DEVELOPMENT AND EXPERIMENTAL INVESTIGATION ON μP BASED 3-ϕ TO 1-ϕ CYCLOCONVERTER FED INDUCTION MOTOR DRIVE

A DISSERTATION

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requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power Apparatus & Electric Drives)

By

SEEMA SINGHAI

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE - 247 667 (INDIA)

MARCH, 1996

Gratis

CANDIDATE'S DECLARATION

This is to declare that the dissertation entitled "**DEVELOPMENT AND EXPERIMENTAL INVESTIGATION ON μP BASED 3-φ TO 1-φ CYCLOCONVERTER FED INDUCTION MOTOR DRIVE**" which is being submitted by me in partial fulfilment of the requirements for the award of the degree of master of Engineering in ***POWER APPARTUS AND ELECTRIC DRIVES*** in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out by me during the period from August 1995 to March 1996 under the supervision and guidance of **Dr. S.P. Gupta**, Professor, Department of Electrical Engineering, University of Roorkee, Roorkee-247 667 (INDIA) and , **Dr. Promod Agarwal**, Lecturer, Department of Electrical Engineering, University of Roorkee, Roorkee-247 667 (INDIA).

The matter embodied in the dissertation has not been submitted by me for the award of any othe degree or diploma.

Date : 26th MARCH 1996

Place : ROORKEE

(SEEMA SINGAI)

CERTIFICATE

Certified that the above statements made by the candidate are correct to the best of my knowledge and belief.

(DR. S.P. GUPTA)
Professor
Department of Electrical Engg.
University of Roorkee,
Roorkee-247 667

(DR. PRAMOD AGARWAL)
Lecturer
Department of Electrical Engg.
Univesity of Roorkee,
Roorkee-247 667

Date : 26 March, 1996
Place : Roorkee

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The above word has an unfortunate tendency to generate genuine gratitude into stilled formality. However this is the only way I have to record permanently my feelings.

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(SEEMA SINGHAI)

ABSTRACT

The aim of present work has been to develop a 3-phase to single phase six pulse noncirculating current type cydoconverter controlled with a small sclae interface and a 8085 microprocessor based control program suitable for driving a small single phase induction motor for laboratory investigations.

The power circuit consists of two converters connected in antiparallel, each made up of six thyristors connected in bridge configuration.

In the present work the firing instants for the various thyristors are determined following cosine wave crossing principle by comparing a series of constant cosine waves with an adjustable frequency and adjustable voltage refrence signal. As exact digital implementation is too slow and impractical for microprocessor therefore, a straight line approximation of the input cosine waves and the refrence wave have been used. The algorithm used gives a nearly sinusoidal output voltage. A complete hardware and software design of the scheme is given and the test results are presented.

For implementing noncirculating current mode a current sensor is used which is in the form of two power diodes connected in antiparallel in the output line of the cycloconverter.

The developed cycloconverter has been tested for R - load, R-L load & Induction motor load. The oscilloscopic records of cycloconverter output voltage and current are obtained and presented for different frequency settings in the frequency range 2.5 to 16.67 Hz.

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CHAPTER-1

INTRODUCTION

1.1 NECESSITY OF VARIABLE SPEED DRIVE IN INDUSTRY

As a result of rapid advances in automation and process control, the field of application of adjustable speed is continuously growing. The problem in selecting an adjustable-speed drive for a particular application is to choose the system that can most economically provide the required range of speed or torque or position control with the desired accuracy and speed of response. Many industrial drives and processes need to be run at different speeds to suit different applications such as cement industries, traction drives etc.The variation of speed of these drives means variation of either voltage or frequency or both.

1.2 CHOICE OF VARIABLE SPEED DRIVE

In many modern adjustable speed drives the demand is for precise and continuous control of speed,torque, or position with long term stability, good transient performance, and high efficiency. Traditionally, adjustable speed drives used dc motors because of ease of variation of speed. However dc drives suffer from a number of limitations. Comparative features of dc machine drives and ac machine drives are as follows:

1. Dc motor is considerably expensive compared to the induction motor and is considerably more expensive than the synchronous motor.Simple rotor construction of induction and synchronous motors results in a higher power weight ratio.

2. The mechanical commutator of dc machine makes the motor unreliable.The motor requires frequent maintenance necessitating long shut downs. Commutator also limits the armature voltage to a maximum of about 1500 V.

In contrast ac motors,specially cage induction motors are more rugged and more reliable. Simple rotor construction also results in a lower cost motor and a higher power/weight ratio.

3. Dc machine drives are unsuitable for use in explosive and dusty environment. Speed of rotation of dc machines are limited.

4. Control principle and converters used in dc drives are simple and cheaper. In ac drives cost of converter and control equipment are considerably higher.

With improvements in technology, ac drives are now finding a wider field of application. Ac drives use either an induction motor(cage type or wound rotor type) or a synchronous motor.

