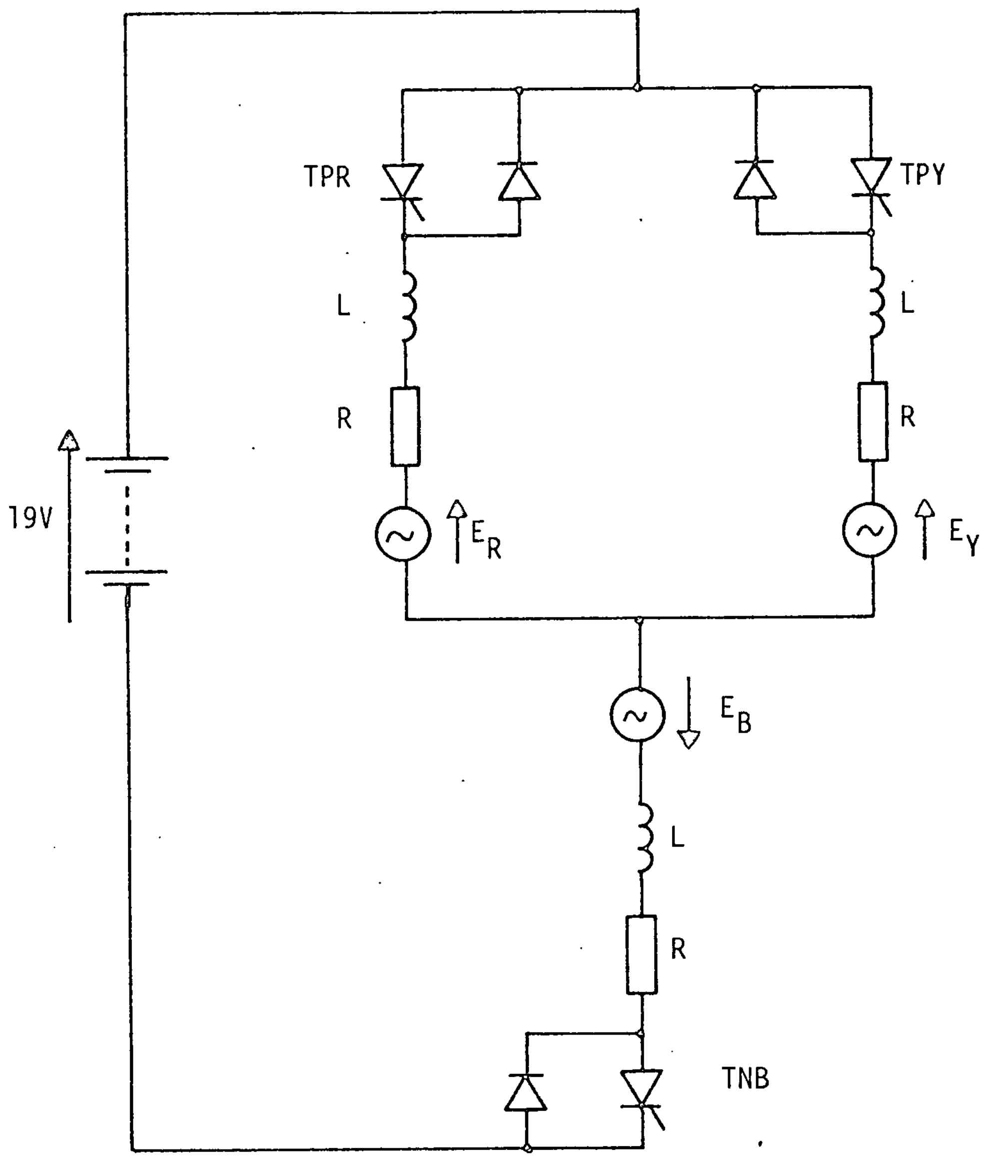


Figure 2.8 Equivalent Circuit of the Inverter Feeding the Motor During the First 60^o of a Cycle, at an Inverter Frequency of 2 Hz

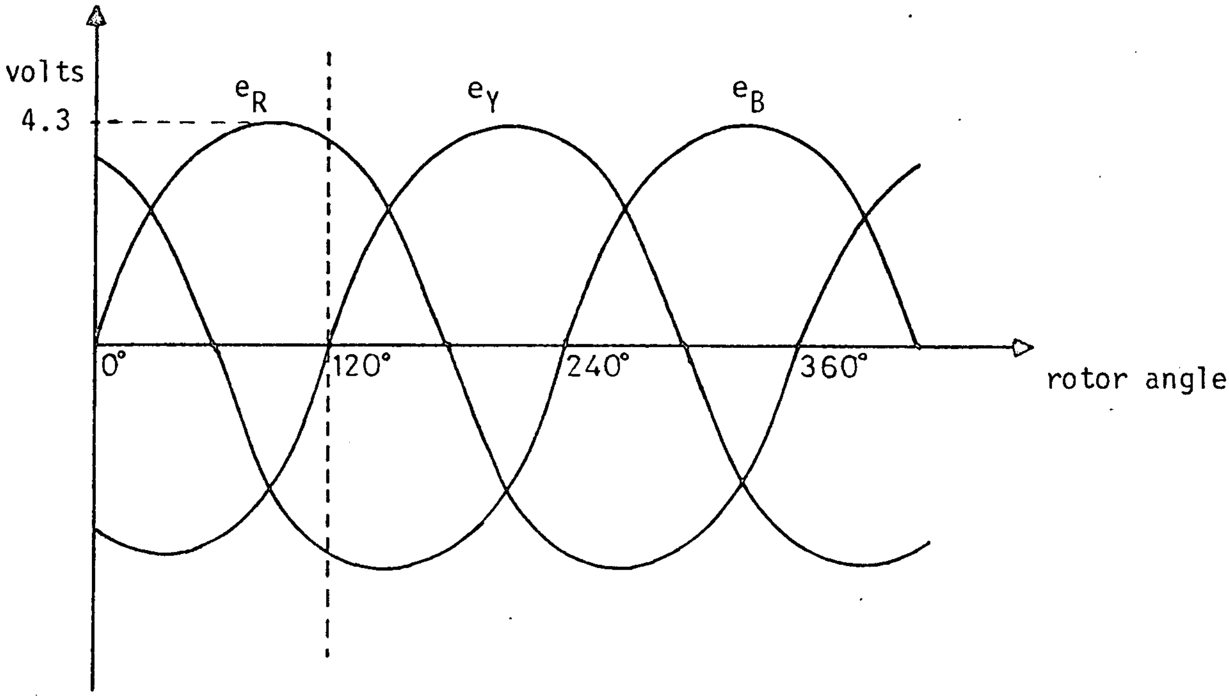


Figure 2.9 The Back E.M.F. in Each Phase Winding against the Rotor Angle Relative to the Stator

$$T = k \cdot B_S \cdot B_R \cdot \sin\alpha \text{ newton-metres}$$

where k = constant

B_S = magnetic flux density set up by the current in the stator

B_R = magnetic flux density set up by the field current

α = angle between B_S and B_R.

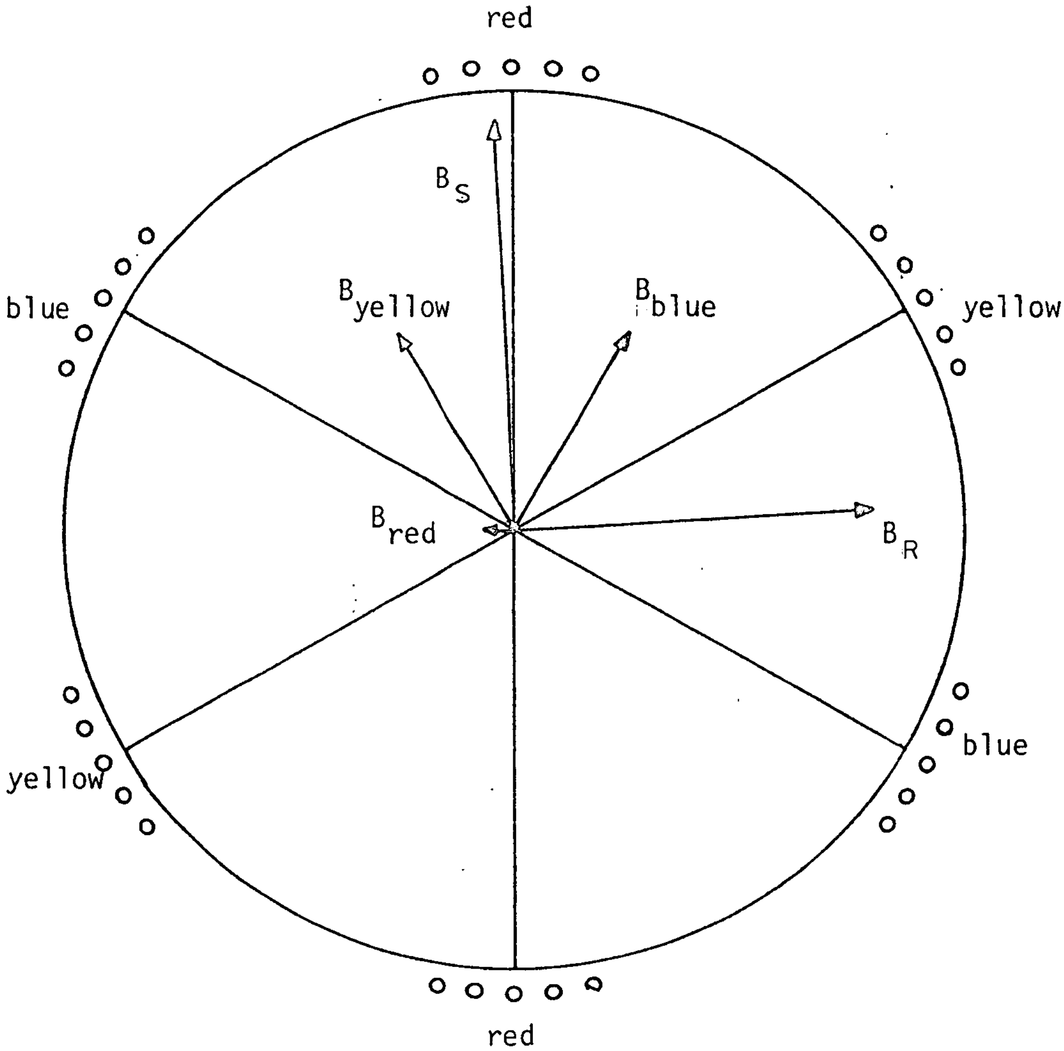
The condition for maximum torque, therefore, is $\alpha = 90^o$.

At high speeds ($X_L >> R$), no torque is developed if $\delta = 0$ (Section 2.3.1). If $V > E_F$, the applied phase voltage V then leads the phase current by 90^o, and in the machine B_S and B_R are in phase.

A setting of δ equal to zero at low speeds when $R >> X_L$ (assuming that the waveforms remain sinusoidal) results in I advancing until it is in phase with V, thus advancing the phase of B_S by 90^o. Since the phase of B_R is fixed with respect to V by the rotor position transducers, B_S now leads B_R by 90^o, and maximum torque is developed.

In the sinusoidal-waveform case, immediately the red phase voltage has become positive with the red phase current in phase, B_S is at an angle just greater than 0^o in figure 2.10, and B_R lags it by 90^o.

When fed from a 120^o conduction inverter, the same rotor angle causes the positive thyristor in the red phase, TPR, and



direction of rotation is anti-clockwise

Figure 2.10 The Magnetic Fields Set Up in the Machine During Low Speed Operation, with $\delta = 0$

the negative thyristor in the yellow phase, TNY, to conduct a d.c. current, fixing B_S at an angle of 60^o where it remains until the rotor has moved through 60^o. The negative thyristor in the blue phase, TNB, then takes over the conduction of the d.c. current from TNY, and B_S advance to 120^o. Therefore, as B_R advances from 270^o to 360^o, α changes from 30^o to 90^o, and the torque T changes from

$$T = \tfrac{1}{2} . k . B_S . B_R \quad \text{newton-metres}$$

to

$$T = k . B_S . B_R \quad \text{newton-metres}$$

Thus the starting torque largely depends on the position of the rotor at starting, maximum torque being obtained at a starting position immediately before a commutation position and minimum torque immediately after a commutation position.

Better average starting torques are obtained if B_R is advanced in phase by 30^o, making δ equal to -30^o. As the rotor moves through a 60^o segment between commutation positions α now varies from 60^o to 120^o, and the torque from $(0.866 . k . B_S . B_R)$ to $(k . B_S . B_R)$ and back to $(0.866 . k . B_S . B_R)$ newton-metres.

CHAPTER 3 : THE CONTROLLED RECTIFIER/INVERTER SYSTEM

A 3-phase controlled rectifier, d.c. link, naturally-commutated variable-frequency inverter system suitable for driving a synchronous machine was designed and built in the laboratory.

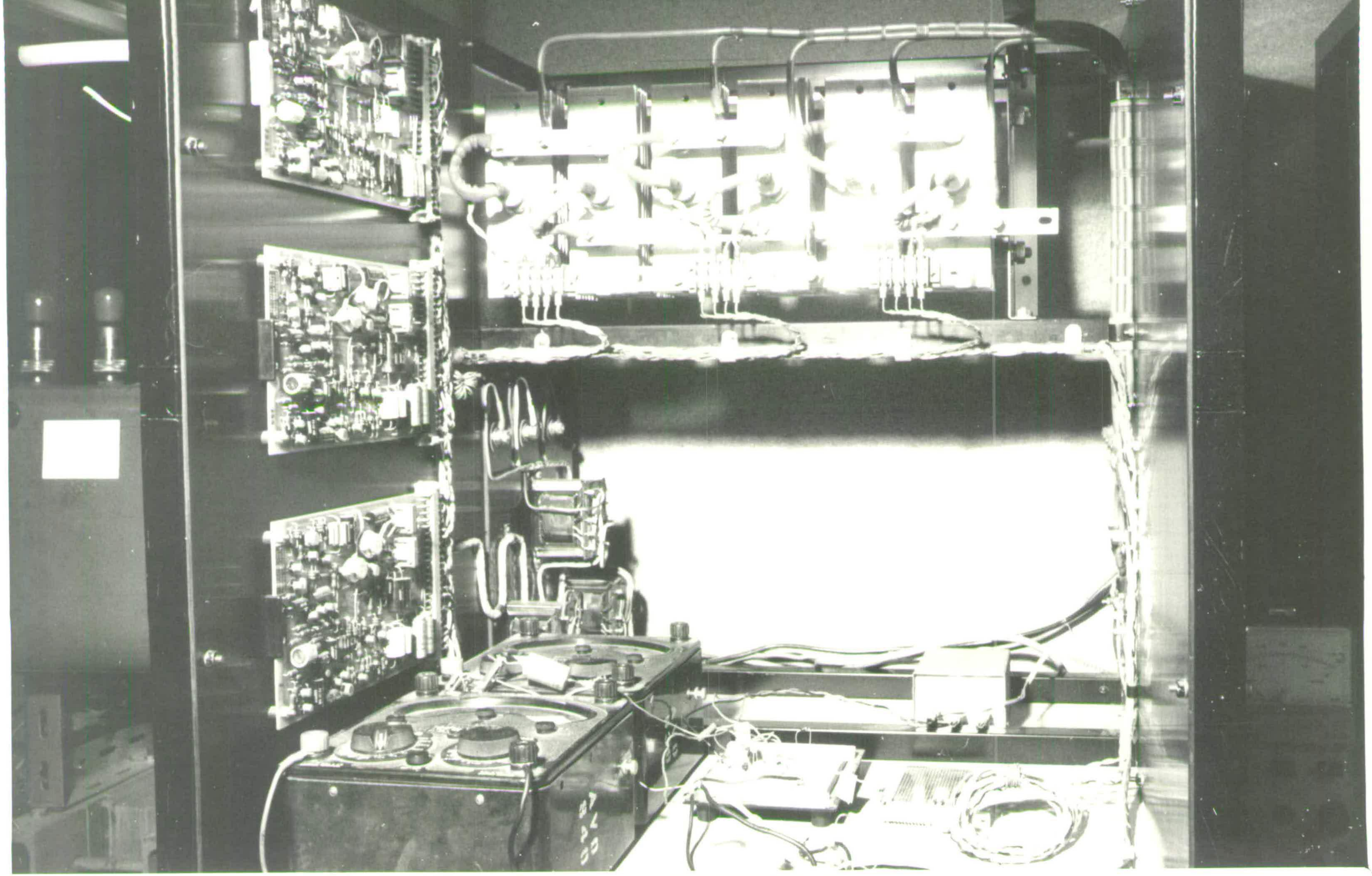
The prototype inverter, inverter mk I, would drive only a two field synchronous machine in which the phase of the field relative to the rotor angle could be altered for operation at different speeds. The inverter mk II was designed to be able to drive a conventional single field synchronous machine.

3.1 THE CONTROLLED RECTIFIER

The controlled rectifier is a standard 6 thyristor bridge rectifier as shown in figure 3.1, built into a steel tubing cube of edge approximately 60 cm, with the electronic control circuitry mounted on side panels (photograph 1).

The rectifier thyristors are triggered by three Westinghouse D82 LED circuits (appendix A), one to fire the thyristors of each phase. Each phase voltage is transformed down to 16.3 V r.m.s. and fed to the appropriate D82 LED circuit to synchronize the output trigger pulses with the phase voltages in the bridge rectifier.

Each D82 LED printed circuit board has two separate but similar circuits with isolated outputs, one circuit producing output trigger pulses in the positive half-cycle of phase voltage,



Photograph 1 The Controlled Rectifier

and the other in the negative half-cycle. Thus the output from circuit 1 in the red phase circuit will fire thyristor 4, and the output from circuit 2 will fire thyristor 1.

As the output train of pulses lasts (nominally) 1/6 of a cycle (ie, 60^0), only one thyristor is pulsed at any instant. If no current is flowing in the rectifier, two thyristors must be pulsed simultaneously to provide a path for the thyristor holding current. There is a facility incorporated in the D82 LED circuits for the trigger pulses from an output of one trigger circuit to be duplicated in the output stage of another trigger circuit. By making the appropriate connections (figure 3.2), each thyristor is pulsed for the full 120^0 over which it is conducting. This pulse duplication is particularly necessary when operating the inverter at very low frequencies, as the rectifier is then switched on and off six times per inverter cycle.

Each circuit of the D82 LED boards has an 'inhibit' input. A positive signal into an inhibit terminal prevents any firing pulses from being generated by that circuit for as long as the inhibit signal is present, the recommended inhibit input current being between 2 and 6 mA. The six inhibit inputs are connected together as in figure 3.3, so that an inhibit signal of between 15 and 35 mA at terminal A will prevent the rectifier from being pulsed. The series diodes are included to prevent any interaction between the six inhibit inputs which might results in a faulty inhibition signal.

An external d.c. input voltage to the D82 LED boards controls the position at which the pulse train appears in the half-cycle. An increase in the value of this voltage advances the phase of the pulse train, thus reducing the value of the rectifier delay angle and increasing the magnitude of the rectifier average output voltage.

The controlled rectifier is fed from the mains supply via a star connected isolating transformer with a phase output voltage of 65 V r.m.s., and a 3-phase variac. Tests (Section 4.2.1) show that the required value of d.c. link voltage at zero machine speed is 17 V, and increases linearly with speed to 60 V at 1500 r.p.m., the machine rated speed. The variac is set such that the d.c. link voltage is 60 V when the rectifier is operating with zero delay, corresponding to a rectifier control voltage of 2.2 V. The control voltage required to give an average d.c. link voltage of 17 V is then 1.35 V (Section 4.1).

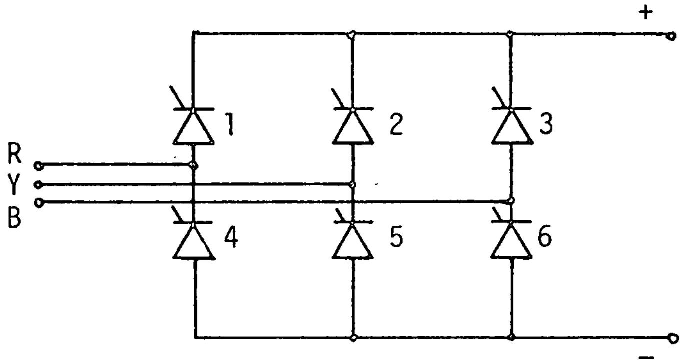


Figure 3.1 The 3-Phase Bridge Rectifier

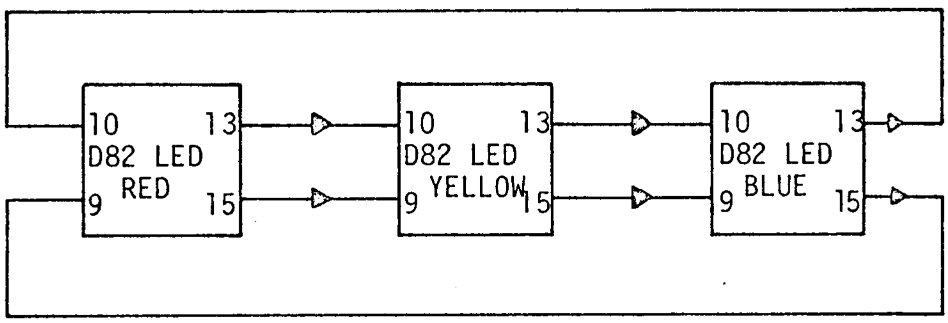


Figure 3.2 Pin Connection in the Westinghouse Circuits for Pulse Duplication

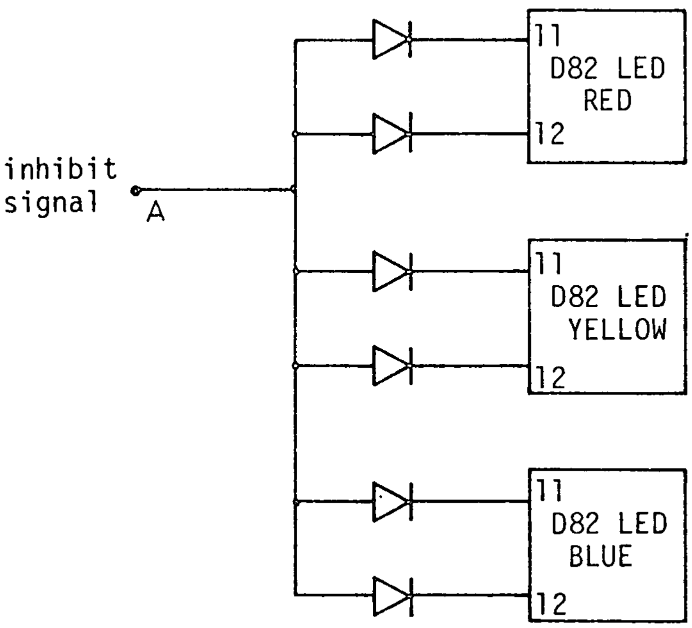


Figure 3.3 Pin Connections in the Westinghouse Circuits for the Rectifier Inhibition

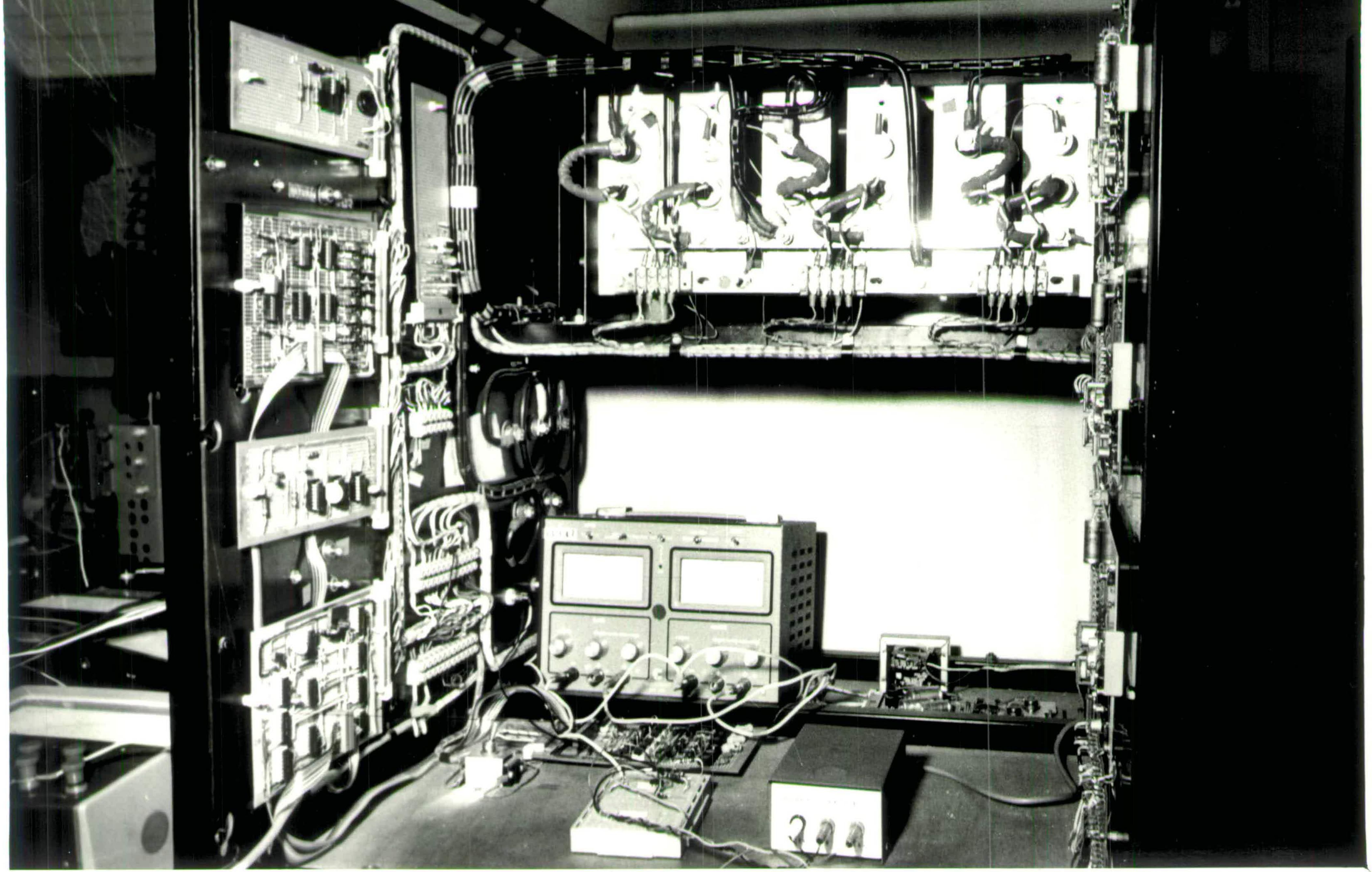
The output from the tachogenerator mounted on the machine is fed into the circuit shown in figure 3.4, so that the control voltage rises linearly with speed from 1.35 V at zero speed to 2.2 V at 1500 r.p.m.

3.2 20 kVA INVERTER MARK I

The inverter is a standard six thyristor bridge, built into a steel tubing box similar to that of the rectifier. The inverter includes feedback diodes around the thyristors, and also diodes in series with the thyristors for reasons that will be discussed in Section 3.2.2. The complete arrangement of the power components of the inverter is shown in figure 3.5.

3.2.1 Rotor Position Detectors

Various methods of monitoring the rotor position were investigated in an undergraduate project[36]. An optical system using light emitting diodes and photo-transistors as shown in figure 3.6 was considered, but rejected as reliability could be badly affected by the presence of dirt. A Hall-effect probe operating by the detection of a magnetic field was tested, but was too susceptible to the presence of strong external fields. Several authors[37,38] describe systems where a synchro is used to determine the rotor angle. These may be suitable for low speed applications, but they become inaccurate when the rotational speed approaches the synchro supply frequency (normally 50 Hz), and they tend to be more expensive than other types of transducer.



Photograph 2   The Inverter Mark I

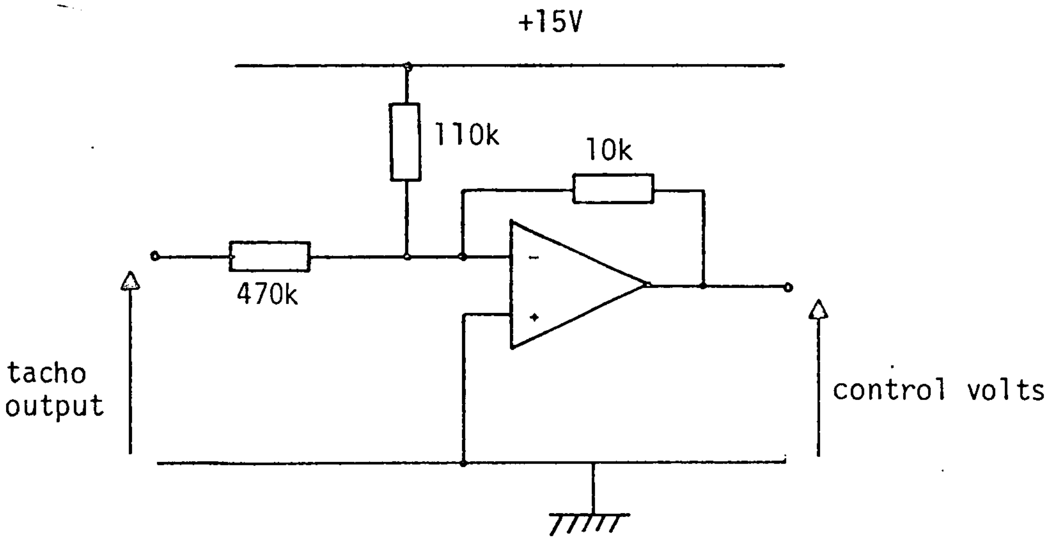


Figure 3.4 Interface between the Tachogenerator and the Westinghouse D82 LED Circuits

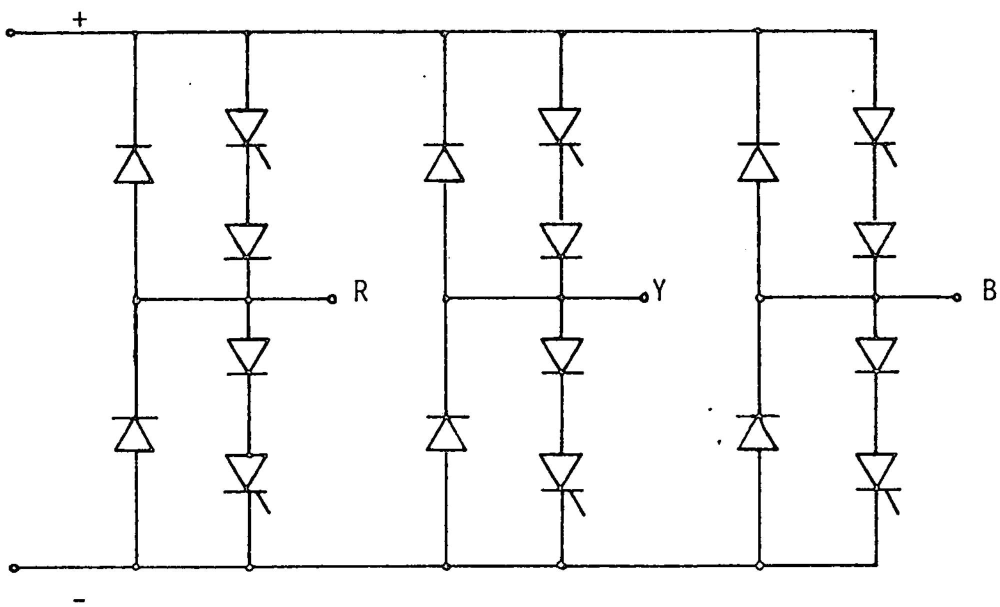


Figure 3.5 The 3-Phase Inverter Bridge

The system which was chosen is based on metal proximity detectors sensing the presence or absence of magnetic tape mounted on a non-conducting drum on the rotor. A detector produces a high frequency oscillation in a small coil at its tip which induces eddy-currents in any metallic object within the small conical detection area. These eddy-currents cause the detector frequency to change, bringing about a voltage change in the output from 24 V to 1 Volt. These probes are not affected by dirt or magnetic fields, and only by metallic objects above a certain size. An added advantage is that they are readily obtainable, as they are used in many industrial automatic control systems[20].

Each 60^o (electrical) one of the 6 inverter thyristors is fired (Section 1.3.2); therefore, it is necessary to specify the 60^o interval within which the rotor reference position is located. A binary code to define each of the six 60^o segments requires three digits, with two bits of information left unused. As the proximity detectors have a digital output (either 1 Volt or 24 Volts), three detectors are mounted on the stator at 120^o (electrical) intervals, with a 180^o strip of magnetic tape mounted on the rotor (figure 3.7). It can be seen from figure 3.8 that each 60^o segment is well defined.

As the machine under test has four poles, one complete rotor revolution describes 720 electrical degrees. Therefore the detectors should be mounted at 60 mechanical degree intervals,

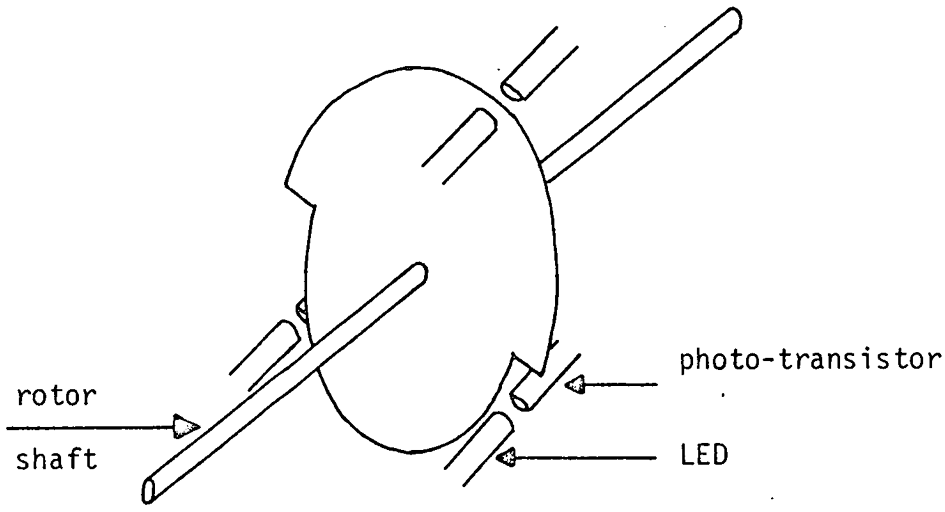


Figure 3.6 An Optical Rotor Position Detection System

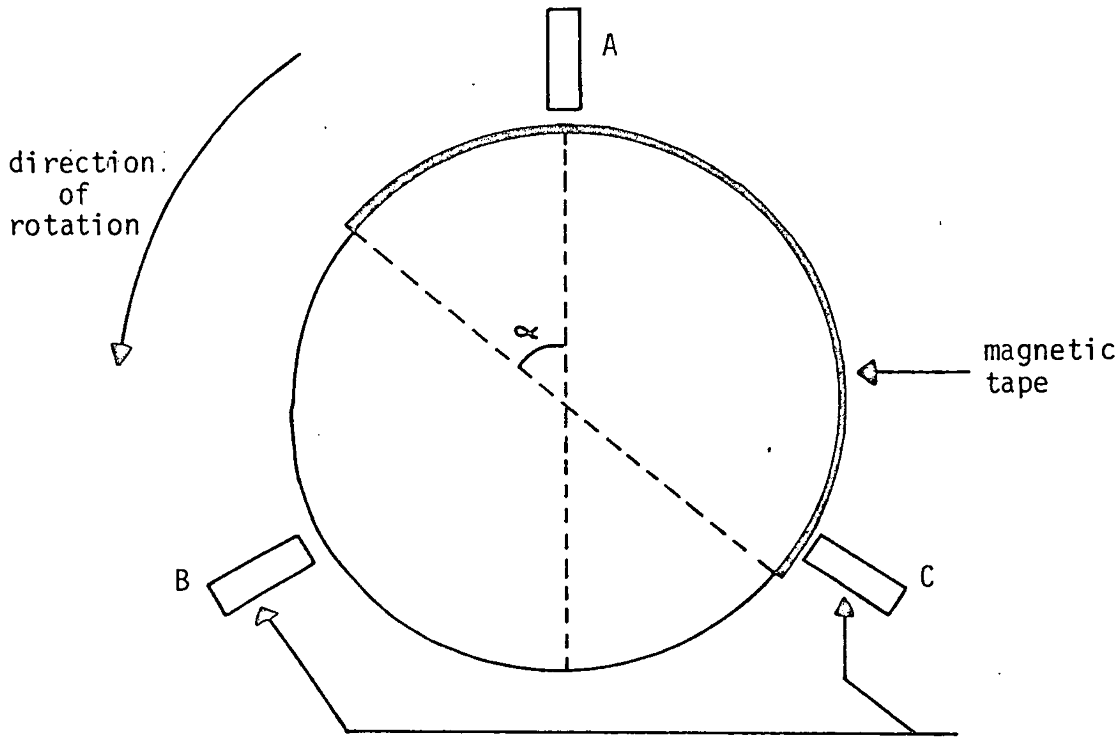


Figure 3.7 The Positioning of the Rotor Position Transducers for a 2 Pole Machine

with two strips of magnetic tape each describing an arc of 90^0 on the rotor, as in figure 3.9. As a total arc of 120^0 between the transducers would cause difficulties in mounting, transducer C was shifted by 90^0 so that it lies midway between transducers A and B, and its output inverted to produce the same result as figure 3.9.

The interface circuit shown in figure 3.10 reduces the transducer outputs to the standard T.T.L. logic levels of 0 Volts and 5 Volts. The outputs from transducers A and B are inverted at this stage, while the output from C is inverter twice.

3.2.2 Inverter Thyristor State Detection[39]

During the low speed mode of operation described in Section 2.3.2 commutation is achieved by inhibiting the rectifier firing until the appropriate inverter thyristor is switched off. It is desirable to have a reliable method of determining when the appropriate thyristor has reverted to the forward blocking state to avoid unnecessary delay in the removal of the rectifier inhibition signal.

Three systems for detecting whether inverter commutation has been achieved were investigated :

(a) d.c. link current detection;

(b) thyristor state detection by measuring the voltage across the thyristor;

0° 60° 120° 180° 240° 300° 360°

Transducer A	1	1	1	0	0	0
Transducer B	0	0	1	1	1	0
Transducer C	1	0	0	0	1	1

Figure 3.8 The Logic Output of the Transducers for Varying Values of Rotor Angle α

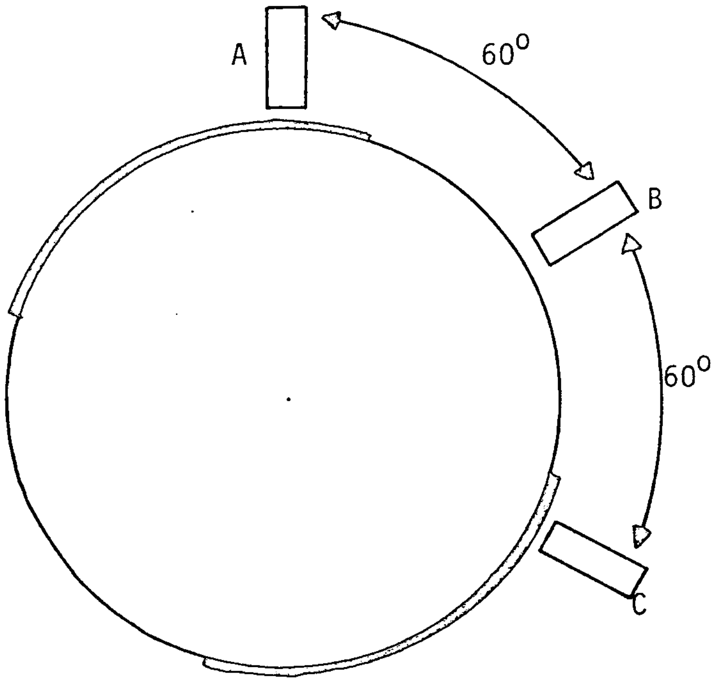


Figure 3.9 Position of the Rotor Position Transducers for a 4 Pole Machine

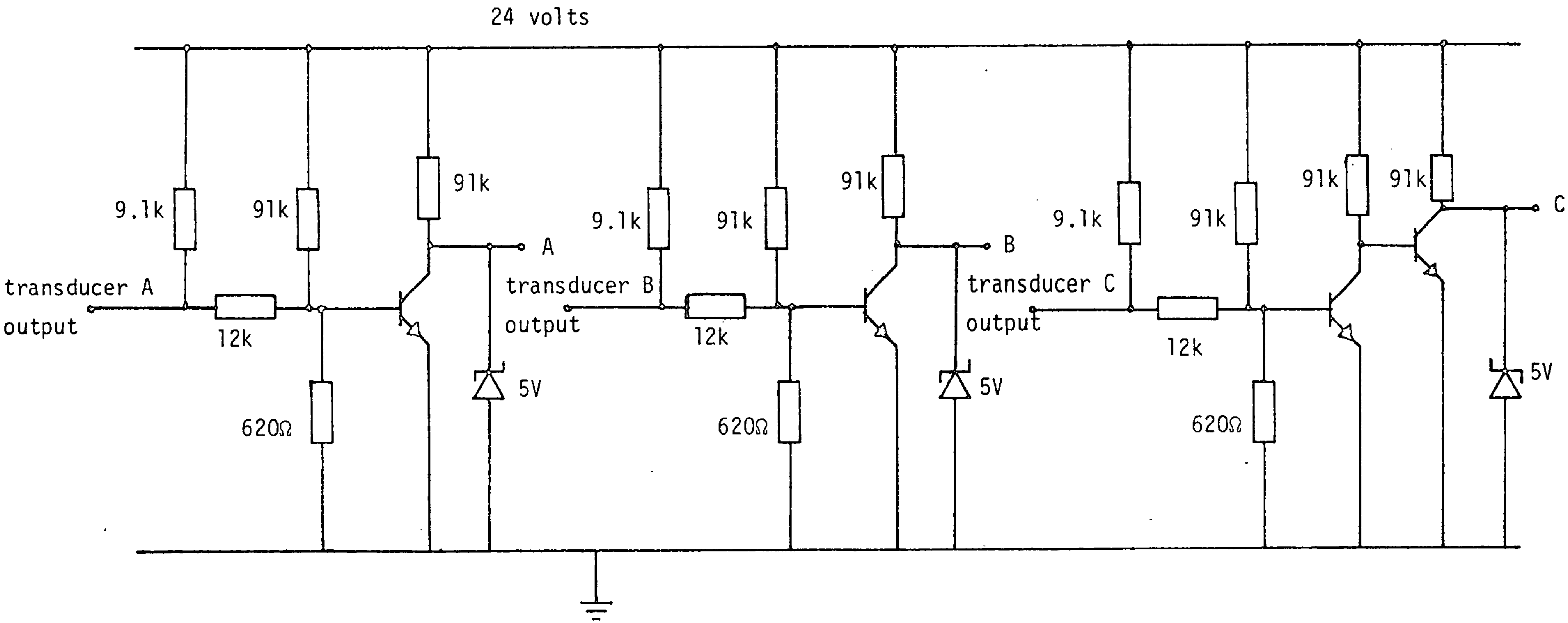


Figure 3.10 The Interface between the Rotor Position Transducers and the Control Logic

(c) thyristor state detection by the measurement of a small detection current circulated through the thyristor.

