PERFORMANCE EVALUATION OF INDUCTION MOTOR UNDER STATOR VOLTAGE CONTROL

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power Apparatus and Electric Drives)

By

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CANDIDATE DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "Performance Evaluation of Induction Motor under stator voltage control" in partial fulfilment of the requirement for the degree of Master of Engineering in Electrical Engineering (Power apparatus & Electrical Drives) submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee is an authentic record of my own work carried out during a period of 19 months from April 87 to Oct. 88 under the supervision of Dr. S. P. Gupta, Reader Electrical Engg. Deptt. U.O.R. Roorkee & Dr. B. N. Sarkar, Prof. & Head of Electrical Engineering Deptt. Institute of Engineering & Technology, Lucknow.

The matter embodied in this dissertation has not been submitted for the award of any other degree or Diploma.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The application of thyristor to induction motor speed control has resulted in a number of unconventional supply systems. One such technique, which has been successfully employed in a number of applications, variable voltage control by means of symmetrically triggered thyristor in the stator phases.

The present work deals with fabrication of a three phase a.c. regulator with antiparallel SCRs in each phase triggered by appropriate analog control circuit in open loop mode. Experimental investigation of regulator performance has been carried out. The waveforms of voltage and current at regulator output are recorded with resistive and induction motor load under (a) Delta connection (b) Star connection with isolated neutral and (c) Star connection with neutral connected to supply neutral. The nautre of these waveforms are explained through qualitative graphical analysis. Load tests on the induction motor under stator voltage control have been carried out with a d.c. generator type of load. Performance of the motor under thyristor control is evaluated and compared with that under variac control.

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CHAPTER - I

INTRODUCTION

1. INDUCTION MOTOR DRIVE :

There are many industrial applications where variable speed drives of electrical machines are needed. The requirement can be met either by d.c. or by a.c. machines. The speed of a d.c. machine can be varied by controlling the armature voltage through a phase-controlled rectifier, or by a d.c.-d.c. converter if the input power supply is d.c. In a d.c. machine, the torque is related to the product of field flux and d.c. armature mmf which remain stationary in space. In an a.c. machine, a three-phase a.c. power supply produces a rotating magnetic field in the airgap which reacts with the rotor mmf wave to develop the torque. The rotor mmf in a synchronous machine is created by a separate field winding which carries d.c. current, whereas in an induction motor it is created by the stator induction effect. The speed of an a.c. machine is related to stator supply frequency which produces the synchronously rotating magnetic field. If the frequency is increased to increase speed of the machine, the magnitude of air-gap flux is reduced due to increased magnetizing reactance, and correspondingly the developed torque is reduced. For this reason, an a.c. machine normally requires variable-voltage variable-frequency power supply for speed control. This type of power supply can be obtained by a d.c. link converter system which consists of a rectifier followed by an inverter, or by a cyclconverter. The machine can be excited by a current source instead of a voltage source. The current source operation has several advantages but somewhat complicates the machine operation. Since the voltage or current waves are fabricated by solid state switches of a converter, the harmonics associated with the waves cause problems of harmonic heating and torque pulsation. The converter which supplies power to the machine is expensive, and is designed with a limited peak power rating which may be substantially less than that of the machine. This influences the machine performance with the utility supply. An ideal voltage-fed invertor should offer zero thevinin impedance at the machine terminal, and similarly an ideal current-fed invertor should have infinite Thevinin impedance. Such conditions are difficult to meet in practice because of cost considerations. The finite source impedance can be shown to have an effect on the harmonic performance and stability condition of the drive system.

The speed of an induction motor is given by

$$N_r = N_s(1-s) \qquad ..(1.1)$$

where

$$N_s = \frac{120\ F}{p} \qquad ..(1.2)$$

S = Slip of the rotor,

P = Nos of pole.

Thus speed can be varied by variation of slip or supply frequency F, or nos of magnetic pole P.

Speed control by pole changing method are not much used in practice. Speed control by variation of frequency need an inverter or a cycloconvertor.

1.1 Cycloconvertor Drive :

A cycloconverter converts a.c. line power from one frequency to that in another frequency through a one step conversion process. The cycloconvertor can be used in the stator circuit of an induction motor or in the rotor circuit if wound rotor machine is used. The latter is known as static Scherbius drive. The cycloconvertor drives are normally used in very large horsepower applications. The cost and complexity of power and control circuits make them uncompetitive with other classes of drives in general applications.

1.2 Voltage-Fed Inverter Drive :

The voltage-fed inverters are generally classified into two types : Square - wave inverter and pulse - width modulated (PWM) inverter. In square - wave inverter a three-phase bridge restifier converts a.c. to variable - voltage d.c., which is impressed at the input of a force-commutated bridge inverter. The inverter generates a variable - voltage variable - frequency power supply to control the speed of the motor. The inverter is called voltage-fed because a large filter capacitor provides a stiff voltage supply to the inverter and the inverter output voltage are not affected by the nature of the load. The voltage-fed square-wave drives are normally used in low to medium hourse power industrial application.

1.3 PWM Inverter Drive :

In this method, the thyristors are switched on and off many times within a half cycle to generate a variable-voltage output which is normally low in harmonic content. Though in this method machine harmonic losses are improved significantly, the inverter efficiency is some what lessened because of many commutotions per half cycle. It need a uncontrolled rectifier, and a bridge inverter, is a costly and complex process.

1.4 Current-Fed Inverter Drive :

A current-fed inverter likes to see a stiff d.c. current source (ideally infinite Thevinin inductance) as opposed to a voltage-fed (ideally zero Thevinin impedance) inverter. In this a phase-controlled rectifier generates variable d.c. voltage which is converted to a current source by connecting a large inductor in series.

Since the induction motor constitutes a lagging power factor load, the thyristor of the inverter need forced commutation. Though regeneration process is simple and no additional component is needed in the power circuit, the current-fed inverter drive has several limitations. The frequency range of the inverter is somewhat lower and it cannot operate at no load, i.e. some minimum load current is required to satisfactorily commutate the inverter. The large size of the d.c. link inductance and the commutation capacitor make the inverter some what bulky and expensive.

1.5 Static Kramer Drive :

This class of drives requires a wound rotor induction motor. The inefficiency of the drive system because of large slip power dissipation can be over come by the static kramer drive. In this scheme, the - slip power of the rotor is rectified by a diode rectifier and is than pumped back to the a.c. line through a line commutated inverter. In this method regeneration and speed reversal are not possible. The static Krammer drives are used in large horsepower pump and blower type application where limited range of speed control is required.

1.6 Static Scherbius Drive :

In the static Kramer drive, the diode rectifier can be replaced by a thyristor bridge permitting slip power to flow in either direction. The speed of such a doubly-fed machine can then be controlled in both subsynchronous and super synchronous region. If the slip power is fed back to the line, the machine will operate in the subsynchronous region and the mode of operation will correspond to static Kramer drive. If, on the other hand, the slippower is pumped in the rotor by reversal of rectifier and inverter operation, the motor will operate in the super-synchronous region. The static Scherbius drive is used in very high horsepower pump and blower type applications.

1.7 Stator Voltage Controlled Drive :

This is a simplest and cheapest method of speed control of a cage type induction motor. The stator voltage can be controlled by connecting variable external impedances between the stator terminals and the a.c. supply mains. Saturable reactors have been used in the past to perform this function, but thyristor circuits now offer several advantage. The thyristor unit is more compact, despite the heat-sink requirements and it weights considerably less. It also has higher efficiency, and the response time is half cycle of the supply frequency, compared with a time lag of 0.1 seoond or more for a saturable reactor circuit. In addition thyristor units from different manufacturers are interchangeble, whereas saturable reactor characteristic vary considerably. Stator voltage control can be achieved in two way, half wave control or full wave control. The performance of the machine under half wave control has not been found very encourageous due to poor performance of the machine. Therefore fully controlled supply voltage at line frequency by symmetrically controlling the trigger angles of three-phase line commutated antiparallel thyristor is the subject matter of this dissertation work. It is used in low to medium power applications, especially with pump or blower type loads, where the torque is low at starting but increases typically as the square of the speed.

1.8 Literature Review :

Illango and Ramamoorty [11] developed Mathematical model of stator voltage control using state space techniques.

Kenly and Bose [13] described speed control of a three phase squirrel cage induction motor by employing triacs in the lines which operates in the normal phase control mode. The closed loop speed regulation of the system is investigated by them through digital phased - locked loop scheme.

Lipo [16] made a theoretical analysis on state variable approach supplemented by experimental varification of a three phase induction motor with voltage controlled by symmetrically triggered thyristor.

Paice [17] made a study of several schemes of stator voltage control and observed that a six thyristor power circuit in conju-ction with a wye-connected motor was most efficient.

Rahman and Shephered [18] made a thyristor and diode connected drive for a three phase induction motor. They found that the steady-state speed of a three phase induction machine can be controlled by variation of the terminal voltage using pairs of thyristors or thyristor-diode combination in the supply lines. The thyristor diode connection has an economic advantage but does result in greater copper losses owing to waveform distortion.

McMurray [21] made a comparative study of symmetrical three phase circuits for phase-controlled a.c. motor drives.

William Shephered, [22] described the analysis of the three-phase induction motor with voltage control by thyristor switching.

William Shephered [23] made steady state analysis of the series resistance inductance circuit controlled by silicon controlled.

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CHAPTER - II

STATOR VOLTAGE CONTROL

Stator Voltage Control is a simple and economical method of speed control of a cage type induction motor. In this scheme, the stator supply voltage is controlled at line frequency by symmetrically controlling the trigger angles of three phase, line commutated antiparallel thyristors as shown in Fig. 2.1. In low power application, triacs can be used giving further simplification to the power and control circuits. The stator voltage can be varied steplessly between zero and the full value within the trigger angle range $0 < \alpha < 180^{o}$, giving the circuit a ''solid-state variac'' characteristic, of course, the load and the supply lines carry rich harmonics at integral frequencies which are generated by the converter. If the machine is star-connected with isolated neutral the triplen harmonics are eliminated. The line side power factor is poorer than that with variac control because of the added harmonics and the additional reactive power taken by the converter due to phase control.

The motors with high slip (typically 10 to 12 percent) are used in this method of speed control which correspondingly causes higher copper loss in the machine. Fig. 2.2 explains the speed control characteristics of a blower type drive. As the stator voltage is reduced, the developed torque is reduced correspondingly, because the torque varies with square of voltage at fixed slip. The stable speed at different stator voltage is given

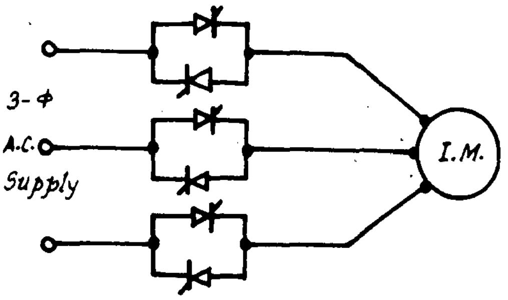


Fig.2.1.Induction motor speed control with phase-controlled A.C. power supply.

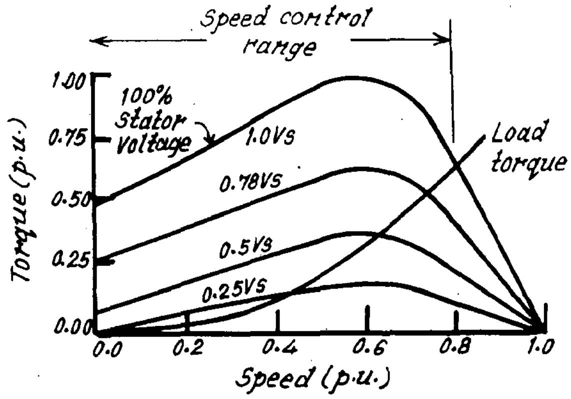


Fig.2.2.Torque-speed curves of induction motor with variable stator voltage.

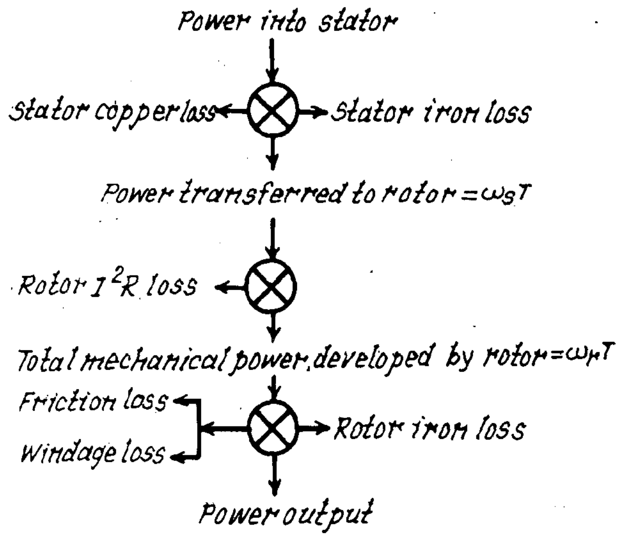


Fig.2.3. Induction motor power flow.

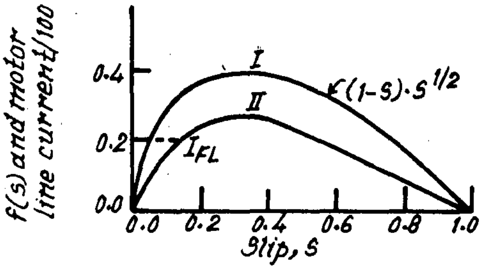


Fig.2.4.Theoretical line current (fan load).

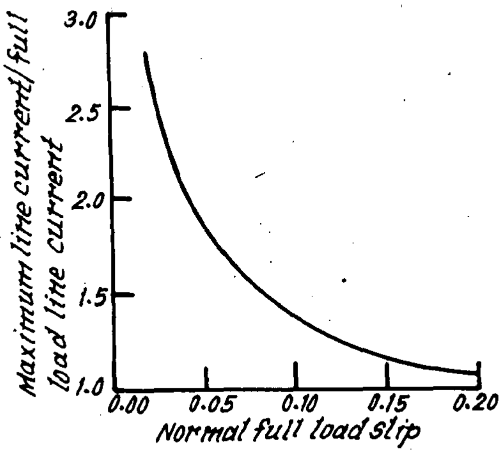


Fig.2.5.Peak line current vs. motor full load slip (fan load).

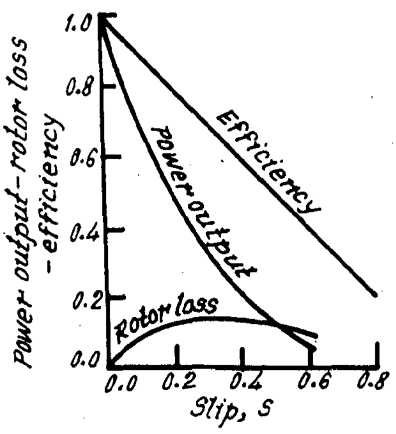


Fig.2.6.Fan motor performance.

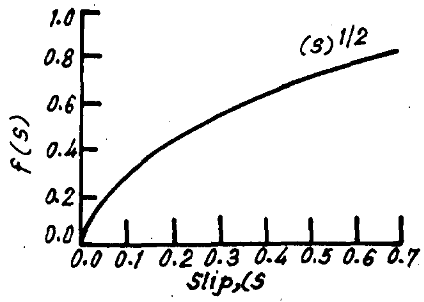


Fig.2.7.Motor line current (constant torque load).

by the point of intersection as shown in the figure. Evidently, the range of speed control will be diminished if the machine is designed with low slip.

2.1 THEORETICAL CONSIDERATIONS IN SPEED CONTROL :

A rotating magnetic field is set up by the voltage applied to the stator windings and the speed of rotation is uniquely determined by the number of poles and supply frequency such that

$$N_s = \frac{120\ f}{P}$$

where N_s is the synchronous speed in r/min; f is the frequency in Hz; and P is the number of ples. The rotating field induces currents in the squirrel cage rotor which interact with the field so as to produce a torque. This torque accelerates the rotor until finally the rotor revolves at some speed N_r, less than the synchronous speed N_s. Now the rotor requires a torque to satisfy the load torque and this same torque is experienced by the rotating magnetic field. Thus a situation occurs in which two rotating members experience the same torque but have a different speed. Therefore, a power difference exists between motor stator power input $\omega_s T$ and rotor output $\omega_r T$ where T is the common torque and ω_s and ω_r are the angular speeds of the air gap field and rotor, respectively. This power difference, called slip power, is fundamental to all induction motors and if the speed of a motor is controlled by varying the rotor speed ω_r, without varying the synchronous speed ω_s; the slip power must be recognised. In the case of cage motors, the slip power $(\omega_s-\omega_r)T$ is dissipated as heat in the rotor and it is seen immediately therefore that, even with sinusoidal voltages and currents, speed control of the cage motor fed from a fixed frequency supply is inevitably an inefficient process. Fig. 2.3 illustrates the power flow diagram for such a motor.

For simplicity, let us ignore magnetizing current required by the stator winding. Assuming sinusoidally varying quantities, the average torque produced by the stator field reacting with the rotor current is given by the following proportionality :

$$T_m \propto \frac{I^2R}{s}$$

where

T_m motor torque

R rotor resistance, assumed constant

I rotor current

s fractional slip.

If the load torque is related to the square of the motor speed as is approximately true for a fan load, we may write

$$T_L \propto (\text{rotor speed})^2 \propto (1-s)^2$$

where T_L is load torque.

Under steady state, motor and load torque are equal so

$$\frac{I^2R}{s} = (1-s)^2$$

or

$$I \propto \frac{(1-s)\sqrt{S}}{\sqrt{R}}$$

This proportionality indicates the input current will be maximum when s = 1/3 and also that the peak input current is inversely proportional to $\sqrt{\text{rotor resistance}}$.

A plot of $(1-s)\sqrt{s}$ is given in Fig. 2.4, which shows the nature of variation of motor current as speed is reduced. The peak value, occurring at $s = 1/3$, will be large if full load current IFL occurs at low slip (2 to 8%), as shown by curve I, whereas it will be low if full load current occurs at large slip, as in the case of motors having high resistance rotor (curve II).

Fig. 2.5 illustrates the increase to be expected in the line input current of fan motors controlled by varying the supply voltage. Using this curve it is seen for example that a motor with a normal full load slip of 12 percent will have a maximum input current about 25 percent greater than the normal full load current. Also note that the rotor and stator losses will increase by about 1.25^2 = 56 percent.

Fig. 2.6 has been drawn to illustrate the motor and fan performance as slip varies, and the efficiency curve represents the best that can be achieved since it only considers the rotor losses.

The way in which the input current will vary with slip when the load is basically constant torque can be determined by substituting $T_m = K$. In this case

$$I \propto \left(\frac{S}{R}\right)^{1/2}$$

As in the previous example, the input current is inversely proportional to $(\text{rotor resistance})^{1/2}$ but there is no maximum value as for the case of a fan load. The plot of $\sqrt{s}$ in Fig. 2.7 indicates how the input current may be expected to vary with slip for the constant torque load case.

The conclusions to be drawn from the foregoing theory can be summarized as follows. If the rotor resistance is substantially constant and the motor full load slip is low, then heating problem of the stator winding may be expected as the speed is reduced because of the large increase of input current. Practical solutions of this problem can be obtained by using machines with high resistance rotors, and hence high full load slip, or better still, special machines with variable resistance rotor characteristic can be employed.

The above conclusions have been drawn from a very simple theory based on sinusoidal voltages. The harmonics introduced by, for example, chopped sine wave control by thyristors are likely to degrade the motor performance further.

The consideration of high rotor resistance at low speeds has led to following options :

(a) Use a solid-iron rotor in which effective rotor resistance varies inversely with air gap voltage.

(b) Place a bar of permanent magnet material, such as Alnico, in the top of each rotor slot. The hysteresis loss in the Alnico causes an increase in the effective rotor resistance, thereby increasing the torque per ampere at low speeds and giving the motor a better torque speed characteristics.

