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MICROPROCESSOR BASED OPTIMAL DIGITAL POSITION
CONTROL WITH A.C SQUIRREL CAGE
MOTOR

by

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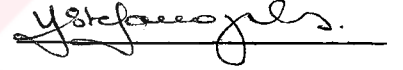
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MICROPROCESSOR BASED OPTIMAL DIGITAL
POSITION CONTROL WITH A.C.
SQUIRREL CAGE MOTOR

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ABSTRACT

The aim of this project is to adjust the speed of a three phase squirrel cage induction motor to any desired value between zero and its rated value, using power electronics components and a microcomputer, and to develop a controlling system which will be able to transfer a load from any initial position to a desired position in minimum time, under some restrictions.

The main parts of the system are, a microprocessor, a converter, an inverter, a main control unit, a three phase squirrel cage induction motor and a tachometer.

MICROPROCESSOR BASED OPTIMAL DIGITAL POSITION CONTROL WITH
A.C. SQUIRREL CAGE MOTOR

CHAPTER 1

INTRODUCTION

The aim of this project is to adjust the speed of a three phase squirrel cage induction motor to any desired value between zero and its rated value, keeping the rotational torque at its maximum value using power electronics components and microcomputer, and to develop a controlling system which will be able to transfer a load from any initial position to a desired final position in minimum time under some restrictions.

The block diagram of the system is as shown in Fig.1.1.

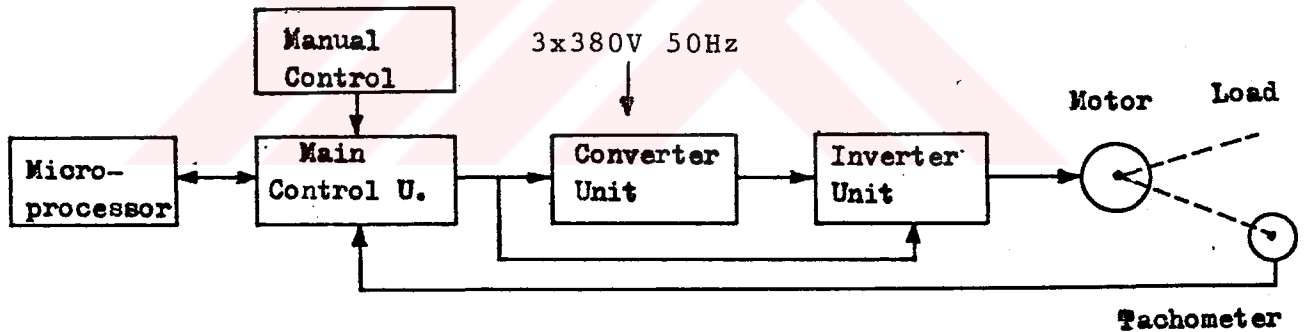


Fig. 1.1. The block diagram of the position control system.

As known it is more difficult to adjust the speed of a three phase squirrel cage induction motor by keeping the rotational torque at its rated value than doing the same operation in d.c. motors. It is an obvious fact that three phase squirrel cage induction motors cannot start under load when they are supplied by a constant frequency constant voltage power supply. However the squirrel cage induction motors are preferred for the following reasons.

- 1- Their production is easy and relatively cheaper.
- 2- They need low maintenance, have long lives, and they are suitable to heavy duty conditions.
- 3- They can work in dirty and moisture damp ambients.
- 4- As they do not generate any sparks, they can be used in every kind of places where there are explosive gases and other flammable materials.

It is because of the mentioned characteristics that squirrel cage induction motors are preferred to be used in speed and position control systems. But it is necessary to design a unit that controls the speed of the squirrel cage induction motor while keeping its rotational torque at its maximum value like a d.c. shunt motor.

The design suggested in the block diagram of Fig.1.1. satisfies the above conditions and also is capable of transferring a load from one position to another desired position at minimum time under the control of a microprocessor.

The functions of each unit shown in the block diagram can be summarized as follows:

1- Converter Unit

The converter unit depending on a control voltage, ranging between 0-10V, supplied by the main control unit, converts the voltage of the 3x380V 50 Hz three phase power supply, to a d.c. voltage which is adjustable between 35V and 450V. Additionally, in times when energy in the system is to be given back to the power supply, the converter allows the energy to flow from the motor to the network, that is; it operates as a dual converter.

2- Inverter Unit

The inverter, linearly depending on a control voltage between 0-10V coming from the main control unit, transforms the adjustable d.c. voltage coming from the converter into an approximate sine wave which has 12 steps. This unit has been designed so as to allow the energy to flow from the power supply to the motor and vice-versa. Thyristors and diodes of 50 Hz have been used as power electronic components.

3- Main Control Unit

Depending on manual control or microprocessor speed reference values and direction control commands, the main control unit sends necessary control voltage signals to the inverter and converter units to provide the rotation of the motor at desired speed and direction, keeping its rotational torque at its maximum value. Namely, based on speed control values coming from the microcomputer or the manual control unit, the main control unit sends necessary commands to the inverter and converter units to adjust the effective value and frequency of the voltage to be applied to the motor to rotate it at a desired speed at its maximum rotational torque.

4- Tachometer

The tachometer provides the feedback about the actual speed of the motor to the main control unit. As a result of this, fluctuations from the desired speed value are minimized.

5- Manual Control Unit

Manual control unit is composed of a direction change switch, a start-stop button and a speed adjustment potentiometer. It allows the user to send manually the information about speed and direction to the main control unit.

6- Microprocessor Unit

The Microprocessor unit gives the necessary commands to the main control board to transfer the load which needs position change, in minimum time from some position to a desired position. The distance to be travelled, the starting and stopping acceleration may be entered to the microcomputer through the keyboard. The microprocessor integrates the speed data with respect to time to calculate the distance covered by the load whose position is controlled. The display on the microcomputer unit displays the speed and the travelled-distance of the load. The microcomputer is capable to make the motor trace any speed-time profile, with some restrictions, by changing the program in the EPROM.

It is possible to make the load travel from one position to another position tracing a given speed-time profile and, wait there for a predefined time and then travel to another position automatically, by changing the program of the EPROM.

The designed and realized system can be used in the following applications.

- 1- Lifts
- 2- Conveyors
- 3- Trains
- 4- Robotics
- 5- Production lines
- 6- Any type of position control systems with high power

The designed system has the following advantages with respect to its counterparts, with regard to the inverter-converter unit and the type of motor used in the system:

- 1- Since the system uses a squirrel cage three phase induction motor it has all of the advantages of using a

squirrel cage induction motor, which have been mentioned above.

2- Since the inverter and converter units allow the energy to be fed back to the power supply, the potential and kinetic energy stored on the load is fed back to the supply or network during braking or lowering times. So energy saving is provided.

3- Since 50 Hz thyristors are used in the inverter unit and the wave shape of the output of that inverter is a approximate sinewave with 12 steps, the system is cheaper, more efficient, and can provide the sufficient power for driving the three phase squirrel cage induction motors.

At high power ranges, 50 Hz thyristors, are cheaper more durable and have less losses during conducting or blocking times than power transistors, F thyristors, and G.T.O's of the same power range.

The voltage applied to a three phase squirrel cage ac motor is not required to be a sinewave without harmonics to drive it. However more harmonics cause overheating in the motor and rotating with steps in lower frequencies.

Since the output wave shape of the designed and realized inverter is a sinewave approximation with 12 steps per period it has less harmonics in comparison with the commercial inverters whose output is a sinewave approximation with 6 steps per period. But it has more harmonics in comparison with the output wave shape of a inverter which uses pulse-width modulation. However in the inverter which uses pulse-width modulation a thyristor is turned-on and off many times during one period of the output wave; that is it has more turn-off losses. In the designed inverter which gives a sinewave approximation output with 12 steps, a thyristor is turned-on and turned-off only once during one period of the output

wave. Because of that the inverter which uses pulse width modulation operates with more energy losses than the inverter which gives an approximate sinewave output with 12 steps.

Consequently, the inverter which provides an approximate sinewave output with 12 steps, and uses 50 Hz thyristors operates the motor without overheating, reduces the tendency of the motor to rotate at step-like fashion at low frequencies, and operates with less power losses. Briefly it is the most suitable inverter to be used to drive three phase squirrel cage induction motors. In addition with respect to component production with possible maximum power rates, thyristors of large power ratings are produced more easily than F-thyristors, G.T.O's or power transistors of similar ratings, that is in high power rates 50 Hz thyristors have no competition.

In the light of the required specifications and the comparisons mentioned above the system described as a block diagram in Fig.1.1. has been constructed as a prototype and it has been tested and proved to satisfy all the desired functions and requirements.

In the following sections each unit mentioned above will be examined and presented in more detail.

CHAPTER 2

THREE-PHASE INDUCTION MOTORS AND SPEED CONTROL

Three-phase induction motors are robust, inexpensive compared with d.c. machines, require little maintenance and have a high power-weight ratio because they can be built without slip rings or commutators. Until recently they have been little used for speed control because by classical methods they become increasingly inefficient as speed is reduced below the synchronous value. They have been regarded chiefly as constant-speed machines that operate on a source of constant frequency and potential difference. The evolution of power semiconductor convertors has now reached a stage at which induction motors may be considered as serious rivals to d.c. machines in many speed control systems.

The basic per phase equivalent circuit of an induction motor is shown in Fig. 2.1. This equivalent circuit is suitable for steady state operation.

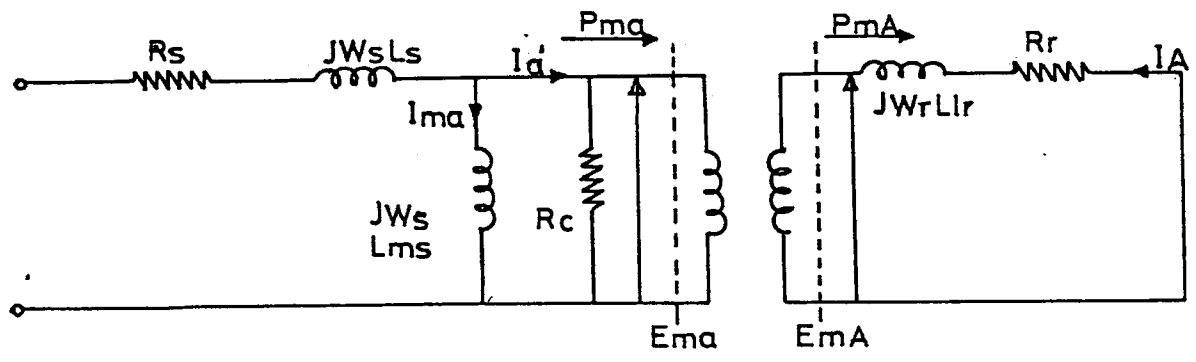


Fig. 2.1. The basic equivalent circuit of an induction motor

In this model some small approximations have been made to account for distributed physical phenomena by lumped circuits.

In this figure;

R_s is the resistance of stator winding

R_r is the resistance of rotor winding

L_{1s} is the leakage inductance of the stator winding

L_{1r} is the leakage inductance of the rotor winding

L_{ms} is the magnetizing inductance of the motor

R_c is the core resistance of the motor.

w_s is the frequency of the alternating current which is applied to the stator windings.

w_r is the rotor angular frequency.

This model can be called an "exact" equivalent circuit.

The following frequency/speed relationship applies to this model:

$$w_r = w_s - \frac{P}{2} w_m \quad (\text{rad/s}) \quad 2.1$$

where

w_m is the angular speed of rotation

P is the number of poles

The slip, s can be defined as follows

$$s = \frac{w_r}{w_s} = \frac{w_s - (P/2) w_m}{w_s} \quad \text{p.u.} \quad 2.2$$

Referring all the variables and parameters of the rotor to the stator the following equivalent circuit can be drawn.

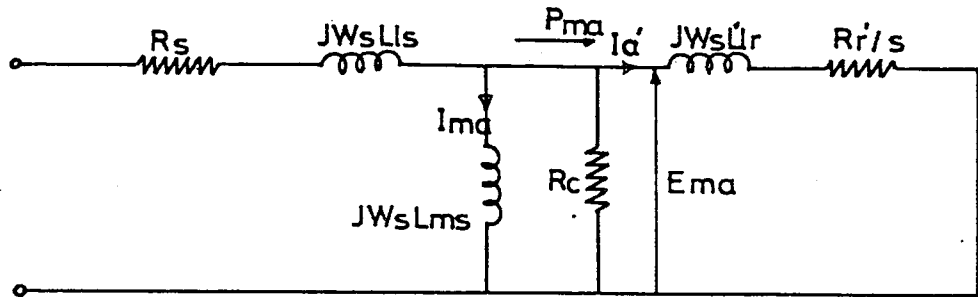


Fig. 2.2. The basic equivalent circuit of an induction motor when all of the parameters referred to the stator

L'_{lr} is the rotor inductance referred to the stator
 R'_r is the rotor resistance referred to the stator

The voltage and the current relations between the stator and rotor windings are as follows.

$$\frac{E_{mA}}{E_{ma}} = s \frac{N_{re}}{N_{se}} \quad ; \quad \frac{I_A}{I'_a} = \frac{N_{se}}{N_{re}} \quad 23$$

where N_{se} and N_{re} are effective number of stator and rotor per phase winding turns respectively.

A rotor circuit impedance \bar{Z}_A is seen by the source supplying the stator as Z'_A and

$$\frac{\bar{Z}_A}{Z'_A} = s \left(\frac{N_{re}}{N_{se}} \right)^2 \quad 24$$

Using the above equations it can be shown that $P_{mA} = s P_{ma}$. Thus the three phase power converted to mechanical form is

$$P_{mech} = 3 (P_{ma} - P_{mA}) = 3(1-s) P_{ma} = 3 \frac{P}{2} \frac{w_m}{w_s} P_{ma} \text{ (W)} \quad 2.5$$

The air gap torque exerted on the rotor is

$$T = \frac{P_{\text{mech}}}{\omega_m} = 3 \frac{P}{2} \cdot \frac{P_{\text{ma}}}{\omega_s} \quad (\text{N.m}) \quad 2.6$$

From Fig.3. it is clear that

$$P_{\text{ma}} = \frac{R'_r}{s} (I'_a)^2$$

Thus

$$T = \frac{3P}{2} \frac{R'_r}{s\omega_s} (I'_a)^2 \quad (\text{N.m}) \quad 2.7$$

The torque-speed characteristic illustrated in Fig.2.3. is typical for a high efficiency machine which is supplied from a constant-voltage constant-frequency source.

A speed range from no-load to a load which would produce stalling is only within about 10 percent of synchronous speed. Consequently the machine is inherently a constant speed motor. However, both because of the induction motor's simplicity and special applications, numerous methods have been found to enable the speed of the induction motor to be adjusted.

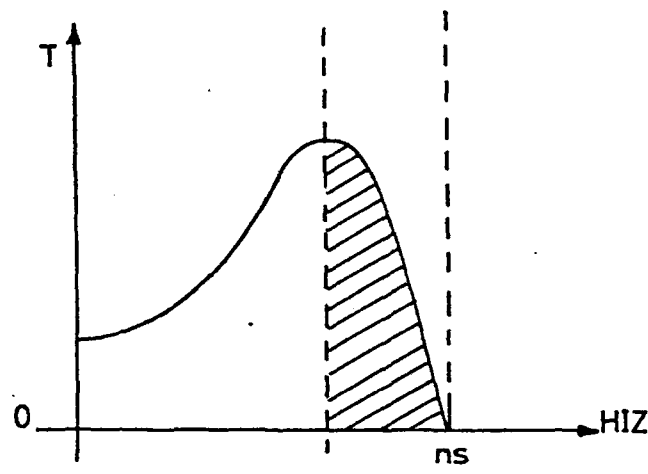


Fig. 2.3. Torque-speed characteristic of a typical induction motor

The methods for speed control of induction motor, that

are also used for starting the motor, are;

- a) Supply frequency
- b) Pole changing
- c) Supply voltage variation
- d) Rotor injected voltage
- e) Rotor resistance
- f) Cascading
- g) Commutator motors
- h) Solid state inverter systems

Because of the high efficiency of the last one, the first seven methods tend to be abandoned for speed control of the induction motor.

For example if the method (c) is used then the Torque speed characteristic becomes as follows.

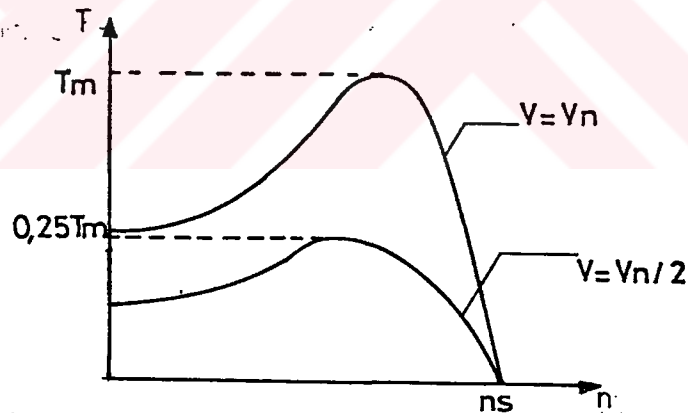


Fig. 2.4. Torque speed characteristics of a induction motor for different terminal voltages

In this system it is clear that by reducing the terminal voltage from V to $V/2$ the breakdown torque is reduced from maximum to maximum/4. This will be shown later that the torque of the induction motor is proportional to the square of the applied voltage.

Inverters (Direct current to alternating current conversion)

Inverters enable a supply of direct current or alternating current of one frequency to be converted to a supply of alternating current at some other frequency or frequencies.

The synchronous speed of an induction motor is the speed of the mmf waveform rotating in the air gap, that is,

$$n_s = \frac{f}{P/2} \text{ rps}$$

where f is the supply frequency and P is the number of poles. The actual rotor speed of a motor with characteristic like that in fig. 2.3 is just less than the synchronous speed and does not alter much with variation of load. Accordingly, for a fixed number of poles, a change in the supply frequency would bring about a proportional change in the synchronous speed and the actual speed would follow in roughly the same manner.