Since, for convenience and safety, the control electronics for each of these systems should be operated close to earth potential, electrical decoupling between the low voltage and high voltage systems is necessary. The light emitting diode (L.E.D.), photo-transistor system shown in figure 3.11 was used to provide an electrical isolation of up to 2.5 kV.

(a) D.C. Link Current Detection.

If current is passing through the d.c. link, then diode D1 in figure 3.12 will be strongly forward biassed. A small reverse current of about 25 mA can then circulate through the detection circuit and activate the L.E.D. When the d.c. link current ceases to flow, D1 will become reverse biassed and the L.E.D. will switch off. Diode D2 is included to protect the L.E.D., which has a reverse breakdown voltage of about 60 V, against any transient increases of voltage in the d.c. link.

The drawback to this system is that it detects when the d.c. link is conducting, not the state of each individual thyristor. In a system incorporating feedback diodes it is possible for the d.c. link current to be zero, yet for current to be circulating between the machine and the inverter, with the thyristor under observation still conducting.

(b) Thyristor State Detection by Voltage Measurement.

A possible method of detecting whether a particular thyristor is conducting or not is to measure the voltage V_T across the device. When the thyristor is conducting, V_T is about 1 Volt ; however, as V_T can also be 1 Volt with the thyristor in the forward blocking state, this system was not followed up.

(c) Thyristor State Detection by Circulating Current Measurement.

When the thyristor in figure 3.13 is conducting, the floating 5 Volt power supply will circulate a detection current of 25 mA through the thyristor, diode D1, the 150 Ω current limiting resistor and the L.E.D., thus switching the photo-transistor on. As soon as the thyristor reaches the forward blocking state, the circulating current will be blocked and the photo-transistor will switch off.

The phase voltages in an inverter driving a synchronous machine will sometimes rise above the d.c. link positive rail voltage, and sometimes fall below the d.c. link negative rail voltage. Under these conditions the L.E.D. in the simple system of figure 3.13 would conduct some of the machine current, probably raising the current passing through it to well above its 60 mA rating. Feedback diodes round the thyristors will shunt the machine current and protect the L.E.D., but simultaneously will provide a path for the circulating detection current, leading to

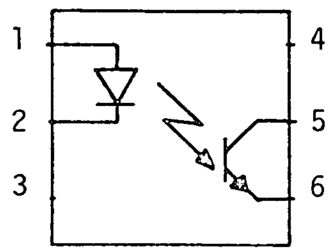


Figure 3.11 The Optical Coupler

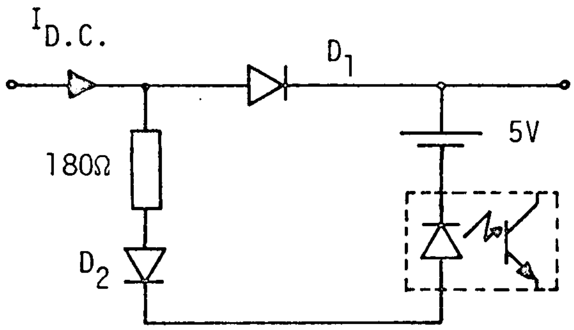


Figure 3.12 The D.C. Link Current Detection Circuit

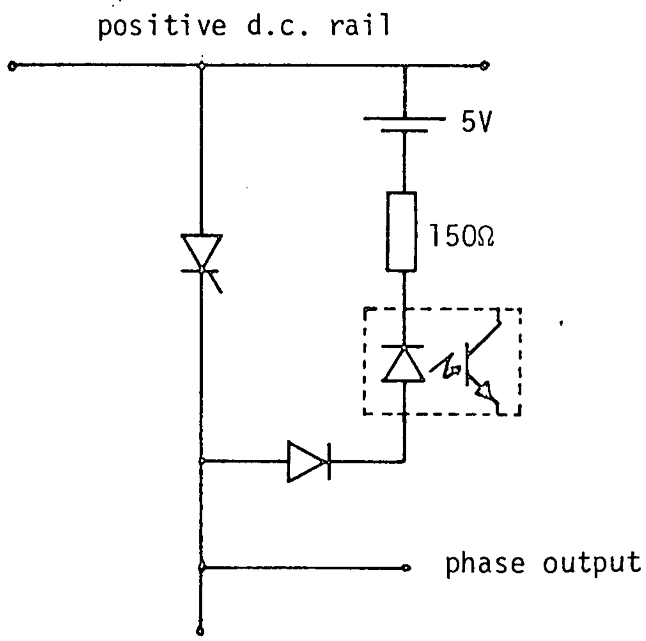


Figure 3.13 The Thyristor State Detection Circuit

incorrect information about the state of the thyristors. The insertion of series diodes as in figure 3.14 prevents the detection currents circulating through the feedback diodes. The series diodes will also protect the L.E.D.'s against the machine currents if it is desired to disconnect the feedback diodes.

It should be noted that the circulating current, at 25 mA, is much smaller than the holding current of the thyristors, which is about 0.7 A. Therefore, the detection circuit will not interfere with inverter operation by providing a latching current for the thyristors.

As it had already been decided to incorporate feedback diodes in the inverter, method (c), thyristor state detection by circulating current measurement, was adopted for use in the system.

3.2.3 Inverter Output Pulse Stage

Three Westinghouse P82D printed circuit boards provide the trigger pulses to the six inverter thyristors, each controlling the thyristors of one phase (figure 3.15).

A P82D printed circuit board has two isolated outputs. The signal from each output is a train of 70 μs pulses with a mark/space ratio of 1:10, each pulse of sufficient magnitude to fire a thyristor. The pulse train from an output can be suppressed by applying a 2-6 mA d.c. signal to the appropriate inhibit input terminal.

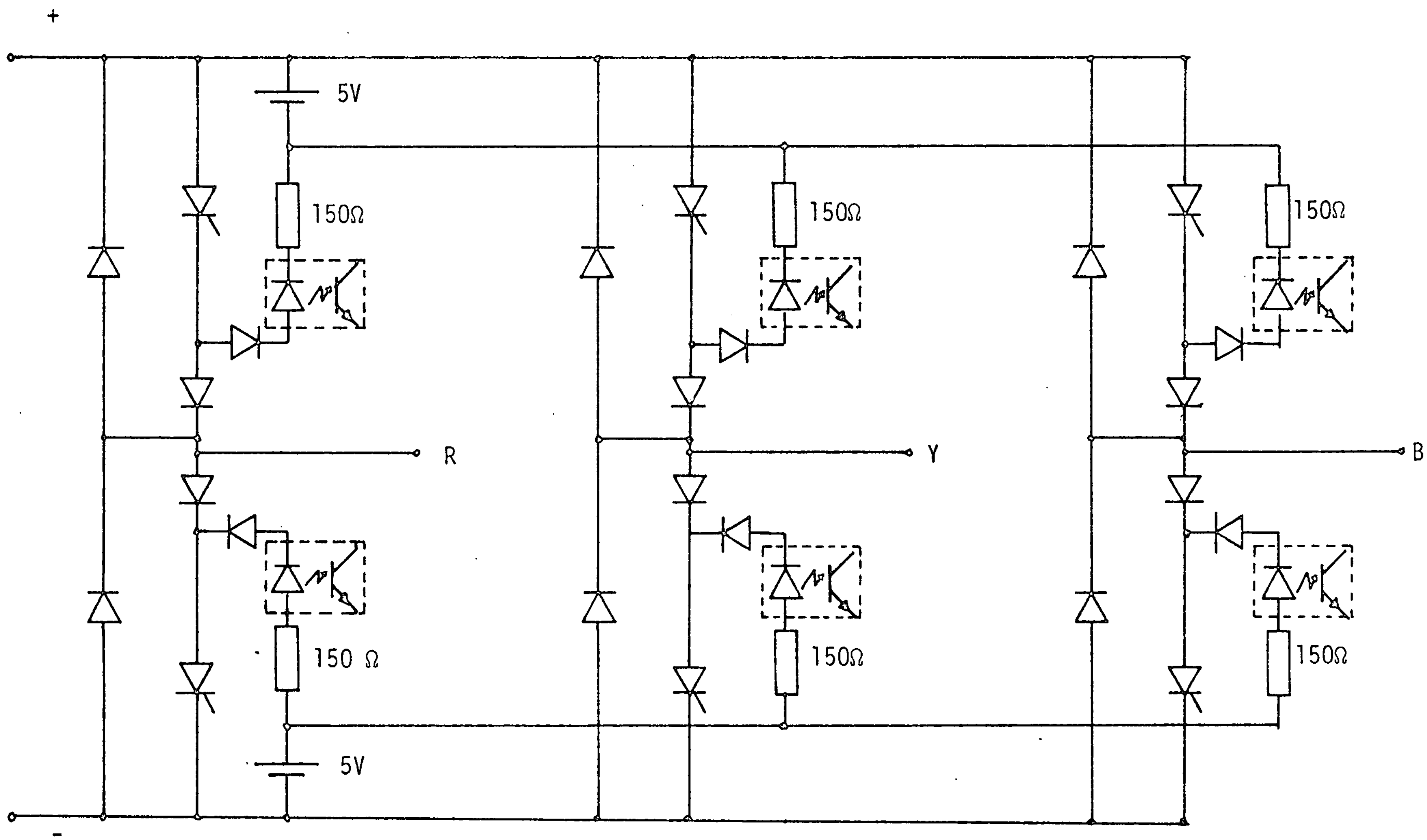


Figure 3.14   The Complete Thyristor State Detection Circuit

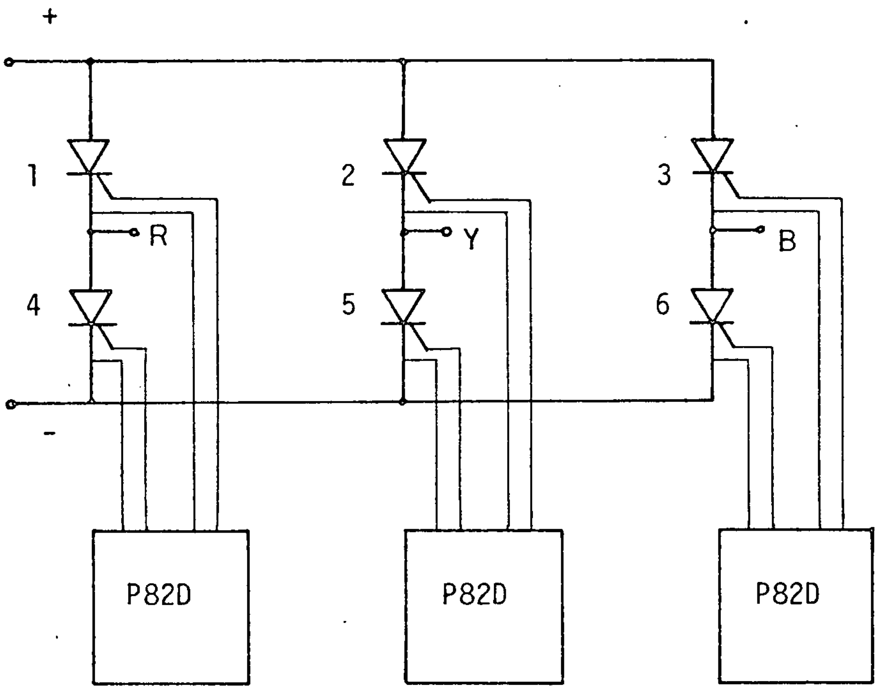


Figure 3.15 The Arrangement of the Westinghouse P82D Circuits

3.2.4 Inverter Thyristor Firing Control

The inverter thyristors should be fired at 60^0 intervals in the sequence 1-6-2-4-3-5-1 to produce the 3-phase quasi-square voltage waveform shown in figure 3.16.

The fundamental of the inverter output phase voltages should be in phase with the phase E.M.F.'s induced in the stator windings by the direct field (Section 2.3.1). For this to occur, thyristor 1 should be triggered at the instant that the induced E.M.F. in the red phase changes from a negative to a positive polarity (figure 3.17).

The rotor position detectors are mounted on a bracket which can be rotated round the rotor (figure 3.18). This bracket is moved until the output from transducer A (after the interface circuit described in Section 3.2.1) changes from logic '1' to logic '0' simultaneously with the open circuit E.M.F. in the red phase changing from a negative to a positive polarity (figure 3.19). The change from logic '1' to logic '0' is then used to initiate the triggering of thyristor 1. Figure 3.20 shows the transducer changes that initiate the triggering of the other thyristors.

A pulse train length of 120^0 was chosen as being suitable to drive a thyristor. 60^0 is insufficient, for, if no current is flowing in the inverter (eg, when initially switching on and also during low speed commutation), two inverter thyristors must be pulsed simultaneously to provide a current path. Only one thyristor is being pulsed at any given instant with a 60^0 pulse

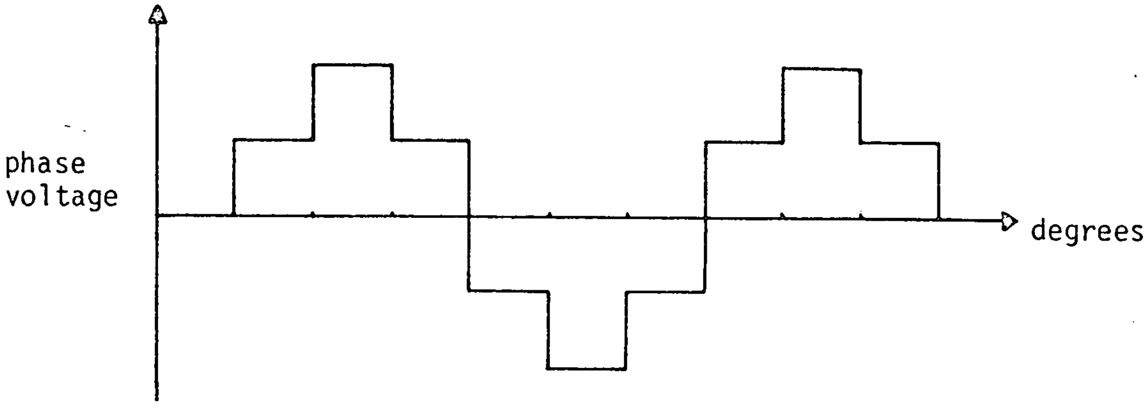


Figure 3.16 Typical Phase Voltage Waveform for an Inverter with Feedback Diodes

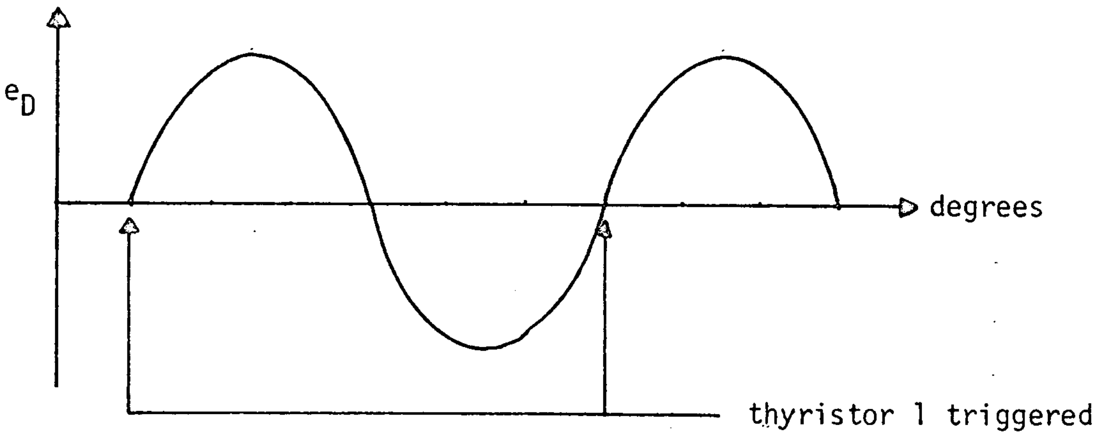


Figure 3.17 The Firing of Thyristor 1 Relative to the Back E.M.F. Induced by the Direct Field

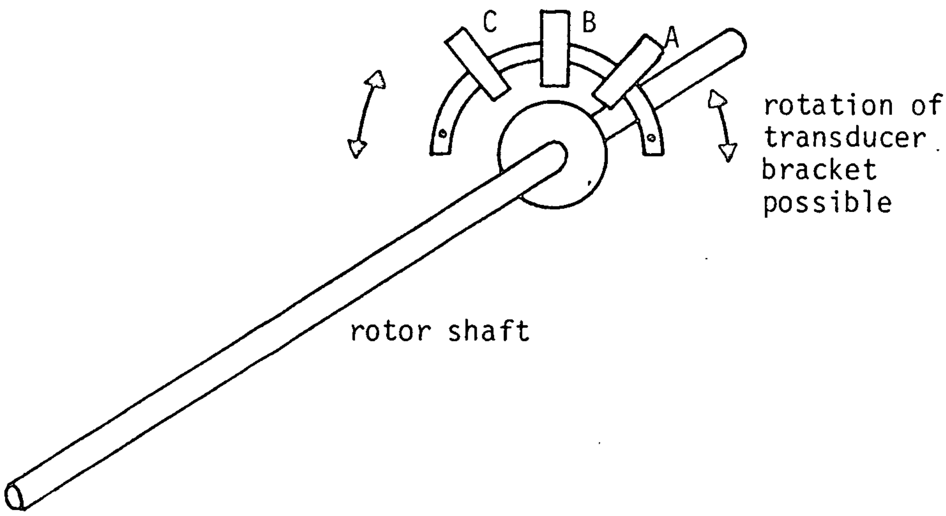


Figure 3.18 The Mounting of the Rotor Position Transducers

train. A 180^{o} pulse train was tried, but this resulted in starting problems (Section 4.2.3).

It can be seen from figure 3.20 that the period of the 120^{o} pulse train for thyristor 1 is described by $A + \overline{B}$ = '0'. This logic zero is fed to the Westinghouse P82D inhibit input controlling the pulse train to thyristor 1, allowing the pulses to appear at the output. A logic '1' will suppress the trigger pulses for the rest of the cycle.

A safety feature is incorporated in the system at this stage. It is necessary to prevent the situation of two thyristors in the same phase conducting simultaneously, causing a short across the d.c. link. The signal from the thyristor state detector (Section 3.2.2) on thyristor 4, 'P' is added to the inhibit signal to thyristor 1, so that the trigger pulses to thyristor 1 are suppressed if thyristor 4 is conducting.

An overide signal, 'D', common to all the inverter thyristors, is also added to the inhibit signal, so that a manually operated switch can suppress the trigger pulses to all the inverter thyristors.

The complete inverter firing control circuit is shown in figure 3.21. The outputs control the thyristor latching circuit described in Section 3.2.7 as well as the Westinghouse P82D circuits, so logic inverters 5 and 6 are included to act as buffers between the circuits.

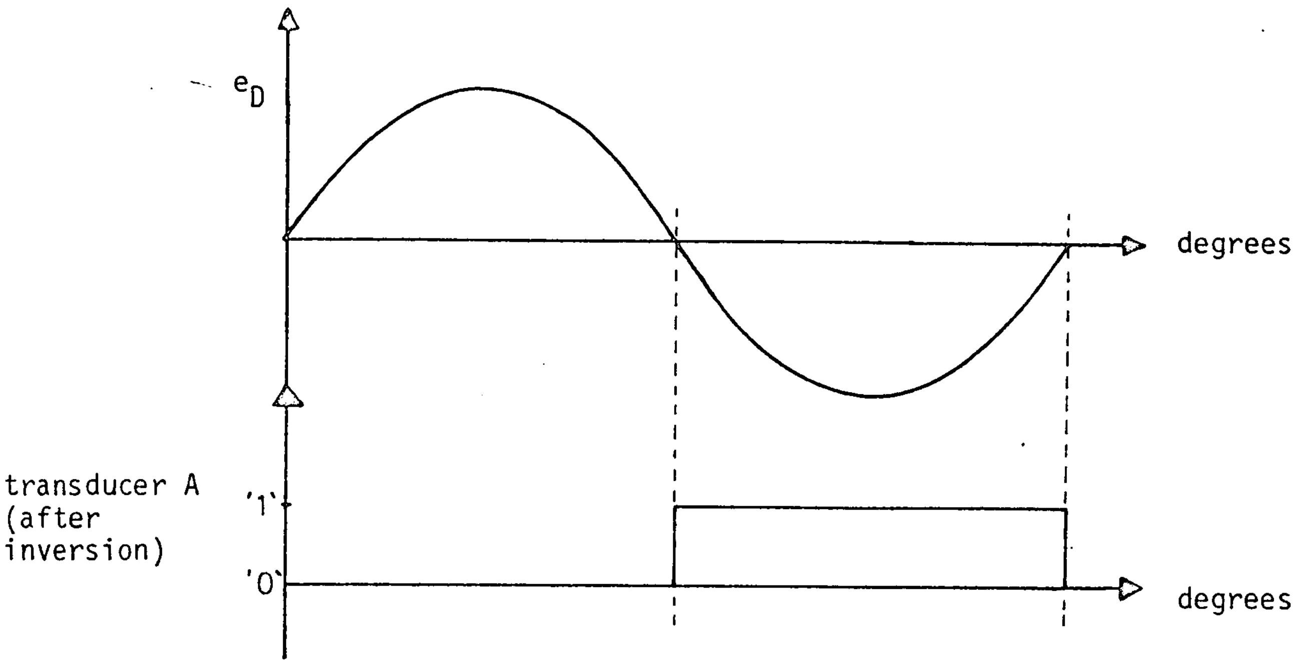


Figure 3.19 Output of Transducer A (After Interface Circuit) Relative to e_D in the Red Phase

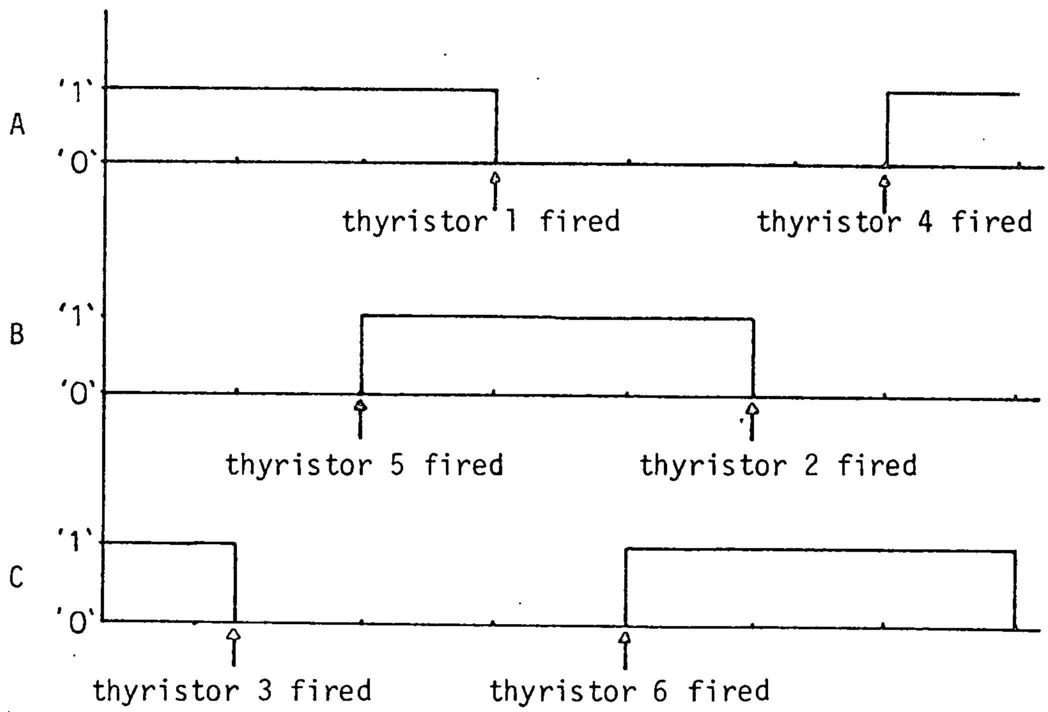


Figure 3.20 The Firing of the Inverter Thyristors Relative to the Rotor Position Transducer (Buffered) Outputs

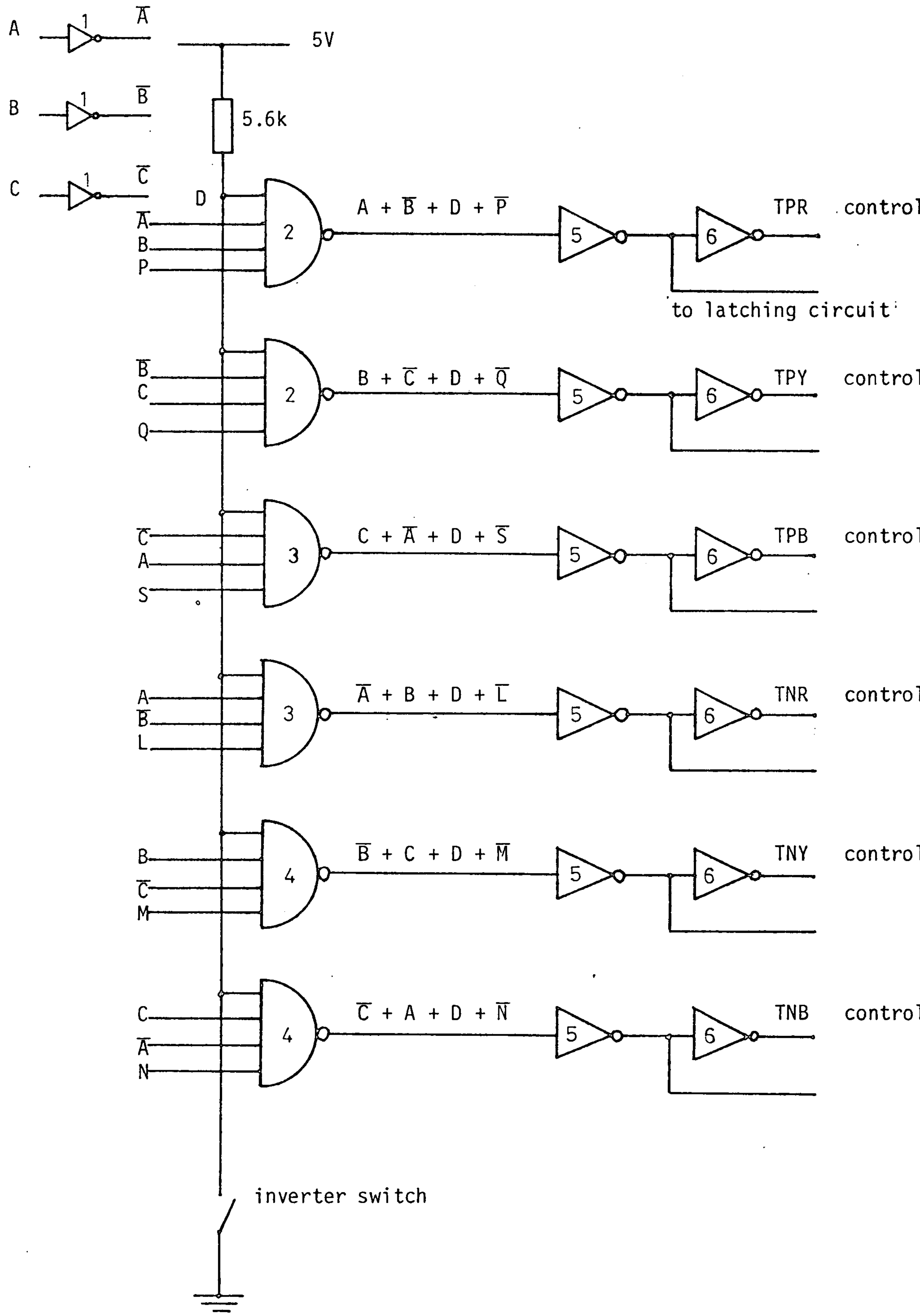


Figure 3.2 1   Inverter Firing Control (CMOS)

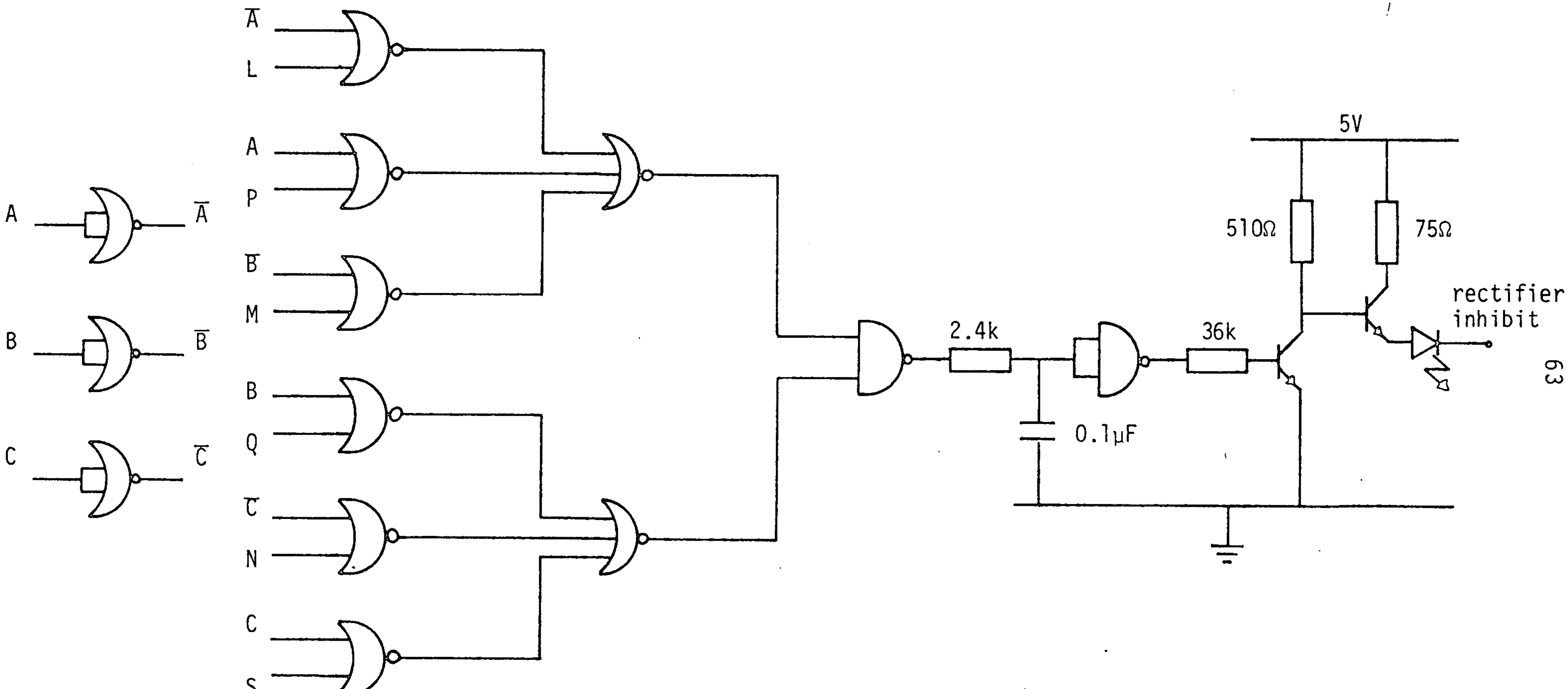
3.2.5 System Protection

The system is protected in two ways against large d.c. link currents which would flow in the event of commutation failure. The first way is the safety feature described in Section 3.2.4, where the possibility of two thyristors in the same phase leg conducting simultaneously is prevented by the suppression of the trigger pulses to the non-conducting thyristor of that phase if the other thyristor is conducting.

The second protection circuit is shown in figure 3.22. Here the signals, L, M, N, P, Q and S from the thyristor state detector (Section 3.2.2) are fed into coincidence logic circuitry along with the signals A, B and C from the rotor position transducers. If a thyristor is still conducting 180° after it was fired, then a signal is fed into the rectifier inhibit inputs (Section 3.1), suppressing the rectifier thyristor firing pulses for as long as that thyristor is conducting. A light emitting diode is placed in series with this signal, so that it can be seen when this circuit is in operation.

3.2.6 Low Speed Inhibit Logic

At very low speeds (up to about 5 Hz), the rectifier firing pulses are suppressed six times per cycle to assist inverter commutation (Section 2.3.2). The signals A, B and C from the three rotor position transducers are fed into NAND gates (figure 3.23) to produce the signal Z in the timing diagram in figure 3.24. A change in the logic level of Z is then used



rectifier inhibit = $A \cdot \overline{L} + \overline{A} \cdot \overline{P} + B \cdot \overline{M} + \overline{B} \cdot \overline{Q} + C \cdot \overline{N} + \overline{C} \cdot \overline{S}$

Figure 3.22 The Circuit which Inhibits the Rectifier in the Event of a Commutation Failure (CMOS)

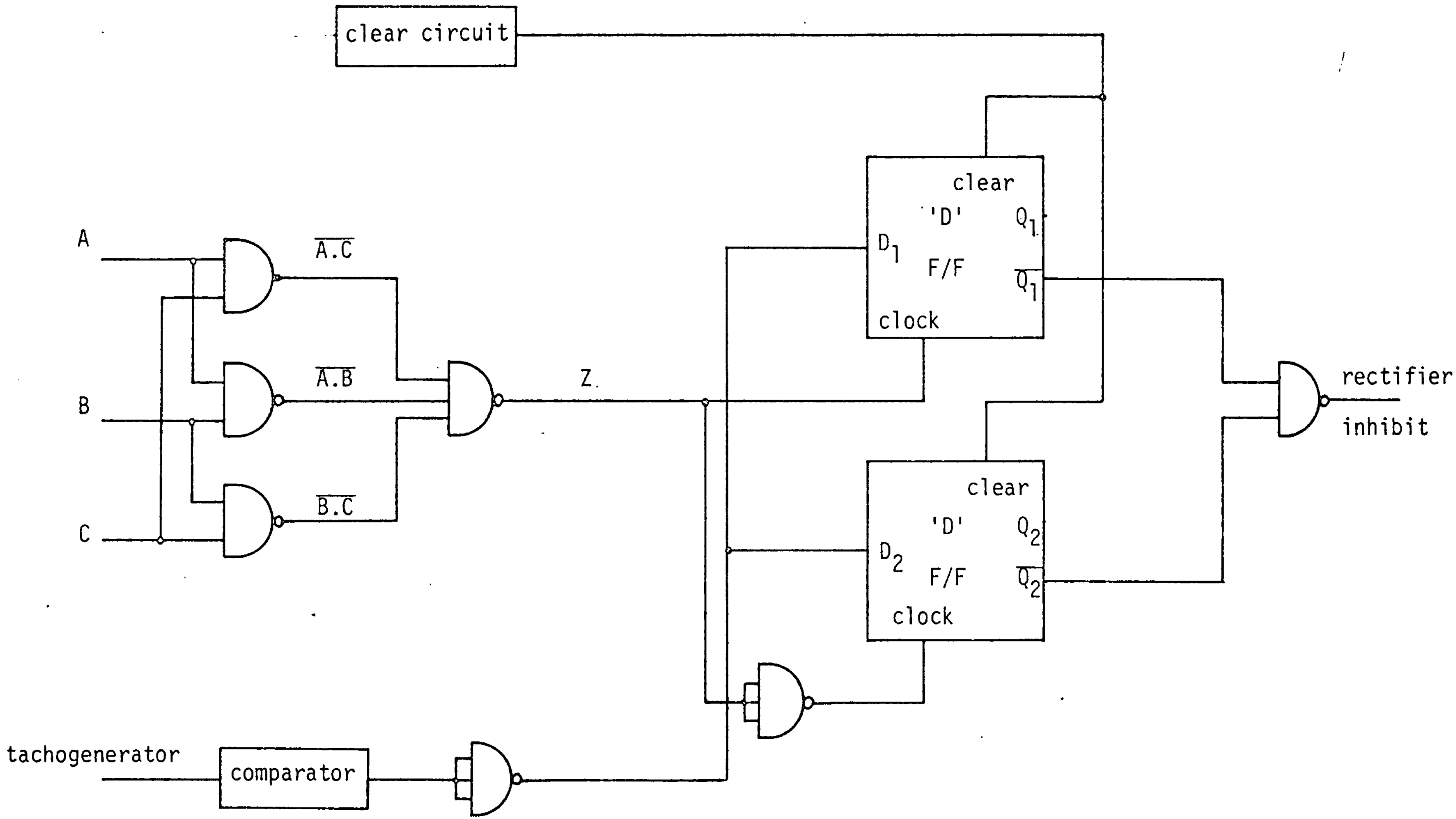


Figure 3.23 Low Frequency Inhibit Logic (T.T.L.)

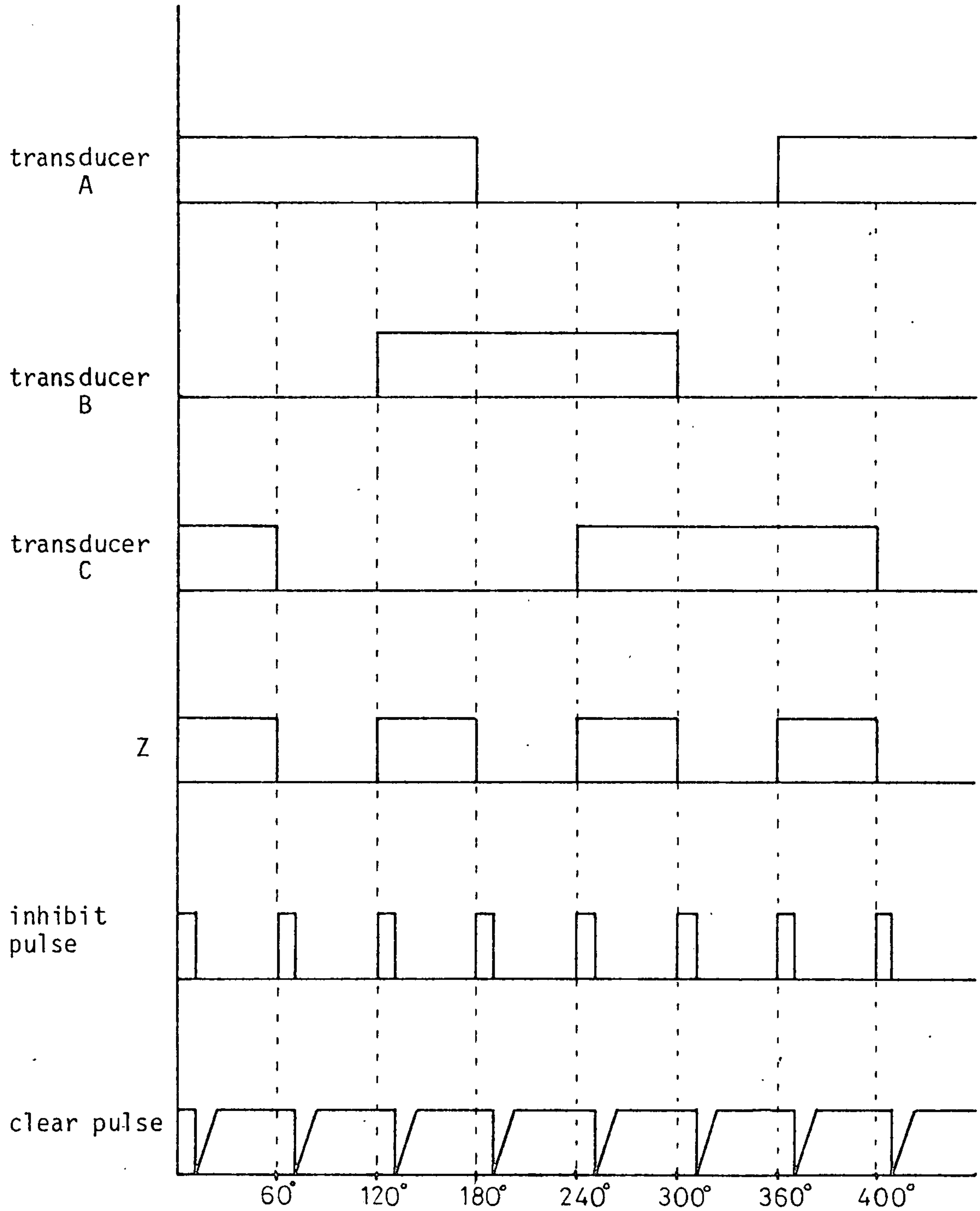


Figure 3.24 Low Frequency Inhibit Logic Timing Diagram

to initiate the rectifier inhibition signal; the positive-going edges of Z, and the positive-going edges of $\overline{Z}$, clock the logic '1' at the D-type flip-flop inputs D_1 and D_2 through to the outputs Q_1 and Q_2 respectively. $\overline{Q}_1$ and $\overline{Q}_2$ are then fed into a NAND gate to produce the rectifier inhibit signal.