(c) Use standard wound rotor induction motor. External rotor resistance is added to modify the torque/speed characteristic so that the torque per ampere at low speeds is increased. Motor heating is reduced, since part of the rotor circuit loss is now dissipated externally.

Speed control may also be obtained by deliberately unbalanceing the stator terminal voltages. By the theory of symmetrical components, the unbalanced three-phase voltages can be resolved into positive and negative-sequence systems. The positive-sequence set establishes balanced currents of the same sequence and these produce a forward-rotating field which develops forward rotor torque in the usual manner. The negative-sequence voltages produce negative-sequence currents which establish a backward-rotating field and develop a counter-torque opposing motion. The positive and negative-sequence currents both contribute to the motor heating, but the resultant torque is the difference between the positive and negative-sequence torques. The low speed performance is, therefore, even poorer than that obtained with symmetrical reduction of stator voltages, and further derating is necessary to limit the temperature rise.

When thyristor switching circuits are used to reduce the stator voltage, either symmetrically or asymmetrically, the resulting voltage and current waveform are highly distorted, and the additional harmonic losses will further accentuate the overheating problem at low speeds. An exact analysis of induction motor behaviour under such operating condition is rather difficult and requires an analogue simulation or a numerical solution on a digital computer.

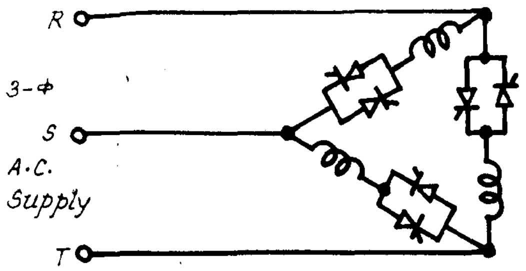


Fig.2.8. Stator voltage control of a Δ-connected induction motor using SCR's.

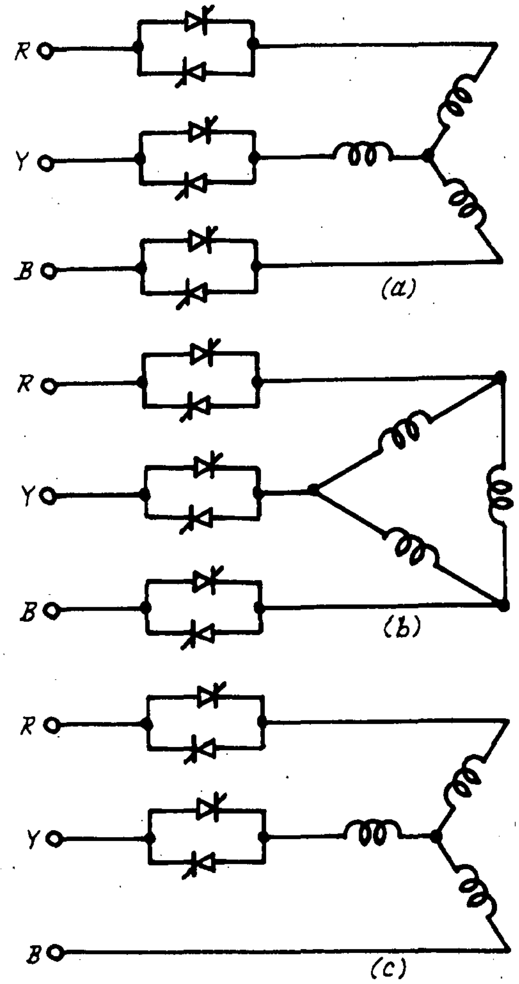


Fig.2.9. Alternative connections for stator voltage control.

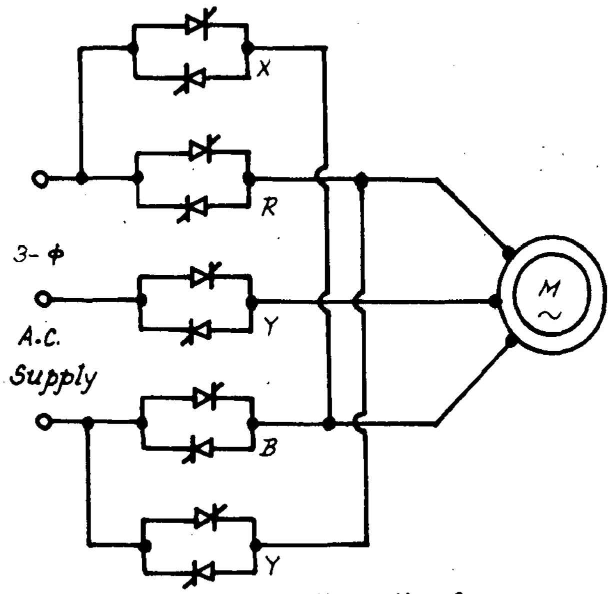


Fig.2.10. Thyristor configuration for a reversible variable speed of induction motor drive.

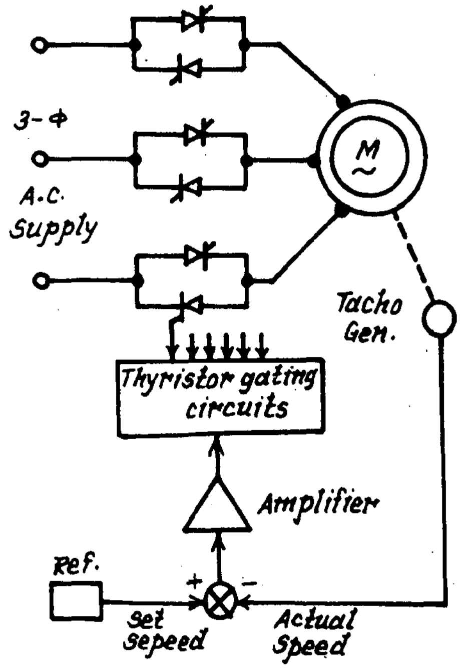


Fig. 2.11. Closed loop system for I.M. speed control by stator voltage control.

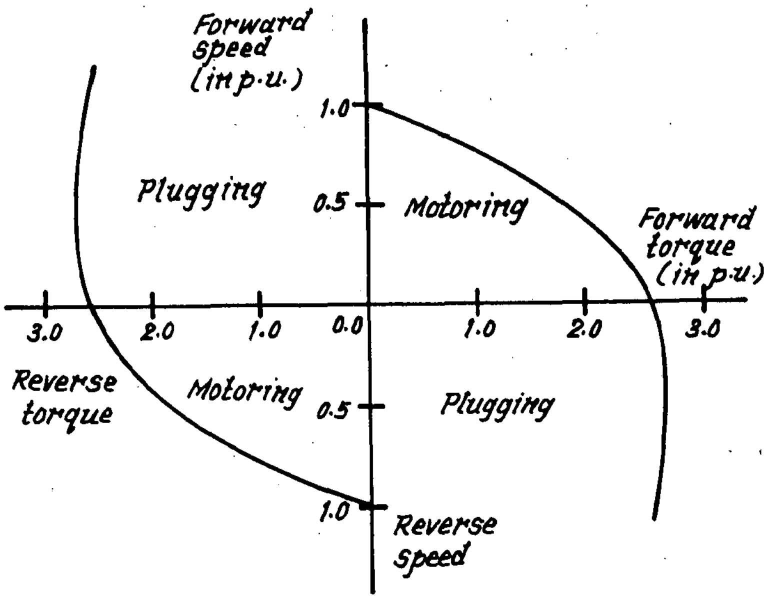


Fig.2.12. Speed-torque characteristics for reversible induction motor drive.

2.2 PRACTICAL CIRCUITS :

The effective load voltage in a single-phase a.c. circuit can be varied by a thyristor controller consisting of a pair of anti-parallel thyristors in series with the load. A three-phase version of this circuit is obtained by combining three single-phase circuits in a delta-connection, as in Fig. 2.8. Each pair of back-to-back thyristors controls the voltage delivered to one phase of the stator, and the phase voltage waveform consists of a series of sine-wave segments. A phase displacement of 120^o is maintained between the sets of gating pulses delivered to each controller in order to produce a symmetrical reduction of the three-phase voltages. In the full-voltage condition, each thyristor receives a gating signal at the start of the positive half-cycle of its anode-to-cathode voltage. The series thyristor pair is then virtually a short-circuit and the stator phase receives a complete cycle of supply voltage. As the thyristor firing is delayed, the conduction period of each thyristor is shortened and the effective stator voltage is reduced. When the firing delay is 180^o, the thyristor controller is open-circuited and the motor voltage and current are both zero. Using a switching device in this manner as a non-linear series impedance has the advantage that the power dissipation in the controller is considerably less than the load power, but the switching action also distorts the stator voltages.

Several alternative power circuits are possible. Thyristor controllers may be inserted in the three a.c. lines of a star or delta-connected load, as in Fig. 2.9(a) and (b). For economy, one thyristor in each back-to-back circuit can be replaced by a rectifier diode. The number of semiconductor devices can be reduced if it is decided to operate with unbalanced stator voltages. Back-to-back thyristors can be inserted in two of the three-phase lines, as in Fig. 2.9(c), with the third line connected directly to the supply. Alternatively, the motor can be operated with a thyristor controller in only one of the three-phase lines. However, these unbalanced circuits tend to accentuate the heating problem since some phases are heavily overloaded.

Speed control may be obtained by decreasing or unbalancing the stator voltages of the induction motor, but the direction of rotation can only be reversed by changing the phase sequence of the applied voltages. This is often achieved by means of a mechanical contactor which interchanges two stator leads. Contactor operation takes place after the stator current has been interrupted by removal of the thyristor gating pulses. Consequently, sparkless operation is obtained and the contactor requires little maintenance. However, the stator phase sequence can also be reversed statically by introducing additional thyristor controllers, as in Fig. 2.10. The extra units X and Y are not gated for normal forward rotation of the motor, but only come into operation when A and C are on open-circuit. This reverses the phase sequence of the applied voltages and thereby changes the direction of rotation. It is, of course, essential that X and Y should not be gated until the gating signals for A and C have been removed, or otherwise a short-circuit condition would result. A current detector in series with A and C inhibits firing of X and Y until a zero-current signal is obtained. Similarly, the triggering of A and C is inhibited until X and Y have been open-circuited.

Variable-speed drives using stator voltage control are normally closed-loop systems, as in Fig. 2.11. The d.c. tacho-generator develops a voltage proportional to the motor speed, and this is compared with the d.c. reference voltage representing the desired speed. The difference between the two signals is the error voltage which controls the thyristor firing angles and thereby alters the terminal voltage and motor speed so that the error is reduced. If the reference voltage is greater than the tacho -generator voltage, the conduction periods of the thyristors are increased. The increased stator voltage allows the development of an increased motor torque and hence the speed rises. If the tacho -generator voltage exceeds the reference voltage, the conduction periods are reduced and the motor torque decreases, causing a reduction in shaft speed. When the motor speed is equal to the desired speed, the conduction periods are just sufficient to allow the development of a motor torque equal to the load torque. In a high-gain feedback system, the desired speed can be accurately maintained and there is no necessity for the motor to have a flat speed-torque characteristic, since the output speed is determined by the reference signal rather than the open-loop characteristic of the motor. Stable operation may be obtained at any point of the induction motor speed-torque characteristic.

In the static reversing of Fig. 2.10, the polarity of the error signal determines whether motoring or braking torque is developed, and operation is possible in the speed-torque quadrants shown (Fig. 2.12). If the reference voltage is positive and exceeds the tacho -generator voltage, forward torque is produced by gating thyristor controllers A and C, and hence the motor accelerates. If the reference voltage is sudenly reduced, the polarity of the error signal changes, and thyristor units A and C and turned off and X and Y are gated on. This reverses the phase sequence of the stator voltage and the motor operates in the plugging region with a rapid reduction in speed. In a crane or hoist application, when the motor is lowering an overhauling load, the speed signal is also greater than the reference voltave, and a braking counter-torque is developed which permits steady-state lowering of the load. Regenerative braking in the induction generator region is possible for full-speed lowering of an overhauling load.

From foregoing discussion it may be inferred that stator voltage control is a feasible method of speed control for high rotor resistance motor. A six thyristor power control circuit in conjunction with a wye connected motor has been found to be the least demanding on motor windings and this type of control is best suited to fan type of loads.

2.3 MODES OF OPERATION :

When phase control is exercised using antiparallel groups of SCRs, as shown in Fig. 2.1, the SCRs have to be triggered in a sequence to obtain balanced phase currents. The firing angle must be same for all the phases. Fig. 2.13 shows the current waveforms

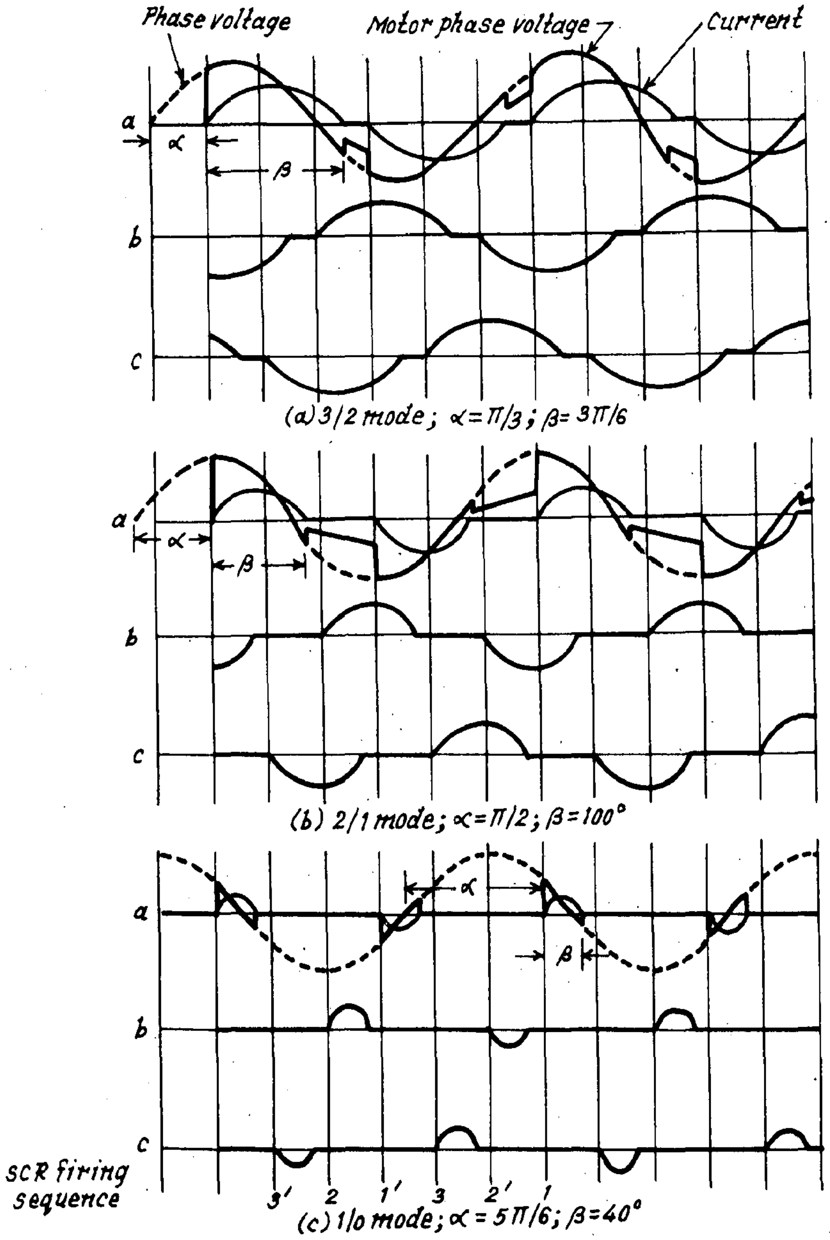


Fig.2.13. Modes of operation.

for three firing angles. It will be observed that the motor exhibits three different modes of operation. When the conduction angle β is more than $2\pi/3$, the number of SCRs conducting at any time will be either 3 or 2. This is called the 3/2 mode. The phases get open circuited for a very short time. If the conduction angle is between $\pi/2$ and $2\pi/3$, the number of SCRs that conduct at any one time will be 2 or 1. This is 2/1 mode. When angle β is less than $\pi/3$, only one SCR or none will conduct at any time. This is the 1/0 mode. The last two modes, i.e. 2/1 mode and the 1/0 mode, are possible only when the stator winding neutral is connected to the supply neutral. As long as the SCRs conduct, the corresponding phase voltage will be known. When the phase gets open circuited the corresponding voltage across the phase will be the induced voltage due to currents flowing in the other stator and rotor windings. The firing sequence of SCRs for all modes of operation will be 1,3', 2,1', 3 and 2'. The interval between successive firing will be $\pi/3$ and the firing frequency will be six times the input frequency. This will ensure that SCRS 1,2,3 are fired 120° away from one another and SCRs in each group (e.g. 1 - 1') have a phase difference of 180° in their firing angles.

The procedure for obtaining the steady-state current waveforms requires the solution of the motor differential equations; such equations are not the same for every mode of operation. Numerical techniques may be employed as suggested by Ilango and Ramamoorty.

**

CHAPTER - III

DEVELOPMENT OF FIRING SCHEME FOR A.C. REGULATOR

3.1 INTRODUCTION :

A simple firing scheme for realising the firing requirements of a three phase a.c. regulator is developed. It produces a set of six wide firing pulses spaced with respect to each other by 60°, which are suitable for firing thyristor 1 to 6 of three phase regulator. Further the firing angle control in 0° to 180° range is possible.

3.2 REQUIREMENT OF FIRING CIRCUIT :

The sequence of firing pulses may be understood from Fig. 3.1(a) which shows a three phase star connected resistive load fed from three phase regulator with neutral point N' connected to supply neutral N. Thyristor T_1 remains forward biased as long as phase voltage V_{RN} (or $V_{RN'}$) remains positive Fig.3.1(b). Thus it can be fired in 0° to 180° range in the positive half of the R-phase voltage, V_{RN}. Similarly thyristor T_4 may be fired in the negative half of V_{RN}.

For a given firing angle α, the firing pulses of T_4 are 180° away with respect to firing pulses of T_1. This applies to thyristor pairs T_3-T_6 and T_5-T_2 also.

Firing pulses of T_3 and T_5 are shifted by 120° and 240° respectively with respect to thyristor T_1. The firing pulses of all the thyristor for $\alpha = 60^\circ$ are shown on same time axix in Fig. 3.1(c).