An induction motor is designed to work at a particular flux density, and as the electromagnetic torque is proportional to the magnetic flux, it is necessary to have a high value of flux density without going too far into the saturation region it is usual to work at the knee of the magnetizing curve to get the highest torque for low losses. If the applied voltage can be said to be almost equal to the induced emf. then from the induced emf. equation.

$$V = k\phi f$$

2.8

where

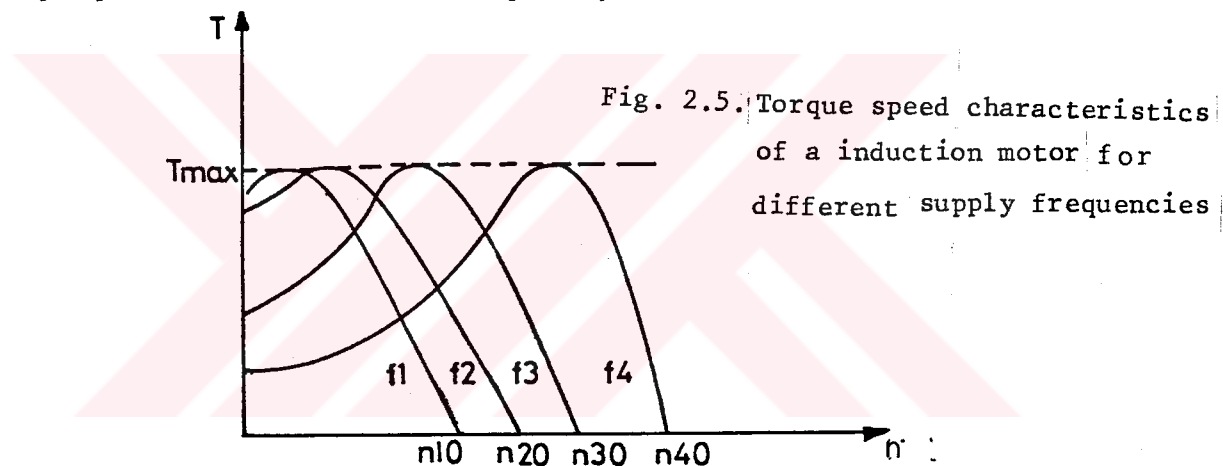
k : constant involving the form factor, the winding factor and the number of turns on the winding,

ϕ : maximum flux per pole

V: rms voltage applied to the motor terminals.

In order that the magnetic flux is kept constant for any frequency, the applied voltage to the induction motor must be adjusted in proportion to the frequency in other words the ratio of applied voltage to frequency should be approximately a constant.

The torque speed characteristic of an induction motor, where supply frequency is adjustable and the terminal voltage is proportional to this frequency, is as follows.



in this figure, f_1, f_2, f_3, f_4 are the supply frequencies and $n_{10}, n_{20}, n_{30}, n_{40}$ are the synchronous speeds corresponding to these frequencies respectively.

The inverter frees the cage induction motor from its inherent limitation of a single speed. There are further advantages in that this machine is relatively cheap to manufacture and there is no need for sliding contacts on slip-rings or commutators. Large induction motor units with inverters now compete more favourably with d.c. units or a.c. commutator units from the aspect of cost, efficiency, maintenance and versatility. These are generalities and there must be many examples of special applications where one of the three types has special advantages over others. But

because of its rugged simplicity the induction motor can be placed almost anywhere while the inverter can be placed in its stationary cubicle wherever it is convenient, and this is a great advantage over the commutator machines. In small systems the cost of the inverter is a great fraction of the total cost but as motor size increases the inverter cost does not increase in proportion and becomes a smaller fraction of the total cost.

Let's now go further into the analysis of the torque and speed of the induction motor.

It was derived that

$$T = \frac{3P}{2} \frac{R'_r}{sW_s} (I'_a)^2 \quad (\text{N.m})$$

From Fig.3. it is clear that

$$I'_a = \frac{\bar{E}_{ma}}{s W_s L'_{lr} + \frac{R'_r}{s}} \quad \text{and}$$

$$(I'_a)^2 = \frac{E_{ma}^2}{(W_s L'_{lr})^2 + \left(\frac{R'_r}{s}\right)^2} \quad \text{so}$$

$$T = \frac{3P}{2} \frac{R'_r}{sW_s} \frac{E_{ma}^2}{(W_s L'_{lr})^2 + \left(\frac{R'_r}{s}\right)^2} \quad 2.9$$

As it is mentioned before, to get the maximum possible torque on the air gap it is necessary to keep the flux density at its maximum or rated value. Since it is well known that the flux density is directly proportional to the current, that is,

$$\phi = k i_{ma}$$

the magnetizing current i_{ma} must be held at its rated value for all frequencies.

$$\text{Thus } E_{ma} = I_{ma} s \omega_s L_{ms} \quad (I_{ma} = I_{ma \text{ rated}})$$

and

$$T = \frac{3P}{2} \frac{R'_r}{s \omega_s} \frac{I_{ma}^2 (\omega_s L_{ms})^2}{(\omega_s L'_{lr})^2 + \left(\frac{R'_r}{s}\right)^2} \quad 2.10$$

Since it is desirable to hold the torque at its rated value for all speeds, for any input frequency ω_s the value of the slip s , that maximizes the air gap torque can be found from 1.5

After finding the slip value for a frequency ω_s ; E_{ma} , ω_m , V_a can be found and so the voltage/frequency ratio of the motor can be found for any frequency. If the motor is supplied by an inverter which output voltage - frequency characteristic is equal to that of the motor then the motor runs always at its maximum efficiency.

CHAPTER 3

1- THREE PHASE DUAL BRIDGE CONVERTER

The designed converter, powered by 3x380V 50 Hz three phase power supply is used to provide a d.c. voltage ranging from 35V to 450V linearly depending on the control signal received from the main control unit. The three phase bridge converter that has been designed comprises 10 thyristors, triggering transformers, a control unit and a filter.

The converter is a dual converter as can be seen from Fig. 3.1. The 6 thyristors on the top enable the energy to flow from the power supply to the system and the 4 thyristors below, from the system to the power supply, in other words the latter allow regeneration. The function of the diode in the circuit is to discharge the energy accumulated in the coil to the capacitor when the thyristors are reverse-polarized by the power supply.

The time relationship of the voltages applied to the a, b, c points of the converter input is shown in Fig. 3.2. The rectified shape of this wave with zero triggering angle i.e. the unclipped rectified shape of this wave is the envelope of the wave given in Fig. 3.2. The d.c. wave shape that can be obtained when the triggering pulses given in Fig. 3.2 are applied to the thyristor in a proper sequence, will be the shaded area in Fig. 3.2. By changing the triggering time of the thyristors, in other words by changing the triggering angle, it is possible to adjust the average value of the d.c voltage at the converter output.

The time-dependent change of the converter output voltage given in Fig. 3.2 is for the case where the output filter is not connected. By introducing a filter element and by adjusting its parameters it is possible to keep the ripples to a minimum at the output voltage. But, these ripples are dependent also on the current drawn by the inver-

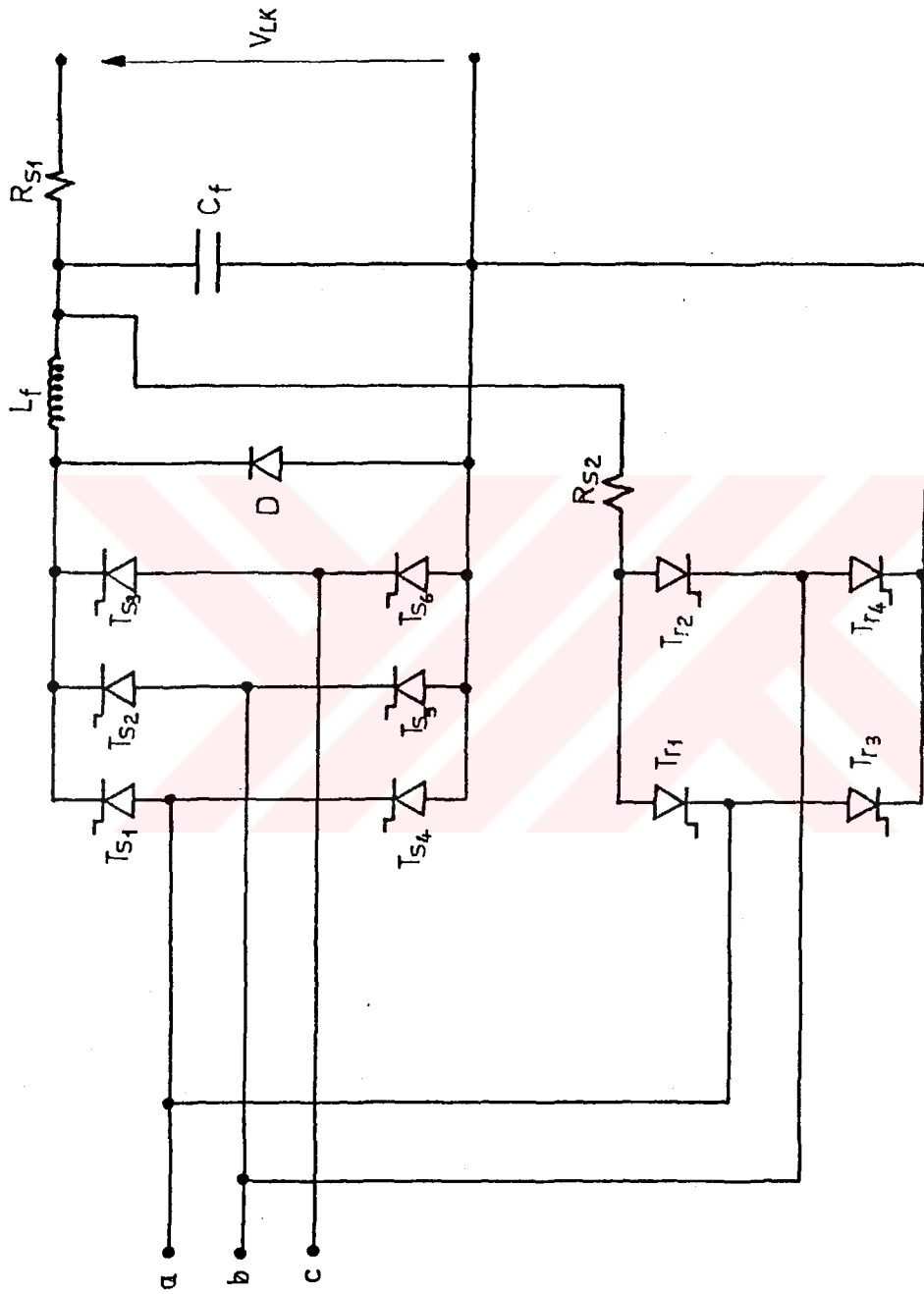


Fig. 3.1. The circuit diagram of the three phase dual bridge converter.

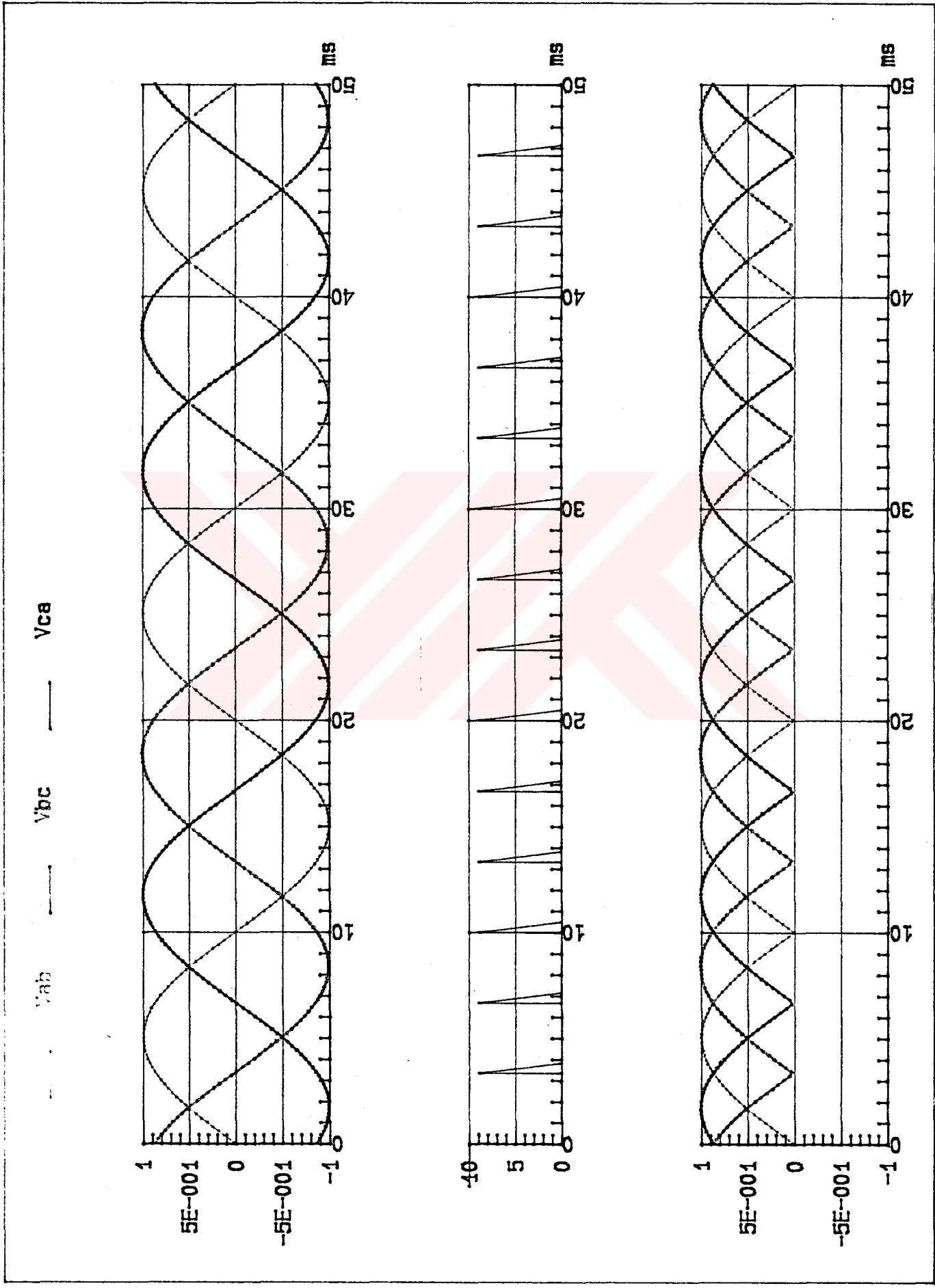


Fig. 3.2 The input output waveform of the converter unit and triggering pulses.

ter unit. When the load current is big, the capacitor value of an ordinary low-pass filter unit must be higher too.

It is advisable to keep the pass-band frequency of the filter at low values as much as possible when choosing the filter elements. But, after a certain value, increasing the values of the filter elements while increasing the cost considerably will not have worthwhile effects in decreasing the ripples.

As can be seen from Fig. 3.21, in cases where the average voltage value is low, the amplitude of the ripples in the output voltage will be higher.

This is due to the fact that in such a case, the difference between the converter output voltage when a thyristor is turned-off, and the converter output voltage when the following thyristor is turned-on, is bigger. That's why when designing filters, the minimum V_{LK} value must be considered in calculating the capacitance of the capacitor and the coil self-inductance. On the other hand, these circuit elements must have a structure suitable to operate at maximum V_{LK} values.

When the energy inherent in the system is fed back to the supply the lower group is turned-on with proper triggering angles.

Here, again, the operating principle is the same, depending on the V_{LK} voltage value and current value to be fed back to the power supply, the thyristors are turned-on with appropriate triggering angles. So the energy inherent in the system is fed back to the power supply in this case the system operates as a generator group. Here, too, the current value to be fed back to the power supply must be retained within certain limits, otherwise the system may be

damaged due to overheating. The point to be taken into account, when the energy is fed back to the power supply, is to trigger a thyristor when the voltage between this thyristor anode and cathode terminal is decreasing in other words the thyristor must be triggered when the derivative of the voltage applied to the cathodes of the thyristors connected to the (+) terminal of the V_{LK} is positive in comparison with the (-) terminal of the V_{LK} . By doing this, energy from the system is discharged back to the power supply till the power supply voltage reaches the V_{LK} voltage value and when the power supply voltage exceeds the V_{LK} voltage value, the energy flowing from the system into the power supply reduces to zero and the thyristors are turned-off automatically. In case of regeneration, the peak value of the power supply voltage must definitely be bigger than the V_{LK} value, otherwise since the thyristors will not be turned-off, they will cause big values of current to pass through the circuit.

In situations where the voltage between the anode (with anode being positive) and cathode terminals of a thyristor is increasing, if the thyristors are triggered, the same result will occur and large values of current will flow in the circuit. An explanation of this can be seen in Fig. 3.3.

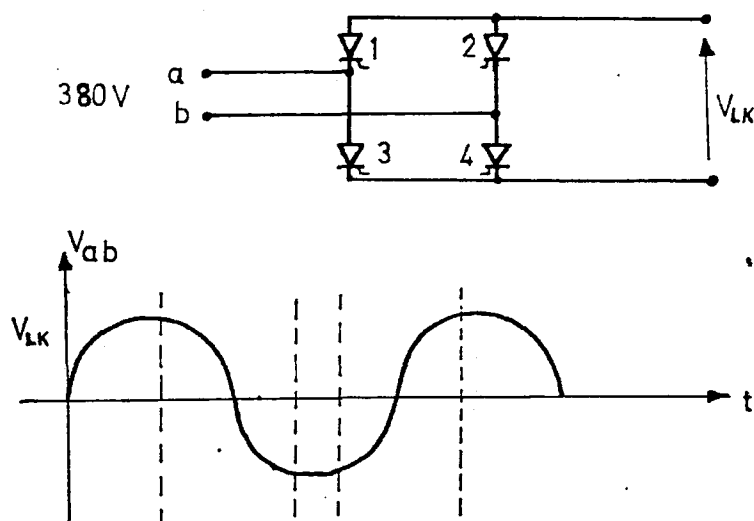


Fig. 3.3. The safety triggering areas for thyristors

CONVERTER CONTROL UNIT

The Converter control board produces the triggering signals, that trigger the thyristors at the proper times for obtaining the necessary V_{LK} value from the power supply or for feeding back the system energy to the power supply, linearly depending on the 0-5V control voltage and energy flow direction command. These triggering signals are transmitted to the G-K terminals of the thyristors by triggering transformers.

The converter control unit circuit diagram is given in Fig 3.5. As it is seen from Fig. 3.5, the voltage with value of $2 \times 15V$, which is obtained by using a transformer connected to the a,b terminals of the power supply, is applied to the (-) inverting input of a comparator after being rectified by a center-tap rectifier and divided by a voltage divider. The voltage which is about 0.2V is applied to the (+) non-inverting input of the same comparator. Therefore a pulse is obtained from the output of that comparator whenever the voltage applied to the (-) input of the comparator falls below 0.2V. This situation is shown in Fig. 3.4.