The circuit in figure 3.25 combines signals from the thyristor state detectors with signals from the rotor position transducers to sense when the appropriate inverter thyristor is switched off. Once commutation is achieved, a short delay of about 100 μs is introduced to allow the thyristor to revert fully to the forward blocking state, then a short negative-going pulse into the clear inputs of the D-type flip-flops removes the rectifier inhibit signal.

When the machine speed has built up sufficiently for the inverter to be commutated naturally, a pre-set comparator (figure 3.26), operating on the signal from the shaft-mounted tachogenerator, changes the D_1 and D_2 flip-flop inputs from logic '1' to logic '0'. A change in logic level of Z will now cause a '0' instead of a '1' to be clocked through the flip-flops, leaving the rectifier uninhibited. The low speed inhibit logic is thus effectively disconnected at higher speeds.

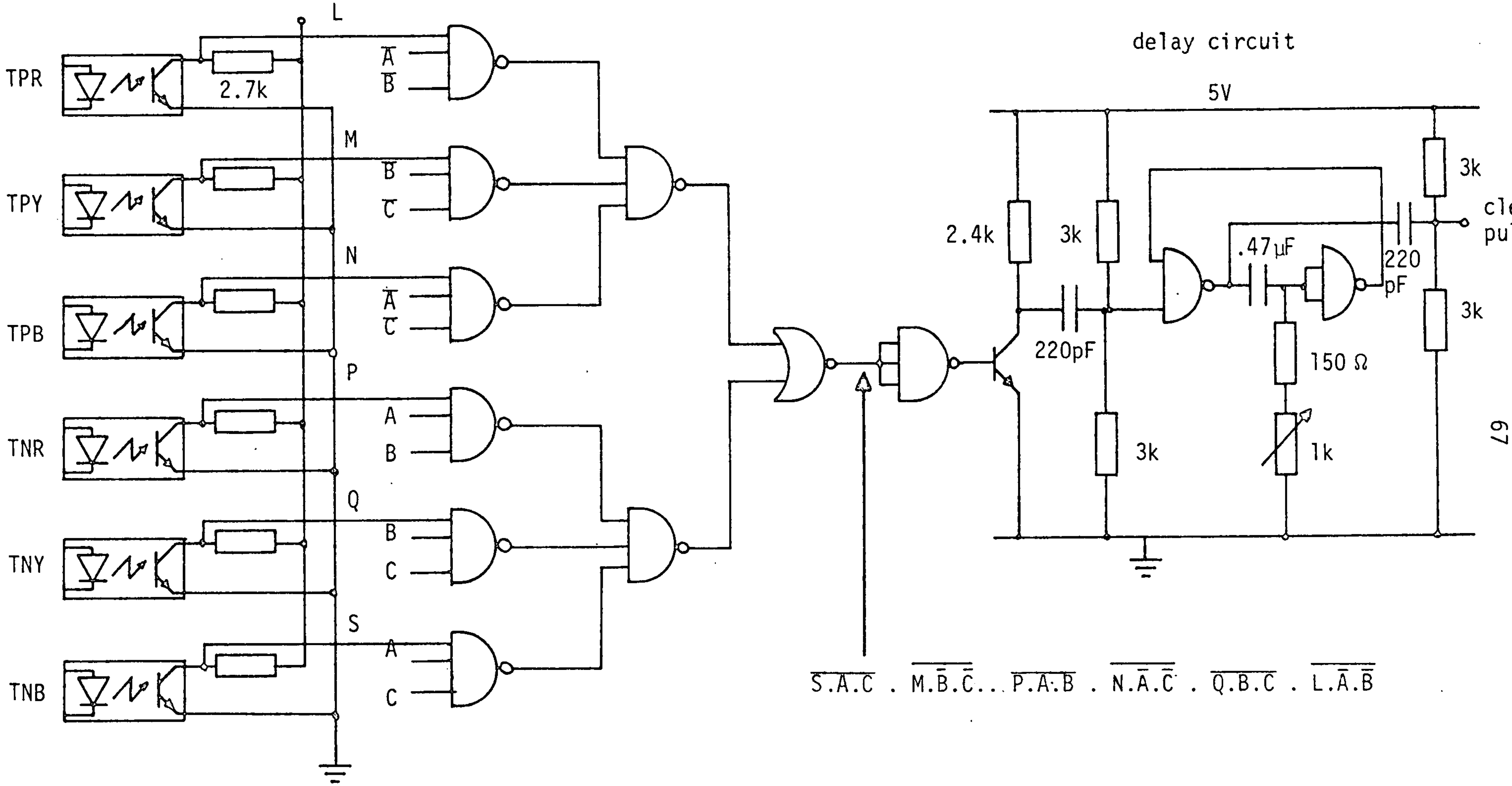


Figure 3.25 The Low Frequency Rectifier Inhibit Clearing Circuit (CMOS)

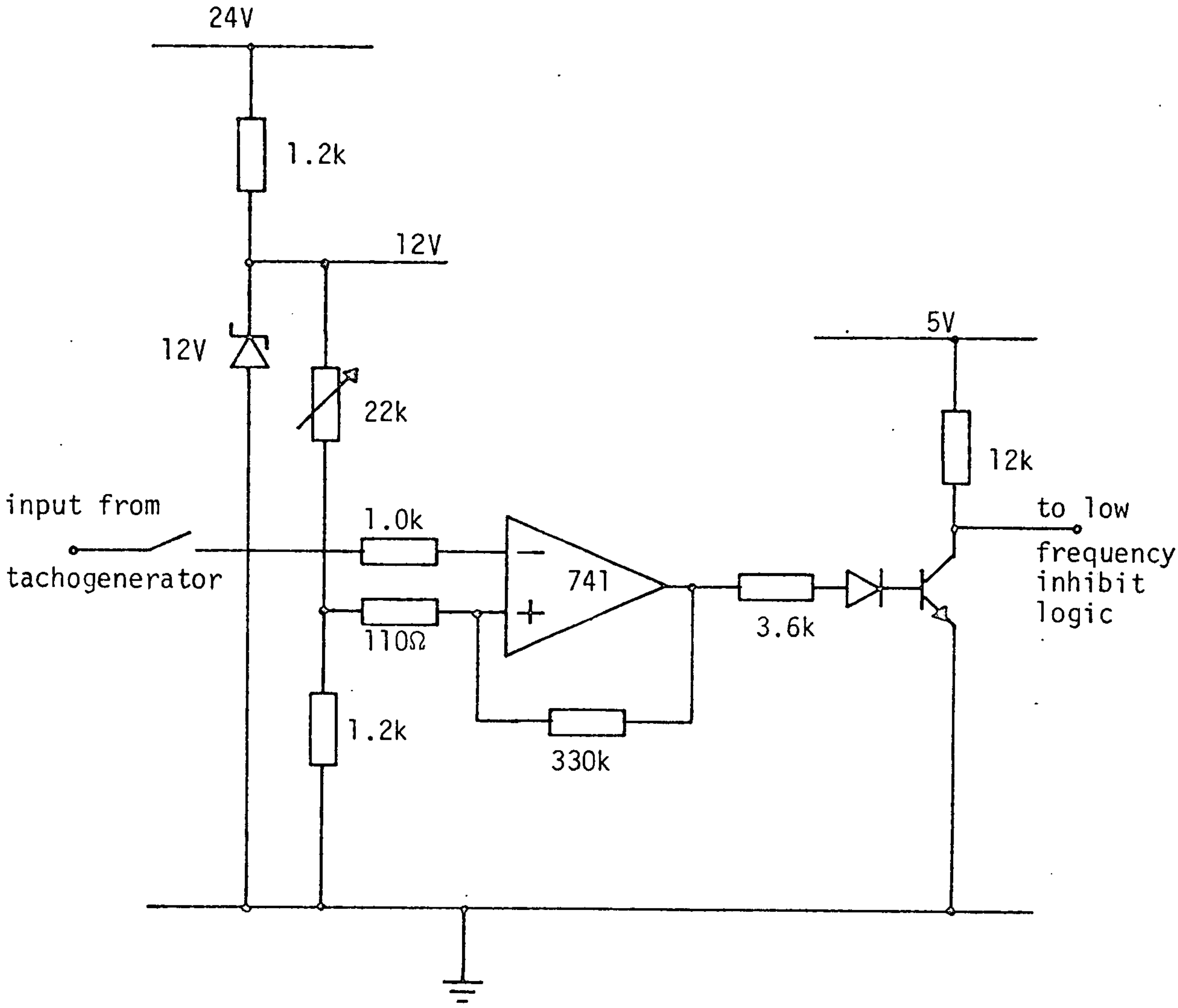


Figure 3.26 Comparator Circuit from Tachogenerator Output

3.2.7 Inverter Thyristor Latching Circuit

When operating at low speeds, and therefore low d.c. link voltages, some problems arose due to the inverter thyristors not latching on when pulsed. This was attributed to two reasons:
(a) Each of the three Westinghouse P82D circuits has its own oscillator, so the pulses to the inverter thyristors are not synchronized with each other. During the low speed commutation mode of operation, the two inverter thyristors which are to conduct must be pulsed simultaneously to provide a path for the thyristor holding current. As the mark/space ratio of the trigger pulses is 1:10, there was often a considerable delay before the pulses to the two thyristors coincided.

(b) The considerable inductance in the system meant that, at low operating voltages, the thyristor current sometimes took longer than the 70μs trigger pulse width to reach the thyristor latching current, with the result that the thyristor reverted to the forward blocking state at the termination of the pulse.

The same two 5 Volt floating power supplies which power the thyristor state detector (Section 3.2.2) are used to circulate a latching current of 1 amp through each thyristor while the thyristor is being pulsed. The output signals from the inverter thyristor firing control circuit (Section 3.2.4) control the power transistor switches T_1 and T_2 via decoupling optical isolators (figure 3.27), so that as soon as thyristor 1 is pulsed, a 1 amp latching current circulates round the loop CD2, thyristor 1,

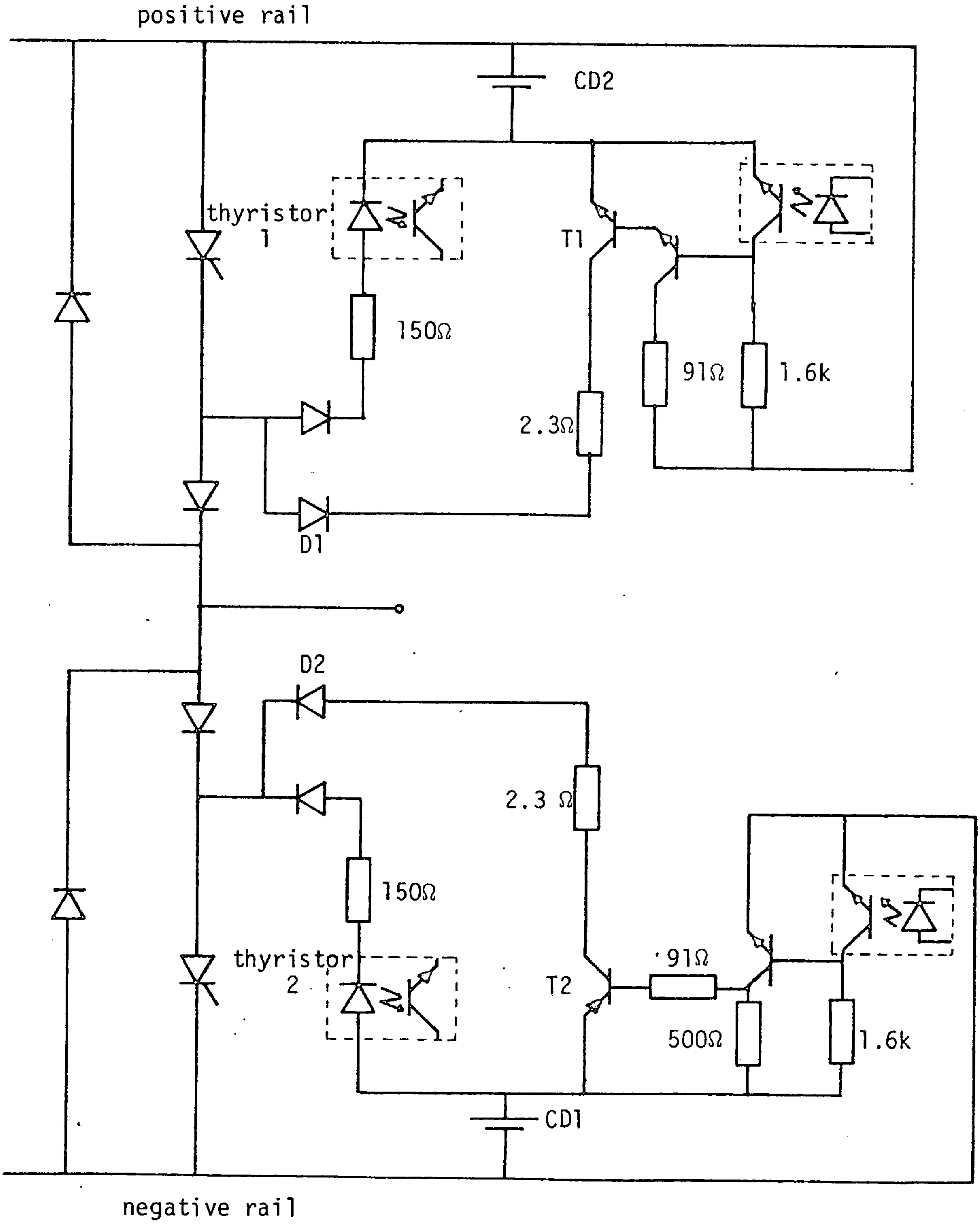


Figure 3.27 Current Detector and Latching Circuit for One Phase

diode D_1, the 2.3 Ω resistor and transistor T_1. The complete circuit is shown in figure 3.28.

3.3 INVERTER MARK II

The system described in Section 3.2 worked successfully when driving a synchronous machine with two independent orthogonal field windings. However, few synchronous machines are of this type, so a system was designed and built to drive a single-field machine.

Section 2.3 describes how the load angle, δ , should increase with speed to produce maximum torque while maintaining natural commutation. In the inverter Mk I this is achieved by increasing the ratio of the field currents $I_Q : I_D$; in the Mk II version it is achieved by advancing the firing of the inverter thyristors with respect to rotor position.

Influenced by the results of computer studies (Section 5.2.3), it was decided to operate the system with three different values of δ . From zero speed to about 0.2 Hz, while the load is predominantly resistive, δ is set at 0^o; from 0.2 Hz to 5 Hz it is set at 30^o, and above 5 Hz it is set at 60^o.

The thyristor-state detection circuit and the inverter thyristor latching circuit are the same as are used in the Mk I inverter, described in Sections 3.2.2 and 3.2.7 respectively. However, the inverter control system was completely redesigned.

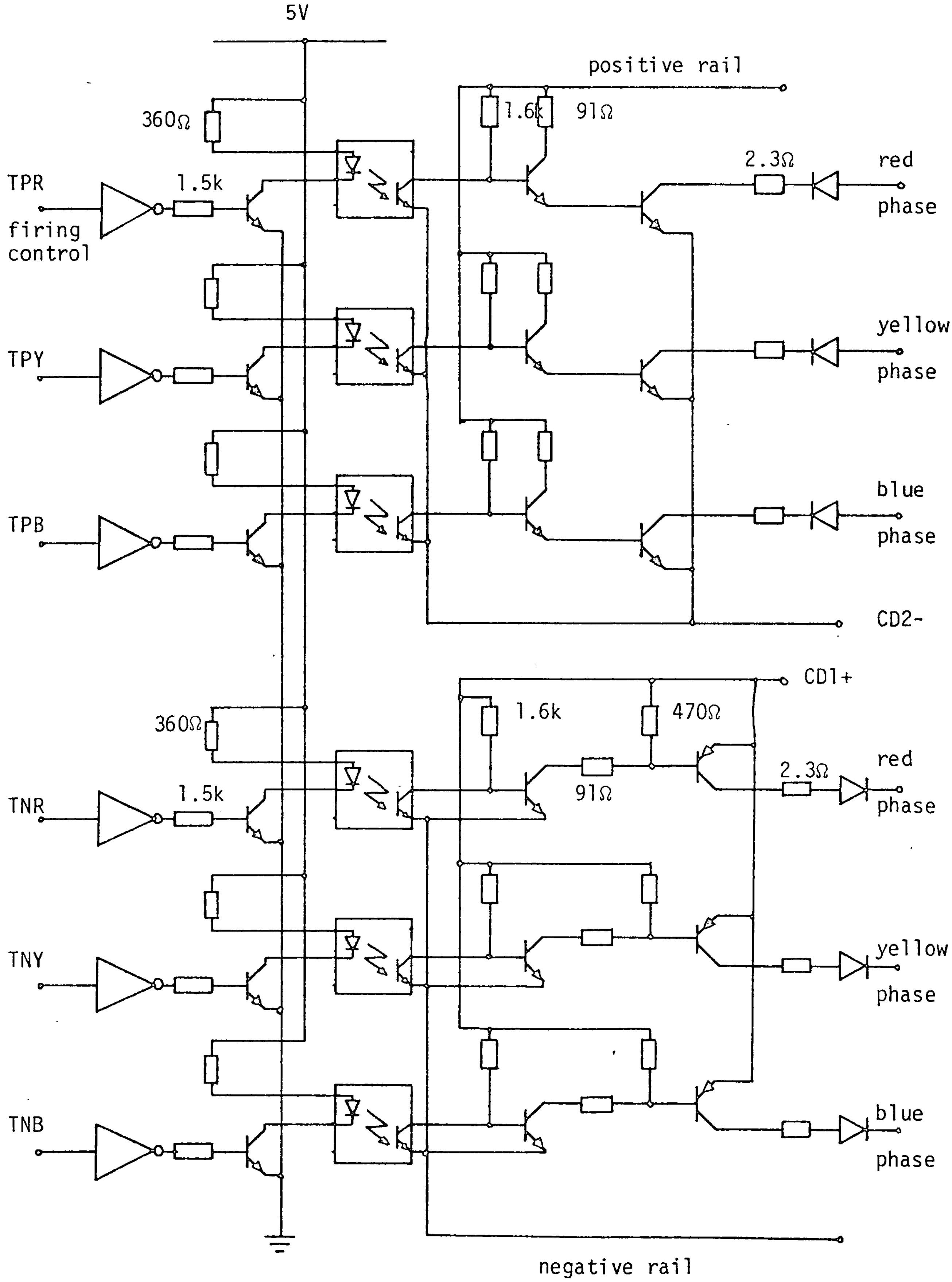


Figure 3.28 The Complete Inverter Thyristor Latching Circuit

(C MO S)

3.3.1 Inverter Firing Control

The firing instants for $\delta = 0^o$ and $\delta = 60^o$ are easily obtainable from the rotor position detector system described in Section 3.2.1. However, it is necessary to introduce a fourth transducer with its own magnetic tape pattern to obtain the firing instants for operation at the intermediate angle of $\delta = 30^o$.

The fourth transducer, D, is set such that each 30^o (electrical) segment is well defined by the four transducers. The magnetic tape arrangement for the fourth transducer for a 4-pole machine is shown in figure 3.29. The outputs from the four transducers are reduced to CMOS logic levels operating from a 12 Volt supply in the buffer circuit shown in figure 3.30, with all the outputs inverted except for C, which is inverted twice for the reasons discussed in Section 3.2.1.

The timing diagram in figure 3.31 shows the outputs from the four transducers (after the buffer stage), and the 120^o periods during which the thyristors are pulsed. The logic expressions for the 120^o periods are given in Table 3.1.

The switching from one value of δ to another is effected by three signals, X, Y and Z, taken from comparators (Section 3.3.2) operating on the tachogenerator output.

As in the inverter Mk I, the possibility of two thyristors in the same phase leg conducting simultaneously is prevented by adding the thyristor state detector signal of one thyristor

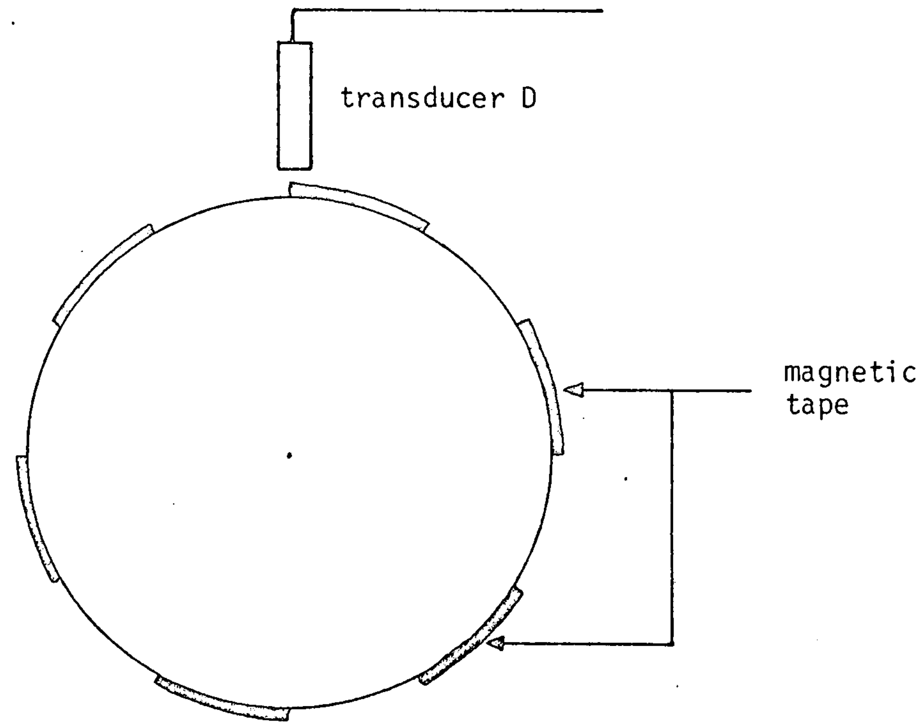


Figure 3.29 Magnetic Tape Arrangement for the Fourth Transducer on a 4-Pole Machine

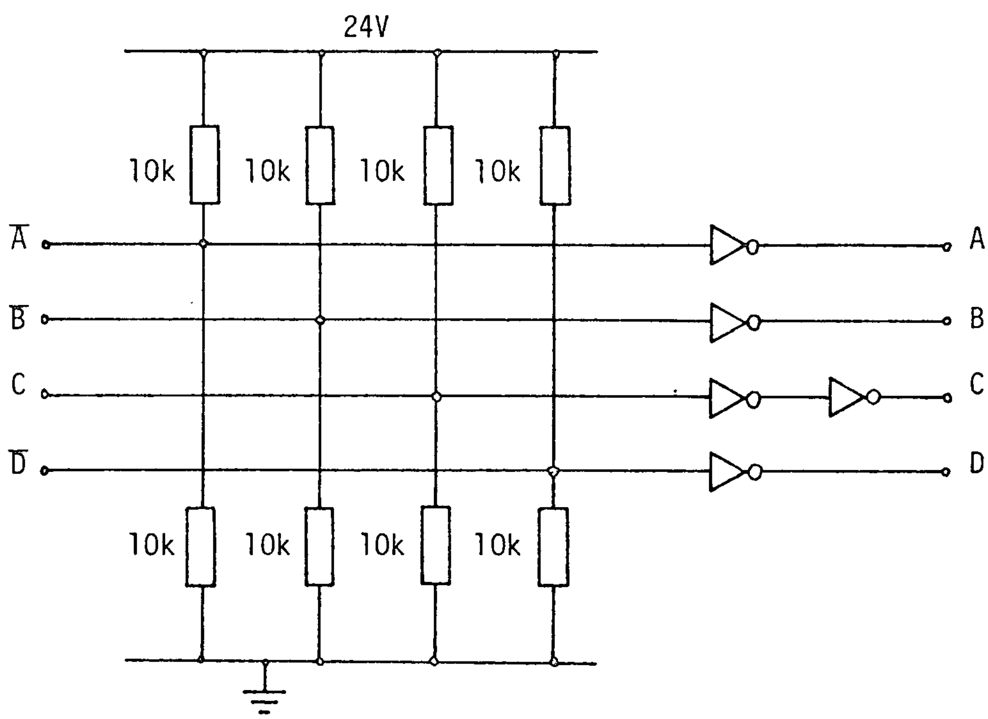


Figure 3.30 Transducer Interface Circuit

(C M O S)

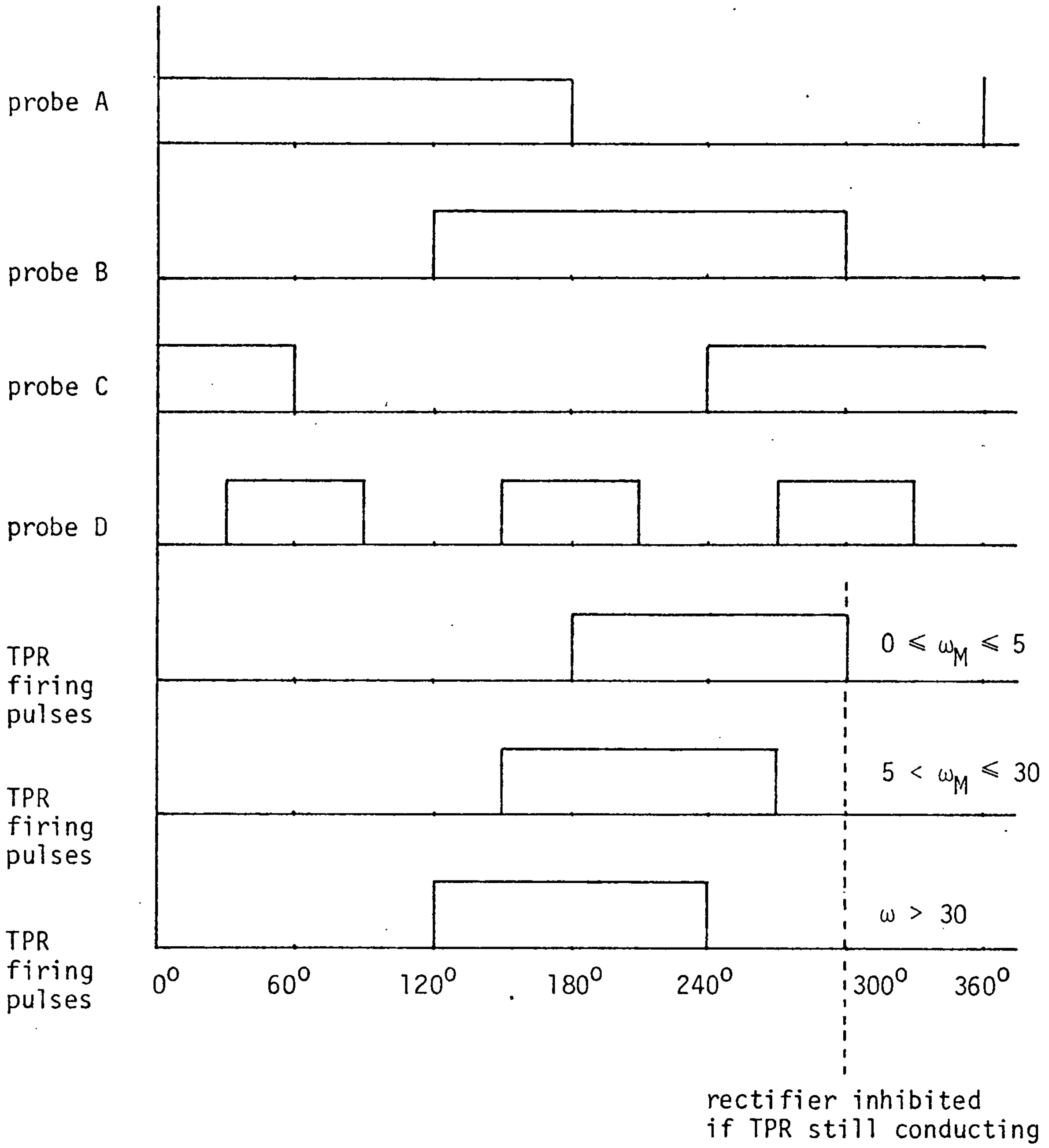


Figure 3.31 The Timing of the Firing Pulses to the Positive Red Thyristor Relative to the Transducer Signals for the 3 Speed Ranges

to the inhibit signal controlling the firing of the other. Thus if thyristor 1 is conducting, the firing pulses to thyristor 4 are suppressed.

The complete logic signals controlling the firing of the inverter thyristors are given below. The firing pulses are inhibited if the output is a logic '1'.

Table 3.1

Thyristor 1 : $X \cdot \overline{(\bar{A} \cdot B)} + Y \cdot \overline{(\bar{A} \cdot B \cdot \bar{D} + B \cdot \bar{C} \cdot D)} + Z \cdot \overline{(B \cdot \bar{C})}$

Thyristor 2 : $X \cdot \overline{(\bar{B} \cdot C)} + Y \cdot \overline{(\bar{B} \cdot C \cdot \bar{D} + \bar{A} \cdot C \cdot D)} + Z \cdot \overline{(\bar{A} \cdot C)}$

Thyristor 3 : $X \cdot \overline{(A \cdot \bar{C})} + Y \cdot \overline{(A \cdot \bar{C} \cdot \bar{D} + A \cdot \bar{B} \cdot D)} + Z \cdot \overline{(A \cdot \bar{B})}$

Thyristor 4 : $X \cdot \overline{(A \cdot \bar{B})} + Y \cdot \overline{(A \cdot \bar{B} \cdot D + \bar{B} \cdot C \cdot \bar{D})} + Z \cdot \overline{(\bar{B} \cdot C)}$

Thyristor 5 : $X \cdot \overline{(B \cdot \bar{C})} + Y \cdot \overline{(B \cdot \bar{C} \cdot D + A \cdot \bar{C} \cdot \bar{D})} + Z \cdot \overline{(A \cdot \bar{C})}$

Thyristor 6 : $X \cdot \overline{(\bar{A} \cdot C)} + Y \cdot \overline{(\bar{A} \cdot C \cdot D + \bar{A} \cdot B \cdot \bar{D})} + Z \cdot \overline{(\bar{A} \cdot B)}$

The inverter firing control circuit is shown in figure 3.32.

3.3.2 The Comparator Circuit

Two pre-set comparators (figure 3.33) operating on the tachogenerator signal control the switching from one value of δ to another.

The tachogenerator output of 40 V at 1500 r.p.m. (full speed for the 4-pole machine) is reduced by a resistor divider to a full speed value of 15 V, then fed into the two comparators. One is

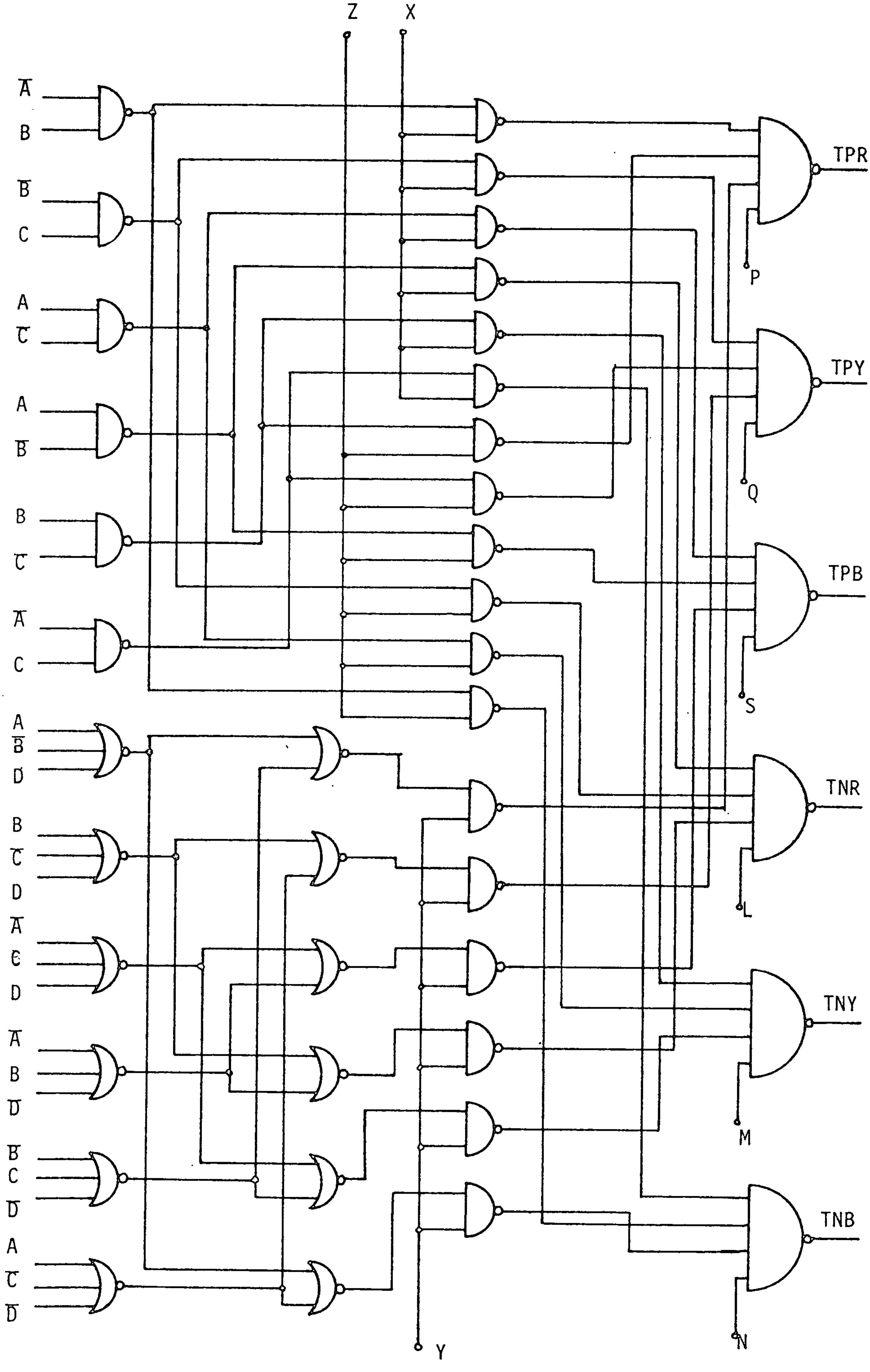


Figure 3.32 Inverter Thyristor Firing Control Circuit(CMOS)

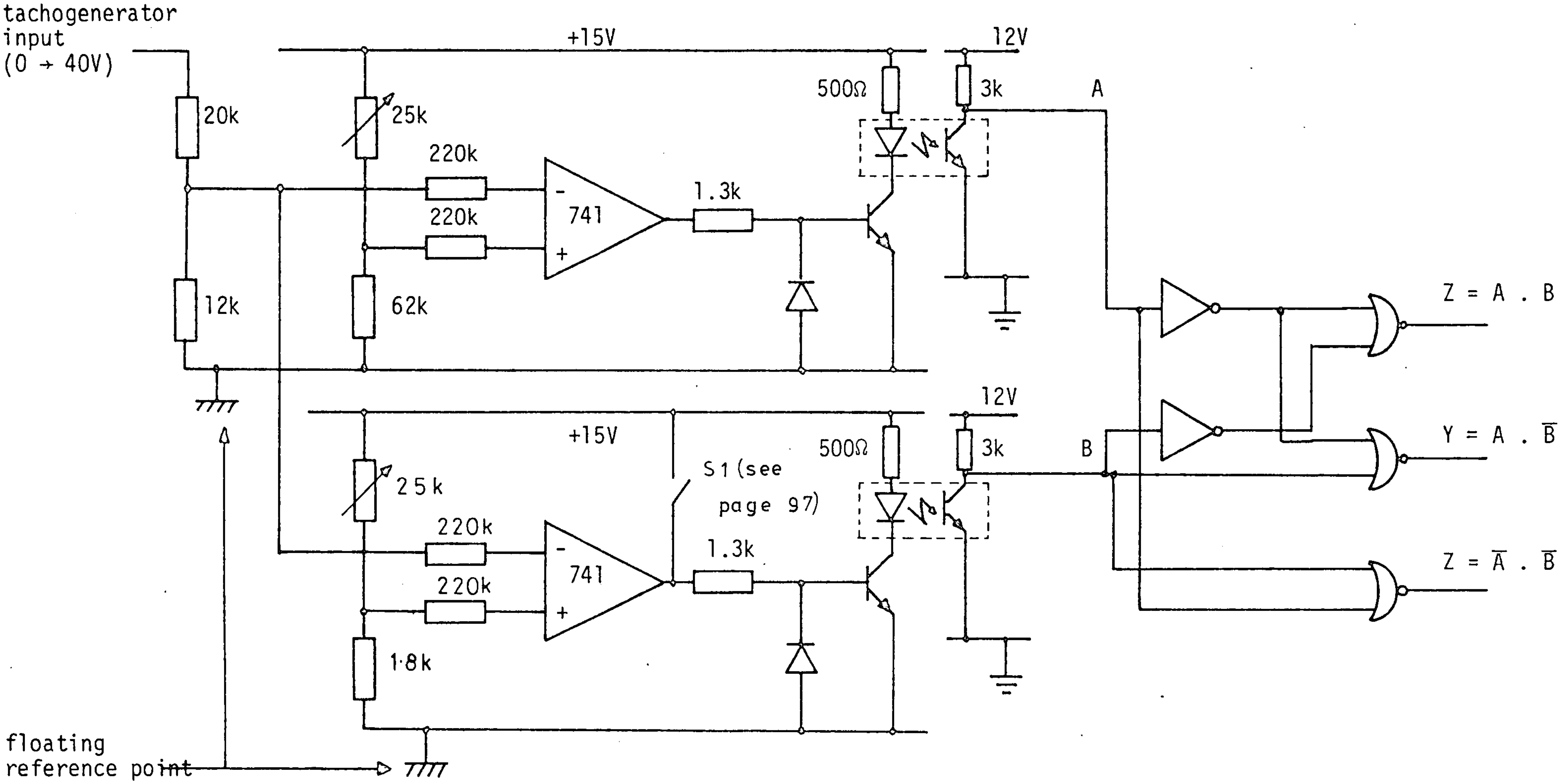


Figure 3.33 The Comparator Circuit (CMOS)

set to switch at 4 r.p.m., while the other switches at about 100 r.p.m., although both switching points can be adjusted by the 25 kΩ potentiometers.

The negative terminal of the tachogenerator is connected to pin 16 on the Westinghouse D82 L.E.D. boards via the rectifier delay angle control circuit (section 3.1). The negative terminal of the comparator is connected to earth, and so is connected to pin 24 via the rectifier inhibition circuitry, so if the tachogenerator output is electrically connected to the comparator output, pins 16 and 24 will be shorted. To prevent this, the comparator outputs pass through decoupling L.E.D. - phototransistor circuits.

After the decoupling circuits, the comparator outputs are combined in NOR gates to form the signals X, Y and Z such that :

$$X = \bar{A} \cdot \bar{B}$$

$$Y = A \cdot \bar{B}$$

$$Z = A \cdot B$$

X is, therefore, at logic '1' at very low speeds when both comparators have a logic 0 output, Y is at logic 1 for the period after comparator A has switched but before comparator B has switched, and Z is at logic 1 at high speeds when both comparators have a logic 1 output. The signals X, Y and Z are then fed into the inverter firing control circuit (Section 3.3.1).

3.3.3 Low Speed Inhibit Logic

Rectifier inhibition can be implemented for either of two reasons : to assist the commutation of an inverter thyristor in the low speed mode of operation, or to protect the system in the event of commutation failure. It was found from computer studies (Section 5.2.3) that the rotor angle at which rectifier inhibition is used to artificially commutate a conducting thyristor for either reason is the same for all 3 values of δ (figure 3.31). Therefore, the same circuit can be used both to perform the low speed commutation and to protect the system if commutation fails at higher speeds.

The circuit in figure 3.34 is similar to that in figure 3.22 except that the former will inhibit the rectifier if thyristor 1, say, is still conducting when the output from transducer B changes from a '1' to a '0', whereas the circuit in figure 3.22 will act 60^{o} later. Thus the rectifier is inhibited 120^{o} after the firing of thyristor 1 (if it is still conducting) when $\delta = 0^{o}$, 150^{o} after firing when $\delta = 30^{o}$ and 180^{o} after firing when $\delta = 60^{o}$. The changeover from artificial commutation to natural commutation occurs while $\delta = 30^{o}$, and is automatic, for the rectifier will not be inhbited if the appropriate thyristor has ceased conducting 150^{o} after it was fired.