Ac motors such as cage rotor induction motor and the synchronous,reluctance and permanent magnet synchronous motors are brushless and have a robust rotor construction which permits reliable maintenance-free operation at high speed. The cage rotor of the induction motor drive has a low inertia and can operate at high temperature and high speed for prolonged periods without maintenance. Induction motor drives can be manufactured in much higher horsepower ratings because the stator current is not limited by commutation and the stator voltage can be 15 KV or more. Unfortunately,induction motors and synchronous motors are inflexible in speed when operated on standard constant frequency ac supply. The synchronous motor operate synchronously at a speed which is determined by the supply frequency and the number of poles for which stator is wound. The induction motor runs slightly below synchronous speed. A certain degree of speed variation can be achieved by reduction of the stator voltage at constant supply frequency. But for an efficient wide range speed control the stator voltage and frequency must be varied.

1.3 TECHNIQUES FOR GENERATION OF ADJUSTABLE FREQUENCY AC POWER

In the past, the various techniques for speed control of ac machines often required the use of auxiliary rotating machines. These auxiliary machines have now been replaced by static ac drive systems using static frequency converter. Advantages of static power conversion are:

* Static frequency converter employs various types of semiconductors, operating as electrically controlled switches. High efficiency is attained because of the low "on-state' conduction losses when power semiconductor is conducting the load current and the low "off-state" leakage losses when the power semiconductor is blocking the source, or load,voltage. The transition times between blocking and conduction, and vice versa varies from 150μs for a large thyristor to 50ns for a field effect transistor.Now it is possible to assemble more than one power semiconductor in a single module. The use of such module reduces the no of necessary heat sinks and electrical interconnections.

* Static converter has great ease of control because the output voltage and frequency can be independently varied over a wide range and closed loop feedback methods can be applied easily. The output volt/hertz ratio can be adjusted and large starting torque can be developed whenever required.

* The operating cost of a frequency converter are low due to its high efficiency and the absence of moving parts which deteriorate with time and require periodic replacement.

* Static converters have low installation costs, require small space and have a low noise level.

* One of the most important advantage of static frequency converter is the availability of Microprocessor for the control of ac drive system.

Microprocessor operate at an adequately high clock frequency to complete the calculations in sufficiently small time to directly control the firing of the power semiconductors in the converter circuit operating from the utility supply frequency. In addition to the direct calculation of the power semiconductor firing times the microprocessor can perform lower priority tasks, such as diagnostics, self-test, start-up and shut-down sequencing, and fault monitoring etc.

These rapid technical advancements and declining prices for power semiconductors and microprocessors, coupled for a high efficiency equipments, have lead to the wide application of adjustable- frequency controllers for ac motors.

There are number of schemes in which variable speed drives can be configured using static frequency converters. The most popular among these are:

1. **dc link inverter**
2. **A direct ac to ac converter as cycloconverter**

Both the above schemes provide an alternating voltage at a frequency which is determined by the reference signal used. In order to maintain rated torque capability of ac drives v/f ratio should be kept constant,and for this both types are capable of voltage control within the converters through their control circuits. But cycloconverter possesses number of advantages over dc link inverter in the case of low speed variable speed drives[1, 2].

These are:

* Dc link converter requires two power conversion stages. AC power at network

frequency is rectified, filtered in the dc link and then inverted to ac at an adjustable frequency. Whereas cycloconverter requires only one conversion stage. Storage elements used in dc link introduces some losses therefore total losses in it are larger then that in a cycloconverter and hence power conversion efficiency is less.

* Cycloconverter is a naturally commutated device and hence there is no real limit on its size which is otherwise constrained due to the size of commutating elements becoming prohibitively bulky. Due to absence of commutating components, losses are less in cycloconverter which would further increase the power conversion efficiency compared to the dc link converter.

* Cycloconverter has the inherent capability of bi-directional power flow and therefore can supply loads of any power factor over the entire output frequency range. In dc link converter it is difficult to incorporate this feature and hence, the cycloconverter is preferable to a dc link converter in large four quadrant drive applications.

* Cycloconverter has a unique property that even with unbalanced output loads the, load presented to input supply is balanced because loss of a device going open circuit is not particularly serious in it, therefore these drives are more reliable. The dc link converter does not posses this ability, the loss of one output device will make the system almost inoperable except on light loads and if a complete output phase is lost then the system is totally inoperable.

* The output voltage waveform of cycloconverter is fabricated from segments of supply voltage waveform, and approximates closely to sine wave, particularly at low output frequencies. Therefore at low output frequencies the cycloconverter can produce a high quality waveform. The link converter drive specially those

producing quasi-square waveform outputs, produce oscillatory torque components,having frequency of six times the output frequency, multiples thereof. At low output frequencies these torque oscillations can have a detrimental effect on performance of the drive. Therefore harmonic losses creates a serious problem in case of a link converter unless the devices are suitably derated.