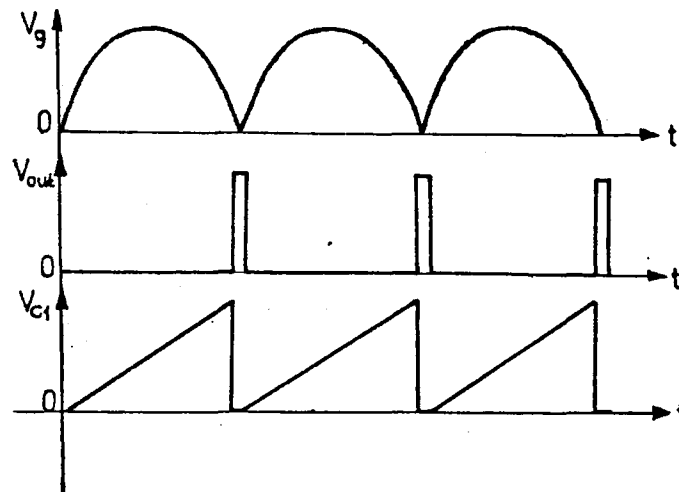


Fig. 3.4. Sawtooth wave between the terminals of the capacitor

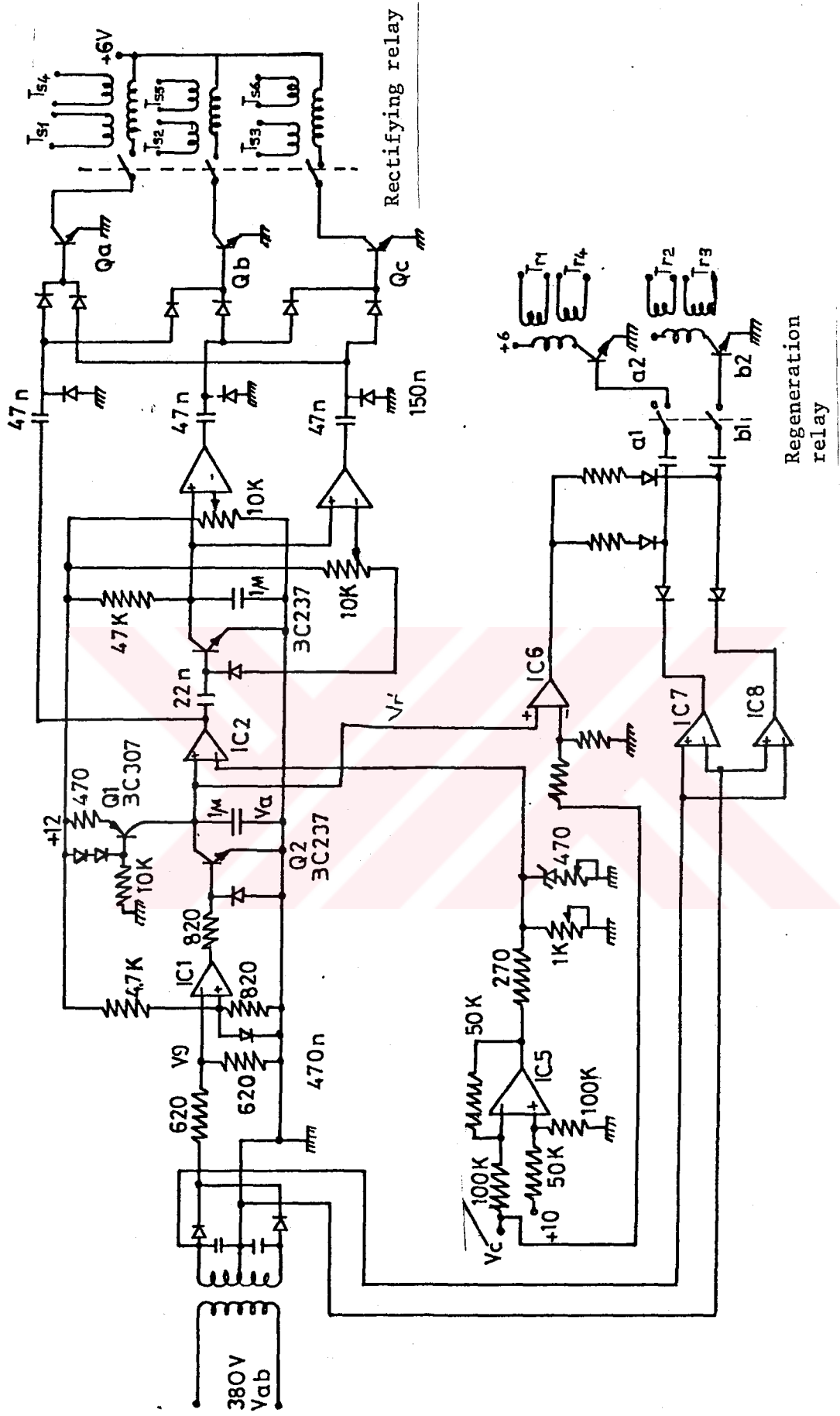


Fig. 3.5. The Converter Control unit circuit diagram.

In the next subunit of the converter there are one capacitor, a current source that charges this capacitor, and a transistor which is connected in parallel to that capacitor. Since pulses obtained from the comparator output are applied to the base of this transistor, whenever the voltage at the output of the divider whose input is connected to the transformer, falls below 0.2V, the transistor Q_2 begins to conduct and discharges the capacitor. By the moment that Q_2 does not conduct, capacitor C is charged with a constant current by the current source that contains the transistor Q_1 , till the transistor Q_2 again begins to conduct. When Q_2 conducts, the capacitor is again discharged and the above mentioned action continues periodically. The time variation of the voltage at the terminals of the capacitor is shown in Fig. 3.4!

This saw-tooth voltage obtained in this manner and synchronized with the power supply voltage is applied to the non-inverting (+) input of the IC2. V_r is the triggering angle control voltage. As it is seen here, as the voltage at the terminals of the capacitor gets over V_r , the output of IC2 goes to +Vcc. Since the IC2 output is connected to the base of Q_a by a capacitor, when the IC2 output increases to +Vcc, Q_a begins to conduct and a pulse is obtained from the output of the transformer, whose input is connected to the collector of that transistor. This pulse provides triggering of the thyristor connected to that transformer. 3.33 ms after the output of IC2 becomes +Vcc, the IC3 output and 6.66 ms later the IC4 output becomes +Vcc. When the outputs of the transformers, whose inputs are connected to the transistors Q_a , Q_b , Q_c , are connected properly to the thyristors, forming a three phase bridge, a d.c voltage, the average value of which can be adjusted depending on the V_r reference voltage, is obtained at the bridge output.

As it is seen from Fig. 3.5 whenever the V_r' voltage increases, the moment at which the thyristors are triggered

slides righthands, in other words the triggering angle becomes bigger and the average value of the converter output voltage decreases. That means, the converter output voltage and the reference voltage V_r are inversely proportioned. Because of this, in order to provide a direct proportion between the converter output voltage and the control voltage V_c , it is necessary to make a relation as $V_r' = -V_c + E_1$ between the voltage V_r and the voltage V_c .

This operation which is provided by the circuit given in Fig.35 can be explained as follows.

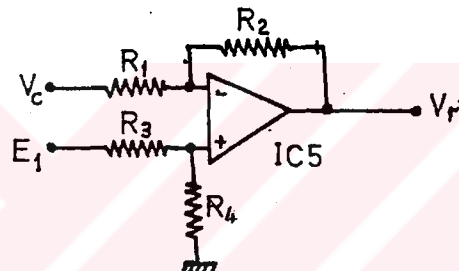


Fig 3.6 The circuit that provides a direct relation between the converter output voltage and control voltage

$$\text{Here } V_r' = -\frac{R_2}{R_1} V_c + \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_3}{R_4}} E_1 \quad 3.1$$

if $R_2 = R_3 = 50 \text{ k}$ and $R_1 = R_4 = 10 \text{ k}$ are chosen then

$$V_r' = -0.5 V_c + E_1 \text{ is obtained.}$$

Since $E_1 = 10 \text{ V}$ is chosen

$$V_r' = -0.5 V_c + 10 \text{ is obtained} \quad 3.2$$

The function of the clamping circuit which is connected to the output of IC5 is to provide the relation $V_{LK} = f(V_c)$ between the converter output voltage and the control voltage, in a desired manner.

The converter control board also contains the control circuit of the regeneration thyristors. Also here a sawtooth voltage, synchronized with the power supply voltage at the terminals of the capacitor, is used.

The converter voltage V_c is applied to the (-) input of the IC6, after being divided by a voltage divider. The sawtooth voltage is applied to the (+) input of the same IC. Consequently, when the sawtooth voltage overflows the reference voltage which is applied to the (-) input of the IC6 the output of the comparator becomes +Vcc; the pulses obtained in this way are used to trigger the thyristors.

IC7 and IC8 comparators sense which thyristors with positive anodes have an decreasing applied voltage at their terminals and allows those thyristors to be triggered. The signal obtained at this step is applied to the triggering transformers after being passed through the regeneration relays contacts and amplified by the transistors. As it can be seen if regeneration relay contacts are open circuited, no current flows to the triggering transformers, and no thyristor is triggered. The voltage divider circuit at the input of IC6 must be adjusted to provide the triggering of the thyristors at the proper times depending on the control voltage V_c . As it is seen from the circuit diagram, IC7 and IC8 comparators, give triggering permission only to the thyristors whose anode voltage, with respect to (-) terminal of d.c link, V_{LK} , is decreasing towards zero. Thus thyristors triggering angles are guaranteed to be between 0° and 90° . As a result of this, if the peak value of the power supply voltage is greater than V_{LK} , thyristors are always turned-off automatically when the instantaneous value of the power supply voltage is approaching to the link voltage value, V_{LK} . Here the controls of the rectifying and regeneration relays are supervised by the main control unit.

The voltage V_{LK} , which is obtained by the converter unit from a 3x380V 50 Hz power supply, is a d.c voltage whose average value can be adjusted as mentioned above.

This voltage is fed to the inverter unit to obtain a suitable approximate sinewave voltage that provides the rotation of the motor at certain constant speed values.



CHAPTER 4

THREE PHASE BRIDGE INVERTER

The inverter circuit, converts, the adjustable d.c. voltage taken from the converter to a 12 step approximate sinusoidal alternating voltage. The realized inverter is composed of 6 main thyristors 6 auxiliary thyristors, 6 regeneration diodes, 12 auxiliary diodes, opto-couplers and some control components. The power circuit diagram of the inverter is shown in Fig.4.2 and the triggering signals which are applied to the thyristors are shown in Fig.14. These signals are produced by the inverter control board. The frequency of these signals can be adjusted between 3.33 Hz and 52 Hz, being linearly dependent on the 0-10V control voltage which is applied to the board.

As it is seen from the triggering signals, when a main thyristor is turned off, the auxiliary thyristor which belongs to that thyristor is turned on; and the auxiliary thyristor is turned-off by itself before the main thyristor is turned on for the second time. The reason for this is that; the value of the current which flows through the auxiliary thyristor is less than the holding current, I_H . Thyristors numbered 1-4, 3-6, 5-2 are connected in series as 3 couples. When one thyristor of those couples conducts the second is turned-off. Otherwise a short circuit, which can damage the thyristors can take place. To prevent the thyristors from such a bad case, which is caused by some wrong triggering signals or some turn-off problems of the thyristors, opto-couplers are added to the circuit as locking elements.

Since the necessary condition to turn-on a thyristor is that the second thyristor must be turned-off, when one of the thyristors, which are connected in series, is to be turned on, it is necessary to consider the state of the second one,

and if the second one is blocking then the first one must be allowed to be turned on.

This is achieved by connecting opto couplers to the thyristors, which are connected in series, as in Fig. 4.1.

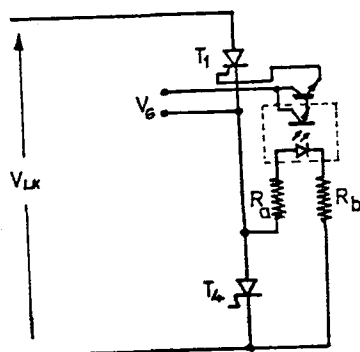


Fig. 4.1. Connection of the opto couplers to the thyristors.

As it is seen from the circuit when the thyristor T4 is conducting the voltage across its terminals is approximately zero and because of that no current flows through the LED of the opto coupler. As a result of that, the photo transistor which is inside the opto-coupler cannot conduct. So T₁ cannot be triggered even if a triggering signal is applied to it. Here the resistance Ra+Rb limits the current of the LED when the value of V_{LK} is high. To minimize the energy which is spent on these resistances the current which flows through them must be low. But such a low current necessitates to put a transistor to the output of the opto-coupler in darlington configuration to supply enough current for triggering the thyristor.

As it is seen from the triggering signals of the thyristors, which are given in Fig. 4.3, two thyristors which are connected in series cannot be turned-on simultaneously but can be turned-off, and that the maximum number of thyristors in the circuit which can be on simultaneously is 3.

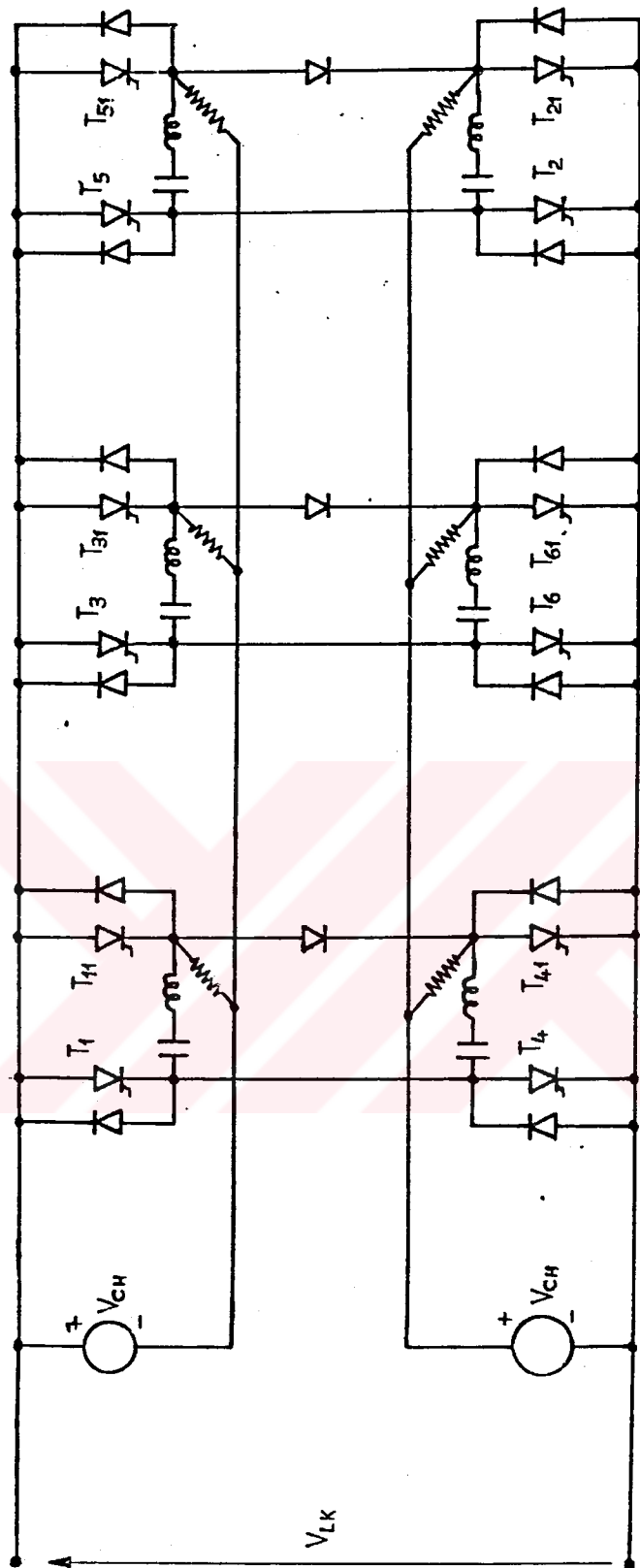


Fig. 4.2. The power circuit diagram of the inverter

The triggering signals, which are given in Fig. 4.3, are used as information signals to modulate the carrier signals which have a frequency of 10 kHz. The carrier signals which are obtained after the above mentioned process and whose envelope is equal to the signals given in Fig. 4.3, are applied to the thyristors gates via triggering transformers and opto-couplers.

The reason for using triggering signals in the form of pulse train is to provide fast triggering and to reduce the triggering losses. When these triggering signals are applied to the gates of the thyristors, and if the load which is connected to the output terminals of the inverter is a purely resistive load, the output wave of the inverter becomes as in Fig. 4.5. The output voltage steps $V_{an} = 1/3 V_{LK}$, $V_{an} = 1/2 V_{LK}$ and $V_{an} = 2/3 V_{LK}$ can be seen easily from Fig. 4.4. As it is seen from Fig. 4.5, the phase-neutral voltage of the output voltage of the inverter, consists of 12 steps per period.

The process; motor rotation direction changing or inverter output voltage phase sequence changing is done by changing the sequence of the thyristor triggering signals. This process is done by changing the phase sequence of the triggering signals before they are applied to the triggering transformer by subminiaturized relays.