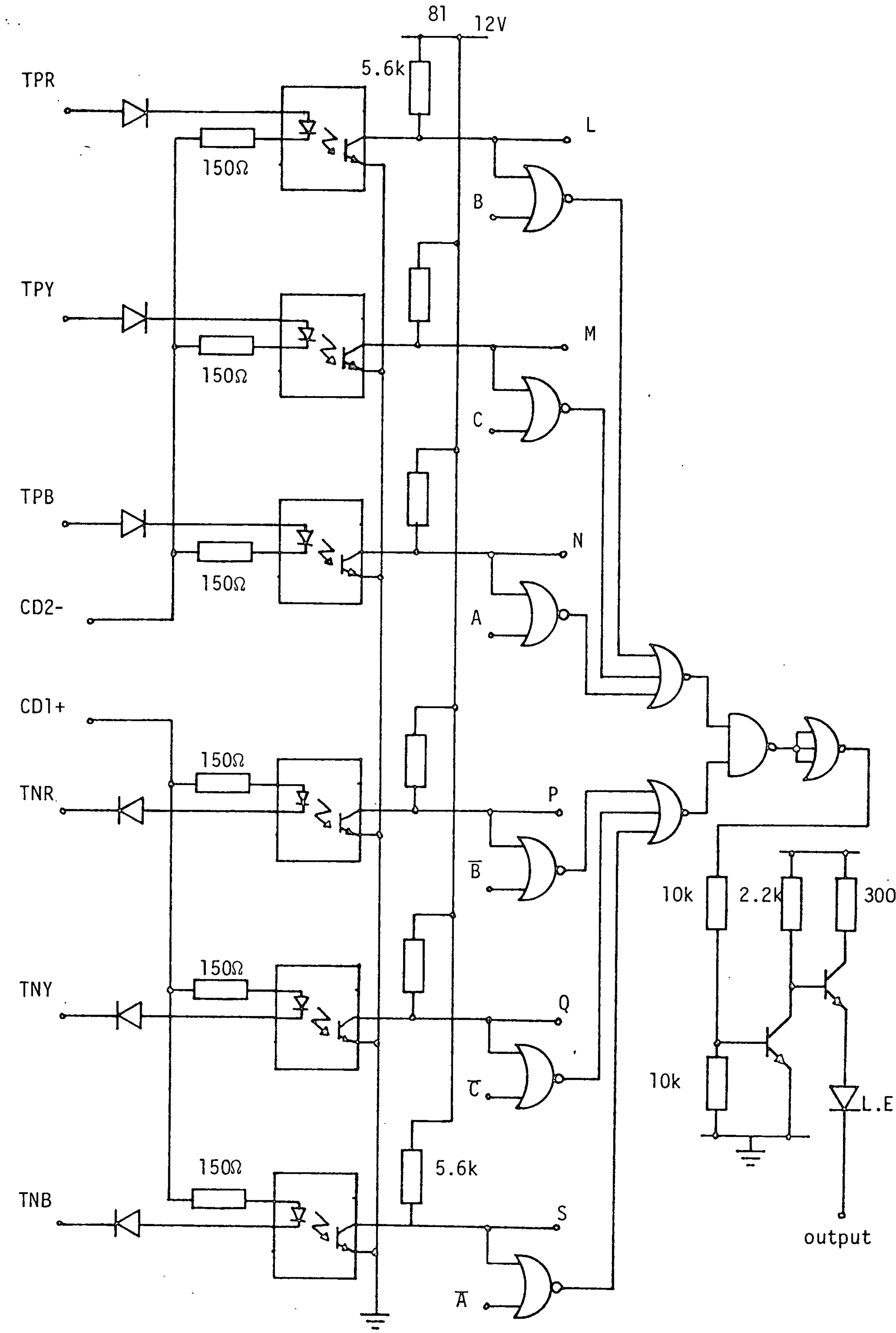


Figure 3.34 The Rectifier Inhibition Control Circuit (CMOS)

3.3.4 Inverter Output Pulse Stage

As the three Westinghouse P82D circuits in the inverter Mk I are under-used, a circuit was designed and built comprising an oscillator, whose output can be gated to any of the six output stages (figure 3.35).

The oscillator pulse width and space width can be controlled by the two 100 kΩ potentiometers, a setting of 50 μs and 400 μs proving suitable. A logic '0' into any of the six inhibit inputs allows the trigger pulses to appear at that driver output, while a logic '1' suppresses them. All the trigger pulses are suppressed if the override switch (switch 2) is closed, effectively switching off the inverter.

A block diagram of the complete system is shown in figure 3.36 .

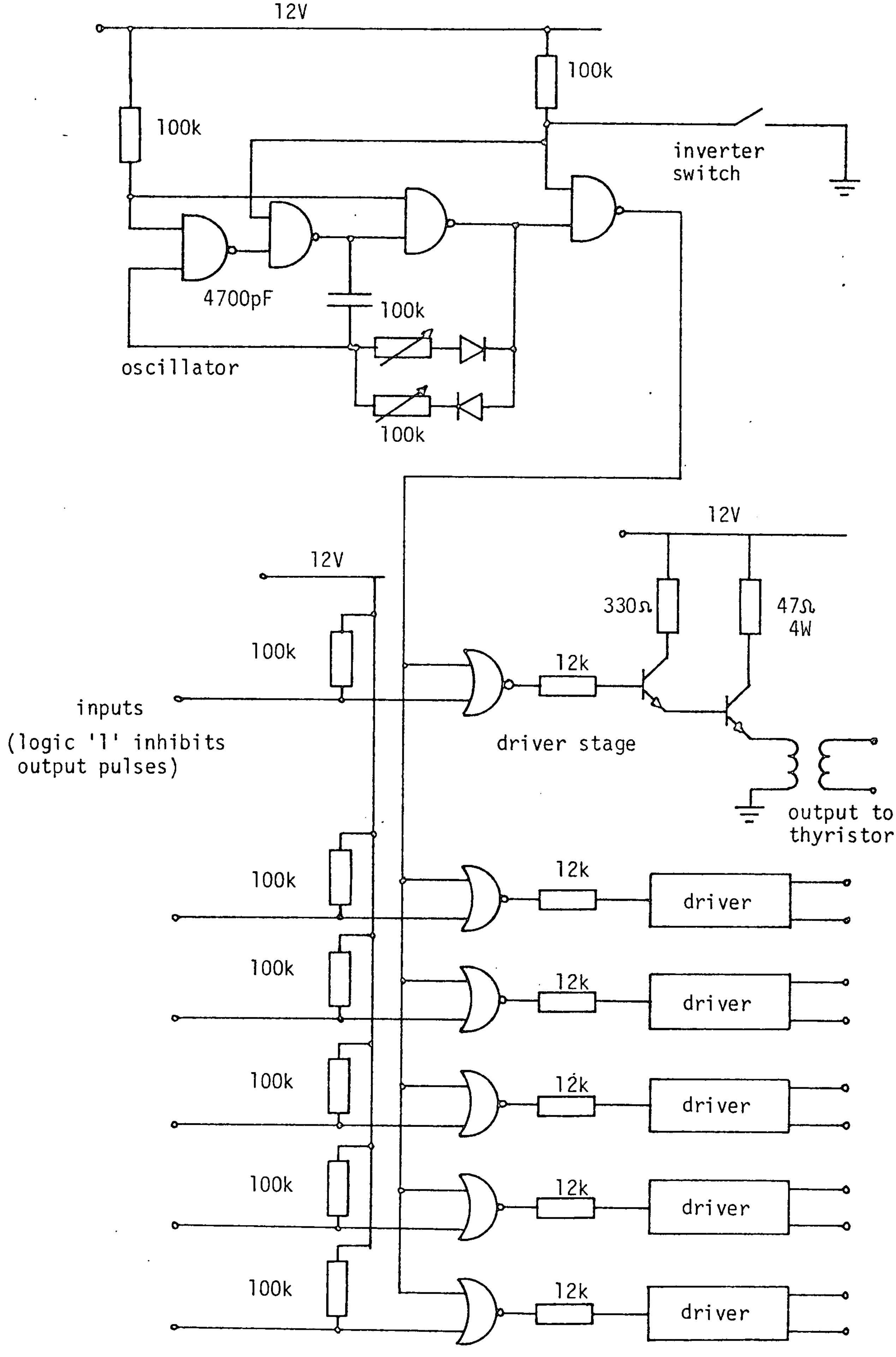


Figure 3.35 Hex Driver Board (C MOS)

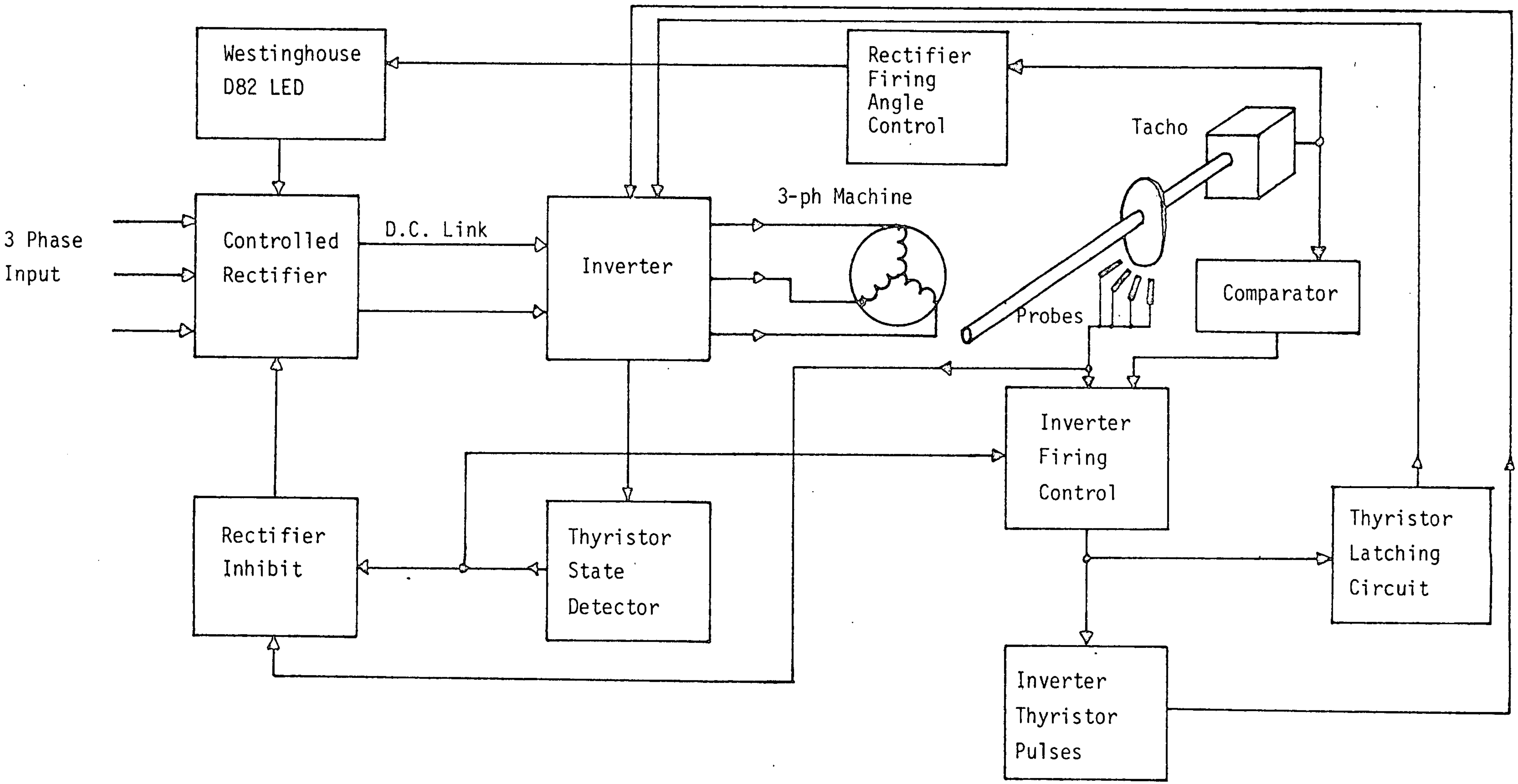


Figure 3.36 Block Diagram of the Complete Rectifier-Inverter-Synchronous Machine System

CHAPTER 4 : EXPERIMENTAL RESULTS

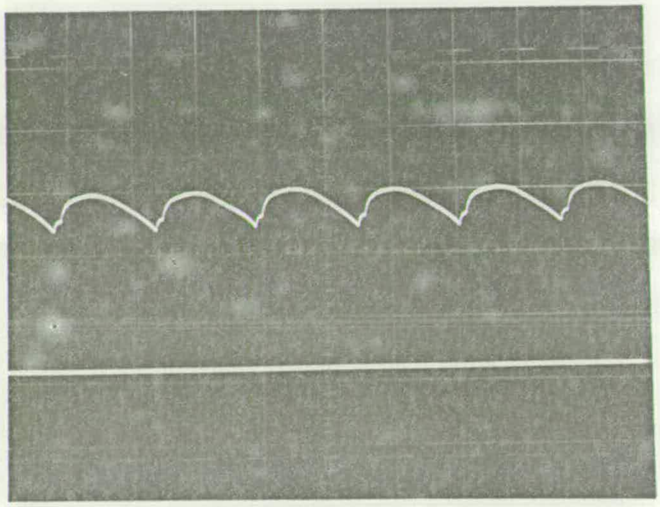
4.1 THE CONTROLLED RECTIFIER

Tests were carried out on the controlled rectifier driving a resistive load. Figure 4.1 shows the rectifier output voltage with zero delay angle (ie, the controlled rectifier is acting as a diode bridge). Some commutation overlap can be observed due to the leakage inductance of the transformer and the variac on the a.c. side of the rectifier. The output voltage with a delay angle of about 30^0 is shown in figure 4.2.

An AVO meter was connected across the load, and a series of readings was taken of the average output voltage against the control voltage to the Westinghouse circuits (figure 4.3). If the output voltage is set at 130 Volts by the variac when operating with a delay angle of zero, then the output can be reduced to 15 Volts in an almost linear fashion by reducing the control voltage from 2.2 Volts to 1.1 Volts. Any further fall in the control voltage causes the firing pulses to disappear, and the output voltage will drop to zero.

4.2 SYSTEM TESTS

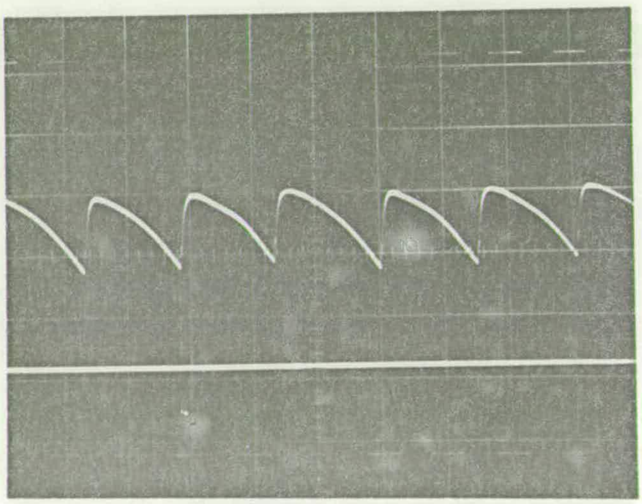
Tests were carried out on the complete controlled rectifier/ inverter system driving the two-field cylindrically wound machine described in Appendix B. All the results in this section were taken using the inverter Mk II. The inverter Mk I produced similar voltage and current waveforms, but the acceleration



$V_{D.C.}$

Scale = 2 ms/div

Figure 4.1 The Rectifier Output Voltage with Zero Delay Angle



$V_{D.C.}$

Scale = 2 ms/div

Figure 4.2 The Rectifier Output Voltage with a 30^0 Delay Angle

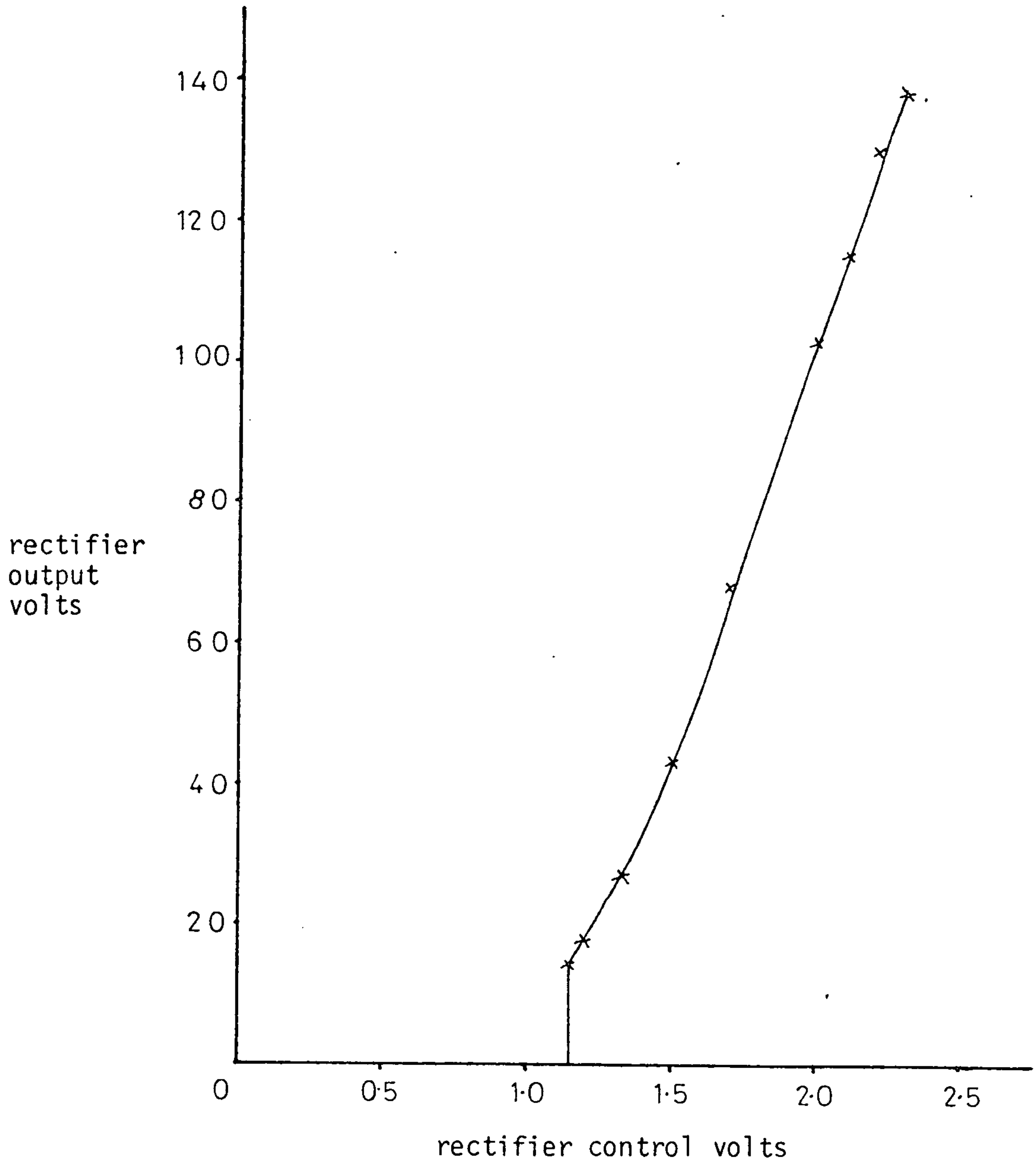


Figure 4.3 Rectifier Output Voltage Against Rectifier Control Voltage for a Variac Setting of 100%

characteristics were different because the manual changes in the load angle, δ , could not be carried out quickly.

Apart from the locked rotor tests (Section 4.2.1), all the results were taken with one field only excited, the other being kept open circuit.

4.2.1 D.C. Link Voltage Control

The delay angle of the controlled rectifier was set to zero, and the d.c. link voltage controlled by the 3-phase variac on the a.c. side of the rectifier. The load angle δ was fixed at 60^{0}, and the system accelerated to full speed (1500 r.p.m.) and held there by suitable control of the d.c. machine on the same rotor shaft. The d.c. link voltage then was increased until natural commutation failed; this occurred at 67 Volts. A full speed d.c. link voltage of 60 Volts was chosen for normal operation, corresponding to a variac setting of 55% when the rectifier delay angle is zero.

When operating under the above conditions, the d.c. link current is 10 amps. To maintain the current at this value at all speeds, and so utilize fully the current handling capabilities of the thyristors, it was found by experiment that the d.c. link voltage should be 17 Volts at zero speed, and increased linearly with speed to 60 Volts at 1500 r.p.m.

4.2.2 Starting

The rotor was locked at an angle of 30^0 (electrical), a position midway between commutation angles, with the positive red and the negative yellow thyristors conducting. The tests were carried out with a reduced applied voltage to keep the motor currents within the machine ratings. The starting torque was measured as the load angle, δ, was varied from -60^0 to $+90^0$ (figure 4.4). The change in δ was effected by adjusting the ratio of the field currents $I_D : I_Q$, while keeping the vector sum $\underset{\sim}{I}_D + \underset{\sim}{I}_Q$ constant so that the resulting field magnitude remained constant. It can be seen from figure 4.4 that the maximum experimental starting torque occurs with a load angle of -15^0, compared with the theoretical maximum of -30^0 (Section 2.3.3). The discrepancy between the curves may be ascribed partly to the fact that the spring balance used for measuring the torque permitted some angular movement of the rotor, and partly to inaccuracies in the positioning of the rotor position transducers.

In the next test the load angle, δ, was set at 0^0, and the starting torque was measured as the locked rotor position was varied between 0^0 and 80^0 (electrical). The results in figure 4.5 show that maximum starting torque occurs immediately before a commutation instant, and the minimum just after commutation. This agrees with the theory in Section 2.3.3, although the theoretical and experimental curves do not coincide, probably for the same reasons as described above.

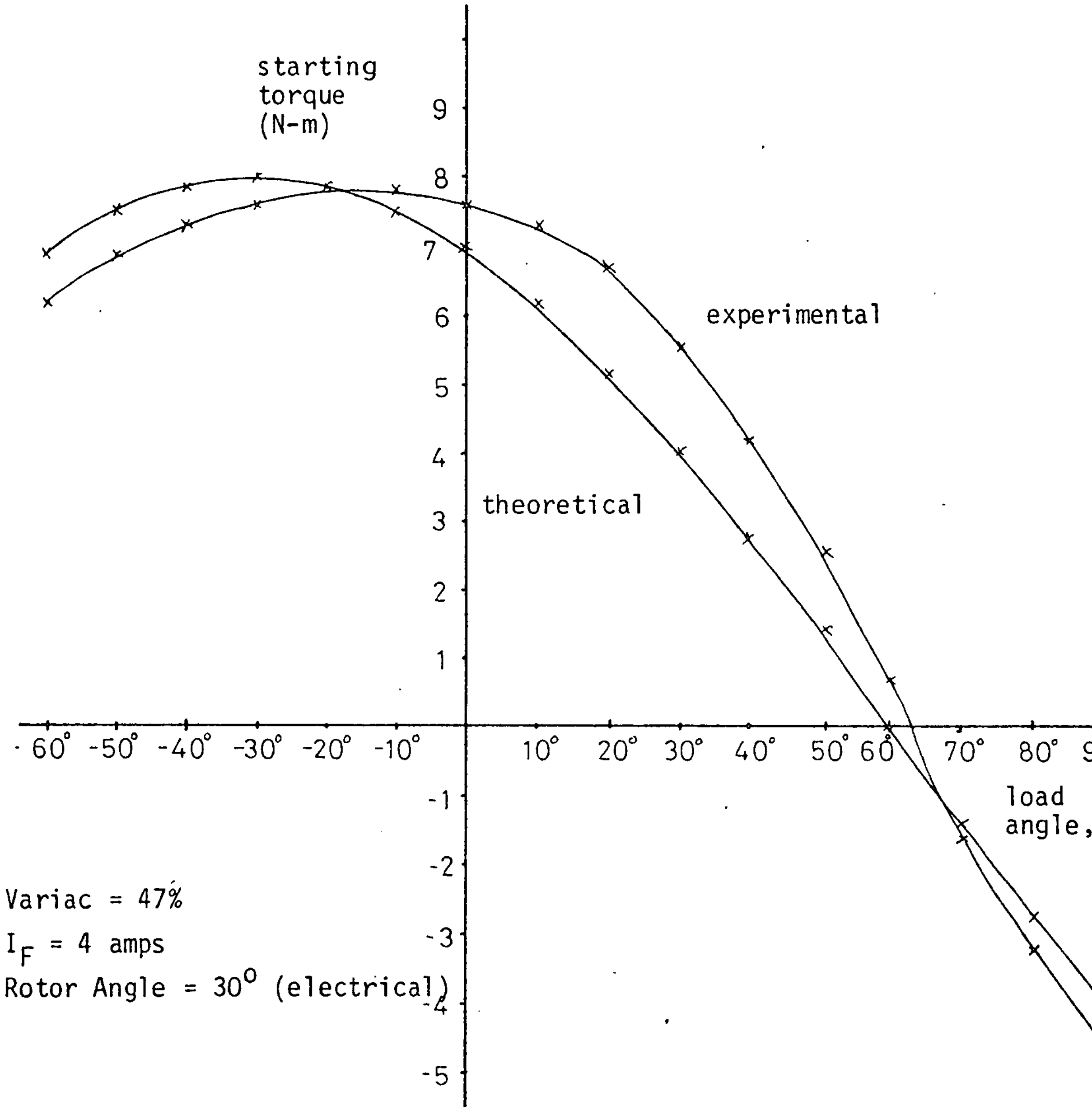
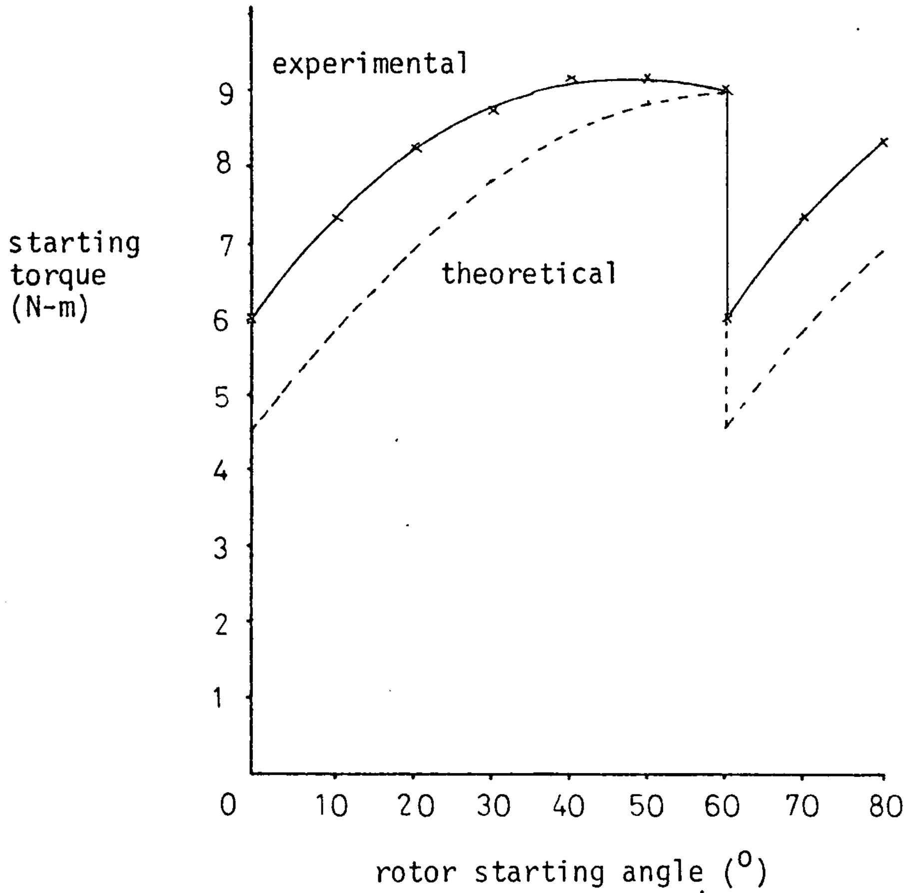


Figure 4.4 Machine Starting Torque Against the Load Angle, δ



Variac = 40%

I_F = 6.5 amps

$\delta = 0^o$

Figure 4.5 Starting Torque Against Rotor Angle

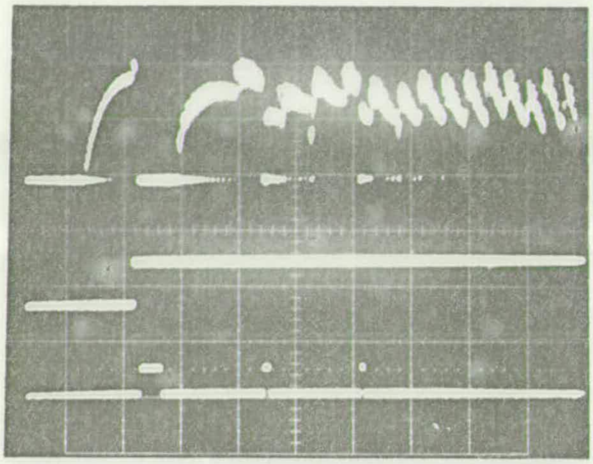
The starting current in the d.c. link is shown in the top trace in figures 4.6 and 4.7. The middle trace indicates when δ changes from 0^o to 30^o, and the bottom trace shows the rectifier inhibit signals in the artificial commutation mode of operation. Oscillograph 4.6 was taken with the rotor starting position set at an angle 10^o (electrical) before a commutation position and oscillograph 4.7 at an angle 10^o (electrical) after a commutation position.

It can be seen that in neither case is the initial d.c. link current significantly greater than its running value, so the thyristors do not have to be highly rated to cope with starting conditions. The slow build up in the d.c. link current is due to the relatively high inductance of the isolating transformer and variac on the a.c. side of the controlled rectifier, together with the inductance of the motor.

It was found from computer simulations (Section 5.2.3) that the changeover from operation with $\delta = 0^o$ to $\delta = 30^o$ should be made at an inverter frequency of between 0.3 Hz and 0.8 Hz. The oscillographs indicate that this will mostly occur before the first commutation, and that artificial commutation is operative only for the first two or three commutations, after which the inverter commutates naturally.

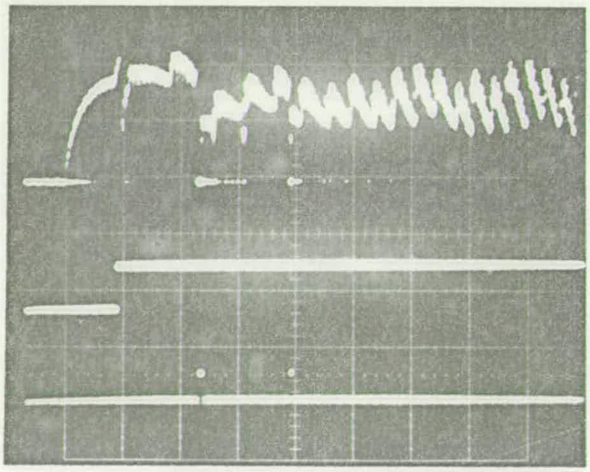
4.2.3 Low Speed Operation - 180^o Pulsing

Initially the system was designed such that each of the inverter thyristors was pulsed for 180^o (electrical), with an inhibition signal applied to both inverter and rectifier firing



Scale = 100 ms/div

Figure 4.6 Starting 10^o Before a Commutation



Scale = 100 ms/div

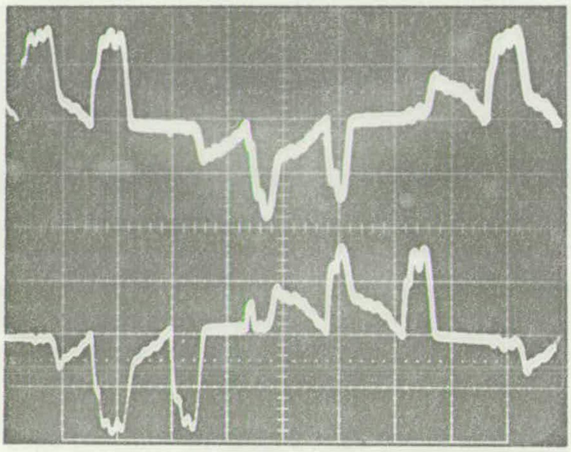
Figure 4.7 Starting 10^o After a Commutation circuits during commutation.

Both current and voltage waveforms (figure 4.8) were very non-sinusoidal and commutation times were long (about 20 ms). The resulting low and very jerky torque proved unable to accelerate the machine up to a speed at which the inverter could be naturally commutated.

4.2.4 Low Speed Operation - 120° Pulsing

The system was redesigned such that each of the inverter thyristors is pulsed for only 120°, and the inverter firing pulses are no longer inhibited during commutation. These changes considerably reduced the rectifier inhibition period during commutation, leading to improvements in the voltage and current waveforms.

The lower trace in figure 4.9 shows the red phase current with δ set at 24°, and the upper trace shows the inhibit signal to the rectifier. Here, the rectifier delay angle is zero, the voltage being controlled by the variac on the a.c. side of the rectifier. It can be seen that the rectifier inhibition period is short relative to a 60° interval. Figure 4.10 shows the red phase voltage on the upper trace, and the red phase current on the lower trace. Figure 4.11 shows the d.c. link current and the rectifier inhibition signal.



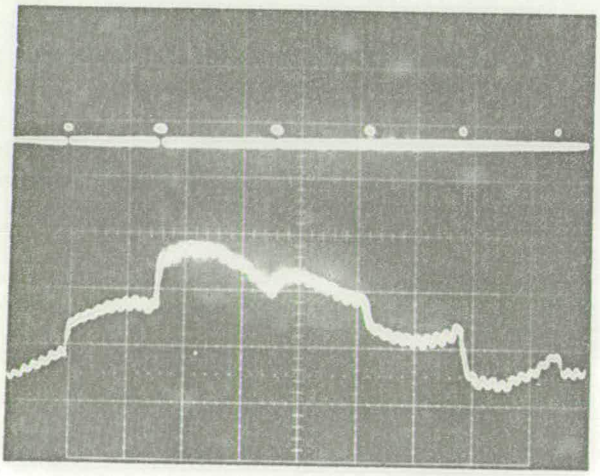
I_R

I_B

$I_Q = 6A$, $I_D = 4{\cdot}5A$

Scale = 20 ms/div

Figure 4.8 Red and Blue Phase Currents - 180^0 Pulsing

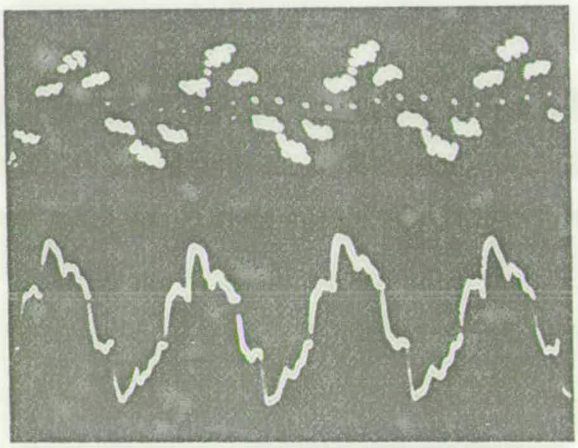


Inhibit Pulses

I_R

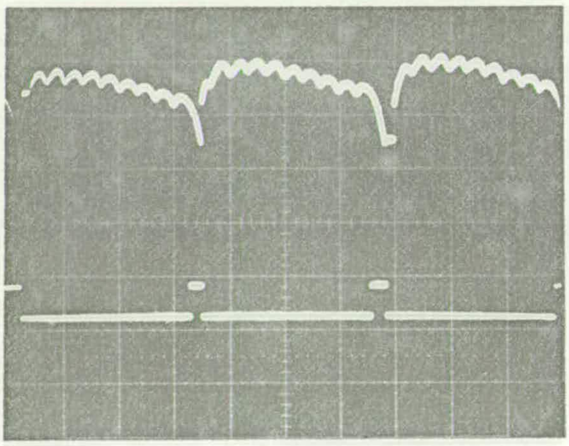
$I_Q = 2{\cdot}0A$, $I_D = 4{\cdot}5A$, 5·1 Hz.
Scale = 20 ms/div

Figure 4.9 Phase Current and Inhibit Signal - 120^0 Pulsing



Scale = 20ms/div

Figure 4.10 Phase Current and Phase Voltage



$I_Q = 2{\cdot}0A$, $I_D = 4{\cdot}5A$

Scale = 10 ms/div

Figure 4.11 D.C. Link Current and Inhibit Pulse

4.2.5 System Operation with Natural Commutation

Tests were carried out on the system when operating with natural commutation. The load angle, δ, was set at 60^{0}, and the d.c. link voltage was controlled in the manner described in Section 4.2.1.

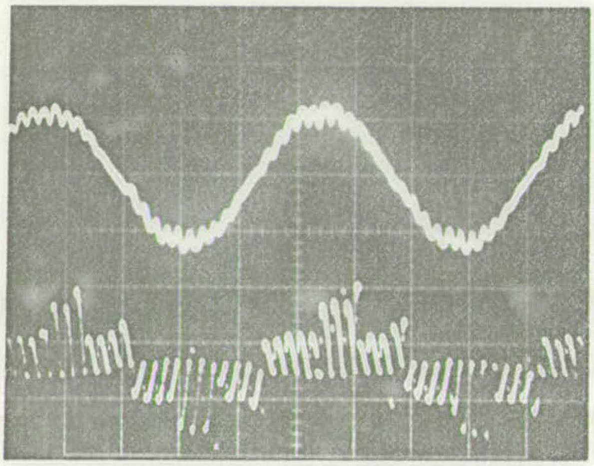
Oscillographs were taken of the red phase currents and voltages, and the d.c. link currents and voltages, at different running speeds (figures 4.12 to 4.17). The 300 Hz rectifier ripple is very apparent at low speeds, as the rectifier is then operating with a large delay angle. This could have been filtered out by inserting a choke in the d.c. link, but this would have tended to change the near sinusoidal phase current waveform into a quasi-square waveform (Section 2.2).

The switch in the comparator circuit (figure 3·33) was made over, so that δ was set at 30^{0} for all speeds apart from the initial turnover. The variac was set in a similar manner to that described in Section 4.2.1, a reasonable setting proving to be 80%, and a further set of oscillographs of current and voltage waveforms were taken (figures 4.18 to 4.23). It can be seen that the phase current waveform approximates more closely to a sine wave with $\delta = 60^{0}$ than with $\delta = 30^{0}$.