Cycloconverter also has few disadvantages these are :

* The input displacement factor of cycloconverter is poor. Under optimum theoretical load condition, the mean input displacement factor is 0.843, which decrease as the output voltage is decreased and/or the load becomes more and more reactive. The link converter does not in general suffers from this problem.

* The maximum attainable output frequency for practical purpose is less than the input supply frequency, due to necessity for always producing a natural commutation of current from one thyrlstor to the next.

* Large no of devices and complex control electronics required by a cycloconverter to produce an acceptable output wave form makes the drive costly.

However with the capacity of semiconductor industry to produce chips that could perform complex functions and at the same time flexible enough to be adopted to several applications have brought tremendous change in power and control industry [7].

The digital control further introduces some distinct advantages, These are:

(a) Faster response

(b) Possible transmission of the signal without any degeneration.

(c) Higher accuracy as it is not affected by ageing, temperature variation and extraneous disturbance.

(d) Less noise.

Therefore with the introduction of microprocessor into the converter control electronics and continuing reduction in the cost of power thyristors the cycloconverter, today is a practical proposition in large power applications and it may soon begin to penetrate the lower power range of the drive market.

CHAPTER-2

OPERATION AND CONTROL OF CYCLOCONVERTER

2.1 INTRODUCTION

The principle of cycloconverter was first introduced in **1923 by Hazltine [3]**, when the mercury arc converter rectifier became available. But it did not gain wide popularity because of complex circuit and cost involved. The introduction of the SCR and the advent of cheap transistorized electronics allowed a rapid improvement in static power converter to take place in 1960's. Now with the availability of reliable transistorized and microprocessor based control circuitry, cycloconverter forms an important static power converter.

In a cycloconverter, the alternating voltage of supply frequency is converted directly to an alternating voltage at load frequency without any intermediate dc stage. In a line commutated cycloconverter, the supply frequency is greater than load frequency. Greater flexibility of output frequency and supply power factor can be achieved if the power semiconductors are commutated independently of either the input or output ac voltages. This independence can be achieved by external commutating circuits using capacitors and auxiliary semiconductors, or by using power semiconductors with self turn-off capability,such as power transistors, power **MOSFET's**, or gate turn- off thyristors **(GTO'S) [2]**.

There are two application areas of the cycloconverter.These are:

1. In the area of variable frequency variable speed drive for ac machines. Here the input power supply to the cycloconverter has a fixed frequency, and variable frequency output of cycloconverter is connected to the machine to be driven, some typical applications are:

* Mill drive.
* Ore crushing plants.
* Coal mining industries.
* Cement industries.
* Wind tunnel fans.
* Large fan drive etc.

2. In the area of constant frequency power supplies such as Air-craft power conversion.Here the function of cycloconverter is to provide a constant frequency power output, from a variable power source connected to its input.

2.2 BASIC PRINCIPLE OF OPERATION [1] [2]

The line commutated cycloconverter consists of a number of phase controlled converter circuits connected to an ac supply system that provides the voltage necessary for natural commutation. The individual circuits are controlled so that a low frequency output is fabricated from segments of the polyphase input voltages.

The basic principle of operation of cycloconverter can be explained with the help of an equivalent circuit shown in **Fig. 2.1**, which is similar to that of a dual converter. The cycloconverter is basically a dual converter, which is controlled through a time varying phase modulation of its firing pulses, so that it produces an alternating, rather than a direct output voltage. By appropriate control, it is possible to produce a continuous variation of both the amplitude and frequency of the output voltage wave.

In **Fig. 2.1**, each of two quadrant converter is represented as an alternating source, connected in series with diode, which represents the unidirectional current flow of converter. Firing angles of two converters are modulated continuously in such a manner, so that each produces the sinusoidal ac voltage at its output terminals. Thus the voltages of two converters have the same amplitude frequency and phase at