As it is known, motor rotation direction changing can also be done by changing the phase sequence of the output voltage of the inverter, by using power relays or semiconductor switches at the output of the inverter. But in this case power loss on these components will be more and since these are bigger than the subminiaturized relays used in the control circuit, the cost will be more too. Because of this reason, in this project the first method is used to change the motor rotation

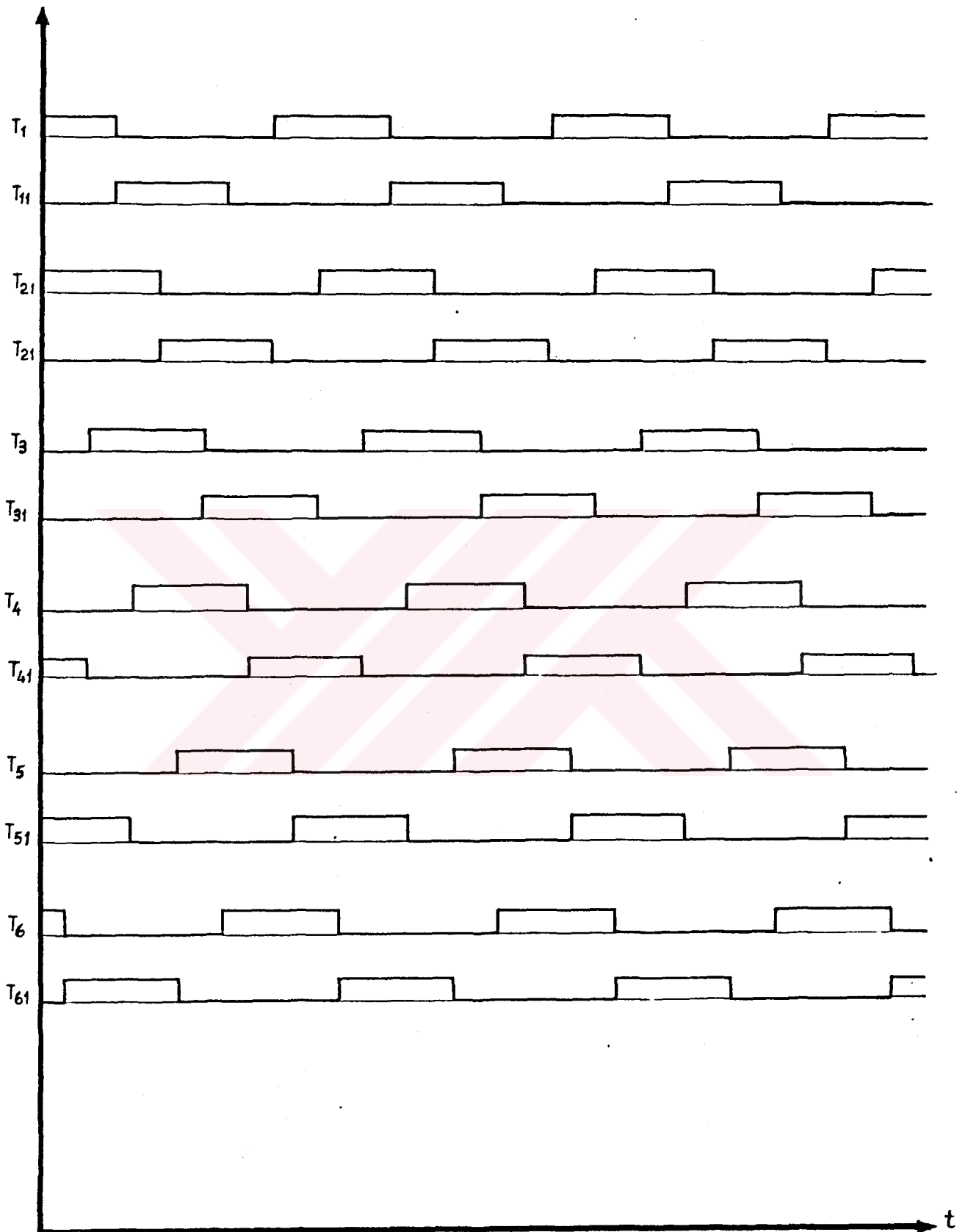
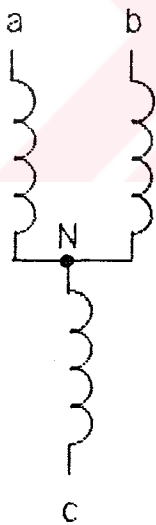
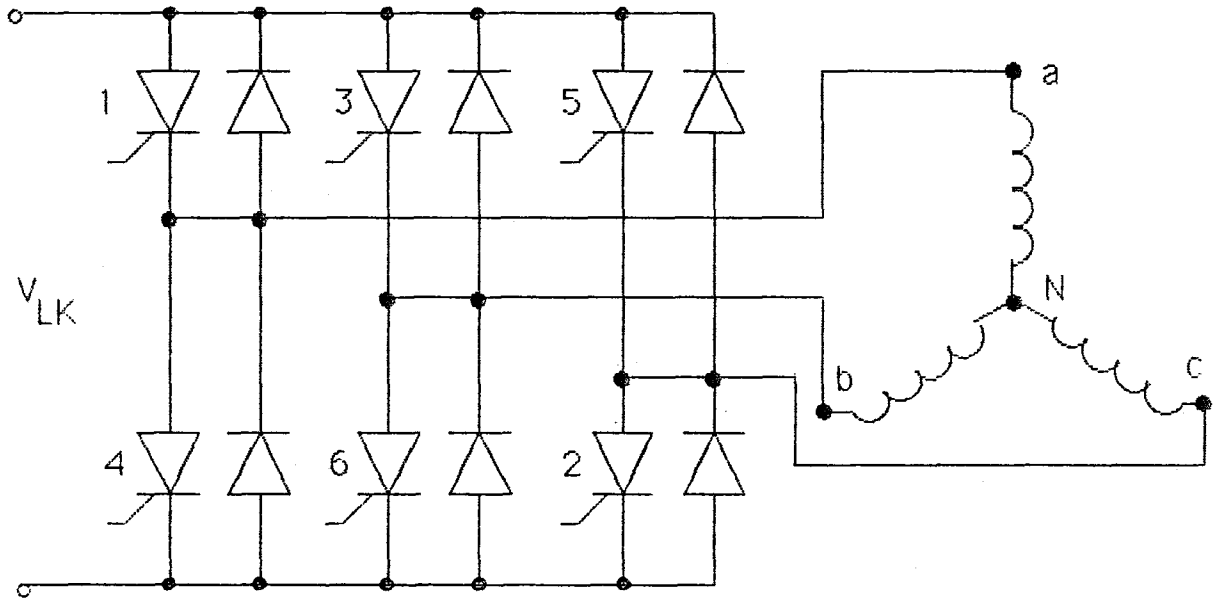


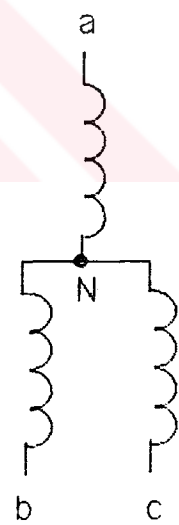
Fig. 4.3. The triggering signals which are applied to the thyristors



$$V_{an} = \frac{1}{3} V_{LK}$$



$$V_{an} = \frac{1}{2} V_{LK}$$



$$V_{an} = \frac{2}{3} V_{LK}$$

Fig. 4.4. Obtaining the voltage steps of the inverter output.

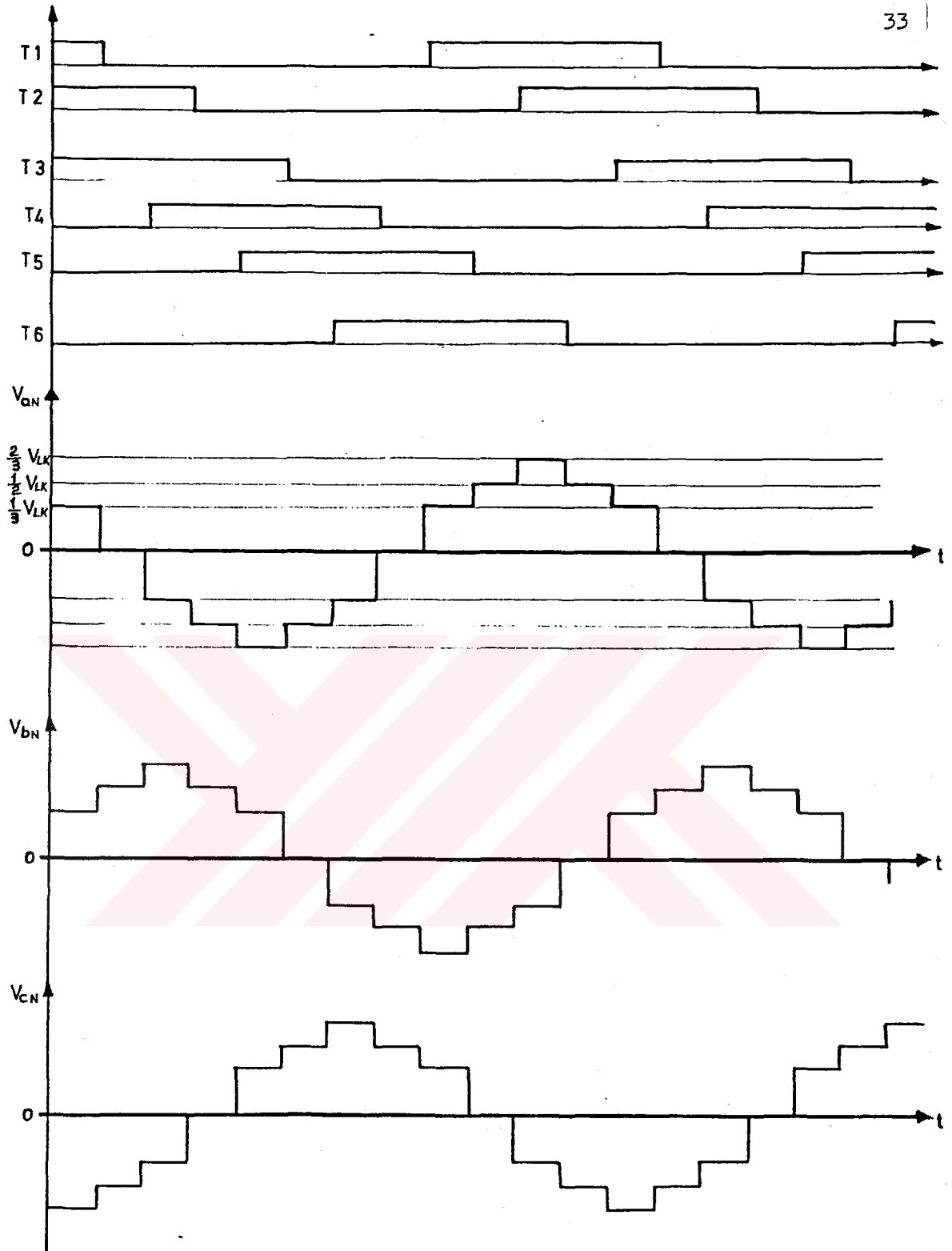


Fig. 4.5. The output waveform of the inverter when the load is purely resistive and output filter is not connected.

direction.

Inverter Control Board

The inverter control board is composed of one voltage/frequency converter which convert the applied the 0-10V control voltage to a square wave, one triggering sequencer which produces 12 triggering signals with constant phase sequence from that square wave to trigger the thyristors with appropriate sequence, one modulator and triggering transformers.

As it is seen from Fig. 4.6. the voltage/frequency converter is composed of one TSC9400 V/F converter and one divide-by-two counter. The $f_o/2$ output of the V/F converter is given to the input of the divide-by-two counter thereby V/F has been buffered and the input voltage which is necessary to get the desirable frequency output has also been dupliated. So since the input voltage has been duplicated the probability of picking up noise will be low and the stability of the V/F converter will be better. For this circuit the frequency/voltage ratio is.

$$f_{out}/V_{in} = 250 \text{ Hz/Volt} \quad 4.1$$

The pulses, which are taken from f_{out} output, are applied to the triggering sequencer, which is given in Fig. 4.7. The binary counter which is connected to the triggering sequencer is designed to count between 0 and 11, that is it gives 12 binary numbers between 0 and 11. Those numbers are encoded by logic gates to get the constant phase sequence triggering signals given in Fig. 4.8. The truth table of the sequencer is given in Table 4.I The relation between the frequency of the sequencer's output signals and the frequency of the counter's output signal is

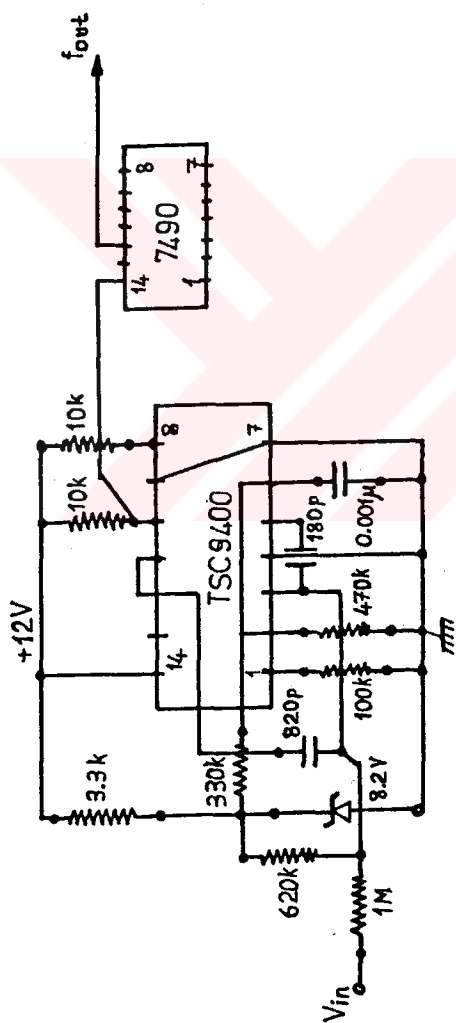


Fig. 4.6. The circuit diagram of the V/F converter.

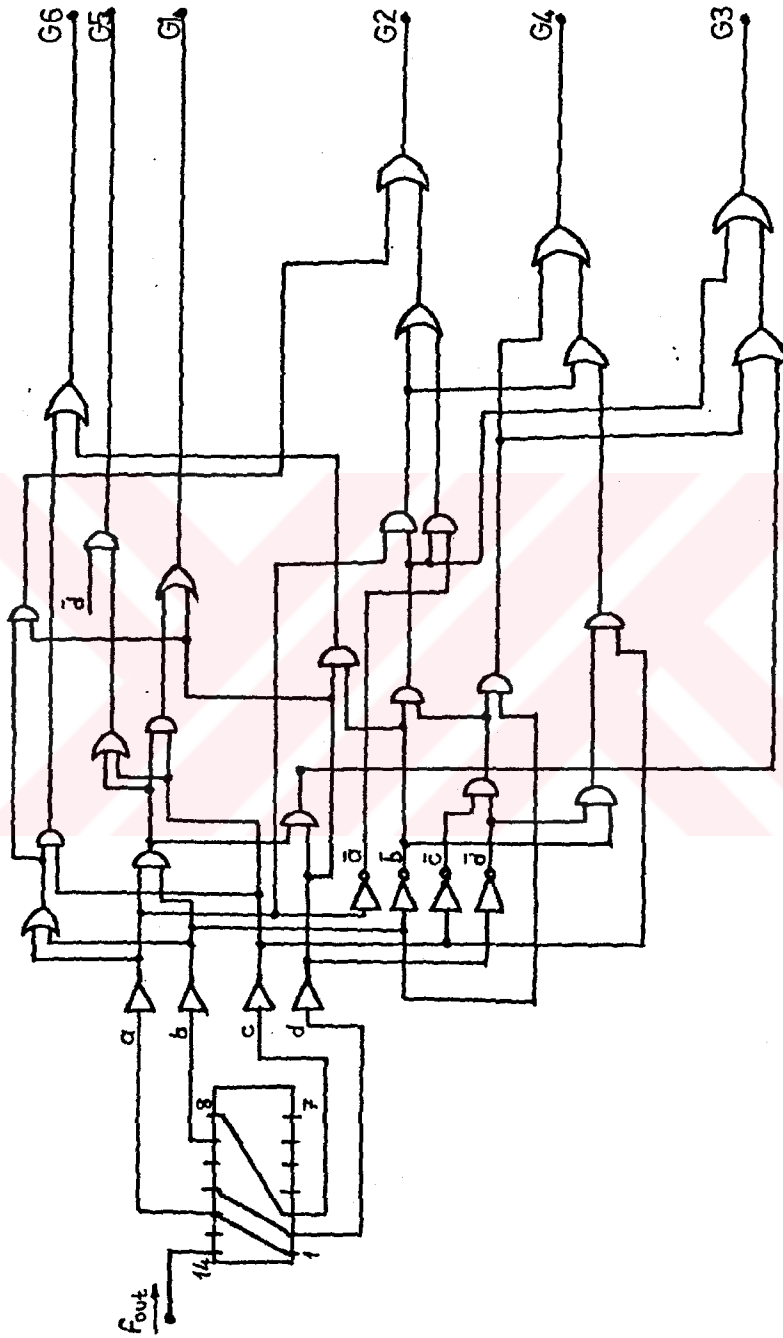


Fig. 4.7. The circuit diagram of the triggering sequencer.

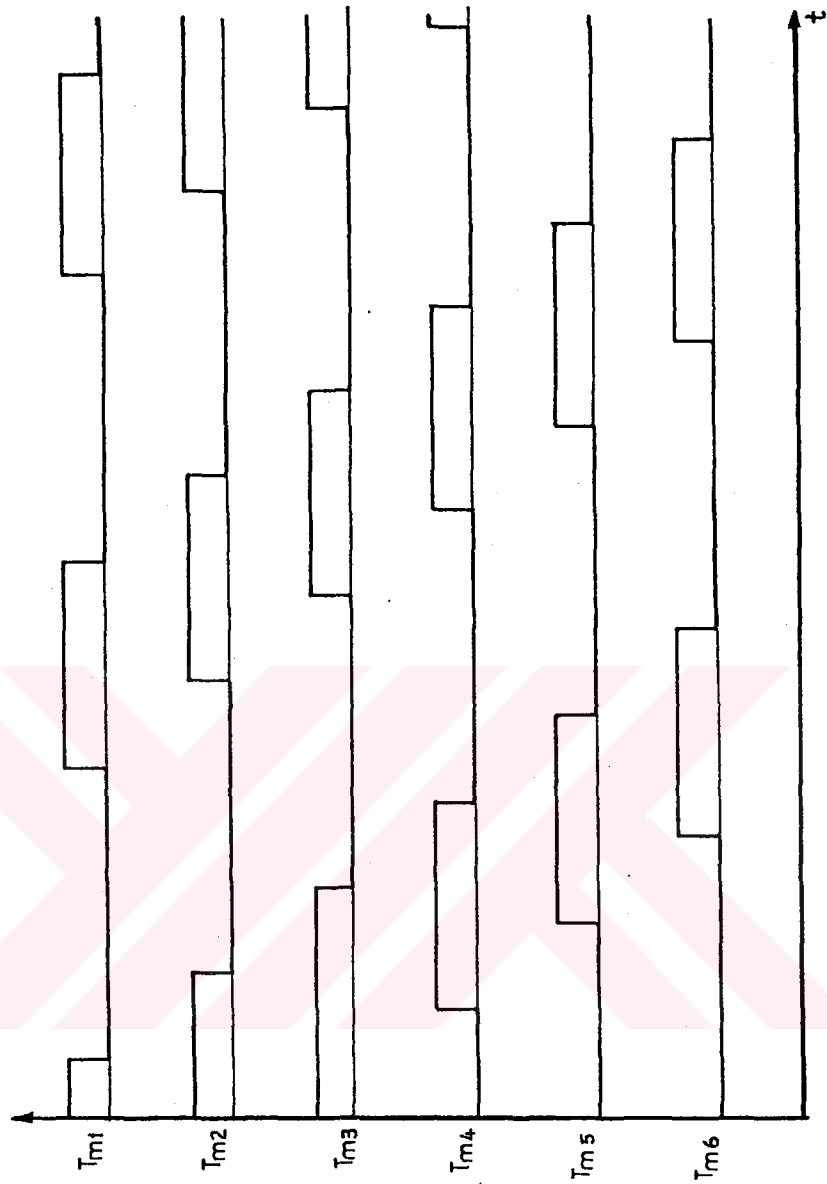


Fig. 4.8. The output waveform of the triggering sequencer

Number	a	b	c	d	G1	G2	G3	G4	G5	G6
0	0	0	0	0	0	1	1	0	0	0
1	1	0	0	0	0	1	1	1	0	0
2	0	1	0	0	0	0	1	1	0	0
3	1	1	0	0	0	0	1	1	1	0
4	0	0	1	0	0	0	0	1	1	0
5	1	0	1	0	0	0	0	1	1	1
6	0	1	1	0	0	0	0	0	1	1
7	1	1	1	0	0	0	0	0	1	1
8	0	0	0	1	1	0	0	0	0	1
9	1	0	0	1	1	1	0	0	0	1
10	0	1	0	1	1	1	0	0	0	0
11	1	1	0	1	1	1	1	0	0	0

G1 = $abc + d$
 G2 = $abcd + abcd + (a+b) d$
 G3 = $abd + bcd + bcd$
 G4 = $bcd + cbd + abcd$
 G5 = $(ab + c)d$
 G6 = $bd + c(a + b)$

Table 4.1. The truth table of the phase sequencer.

$$\frac{f_{\text{out}}}{f_{\text{ts}}} = \frac{12}{1} \quad 4.2$$

Consequently the relation between the frequency of the signals that will be applied to the thyristors and the input control voltage is

$$\frac{f_G}{V_{\text{in}}} = \frac{250}{12} = 20.83 \text{ Hz/Volts} \quad 4.3$$

Signals which are taken from the output of the sequencer are encoded so that the main and auxiliary thyristors are triggered in an appropriate manner and they are buffered before they are used as information signals to modulate the 10 kHz carrier signal.