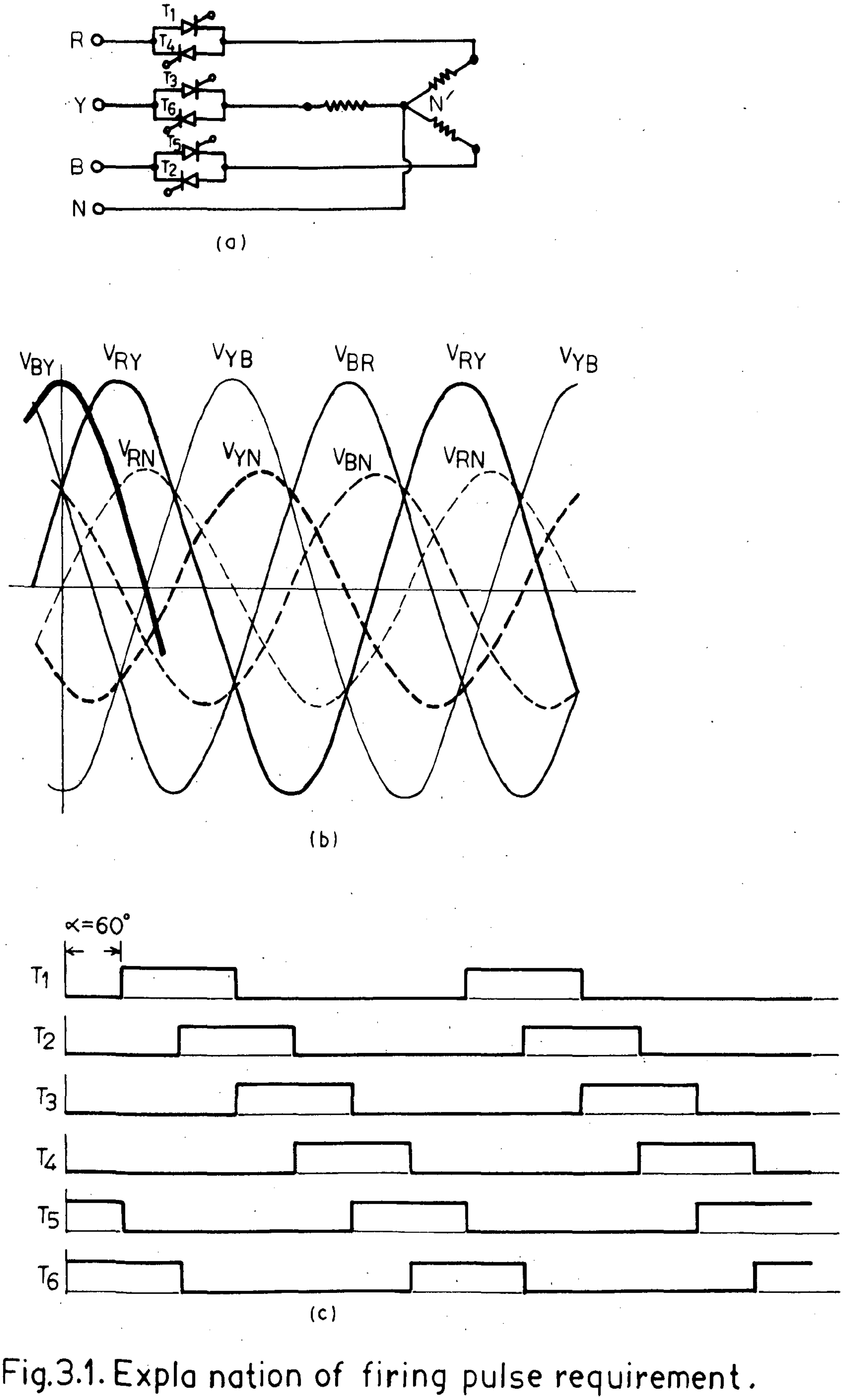


Fig.3.1. Expla nation of firing pulse requirement.

It is necessary to generate wide firing pulses to take care of inductive loads. The pulse width should not be less than 60^o and should not be more than 180^o. A pulse of less than 60^o width creats problem even on resistive loads at large firing angle (3) and a pulse width of more than 180^o will evidently result in firing at zero degree itself as adjusted firing angle approaches 180^o.

3.3 <u>REALISATION OF FIRING SCHEME</u> :

The firing requirement stated above is realised through a firing scheme shown in Fig. 3.2. The three phase supply is stepped down using three single phase centre taped transformers so that on secondry side voltages V_{RY}, V_{YR}, V_{YB}, V_{BY}, V_{BR}, V_{RB} are available with respect to common ground point, as shown. These voltage waveforms are shown in Fig. 3.1(b) from where it is noted that peak of V_{BY} coincides with zero crossing point of V_{RN} where positive cycle of V_{RN} begins. Each of these voltages is connected to inverting input pin of corresponding comparator after clipping the negative half cycle. Non inverting pins of all comparator are connected to adjustable control voltage E_c whose peak voltage is equal to the peak of secondry line voltage V_{RY} etc. The comparator, LM 324, compares the two inputs and provides an output as shown in Fig. 3.3(ii) for the case of 4th comparator which compares V_{BY} and E_c. The comparator output is connected to monostable chip 74121 which produces pulses of required width at rising edges of comparator output as shown in Fig. 3.3(iii). The pulse width is adjusted to a little more than 60^o (3.35 ms). These pulses decides

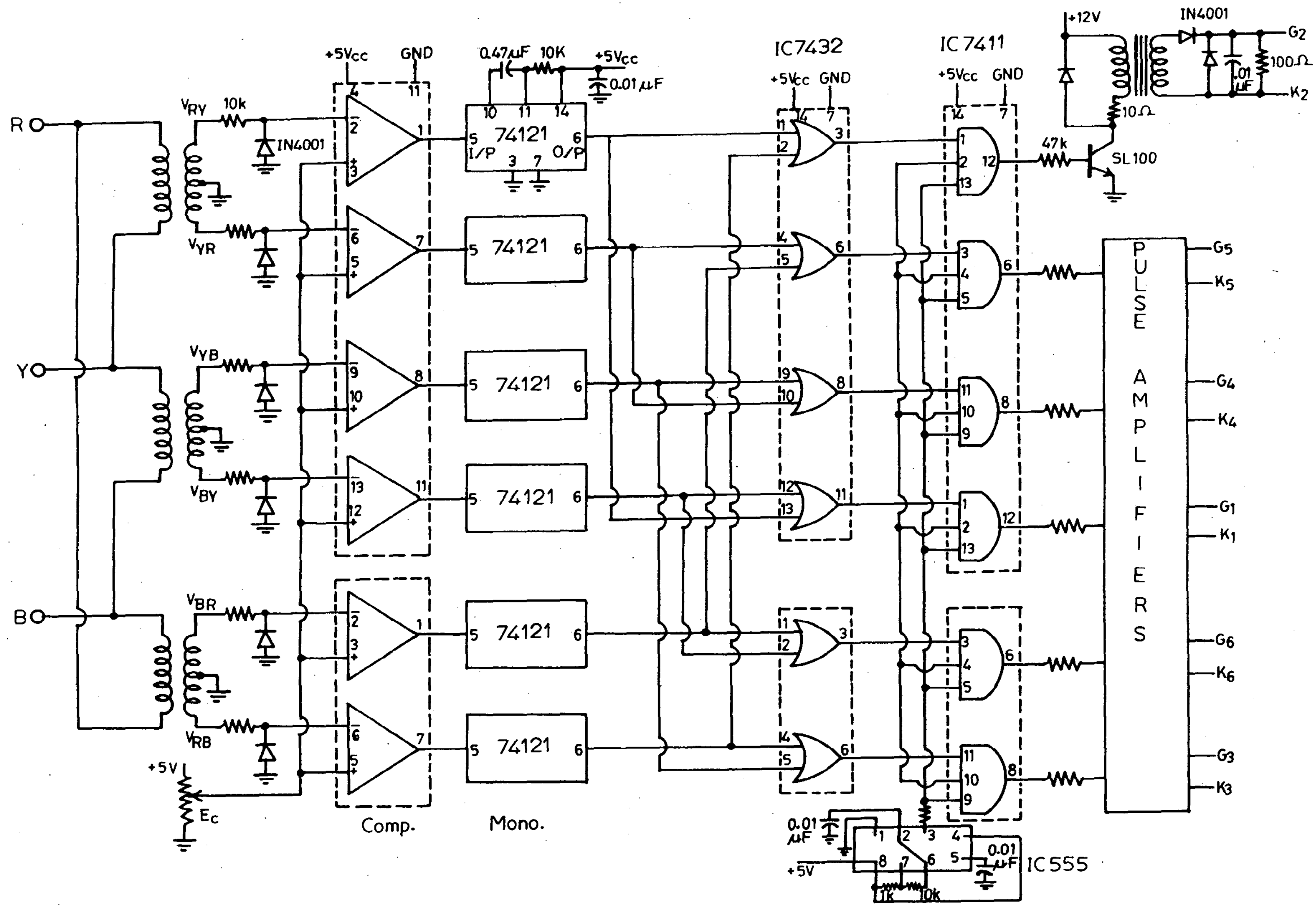


Fig. 3.2. Firing scheme diagram.

the firing angle. As is evident from Fig. 3.3(i) a variation of E_c from peak value to zero will produce firing angle for positive thyristor of phase R [Thyristor T_1, Fig. 3.1(a)] which vary from 0^o to 90^o. It can be shown, in asimilar manner that the first comparator will provide firing pulses for thyristor T_2, second will provide firing pulses for T_5, 3rd for T_4, 5th for T_6 and 6th for T_3 as indicated in Fig. 3.2. These pulses so obtained for thyristor T_1 to T_6 are phase shifted with respect to each other by 60^o as shown in Fig. 3.1(c). In order to further increase the pulse width the pulses of two successive thyristor are provided at the inputs of a 2-input OR gate. Thus increasing the pulse width to about 120^o as shown in Fig. 3.3(iv). The wide pulses are finally ANDED with high frequency pulses obtained from 555 oscillator Fig. 3.3(v) to enable transfering them across Isolation transformer. The last stage is pulse amplification and Isolation which is realised through transistor SL 100 and pulse transformers combination.

3.4 DESIGN OF FIRING CIRCUIT :

The firing circuit consists of three step down transformer, comparator, monoshots, OR gates, AND gates, oscillator and pulse amplifiers. The description of these component is as follows.

3.4.1 Step Down Transformers :

Three nos step down transformer $400\sqrt{2}$ V/10 V are being used. Input to these transformer is taken from same terminal from which the regulator is being fed to ensure the same phase sequence.

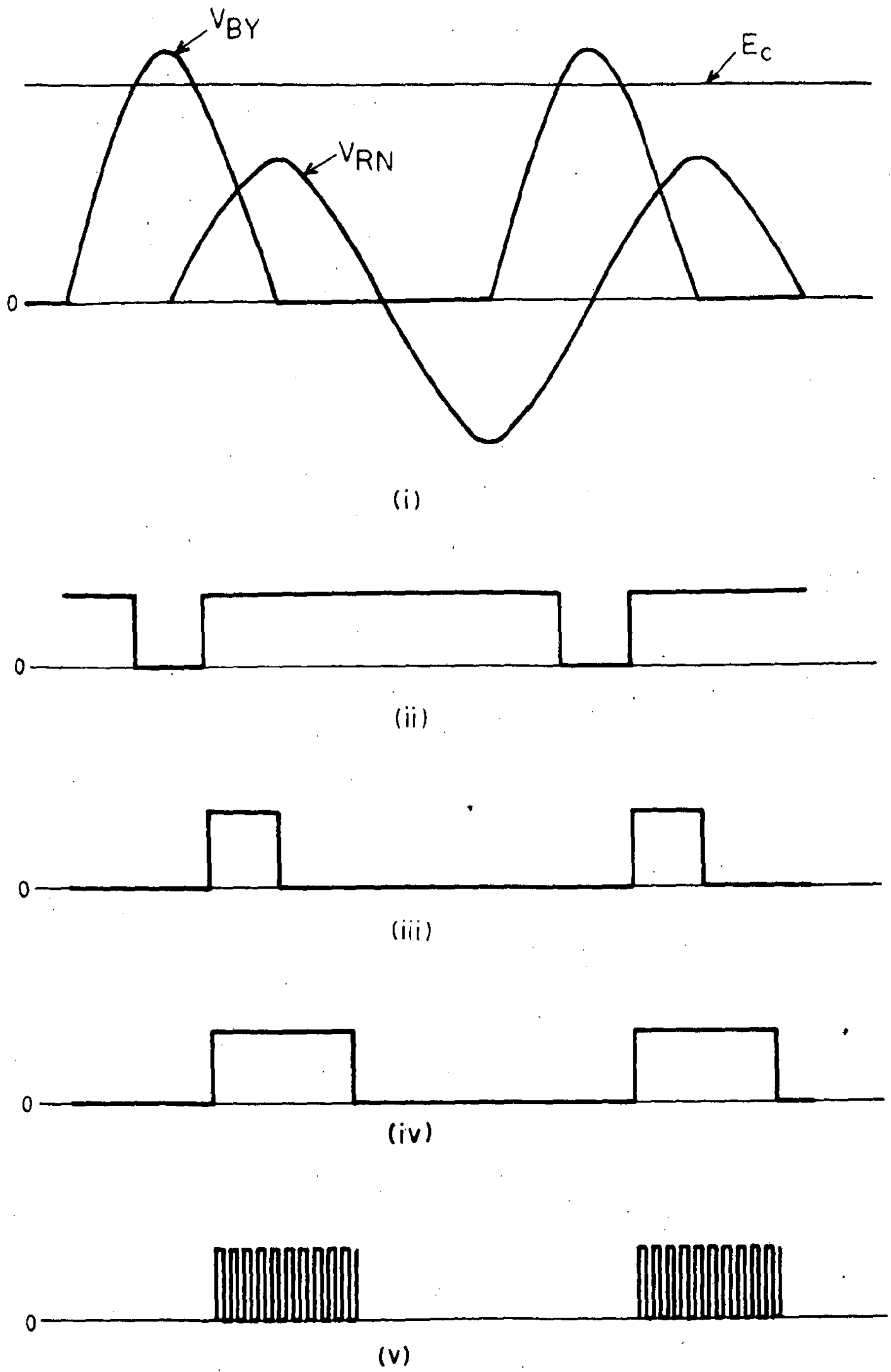


Fig. 3.3

3.4.2 Comparator :

IC LM 324 has been used as comparator. The pins detail are shown in Fig. 3.4. Each chip has four comparator and hence two such chips are being used to obtain required 6 comparator.

3.4.3 Monoshot :

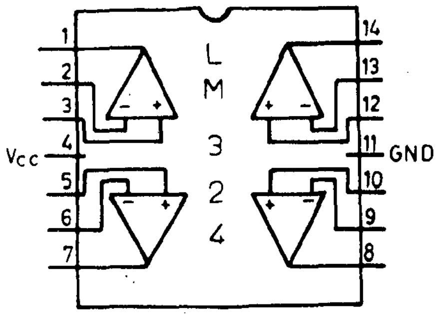
IC 74121 has been used as monoshot. Six such chips are required. The pin connection details and its functional table is shown in Fig. 3.4. The duration of the out pulse is determined by the timing resistor Rext connected between pin No. 14 and 11. The timing resistance Rext must be in the range of 1.4 K ohm to 40 K ohm. The maximum allowable value of timing capacitor is 1000 µF. The duration of the output pulse is given by TON = 0.7 R_{ext} C_{ext}. TON is selected as 3.32 m second (approx) so that reliable turning-on time for thyristor is assured.

$$\text{Hence } C_{ext}\, R_{ext} = \frac{3.32}{0.7} \text{ mS}$$
$$= 4.8 \text{ mS.}$$

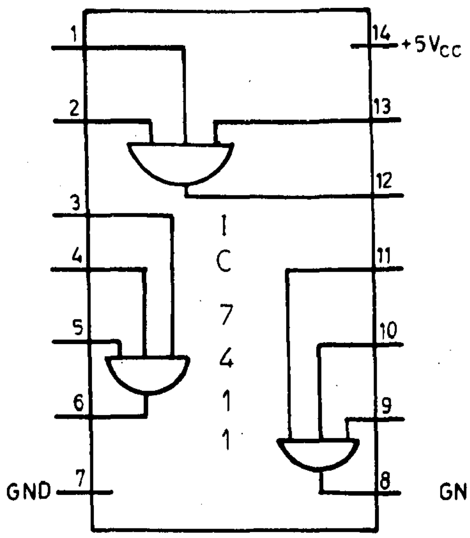
Therefore the values of R_{ext} and C_{ext} are selected as 10 K and 0.47 µF respectively.

3.4.4 OR Gate :

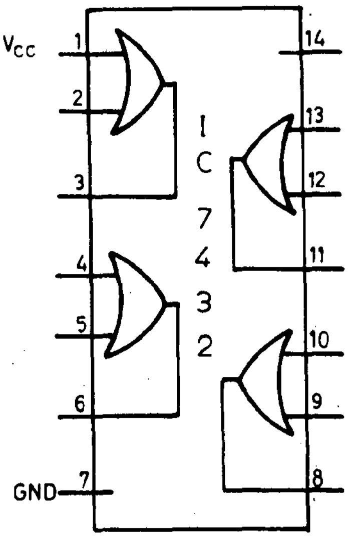
To further increase the pulse width IC 7432 has been used. Each chip has four, 2-Input OR gate. Two such chips are required. Pin details of this chips are also shown in Fig. 3.4.



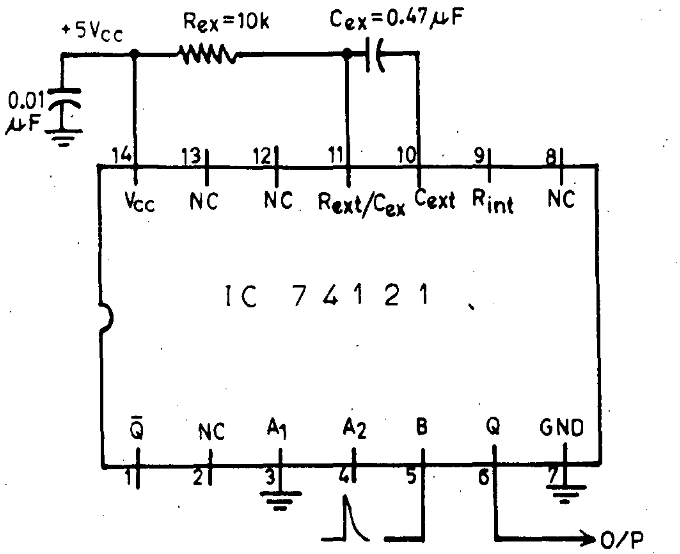
Comparator



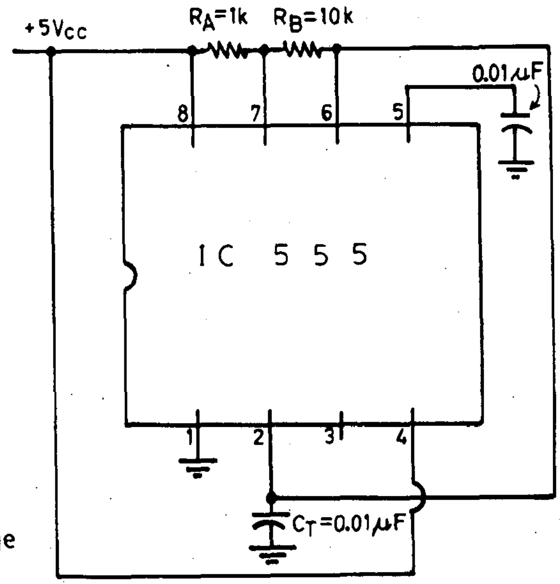
3-I/P AND Gate



2I/P OR Gate



Monostable operation of IC 74121 for rising edge



Astable operation of IC 555 timer

Functional Table for IC 74121				
Input			Output	
A_1	A_2	B	Q	$\bar{Q}$
L	X	H	L	H
X	L	H	L	H
X	X	L	L	H
H	H	X	L	H
H	↓	H	⊓	⊔
↓	H	H	⊓	⊔
↓	↓	H	⊓	⊔
L	X	↑	⊓	⊔
X	L	↑	⊓	⊔

NC— No internal connection
X — Irrelevent
↑ — Transition low to high
↓ — Transition high to low

Fig. 3.4. Pin details/connection diagram of different I.C.Chips.

3.4.5 AND Gate :

Two nos. of IC 7411 has been used in the firing circuit for ANDING the firing pulses with high frequency pulse in order to reduce gate losses. The pin details of these chip are also shown in Fig. 3.4.

3.4.6 Oscillator :

IC 555 has been used as anoscillator.The pin details and external connection of IC 555 are given in Fig. 3.4. The external capacitor C_T charges through R_A and R_B and discharges through R_B only. Thus the duty cycle may be set precisely by the ratio of these two resistors.