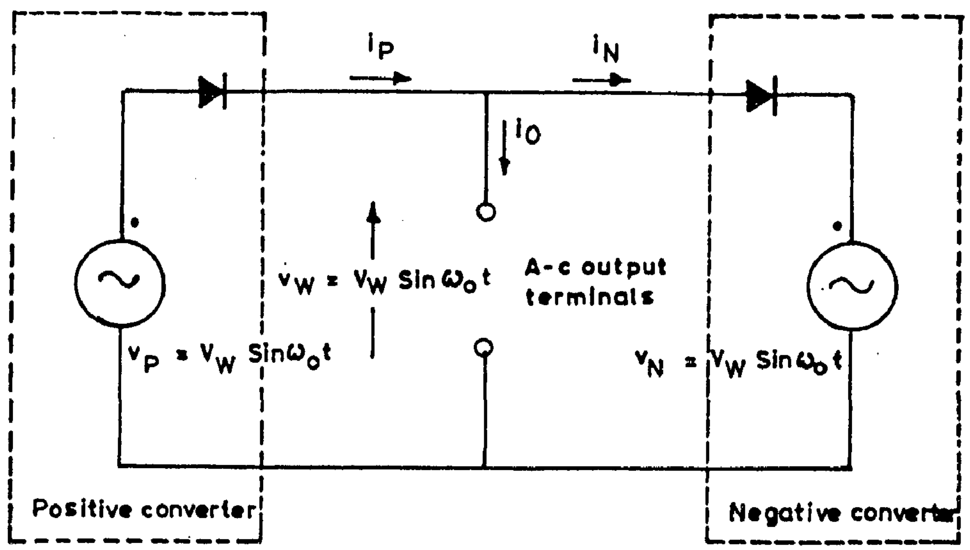


FIG. 2.1 IDEALIZED EQUIVALENT OUTPUT CIRCUIT OF THE CYCLOCONVERTER

all times, and voltage at the output terminal of cycloconverter is equal to the voltage of either of these generators. Because of the unidirectional current carying property of individual converters, the positive current must always be carried by positive converter and negative current by negative converter. Therefore in the general case of a non-unity displacement factor load, during any half cycle of load current, the associated 2-quadrant converter operates both in its rectifying and in its inverting region, and produces both "positive" and "negative" portions of load voltage wave for given period of time as shown in **Fig. 2.2**.

In **Fig. 2.2 (a)**, the load displacement angle is 0^0, therefore each converter carries the load current only while it operates in its rectifying region, and it remains idle throughout the whole period in which its terminal voltage is in the inverting region of operation.

In **Fig. 2.2 (b)**, the displacement angle of the load is 60^0 lagging. During the first 120^0 period of each half cycle of load current, the associated converter operates in its rectifying region,and delivers power to the load. During the latter 60^0 of period of each half cycle of load current, on the other hand the associated converter operates in its inverting region, and under this condition the load is regenerating power back in to the ac system at the input side.

In **Fig. 2.2 (c)** the displacement angle of load is 60^0 leading, therefore during the first 60^0 period of load current half cycle, the associated converter operates in its inverting region, and during the latter 120^0 period in its rectifying region.

In **Fig. 2.2 (d)** the displacement angle of load is 180^0, therefore during each half cycle of load current, the associated converter operates in its inverting region.