One of the big problems in designing an inverter with thyristors is "commutation", that is turning-off a thyristor which is conducting a current. Because of that it is necessary to consider this case with more details.

As it is known to turn-off a thyristor it is necessary to satisfy the following conditions.

- 1- The thyristor current must be reduced to zero.
- 2- The thyristor must be reverse biased for a time longer than turn-off time of the thyristor (t_q)
- 3- During the following voltage application, the critical voltage increase rate $(dV/dt)_{\text{cr}}$ must not be exceeded.
- 4- In the case of inductive load an alternative path must be provided.

The first and second conditions are satisfied by choosing capacitors and coils with suitable values, and charging the capacitor with enough energy.

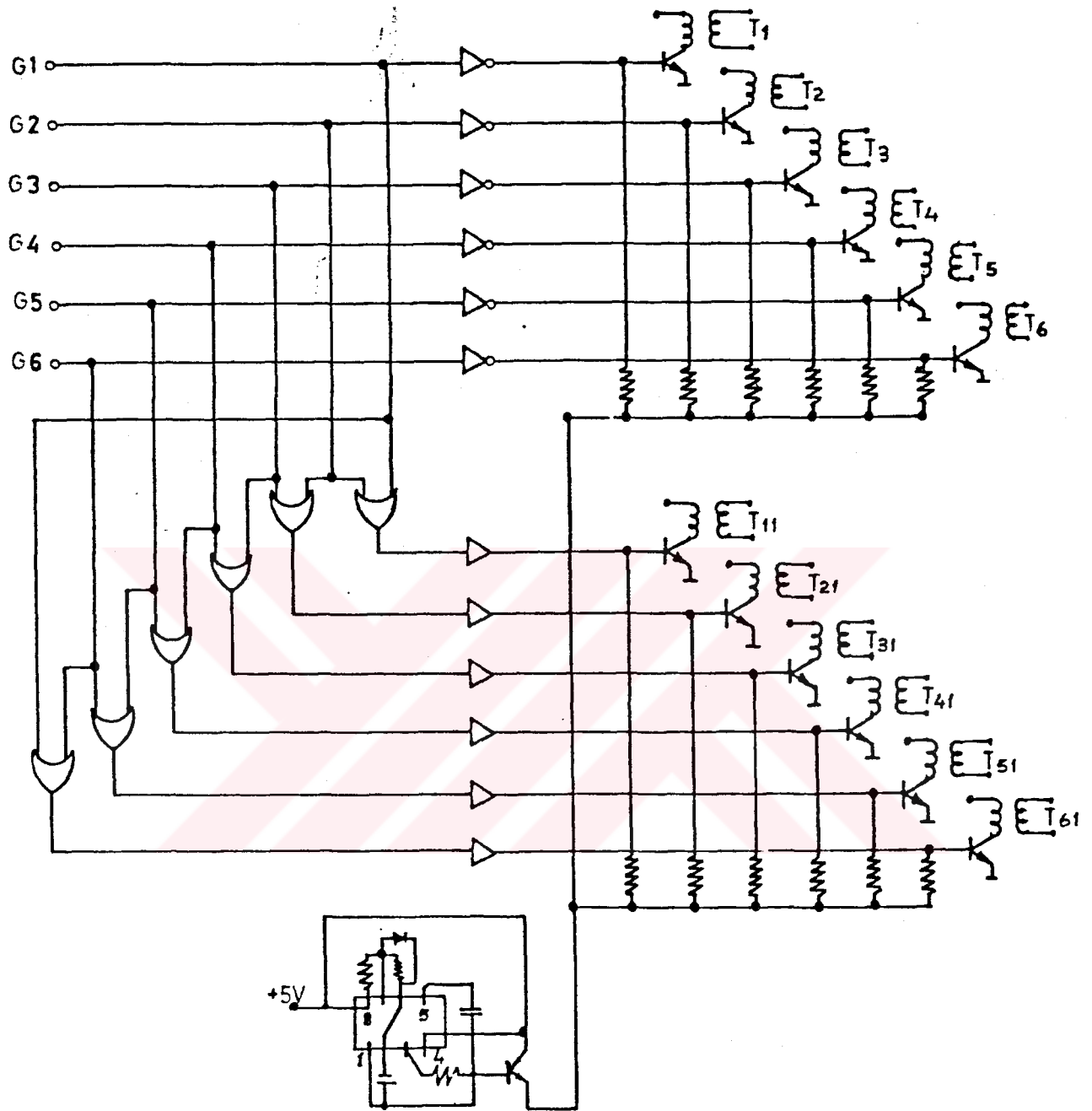


Fig. 4.9. The circuit diagram for modulation and triggering transformers.

The third condition is met by connecting, a resistor and capacitor series combination in parallel to the thyristor. The Fourth conditions is satisfied by connecting a diode parallel to the thyristor with reverse direction.

After this introduction part the commutation circuit components can be discussed.

The charging and discharging of the turn-off capacitors can be examined as two different cases.

$$1- V_{LK} < V_{CH}$$

$$2- V_{LK} > V_{CH}$$

where V_{CH} is the voltage of an auxiliary d.c. power supply which charges the capacitor in case V_{LK} is too low to charge the capacitor.

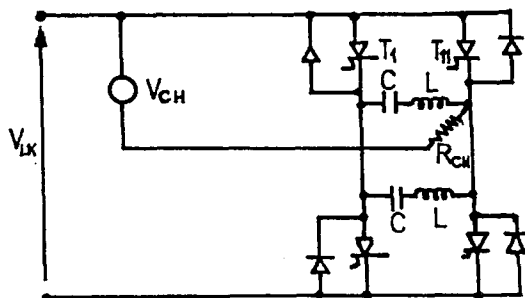


Fig. 4.10. The circuit diagram of one brach of the inverter.

$$1- \text{Case 1: } V_{LK} < V_{CH}$$

As it is seen from the triggering signals of the

thyristors. When the main thyristor T_1 is being turned on T_{41} is also turned-on. At this instant the commutation capacitors C_1 and C_2 are charged sinusoidally to the voltage V_{LK} , such that plate a is (+), in approximately $\pi\sqrt{LC}$ seconds. After this time C_2 stands by approximately with this charge. But C_1 is charged by V_{CH} via R_{CH} till T_{11} is turned-on, that is the time at which T_1 is turned-off.

During the charging case the equivalent circuit can be drawn as follows.

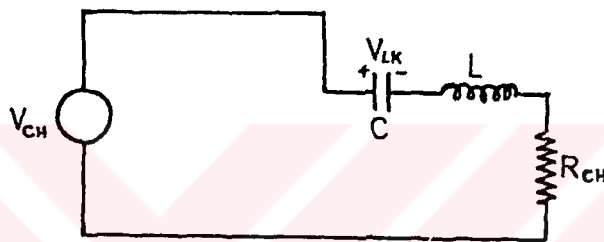


Fig. 4.11. The equivalent circuit for charging time.

Since the resistance of the resistor R_{CH} is too high, the coil L will have no important effect on the circuit behavior. So the circuit can be simplified.

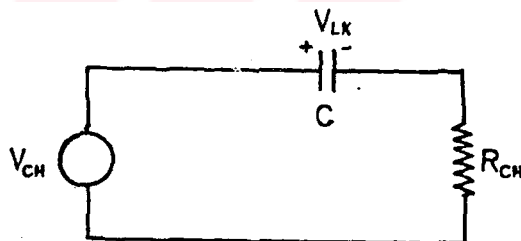


Fig. 4.12. Simplified circuit for charging time

Solving the Kirchoff equations for that circuit, the voltage across the capacitor terminals can be derived as follows.

$$V_C(t) = V_{LK} + (V_{CH} - V_{LK}) e^{-t/(R_{CH} \cdot C)} \quad 4.4$$

Since Every main thyristor conducts during a time period equal to $5/12$ of the output voltage period of the inverter, the charging time of the capacitor is equal to $5/12$

of that period. Because of that, the capacitor must be charged with enough energy to turn-off the main thyristor when the output voltage wave has its minimum frequency value, that is 3.33 Hz.

When the frequency of the output signal has its minimum value, the output voltage and V_{LK} have also their minimum values.

When T_{11} is turned on to turn-off the main thyristor T_1 , the equivalent circuit can be drawn as follows.

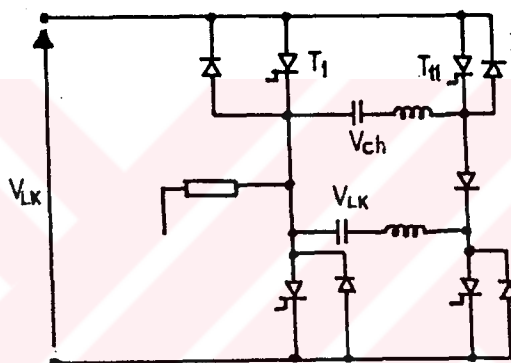


Fig. 4.13. The circuit diagram of one branch of the inverter during the turn-off time.

Let's examine the commutation or turn-off phenomena for the case where the frequency and voltage of the inverter output are at their minimum values.

During the commutation phenomena only thyristors T_1 and T_{11} conduct and the equivalent circuit becomes as follows

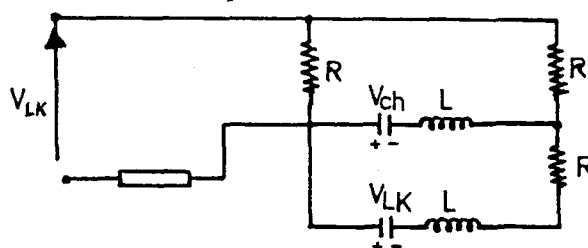


Fig. 4.14. The equivalent circuit of Fig. 4.13.

Since V_{LK} is too low with respect to V_{CH} it has no important effect on the commutation phenomenon. More specifically C_2 begins to be discharged after the voltage between points a and b becomes lower than V_{LK} and since it has low energy it will have unnoticeable effects on the turn-off phenomenon.

It is clear that the potential difference between the terminals of the C_2 will supply the potential difference between the terminals of the C_1 . And if the value of the C_1 is calculated so that it will be enough to turn-off the thyristor by itself, it is obvious that C_1 will turn-off the thyristor with more guarantee when it is supplied by the energy of C_2 .

Because of that it is better to examine and calculate the necessary values of capacitor C_1 and coil L , neglecting the effect of the C_2 .

The Turn-off phenomenon may be examined for two typical loads that is; for pure resistive load and pure inductive load. All other types of load can be made up as some combination of these loads.

1.1. Case 1: Pure Resistive Load

For this case the equivalent circuit is as follows.

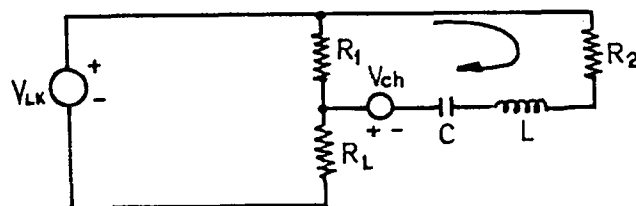


Fig. 4.15. The equivalent circuit of one branch of the inverter during the turn-off time where load is purely resistive

Here R_1 is the equivalent resistance of T_1 and D_1 which are connected in parallel with reverse direction, and R_2 is the equivalent resistance of T_{11} and D_{11} which are connected in parallel. Since the value of the resistor R_1 is too low w.r.t. R_L the equivalent resistance of $R_1 // R_L$ will

be approximately equal to R_1 . Taking the Thevenin equivalent of the left hand side of the above circuit, the following equivalent circuit can be drawn.

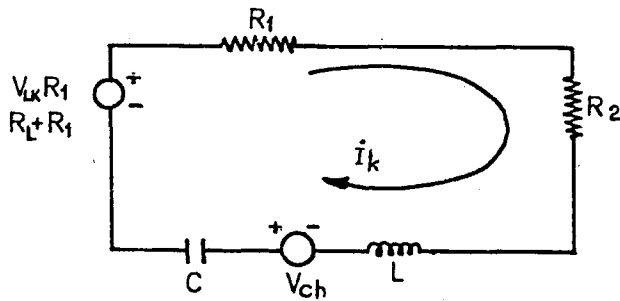


Fig. 4.16. Simplified circuit diagram out Fig. 4.15.

From this circuit it can be shown that

$$i_k = \frac{\frac{V_k R_1}{R_1 + R_1} + V_{ch}}{L \beta} e^{-at} \sin \beta t \quad (1.2) \quad 4.5$$

$$\text{Here } a = \frac{R_1 + R_2}{2L} ; \beta = \sqrt{\frac{1}{LC} - \left(\frac{R_1 + R_2}{2L}\right)^2}$$

and $\frac{1}{LC} > \frac{R_1 + R_2}{2L}$ has been taken into consideration.

To reduce the current, which flows through the Thyristor T_1 to zero the commutation current i_k must be greater than the load current i_L and to turn-off the thyristor this case must be maintained for a time longer than the thyristor turn-off time (t_q).

1.2. Case 2: Inductive load which has enough self inductance to maintain the load current approximately constant during the turn-off time which is approximately equal 60-100 μs .

In this case the equivalent circuit becomes as follows

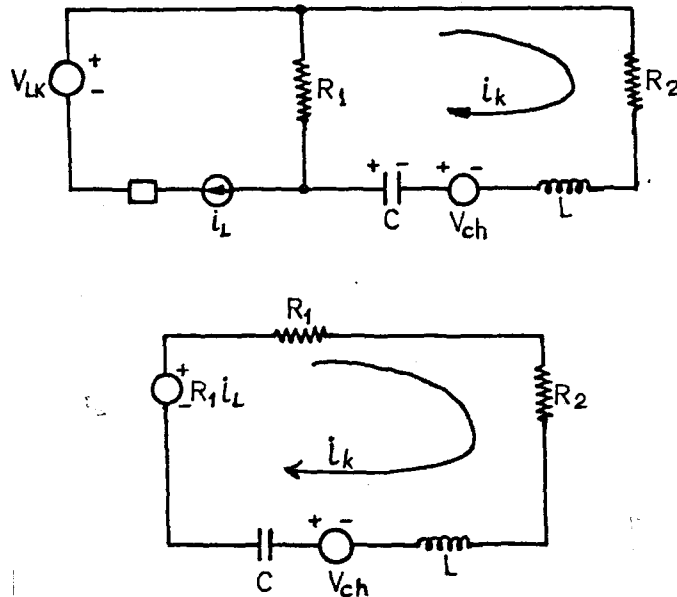


Fig. 4.17. The equivalent circuit diagram of one branch of the inverter during the turn-off time where load is inductive.

This equivalent circuit is only valid during the turn-off time.

For this circuit it can be shown that

$$i_k = \frac{V_{ch} + R_1 I_L}{L \beta} e^{-at} \sin \beta t \quad 4.6$$

$$a = \frac{R_1 + R_2}{2L} ; \beta = \sqrt{\frac{1}{LC} - \left(\frac{R_1 + R_2}{2L}\right)^2}$$

As it is mentioned earlier to turn-off a thyristor it is necessary to reduce its current to zero, apply a reverse voltage to it and this case must be maintained for a time longer than the turn-off time of the thyristor. As it is seen from the above circuit, this case takes place when $i_k > i_L$.

To reduce the turn-off losses and to use a capacitor with smaller capacitance the case $i_k > i_L$ must be maintained for a time a little longer than the turn-off time of the

thyristor. But during this phenomena $(di/dt)_k$ must not be exceeded.

Since during the turn-off phenomena the current which flows through the turn-off capacitor, i.e. i_k , is a damped sinusoidal current, to carry out the above mentioned conditions the capacitor current must be as follows.

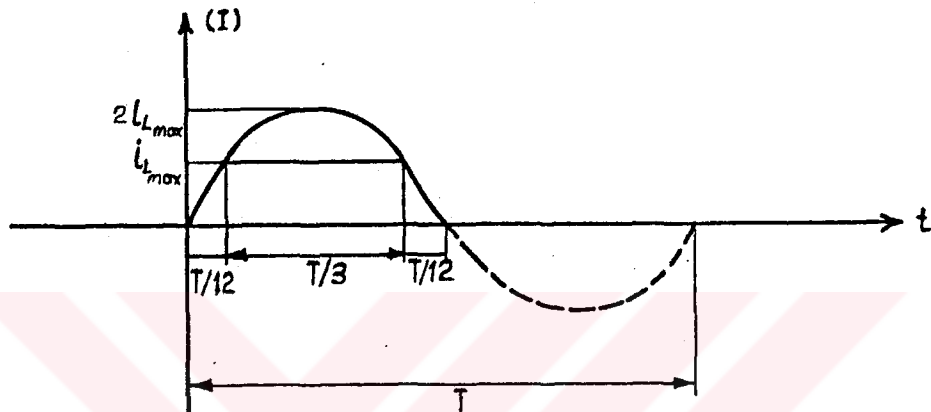


Fig. 4.18. The wave shape of the commutation current.

Here T is the resonating period of the commutation circuit which is composed of R, L and C .