In free mode of operation the capacitor charges and discharges between $\frac{V_{CC}}{3}$ and $\frac{2}{3}$ V_{CC}. The charging and discharging time and hence, the frequency is independent of the supply voltage. The charging time (output high) is given by

$$t_1 = 0.693\ (R_A + R_B)\ C_T$$

The discharging time (output low) is given by

$$t_2 = 0.693\ R_B C_T$$

Thus the total time period is given by,

$$T = t_1 + t_2 = 0.693\ (R_A + 2\ R_B)\ C_T$$

Frequency of oscillation is therefore,

$$F = \frac{1}{T} = \frac{1.44}{(R_A+2R_B)C_T}$$

Taking $R_A = 1$ K, $R_B = 10$ K, and $C_T = 0.01$ µF.

The oscillator frequency is approximately 7 K Hz.

3.4.7 Pulse Amplifier :

The pulse output from AND gate may not be strong enough to turn ON thyristor, therefore, the output of AND gate is amplified through an amplifier as shown in Fig. 3.2. A transistor SL 100 is used for this purpose. The load resistance R_c is taken as 10 ohm. and base resistance R_{base} as 4.7 K to achieve the desired amplification. The gate and cathode terminals are at higher potentials of the power circuit, therefore the control circuit should not be directly connected to the power circuit. A pulse transformer is used for electrical Isolation between control circuit and power circuit. A diode IN 4001 is connected across R_C and pulse transformer primary winding to avoid the saturation of pulse transformer core. A diode IN 4001 is connected in series with secondry of pulse transformer to block the negative pulses. Gate should also be protected against over voltages. This is achieved by connecting a diode IN 4001 across gate to cathode [8].

A common problem encountered in the SCRs circuitry is spurious firing of the thyristor. Trigger pulses may be induced at the gates due to turn ON or turn OFF of a neighbouring SCRs in the power circuit. These undesirable pulses may turn ON the thyristor, thus causing improper operation of the circuit. The SCRs gates are protected against such spurious signals by connecting a capacitor (0.01 μF) and a resistance (100 ohm) across the gate to cathods to bypass the noise pulse.

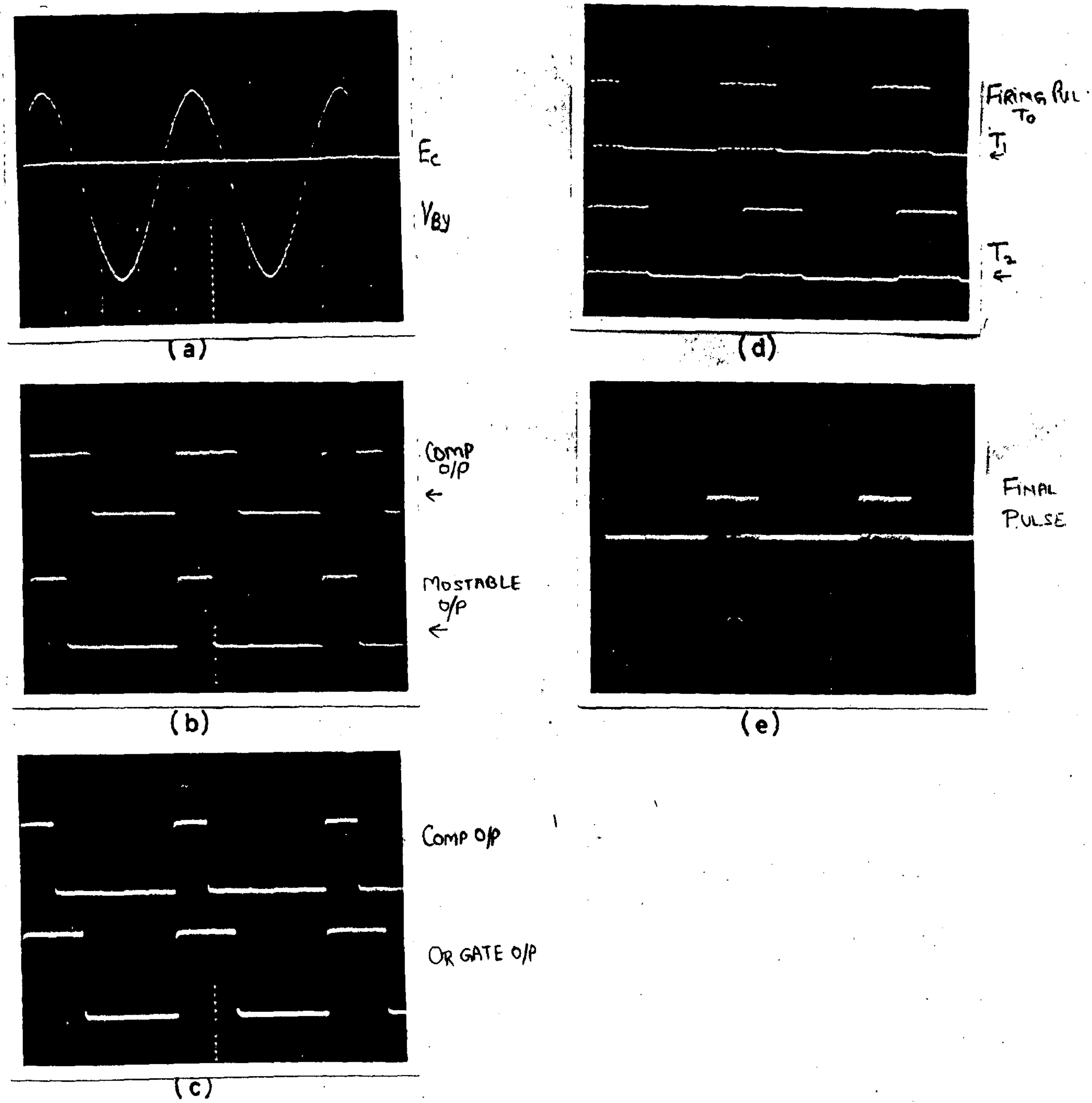


FIG. 3.5 : OSCILLOGRAM OF FIRING CIRCUIT.

3.5 OSCILLOGRAM OF THE FIRING CIRCUIT :

The oscillograms recorded at the outputs are shown in Fig. 3.5 (a to e). Fig 3.5(a) shows the comparator sinosoidal input waveform at pin no. 2 and the control voltage E_c waveform at pin no. 3 of a comparator. Fig. 3.5(b) shows the output of a comparator and that of a monoshot. It is clear from the oscillogram that for each rising edge of comparator output we are getting a corresponding pulse at the output pin no. 6 of monostable chip. Fig 3.5(c) shows the waveforms at output pin no. 6 of monoshot and at the output pin no. 3 of a OR gate chip. It is clearly seen that pulse width of firing pulse has increased sufficiently. Fig 3.5(d) shows the firing pulses going to thyristor T_1 and that of thyristor T_2. It is clearly seen that the required phase difference of 60^o exist between the two pulse.

Fig 3.5(e) shows the final pulses going to a thyristor. High frequency ANDING for minimising gate losses is clearly seen in the oscillogram.

CONCLUSION :

The Fig. 3.2 shows the complete firing scheme in terms of actual pin connection and components value. The firing scheme has been found satisfactory for three phase a.c. regulator made of 16 amp, 1200 PIV rating SCRs feeding a three phase Induction Motor.

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CHAPTER - IV

DEVELOPMENT OF EXPERIMENTAL SET UP

4.1 INTRODUCTION :

In this chapter specification of the induction motor, loading arrangement, selection of thyristor rating for fabrication of three phase a.c. regulator and the various protection are discussed. Brief description of the experimental setup is also explained.

4.2 SELECTION OF MOTOR AND LOADING ARRANGEMENT :

The induction motor with the following specification is selected.

Nos of phase	=	3
Voltage		400/440 Primary
		400 volt. Y Secondry
Amp.		5.5 Amp- Primary
		3.5 Secondary.
Frequency		50 Hz.

As all the six terminals on stator side are available, star or Delta can be made, although Delta connection is recommended on motors name plate.

The loading arrangement comparises of a d.c. machine which is coupled with the above induction motor. This machine has been used as a separately excited generator for loading purpose. The specification of this machine are as follows :

Power output	= 3.45 KW
Voltage rating	= 0 - 220 volt.
Amp.	= 20
RPM	= 750/1000/1500/3000.

4.3 SELECTION OF SCRs FOR A.C. REGULATORS :

The SCRs of the a.c. regulators must be able to withstand the maximum voltage coming across them and carry maximum current corresponding to any operating condition.

4.3.1 SCRs Voltage Rating :

The supply voltage line to line input to the regulator is 440 volt. When none of the thyristor conduct, under the assumption of the same leakage current for all the thyristor, load neutral connected to supply neutral, the maximum voltage that a thyristor will be required to block will be equal to the peak of phase voltage. Under the fault condition the voltage across the blocking thyristor may be still higher. Let us imagine that due to device failure, thyristor in one of the phase is rendered conductive, them full line to line voltage is applied across the blocking thyristor of the other two phases. Thus maximum peak inverse voltage (PIV) across each pair of S.C.Rs is given by.

$$PIV = \sqrt{2}\ V$$

$$= \sqrt{2} * 440$$

$$= 616.0 \text{ Volt.}$$

Allowing a safety factor of about 2.0 so that S.C.R. can easily take a reasonable transient over voltage, 1200 PIV rating is selected.

4.3.2 S.C.R. Current Rating :

Thyristor current rating is chosen on the basis of maximum current they are required to carry. The maximum current for a given load is obtained at the maximum conduction angle, which at the most can be 180^{o} (when supply neutral is connected to load neutral).

The full load current of the induction motor is 5.5 Ampere (Peak value = 5.5 $\sqrt{2}$ = 7.7 Amps.).Allowing a factor of about 2.0, which takes care of incresed stator current on reduced speed of operation, S.C.Rs of 16 Amp. current rating are used.

The S.C.Rs selected have the following specification :

SCR type SSE

Current rating 16 Ampere

Peak inverse voltage rating 1200 volt.

These SCRs have been mounted formly on heat sinks. SCRs are protected against over current by providing series fuses.

4.4 VARIOUS PROTECTIONS :

One of the several advantage of SCRs is that they are small in size. However from the stand point of protection, small size is a disadvantage. SCRs have low mass and surface area and therefore low thermal time constant. They are very delicate devices so protection is necessary. Various failure modes and protection techniques are discussed here.

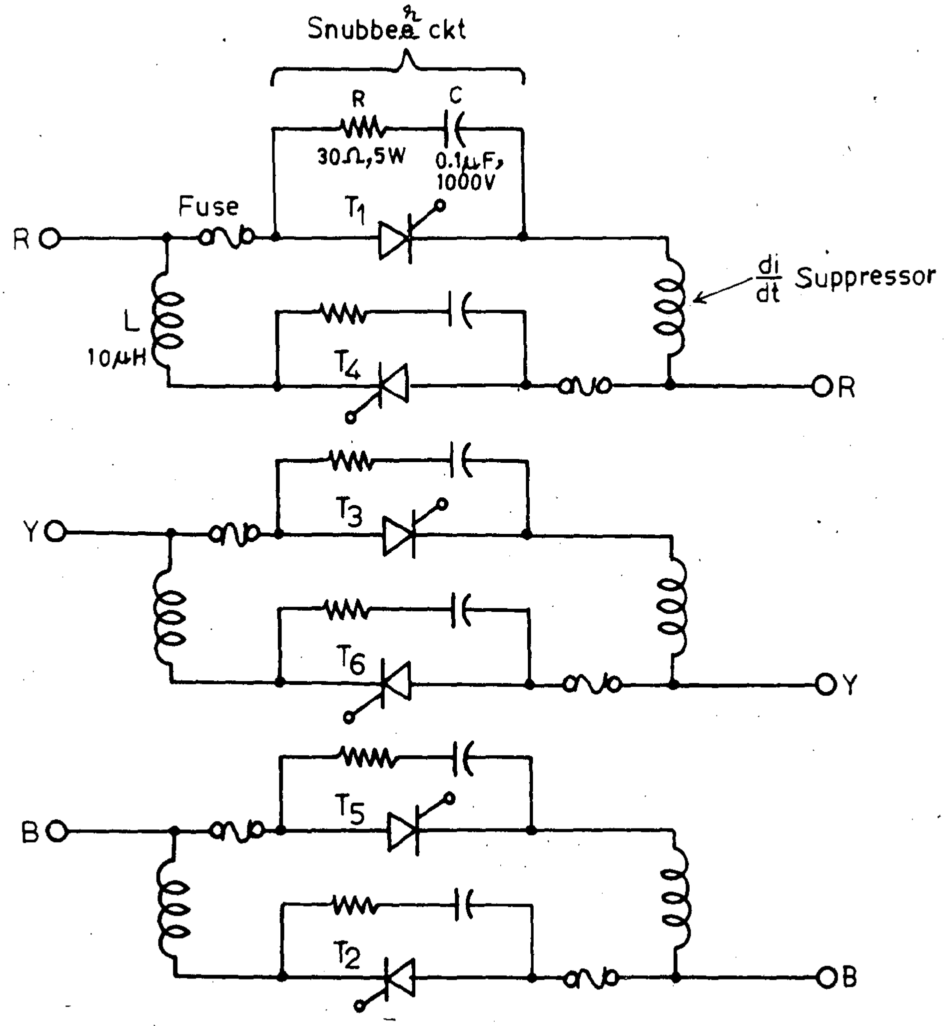

Fig. 4.1. Configuration of 3-phase regulator.

4.4.1 di/dt Protection :

When an SCR is forward biased and it is triggered by a gate pulse, conduction of the anode current starts in the immediate vicinity of the gate connection. The current thereafter spreads across the whole area of the junction. If the rate of rise of anode current is large, local ''hot spots'' will be created near the gate connection due to high current density. This localized heating may burn out the S.C.R. Therefore, the rate of rise of the anode current (di/dt) at switch-on must not exceed a specified limiting value. Normally, a small inductor, called a di/dt inductor, is inseeted in the anode circuit to limit the di/dt of the anode current. A typical di/dt limit in SCRs is in the range 20 to 500 A/μ Sec.

4.4.2 dv/dt Protection :

When a forward voltage is applied across the thyristor, the two outer junction are forward biased, and the central junction is reversed biased. A reverse-biased p-n junction the characteristic of a capacitor. Therefore when a forward voltage is applied, a charging current flows :

$$i = C_j \frac{dV_{AR}}{dt}$$

where C_j is the junction capactor.

If the rate of application of forward voltage is high, the charging current can be so high that the SCR will turn on without a gate pulse. This phenomenon, known as dv/dt turn-ON will lead to improper operation in a circuit.

To protect against dv/dt turn-on of an SCR, a Snubber circuit, which is a R.C. series circuit in its simplest form, is used across the thyristor.

4.4.3 <u>Over-Heating Protection</u> :

When a thyristor is conducting, the anode-to-cathode resistance is very low but not zero. The voltage across the device is in the range of 1 to 2 V. A large anode current following through the device may produce sufficient heat to destroy the device. Therefore thyristors are invariably mounted on heat sinks so that heat is conducted from the device to the heat sink, and from there it is radiated and conducted to the atmosphere.

4.4.4 <u>Over-Current Protection</u> :

The thermal capacity of a semiconductor device is small. Therefore continuous over loading, surge currents of long duration or large surge currents of small duration may increase the junction temperature beyond the permissible limit and destroy the device. Over-current protection is provided by a circuit breaker and a fast acting fuse in series with thyristor.

4.4.5 <u>Gate Protection</u> :

Gate protection is required for over-voltage and over current. Because of the low power level of the control circuitry, this protection can be provided by simple means. The gate can be protected against over voltage by connecting a series resistance.

A common problem encountered in the SCR circuitry is spurious (or noise) firing of the device. Trigger pulses may be

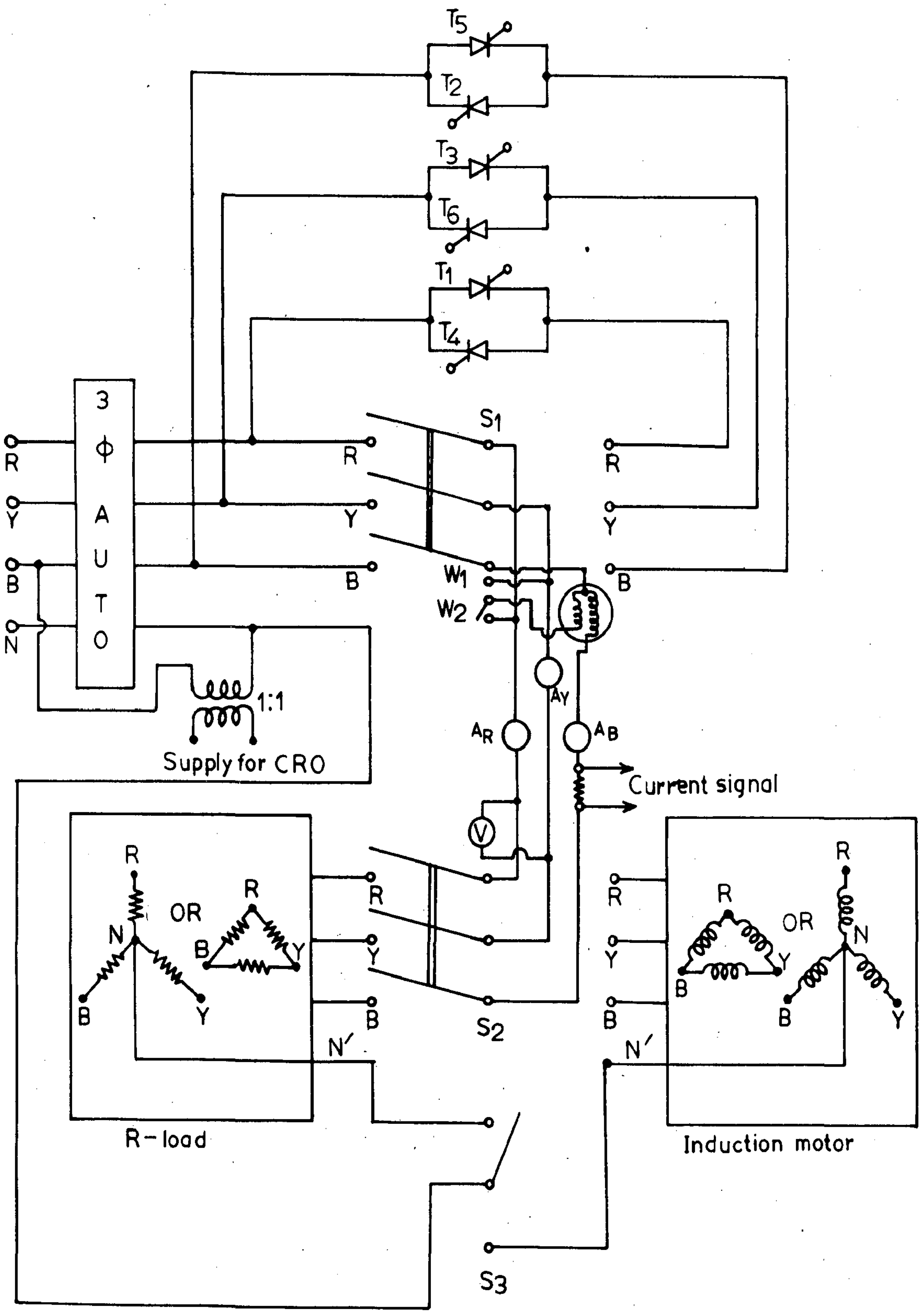

Fig.4.2. Experimental set-up.

induced at the gates due to turn-on or turn-off of a neighboring SCR or transients in the power circuit. These undesirable trigger pulses may turn on the device, thus causing improper operation of the circuit. Gates are protected against such spurious firing by using shielded cables or twisted gate lead connections. Most often a capacitor and a resistor are connected across the gate-to-cathode to bypass the noise pulses.

The fabricated a.c. regulator with above protection is shown in Fig. 4.1.