The basic principle of firing angle control of the converter can be explained,

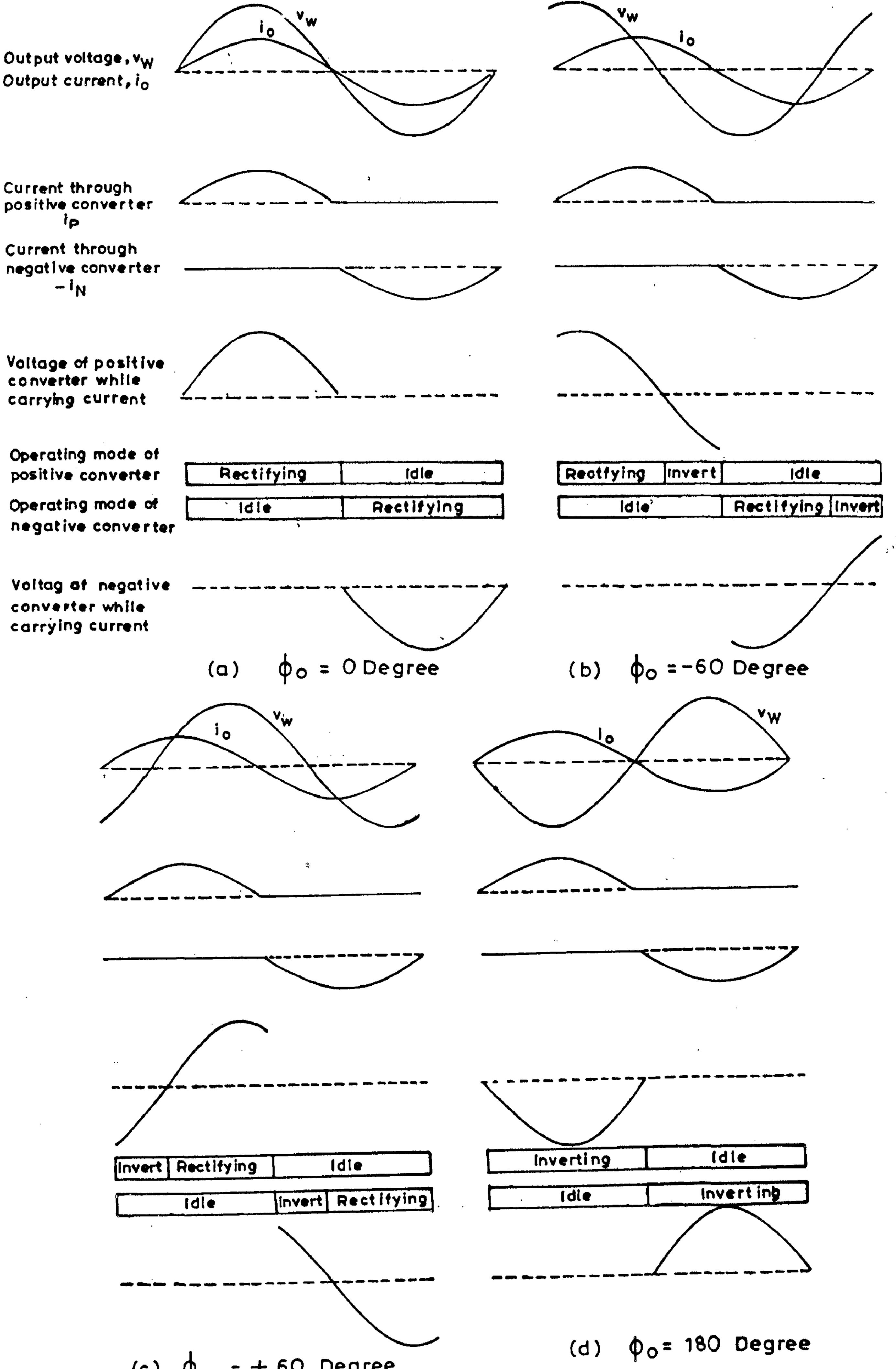


FIG. 2.2 WAVEFORM ILLUSTRATING THE OPERATION OF IDEALIZED CYCLOCONVERTER

with the help of a three phase half wave controlled converter supplying inductive load that maintains continuous current flow. The rectifier firing is slowly varied as shown in **Fig. 2.3 (a)**. At point A there is zero delay, the mean output voltage is therefore has its maximum value. At B the mean output voltage is reduced slightly by introduction of a small firing delay. The firing delay is increased continuously at point C,D and E, which results in continuous decrease in the output voltage and finally at F it is made equal to 90^0 which gives zero output voltage. Thus by changing the delay angle of successive pulses of the converter from 90^0 to 0^0 and back to 90^0 positive half cycle of output voltage is obtained.In a similar way negative output voltage of the converter can be controlled by varying firing delays within the range 90^0 to 180^0 as shown in **Fig. 2.3 (b)**.

Therefore if the firing angle is varied from 0 to 180^0 and back to 0, one complete cycle of the low frequency variation is superimposed on the average output voltage. The superimposed frequency is determined solely by the rate of variation of α and is independent of the supply frequency. One complete cycle of low frequency wave form is shown in **Fig. 2.3 (c)**.

Thus cycloconverter is basically a switching arrangement, each thyristor switch opens and closes at suitable instants, so that low frequency output waveform is fabricated from segments of the input waveform. The harmonic content of the output waveform decreases as the ratio of output to input frequency is decreased and as the number of supply phases is increased.

The average output voltage of phase controlled converter can therefore, be varied sinusoidally through a complete cycle by suitable variation of delay angle. But because of the unidirectional current carrying property of the silicon controlled rectifier two similar circuits must be connected in inverse parallel in order to produce a complete cycle of output current.