From the given i_k versus time fig., the angular frequency or the period of the i_k can be derived as follows.

$$T/3 = tq \rightarrow T = 3 tq \quad 4.7$$

$$W = \frac{2\pi}{T} = \frac{2\pi}{3tq} =$$

$$I_{kmax} = \frac{Vc + R_1 I_L}{L} \quad ; \quad \beta = \frac{2\pi}{3tq}$$

$$I_{kmax} = 2I_{Lmax}$$

$$2I_{Lmax} = \frac{Vc + R_1 I_{Lmax}}{L \frac{2\pi}{3tq}}$$

$$L = \frac{Vc + R_1 I_{Lmax}}{\frac{4\pi}{3tq} I_{Lmax}} \quad 4.8$$

$$C = \frac{1}{L \left[\beta^2 + \left(\frac{R_1 + R_2}{2L} \right)^2 \right]} = \frac{1}{L \left[\left(\frac{2\pi}{3tq} \right)^2 + \left(\frac{R_1 + R_2}{2L} \right)^2 \right]} \quad 4.9$$

The formulas which are derived above are valid also for purely resistive load, if $V_{LK}/(R_1+R_L)$ is approximately equal to i_L , that is if the resistive load draws a current equal to i_L .

$$2- V_{LK} > V_{CH}$$

As it is seen from the triggering signals of the thyristors when the main thyristor T_1 is turned on the auxiliary thyristor T_{41} is in its conducting state. So the capacitor C_1 and C_2 are charged up to V_{LK} by a sinusoidal current whose period is approximately equal to LC . Since $V_{LK} \sim V_{CH}$, no current is drawn from V_{CH} to charge the capacitors. Because of that, V_{CH} has no effect on capacitor charging when $V_{LK} > V_{CH}$.

The capacitors C_1 and C_2 which are charged with V_{LK} maintain their charge till T_{11} is turned-on, that is the time the main thyristor T_1 is turned-off. When T_{11} is turned-on the equivalent circuit becomes as follows.

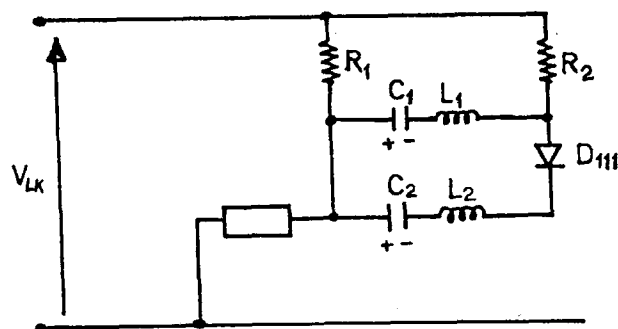


Fig. 4.19. The circuit diagram when T_{11} is turned-on

Here

R_1 : equivalent resistance of T_1 and D_1 which are connected in reverse parallel.

R_2 : equivalent resistance of T_{11} and D_{11} which are connected in reverse parallel.

Since the internal resistance of the D_{1111} is too low to affect the analysis it has been neglected.

For the case $V_{LK} < V_{CH}$ it has been shown that the type of load, that is inductive or resistive has no important effect on component value choice, if they draw the same current in the sense of amplitude. Because of that the case $V_{LK} > V_{CH}$ will be examined just for inductive load.

For the case $V_{LK} > V_{CH}$, if it is taken into consideration that the load inductance will keep its current during the turn-off time, approximately constant the equivalent circuit becomes as follows.

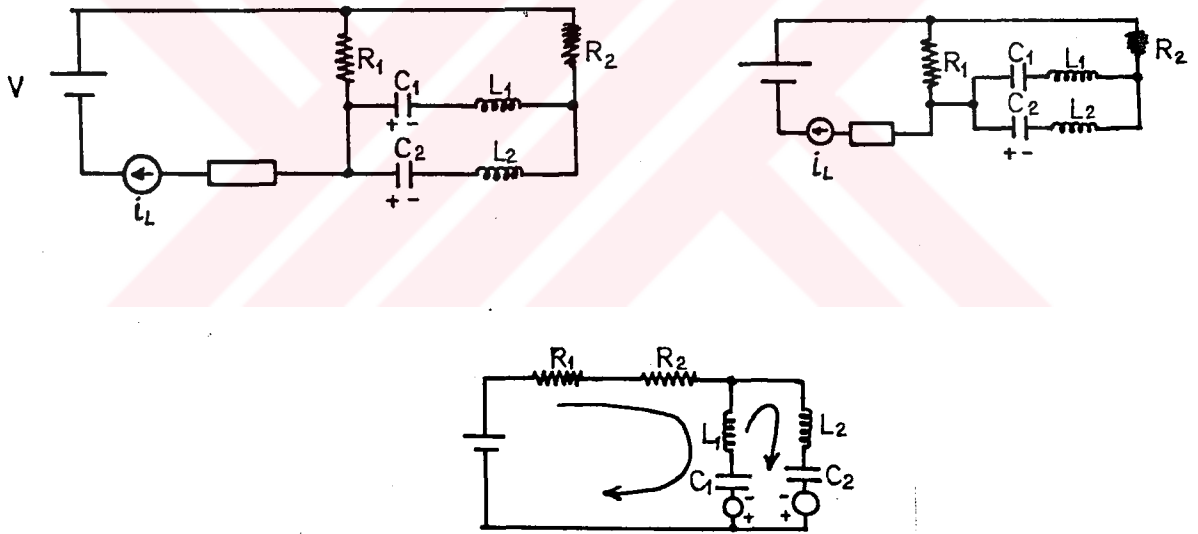


Fig. 4.20. The equivalent circuit diagram for Fig. 4.19.

If the closed loop equations for this circuit are solved it can be shown that.

$$\dot{i}_k = \frac{2(V_c + R_1 I_L)}{L \beta} e^{-at} \sin \beta t \quad 4.10$$

$$\text{Here } \beta = \sqrt{\frac{1}{LC} - \left(\frac{R_1 + R_2}{L}\right)^2}$$

$$a = \frac{R_1 + R_2}{L}$$

If this current is compared with the current which is derived for the case $V_{CH} < V_{LK}$, taking into consideration that $1/LC \gg (R_1+R_2/L)^2$, it is seen that the angular frequency is the same for two cases but the current of the later case is twice of the former case.

As a result of that it can be said that for the case where $V_{LK} > V_{CH}$ the thyristor current that can be commutated is two times greater than that of the case where $V_{LK} < V_{CH}$. i.e. for the case where $V_{LK} > V_{CH}$ the commutation or turn-off phenomena is carried out with more guarantee.

Because of that, calculations to find necessary capacitor and coil values must be done for the case $V_{CH} < V_{LK}$ and V_{LK} when V_{LK} has its minimum value, implying that the capacitor has its minimum charge.

Since a procedure has been defined to find necessary values for the capacitors and coils that can carry out the turn-off process of the main thyristor, the value of the V_{CH} can be now examined.

The following criteria must be taken into consideration for determining the value of V_{LK}

- 1- Auxiliary thyristor holding current I_H
- 2- Energy loss on charging resistors R_{CH} .

Lets examine these two criteria for one branch of the inverter power circuit.

1- When T_{11} is turned on to turn-off the main thyristor T_1 , a current of value $V_{CH}/R(A)$ is drawn by R_{CH} from V_{CH} . If $V_{CH}/R > I_H$, then T_{11} continues to conduct after it turns-off the main thyristor T_1 . As a result of that the following disadvantages will occur.

- a) More power losses on R_{CH}
- b) If T_{41} is turned-on as a result of some error in triggering signals or turn-off phenomena then a short-circuit takes place.

2- Minimizing The Power Losses During The Charging Time

The speed range, in which the motor runs most of the time is the range between half of the nominal speed and the nominal speed and these speeds approximately corresponds to $V_{LKmax}/2$ and V_{LKmax} respectively.

The range below the half of the nominal speed is only used for starting or braking operation. Because of that to reduce the power losses during the capacitor charging time, no current must be drawn from V_{CH} through R_{CH} when the motor runs at some speed where $V_{LK} > V_{LKmax}/2$. Since the resistance of the coils in this circuit is too low, if capacitors are charged through these coils energy losses will be too low. So it is clear that auxiliary charging supply p.d must be less than V_{LKmax} . But, in the case where V_{CH} is too low, capacitors with higher capacity are needed to be able to turn-off the main thyristor. And this causes the following disadvantages.

a) Capacitors with higher capacity needs resistors with less value to be charged during the time in which main thyristor conducts, and this make V_{CH}/R to be higher than I_H .

b) When motor runs around the nominal speed wehere $V_{LK} = V_{LKmax}$ the capacitor charge will be too much than the needed value to turn-off the thyristors, and this will cause more power losses on the commutation circuitry.

Consequently, considering all of the above mentioned

criteria, it is clear that the value of V_{CH} in volts must be chosen between $1/2 V_{LKmax}$ and $3/4 V_{LKmax}$ depending on circuit parameters.

As it is mentioned before, the capacitor and coil values, which are enough to commutate the main thyristor when motor starting i.e. $V_{LK}=V_{LKmin}$, can commutate the thyristor with more guarantee when V_{LK} has its higher values in volts, and load current is same with that of the former case. Because of that, after determining the value of V_{CH} and maximum load current the necessary values for the coils, capacitors and charging resistors must be calculated for the case where V_{LK} has its minimum value.

As it is shown before, capacitors charges, by V_{CH} through R_{CH} , exponentially; that is.

$$V_{ch} = V_{LK} + (V_{CH} - V_{LK}) \cdot 1 - e^{-(t/R_{CH} \cdot C)} \quad 4.11$$

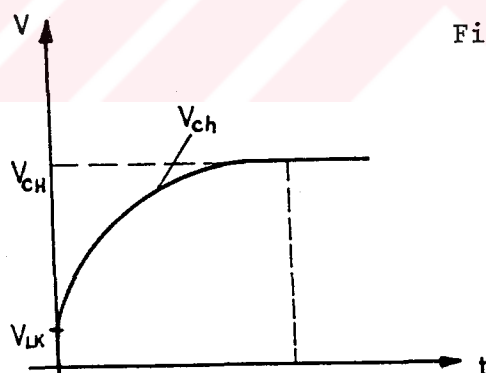


Fig. 4.21. The variation of the capacitor voltage during the charging time.

It is better to determine the value of the V_{ch} , capacitor voltage, which causes minimum losses but allows to turn-off the main thyristors when they conduct maximum load current.

To see this clearly it is better to compare capacitor charging and power losses to get this. Charge voltage for $V_{LK}=V_{LKmin}$ where the charging time is at its maximum value and power losses on resistor is maximum.

When V_{LK} is minimum the period of the output voltage of the inverter is 300ms and the capacitor charging time is $300.5/12=125\text{ms}$.

To simplify calculation $V_{LK}=0$ will be assumed.

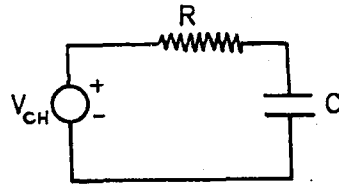


Fig. 4.22. The equivalent circuit of the capacitor charging circuit where V_{LK} is low.

For the above circuit it can be shown that.

$$V_c = V_{CH} (1 - e^{-(t/R_{CH} \cdot C)})$$

$$P_{Rort} = 1.666 V_{CH}^2 \cdot C (1 - e^{-(0.25/R \cdot C)}) \quad 4.12$$

Where P_{Rort} is the average power consumed by R_{CH} during the charging time.

In addition to that when an auxiliary thyristor is turned on to turn-off a main thyristor, auxiliary power supply delivers a current approximately equal to V_{CH}/R_{CH} through the closed loop which consists of V_{CH} , R_{CH} and the auxiliary thyristor. During this time the power consumed by R_{CH} is.

$$P = V_{CH}^2/R. \quad 4.13$$

This amount of power is consumed till the auxiliary thyristor current falls below its holding current I_H and it is turned-off by it self.

Comparing the capacitor charging and total power consumption on R_{CH} for some values of R_{CH} it can be easily seen that if the capacitor is charged up to $0.9 V_{CH}$ during the $5/12$ of the period the best efficiency will be reached.

After selecting $V_{ch}=0.9 V_{CH}$, the charging resistor value, which will charge the capacitor up to $0.9 V_{CH}$ during the $5/12$ of the period, for the case where the frequency of the output voltage of the inverter is minimum, must be found.

After that, using formulas 4.8 and 4.9 the optimal L and C , that is coil and capacitor, values can be calculated.



CHAPTER 5

MAIN CONTROL CARD

The main control card transmits suitable signals to the inverter and converter unit depending on the given speed reference and feedback signals, coming from the tachometer, to keep the speed of the motor at the desired (set) value. When the direction changing signal is applied it decelerates and stops the motor, changes the state of the direction changing relays and brings the motor speed to the preset value with the reverse rotation direction. If the speed reference is changed instantly the main control unit does not allow the motor to change its speed instantly but with a predefined constant acceleration. When the direction changing signal is applied it does not allow the motor to change its rotational direction instantly, either. It allows the motor to change its direction after the motor first slows down and stops rotating.

The circuit diagram of the main control board is given in Fig. 5.1. Here the circuit which is composed of the components Q_1 , Q_2 , IC1, IC2, enables the voltage of the capacitor to reach linearly the given set value V_r , from the present value.

Q_1 provides the discharging of the capacitor C_1 with a constant current and Q_2 provides the charging with a constant current. If the voltage V_r is greater than the voltage between the terminals of the capacitor, then the output of IC1 becomes zero and that of IC2 becomes $+V_{cc}$. As a result of that, since the base voltage of Q_1 is reduced to zero, Q_1 does not conduct. Since there is a diode between the output of IC2 and Q_2 , and output voltage of IC2 is greater than the voltage at the collector of Q_2 no current flows between the IC2 output and the Q_2 collector. Consequently Q_2 charges the capacitor C_1 with a constant current till its

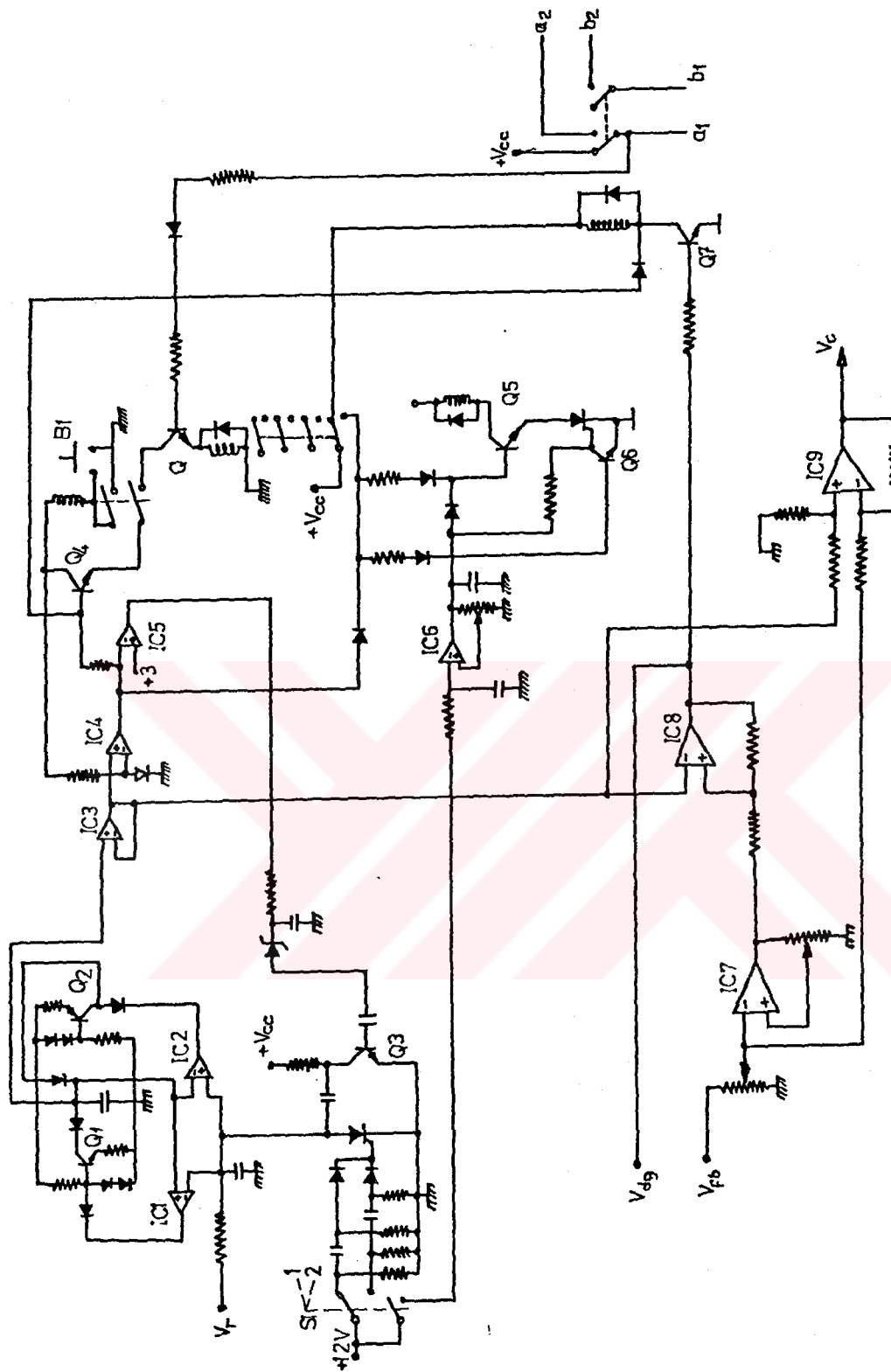


Fig. 5.1. The circuit diagram of the main control board.

voltage becomes equal to the voltage V_r . When the reference voltage V_r is less than the voltage between the terminals of the capacitor C_1 , the phenomena takes place as follows; the IC2 output becomes zero and the IC1 output becomes $+V_{cc}$. As a result of that the current provided by Q_2 flows through the output of IC2. Since there is a diode between Q_2 and the capacitor C_1 , Q_2 will have no effect on the voltage of C_1 . On the other hand, C_1 will be discharged with the constant current drawn by Q_1 , and its voltage will decrease linearly to the voltage V_r . So the capacitor voltage is changed linearly from its present value to the value V_r and is kept constant at that value.

The voltage between the terminals of C_1 is applied to the inputs of IC4 and IC8 after being buffered by IC3. Since a voltage of 0.5 V is applied to the inverting (-) input of the IC4, when the voltage V_r falls below 0.5 V, which corresponds to the 35 V value of the link voltage V_{LK} , the output of IC4 becomes zero. As it is seen from the figure the rectifier relay coil is fed through the transistors Q_4 , Q_6 , and the starting relay contacts, which are connected in series. If one of them is not conducting then the rectifying relay gets its off-state (normal state); that is the rectifying thyristors are not triggered. If button B1 is pushed, the starting relay closes and keeps its state till the power is cut off. The reason of putting this relay into the circuit is to prevent the power circuit from operating immediately after the system is connected to the power supply, in which case some transients can occur.

This button is pushed after the system is connected to the power supply and the starting relay stays closed while the system is connected to the power supply.

To provide the conducting of Q_4 ;

1- The reference voltage V_r has to be greater than 0.5 V which means the output of IC4 has to be greater than 0.5 V.

2- The transistor Q_7 has to be not conducting.