The acceleration of the machine under the no load condition is shown in figures 4.24 and 4.25, the former with the variac set at 55% and $\delta = 60^{0}$ at the higher speeds, and the latter with the variac set at 80% and $\delta = 30^{0}$ at higher speeds. In both

Scale = 10A/div

Scale = 20V/div



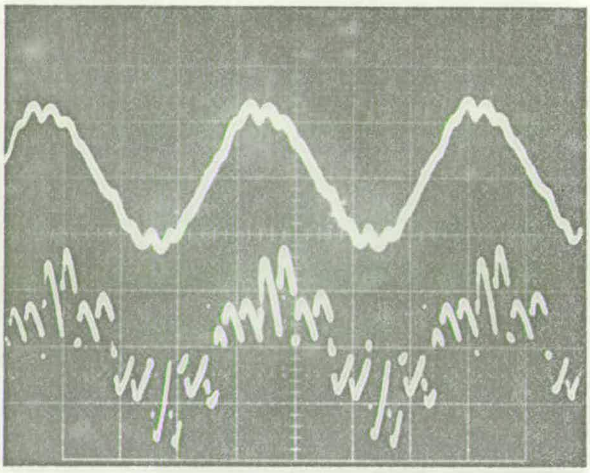
I_R

V_R

Figure 4.12 Phase Current and Voltage at 12.5 Hz, $\delta = 60^0$

Scale = 10A/div

Scale = 20V/div



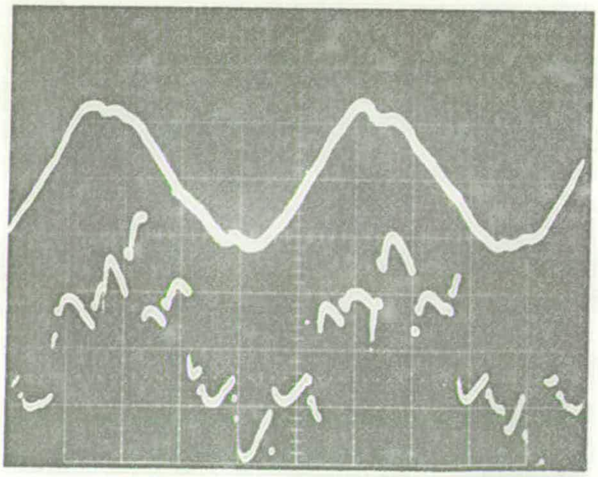
I_R

V_R

Figure 4.13 Phase Current and Voltage at 25 Hz, $\delta = 60^0$

Scale = 10A/div

Scale = 20V/div



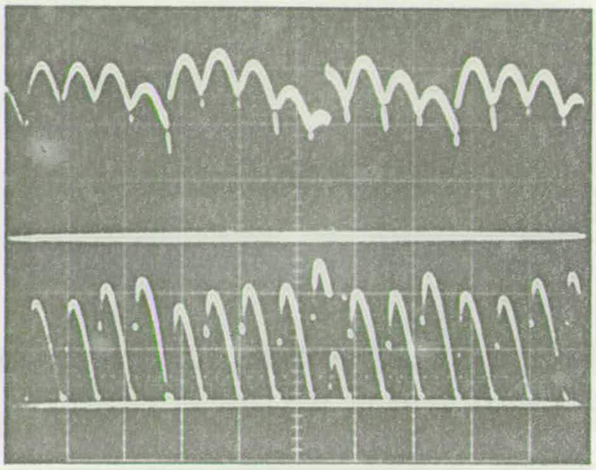
I_R

V_R

Figure 4.14 Phase Current and Voltage at 40 Hz, $\delta = 60^0$

Scale = 10A/div

Scale = 20V/div



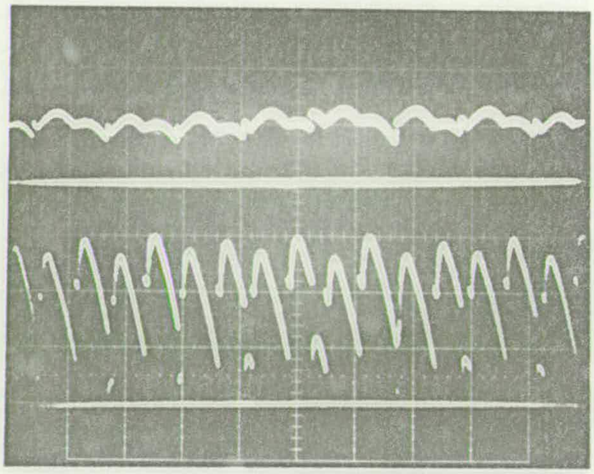
$I_{D.C.}$

$V_{D.C.}$

Figure 4.15 D.C. Link Current and Voltage at 12.5 Hz, $\delta = 60^{o}$

Scale = 10A/div

Scale = 20V/div



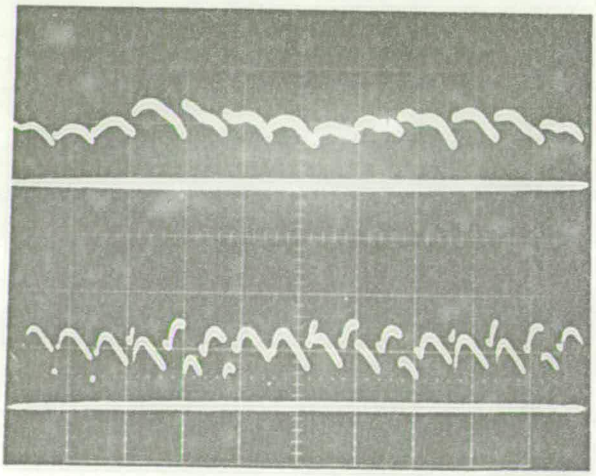
$I_{D.C.}$

$V_{D.C.}$

Figure 4.16 D.C. Link Current and Voltage at 25 Hz, $\delta = 60^{o}$

Scale = 10A/div

Scale = 50V/div



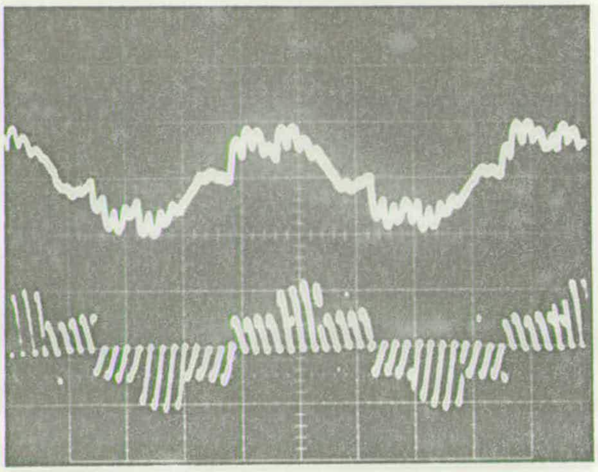
$I_{D.C.}$

$V_{D.C.}$

Figure 4.17 D.C. Link Current and Voltage at 40 Hz, $\delta = 60^{o}$

Scale = 10A/div

Scale = 50V/div



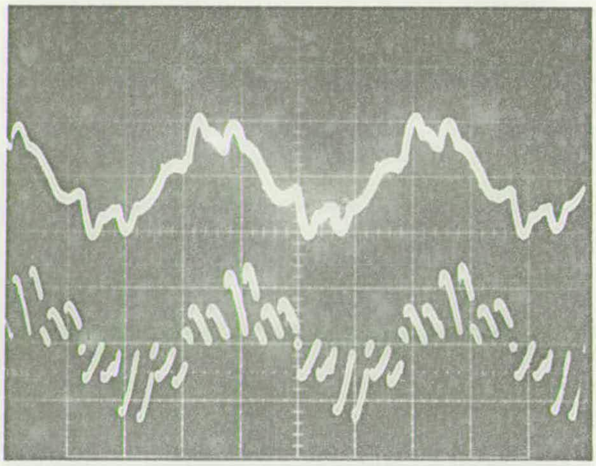
I_R

V_R

Figure 4.18 Phase Current and Voltage at 12.5 Hz, $\delta = 30^0$

Scale = 10A/div

Scale = 50V/div



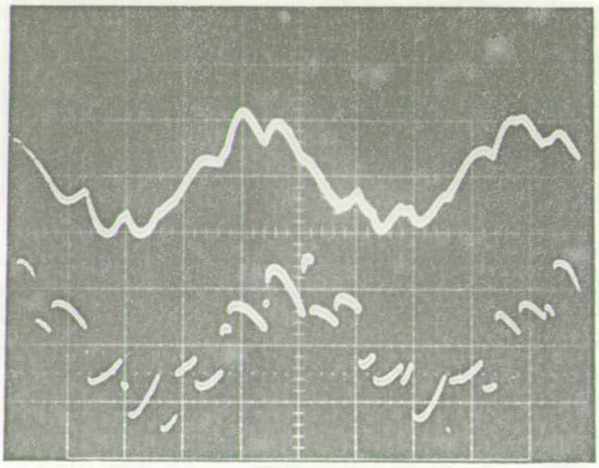
I_R

V_R

Figure 4.19 Phase Current and Voltage at 25 Hz, $\delta = 30^0$

Scale = 10A/div

Scale = 50V/div



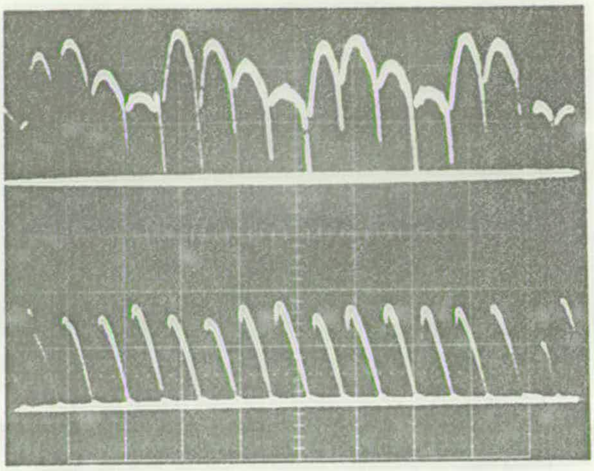
I_R

V_R

Figure 4.20 Phase Current and Voltage at 40 Hz, $\delta = 30^0$

Scale = 4A/div

Scale = 50V/div



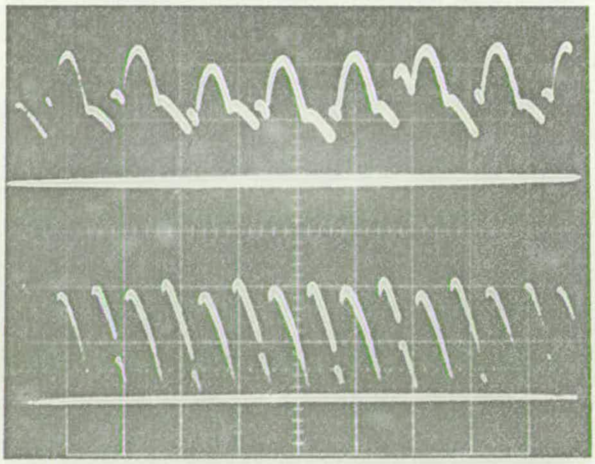
$I_{D.C.}$

$V_{D.C.}$

Figure 4.21 D.C. Link Current and Voltage at 12.5 Hz, $\delta = 30^0$

Scale = 4A/div

Scale = 50V/div



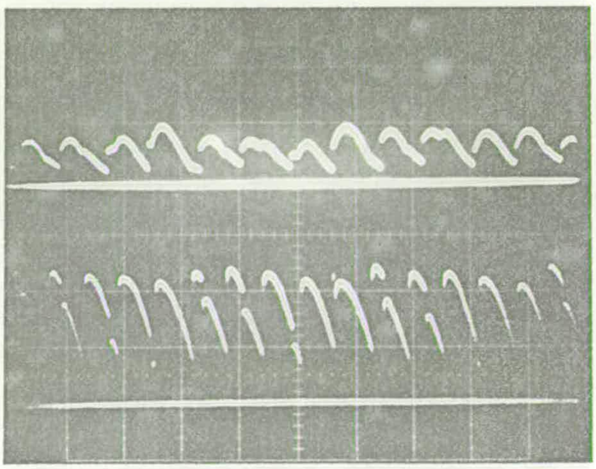
$I_{D.C.}$

$V_{D.C.}$

Figure 4.22 D.C. Link Current and Voltage at 25 Hz, $\delta = 30^0$

Scale = 10A/div

Scale = 50V/div



$I_{D.C.}$

$V_{D.C.}$

Figure 4.23 D.C. Link Current and Voltage at 40Hz, $\delta = 30^0$

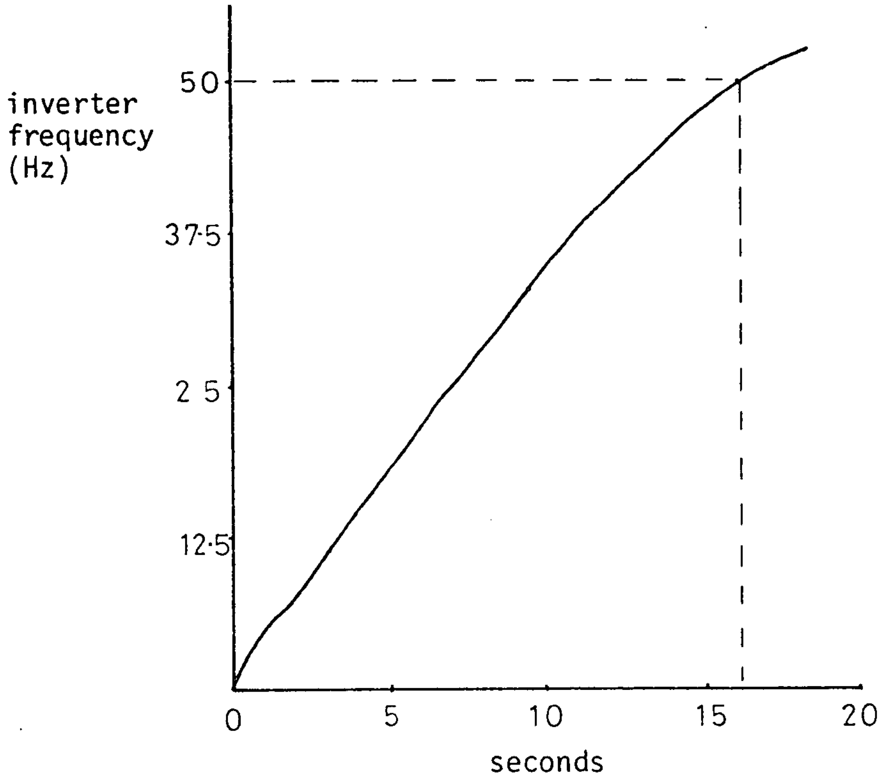


Figure 4.24 Inverter Frequency v Time for $\delta = 60^0$

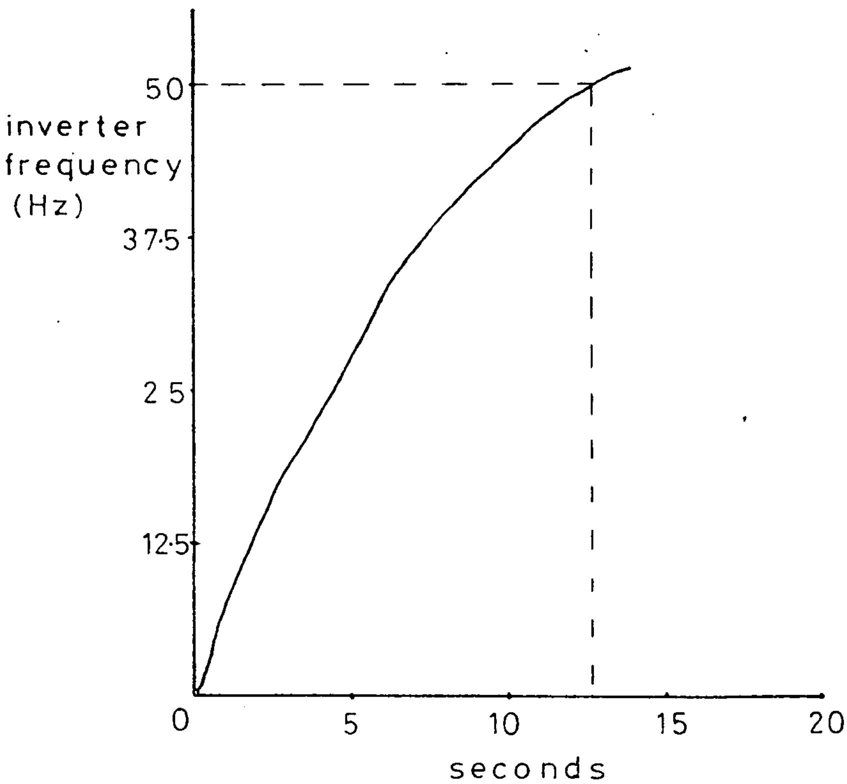


Figure 4.25 Inverter Frequency v Time for $\delta = 30^0$

cases the machine accelerates smoothly to synchronous speed (and beyond, if required). The reduction in acceleration as the speed increases is due to the larger windage and friction losses at higher speeds.

Graphs of $V_{D.C.}$ against speed for variac settings of 55% and 80% are given in figures 4.26 and 4.27 respectively. The sharp voltage drop in figure 4.26 corresponds with the changeover from operation with $\delta = 30^0$ to $\delta = 60^0$. The sudden increase in d.c. link current (from 5.5 A to 10.4 A) causes the reduction in $V_{D.C.}$ due to the relatively high impedance on the a.c. side of the controlled rectifier.

The variation of $I_{D.C.}$ with speed for variac settings of 55% and 80% are shown in figures 4.28 and 4.29 respectively. In figure 4.28 $I_{D.C.}$ remains virtually constant after the change-over from operation with $\delta = 30^0$ to operation with $\delta = 60^0$. In figure 4.29 there is an initial transient increase in current, (this can be examined more closely in figure 4.30), after which $I_{D.C.}$ remains virtually constant.

4.2.6 Commutation Failure

The effectiveness of the system protection in the event of a commutation failure during high speed operation was tested. If commutation of a thyristor has not been achieved by the time that the complementary thyristor in the same phase leg is due to be pulsed, the firing of the complementary thyristor is delayed

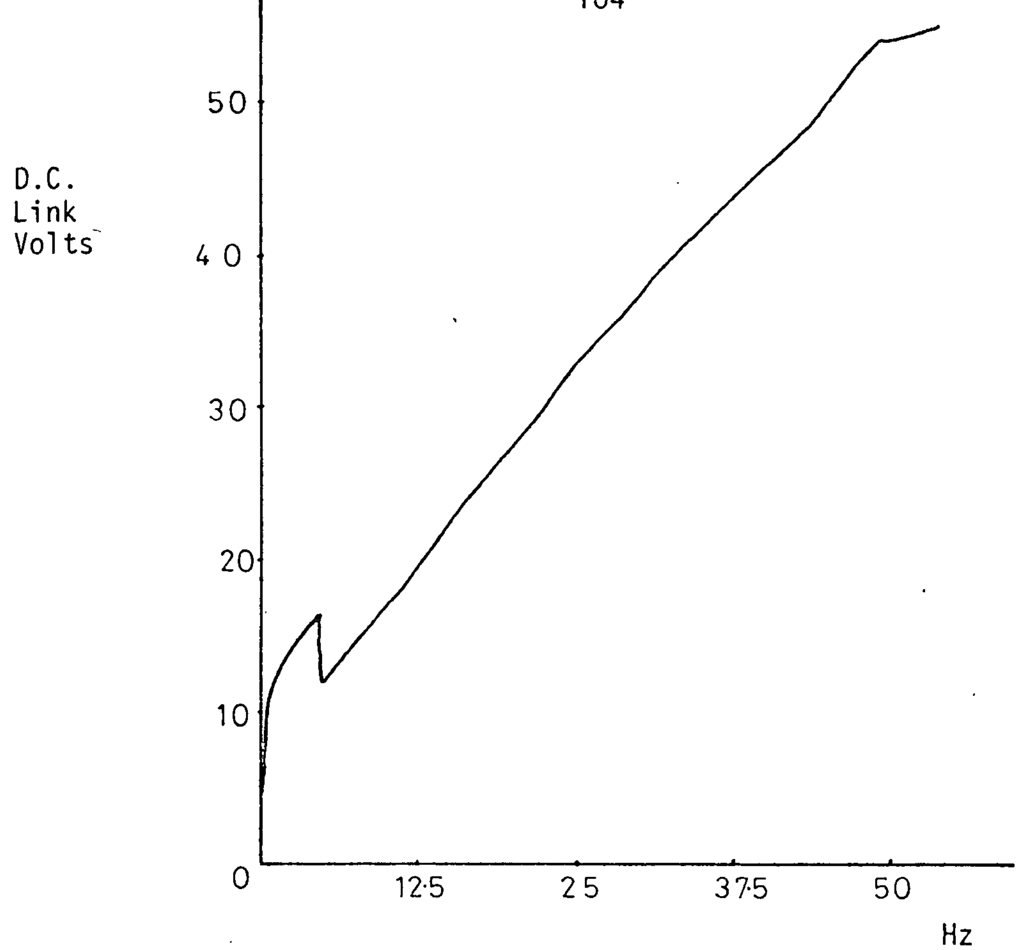


Figure 4.26 D.C. Link Volts Against Inverter Frequency for $\delta = 60^{o}$

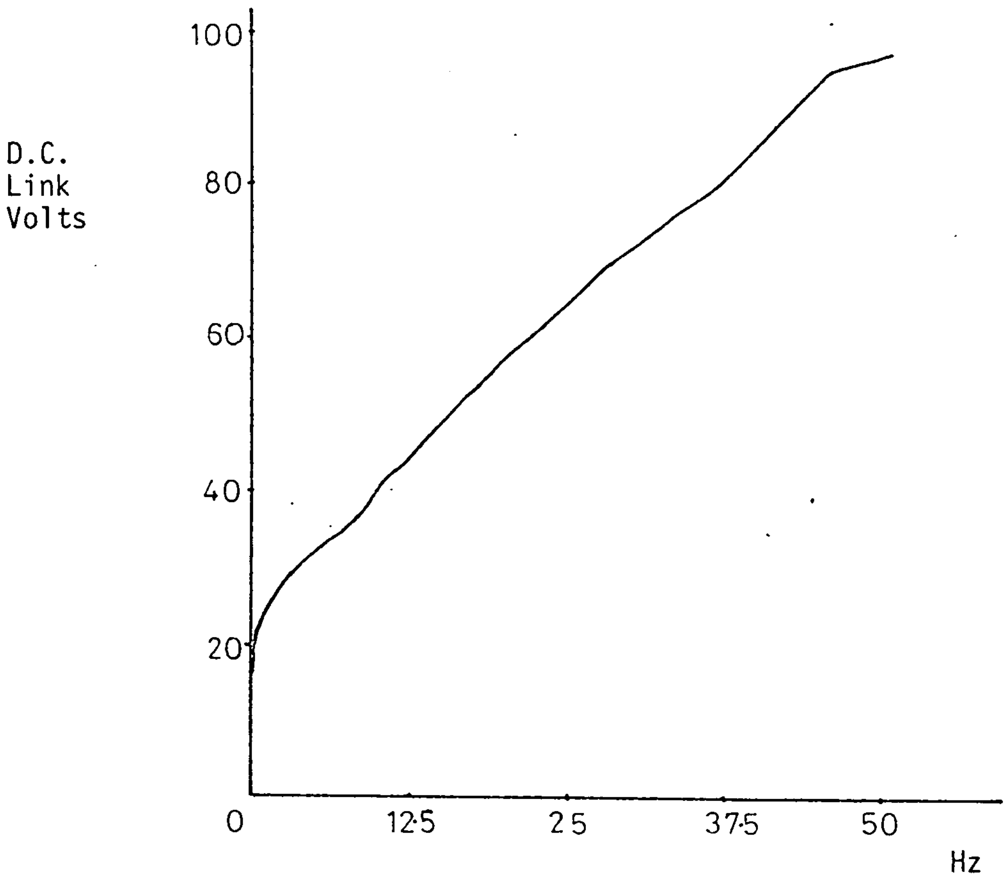


Figure 4.27 D.C. Link Volts Against Inverter Frequency for $\delta = 30^{o}$

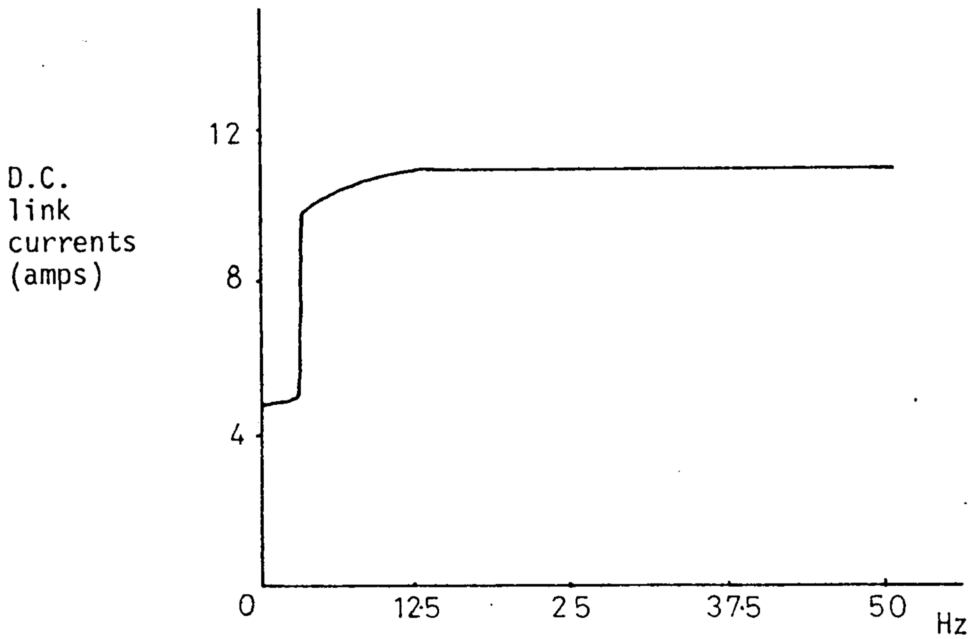


Figure 4.28 D.C. Link Current Against Inverter Frequency for $\delta = 60^{o}$

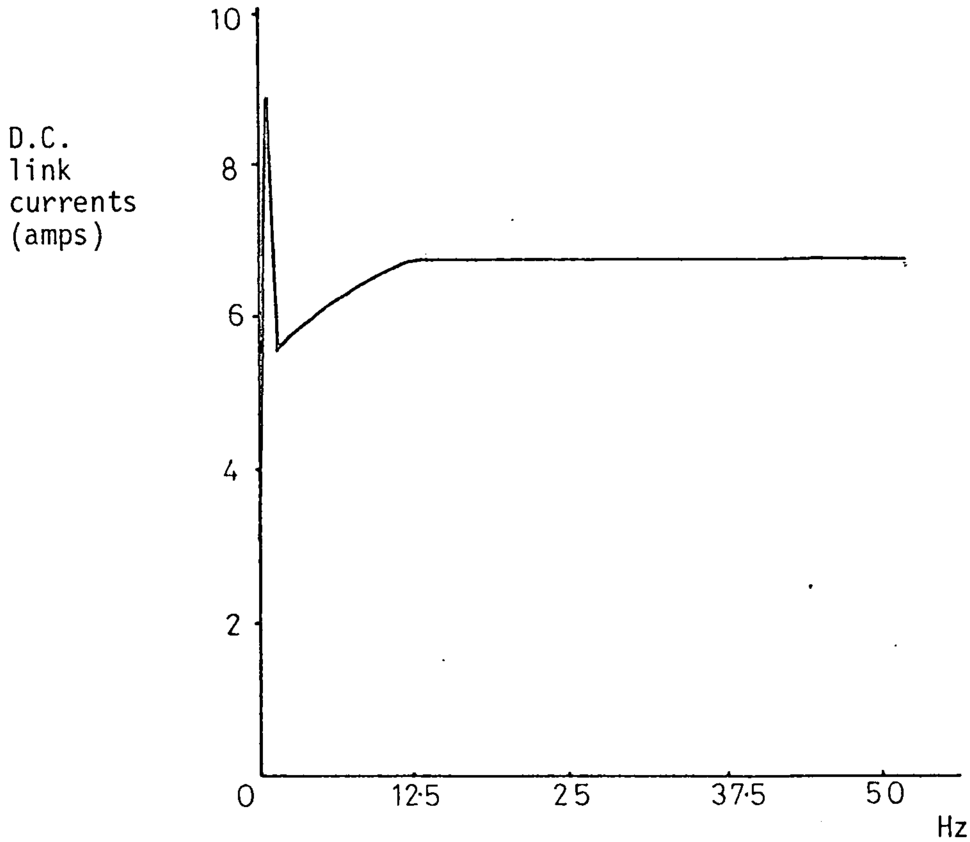


Figure 4.29 D.C. Link Current Against Inverter Frequency for $\delta = 30^{o}$

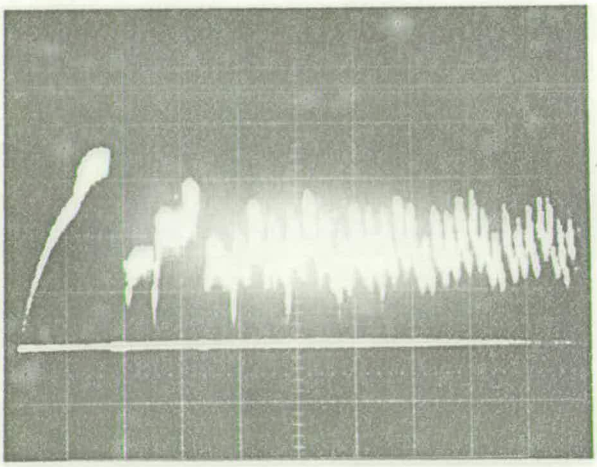


Figure 4.30 D.C. Link Current when Starting 10^{0} After a Commutation, with $\delta = 30^{0}$

to prevent the two thyristors creating a short circuit across the d.c. link (Section 3.3.1). At the same time, if the load angle, δ, equals 60^0, the firing pulses to the controlled rectifier are suppressed until commutation has been effected, while if $\delta = 30^0$, the rectifier firing pulses are suppressed 30^0 earlier, ie, if a thyristor is still conducting 150^0 after it was fired.

The inverter frequency was held constant at 40 Hz, with δ set at 60^0, and the d.c. link voltage was increased gradually until the power factor became lagging. The protection circuitry then came into operation, thus preventing a d.c. link short circuit, but the system operated very jerkily, with pulses of d.c. link and phase current with a magnitude approximately double their steady-state values appearing in between periods of rectifier inhibition. The system then had to be switched off completely and restarted in order to return to stable operation. The phase current waveform before a commutation failure is compared to it after a failure in figures 4.31 and 4.32.

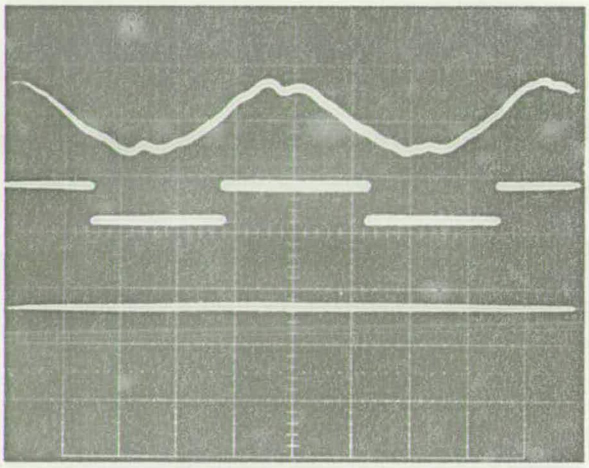


Figure 4.31 Normal Operation at 40 Hz, $\delta = 60^o$

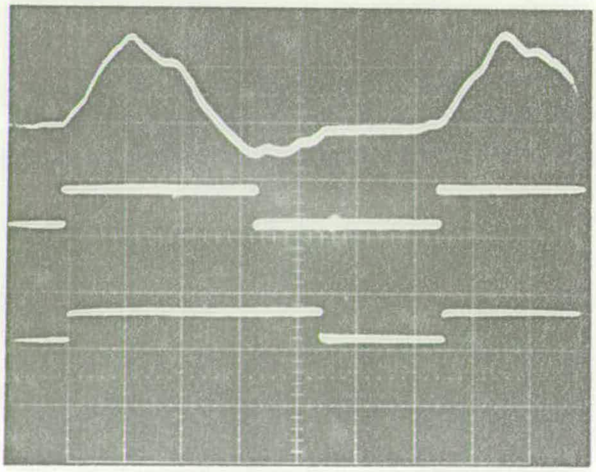


Figure 4.32 Faulty Operation at 40 Hz, $\delta = 60^o$

CHAPTER 5 : COMPUTER STUDY

The theoretical model used to calculate the output torque and the commutation safety margin in Chapter 2 is based on a system with sinusoidal waveforms. In practice, the inverter waveforms are not sinusoidal, so a computer model was developed to allow a more accurate study of the system characteristics.

5.1 THE COMPUTER MODEL

To simplify the programming and to keep the computer time within the allowed limits only the inverter and synchronous machine were simulated, the inverter being fed from a d.c. source. This will be a constant current source if there is a choke in the d.c. link, and a constant voltage source if the inverter is connected directly to the rectifier, with no d.c. link choke.

5.1.1 Inverter with Feedback Diodes

An inverter with feedback diodes does not have a choke in the d.c. link (Section 2.2) and therefore may be considered to have a constant voltage d.c. input. The positive inverter input, therefore, is set at $+\frac{V_{D.C.}}{2}$ Volts and the negative at $-\frac{V_{D.C.}}{2}$ Volts, with the centre point earthed (figure 5.1).

In the computer model the machine is connected in a delta configuration, although in the laboratory it is star connected as it is convenient to have a neutral point when taking experimental results. A delta connected machine is easier to simulate when it is operating from a constant voltage source, as the phase voltage is equal to the line voltage, a known quantity, whereas to find the phase voltage in a star connected machine requires the calculation of the neutral point voltage.

A star connected resistive load with its neutral point earthed is connected to the output of the inverter, in parallel with the machine. This allows any of the voltages VR, VY and VB (the machine terminal voltages with respect to earth) to be determined even if that phase is not connected to either the positive or negative d.c. rails by the inverter thyristors or feedback diodes, as the machine then circulates a small current through the resistor which fixes the voltage with respect to earth. The resistances must be made sufficiently high such that the currents through them are small relative to the average machine currents, but not so high that the loop gain of the model becomes greater than unity, causing an instability in the model.

A transformation is carried out on the 3-phase stator to reduce it to the equivalent 2-phase stator in figure 5.2. If, in the 3-phase system

$$i_R = I_{MS} \text{ Cos } \omega t$$

$$i_Y = I_{MS} \text{ Cos } (\omega t - 120^o)$$

$$i_B = I_{MS} \text{ Cos } (\omega t + 120^o)$$

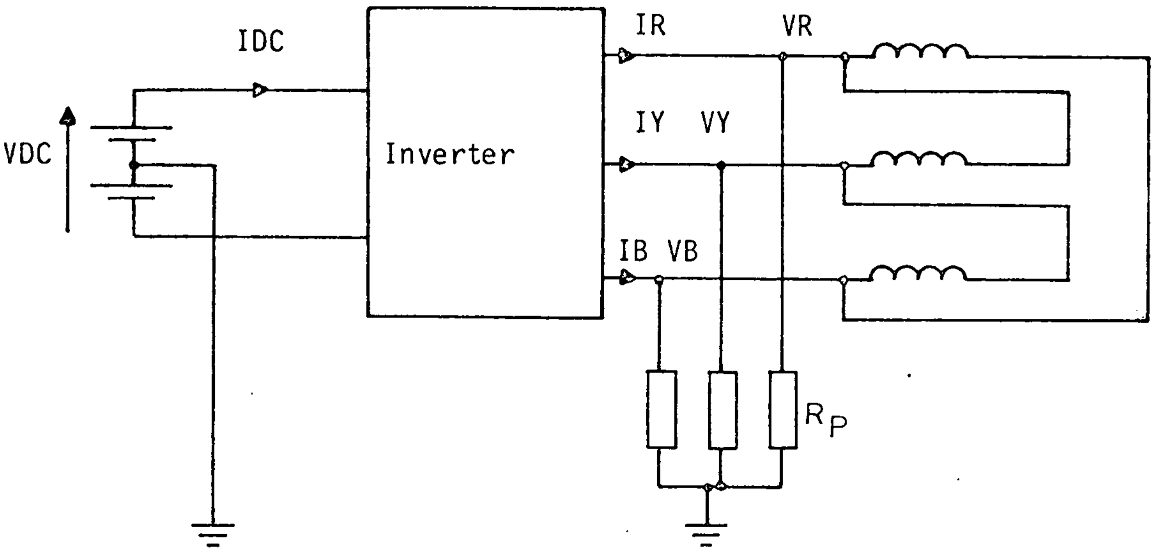


Figure 5.1 System Model Used for the Computer Simulation

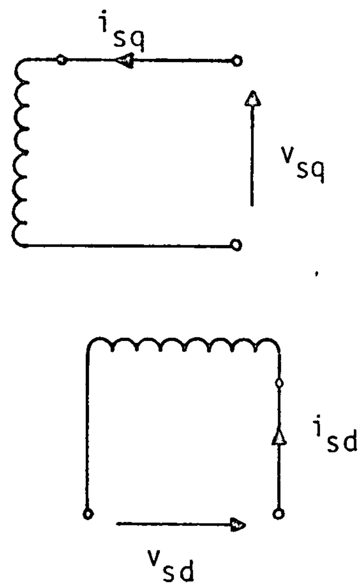


Figure 5.2 The Equivalent 2-Phase Stator

then, in the 2-phase system,

$$i_{SD} = \sqrt{(\tfrac{3}{2})} . I_{MS} . \text{Cos } \omega t$$

$$i_{SQ} = \sqrt{(\tfrac{3}{2})} . I_{MS} . \text{Sin } \omega t$$

Similar equations can be derived for the stator voltages.

The sign conventions for the stator are :

(a) positive stator power is into the stator;

(b) positive rotation is anti-clockwise;

(c) positive sequence in space is the Q axis follows the D axis as in figure 5.3;

(d) positive sequence in time is that i_{SQ} lags i_{SD} as in figure 5.4;

(e) positive current i_{SD} produces magnetic flux ϕ_{SD} in $+D_S$ direction.

A transformation is also carried out to reduce the field and damper windings on the rotor to equivalent 2-phase (figure 5.5). The magnetic field ϕ_{RQ} is then produced by the field winding together with the resultant effect of the damper windings on the quadrative axis, while ϕ_{RD} is produced by the resultant effect of the damper windings on the direct axis.

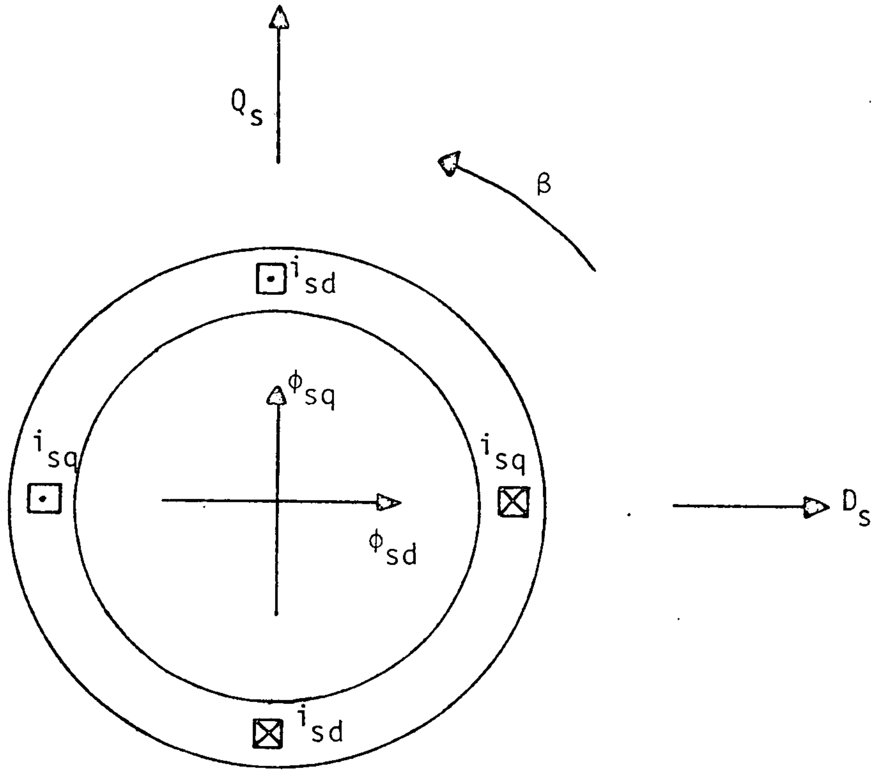


Figure 5.3 Space Diagram of 2-Phase Stator

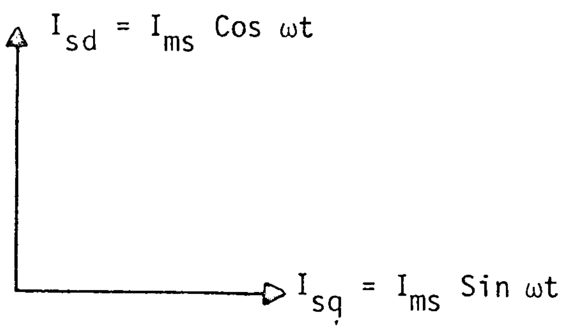


Figure 5.4 Phasor Diagram of 2-Phase Stator

The sign conventions for the rotor are :

(a) positive rotor power is out of the rotor;

(b) positive rotation is anti-clockwise;

(c) positive sequence in space is the Q axis follows the D axis as in figure 5.6;

(d) positive sequence in time is that i_{RQ} lags i_{RD} as in figure 5.7;

(e) positive current i_{RD} produces magnetic flux ϕ_{RD} in $-D_R$ direction;

(f) positive current i_{RQ} produces magnetic flux ϕ_{RQ} in $-Q_R$ direction.

The stator is now referred to the rotor in a D-Q transformation (figure 5.8), such that

$$i_{RSD} = i_{SD} \text{ Cos } \beta + i_{SQ} \text{ Sin } \beta$$

$$i_{RSQ} = -i_{SD} \text{ Sin } \beta + i_{SQ} \text{ Cos } \beta$$

where β is the angle between the stator direct axis and the rotor direct axis. β is therefore a time varying quantity, where $\frac{d\beta}{dt}$ is the machine mechanical angular velocity.