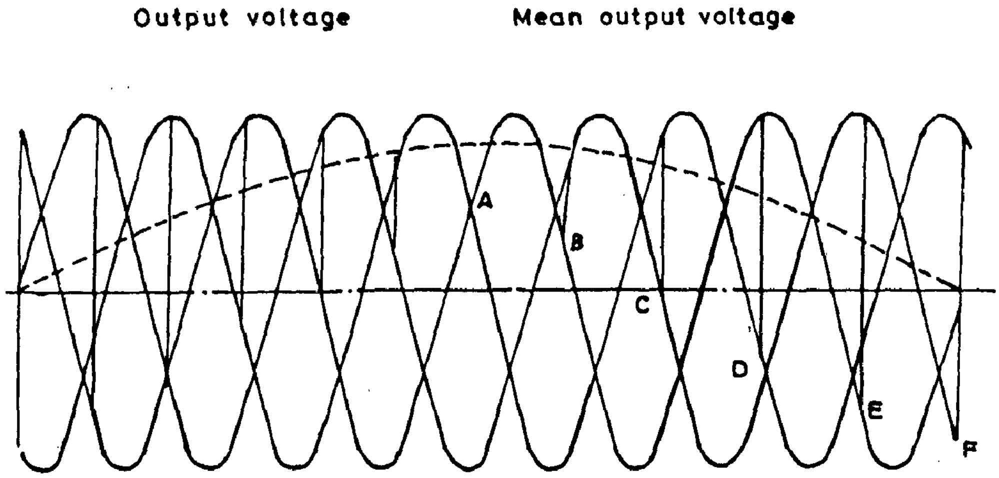


FIG. 2.3(a) SINSUIDAL VARIATION OF THE' AVERAGE OUTPUT VOLTAGE OF A PHASE-CONTROLLED RECTIFIER

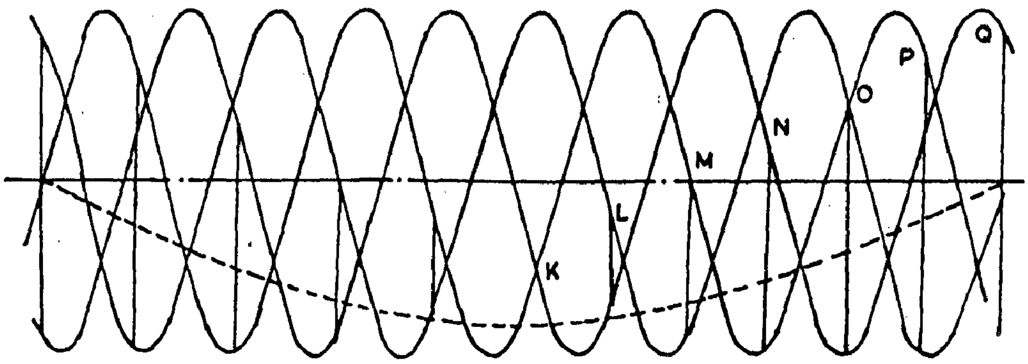


FIG. 2.3(b) SINSUIDAL VARIATION OF AVERAGE COUNTER emf OF A PHASE-CONTROLLED INVERTER

In a cycloconverter the positive and negative converter groups must each supply a half-cycle of the low-frequency output current. when a resistive load is being supplied, there is no need for inverter opoeration because the positive group supplies load current during the positive half cycle of output voltage and the negative group conducts for the negative half-cycle. When an inductive load is being supplied, the low-frequency current lags the output voltage. This means that each cycloconverter group must continue to conduct after its output voltage changes polarity. During this period the group functions as an inverter, and power is returned to the ac supply, intverter operation continoues unitl such time as the load current reduces to zero and reverses, when the other group starts to conduct. In this manner, energy can be transferred in either direction by the cycloconverter.

Thus, the cycloconverter is able to deliver low-frequency ac power to any type of reactive load, and the phase displacement between the half-cycles of current conduction and output voltage determines the intervals of rectifier and inverter operation.

Fig. 2.3(c) shows one complete cycle of low-frequency output current, with a lagging power factor of 0.6, and the periods of rectification and inversion are indicated for positive group.

The cycloconverter is commonly required to deliver a 3-phase output from 3-phase input the basic cycloconverter module essentially consists of a dual converter, which of course, produces only a single phase output.

Many alternative arrangements of cycloconverter circuit having varying degrees of complexity, and providing either single or multiphase outputs are possible. Any type of converter configuration can be used in making cycloconverter. When a three phase output of variable magnitude and variable frequency is required, three single phase