The transistor Q_7 feeds the regeneration relays and when the regeneration relay is fed, the rectifying relay is released. So regeneration and rectifying relays are not allowed to be closed together, at a time. The transistor Q_6 is a second transistor which serves the above mentioned purpose. This does not allow the rectifying relay to be closed unless the regeneration relay is released. When the regeneration relay is at its off state or is released, the a_o pin of the regeneration relay contact is connected to $+V_{cc}$, thus the transistor Q_6 conducts and lets the rectifying relay to be closed. The voltage, V_{fb} , taken from the tachometer to measure the actual speed of the motor, is applied to IC8 after being divided by a potentiometer and amplified by IC7. The inverting (-) input of IC8 is connected to the positive plate of C_1 . The output of IC8 controls the transistor which is connected in series with the coil of the regeneration relay. Thus, if the motor speed exceeds the set value, the regeneration relay closes and energy flows from the motor to the power supply.

Let the output of the IC7 be denoted by V_7 and the output of IC3 by V_3 , then the following relation can be written:

$$V_7 > V_3 \Leftrightarrow \text{IC8 output is } +V_{cc}$$

$$V_7 < V_3 - V_h \Leftrightarrow \text{IC8 output is } 0$$

Here V_h is the hysteresis voltage value.

Since the circuit is basically a comparator its output has to be either $+V_{cc}$ or 0.

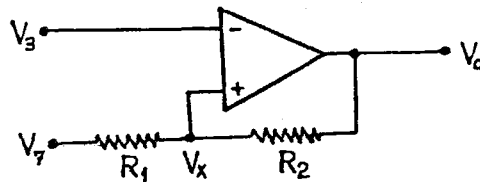


Fig. 5.2. The regeneration relay control circuit which includes IC8.

1- The case $V_7 > V_3$

In this case the voltage V_x is $V_x = V_7 + (V_o - V_7) R_1 / (R_1 + R_2)$ and the output, V_o , stays at $+V_{cc}$ till V_x becomes less than V_3 in volts, and this case in terms of the voltage V_7 corresponds to the voltage values where

$$V_7 < V_3 \left(\frac{R_1 + R_2}{R_2} \right) - V_o \frac{R_1}{R_2} \quad 5.1$$

2- The case $V_7 < V_3$

Here the voltage V_x is $V_x = V_7 \frac{R_2}{R_1 + R_2}$ and the output stays at zero level till V_x becomes greater than V_3 . This case in terms of the voltage V_7 corresponds to the values where $V_7 > V_3 \frac{R_1 + R_2}{R_2}$. 5.2

As it is seen, for any value of V_3 the difference between the value of V_7 , which changes the output of the comparator from $+V_{cc}$ to zero, and the value of V_7 , which changes the output from zero to $+V_{cc}$, is equal to $V_{cc} \frac{R_1}{R_2}$. This value is called the hysteresis voltage, V_h .

As a result of that it is clear that if the speed of the motor exceeds the set value, the output of IC8 will be $+V_{cc}$, but in order for the output of IC8 to be zero the motor speed has to fall below the set value by an amount corresponding to the hysteresis value. If the hysteresis voltage value is too low then the output of IC8 will change even if the fluctuation in the motor speed is too low. As a result of that the regeneration and rectifying relays will close and open very frequently. On the other hand if the hysteresis value is too big, then the output of IC8 will not change even if there are big fluctuations in the motor speed and the relays will not change their state. Thus the energy flow direction will not change although there is a big deviation in the motor speed from the set value. As it can be seen from the circuit diagram in order for the regeneration relay, which is fed by transistor Q_7 , to close, the rectifying relay has to be released (opened). This lock is used to prevent the relays from being closed at the same time, and this corresponds to the case where the rectifying and regeneration thyristors do not conduct at the same time. The circuit which includes IC9 and uses the reference voltage V_r , and the speed feedback voltage V_{fb} as its inputs, provides the use of the information obtained from the tachometer as negative feedback signal. So, if the motor speed exceeds the set value then the control voltage V_c which is sent to the converter and inverter unit is decreased, and if the motor speed falls below the set value the control voltage is increased to provide the minimum deviation from the speed set value. The circuit diagram and the input output relations of the circuit which provides the above mentioned tasks are given below:

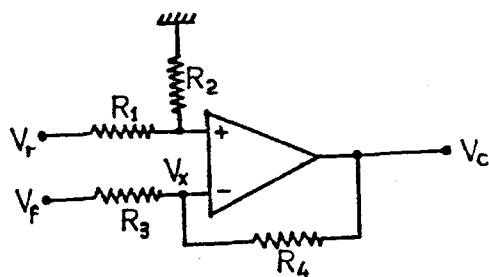


Fig. 5.3. The circuit that allows to use tachometer output voltage as speed feedback signal.

$$V_c = V_r \cdot \frac{R_2}{R_1 + R_2} \cdot \frac{R_3 + R_4}{R_3} - V_f \left(\frac{R_4}{R_3} \right)$$

Since $R_2 \gg R_1$

$$V_c = V_r + \frac{R_3}{R_4} (V_r - V_f) \text{ is obtained.} \quad 5.3$$

As it is seen from this relation the value $V_r - V_f$ is added to the V_r , after being multiplied by R_3/R_4 whose value is less than 1. As a result of that in the case of instant peak loads, the motor is prevented from being forced to handle these peak loads and being overloaded.

The button S_1 seen in the circuit is used to change the rotation direction of the motor.

When the state of the S_1 is changed from 1 to 2 a pulse is applied to the gate of the thyristor T_1 via a capacitor and a diode. As a result of that T_1 is turned on and the voltage V_r' becomes approximately zero. If the voltage between the terminals of C_1 is higher than 0.5 Volt, then since V_r' is equal to zero the capacitor C_1 is discharged by the constant current produced by the transistor Q_1 , towards zero. When the voltage between the terminals of C_1 falls below 0.5 Volt the output of IC4 becomes zero and that of IC5 becomes $+V_{cc}$.

After the output of IC5 becomes $+V_{cc}$ the capacitor C_3 begins to be charged exponentially through the resistor R,

by the voltage V_{cc} , coming from the output of IC5, and when the voltage at the terminals of C_3 exceeds the voltage V_z , namely the zener voltage, Q_3 begins to conduct. The time interval between the instant at which the output of IC5 becomes $+V_{cc}$ and the instant at which the transistor Q_3 begins to conduct depends on the values of R and C_3 . When the output of IC4 becomes zero the transistor Q_4 ceases conducting, and the rectifying relay gets its off state; that is it releases. At the same time since the voltage applied to the base of the transistor Q_6 is reduced to zero the transistor Q_6 stops conducting, that is the thyristor T_3 becomes ready to be triggered. Since the switch S_1 is at position 2 the output of IC6 is equal to $+V_{cc}$. As a result of that, the transistor Q_5 and the thyristor T_2 begin to conduct and the direction changing relay closes. If the circuit is examined carefully it can be seen that the following conditions have to be provided to let the direction changing relay to close.

- 1- Switch S_1 has to be at position 2.
- 2- The output of IC4 has to be zero
- 3- The rectifying relay has to be released (opened)

If the rectifying relay does not release, the voltage applied to the base of the transistor Q_6 is not ceased and the thyristor is not allowed to be turned-on. When the transistor Q_3 begins to conduct, the thyristor T_1 is turned-off and V_r' becomes equal to V_r . After this moment the capacitor C_1 begins to be charged linearly from its present value to the voltage V_r . The reason to turn-off the thyristor T_1 with a time delay after the output of IC4 becomes zero is to provide that the rectifying relays be off and to supply no voltage from the rectifying thyristors to the inverter unit, during the time at which the direction changing relays change their state. The above mentioned procedure causes the motor to slow down linearly, stop, and change its rotation

direction when V_{LK} is equal to zero, and obtain the preset speed value automatically when the position of S_1 is changed from 1 to 2.

When the state of S_1 is changed from position 2 to position 1 the above mentioned sequence takes place in a similar manner.

In this case the following conditions are necessary to let the direction changing relays to be released.

- 1- Switch S_1 has to be at position 1.
- 2- The output of IC4 has to be zero.
- 3- The rectifying relay has to be released.

Consequently, the main control card provides the rotation of the motor at a speed value which is set by a potentiometer by sending suitable control voltages to the inverter and converter units. When the set speed of the motor is changed by using the potentiometer, the motor speed is changed from the old set value to the new set value linearly; that is with a constant acceleration. So the motor is prevented from accelerating the driven mass with an acceleration which can overload the motor. The acceleration of the motor rotation is determined by the capacitor C_1 and the constant current sources which charge and discharge this capacitor linearly. The acceleration of the motor rotation is linearly dependent on the value of C_1 in μf . So if the inertia of the mass driven by the motor is big, then the acceleration of the motor rotation has to be held low, so as not to overload the motor i.e. the value of the capacitor C_1 has to be held bigger in μf .

In order to change the rotation direction of the motor it is just enough to change the position of the switch S_1 . When the position of the S_1 is changed the motor slows down

with the maximum possible deceleration, changes its rotation direction when it reaches zero speed value and gets its preset speed value with the maximum possible acceleration. So that the rotation direction changing of the motor is executed in minimum time.



MICROPROCESSOR AND PROGRAMMING UNIT

Programming unit is composed of a 6502 C.P.U and its peripherals. The C.P.U clock rate is 1 MHz. A 16-touch keyboard for data inputs, an A/D converter and a D/A converter for data inputs and outputs has been used. In addition a versatile Interface Adapter (VIA), and a peripheral Interface Adapter (PIA) has been used to connect these to the C.P.U.

The information that can be entered through the 16-touch keyboard are:

- 1- the distance through which the load, whose position is being controlled, will be transferred
- 2- information about positive acceleration
- 3- information about negative acceleration (deceleration)

The C.P.U can transmit suitable speed references through the D/A to the main control unit depending on the data entered through the keyboard. Since a tachometer output is connected to the A/D converter input, the actual motor speed can be read through the A/D. This "speed" information taken from the tachometer is turned into a "distance" information by integrating it with respect to time. So the distance which has been travelled by the object from the starting point may be known at any time. Depending on this information the time at which the motor speed will be reduced or at which the negative acceleration will be applied to the transferred object can be determined. Then according to the information about negative acceleration which are entered through the keyboard, linear deceleration is provided and the motion of the object is stopped. Since the information about the actual speed of the motor and thereby the distance travelled by the object is entered as a feedback signal to

the microcomputer, the object is delivered to the final destination with minimum position error. The speed-time profiles according to which the motor moves the object from one position to the desired position are given in Fig . This speedtime profiles are time-optimal position control profiles when the acceleration and deceleration is limited and the motor speed is restricted.

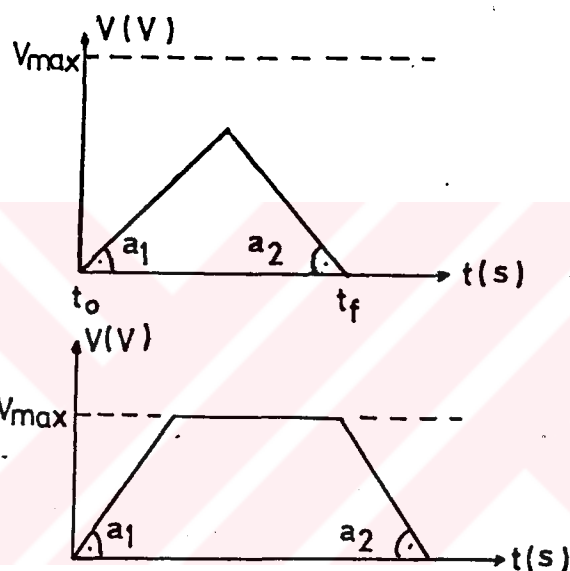


Fig. 6.1. The time-optimal speed-time profiles where acceleration and maximum speed is limited.

The real speed of the motor, the object position and the data entered through the keyboard may be observed with the aid of the four digit displays located on the microcomputer unit.

The microcomputer is capable of giving control signals to the inverter and converter units to drive the motor so as to trace any speed-time profiles, without exceeding the torque, power and speed limits of the motor, by changing the program in the EPROM. It is possible to move the object from one position to another position in minimum time; to make the object wait there for a certain time and then to move it to

another position by writing a suitable program to the EPROM. But when the given command causes the motor to be overloaded even if the microcomputer requests, the main control board rejects that command and does not allow the microcomputer to drive the motor in such a critical manner. The speed reference signal coming from the main control board is a 0-10 V d.c voltage; that is the motor stops when 0 Volt control voltage is coming from the main control board and runs with rated speed when 10 V control voltage is coming from the main control board.

When the command is given by the microcomputer, the potentiometer that gives the speed reference to the main control board manually, must be unactivated.

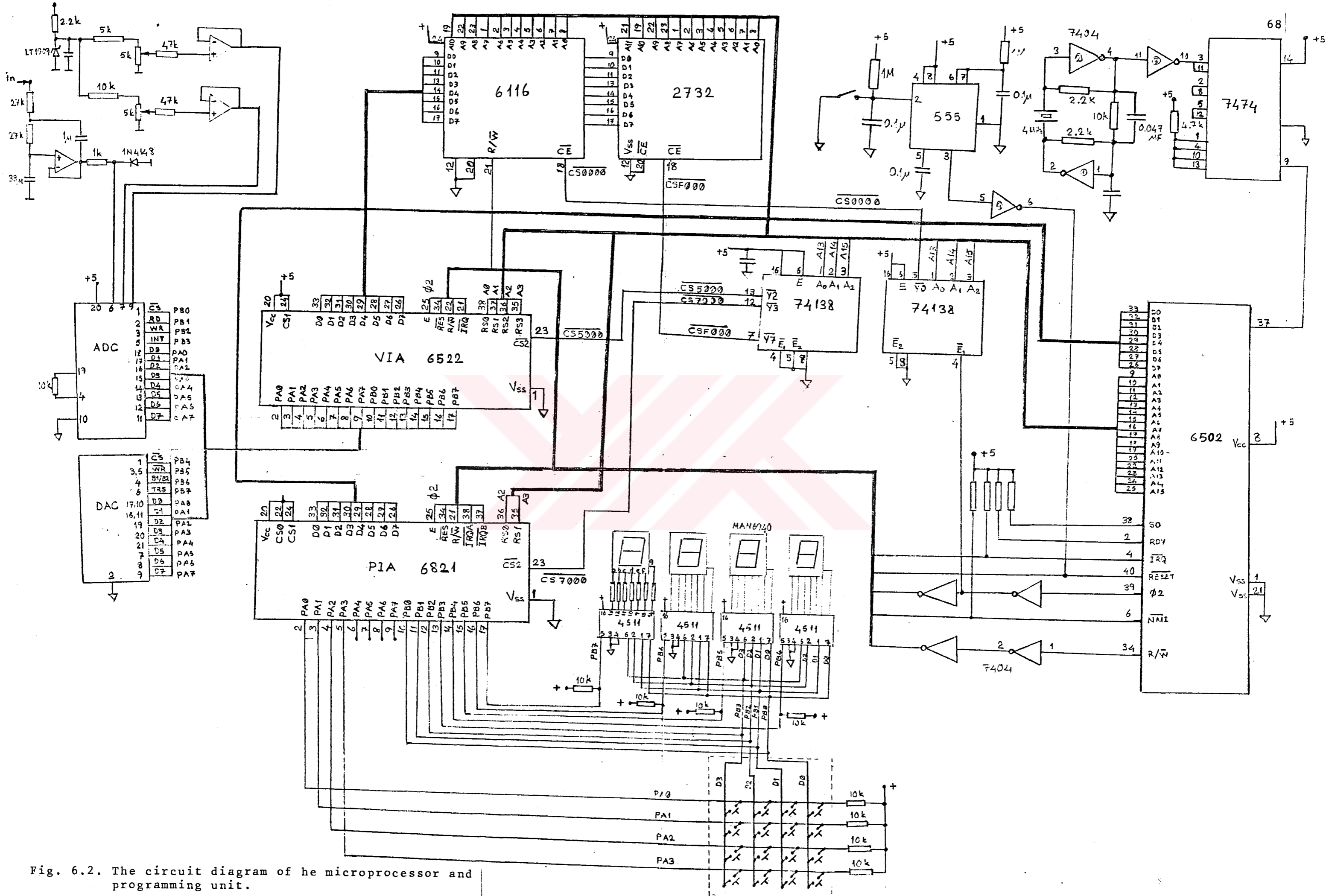


Fig. 6.2. The circuit diagram of the microprocessor and programming unit.

CHAPTER 7

CONCLUSIONS AND RESULTS

The aim of this research project was to demonstrate the possibility of using a three phase squirrel cage motor instead of a d.e. motor in a digital position or velocity control system and to design and construct the necessary converter, inverter and controller units for a prototype.

The designed system operates on the principle that the speed of a three phase squirrel cage motor can be controlled by a variable amplitude and variable frequency supply voltage. For this purpose first a converter unit converts the 3x380 V 50 Hz supply voltage into a d.c. voltage which is adjustable between 35 and 450 Volts. In turn the inverter unit transforms this adjustable d.c. voltage coming from the converter into an approximate sine wave whose amplitude and frequency are controllable. Thus the converter-inverter combination generates the a.c. voltage with adjustable effective value and frequency to be applied to the squirrel cage motor to rotate it at a desired speed at its maximum rotational torque.

The converter unit has been constructed with power electronic components as a dual converter and it allows regeneration; that is it allows during braking or slowing down energy to be fed back to the supply.

The inverter has also been constructed using 50 Hz thyristors of large power rating, and it allows regeneration.

The inverter produces an approximate sine wave output with 12 steps per period. Commercially available inverters produce an approximate sine wave with only 6 steps per

period. This means that commercial inverters produce an output which has more harmonics than the inverter output achieved in this design. More harmonics however mean bigger losses, overheating in the motor and step-wise rather than continuous rotation in lower frequencies. The designed inverter is more successful in the sense that the 12 step sine wave approximation obtained in its output has fewer harmonics thus reducing drastically the overheating problem and eliminating the step-wise rotation at lower frequencies. The 12-step sine wave approximation actually contains more harmonics in comparison with the output of an inverter that uses pulse width modulation. However in inverters using pulse width modulation thyristors are turned on-and-off many times during one period of the output wave thus creating wear in the power electronic components reducing their lifetime, and causing appreciable energy losses. In the designed inverter however thyristors are turned on-and-off only once during one period of the output wave thus causing fewer energy losses and ensuring a longer lifetime for the components.

The microprocessor based design implemented in the realization of the prototype renders the control system flexible in the sense that it can track any desired speed-time profile by changing the program in the EPROM, provided that the reference inputs do not violate the restrictions concerning the maximum operating speed of the motor and the possible maximum values of acceleration on deceleration that the motor can withstand.

In short the designed digital control system can achieve any speed-time profile as long as the torque, power and speed limits of the motor are not exceeded.

The realized position control system has been tested to see if it satisfies the expected functions and characteristics. According to the test results it was seen that the system satisfies the expected functions and characteristics and can be used as a time-optimal position controlling system.