4.5 BRIEF DESCRIPTION OF EXPERIMENTAL SET UP :

Fig. 4.2 shown the complete details of the experimental set up. It has the facilities to connect/disconnect the resistive load or an induction motor load either by a three phase auto - transformer supply or by the a.c. regulator. To have this facility two nos, three pole two way switch S_1 and S_2 have been used. Further set up has the facility to connect or disconnect the supply neutral N to the load neutral N' with the help of a single pole two way key S_3. Supply for the C.R.O is taken from an isolation transformer as shown in figure. To record the current waveforms on C.R.O. correctly, It is necessary to take current signal across a small resistance (a shunt) connected in series with ammeter as shown in figure. For measurement of input power input voltage, and input currents respective meters of required rating are used as shown.

(a)

(b)

(c)

Fig 4.3 Photographs of Experimental Setup

Fig. 4.3 shows photographs of experimental set up.

4.6 CONCLUSION :

The guidelines for the selection of various components of the power circuit and its protection are discussed and the a.c. regulator is fabricated for the speed control of induction motor.

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CHAPTER - V

GRAPHICAL ANALYSIS AND LOAD TEST

5.1 INTRODUCTION :

In this chapter an effort has been made to investigate the voltage and current waveform at input and output of the three phase regulators. As it is easier to predict such waveforms when the load is resistive, the predicted and oscilloscopic reoords are also presented for the sake of comparison.

5.2 GENERAL :

The fabricated regulator can work at a firing angle adjusted anywhere between zero to 180^o. However, for the purpose of oscillographic study certain values of firing angle are selected. Further the oscillograms are recorded for both resistive and induction motor (unloaded and loaded) loads. In each case the following connection of the loads are considered.

(i) Star connection, with neutral connected to supply neutral.

(ii) Star connection with isolated neutral.

(iii) Delta connection.

The discussion that follows is presented for each connection in above order.

5.3 STAR CONNECTION WITH NEUTRAL CONNECTED TO SUPPLY NEUTRAL :

The Schematic diagram of this connection for balanced resistive load is given in Fig. 5.1(a).

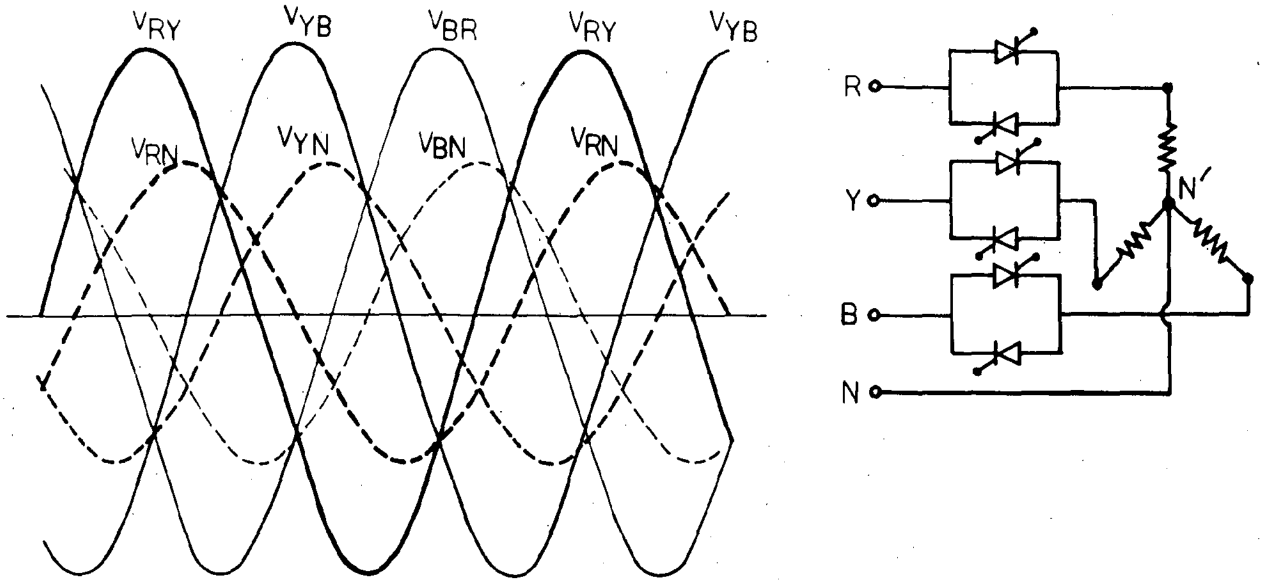


Fig.5.1(a)

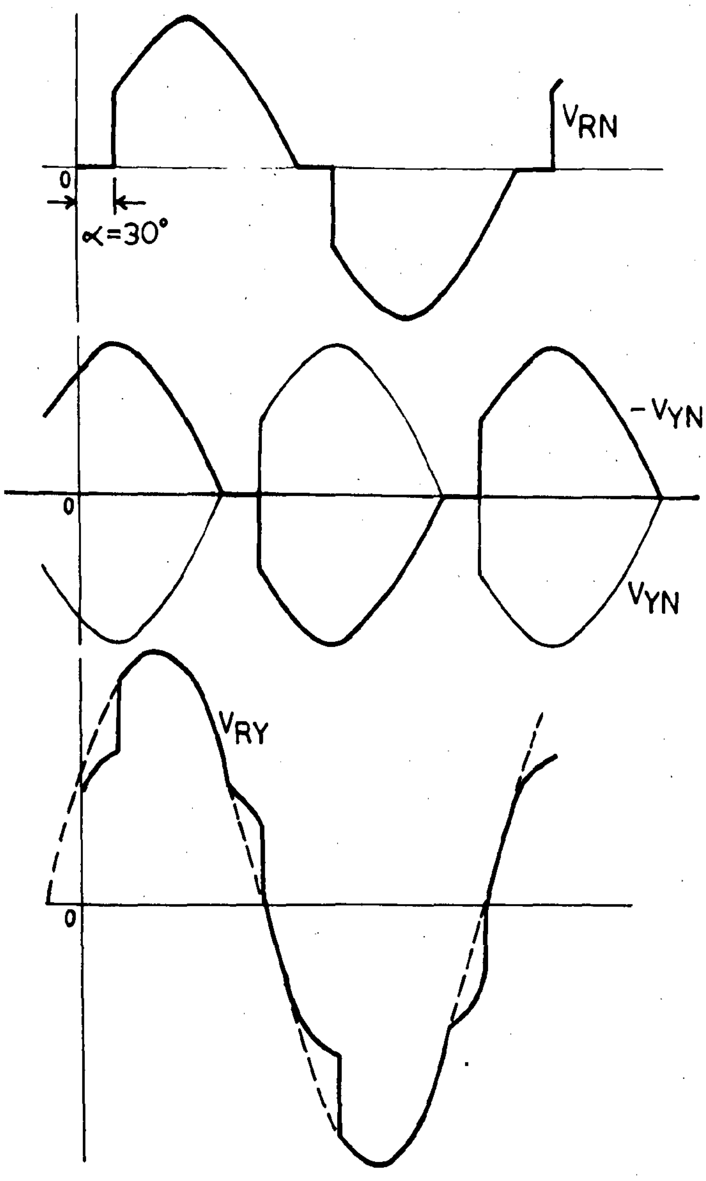
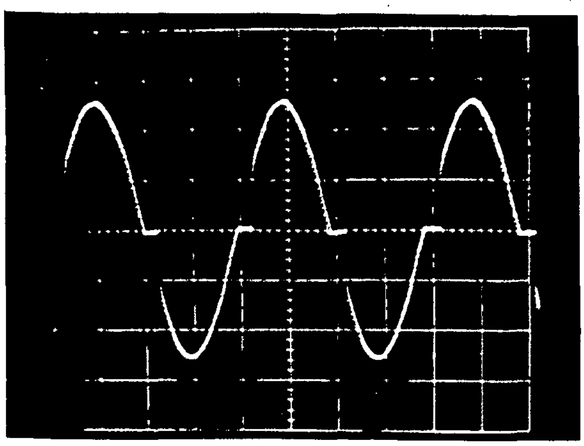


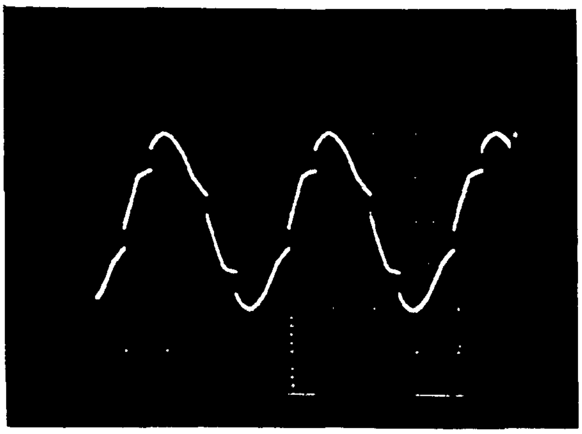
Fig.5.1(b)

It is noted that thyristor T_1 remains forward biased during the entire positive half cycle of voltage V_{RN} and is reversed biased in the following negative half cycle. The opposite is applicable to thyristor T_4. The phase voltage waveforms V_{AN} for a typical firing angle $\alpha = 30^o$ is shown in Fig. 5.1(b). The load being resistive, the current in phase 'R' will be of identical nature. The line voltage waveform V_{RY} can be constructed by adding the waveforms of V_{RN} and $- V_{YN}$ as shown. The oscillograms of phase voltage and line voltage for $\alpha = 30^o$ are given in Fig. 5.2(a) and 5.2(b) respectively, which are in accordance with the predicted waveforms. Also whown in the Fig. 5.2(c) is the voltage across anode to cathode of a thyristor during above operation. It can be seen that due to antiparallel connection of each pair, This voltage is almost zero whenever any of the two thyristor of the pair is conducting.

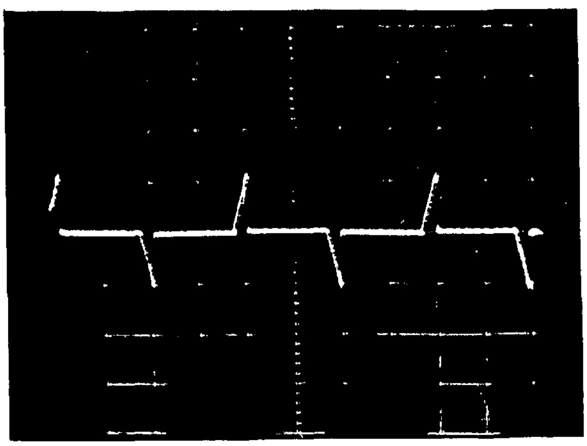
Fig. 5.2(d) and Fig. 5.2(e) show the oscillogram at $\alpha = 72^o$, phase voltage and phase current are shown in Fig. 5.2(d) whereas line voltage is shown in Fig. 5.2(e). It may be noted that the waveform of phase current appears to be not in phase with phase voltage waveform. This is on account of taking current signal across ammeter terminal. This signal does not represent true nature of the current going through ammeter. Instead it shows the voltage drop across ammeter impedence which is inductive and hence it leads the current flowing through it. This recording error has been overcome in future oscillograms by taking current signal across a small resistance (a shunt) connected in series with ammeter.



(a), Phase voltage, $\alpha = 30^{o}$



(b), Line voltage, $\alpha = 30^{o}$



(c), Anode to cathode thyristor voltage.

Fig. 5.2 : WAVEFORMS OF R-LOAD, NEUTRAL CONNECTED TO SUPPLY NEUTRAL

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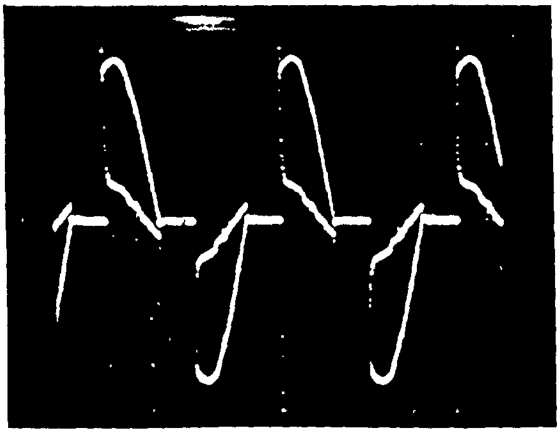
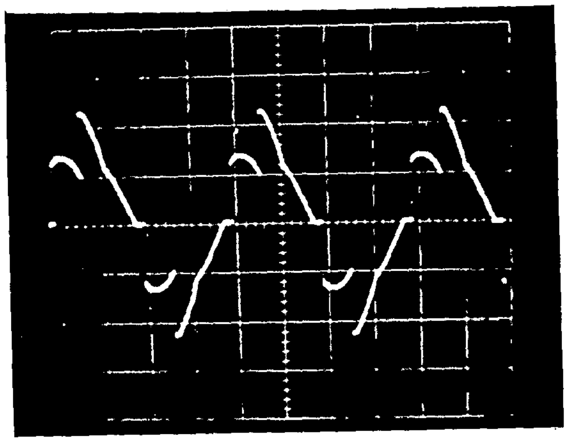
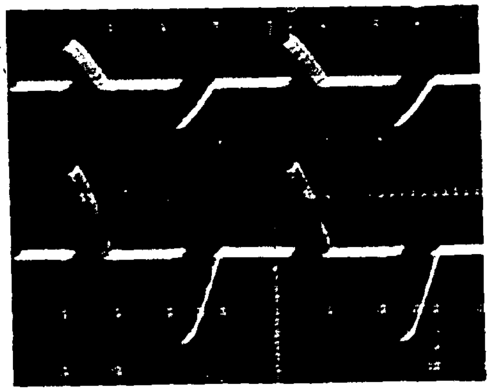


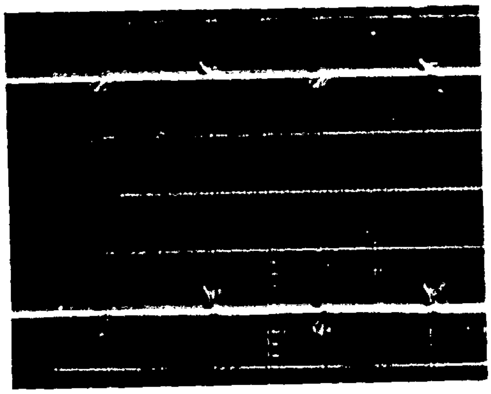
(d), α = 72°
Phase voltage and current.



(e), α = 72°, Line voltage



(f), Phase voltage
α = 126° phase current.



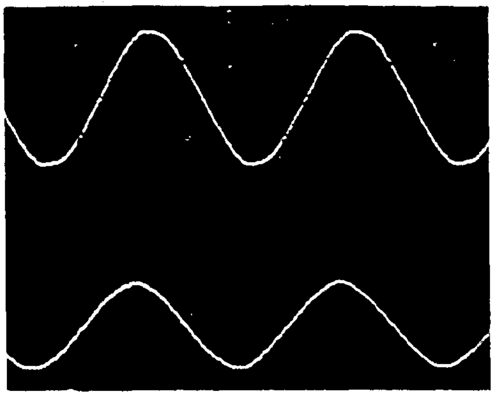
(g), α = 165°

Fig. 5.2(f) and Fig. 5.2(g) show the phase voltage and phase current waveform at firing angle of 126° and 165° respectively.

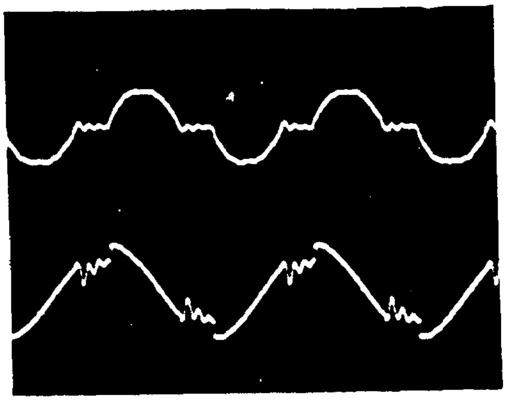
Oscillograms on motor load for this connection are shown in Fig. 5.3(a to e). Upper waveform represents phase currents and lower waveform represents phase voltage. Oscillogram of Fig. 5.3(a), 5.3(b), and 5.3(c) are recorded at firing angle $\alpha = 36^{\circ}$, 90° and 120° respectively.

In each case the motor was loaded by keeping same set of Lamps ON across the armature terminal of the loading D.C. generator. The voltage and hence current waveforms are nearly sinosoidal at low firing angle as is evident from Fig. 5.3(a). In Fig. 5.3(b) the phase currents builds up from zero value as corresponding thyristor is fired and continuous flowing even after the thyristor anode to cathode voltage ha s become zero on account of the lagging nature.

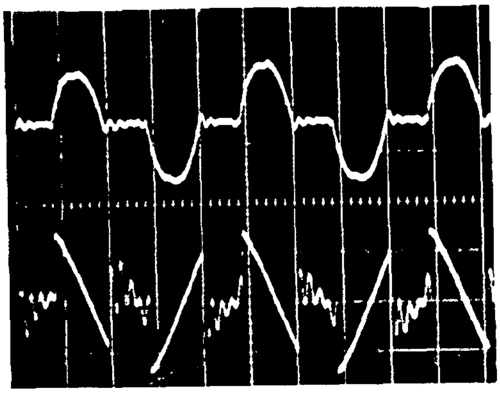
As current in a particular phase becomes zero the voltage appearing across that phase is due to induced e.m.f. In present case a slip ring induction motor whose sliprings are short circuited has been used. The high frequency ripples in the induced e.m.f. are possibility due to slot openings in the machine. The effect of variation in motor load can be seen from the oscillogram of Fig. 5.3(d) and 5.3(e) which represent current and voltage waveform at $\alpha = 72^{\circ}$ for unloaded and loaded machine respectively. Under no load the power factor is poor with respect to loaded case have the angle of lags being larger, the current keeps flowing for longer period after the forward voltage across corresponding thyristor becomes zero. Thus the voltage and current waveforms have less harmonic under no load condition.



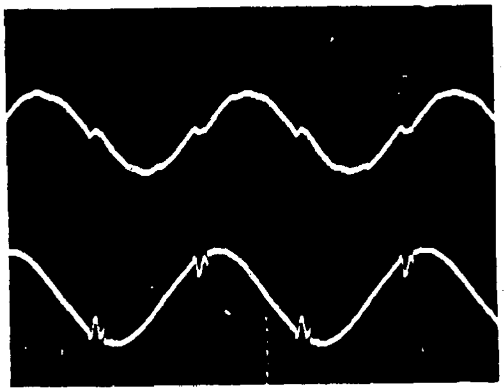
(a), α = 36°



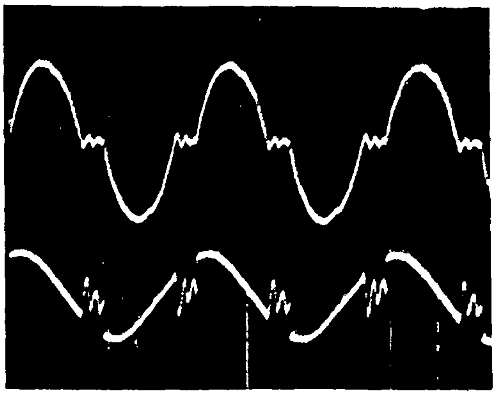
(b), α = 90°



(c), α = 120°



(d), α = 72°



(e), α = 72°

Fig. 5.3 : INDUCTION MOTOR WAVE FORMS WITH LOAD NEUTRAL CONNECTED TO SUPPLY NEUTRAL.

5.4 VOLTAGE WAVEFORMS ACROSS LOAD UNDER ISOLATED NEUTRAL OPERATION:

With no neutral on load side, one thyristor each in at least two phases must conduct to establish load current. If the six thyristor are symmetrically fired in sequence 1,2,3,4,5, and 6, then also follow same sequence during natural-turn off. When a thyristor is reversed biased, it continues conducting for some time before comming off, describing the overlap angle μ, due to inductive nature of the load. The load voltage waveform across any two load terminals, say, Y' and B' can be theoretically constructed in the following manner.