The equivalent circuit for the referred stator machine is shown in figure 5.9, where

R_D, R_Q are the stator winding resistances;

L_{SS} = magnetising inductance;

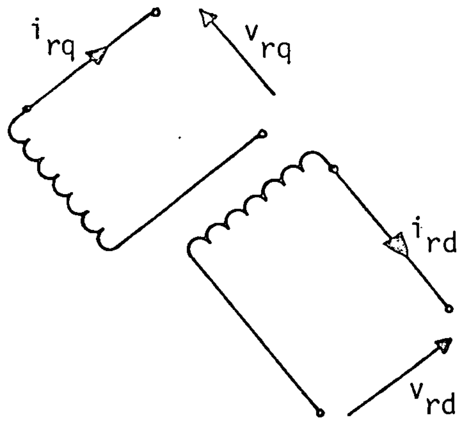


Figure 5.5 Equivalent 2-Phase Rotor

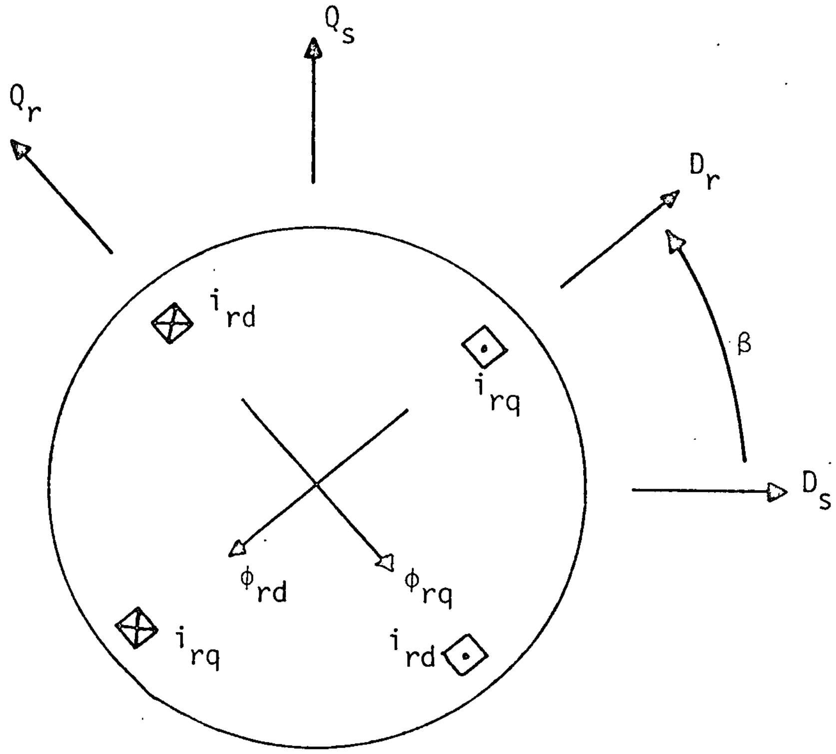


Figure 5.6 Space Diagram of 2-Phase Rotor

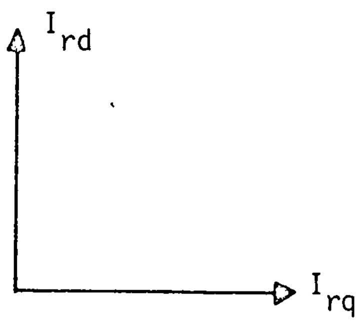


Figure 5.7 Phasor Diagram of 2-Phase Rotor

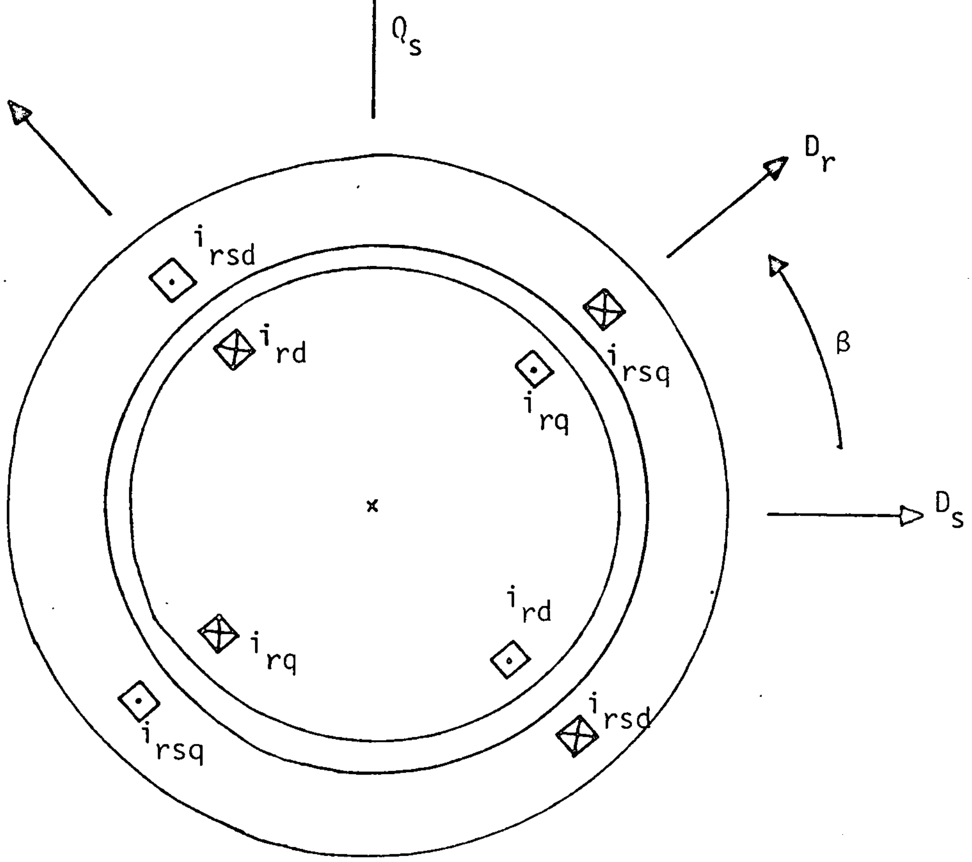


Figure 5.8 The Stator Referred to the Rotor

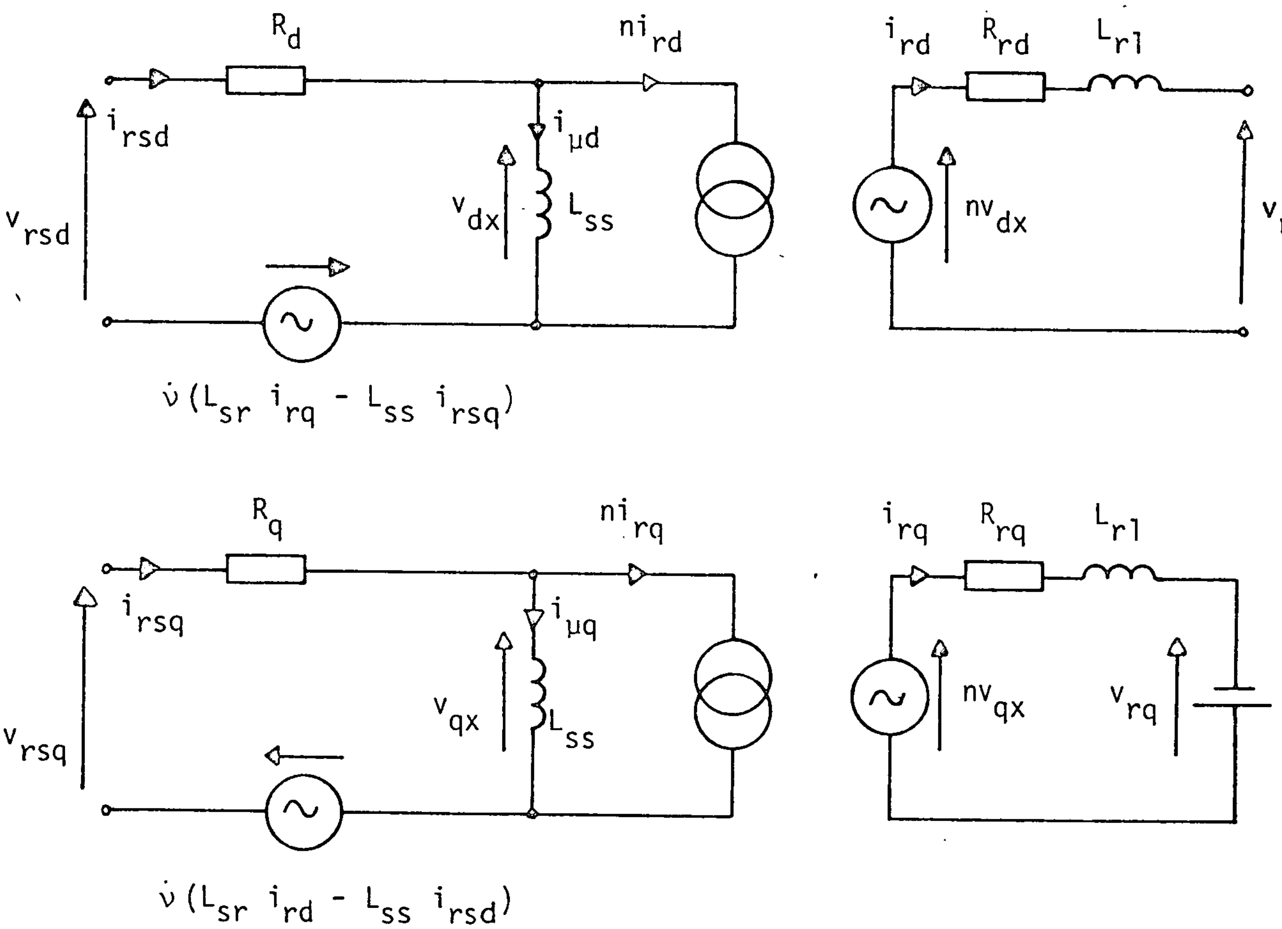


Figure 5.9 Machine 2-Phase Equivalent Circuit With The Stator Referred to the Rotor

R_{RD} = rotor resistance in D-phase;

R_{RQ} = rotor resistance in Q-phase;

L_{RD} = leakage inductance referred to the D phase of the rotor;

L_{RQ} = leakage inductance referred to the Q phase of the rotor;

$n = \frac{N_{rotor}}{N_{stator}}$, the effective turns ratio;

L_{SR} = rotor-stator mutual inductance;

$\dot{\nu} = \frac{d\beta}{dt}$, the angular velocity.

The terms $\dot{\nu}(L_{SR}\ i_{RQ} - L_{SS}\ i_{RSQ})$ and $\dot{\nu}(L_{SR}\ i_{RD} - L_{SS}\ i_{RSD})$ are the E.M.F.'s produced in the stator windings due to the motion of the magnetic fields with respect to the windings. A simplification in these terms may be made as follows

$$\dot{\nu}(L_{SR}\ i_{RQ} - L_{SS}\ i_{RSQ}) = \dot{\nu}\left[\frac{L_{SR}}{n} . n . i_{RQ} - L_{SS}(n\ i_{RQ} + i_{MQ})\right]$$

$$= \dot{\nu}\ (-L_{SS} . i_{MQ}) \quad \text{since} \quad \frac{L_{SR}}{n} = L_{SS} .$$

Similarly,

$$\dot{\nu}(L_{SR} \cdot i_{RD} - L_{SS} \cdot i_{RSD}) = \dot{\nu}(-L_{SS} \cdot i_{MD}).$$

The equivalent circuit can be simplified further by referring the rotor circuits to the stator, as in figure 5.10, where

$$L_{SD} = \frac{L_{RD}}{n^2}$$

$$R_{SD} = \frac{R_{RD}}{n^2}$$

$$L_{SQ} = \frac{L_{RQ}}{n^2}$$

$$R_{SQ} = \frac{R_{RQ}}{n^2}$$

$$I_{FR} = \frac{3}{2} \cdot \sqrt{2} \cdot n \cdot I_F$$

I_F = field current.

In the computer program the inverter voltages and currents at time T go through the above transformations and are fed into the equivalent circuit in figure 5.10 to find the voltages and currents of the equivalent circuit at time T + DT, where DT is a small time increment. The inverse transformations are then carried out to produce the 3-phase inverter voltages and currents at time T + DT. The complete program is listed in Appendix C.

A typical printout from the computer is given in figure 5.11, with the program input parameters listed at the top and the outputs listed beneath. The meanings of the input parameter symbols are given below.

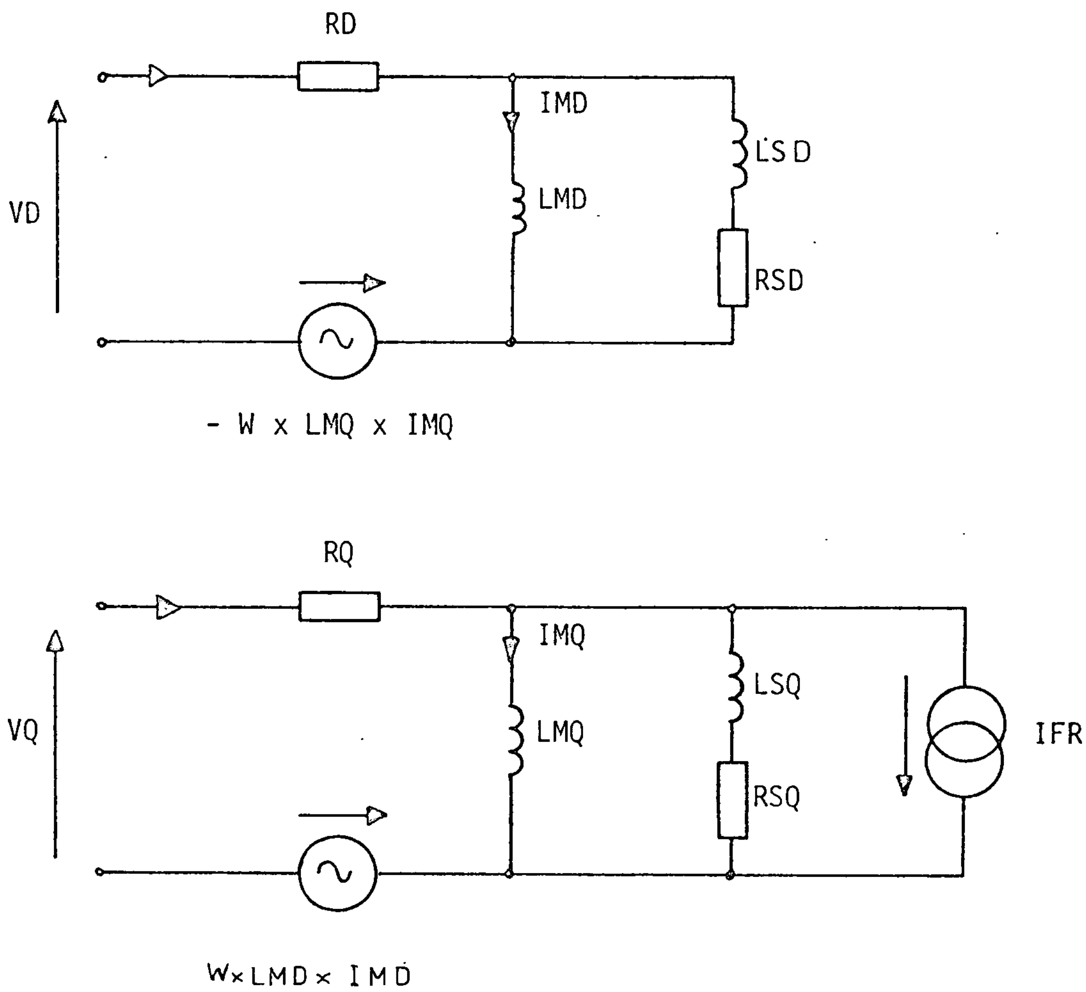


Figure 5.10 Simplified 2-Phase Equivalent Circuit

314.0 0.120 0.120 0.012 0.012

RSD	RSQ	RD	RQ	RP
21.080	21.080	3.080	3.080	125

PHIO	FC	RC	CYCLES	DD	IC
-150	62	1	20	2	1

IFR	IMD	IMQ	ISD	ISQ	VDC
14.1	3.9	-7.1	0.6	-1.8	220.0

ANGLE	COMM	VR	VY	VB	IDC	IR	IY	IB	IMD	IMQ	ISD	ISQ	TOR
0	1	110	-110	110	8	-0.3	-7.2	7.5	3.9	-7.0	1.4	-4.3	5.8
10	10	110	-110	110	12	10.8	-10.9	0.2	3.5	-6.6	-1.9	1.2	4.9
20	11	110	-110	110	12	13.9	-11.1	-2.8	3.3	-6.3	-1.7	2.4	5.2
30	11	110	-110	110	12	13.5	-10.7	-2.8	3.3	-6.1	-0.2	1.6	6.1
40	11	110	-110	110	11	11.9	-9.8	-2.0	3.5	-6.2	1.0	-0.2	6.6
50	11	110	-110	110	9	10.1	-8.3	-1.8	3.7	-6.5	1.3	-1.8	6.4
60	11	110	-110	-110	9	7.7	-7.0	-0.7	3.8	-7.0	1.1	-3.7	5.6
60	1	110	-110	-110	9	8.0	-6.4	-1.6	3.7	-6.9	0.8	-3.3	5.5
70	10	110	-110	-110	12	11.4	0.3	-11.7	3.4	-6.5	-2.0	1.6	4.8
80	10	110	-110	-110	13	11.7	2.5	-14.2	3.2	-6.2	-1.3	2.5	5.5
90	10	110	-110	-110	12	11.1	2.7	-13.8	3.3	-6.1	0.0	1.6	6.3
100	10	110	-110	-110	11	10.2	1.9	-12.1	3.5	-6.2	1.2	-0.1	6.8
110	10	110	-110	-110	10	9.2	0.6	-9.8	3.7	-6.5	1.9	-2.3	6.7
120	10	110	-110	-110	9	7.6	-0.2	-7.4	3.9	-7.0	1.5	-4.2	5.9
120	1	110	110	-110	8	7.6	-0.4	-7.2	3.9	-7.0	1.5	-4.3	5.8
130	10	110	110	-110	12	0.2	10.8	-11.0	3.5	-6.6	-1.9	1.2	4.9
140	11	110	110	-110	12	-2.8	14.0	-11.2	3.3	-6.3	-1.7	2.4	5.2
150	11	110	110	-110	12	-2.8	13.6	-10.8	3.3	-6.1	-0.2	1.6	6.2
160	11	110	110	-110	11	-2.0	11.9	-9.9	3.5	-6.2	1.0	-0.1	6.7
170	11	110	110	-110	9	-1.8	10.1	-8.3	3.7	-6.5	1.2	-1.8	6.4
180	11	-110	110	-110	9	-0.7	7.7	-7.0	3.8	-7.0	1.1	-3.7	5.7
180	1	-110	110	-110	9	-1.7	8.0	-6.4	3.7	-6.9	0.8	-3.2	5.5
190	10	-110	110	-110	12	-11.6	11.3	0.3	3.4	-6.5	-2.0	1.6	4.8
200	10	-110	110	-110	12	-14.1	11.6	2.5	3.2	-6.2	-1.4	2.5	5.5
210	10	-110	110	-110	12	-13.7	11.0	2.7	3.3	-6.0	0.0	1.6	6.3
220	10	-110	110	-110	11	-12.0	10.1	2.0	3.5	-6.2	1.2	-0.2	6.8
230	10	-110	110	-110	10	-9.7	9.1	0.6	3.7	-6.5	1.8	-2.4	6.7
240	10	-110	110	-110	8	-7.3	7.5	-0.2	3.8	-7.0	1.5	-4.2	5.8
240	1	-110	110	110	8	-7.2	7.5	-0.3	3.8	-7.0	1.5	-4.3	5.8
250	10	-110	110	110	12	-10.9	0.2	10.8	3.5	-6.6	-1.9	1.2	4.9
260	11	-110	110	110	12	-11.2	-2.8	14.0	3.3	-6.3	-1.7	2.4	5.2
270	11	-110	110	110	12	-10.8	-2.8	13.6	3.3	-6.2	-0.2	1.6	6.2
280	11	-110	110	110	11	-9.9	-2.0	11.9	3.5	-6.2	1.1	-0.2	6.7
290	11	-110	110	110	9	-8.4	-1.7	10.1	3.7	-6.5	1.3	-1.8	6.4
300	11	-110	-110	110	9	-7.0	-0.7	7.7	3.8	-7.0	1.2	-3.7	5.7
300	1	-110	-110	110	9	-6.5	-1.6	8.1	3.7	-6.9	0.8	-3.2	5.6
310	10	-110	-110	110	12	0.2	-11.7	11.4	3.4	-6.5	-2.0	1.7	4.8
320	10	-110	-110	110	13	2.5	-14.2	11.7	3.2	-6.2	-1.4	2.6	5.5
330	10	-110	-110	110	12	2.7	-13.8	11.1	3.3	-6.0	0.0	1.7	6.3
340	10	-110	-110	110	11	2.0	-12.1	10.2	3.5	-6.1	1.2	-0.1	6.8
350	10	-110	-110	110	10	0.6	-9.7	9.1	3.7	-6.5	1.8	-2.3	6.7
360	10	-110	-110	110	8	-0.1	-7.4	7.5	3.8	-7.0	1.4	-4.1	5.8

AVERAGE SUPPLY AMPS = 11
AVERAGE TORQUE = 6.0

AVERAGE INPUT POWER = 2363 -INHIB. NEG
AVERAGE OUTPUT POWER = 1899
AVERAGE SHUNT LOSS = 290
AVERAGE SERIES LOSS = 240
AVERAGE ROTOR LOSS = 184

<u>Figure 5.11</u> Typical Computer Printout for the Inverter/Synchronous Machine Model

(1) WM is the inverter operating frequency in radian $seconds^{-1}$.

(2) LMD, LMQ, LSD, LSQ, RSD, RSQ, RD, RQ and IFR are the machine parameters in the equivalent circuit in figure 5.10.

(3) RP is one of the 3-phase, star connected resistances on the output of the inverter included as a computational aid.

(4) PHIO is a measure of the machine load angle δ such that PHIO = $-(120 + \delta)$.

(5) FC sets the angle at which artificial commutation is introduced to aid natural commutation. If a thyristor has not commutated at an angle (120^0 + FC) after it is triggered, the d.c. link voltage is set to zero until commutation is achieved.

(6) RC determines the presence or absence of stator-induced currents, in the rotor, ie, it effectively determines whether the machine has damper windings on the rotor. No currents flow in the arms (LSD + RSD) and (LSQ + RSQ) if RC = 0, whereas they may if RC = 1.

(7) Large transients may occur in the first few cycles before a steady state is reached, depending on the initial conditions. The number of cycles performed before the cycle printed in the output may be set by 'CYCLES'.

(8) DD sets the step interval between calculations, such that the step angle in degrees is $\frac{1}{DD}$. The time step is then
$DT = \frac{1}{DD} \cdot \frac{\pi}{180 \,.\, WM}$ seconds.

(9) At the beginning of the first cycle, the positive red thyristor is starting the first 60^{o} of its conduction period, the negative yellow thyristor its second 60^{o} and the positive blue its third 60^{o}. However, in the laboratory system the thyristors are pulsed for 120^{o} of the cycle, so only the red and yellow thyristors receive trigger pulses, and as at starting no currents are already flowing in the inverter, the blue thyristor will not conduct. In the program, if IC is set at zero, only the positive red and negative yellow thyristors conduct at the start of the first cycle, whereas if IC is set at 1, then all three will conduct.

(10) The equivalent circuit currents, IMD, IMQ, ISD and ISQ may be set to suitable values for the start of the first cycle to reduce the magnitude of the transients, and therefore the time that it takes for the transients to die away.

(11) VDC is the d.c. link voltage which feeds the inverter.

The system parameters which are listed in the computer output are described below.

(1) ANGLE (in degrees) is the angle in the cycle. The value of each of the inverter/machine parameters is listed at 10^{o} intervals, with every multiple of 60^{o} printed twice, once immediately before and once immediately after the firing of the next thyristor.

(2) COMM is the number of degrees in excess of 120^{0} which it takes for the appropriate thyristor to commutate. The answer is the final figure which appears in the 60^{0} segment, commutation having failed if the figure reaches 60.

(3) VR, VY and VB are the inverter output terminal voltages with respect to earth.

(4) IDC is the d.c. link input current to the inverter.

(5) IR, IY and IB are the inverter line currents.

(6) IMD, IMQ, ISD and ISQ are the equivalent circuit currents.

(7) TOR is the output mechanical torque developed by the machine.

(8) AVERAGE SUPPLY AMPS is the average value of IDC, sampled at 10^{0} intervals.

(9) AVERAGE TORQUE is the average value of TOR, sampled at 10^{0} intervals.

(10) AVERAGE INPUT POWER is the product of AVERAGE SUPPLY AMPS and VDC.

(11) AVERAGE OUTPUT POWER is the average torque multiplied by the speed.

(12) AVERAGE SHUNT LOSS is the power loss in the computer resistance RP.

(13) AVERAGE SERIES LOSS is the power loss in RD and RQ.

(14) AVERAGE ROTOR LOSS is the power loss in RSD and RSQ.

The input power does not always balance the output power plus losses, as the input and output powers are sampled only every 10^0, whereas the resistance losses are sampled more frequently.

The program has two main limitations. The first is that it does not allow analysis of the system subsequent to a commutation failure. This leads to computed inverter waveforms being virtually unchanged from those before the failure, whereas this is certainly not the case for the experimental system.

The second limitation of the program concerns the d.c. link supply. In the laboratory the d.c. link is supplied from a controlled rectifier which provides a constant d.c. voltage with a 300 Hz ripple superimposed on it. When the rectifier is inhibited the d.c. link voltage falls gradually to zero following a 50 Hz sine wave as in figure 5.12: it does not fall immediately to zero, as in the computer program. The resulting effect is that commutation times when artificial commutation is employed will be shorter in the computer simulation than on the laboratory equipment.

5.1.2 <u>Inverter without Feedback Diodes</u>

An inverter without feedback diodes has a choke in the d.c. link (Section 2.2), and therefore may be considered to have a

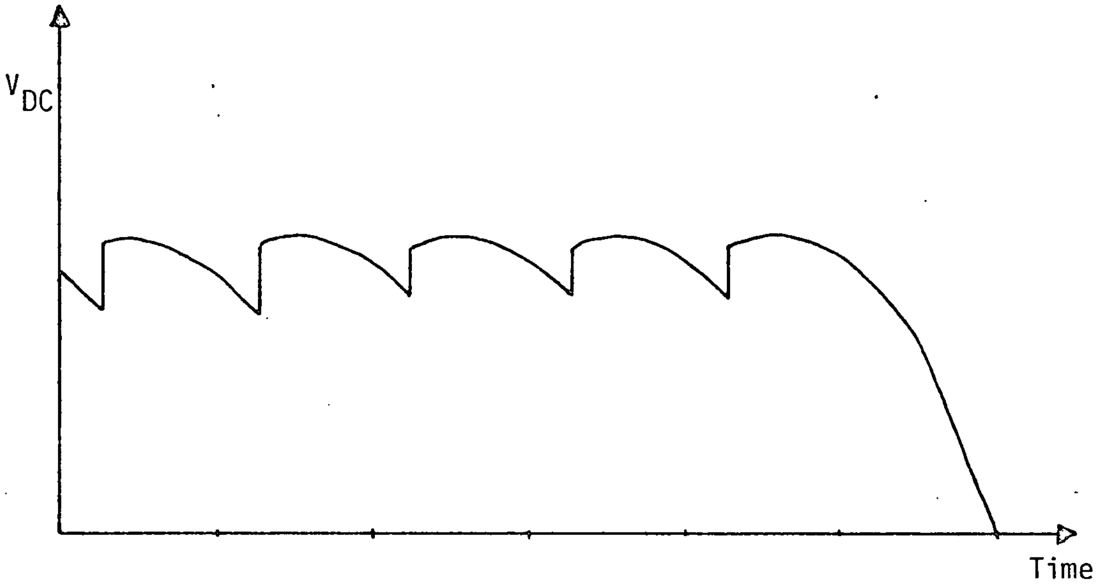


Figure 5.12 The Decay of V_{DC} with Time when the Laboratory Rectifier is Inhibited

constant current input. The d.c. link current, therefore, is set at a constant value IDC, with the d.c. link voltage VDC fixed by the machine. The rest of the model is similar to the model of the inverter with feedback diodes, with the appropriate changes made to prevent simulated current flowing through feedback diodes to the d.c. link rails.

Artificial commutation with this model is achieved by setting IDC at zero. This constitutes an inaccuracy in the model, since the d.c. link current cannot instantaneously fall to zero, as the two conducting rectifier thyristors will continue to conduct until the current through them falls to zero. (NB - a d.c. link choke does not normally affect the time taken for IDC to reduce to zero, as it usually has a flywheeling thyristor around it which is fired simultaneously with the rectifier inhibition.)

A typical printout from the computer is shown in figure 5.13. The complete program is listed in Appendix C.

5.2 COMPUTER RESULTS

Suitable machine and inverter parameters (similar to those of the experimental system) were fed into the program to study the system under a variety of conditions, and to compare systems with and without inverter feedback diodes. The program in particular is used to examine the effects on the system of both machine saliency and the presence of rotor damper windings. In addition it is used to determine the optimum starting conditions.

WM	LMD	LMQ	LSD	LSQ
314.0	0.120	0.120	0.012	0.012

RSD	RSQ	RD	RQ	RP
21.080	21.080	3.080	3.080	125.00

PHIO	FC	RC	CYCLES	DD	IC
-150	62	1	20	2	1

IFR	IMD	IMQ	ISD	ISQ	IDC
14.1	3.9	-7.1	0.6	-1.8	10.0

ANGLE	COMM	VR	VY	VB	VDC	IR	IY	IB	IMD	IMQ	ISD	ISQ	TOR
0	1	65	-130	65	195	0.4	-9.0	8.5	3.8	-8.3	2.2	-2.0	7.8
10	8	29	-145	116	174	9.8	-8.8	-0.9	3.2	-8.0	-2.6	1.4	3.5
20	8	45	-156	111	201	9.6	-8.7	-0.9	3.2	-7.9	-1.3	1.0	4.6
30	8	64	-166	102	230	9.5	-8.7	-0.8	3.2	-7.9	-0.1	0.5	5.6
40	8	85	-175	90	259	9.3	-8.6	-0.7	3.4	-7.9	0.9	-0.3	6.5
50	8	107	-180	73	287	9.2	-8.6	-0.6	3.6	-8.1	1.7	-1.1	7.2
60	8	129	-182	53	311	9.0	-8.5	-0.4	3.8	-8.3	2.2	-2.0	7.8
60	1	130	-65	-65	195	9.0	-8.5	-0.4	3.8	-8.3	2.2	-2.0	7.8
70	8	145	-116	-29	174	8.8	0.9	-9.8	3.2	-8.0	-2.6	1.4	3.6
80	8	155	-110	-45	201	8.8	0.9	-9.6	3.2	-7.9	-1.3	1.0	4.6
90	8	166	-102	-64	229	8.7	0.8	-9.5	3.2	-7.9	-0.1	0.4	5.6
100	8	174	-89	-84	258	8.6	0.7	-9.3	3.4	-7.9	0.9	-0.3	6.5
110	8	180	-73	-106	286	8.6	0.6	-9.2	3.6	-8.1	1.6	-1.1	7.2
120	8	182	-54	-128	310	8.5	0.4	-9.0	3.8	-8.3	2.2	-2.0	7.8
120	1	65	65	-129	194	8.5	0.4	-9.0	3.8	-8.3	2.2	-2.0	7.8
130	8	116	29	-144	173	-0.9	9.8	-8.8	3.2	-8.0	-2.6	1.4	3.5
140	8	111	45	-155	200	-0.9	9.6	-8.8	3.2	-7.9	-1.3	1.0	4.6
150	8	102	64	-166	229	-0.8	9.5	-8.7	3.2	-7.9	-0.1	0.5	5.6
160	8	90	84	-174	259	-0.7	9.3	-8.6	3.4	-7.9	0.9	-0.2	6.5
170	8	74	106	-180	287	-0.6	9.2	-8.6	3.6	-8.1	1.7	-1.1	7.2
180	8	54	129	-183	311	-0.4	9.0	-8.5	3.8	-8.3	2.2	-1.9	7.8
180	1	-65	130	-65	195	-0.4	9.0	-8.5	3.8	-8.3	2.2	-2.0	7.8
190	8	-29	145	-116	174	-9.8	8.8	0.9	3.2	-8.0	-2.6	1.4	3.5
200	8	-45	156	-111	201	-9.6	8.7	0.9	3.2	-7.9	-1.3	1.0	4.6
210	8	-64	166	-102	230	-9.5	8.7	0.8	3.2	-7.9	-0.1	0.5	5.6
220	8	-85	175	-90	260	-9.3	8.6	0.7	3.4	-7.9	0.9	-0.3	6.5
230	8	-107	180	-73	287	-9.2	8.6	0.6	3.6	-8.1	1.7	-1.1	7.2
240	8	-129	182	-53	311	-9.0	8.5	0.4	3.8	-8.3	2.2	-2.0	7.8
240	1	-130	65	65	195	-9.0	8.5	0.4	3.8	-8.3	2.2	-2.0	7.8
250	8	-145	116	29	174	-8.8	-0.9	9.8	3.2	-8.0	-2.6	1.4	3.6
260	8	-155	110	45	201	-8.8	-0.9	9.6	3.2	-7.9	-1.3	1.0	4.6
270	8	-166	102	64	229	-8.7	-0.8	9.5	3.2	-7.9	-0.1	0.4	5.6
280	8	-174	89	84	258	-8.6	-0.7	9.3	3.4	-7.9	0.9	-0.3	6.5
290	8	-180	73	106	286	-8.6	-0.6	9.2	3.6	-8.1	1.6	-1.1	7.2
300	8	-182	54	128	310	-8.5	-0.4	9.0	3.8	-8.3	2.2	-2.0	7.8
300	1	-65	-65	129	194	-8.5	-0.4	9.0	3.8	-8.3	2.2	-2.0	7.8
310	8	-116	-29	144	173	0.9	-9.8	8.8	3.2	-8.0	-2.6	1.4	3.5
320	8	-111	-45	155	200	0.9	-9.6	8.8	3.2	-7.9	-1.3	1.0	4.6
330	8	-102	-64	166	230	0.8	-9.5	8.7	3.2	-7.9	-0.1	0.5	5.6
340	8	-90	-84	174	259	0.7	-9.3	8.6	3.4	-7.9	0.9	-0.2	6.5
350	8	-74	-106	180	287	0.6	-9.2	8.6	3.6	-8.1	1.7	-1.1	7.2
360	8	-54	-129	183	311	0.4	-9.0	8.5	3.8	-8.3	2.2	-1.9	7.8

AVERAGE SUPPLY VOLTS = 249
AVERAGE TORQUE = 6.2

AVERAGE INPUT POWER = 2490
AVERAGE OUTPUT POWER = 1955
AVERAGE SHUNT LOSS = 351
AVERAGE SERIES LOSS = 166
AVERAGE ROTOR LOSS = 87

Figure 5.13 Typical Computer Printout for the Model of the System Using an Inverter Without Feedback Diodes

5.2.1 Effect of Rotor Impedance

The simulated machine used to examine the effect of rotor impedance on the system performance had the following parameters :

LMD = 0.12 H, LMQ = 0.12 H, LSD = 0.012 H, LSQ = 0.012 H,

RD = 3.08 Ω, RQ = 3.08 Ω, RP = 125 Ω, PHIO = -150°,

WM = 314 rad s^{-1}, IFR = 14.1 A, VDC = 220 V, FC = 62°

Table 5.1 shows the effect of the rotor resistances RSD and RSQ on the commutation safety angle (180° minus the angle for which each thyristor conducts), the average torque and the average d.c. link current.

	RSD (Ω)	RSQ (Ω)	Safety Angle	$T_{av.}$ (N-m)	$IDC_{av.}$ (A)
(1)	∞ *	∞ *	37°	5.7	10
(2)	21.08	21.08	50°	6.0	11
(3)	200	21.08	43°	5.6	10
(4)	21.08	200	49°	6.1	10

Table 5.1

* Footnote : This was achieved by setting RC = 0, thereby preventing all rotor currents from flowing (apart from the field excitation current).

It can be seen from Table 5.1 that induced rotor currents increase markedly the commutation safety angle. However, this is an illusory improvement to the system, since the phase current waveforms become much less sinusoidal, as can be seen in figures 5.14 to 5.17. Immediately after the commutation of a thyristor, the current in that phase becomes nearly constant. A small change in the d.c. link voltage can then bring about a large change in the commutation safety angle. This was tested by increasing VDC from 220 V to 264 V in cases (1) and (2) in Table 5.1. In case (1), with no induced rotor currents, the system continued to run in a stable manner, albeit with a reduced commutation safety angle, whereas in case (2), with RSD and RSQ both equal to 21.08 Ω, commutation failed.

It can be seen that the phase current does not have the same tendency to remain constant after a commutation in case (4) (figure 5.17), that it has in cases (2) and (3) (figures 5.15 and 5.16), indicating that the system will commutate in a stable fashion if RSQ is high, independent of the value of RSD. Thus, since the field winding is on the quadrature axis, more stable commutation is achieved if the resistance of the field winding is kept high.