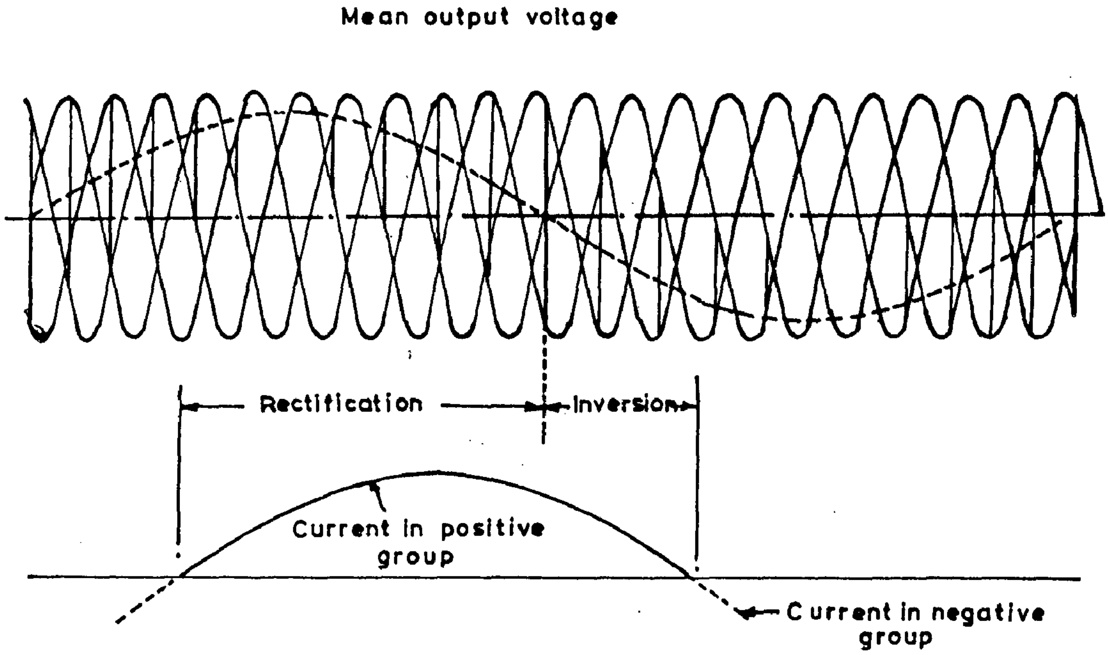


FIG.2.3(c) VOLTAGE AND CURRENT WAVEFORMS FOR THE POSITIVE GROUP OF A PHASE-CONTROLLED CYCLOCONVERTER FEEDING AN INDUCTIVE LOAD AT 0·6 POWER-FACTOR

cycloconverters should be connected in, such a way, so that they produce 120^0 phase displacement between their outputs. Such an arrangement for providing a 3-phase output gives "symmetrical" circuits. The schematic diagram of a symmetrical 3-pulse cycloconverter circuit is shown in **Fig 2.5** and corresponding basic circuit is shown in **Fig 2.6.** This comprises 3 identical 3-pulse converters, one for each output phase. The schematic diagram of a "symmetrical" 6-pulse midpoint cydoconveter circuit is shown in **Fig 2.7.** This comprises three identical 4-quadrant 6-pulse bridge converters, one for each output phase. The input terminals of each of the three converters are fed from an isolated secondary winding on the input transformer. Thus there is no connection between the output terminals of the bridge circuits via their input connections, and it is permissible to make connections between three phase loads.

Other possible "symmetrical" cycloconverter circuits are

* "Symmetrical" sixpulse midpoint circuit.
* "Symmetrical" twelve-pulse midpoint circuit.
* "Symmetrical" six pulse Bridge circuit with isolated loads.
* "Symmetrical" twelve-pulse Bridge circuit".
* "Open delta cycloconverter circuit".
* "Open delta three-pulse midpoint circuit".
* "Ring connected cycloconverter circuits".

2.3 OUTPUT VOLTAGE

For the operation of cycloconverter it is necessary that output voltage waveform of both positive and negative converters, should be in same phase at all times. This requires that if α_p is the delay angle of positive group, the corresponding delay angle of negative group must be α_n=180-α_p. However this relationship only ensures that the mean output voltages of the two converters become identical, the instantaneous voltages being quite different.