As long as one thyristor in phase Y and one thyristor in phase B are conducting, terminals Y' and B' are connected to Y and B respectively and hence

$$V_{Y'B'} = V_{YB}$$

Voltage $V_{Y'B'}$ will be other than V_{YB} only when both thyristors of either phase Y or phase B are off. During these periods the nature of $V_{Y'B'}$ may be determined analytically as follows.

Let

$$V_{YB} = \sqrt{3}\, V_m \text{ Sin } \theta \qquad ..(5.1)$$

$$V_{BR} = \sqrt{3}\, V_m \text{ Sin } (\theta - \frac{2\pi}{3}) \qquad ..(5.2)$$

$$V_{RY} = \sqrt{3}\, V_m \text{ Sin } (\theta + \frac{2\pi}{3}) \qquad ..(5.3)$$

and

$$V_R = V_m \text{ Sin } (\theta + \frac{\pi}{2}) \qquad ..(5.4)$$

$$V_y = V_m \text{ Sin } (\theta - \pi/6) \qquad ..(5.5)$$

$$V_B = V_m \text{ Sin } (\theta + 7\pi/6) \qquad ..(5.6)$$

If thyristor T_3 and T_6 are simultaneously off, phase Y of the load will not carry any current. Under this condition, referring Fig. 5.4(i)

$$V_{Y'B'} = V_{Y'N'} + V_{N'B'}$$

or

$$V_{Y'B'} = V_{Y'N'} + \frac{V_{R'B'}}{2} \qquad ..(5.7)$$

$V_{Y'N'}$ is the induced e.m.f. in phase $V_{Y'N'}$ which may be considered to be same as V_Y, ignoring the effect of leakage impedance of the stator, Since the other two phases R and B are conducting, $V_{R'B'} = V_{RB}$. Thus equation 5.7 may be written as

$$V_{Y'B'} = V_Y + \frac{V_{RB}}{2}$$

or

$$V_{Y'B'} = V_m \operatorname{Sin}(\theta - \frac{\pi}{6}) - \frac{\sqrt{3}}{2} V_m \operatorname{Sin}(\theta - \frac{2\pi}{3}) \qquad ..(5.8)$$

equation 5.8 describes the behaviour of voltage $V_{Y'B'}$ when both thyristors of phase Y are off.

Similarly when both thyristors of phase B are off,

$$V_{Y'B'} = V_{Y'N'} + V_{N'B'} \qquad ..(5.9)$$

$$= \frac{V_{Y'R'}}{2} - V_{B'N'} \qquad ..(5.10)$$

$$= \frac{V_{YR}}{2} - V_B \qquad ..(5.11)$$

or $$V_{Y'B'} = -\frac{\sqrt{3}}{2} V_m \operatorname{Sin}(\theta + \frac{2\pi}{3}) - V_m \operatorname{Sin}(\theta + \frac{7\pi}{6}) \qquad ..(5.12)$$

The waveform of load voltage $V_{Y'B'}$ for two typical firing angles $\alpha = 25^o$ and $\alpha = 90^o$ are shown in Fig. 5.4(iia) and 5.4(iib).

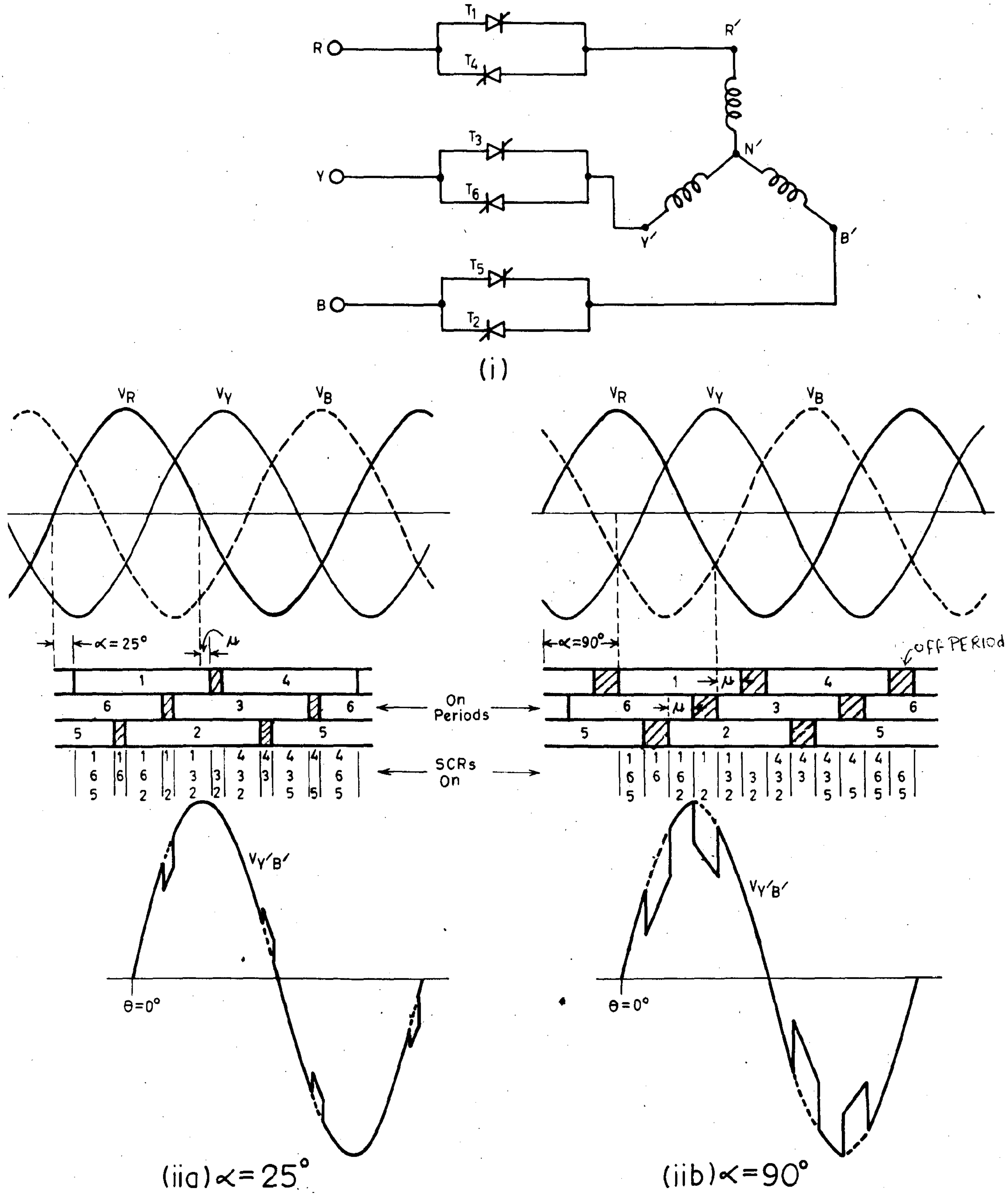


Fig.5.4. Theoretical load voltage waveforms with isolated neutral.

The conduction period of various thyristor and the number of conducting thyristors at different instants are also shown.
In the case when $\alpha = 25^o$, Fig. 5.4(iia) it may be noticed that conduction of thyristor T_1 begins at $\alpha = 25^o$ and it continues μ^o after thyristor T_1 reverse biased. Thyristor T_1 becomes reverse biased at that instant when V_R becomes zero and V_Y becomes equal and opposite to V_B, thus making potential of N' zero and therefore voltage $V_{RN'}$ too becomes zero putting thyristor T_1 under reverse biased ondition. Phase R again conducts when thyristor T_4 is triggered 180° away from triggering instant of thyristor T_1. For a small period both thyristor T_1 and T_4 remains in off state making phase R of the load non conducting. In a similar manner other two phases become non conducting cyclically. The waveforms of voltage $V_{Y'B'}$ is seen ——> to have two notches in the positive half cycle and two in the negative half cycle. The first notch in the positive half cycle correspond to the condition when both T_3 and T_6 are off. The voltage $V_{Y'B'}$ during this period is given by equation 5.8. The second notch of the positive half cycle correspond to the case when T_2 and T_5 are simultaneously off and the voltage $V_{Y'B'}$ during this period is given by equation (5.12). Similarly the two notches of the negative half cycle may be obtained.

At $\alpha = 90^o$ [Fig.5.4(iib)], thyristor T_1 becomes reverse biased at an instant latter with respect to previous case. This is due to the fact that when V_R becomes zero thyristor T_1 and T_2 continue conduction untill T_3 is triggered. At this instant T_1 becomes reverse biased but it continues conduction for the overlap period μ^{o}. The waveform of voltage $V_{Y'B'}$ is again seen to have notches which can be obtained as already explained in first case.

It is seen that a.c. regulator works in 3/2 mode of operation upto $\alpha = (90 + \mu)^{o}$. Beyond this value the mode of operation become 2/0. The useful range of firing angle is 120^{o}.

For resistive loads the line voltage waveform will have notches whose nature will be different with respect to the motor load on account of absence of the induced e.m.f. across the open phase. Accordingly equation 5.8 and 5.12 will modify as follows.

when Phase Y is open

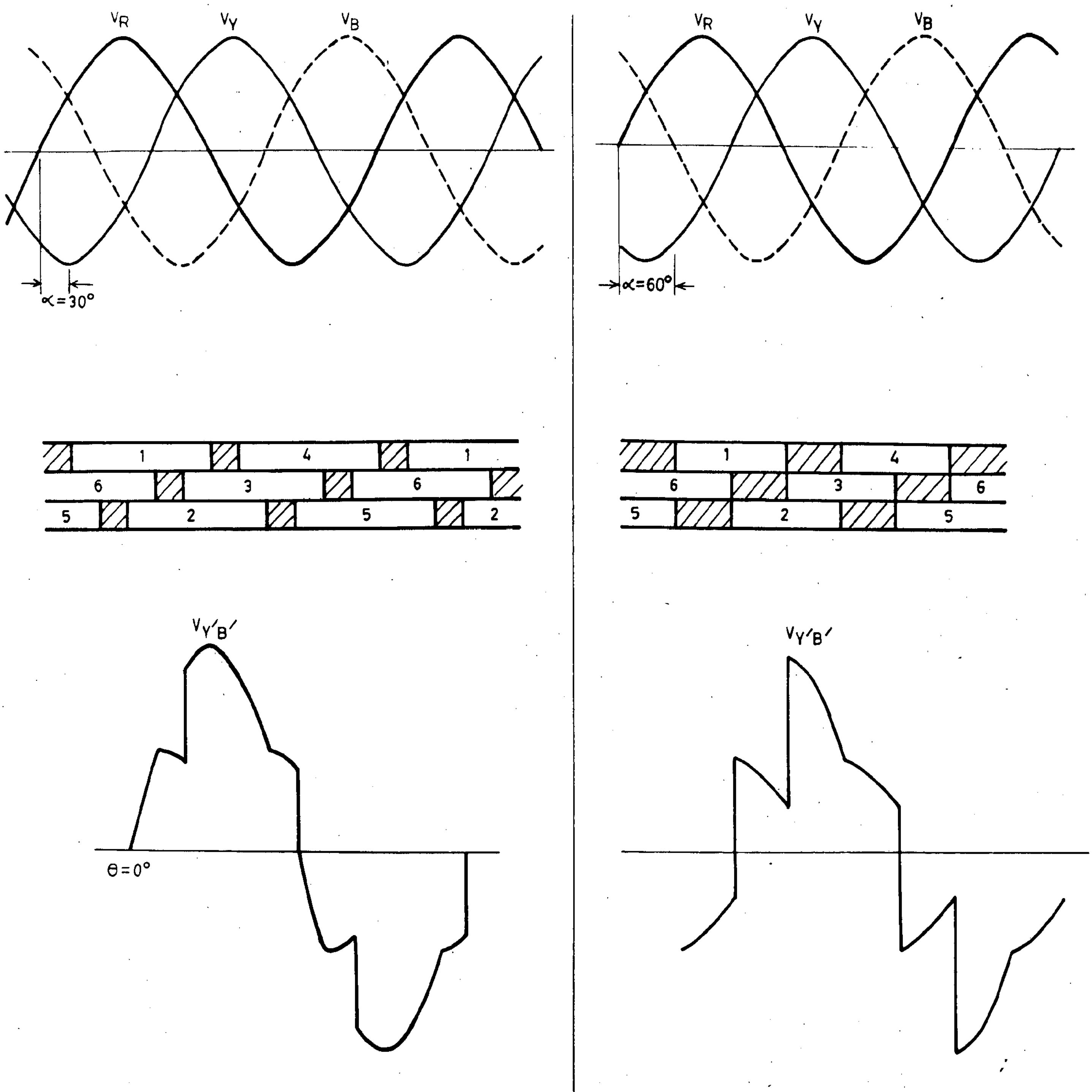
$$V_{Y'B'} = - \frac{\sqrt{3}}{2} V_m \operatorname{Sin}(\theta - \frac{2\pi}{3}) \qquad ..(5.13)$$

when Phase B is open

$$V_{Y'B'} = - \frac{\sqrt{3}}{2} V_m \operatorname{Sin}(\theta + \frac{2\pi}{3}) \qquad ..(5.14)$$

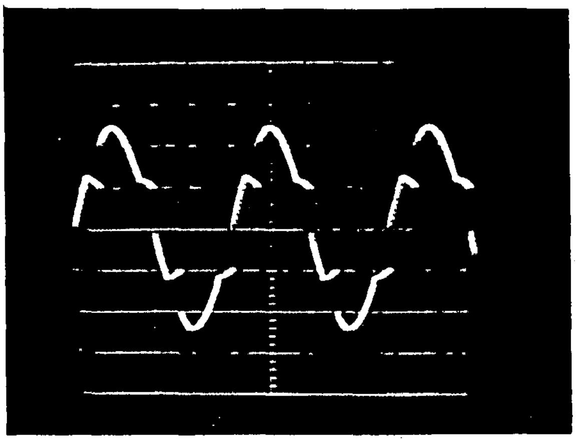
5.4.1 Load Voltage (Resistive load) Waveforms :

Development of waveform of load voltage $V_{Y'B'}$ for resistive load is illustrated in Fig. 5.5 for two values of firing angle α. When $\alpha = 30^{o}$ (Fig. 5.5(a)), the a.c. regulator operates in 3/2 mode and phases Y and B experience open circuit alternately. Waveform of $V_{Y'B'}$ accordingly has notches whose nature is given by equation 5.13 and 5.14. This waveform compares well with oscillogram of Fig. 5.6(a), which shows the line voltage waveform at $\alpha = 36^{o}$. Fig. 5.5(b) shows the waveform of $V_{Y'B'}$ at $\alpha = 60^{o}$. In this case only two thyristor conduct at any time. The notches can again be obtained as before. This waveform may be compared with the oscillogram of Fig. 5.6(b), in which line voltage waveform at $\alpha = 72^{o}$ is shown. If firing angle is increased to 120^{o},

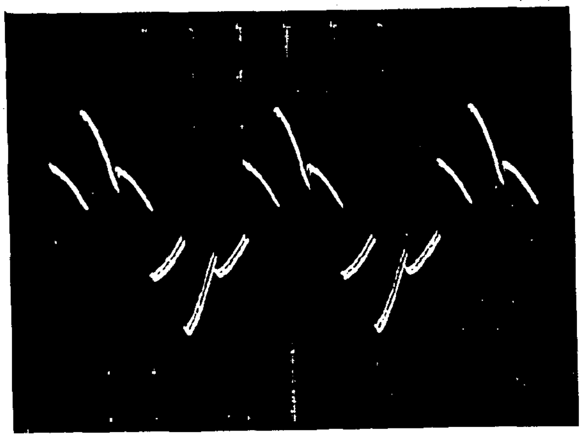


(a) α = 30° (b) α = 60°

Fig. 5.5. Theoretical line voltage waveforms for R Load.



(a), α = 30°



(b), α = 72°

FIG. 5.6 : LINE VOLTAGE WAVEFORMS ON R-LOAD NEUTRAL ISOLATED.

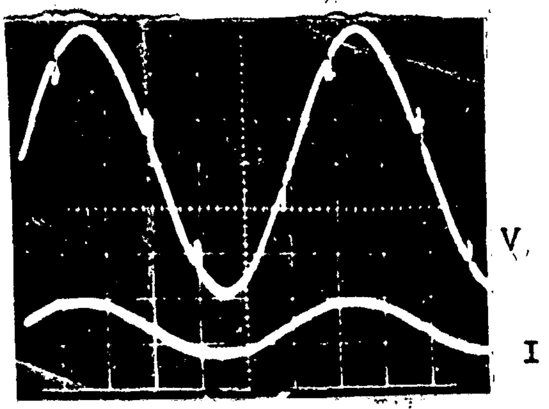


Fig. 5.7(a), $\alpha = 25^{\circ}$

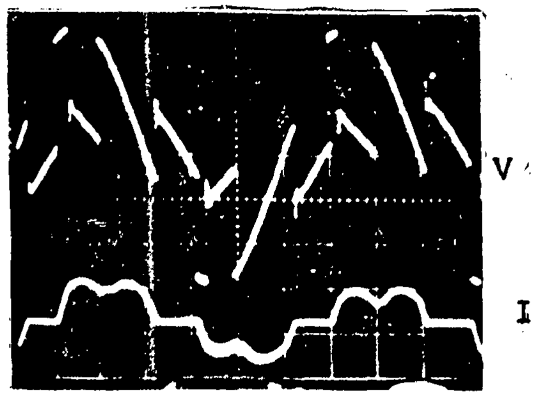


Fig. 5.7(b), $\alpha = 90^{\circ}$

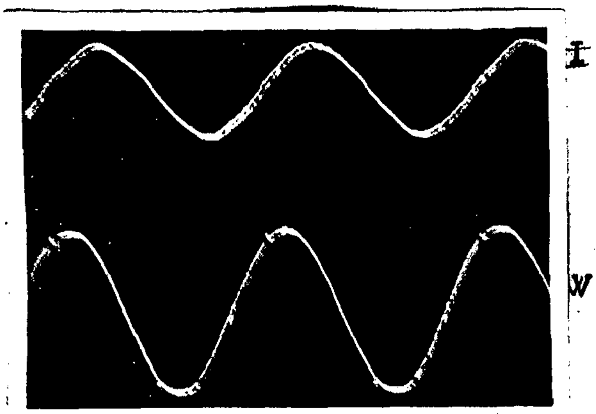


Fig. 5.8(a), $\alpha = 36^{\circ}$

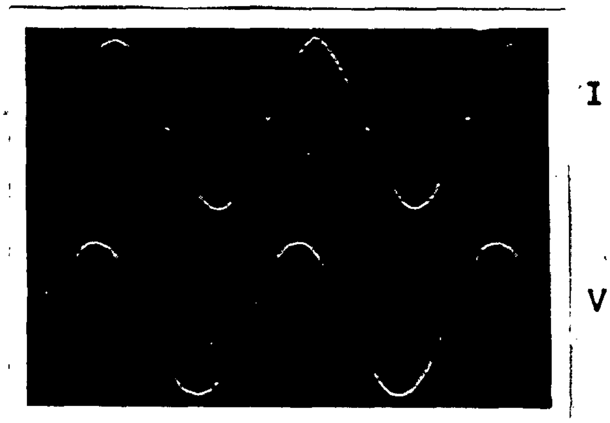


Fig. 5.8(b), $\alpha = 36^{\circ}$

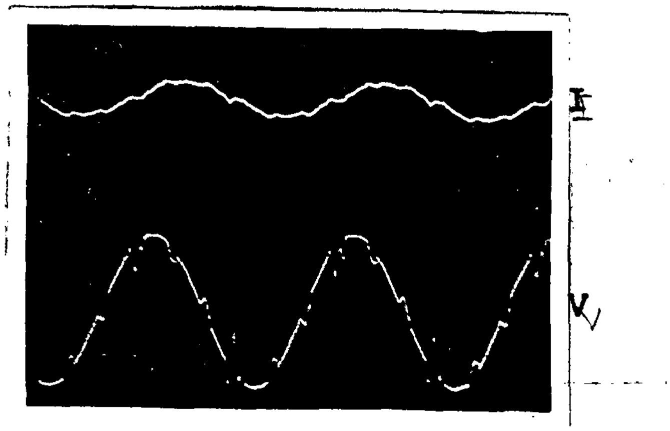


Fig. 5.9(a), $\alpha = 72^{\circ}$

Fig. 5.9(b), $\alpha = 72^{\circ}$

INDUCTION MOTOR WAVE FORMS WITH ISOLATED NEUTRAL.

regulator will come to off state (zero mode). Thus with isolated neutral a star connected load can have maximum to zero voltage as firing angle is increased from zero to 120°.