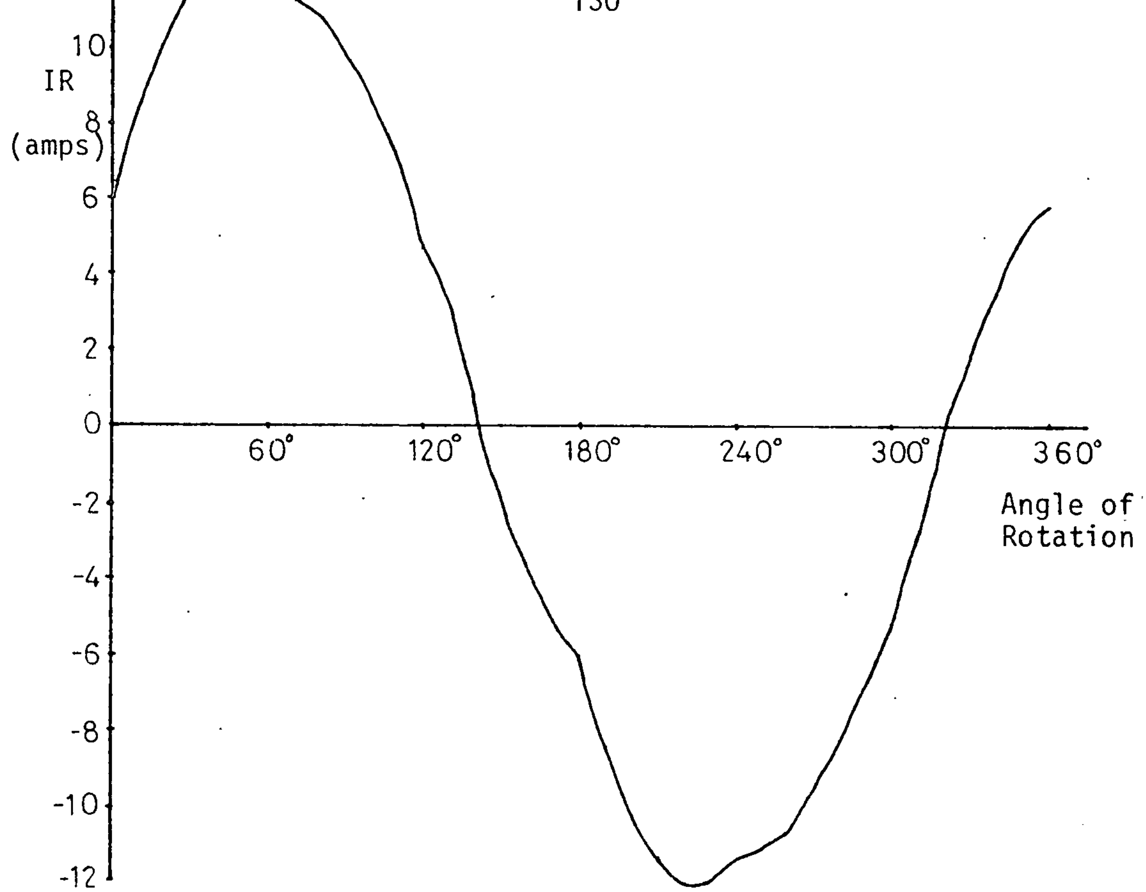


Figure 5.14 IR Against Rotor Angle for RSD and RSQ $\rightarrow \infty$

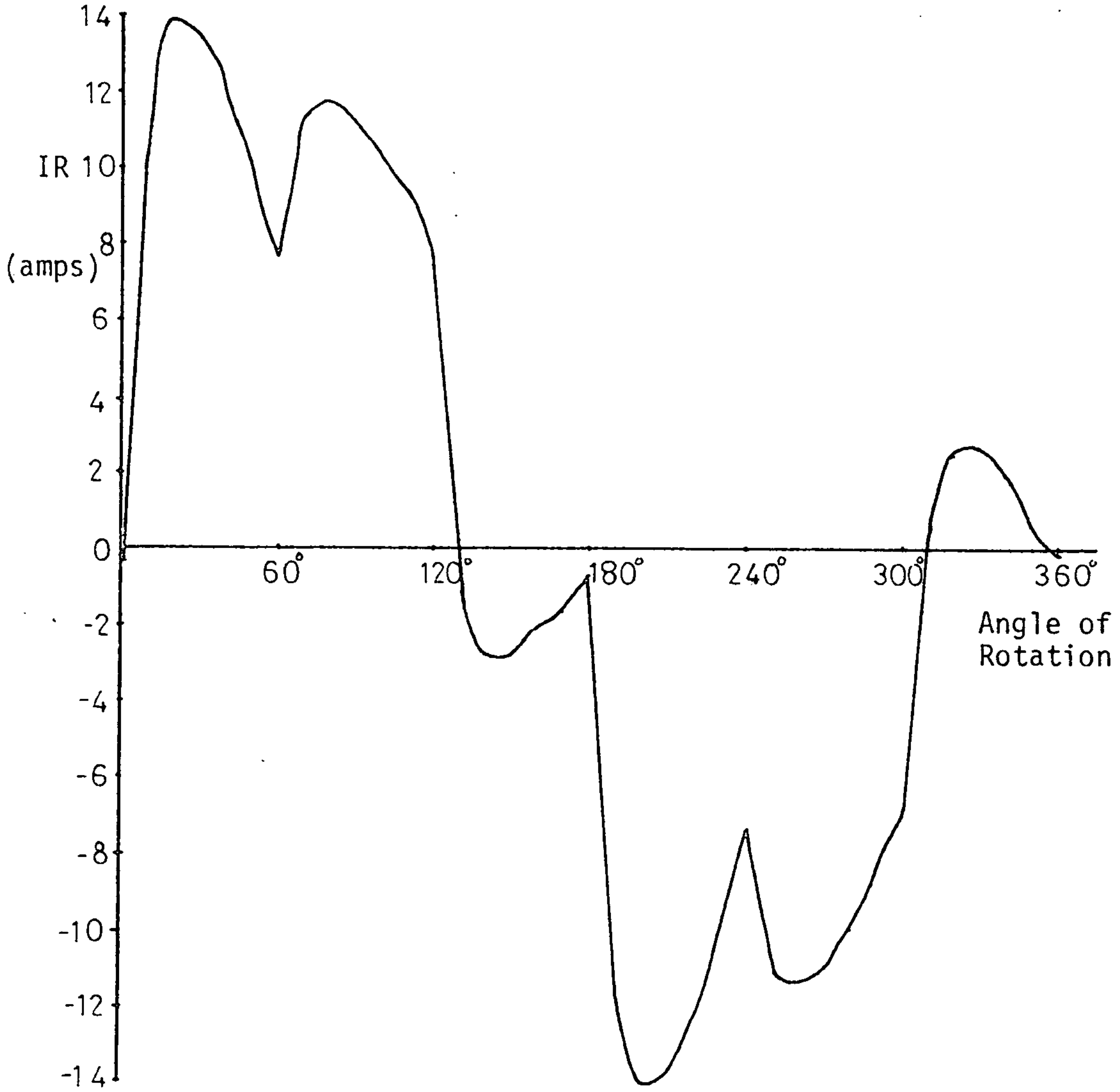


Figure 5.15 IR Against Rotor Angle for RSD = RSQ = 21.08 Ω

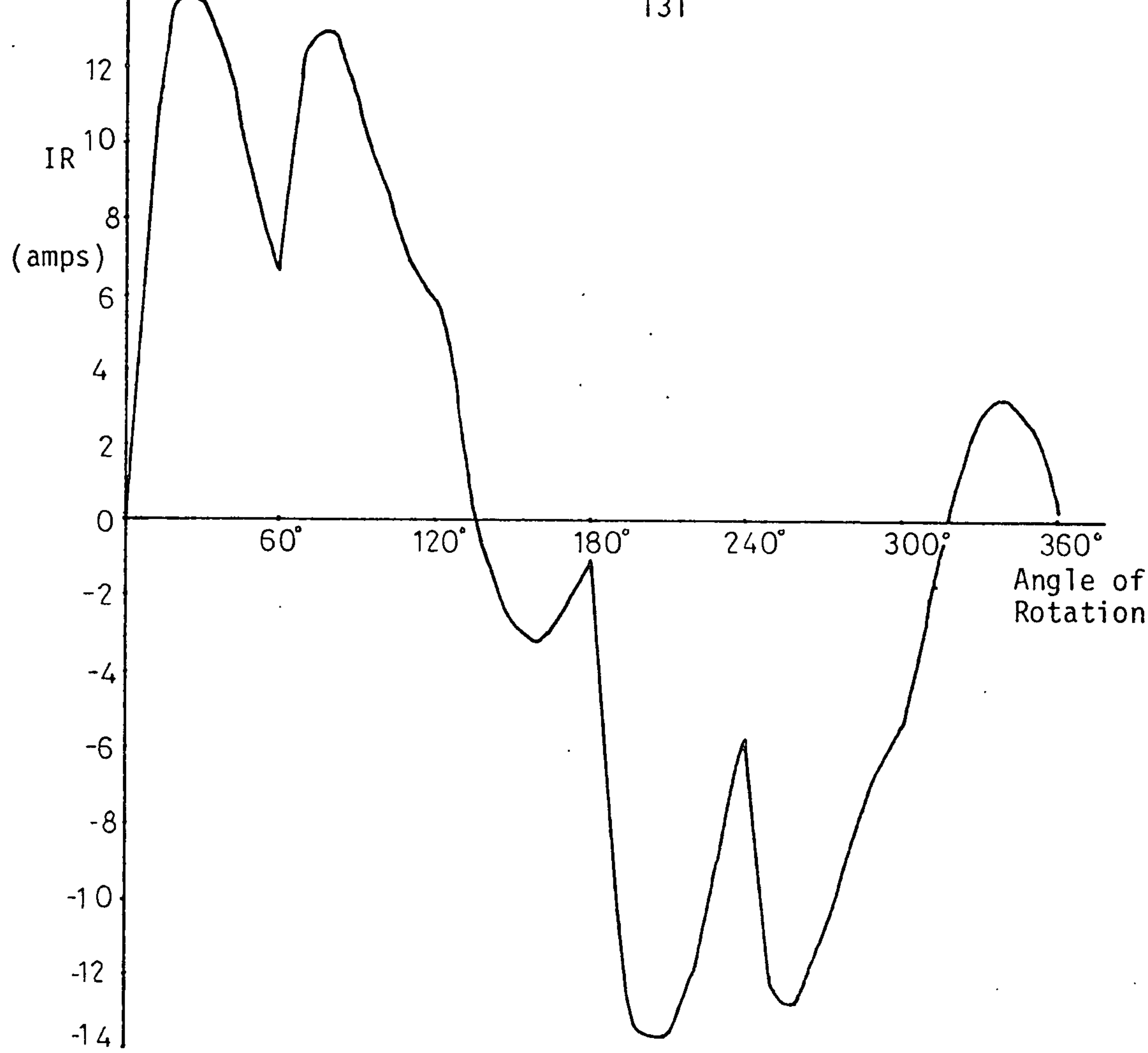


Figure 5.16 IR Against Rotor Angle for RSD = 200 Ω, RSQ = 21.08 Ω

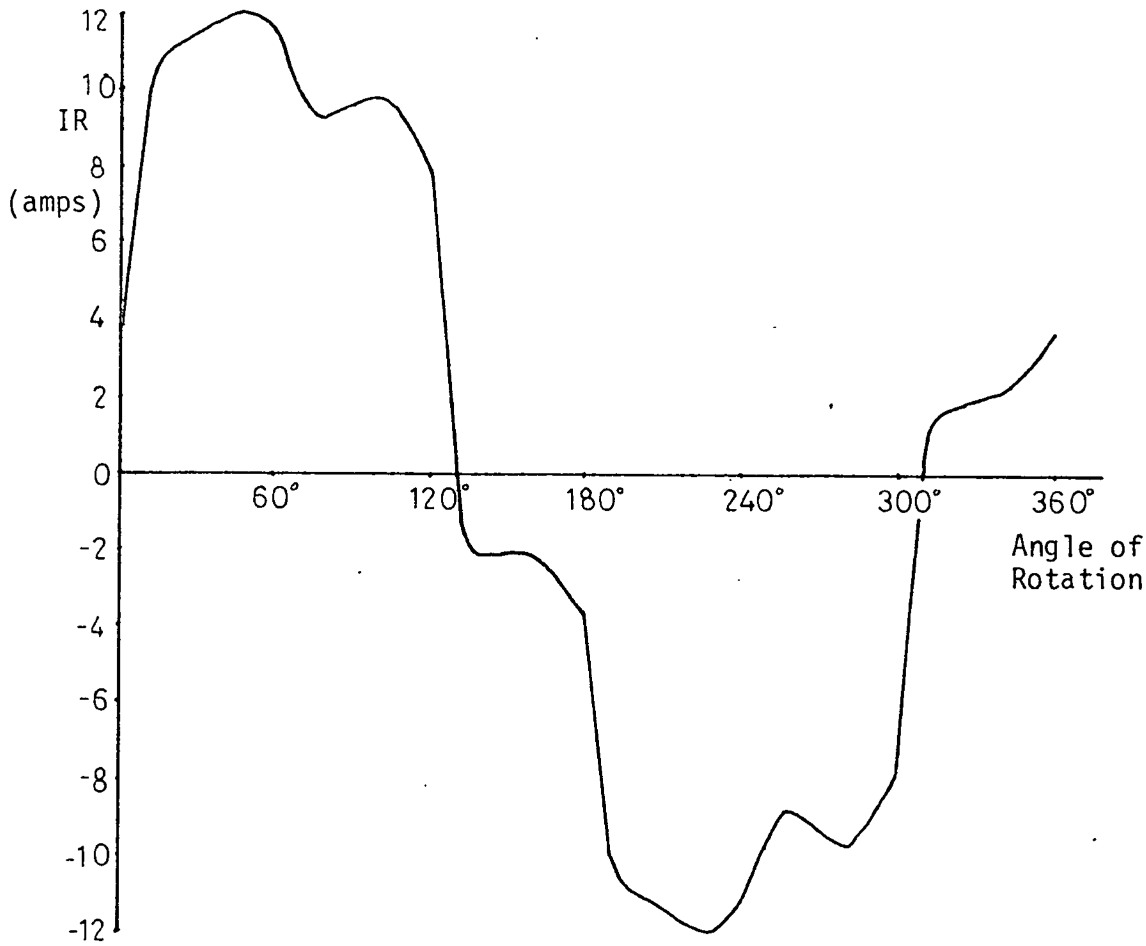


Figure 5.17 IR Against Rotor Angle for RSD = 21.08 Ω, RSQ = 200 Ω

5.2.2 Effect of Saliency

The experimental machine used in the laboratory has a cylindrically wound rotor, and the computer results in Section 5.2.1 are for a similar machine. However, since many synchronous machines in use today have salient poles, the simulated machine has been adapted to take into account rotor saliency.

The principle effect of saliency is to reduce the magnetizing inductance on the direct axis, LMD, typically by a factor of two (NB - the rotor field winding produces a magnetic flux ϕ_Q along the quadrature axis). For this set of results RC = 0, thus preventing any induced currents from flowing in the rotor. This eliminates the effect of saliency on both the leakage reactances and on the damper winding resistances.

In this set of results a salient pole machine with LMQ = 0.06 H and LMD = 0.03 H is compared to a cylindrically wound machine with LMD = LMQ = 0.06 H. Both simulated machines have ratings of 100 V per phase and 8 A per phase, and a commutation safety angle of 20^{o} was considered adequate. The rest of the system parameters are as follows :

RD = 3.08 Ω, RQ = 3.08 Ω, RP = 125 Ω,
WM = 314 rad. s^{-1}, VDC = 220 V, FC = 40^{o}

Suitable values for IFR and PH10 were calculated from theory based on sinusoidal waveforms (appendix D) such that at full speed (WM = 314 rad. s^{-1}) the machines would be running at rated current and voltage, and the inverter with a commutation safety angle of 20^o. For the cylindrical machine IFR = 20.7 A and PHIO = -141^o, and for the salient pole machine IFR = 19.7 A and PHIO = -132^o.

The computer results are shown in Table 5.2 below.

Machine Type	Commutation Safety Angle	IDC Average (A)	Average Torque (N-m)	Peak Phase Current (A)
Cylindrical	38^o	10	6.0	12.2
Salient Pole	38^o	9	5.5	10.8

Table 5.2

The phase current waveforms for the cylindrical and the salient pole machine are shown in figure 5.18 and 5.19 respectively.

It can be seen from the above results that if the correct adjustment is made to the value of PHIO, saliency has little effect on the performance of the system.

5.2.3 Low Speed Operation

The program was used to assist in determining the optimum values for PHIO and FC (defined in Section 5.1.1) during the starting procedure of a cylindrical machine with no induced rotor

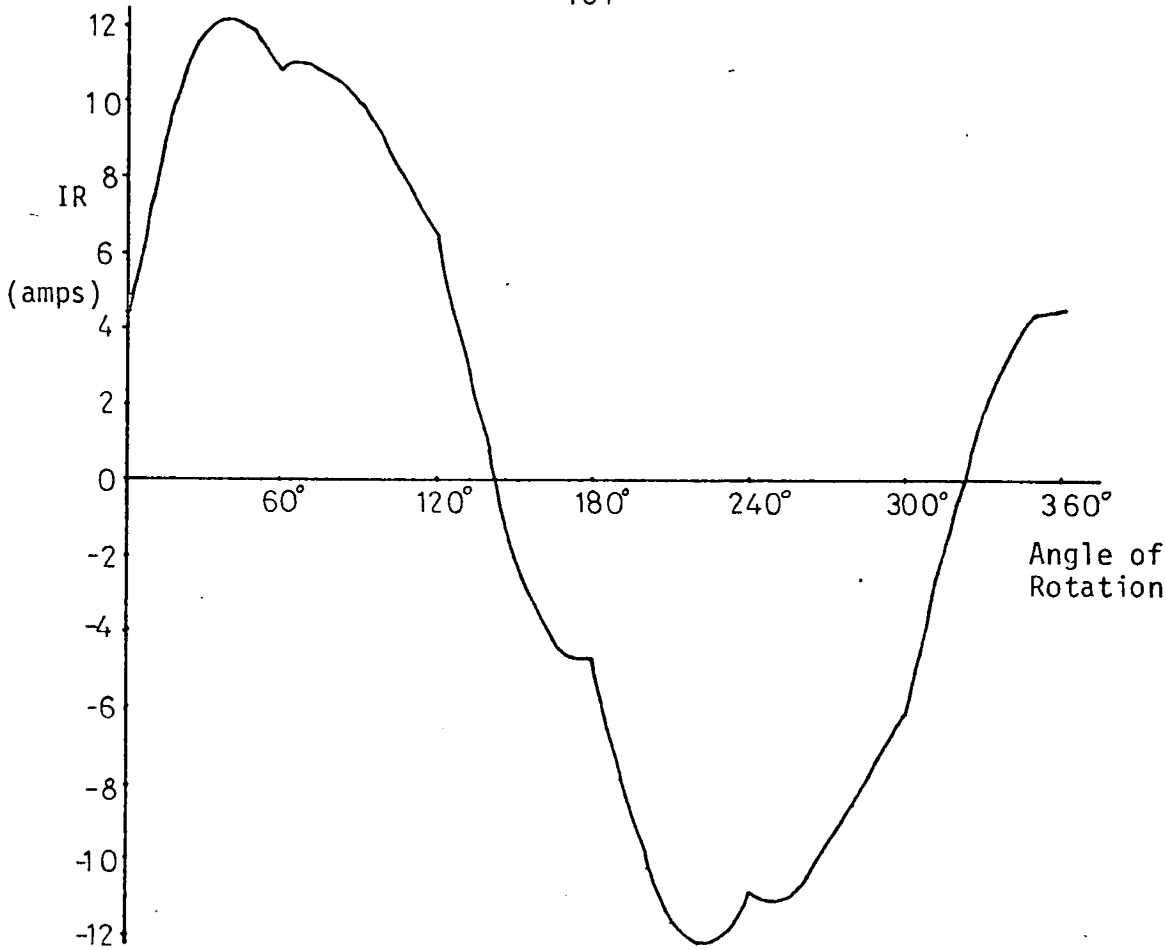


Figure 5.18 IR Against Rotor Angle in a Cylindrical Machine

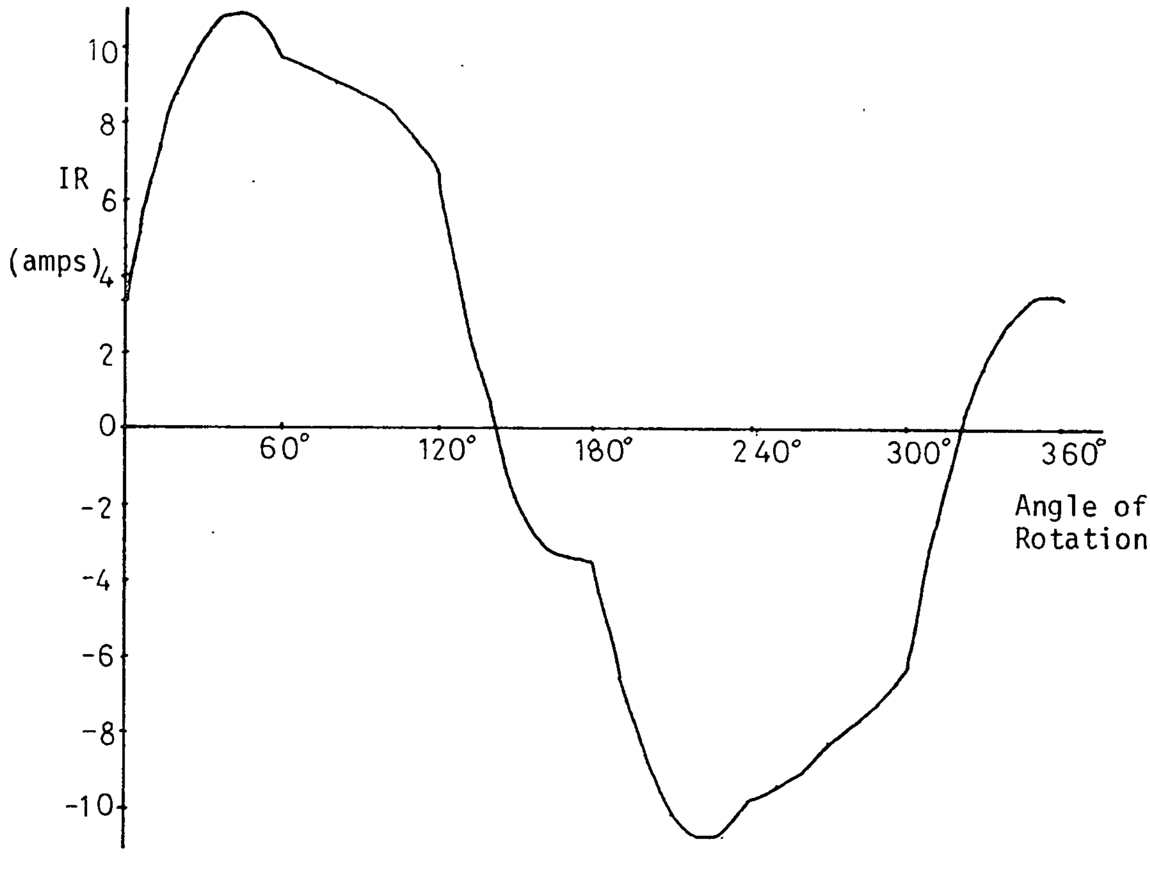


Figure 5.19 IR Against Rotor Angle in a Salient Pole Machine

currents. The resulting torques and peak phase currents for different values of PHIO and FC at various speeds are tabulated in Table 5.3.

Speed (rad s^{-1})	PHIO	FC	Commutation	Torque (N-m)	I_{ph} (peak)(A)
0.5	-120^{o}	0^{o}	Successful	14.7	7.7
0.5	-120^{o}	30^{o}	Successful	16.6	10.1
0.5	-150^{o}	30^{o}	Successful	12.3	10.3
0.5	-150^{o}	0^{o}	Successful	8.9	7.9
1.0	-120^{o}	0^{o}	Successful	13.0	7.4
2.0	-120^{o}	0^{o}	Successful	11.1	6.9
2.0	-120^{o}	30^{o}	Failure	-	-
2.0	-150^{o}	30^{o}	Successful	10.3	9.7
2.0	-150^{o}	0^{o}	Successful	8.0	7.4
5.0	-120^{o}	0^{o}	Successful	6.3	5.1
5.0	-120^{o}	30^{o}	Failure	-	-
5.0	-150^{o}	30^{o}	Successful	8.5	7.9
5.0	-150^{o}	50^{o}	Failure	-	-
5.0	-150^{o}	0^{o}	Successful	6.2	6.1
5.0	-165^{o}	0^{o}	Successful	4.5	6.7

Table 5.3

(Successful commutation signifies that the commutation of the thyristors is effected within 180^{o} of their being fired.)

It can be seen from Table 5.3 that a maximum torque at a speed of 0.1 rad s^{-1} is achieved with PHIO = -120^{o} and FC = 30^{o}. However, at speeds of 2 rad s^{-1} and 5 rad s^{-1} these conditions result in commutation failure, so a more stable system has PHIO = -120^{o} and FC = 0^{o}, with only a slight reduction in torque. These are also the optimum settings for PHIO and FC at a speed of 2 rad s^{-1}, but at 5 rad s^{-1} it can be seen that a higher torque is obtained if PHIO = -150^{o} and FC = 30^{o}.

In the experimental system, the machine accelerates from rest with PHIO = -120^{o} and FC = 0^{o}, and at 3 rad s^{-1} PHIO is changed to -150^{o} and FC to 30^{o}.

5.2.4 Commutation Failure

The effects of commutation failure were simulated on the computer to study more closely the experimental observations (described in Section 4.2.6) of doubling of the machine and d.c. link currents when the rectifier inhibit signal is removed.

The inverter was run for one cycle with VDC = 0, to simulate the inhibition of the rectifier during a commutation failure, then VDC was restored to its original value of 220 Volts. The computed results are given in figure 5.20, and may be compared to the steady state conditions in figure 5.21. It can be seen that the d.c. link current increases from a maximum of 12 A in the steady state conditions to a maximum of 32 A in the transient conditions, and the phase current from 12.2 A to 33.3 A, which

314.0	0.060	0.060	0.012	0.012	
RSD	RSQ	RD	RQ	RP	
21.080	21.080	3.080	3.080	125.00	
PHIO	FC	RC	CYCLES	DD	IC
-141	40	0	1	2	1
IFR	IMD	IMQ	ISD	ISQ	VDC
20.7	-3.3	-0.5	0.0	0.0	220.0

NGLE	COMM	VR	VY	VB	IDC	IR	IY	IB	IMD	IMQ	ISD	ISQ	TOR
0	1	110	-110	110	20	28.3	-19.2	-9.1	-3.3	-0.5	0.0	0.0	-4.1
10	1	110	-110	110	20	30.8	-19.2	-11.6	-1.3	1.3	0.0	0.0	-1.6
20	1	110	-110	110	20	32.6	-18.6	-13.9	1.3	2.4	0.0	0.0	1.7
30	1	110	-110	110	19	33.4	-17.6	-15.8	4.3	2.5	0.0	0.0	5.3
40	1	110	-110	110	17	33.3	-16.3	-17.0	7.3	1.7	0.0	0.0	9.0
50	1	110	-110	110	16	32.4	-14.9	-17.5	10.0	-0.1	0.0	0.0	12.5
60	1	110	-110	110	14	30.8	-13.5	-17.3	12.4	-2.8	0.0	0.0	15.4
60	1	110	-110	-110	32	30.7	-13.5	-17.2	12.5	-2.9	0.0	0.0	15.5
70	10	110	-110	-110	31	30.4	-10.4	-20.0	13.5	-3.6	0.0	0.0	16.8
80	20	110	-110	-110	30	29.6	-7.5	-22.1	14.7	-4.8	0.0	0.0	18.2
90	30	110	-110	-110	29	28.3	-5.1	-23.2	15.9	-6.6	0.0	0.0	19.7
100	40	0	0	0	27	26.5	-3.2	-23.3	16.7	-9.0	0.0	0.0	20.7
110	50	0	0	0	21	20.8	-0.2	-20.6	14.4	-12.0	0.0	0.0	17.9
120	51	110	-110	-110	20	18.6	0.3	-19.0	14.1	-14.9	0.0	0.0	17.6
120	1	110	110	-110	20	18.6	0.3	-18.9	14.1	-15.0	0.0	0.0	17.5
130	10	110	110	-110	20	15.3	3.6	-18.9	13.1	-15.4	0.0	0.0	16.3
140	20	110	110	-110	19	12.2	6.1	-18.3	12.3	-16.1	0.0	0.0	15.3
150	30	110	110	-110	18	9.7	7.6	-17.3	11.7	-17.0	0.0	0.0	14.5
160	40	0	0	0	16	7.7	8.2	-15.8	10.9	-18.3	0.0	0.0	13.6
170	50	0	0	0	10	4.5	5.9	-10.4	7.3	-19.9	0.0	0.0	9.1
180	60	0	0	0	5	2.1	3.0	-5.1	3.6	-20.9	0.0	0.0	4.5

Commutation Failure

Figure 5.20 Computer Printout for System in which VDC has just been Increased from 0 V to 220 V

314.0 0.060 0.060 0.012 0.012

RSD	RSQ	RD	RQ	RP
21.080	21.080	3.080	3.080	125.00

PHIO	FC	RC	CYCLES	DD	IC
-141	40	0	5	2	1

IFR	IMD	IMQ	ISD	ISQ	VDC
20.7	5.6	-15.1	0.0	0.0	220.0

NGLE	COMM	VR	VY	VB	IDC	IR	IY	IB	IMD	IMQ	ISD	ISQ	TOR
0	1	110	-110	110	12	4.4	-10.7	6.3	5.4	-15.3	0.0	0.0	6.7
10	10	110	-110	110	12	7.6	-11.0	3.4	4.7	-14.3	0.0	0.0	5.8
20	20	110	-110	110	11	10.0	-10.6	0.7	4.4	-13.5	0.0	0.0	5.5
30	23	110	-110	110	10	11.7	-9.5	-2.2	4.2	-13.0	0.0	0.0	5.2
40	23	110	-110	110	9	12.2	-8.4	-3.8	4.6	-13.1	0.0	0.0	5.7
50	23	110	-110	110	8	11.9	-7.2	-4.7	5.0	-13.8	0.0	0.0	6.1
60	23	110	-110	110	7	10.8	-6.0	-4.7	5.2	-15.1	0.0	0.0	6.4
60	1	110	-110	-110	12	10.7	-6.0	-4.7	5.2	-15.2	0.0	0.0	6.4
70	10	110	-110	-110	12	11.0	-3.1	-7.9	4.5	-14.1	0.0	0.0	5.6
80	20	110	-110	-110	12	10.6	-0.4	-10.3	4.3	-13.4	0.0	0.0	5.4
90	22	110	-110	-110	11	9.9	1.8	-11.7	4.5	-13.0	0.0	0.0	5.6
100	22	110	-110	-110	10	8.8	3.4	-12.2	4.8	-13.2	0.0	0.0	6.0
110	22	110	-110	-110	8	7.6	4.3	-11.9	5.2	-14.0	0.0	0.0	6.4
120	22	110	-110	-110	7	6.4	4.4	-10.8	5.4	-15.2	0.0	0.0	6.7
120	1	110	110	-110	12	6.4	4.4	-10.7	5.4	-15.3	0.0	0.0	6.7
130	10	110	110	-110	12	3.4	7.5	-11.0	4.7	-14.3	0.0	0.0	5.8
140	20	110	110	-110	12	0.7	9.9	-10.7	4.4	-13.6	0.0	0.0	5.5
150	23	110	110	-110	10	-2.1	11.7	-9.6	4.2	-13.0	0.0	0.0	5.2
160	23	110	110	-110	9	-3.7	12.2	-8.5	4.6	-13.1	0.0	0.0	5.7
170	23	110	110	-110	8	-4.6	11.9	-7.3	5.0	-13.8	0.0	0.0	6.1
180	23	110	110	-110	7	-4.7	10.8	-6.0	5.2	-15.0	0.0	0.0	6.4
180	1	-110	110	-110	12	-4.7	10.7	-6.0	5.2	-15.1	0.0	0.0	6.4
190	10	-110	110	-110	12	-7.9	10.9	-3.1	4.5	-14.1	0.0	0.0	5.6
200	20	-110	110	-110	11	-10.2	10.6	-0.4	4.3	-13.3	0.0	0.0	5.3
210	22	-110	110	-110	11	-11.7	9.8	1.9	4.5	-13.0	0.0	0.0	5.5
220	22	-110	110	-110	10	-12.2	8.7	3.5	4.8	-13.2	0.0	0.0	5.9
230	22	-110	110	-110	8	-11.9	7.5	4.3	5.2	-14.0	0.0	0.0	6.4
240	22	-110	110	-110	7	-10.8	6.3	4.5	5.3	-15.2	0.0	0.0	6.6
240	1	-110	110	110	12	-10.7	6.3	4.4	5.3	-15.3	0.0	0.0	6.6
250	10	-110	110	110	12	-11.0	3.4	7.6	4.7	-14.3	0.0	0.0	5.8
260	20	-110	110	110	12	-10.6	0.7	10.0	4.4	-13.6	0.0	0.0	5.5
270	23	-110	110	110	10	-9.5	-2.2	11.7	4.2	-13.0	0.0	0.0	5.2
280	23	-110	110	110	9	-8.5	-3.7	12.2	4.6	-13.1	0.0	0.0	5.7
290	23	-110	110	110	8	-7.3	-4.6	11.9	5.0	-13.8	0.0	0.0	6.2
300	23	-110	110	110	7	-6.1	-4.7	10.8	5.2	-15.1	0.0	0.0	6.4
300	1	-110	-110	110	12	-6.1	-4.7	10.8	5.2	-15.1	0.0	0.0	6.5
310	10	-110	-110	110	12	-3.1	-7.9	11.0	4.5	-14.1	0.0	0.0	5.6
320	20	-110	-110	110	12	-0.4	-10.2	10.7	4.3	-13.3	0.0	0.0	5.4
330	22	-110	-110	110	11	1.8	-11.7	9.9	4.5	-13.0	0.0	0.0	5.6
340	22	-110	-110	110	10	3.4	-12.2	8.8	4.8	-13.2	0.0	0.0	6.0
350	22	-110	-110	110	8	4.3	-11.9	7.6	5.2	-14.0	0.0	0.0	6.4
360	22	-110	-110	110	7	4.5	-10.8	6.3	5.4	-15.2	0.0	0.0	6.7

AVERAGE SUPPLY AMPS = 10

AVERAGE TORQUE = 6.0

AVERAGE INPUT POWER = 2149 -INHIB. NE

AVERAGE OUTPUT POWER = 1883

AVERAGE SHUNT LOSS = 290

AVERAGE SERIES LOSS = 217

AVERAGE ROTOR LOSS = 0

Figure 5.21 Computer Printout for System in Steady State agrees reasonably well with experimental observations.

At 180^0 a second commutation failure occurs due to the transient conditions. This will result in a further inhibition of the rectifier, followed by more large currents when the inhibition is removed. The sequence of periods of rectifier inhibition followed by large inverter currents followed by a further inhibition can be broken only by switching off the system completely, and starting afresh.

5.2.5 System Operation using an Inverter without Feedback Diodes

The program with the modifications described in Section 5.12 was used to simulate the operation of a cylindrically wound, synchronous machine driven by an inverter without feedback diodes.

The following system parameters, similar to those used in Section 5.2.1, were fed into the computer.

LMD = 0.12 H, LMQ = 0.12 H, LSD = 0.012 H, LSQ = 0.012 H,

RD = 3.08 Ω, RQ = 3.08 Ω, RP = 125 Ω, PHIO = -150^0,

WM = 314 rad. s^{-1}, IFR = 14.1 A, IDC = 10 A, FC = 62^0.

The resulting waveforms for different rotor impedances are given in figures 5.22 to 5.24 and the main features are summarized in Table 5.4.

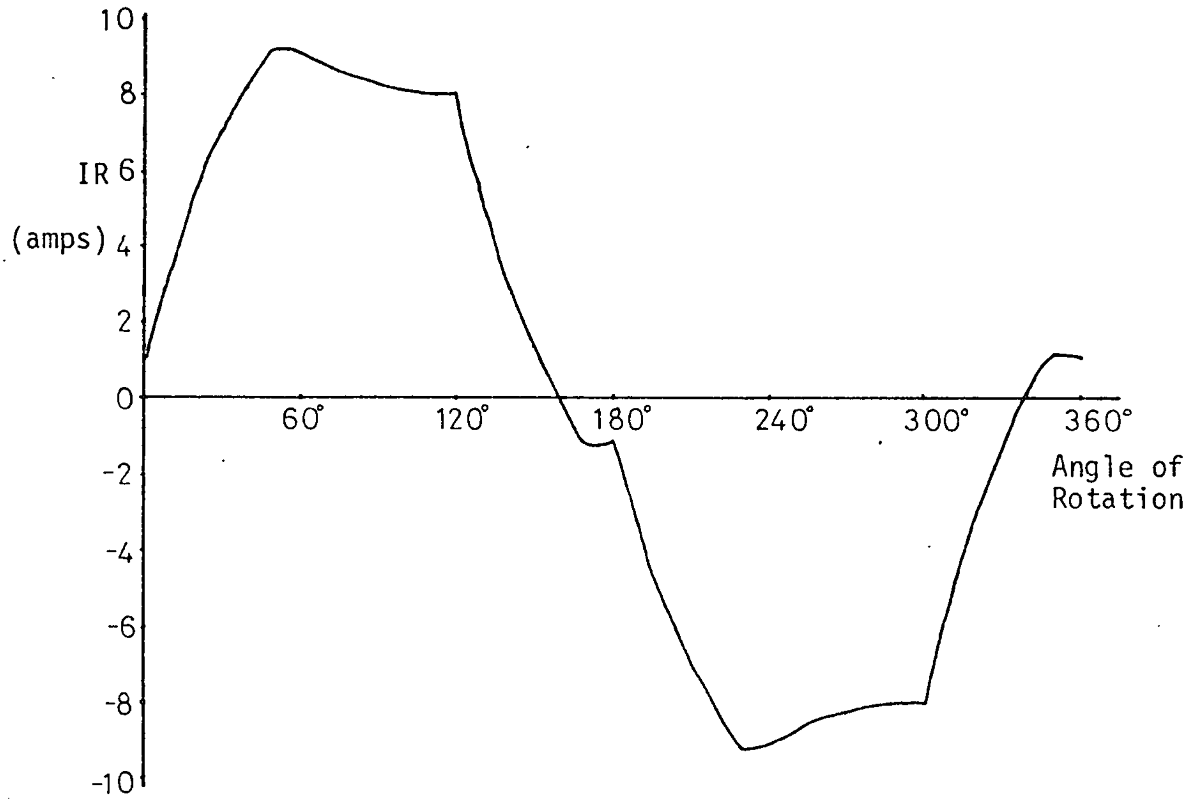


Figure 5.22 IR Against Rotor Angle for an Inverter Without Feedback Diodes; RSD, RSQ → ∞

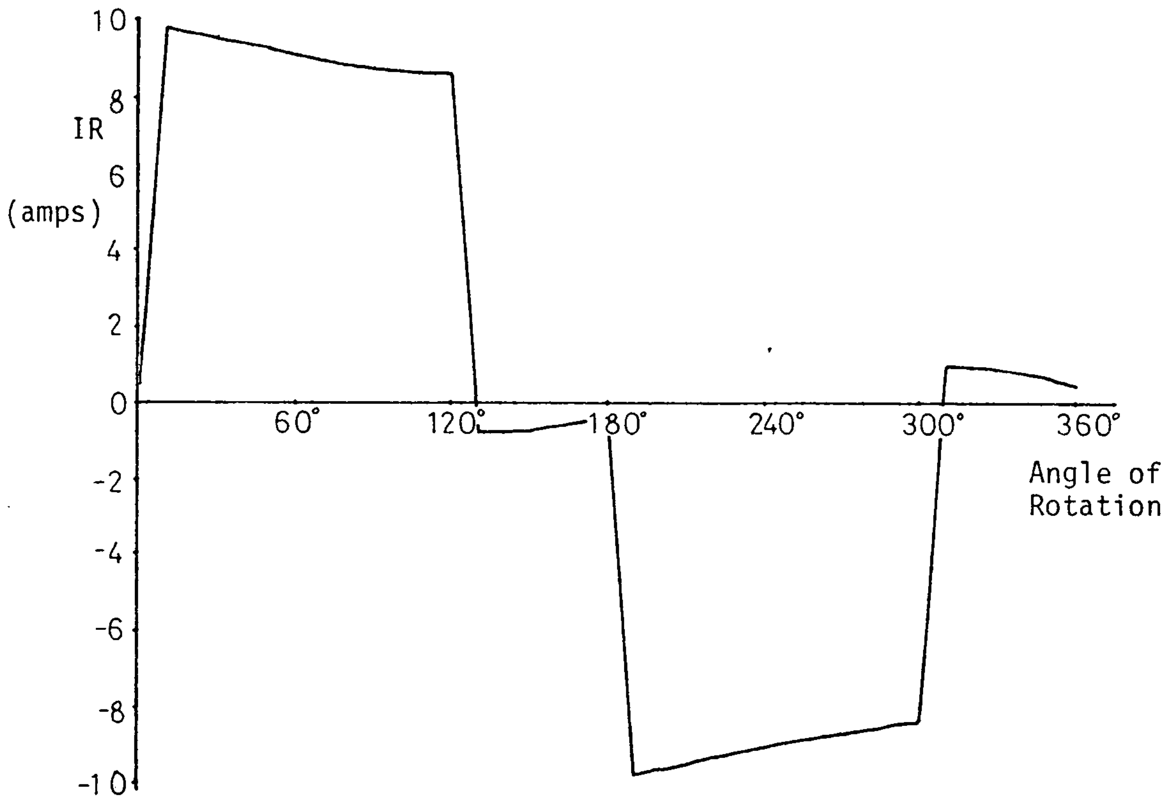


Figure 5.23 IR Against Rotor Angle for an Inverter Without Feedback Diodes; RSD = RSQ = 21.08 Ω

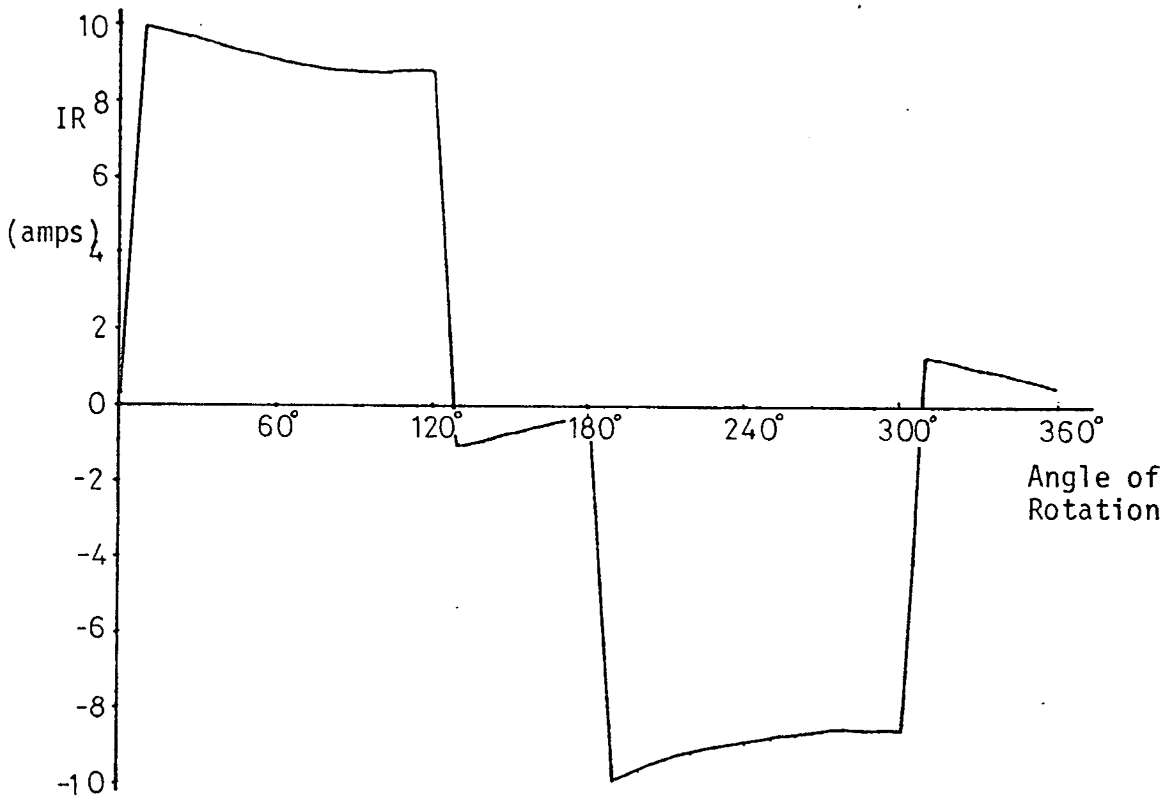


Figure 5.24 IR Against Rotor Angle for an Inverter Without Feedback Diodes; RSD = RSQ = 1.08 Ω

	RSD (Ω)	RSQ (Ω)	Safety Angle	$T_{av.}$ (N-m)	$V_{D.C.}$ (average) (V)
(1)	∞ *	∞ *	20^0	7.8	341
(2)	21.08	21.08	52^0	6.2^0	249
(3)	1.08	1.08	52^0	6.3	243

Table 5.4

* Footnote : This was achieved by setting RC = 0, thus stopping all induced currents in the rotor.

It can be seen that a low rotor impedance greatly increases the commutation safety angle, at the cost of a reduction in torque. In a further test with RC = 0 (RSD = RSQ = ∞), IDC was fixed at 8 A. This increased the safety angle to 33^0 - still considerably less than case (2) and (3) in Table 5.1 - but reduced the average torque to 5.3 N-m.

The computer simulation confirms the conclusion which were drawn in Section 2.2 that the presence of damper windings on the rotor considerably improves the performance of a system in which a synchronous motor is driven by an inverter without feedback diodes.

CHAPTER 6 : DISCUSSION

In this chapter the experimental and computer results are examined, and the advantages and disadvantages of the laboratory system discussed.

6.1 CONTROL OF AN INVERTER WITH FEEDBACK DIODES

6.1.1 Starting Procedure

The optimum theoretical value for the load angle, δ , at starting is -30^o if each thyristor conducts for 120^o and 0^o if they conduct for 180^o (Section 2.3.3). The computer simulation (Section 5.2.3) and experimental results (Section 4.2.2) indicate that if $\delta = 0$ and the thyristors conduct for periods of 150^o or more, commutation is liable to fail at speeds of about 2 rad. s^{-1}. Therefore, as the machine is likely to accelerate from rest to 2 rad. s^{-1} in less than 1 cycle, the conduction period at starting should be fixed at 120^o (FC = 0^o in the computer simulation).

Although a setting of $\delta = -30^o$ produces the maximum average starting torque, with a minimum equal to 0.87 x the maximum, the torque falls off rapidly with speed. Unless provision is made for an intermediate value of δ (say, $\delta = 10^o$), it is preferable to sacrifice some starting torque by setting $\delta = 0^o$ at starting, and switch to a higher value of δ (say, $\delta = 30^o$) at about 3 rad. s^{-1}. The minimum starting torque with $\delta = 0^o$ is 0.5 x the maximum, with an average of 0.87 times that with $\delta = -30^o$, but the reduction in the value of torque with speed is much less pronounced than with $\delta = -30^o$.

At about 3 $rad.s^{-1}$ δ is switched to 30^o, and artificial commutation (ie, commutation by the controlled rectifier) of an inverter thyristor is set to occur 150^o after that thyristor is fired (FC = 30^o in the computer simulation). As soon as the frequency of the system has increased sufficiently for the machine to commutate the inverter with a 30^o safety margin, artificial commutation is no longer employed since the rectifier is inhibited only if any thyristor conducts for more than 150^o. Thus the changeover from artificial commutation to natural commutation occurs smoothly and automatically as soon as the system is capable of naturally-commutated operation, keeping to a minimum the period of reduced torque and high harmonic content inherent in a system operating with artificial commutation.

6.1.2 High Speed Operation

At speeds greater than about 5 Hz when the inverter is commutated by the synchronous machine, the appropriate value for δ depends to a large extent on the machine ratings (Section 2.3.1). It is, however, preferable to operate with $\delta \geqslant 30^o$, since the current waveform becomes less sinusoidal as δ decreases (Section 4.2.5).

Since there is no filtering of the d.c. supply to the inverter, the 300 Hz rectifier ripple can be seen on the inverter output voltage and, to a lesser extent, current waveforms. However, it is most marked when the rectifier is operating with a large delay angle, when the inverter frequency is sufficiently small relative to the rectifier operating frequency for the machine to integrate the incoming waveforms and maintain a steady torque. At inverter frequencies approaching the rectifier operating frequencies, when beating between the frequencies might have caused problems such as varying the commutation safety angle, the rectifier is operating with a low delay angle and the magnitude of the ripple is small.

The effectiveness of the protection to the system in the event of a commutation failure occurring during high speed operation is limited. A direct short of the d.c. link cannot occur, as no inverter thyristor can be triggered if the complementary thyristor in the same phase leg is still conducting, but the very jerky operation with currents up to double their normal magnitudes is highly undesirable. As the high currents occur when the rectifier inhibition is removed and the full d.c. link voltage is suddenly applied to the inverter in the event of a commutation failure at a speed greater than about 10 Hz, it would be better to inhibit the rectifier and for it to remain inhibited until the machine speed has reduced to 10 Hz.