The actual output wave shape of the inverter output for purely resistive load is given in Fig.7.1. As it is seen from this figure the inverter output has 12 steps per period. The output of the converter unit is given in Fig.7.2. For different parameters entered to the microprocessor unit the actual speed-time relation of the motor is given in Fig.7.3., 7.4., and 7.5. As it is seen from these figures the realized position control system operates as a time optimal position control system. According to the position and acceleration data entered through the keyboard of the microprocessor unit motor accelerates with a constant acceleration gets its maximum speed and decelerates with a constant deceleration to bring the mass whose position is to be controlled to the desired position. If the distance to be travelled is short then motor begins deceleration without reaching its maximum speed value.

Some photographs of the realized system are given in the following pages.

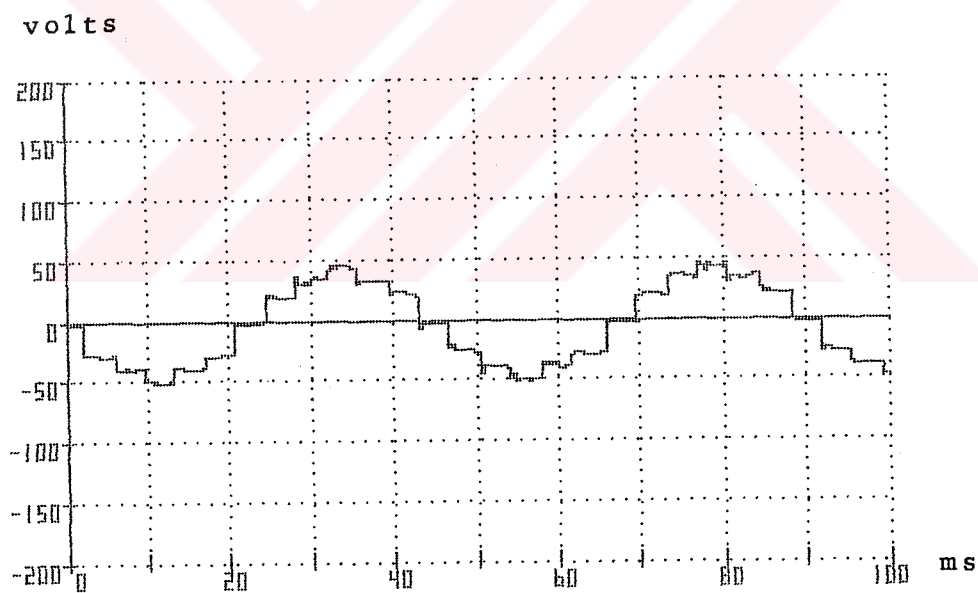
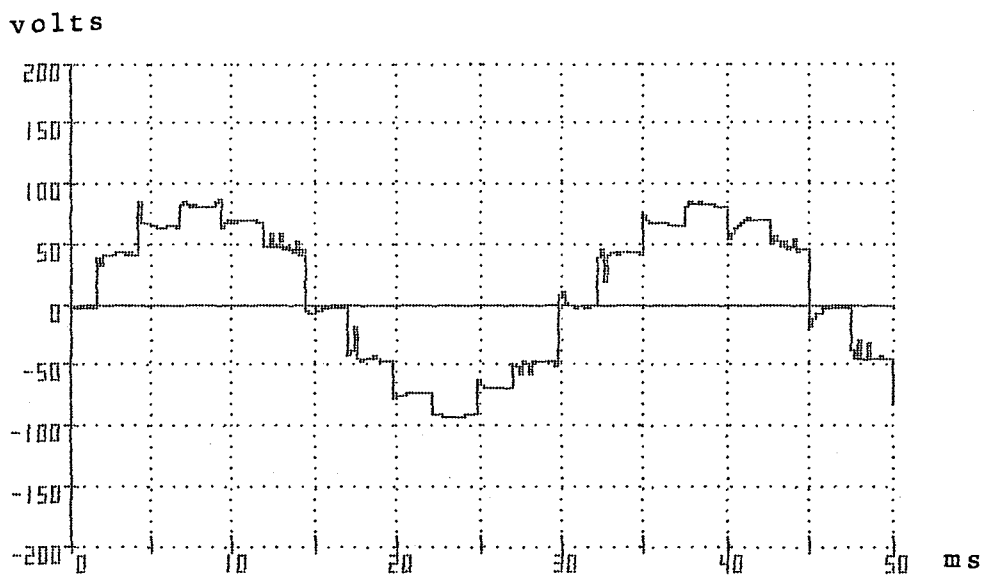


Fig. 7.1. The actual output waveshape of the inverter unit for purely resistive loads.

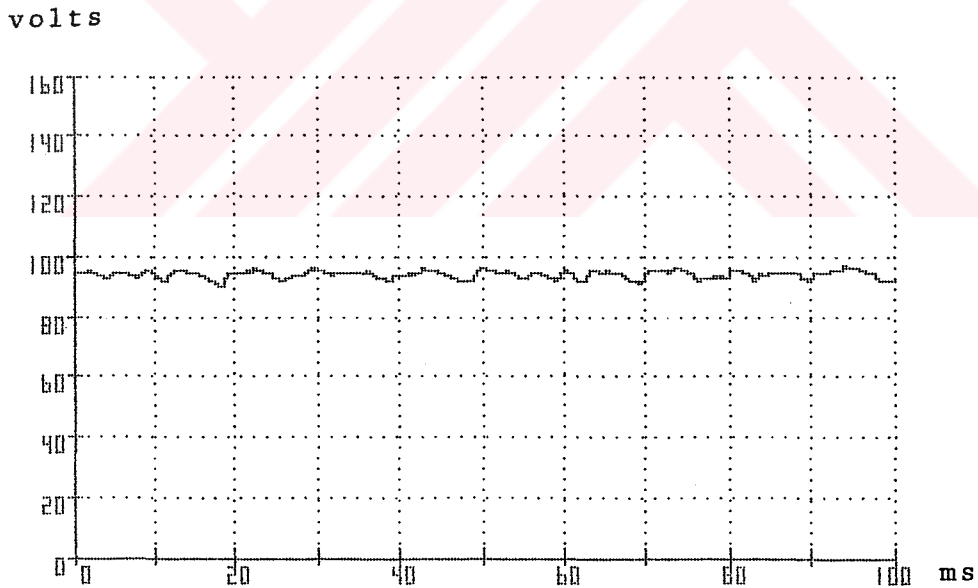
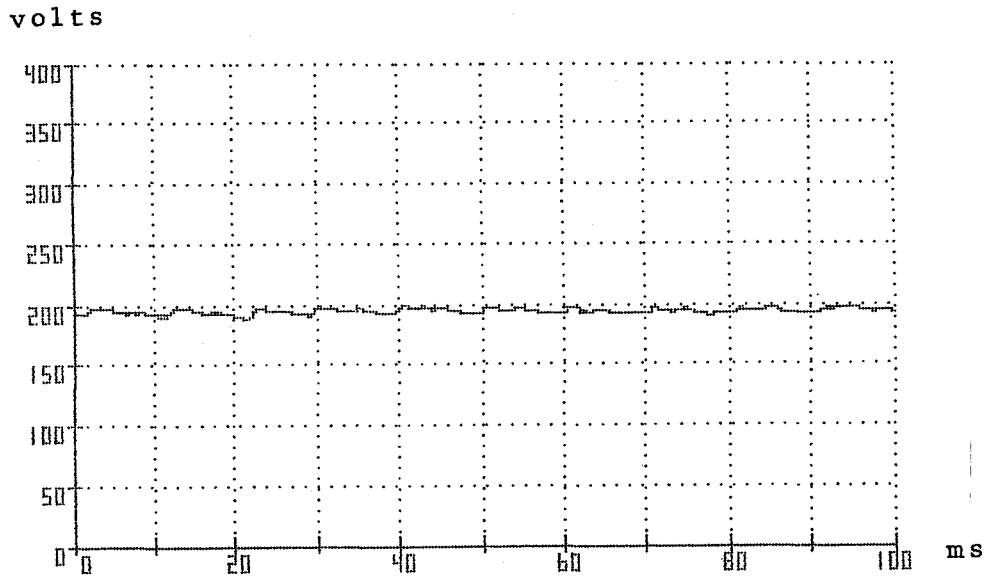


Fig. 7.2. The actual output Waveshape of the converter unit for different average values.

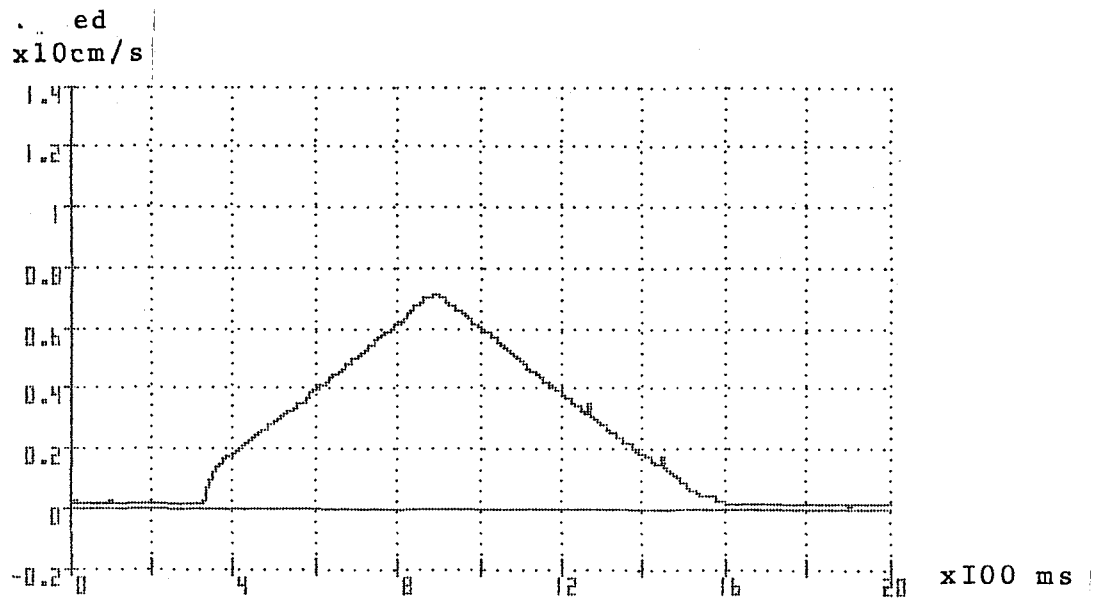


Fig. 7.3. The actual speed-time profile of the motor where destination = 100, acceleration = 3.

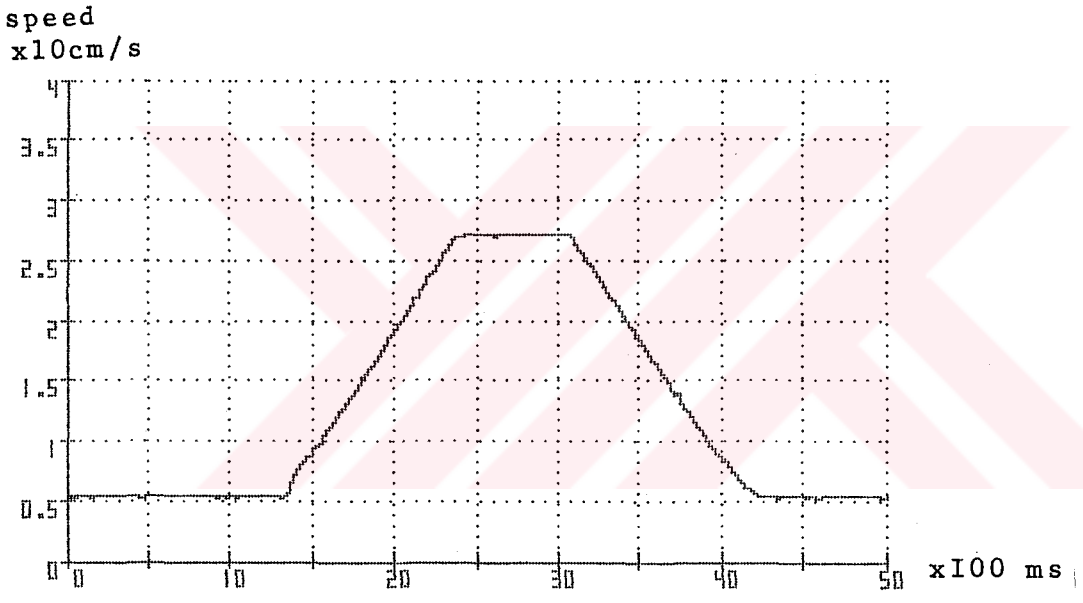


Fig. 7.4. The actual speed-time profile of the motor where destination = 200, acceleration = 5.

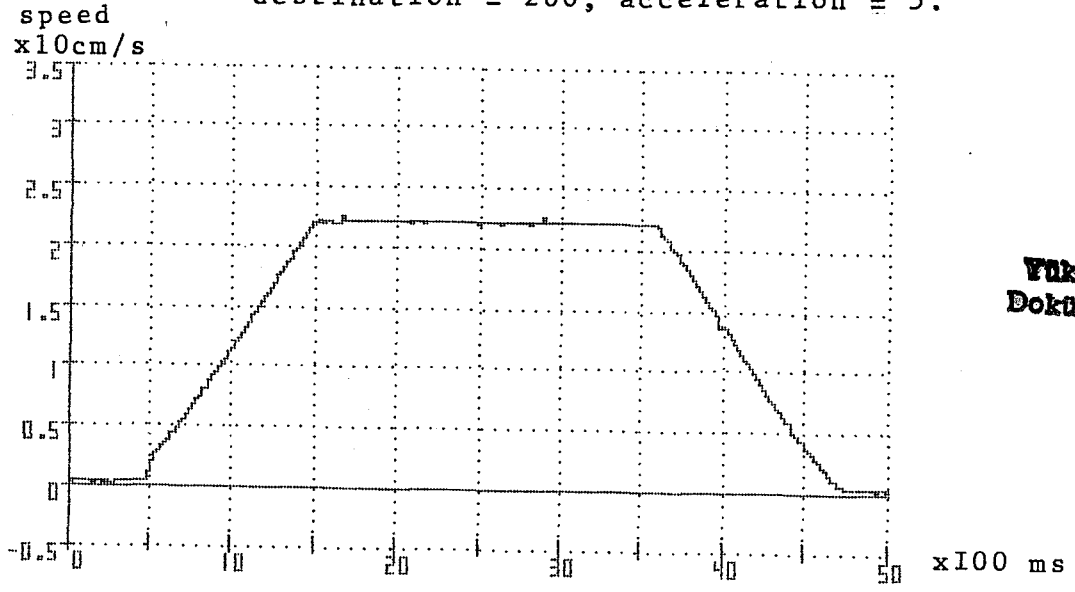
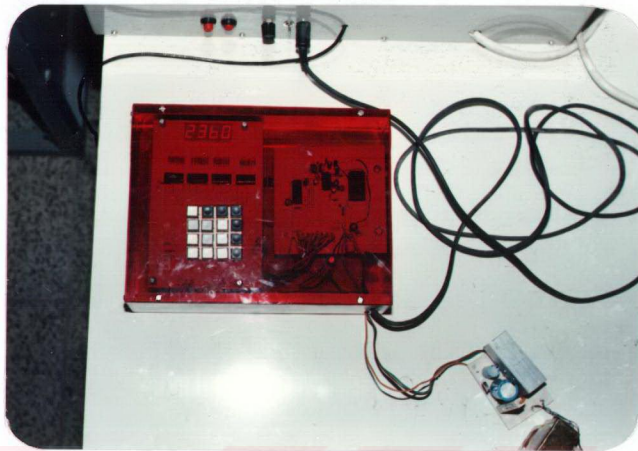
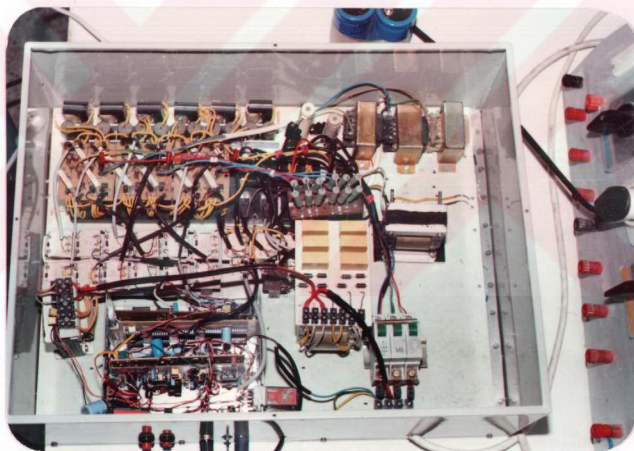


Fig. 7.5. The actual speed-time profile of the motor where destination = 300, acceleration = 5.

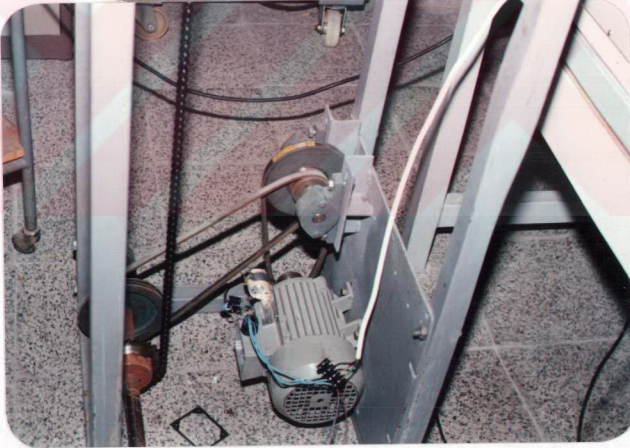
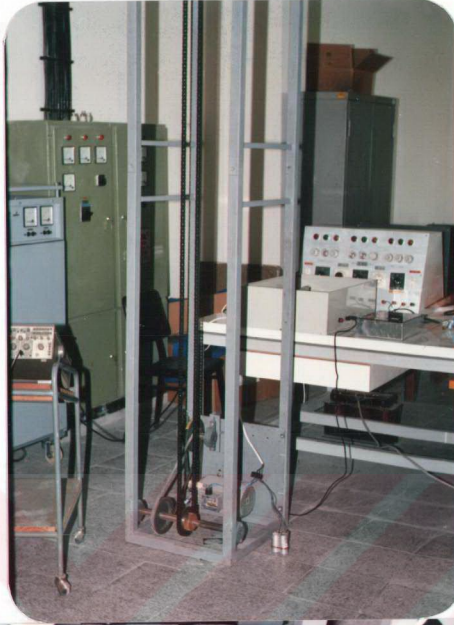
T. C.
Yükseköğretim Kurulu
Dokümantasyon Merkezi



The microprocessor and programming unit



The converter, inverter and main control unit



The lift conveyor model

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