5.4.2 Load Voltage (Motor load) Waveforms :

Development of waveform of load voltage $V_{Y'B'}$ for motor load has been already explained [Fig. 5.4(iia and b)] for $\alpha = 25^{\circ}$ and 90°, while recording the oscillogram in the present work, only phase voltages across the stator have been recorded along with phase currents. Line voltage waveforms have not been recorded. The line voltage waveforms of above figures, therefore, can not be directly compared with those obtained in the present work. However such oscillograms are given in reference [13] and are reproduced in Fig. 5.7(a) and (b) for the case of $\alpha = 25^{\circ}$ and 90° respectively. A close resemblence in the nature of theoretical and experimental waveform is noted.

In present work the oscillogram on motor load are recorded and shown in Fig 5.8and5.9 for $\alpha=36^{\circ}$and 72° respectively.Fig.5.8(a)shows the current (top trace) and voltage (bottom trace) waveforms under no load condition where as Fig. 5.8(b) shows the same waveform when machine is loaded. The effect of notches in these waveforms is almost negligible resulting in sinosoidal waveforms. A reduction in angle of lag of current with respect to voltage may be noticed as machine is loaded.

Fig. 5.9(a) and (b) shows the unloaded and loaded machine waveforms at $\alpha = 72^{\circ}$. The voltage waveforms consists of six notches per cycle. The notches are more pronounce when the machine is loaded. The waveforms of line current also exhibits richness in harmonics as the machine is loaded.

Table - 1 [13] gives summary of conduction state of the thyristor under isolated neutral operation from where the modes of operation i.e. 3, 3/2, 2, 2/0, and 0 can be identified for a given firing angle α. Both resistive load and motor load are considered.

5.5 VOLTAGE WAVEFORMS ACROSS DELTA CONNECTED LOAD :

When the load is delta connected one thyristor each in atleast two phases must conduct to allow load current to be established. Such connection is shown in Fig. 5.10. The voltage across any two lines of the load, say $V_{Y'B'}$ will be as follows.

$V_{Y'B'} = V_{YB}$, when thyristor T_3 and T_2 or thyristor T_5 and T_6 are ON

$= \frac{V_{R'B'}}{2}$, when thyristor T_3 and T_6 are off

$= \frac{V_{Y'R'}}{2}$, when thyristor T_5 and T_2 are off.

Following the expression of phase and line voltages given in preceeding section, the expression of $V_{Y'B'}$ may be written as follows :

$V_{Y'B'} = V_{YB}$, when supply lines Y and B are carrying currents

$= -\frac{\sqrt{3}}{2} V_m \sin(\theta - \frac{2\pi}{3})$, when current in line Y is zero.

$= -\frac{\sqrt{3}}{2} V_m \sin(\theta + \frac{2\pi}{3})$, when current in line B is zero.

above expressions are similar to the case of star connected resistive load with isolated neutral described in equation 5.13 and 5.14. As such when delta connected resistive load is considered

TABLE - 1 : Summary of Thyristor Conduction States per 60^{o} Interval.

Firing Angle α	Number of Thyristor On					
	R Load			RL Load		
	3	2	None	3	2	None
$0 \leq \alpha \leq \mu^{o}$	$60-\alpha$	α	-	60	-	-
$\mu^{o} \leq \alpha \leq 60^{o}$				$60-(\alpha-\mu)$	$\alpha - \mu$	
$60^{o} \leq \alpha \leq 90^{o}$	-	60	-	μ	$60 - \mu$	-
$90^{o} \leq \alpha \leq (90^{o}+\mu)$	-	$150-\alpha$	$\alpha-90$	$(90+\mu)-\alpha$	$\alpha-30-\mu$	-
$(90+\mu)^{o} < \alpha < 120^{o}$				-	$150-\alpha+\mu$	$\alpha-(90+\mu)$
$120^{o} \leq \alpha \leq 180^{o}$	-	-	60	-	-	60

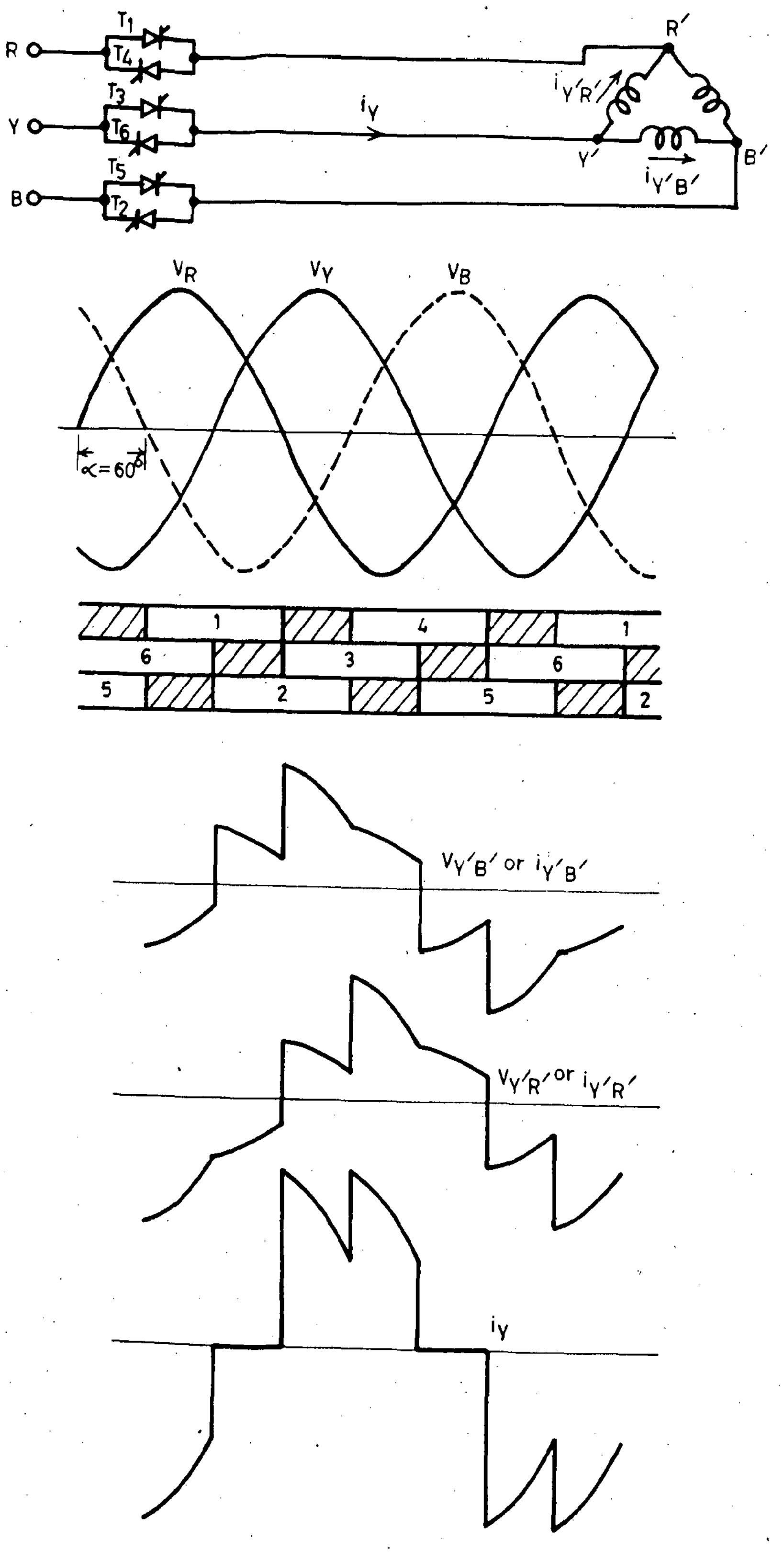


Fig.5.10. Load voltage and current waveforms under Δ-connection (Resistive load).

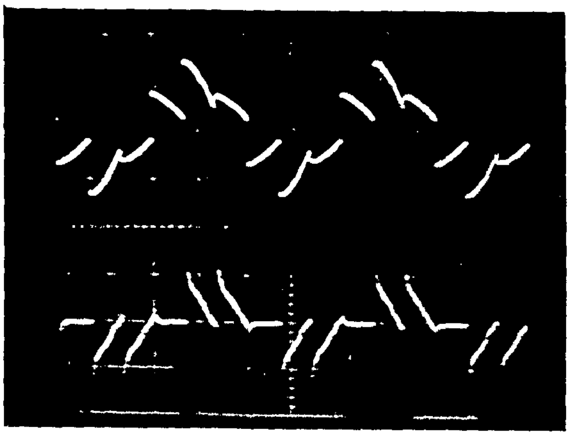


FIG 5·11 LINE VOLTAGE AND CURRENT WAVE FORM ON DELTA CONNECTED R-LOAD.

the waveform of load voltages such as $V_{Y'B'}$ will be similar, at a given firing angle, to those obtained in the preceeding section for isolated star connection. This is shown for firing angle $\alpha = 60^o$ in Fig. 5.10. Since the load is resistive phase currents and phase voltages of the load will be in same phase. The waveform of line current say i_y, i_y, may be obtained by noting that

$$i_y = i_{Y'B'} + i_{Y'R'}$$

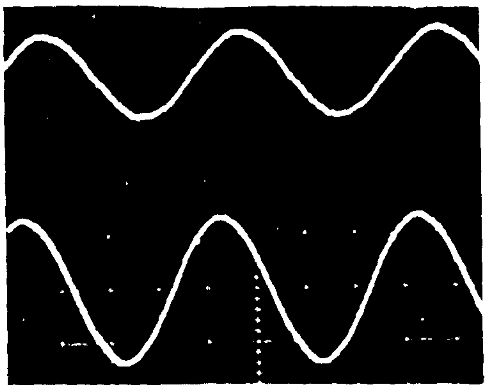
the waveform of $V_{Y'B'}$ (or current $i_{Y'B'}$), $V_{Y'R'}$ (or current $i_{Y'R'}$) and current i_y are shown in Fig. 5.10.

Fig. 5.11 shows the oscillogram of voltage and current waveforms at $\alpha = 72^o$ for such connection (Resistive load). The close resemblance in the nature of these waveforms is observed.

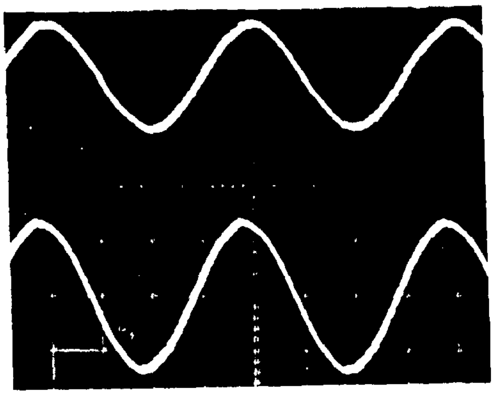
Voltage waveforms across motor load under delta connection can be derived in a manner similar to the one followed under star connection with isolated neutral. At a given firing angle the conduction periods of different thyristors may be determined exactly on the lines discussed earlier (Fig. 5.4). Fig. 5.12 shows the oscillograms of line voltage (which is same as phase voltage) and line current at stator terminals for firing angle α equal to 36^o, 72^o and 90^o under unloaded and loaded conditions. Fig. 5.12(a) and (b) shows the current (upper trace) and voltage (lower trace) waveforms under unloaded and loaded conditions respectively. It is seen that the influence of notches in voltage is nearly absent resulting in sinusoidal voltage and current waveforms. Fig. 5.12(c) and (d) shows these oscillogram when firing angle α is 72^o. The influence of notches is again negiligible under no load conditions but is present under loaded condition,

AT NO LOAD ↓

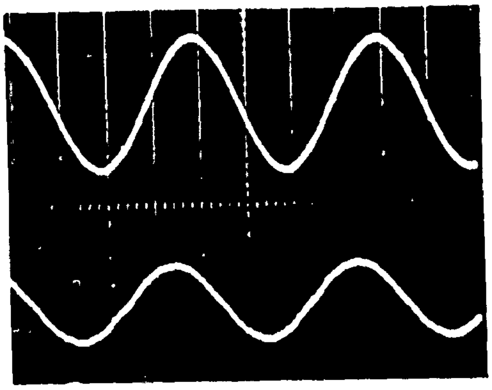
AT LOAD ↓



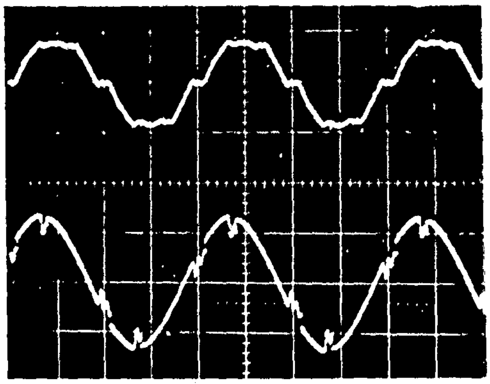
(a), $\alpha = 36^{o}$



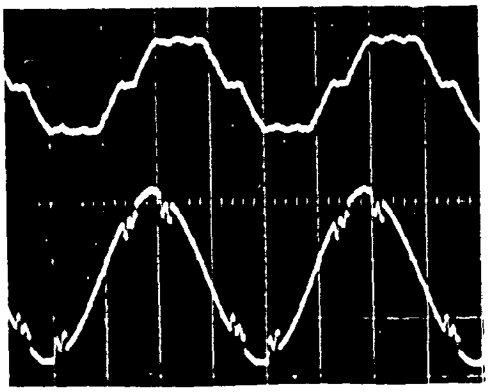
(b), $\alpha = 36^{o}$



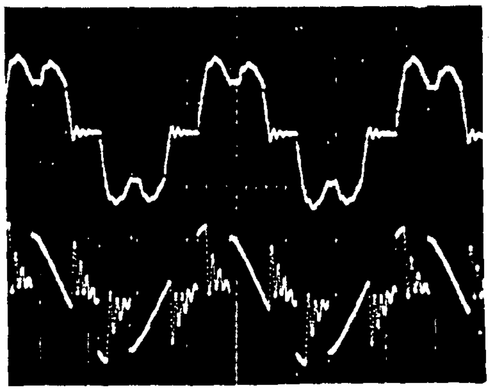
(c), $\alpha = 72^{o}$



(d), $\alpha = 72^{o}$



(e), $\alpha = 90^{o}$



(f), $\alpha = 90^{o}$

Fig. 5.12 : OSCILLOGRAMS OF MOTOR VOLTAGE AND CURRENT UNDER DELTA CONNECTION.

the current waveform also deviates from sinusoidal nature under loaded condition. Fig. 5.12(e) and (f) shows the result at $\alpha = 90^o$. The notches gain prominance under loaded condition.

A comparison of Fig. 5.12(f) with Fig. 5.7(b) reveals considerable resemblence. This shows that line voltage and line current waveforms under isolated neutral star connection closely resemble with those under delta connection.

5.6 LOAD TEST :

The performance of induction machine has been experimently recorded by conducting load test. For this purpose a directly coupled, separately excited d.c. generator feeding a resistive load of contant ohmic value has been considered as load on the machine. Such an arrangement offers a load characteristic where load torque is proportional to speed. The procedure adopted for conducting the load test has been to allow the motor run at highest possible speed (corresponding to lowest firing angle) and adjust the ohmic value of resistance connected across the loading generator so that the current drawn by the induction motor is about 60% of its rated value. The firing angle is now gradually increased with the help of potentiometer (a ten turn calibrated potentiometer is used). Keeping the ohmic value of loading resistance unchanged. Observations of potentiometer marking and corresponding value of α, stator voltage, stator line current, three phase input power to stator, motor speed and voltage, current at generator aramuture terminal are recorded. These observations are shown in Table- II. Load test results when motor is supplied from variac are also recorded for comparison and are given in Table - III.

Since cosine firing principle has been used in the control circuit, the markings on potentiometer could have been calibrated in terms of firing angle α. However the measurement on oscilloscope revealed some difference in the value of α with respect to its expected value as shown in Fig. 5.13. The value of α corresponding to a pot position has therefore been read from

TABLE - II

Sl. No.	POT Position	Corres-ponding α in degree	V_s	I_s	W_1 m.f. = 8	W_2 m.f. = 8	N_r	V_L	I_L	$(W_1+W_2)\times 8$ watts
1	2.0	36.5	450	3.30	42.0	125	831	155.0	4.6	1336
2	2.5	41.5	385	3.30	40.0	124	823	152.0	4.55	1312
3	3.0	46.0	380	3.35	40.0	121	813	150.0	4.5	1288
4	3.5	50.0	365	3.30	40.0	119	801	148.0	4.5	1272
5	4.0	54.0	350	3.30	41.0	116	787	146.0	4.4	1256
6	4.5	58.0	340	3.30	44.0	112	767	142.0	4.35	1248
7	5.0	62.0	320	3.40	45.0	110	742	136.0	4.3	1240
8	5.5	65.5	310	3.50	48.0	107	710	132.0	4.2	1240
9	6.0	67.5	295	3.65	48.0	103	667	124.0	4.1	1208
10	6.5	72.0	280	3.8	48.0	100	622	116.0	3.92	1184
11	7.0	75.0	270	3.9	48.0	96	565	108.0	3.8	1152
12	7.5	78.0	255	4.0	46.0	94	500	85.0	3.5	1120
13	8.0	80.5	240	4.05	44.0	89	425	82.0	3.25	1064
14	8.5	83.0	230	4.07	40.0	84	350	66.0	2.9	992
15	9.0	85.5	220	4.05	37.0	78	268	52.0	2.55	920
16	9.5	87.5	210	3.95	32.0	70	190	36.0	2.2	816
17	10.0	90.0	200	3.80	30.0	64	140	28.0	1.9	752

5.6 LOAD TEST :

The performance of industion machine has been experimently recorded by conducting load test. For this purpose a directly coupled, separately excited d.c. generator feeding a resistive load of contant ohmic value has been considered as load on the machine. Such an arrangement offers a load characteristic where load torque is proportional to speed. The procedure adopted for conducting the load test has been to allow the motor run at highest possible speed (corresponding to lowest firing angle) and adjust the ohmic value of resistance connected across the loading generator so that the current drawn by the induction motor is about 60% of its rated value. The firing angle is now gradually increased with the help of potentiometer (a ten turn calibrated potentiometer is used). Keeping the ohmic value of loading resistance unchanged. Observations of potentiometer marking and corresponding value of α, stator voltage, stator line current, three phase input power to stator, motor speed and voltage, current at generator aramuture terminal are recorded. These observations are shown in Table- II. Load test results when motor is supplied from variac are also recorded for comparison and are given in Table - III.