6.2 INVERTER/SYNCHRONOUS MACHINE SYSTEMS

6.2.1 Comparison with an Inverter without Feedback Diodes

If a synchronous machine is designed to be connected directly to the mains supply, it is likely to have damper windings on the rotor to damp out any deviations of machine speed from synchronous speed. However, damper windings are not required if the machine is designed to be driven always by an inverter with rotor position control as synchronous speed is then controlled by the machine speed. Consequently, a reduction in the machine cost could be made by the elimination of the damper windings.

If a comparison is made between case (1) in Section 5.2.1 and the case described in Section 5.2.5 where IDC = 8 A, it can be seen that on a machine where the rotor impedance is high, the inverter with feedback diodes both develops a higher average torque and operates with a larger commutation safety angle than the inverter without feedback diodes. A further advantage of the inverter with feedback diodes is that the output current waveform approximates far more closely to a sinusoidal waveform, so the iron losses in the machine will be smaller.

If damper windings are incorporated in the machine, it can be seen from a comparison of case (2) in Section 5.2.1 and case (2) in Section 5.2.5 that an inverter without feedback diodes both develops the greater average torque and operates with the larger commutation safety angle (the discrepancy between the safety angles is in reality greater than 2^o, due to the periods of constant phase current which occur after a commutation in the case of the inverter with feedback diodes, as discussed in Section 5.2.1).

A low field winding impedance (case (4), Section 5.2.1), produces an effect on the system similar to the effect of damper windings, so in a system where the inverter has feedback diodes, the machine should have a high field-winding impedance as well as no damper windings.

6.2.2 The Effect of Saliency in the Synchronous Machine

The computer simulation (Section 5.2.2) indicates that saliency in the synchronous machine has little effect on the performance of the system, as long as a suitable adjustment is made to the high speed value of the load angle, δ. In a fourth year undergraduate project [40], the inverter Mk I was used to drive successfully a salient pole machine, and these results tended to confirm the computed results that the presence of saliency makes little difference to the system performance.

6.2.3 The System as a Variable Speed Drive

The inverter together with the rotor position transducers, in an inverter/synchronous machine system in which the inverter frequency is controlled by the machine rotational speed, acts as the equivalent to the mechanical commutator in a d.c. machine, giving the system similar control characteristics to the separately excited d.c. motor. However, the inverter/synchronous machine system has an extra condition to be met, namely that the inverter must always commutate successfully, the approximate condition for which is that $V_{ph} < E_F \cos\delta$ (Section 2.3.1). Thus the control system must incorporate the condition that for a fixed load angle δ the maximum permissible value for V_{DC} is $(k \cdot \omega \cdot I_F)$, where I_F = the field current, ω = the machine angular velocity and k = a constant.

A useful facility which both adds to the system speed of response and conserves energy is regenerative braking of the machine. An inverter without feedback diodes is capable of passing energy back from the machine to the mains supply by reversing the polarity of the d.c. link by controlling the inverter as a controlled rectifier and the rectifier as a line-commutated inverter [41] (figure 6.1). This may be achieved at the small cost of some additional circuitry to control the firing of the thyristors in the two bridge converters.

The inclusion of feedback diodes in the inverter precludes the above method , as the diodes do not permit the reversal of the d.c. link polarity. However, if the inverter thyristors are not triggered, the feedback diodes form a diode bridge rectifier, giving the d.c. link the same polarity as when motoring. The machine energy can then be returned to the mains by the firing of thyristors T1 and T2 in figure 6.2, thus forming a cross-over of the d.c. link polarity. The diode bridge can then drive the controlled rectifier as a line-commutated inverter.

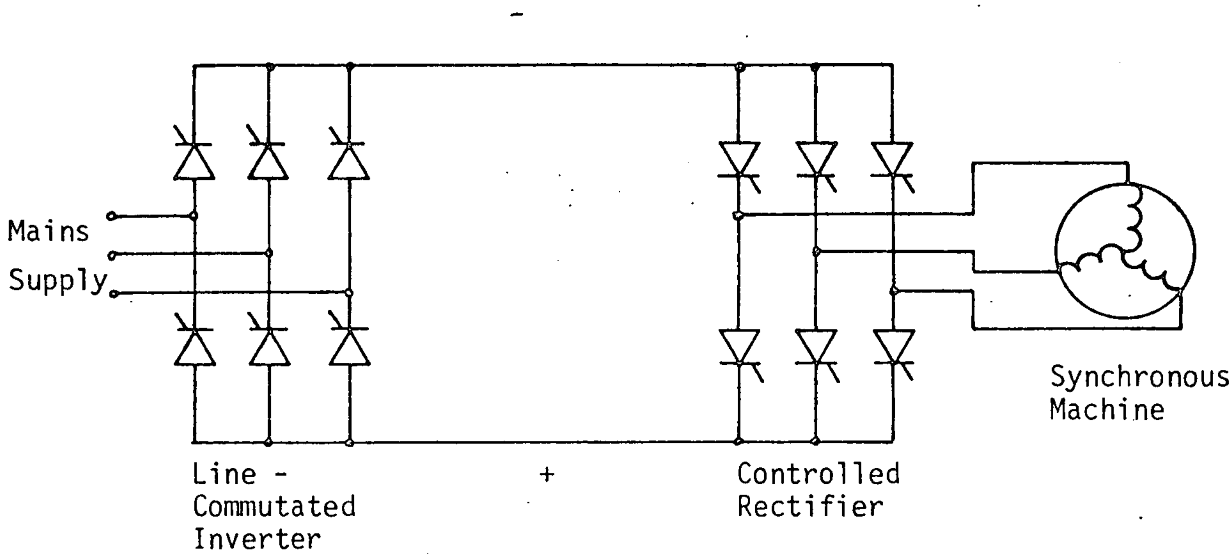


Figure 6.1 Regenerative Braking May Be Employed in a System Without Feedback Diodes by Reversing the Polarity of the DC Link

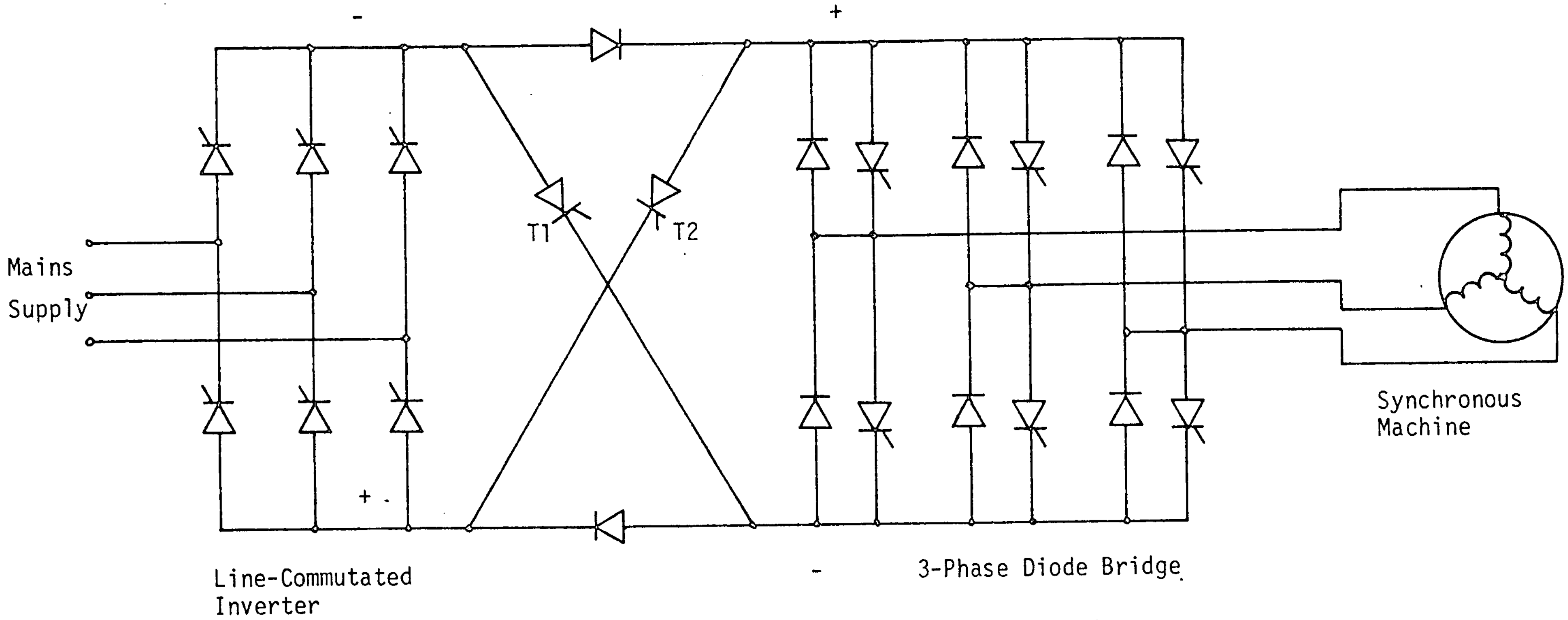


Figure 6.2 Regenerative Braking in a System with Feedback Fiodes may be Effected by Firing Thyristors T1 and T2

CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 CONCLUSIONS

A controlled rectifier/variable frequency inverter/ synchronous machine system, employing rotor position detectors to control the firing of the inverter thyristors, has been successfully developed. At low speeds the inverter thyristors are commutated by reducing the d.c. link current to zero six times per cycle, while at higher speeds the machine back E.M.F.'s are used to commutate naturally the inverter.

The inclusion of feedback diodes round each inverter thyristor permits the motor to operate with sinusoidal currents instead of rectangular currents. Higher torques for a given commutation safety angle are then achieved if the machine has a high rotor impedance. However, the presence of damper windings on the rotor normally reduces the rotor impedance sufficiently that, for a given commutation safety angle, higher torques are obtained without feedback diodes in the inverter.

A thyristor state detection circuit has been developed which detects whether the inverter thyristors are in the forward blocking state or not. This circuit has three applications in the system :

1. To limit the period of rectifier inhibition during the artificial commutation mode of operation to the time which it takes for the appropriate thyristor to commutate.

2. To enable the inverter thyristors to switch from being artificially commutated to being naturally commutated at the lowest speed which the system can operate with natural commutation.

3. To prevent a short circuit of the d.c. link by the inhibition of firing pulses to any thyristor if its complementary thyristor in the same phase leg is still conducting.

7.2 RECOMMENDATION FOR FUTURE WORK

The main requirements of the pumped storage scheme application described in Section 1.1 that the inverter should accelerate the synchronous machine to synchronous speed as quickly as possible, at which point the inverter is disconnected and the machine driven directly from the grid system, are met by the system described in Chapter 3. By the addition of a suitable d.c. link voltage control, the system may also be used for uni-directional, variable speed drive applications with the facility for regenerative braking. However, a considerable amount of extra control circuitry must be added if the system is to be capable of reversing the direction of machine rotation.

Future work could involve the inclusion of a microprocessor in the system as a replacement for much of the control electronics. The microprocessor would have inputs from the rotor position transducers, the thyristor state detectors and the tachogenerator, together with an input giving the required machine speed, and the outputs would control the inverter thyristor firing, the rectifier delay angle and the rectifier inhibit signal. By suitable programming the system could be made more flexible, and the reversal of the direction of rotation would be made considerably easier.

A further improvement which could be made to the system is to use the signals from the rotor position transducers to measure the angular velocity of the machine. The tachogenerator is an expensive piece of equipment which can be made redundant by the rotor position transducers.

APPENDIX A

Printed circuit boards manufactured by Westinghouse[43] are used to control the firing of the rectifier thyristors, and also to provide the firing pulses in the inverter Mark I. The circuit diagrams for the D82 LED circuits in the rectifier and the P82D circuits in the inverter are shown in figures A1 and A2 respectively, and the input/output terminals are listed below.

Terminal No	1	Cathode	Side 2
	2	Gate	Side 2
	3	Cathode	Side 2
	4	Gate	Side 2
	5	Cathode	Side 1
	6	Gate	Side 1
	7	Cathode	Side 1
	8	Gate	Side 1
	9	Pulse Duplication In (Side 1)	
	10	Pulse Duplication In (Side 2)	
	11	Side 2 Inhibit	
	12	Side 1 Inhibit	
	13	Pulse Duplication Out (Side 1)	
	15	Pulse Duplication Out (Side 2)	
	16	Control Positive	
	18	Control Negative	
	21	Positive Rail, a.c. Centre Tap	
	22	A.C. 16.3 V r.m.s.	
	23	A.C. 16.3 V r.m.s.	
	24	Negative Rail	

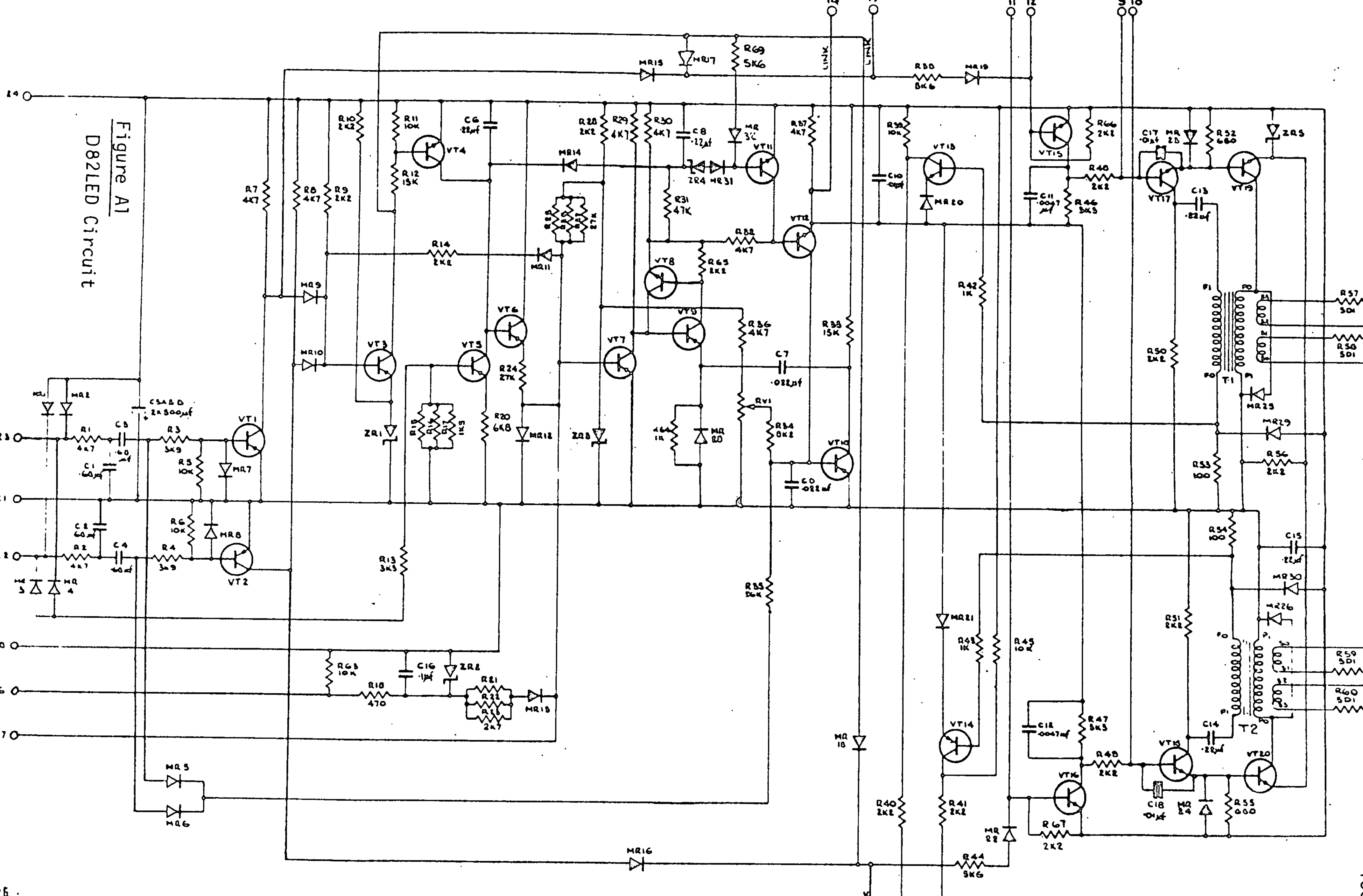


Figure A1
D82LED Circuit

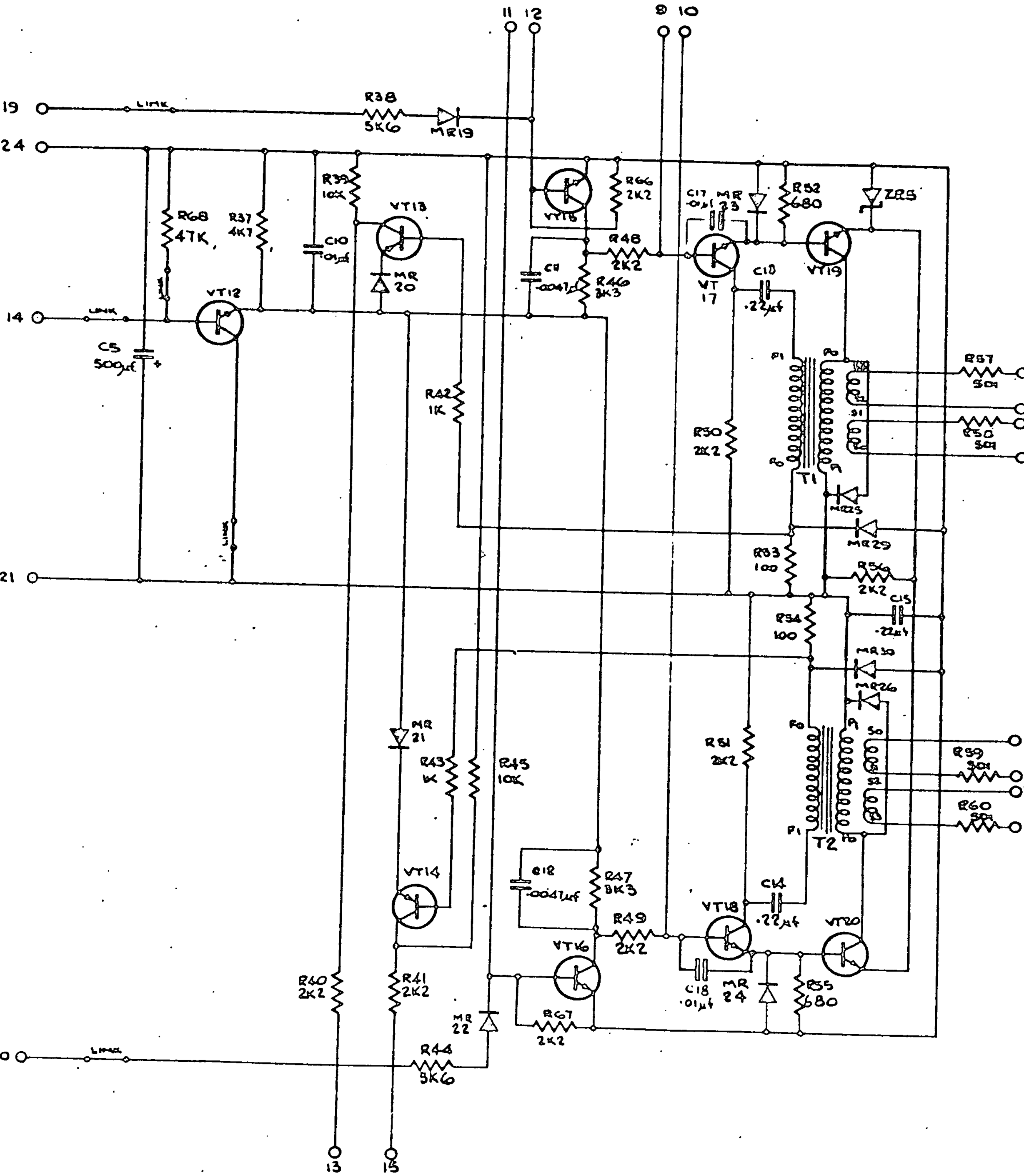


Figure A2 Circuit Diagram of Westinghouse P82D Circuit

APPENDIX B

The synchronous machine which was used in this project is a cylindrically wound, 4-pole machine with a 3-phase winding on the stator, and a 2-phase winding on the rotor brought out via sliprings to terminals on the stator. The machine was designed such that it could be run as an induction motor as well as a synchronous motor, so the air gap is smaller than is usual for a synchronous machine.

The main machine parameters are listed below[44].

Rated Power	2kVA
Rated Voltage	240V
Rated Speed	1500 r.p.m.
Number of Poles	4
Turns Ratio	3.3
Rated Efficiency	77%
Stator Magnetizing Inductance	25.4 mH
Stator Winding Resistance	0.5 Ω
Stator Leakage Inductance	3.3 mH
Rotor Leakage Inductance	21.4 mH
Rotor Winding Resistance	6.7 Ω

The effective rotor winding resistance was increased by connecting an external resistance of 38 Ω in series with each field winding.

APPENDIX C

Computer Program for System with Feedback Diodes

```
SELECTINPUT (21)
SELECTOUTPUT (25)
%BEGIN
%REAL LA,LB,LC,LD,X
%REALARRAY G(0:35),H(0:35),M(0:10),I(0:10),Y(0:10),V(0:10)
%INTEGERARRAY A(0:10)
%INTEGER J,JA,JB,JC,JG,JH
%CYCLE J=0,1,10;READ(M(J));READ(A(J));READ(I(J));READ(Y(J));%REPEAT


NEWLINE;SPACES(5)
PRINT STRING ('  WM      LMD    LMQ    LSD    LSQ')
NEWLINE;SPACES(5)
PRINT(M(0),3,1);%CYCLE J=1,1,4;PRINT(M(J),1,3);%REPEAT
NEWLINE;SPACES(5)
PRINT STRING ('   RSD    RSQ     RD      RQ      RP')
NEWLINE;SPACES(5)
%CYCLE J=5,1,8;PRINT(M(J),1,3);%REPEAT;PRINT(M(9),5,2)
NEWLINE;SPACES(5)
PRINT STRING ('  PHIO     FC     RC  CYCLES  DD     IC')
NEWLINE;SPACES(5)
%CYCLE J=0,1,5;PRINT(A(J),5,0);%REPEAT
NEWLINE;SPACES(5)
PRINT STRING ('   IFR    IMD    IMQ    ISD    ISQ    VDC')
NEWLINE;SPACES(5)
%CYCLE J=0,1,4;PRINT(I(J),3,1);%REPEAT;PRINT(I(10),3,1)
SELECTINPUT (22)
                      JC=0;   LA=0;   LB=0;   LC=0;   LD=0
%CYCLE JA=1,1,6
                %CYCLE JB=0,1,6
READ(X);%CYCLE J=1,1,10;READ(V(J));READ(I(J));%REPEAT
->K1 %IF JB=6
             V(0)=(V(7)+V(8)+V(9))/3
G(JC)=I(7);LA=G(JC) %IF G(JC)>LA;LB=G(JC) %IF G(JC)<LB
H(JC)=V(7)-V(0);LC=H(JC) %IF H(JC)>LC;LD=H(JC) %IF H(JC)<LD
               JC=JC+1
K1:            %REPEAT
%REPEAT
LA=-LB  %IF  -LB>LA;      LC=-LD  %IF  -LD>LC
%IF  LA<0.1  %OR  LC<0.1  %THEN  ->K2
      LB=30/LA;      LD=30/LC
NEWLINE;PRINT STRING ('     MAX.  IR  ')
PRINT STRING ('(30 DIVISIONS)  =');PRINT(LA,3,1);PRINT STRING ('
NEWLINES(2);PRINT STRING ('     MAX.  VR  ')
PRINT STRING ('(30 DIVISIONS)  =');PRINT(LC,3,1);PRINT STRING ('
NEWLINES(2);PRINT STRING ('    0')
%CYCLE J=1,1,6;PRINT STRING ('    I    0');%REPEAT
%CYCLE J=0,1,35;NEWLINE;PRINT(J*10,3,0)
                JG=INT (G(J)*LB);  JH=INT (H(J)*LD)
             %IF JG>JH  %THEN SPACES(30+JH) %AND PRINT STRING ('+')
     %AND SPACES(JG-JH-1) %AND PRINT STRING ('X') %AND ->K3
       %IF JG<JH %THEN SPACES(30+JG) %AND PRINT STRING ('X') %C
    %AND SPACES(JH-JG-1) %AND PRINT STRING ('+') %C
     %ELSE SPACES(30+JG) %AND PRINT STRING ('*')
K3:%REPEAT
  NEWLINE;PRINT STRING ('    0')
     %CYCLE J=1,1,6;PRINT STRING ('    I    0');%REPEAT
K2: %ENDOFPROGRAM
```

Computer Program for System without Feedback Diodes

```
SELECTINPUT (21)
SELECTOUTPUT (25)
%BEGIN
%REAL LA,LB,LC,LD,X
%REALARRAY G(0:35),H(0:35),M(0:10),I(0:10),Y(0:10),V(0:10)
%INTEGERARRAY A(0:10)
%INTEGER J,JA,JB,JC,JG,JH
%CYCLE J=0,1,10;READ(M(J));READ(A(J));READ(I(J));READ(Y(J));%REPEAT


NEWLINE;SPACES(5)
PRINT STRING ('  WM      LMD    LMQ    LSD    LSQ')
NEWLINE;SPACES(5)
PRINT(M(0),3,1);%CYCLE J=1,1,4;PRINT(M(J),1,3);%REPEAT
NEWLINE;SPACES(5)
PRINT STRING ('   RSD    RSQ     RD      RQ      RP')
NEWLINE;SPACES(5)
%CYCLE J=5,1,8;PRINT(M(J),1,3);%REPEAT;PRINT(M(9),5,0);M(10)=M(9)/2
NEWLINE;SPACES(5)
PRINT STRING ('  PHIO     FC     RC  CYCLES  DD     IC')
NEWLINE;SPACES(5)
%CYCLE J=0,1,5;PRINT(A(J),5,0);%REPEAT
NEWLINE;SPACES(5)
PRINT STRING ('   IFR    IMD    IMQ    ISD    ISQ    IUC')
NEWLINE;SPACES(5)
%CYCLE J=0,1,4;PRINT(I(J),3,1);%REPEAT;PRINT(I(10),3,1)
SELECTINPUT (22)
                      JC=0;    LA=0;    LB=0;    LC=0;    LD=0
%CYCLE JA=1,1,6
                 %CYCLE JB=0,1,6
READ(X);%CYCLE J=1,1,10;READ(V(J));READ(I(J));%REPEAT
->K1 %IF JB=6
              V(0)=(V(7)+V(8)+V(9))/3
G(JC)=I(7);LA=G(JC) %IF G(JC)>LA;LB=G(JC) %IF G(JC)<LB
H(JC)=V(7)-V(0);LC=H(JC) %IF H(JC)>LC;LD=H(JC) %IF H(JC)<LD
                JC=JC+1
K1:             %REPEAT
%REPEAT
LA=-LB  %IF  -LB>LA;        LC=-LD  %IF  -LD>LC
%IF  LA<0.1  %OR  LC<0.1  %THEN  ->K2
      LB=30/LA;       LD=30/LC
NEWLINE;PRINT STRING ('     MAX.  IR  ')
PRINT STRING ('(30 DIVISIONS)  =');PRINT(LA,3,1);PRINT STRING ('    X
NEWLINES(2);PRINT STRING ('     MAX.  VR  ')
PRINT STRING ('(30 DIVISIONS)  =');PRINT(LC,3,1);PRINT STRING ('    +
NEWLINES(2);PRINT STRING ('     0')
%CYCLE J=1,1,6;PRINT STRING ('     I     0');%REPEAT
%CYCLE J=0,1,35;NEWLINE;PRINT(J*10,3,0)
                 JG=INT (G(J)*LB);  JH=INT (H(J)*LD)
             %IF JG>JH  %THEN SPACES(30+JH) %AND PRINT STRING ('+') %
      %AND SPACES(JG-JH-1) %AND PRINT STRING ('X') %AND ->K3
        %IF JG<JH %THEN SPACES(30+JG) %AND PRINT STRING ('X') %C
    %AND SPACES(JH-JG-1) %AND PRINT STRING ('+') %C
     %ELSE SPACES(30+JG) %AND PRINT STRING ('*')
K3:%REPEAT
  NEWLINE;PRINT STRING ('     0')
      %CYCLE J=1,1,6;PRINT STRING ('     I     0');%REPEAT
K2: %ENDOFPROGRAM
```

APPENDIX D

Salient Pole Machine Calculations

Suitable values for IFR and PHIO for the computer simulation of both the cylindrical and the salient-pole machine were calculated from standard synchronous machine theory[45], based on the laboratory machine ratings. Sinusoidal waveforms are assumed in the calculations presented.

The phasor diagram for a synchronous machine operating at 50 Hz, with a phase voltage of 100 volts and phase current 8 amps is shown in figure A.3. A commutation safety angle of 20^o is considered suitable, so the phase current leads the phase voltage by 20^o. From the phasor diagram

$$V \text{ Sin } \delta = I \text{ Cos } (20^o + \delta) \,.\, \omega \,.\, LMD$$

and $$V \text{ Cos } \delta = E - I \text{ Sin } (20^o + \delta) \,.\, \omega \,.\, LMQ$$

In the computer simulation LMQ = LMD = 0.06 H for the cylindrical machine, while LMQ = 0.06 H and LMD = 0.03 H for the salient pole machine. Since the machine in the computer model is delta connected, and the laboratory machine is star connected, the computer parameters LMD and LMQ are divided by a factor of 3 in the analysis of the laboratory system.

Thus, for the cylindrical machine,

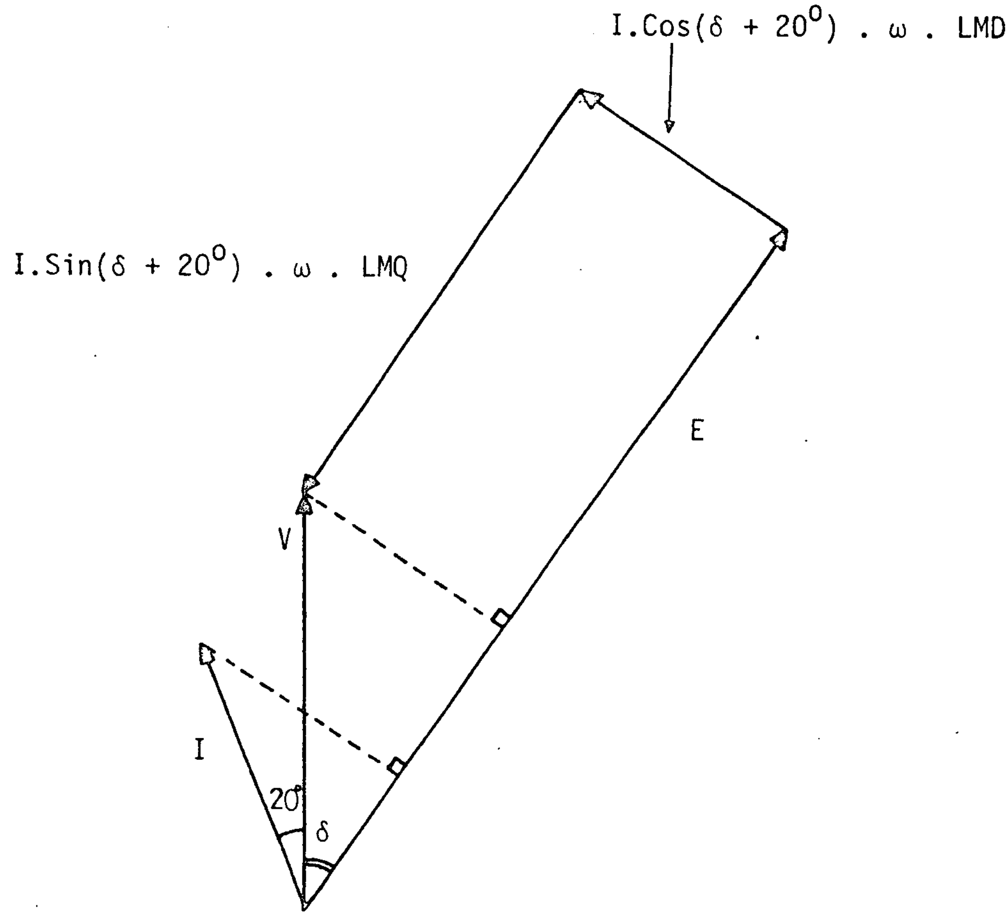


Figure A3 Equivalent Circuit for a Salient-Pole Synchronous Machine

$$100 \sin\delta = 8 \times \cos(20^{o} + \delta) \times 100 \times \pi \times 0.02 \quad (1)$$

and $$100 \cos\delta = E - 8 \times \sin(20^{o} + \delta) \times 100 \times \pi \times 0.02 \quad (2)$$

Solving equations (1) and (2), $\delta = 21^{o}$ and E = 126 volts. IFR, the field current is calculated by

$$IFR = \frac{E}{2 \times \pi \times 50 \times LMQ}$$

$$= 20.7 \text{ amps}$$

PHIO is defined by

$$PHIO = -(120^{o} + \delta)$$

so $$PHIO = -141^{\circ}$$

In the salient-pole machine

$$100 \sin\delta = 8 \times \cos(20^{o} + \delta) \times 100 \times \pi \times 0.01 \quad (3)$$

and $$100 \cos\delta = E - 8 \times \sin(20^{o} + \delta) \times 100 \times \pi \times 0.02 \quad (4)$$

Solving equations (3) and (4), $\delta = 12^{o}$ and E' = 124 volts. Therefore,

$$IFR = \frac{124}{2 \times \pi \times 100 \times 0.02}$$

$$= 19.7 \text{ amps}$$

and PHIO = -132°

These values were then substituted into the program in Section 5.2.2.

REFERENCES

1. R Langlois-Berthelot : "Electro-Magnetic Machines".

2. T J Hammons, J Loughran : "Starting Methods for Generator/Motor Units Employed in Pumped-Storage Stations", Proc IEE, Vol 117, No 9, pp 1829-40, (Sept 1970).

3. C H Mock : "Electrical Features of Raccoon Mountain Pumped Storage Scheme", Trans IEEE, PAS, pp 1875-80, (1972).

4. IEEE Committee Report : "Survey of Pumped-Storage Projects in the United States and Canada to 1975", Trans IEEE, Vol PAS-95, No 3, pp 851-8, (May/June 1976).

5. T J Hammons, J Loughran : Discussion on "Starting Methods for Generator/Motor Units Employed in Pumped-Storage Stations", Proc IEE, Vol 118, No 10, pp 1475-85, (Oct 1971).

6. C P Grant : "A Static Converter for Starting a Synchronous Machine", Student's Report on Fourth Year Project, Ref HSP/186, University of Edinburgh, 1976.

7. C Lehuen, G Ruelle and D Simonnot : "Asynchronous Starting of Motor-Generators of Pumped-Storage Stations. Development of the Water Tank Rotor", CIGRE International Conference on Large High Tension Electric Systems, (Aug/Sept 1972).

8. T Petersson : "Converter Starting of Pumped-Storage Units", IEE Power Division Colloquium on Inverter-Fed Synchronous Machines, (May 1977).

9. T Petersson, K Frank : "Starting of Large Synchronous Motor Using Stating Frequency Converter", Trans IEEE, Vol PAS-91, No 1, pp 172-9, (1971).

10. : "Synchronous Starting of Pump Motor by Static Frequency Converter", Water Power, (March 1970), pp 108-9.

11. B J Chalmers, R Bruce : "Battery-Fed Traction Drive with Force-Commutated Voltage Source Inverter Supply to a Synchronous Machine", IEE Power Division Colloquium on Inverter-Fed Synchronous Machine, (May 1977).

12. K W J Bishop : "Application of Variable Frequency A.C. Drives", IEE Conference on Power Electronics - Power Semiconductors and Their Applications, London, pp 85-7, (Sept 1977).

13. R L Hodkinson, J Mills : "High Power Transistor Inverters for A.C. Drives", IEE Conference on Power Electronics - Power Semiconductors and Their Applications, London, pp 41-4, (Sept 1977).

14. E H Wakefield : "An A.C. Drive Electric Vehicle", Trans IEEE, Vol 1A-10, No 5, pp 544-52, (Sept/Oct 1974).

15. B D McLeod, A Renfrew and J Shepherd : "An Inverter Drive Suitable for Traction", IEE Conference on Power Electronics - Power Semiconductors and Their Applications, London, pp 51-56,(Dec 1974).

16. G R Slemon, S B Dewan and J W A Wilson : "Synchronous Motor Drive with Current-Source Inverter", Trans IEEE, Vol 1A-10, No 3, pp 412-6, (May/June 1974).

17. N Sato : "Characteristics of SCR Three-Phase Improved Bridge Inverter", Electrical Engineering in Japan, Vol 84, No 5, pp 30-41, (May 1964).

18. S Nonaka, H Okada : "Three-Phase SCR Inverter Using a New Commutation Method", Electrical Engineering in Japan, Vol 86, No 7, pp 22-33, (July 1966).

19. S Hayashi, S Toyoda and J Wakabayashi : "Analysis of a Three-Phase Static Inverter Circuit with Rectifiers", Electrical Engineering in Japan, Vol 88, No 12, pp 79-88, (1968).

20. A Renfrew : "An Inverter Drive for Tractions and Industrial Applications", PhD Thesis, University of Edinburgh, (1975).

21. T A Lipo, F G Turnbull : "Analysis and Comparison of Two Types of Square-Wave Inverter Drives", Trans IEEE, Vol 1A-11, No 2, pp 137-147, (March/April 1975).

22. D W Miller, R G Lawrence : "Variable Frequency Inverter and its Application to Motor Drives", Electronics and Power, pp 675-8, (Oct 1976).

23. M K Blumenthall : "Current-Source Inverter Drive System with Low Speed Pulse Operation IEE Conference on Power Electronics - Power Semiconductors and their Applications, London, pp 88-91, (Sept 1977).

24. R W Stokes : "High Voltage, High Power Transistor Inverters", IEE Conference on Power Electronics - Power Semiconductors and their Applications, London, pp 37-40, (Sept 1977).

25. H Foch, B Trannoy and J Roux : "Three Phase Inverter Using Power Transistors. Application as an Induction Motor Feed", IEE Conference on Power Electronics - Power Semiconductors and their Applications London, pp 50-3, (Sept 1977).

26. T Sueoko, S Ishibashi, H Udagawa, A Honda and Y Yamaguchi : "High Power Gate Controlled Thyristors", IEE Conference on Power Electronics - Power Semiconductors and their Applications London, pp 1-4, (September 1977).

27. E Alexanderson, A Mittag : "The Thyratron Motor", Electrical Engineering (AIEE), pp 1517-23, (Nov 1934).

28. U Putz : "The Converter-Fed Brushless Synchronous Motor", IEE Conference on Power Electronics - Power Semiconductors and their Applications London, pp 71-76 (Dec 1974).

29. S Miyairi, Y Tsunehiro : "Analysis and the Characteristics of a Commutatorless Motor as a D.C. Motor", Electrical Engineering in Japan, Vol 85, No 9, pp 51-62, (1965).

30. H Gaede : "A New Brushless D.C. Drive for Industrial Power Ranges and Applications", IEE Conference on Electrical Variable Speed Drives, London, pp 132-6, (Oct 1972).

31. J M de Rubinat, A Rochet : "Thyristor Naturally Commutated Converters for Variable Speed Drives with High Power A.C. Machines", IEE Conference on Power Electronics - Power Semiconductors and their Applications, London, pp 160-3, (Dec 1974).

32. A C Williamson, N A H Issa and A R A M Makky : "Variable-Speed Inverter Fed Synchronous Motor Employing Natural Commutation", Proc IEE, Vol 125, No 2, pp 113-20, (Feb 1978).

33. B J Chalmers, K Pacey and J P Gibson : "Brushless D.C. Traction Drive", Proc IEE, Vol 122, No 7, pp 733-8, (July 1975).

34. N Sato : "Characteristics of Three-Phase Bridge Inverter with Feedback Rectifiers and Turn-Off SCR", Electrical Engineering in Japan, (Feb 1965).

35. K R Jardan : " Modes of Operation of 3-Phase Inverters", Trans IEEE, Vol IGA-5, No 6, pp 680-5, (Nov/Dec 1969).

36. D H Walker : "A Shaft Position Sensor for use with Thyristor Control", Student's Report on Third Year Project, Ref 3.P.57, University of Edinburgh, 1972.

37. N V Hurley, H R Bolton : "A Novel Current-Source Inverter for the Supply of a Brushless D.C. Machine", IEE Conference on Power Electronics - Power Semiconductors and their Applications, London, pp 54-7, (Sept 1977).

38. G R Slemon, J B Forsythe and S B Dewan : "Controlled-Power-Angle Synchronous Motor Inverter Drive System", Conf Record of 5th Annual IGA Group IEEE Meeting, Chicago, pp 663-7, (Oct 1970).

39. D E Macpherson, H W Whittington : "Zero Current Detection in Thyristor Circuits", IEE Conference on Power Electronics Power Semiconductors and their Applications, London, pp 26-8, (Sept 1977).

40. R P Kerr : "An Inverter Driven Synchronous Motor", Student's Report on Fourth Year Project, Ref HSP 22 University of Edinburgh, 1978.

41. J Edgar : "Regenerative Control of a d.c. Machine", Student's Report on Fourth Year Project, Ref HSP 18 University of Edinburgh, 1976.

42. B D Bedford, R G Hoft : "Principles of Inverter Circuits John Wiley and Sons, New York, 1st Ed, (1964).

43. : "Driver and Controller Modules Thyristor Applications", Westinghouse Product Informatio Booklet.

44. J A Lee : "An Inverter-Synchronous Machin Drive", Student's Report on Fourth Year Project, Ref HSP 17 University of Edinburgh, 1975.

45. M G Say : "Alternating Current Machines", Pitman Publishing Ltd, 1st Ed, (1976), pp 381-5.