Since cosine firing principle has been used in the control circuit, the markings on potentiometer could have been calibrated in terms of firing angle α. However the measurement on oscilloscope revealed some difference in the value of α with respect to its expected value as shown in Fig. 5.13. The value of α corresponding to a pot position has therefore been read from

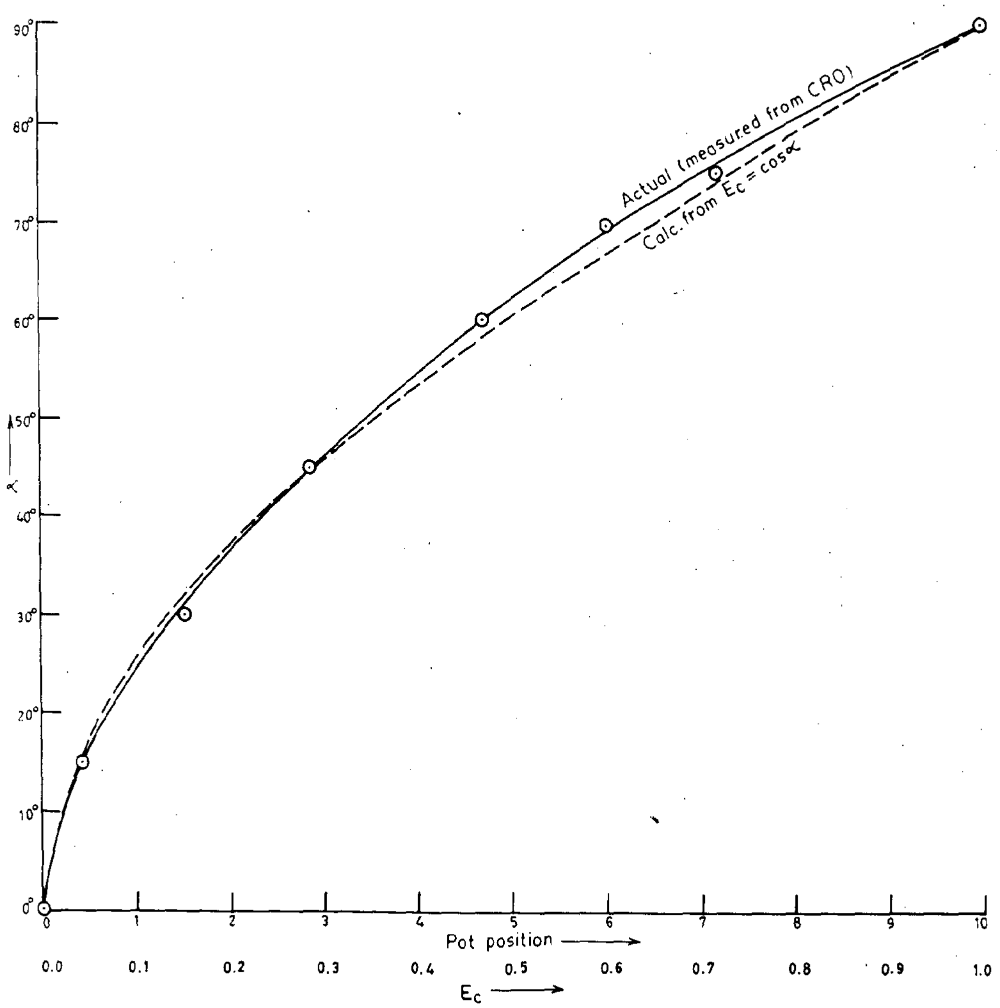


Fig. 5.13. Calibration of potentiometer.

TABLE - II

Sl. No.	POT Position	Corres-ponding α in degree	V_s	I_s	W_1 m.f. = 8	W_2 m.f. = 8	N_r	V_L	I_L	$(W_1+W_2)\times 8$ watts
1	2.0	36.5	450	3.30	42.0	125	831	155.0	4.6	1336
2	2.5	41.5	385	3.30	40.0	124	823	152.0	4.55	1312
3	3.0	46.0	380	3.35	40.0	121	813	150.0	4.5	1288
4	3.5	50.0	365	3.30	40.0	119	801	148.0	4.5	1272
5	4.0	54.0	350	3.30	41.0	116	787	146.0	4.4	1256
6	4.5	58.0	340	3.30	44.0	112	767	142.0	4.35	1248
7	5.0	62.0	320	3.40	45.0	110	742	136.0	4.3	1240
8	5.5	65.5	310	3.50	48.0	107	710	132.0	4.2	1240
9	6.0	67.5	295	3.65	48.0	103	667	124.0	4.1	1208
10	6.5	72.0	280	3.8	48.0	100	622	116.0	3.92	1184
11	7.0	75.0	270	3.9	48.0	96	565	108.0	3.8	1152
12	7.5	78.0	255	4.0	46.0	94	500	85.0	3.5	1120
13	8.0	80.5	240	4.05	44.0	89	425	82.0	3.25	1064
14	8.5	83.0	230	4.07	40.0	84	350	66.0	2.9	992
15	9.0	85.5	220	4.05	37.0	78	268	52.0	2.55	920
16	9.5	87.5	210	3.95	32.0	70	190	36.0	2.2	816
17	10.0	90.0	200	3.80	30.0	64	140	28.0	1.9	752

TABLE - III

Sl. No.	V_s volts	I_s Amp.	W_1 Watts	W_2 Watts	N_r rpm	V_L Volts	I_L ampere	(W_1+W_2) xm.f.(8) Watts
1	400	3.3	37.0	122.0	850	152.0	4.5	1272
2	380	3.3	40.0	119.0	832	150.0	4.5	1272
3	360	3.3	42.0	112.0	812	146.0	4.4	1232
4	340	3.4	44.0	110.0	786	142.0	4.4	1232
5	320	3.5	45.0	105.0	754	134.0	4.3	1200
6	300	3.6	47.0	102.0	710	128.0	4.2	1192
7	280	3.7	45.0	100.0	654	118.0	4.0	1160
8	260	3.9	45.0	95.0	583	108.0	3.7	1120
9	240	4.0	40.0	90.0	504	94.0	3.5	1040
10	220	4.1	35.0	85.0	397	74.0	3.1	960
11	200	4.1	30.0	80.0	290	56.0	2.6	880

the solid line curve of fig. 5.13.

Fig. 5.14 shows the range of speed control that could be obtained by varying firing angle. Speed control in almost entire subsynchronous region is realised.

Fig. 5.15 shows the variation of speed against stator voltage as firing angle is varied. Also shown in the same figure is speed and stator voltage relationship under sinusoidal supply (variac control). At a given speed the required load torque is developed by the motor at a higher voltage when supplied from regulator with respect to sinusoidal supply. This is due to the fact that under non sinusoidal supply from regulator the motor develops in addition to forward torque, a negative torque too, corresponding to harmonic voltages and currents. Thus in order to develop same average torque the motor must develop more positive torque and hence more stator voltage.

Fig. 5.16 shows the nature of stator current variation with speed under regulator supply as well as variac supply. It is noted that the nature of current variation is same in both the cases and the magnitude of stator current is also nearly same at a given speed.

Fig. 5.17 shows variation of total input power with respect to speed under regulator as well as variac supply. Where as the power output of the motor at a given speed is same in both the cases (since the load demands a particular value of torque at a given speed), the input power to the motor is seen to be more in the case of thyristor control. The additional power is obviously goes as a loss in the motor on account of loss contribution of harmonic currents.

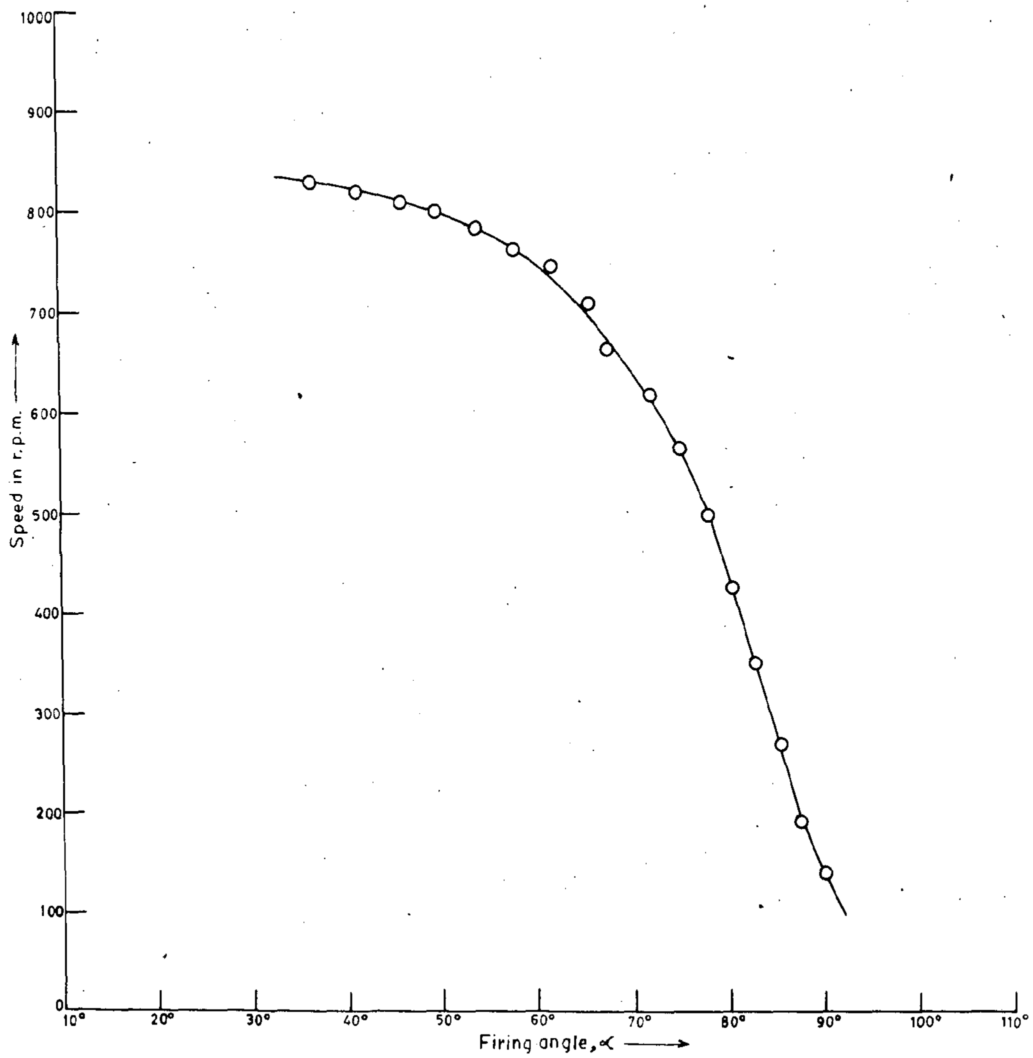


Fig. 5.14. Speed control by variation of α.

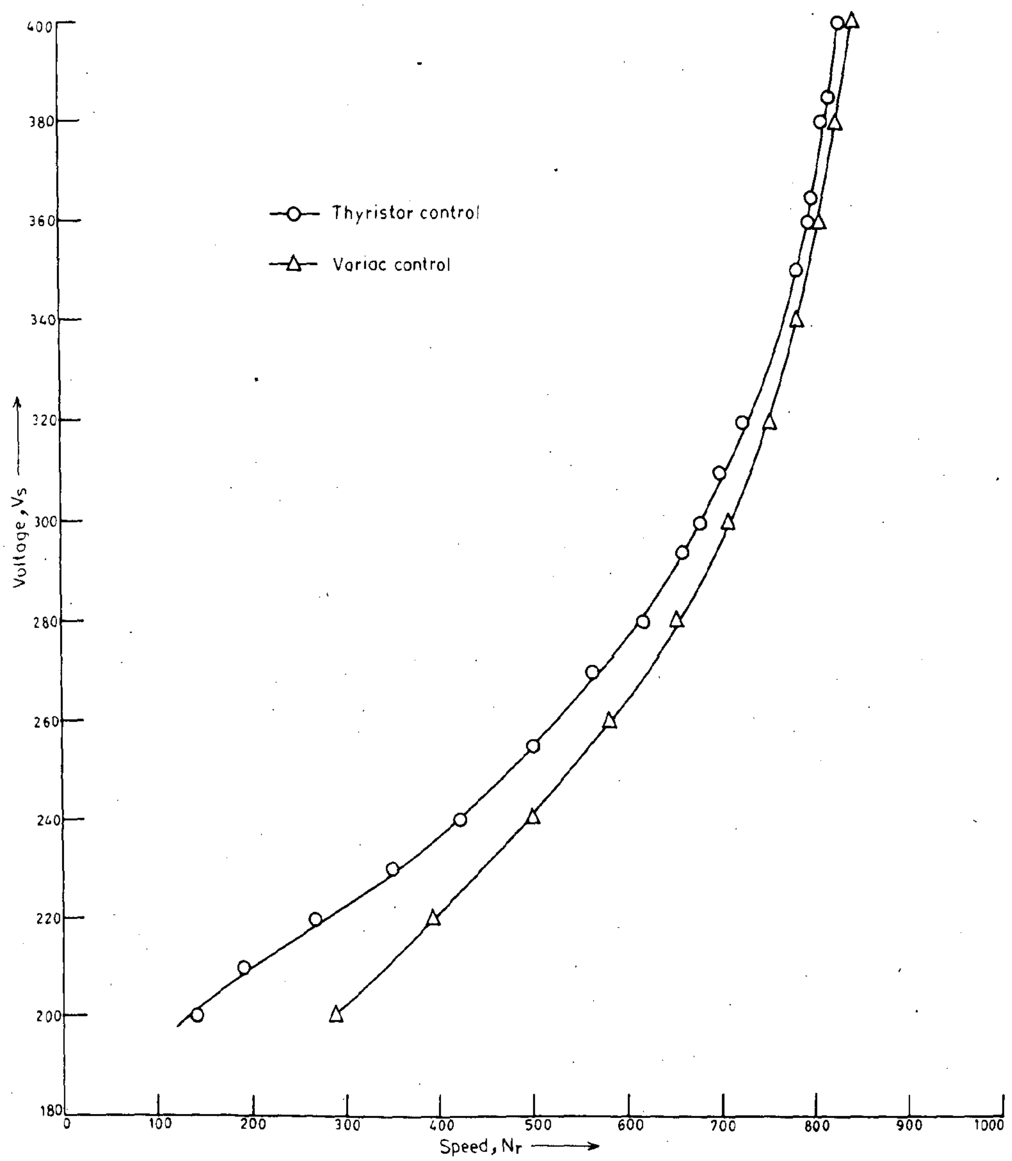


Fig. 5.15. Stator voltage vs. speed.

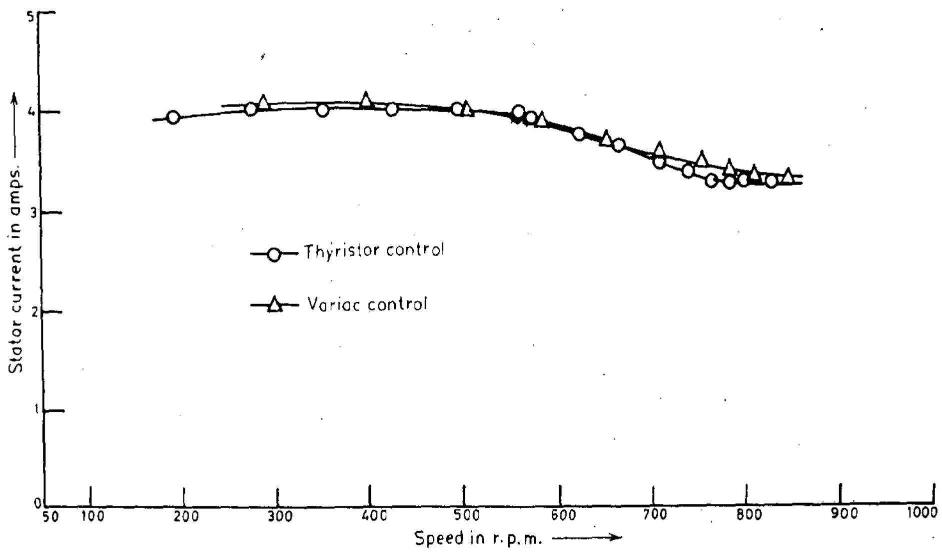


Fig.5.16. Stator current vs. speed.

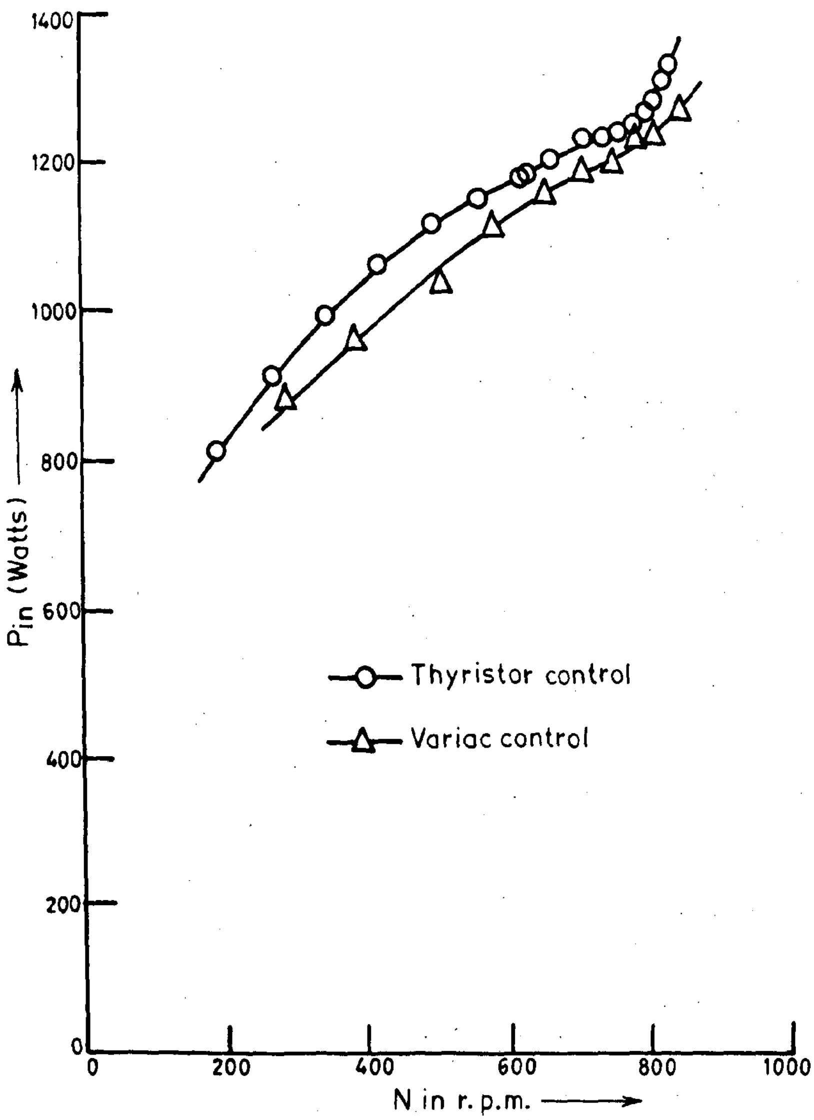


Fig. 5.17. Total power vs. speed.

The load test results indicate that motor performance has more or less same nature as under variac control. Further for a d.c. generator type of load the scheme of speed control through a.c. regulator is found satisfactory.

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CHAPTER - VI

CONCLUSIONS

In present dissertation an a.c. regulator suitable for providing stator voltage control for a three phase squirrel cage Ind. Motor with antiparallel SCRs in each phase triggered from suitable control circuit. It is well known that a regulator with above configuration feeding a star connected induction motor offers better performance than a regulator with any other configuration. It is also on established fact that stator voltage control is a feasible method of speed control for induction motors having relatively high rotor resistance and driving a pump/ fan type of load.

The main aim of present work was to fabricate a three phase a.c. regulator along with a suitable control circuit. The regulator has been successfully fabricated and tested on both resistive and motor load. The waveforms of voltage and current and the results of load tests are found to be in line with those available in literature on this subject. The waveforms and load test results have been explained with qualitative comments. Speed control between wide limits in subsynchronous region has been obtained.

The voltage and current waveforms are found to be substantially same for delta and isolated neutral star connection. In the case of star connection with neutral connected to supply neutral the potential of star point is always zero and hence thyristor pair in each phase can function independently permitting the regulator to conduct current even when only one thyristor is able to conduct. This allows the highest firing angle to be increased beyond 120^{o}, which is the limit in the other two connections investigated.

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