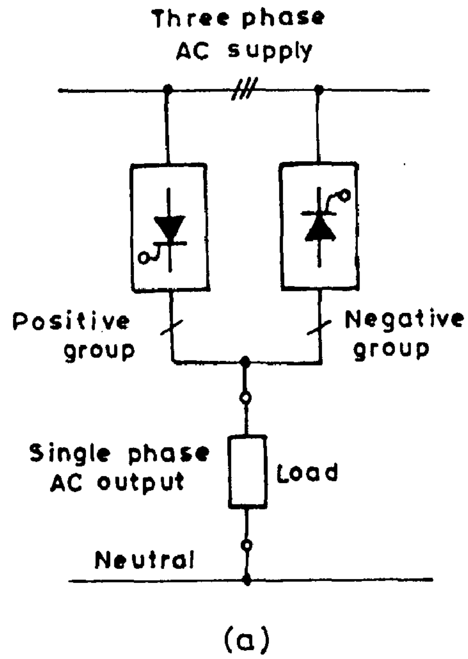


FIG. 2. 4 (a) THREE PHASE TO SINGLE PHASE CYCLO-CONVERTER SCHEMATIC DIAGRAM

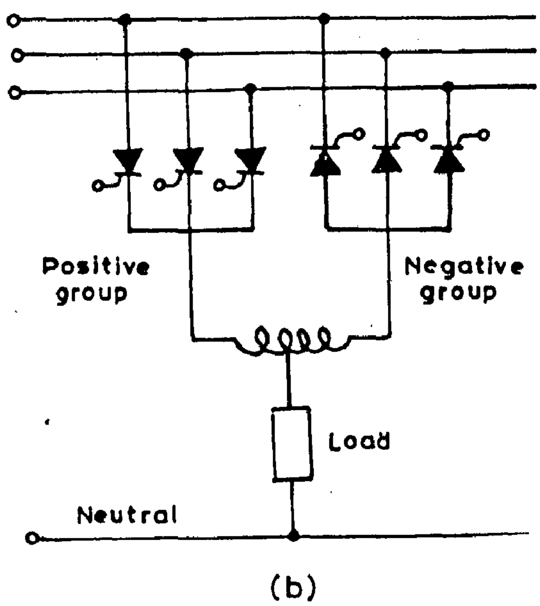


FIG. 2. 4 (b) THREE PHASE TO SINGLE PHASE THREE PULSE CYCLOCONVERTER BASIC CIRCUIT

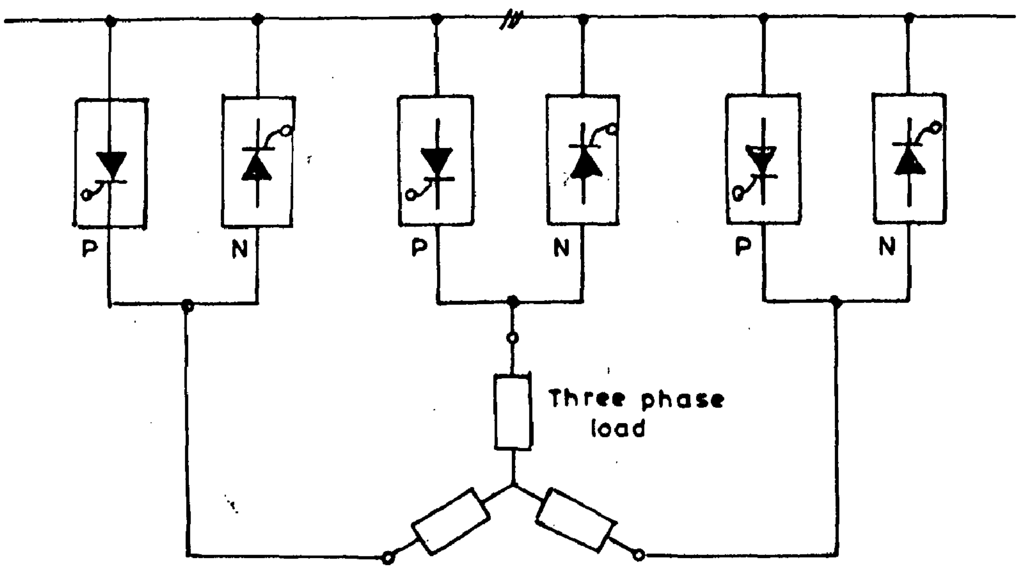


FIG. 2. 5 THREE PHASE THREE-PULSE CYCLOCONVERTER SCHEMATIC DIAGRAM

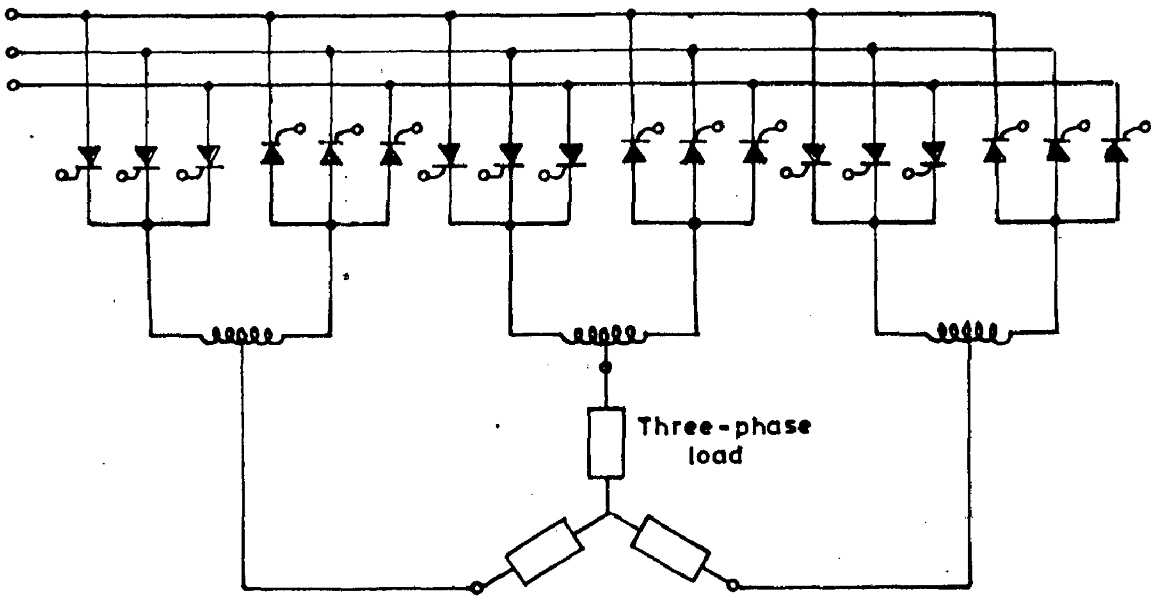


FIG. 2.6 THREE PHASE THREE-PULSE CYCLOCONVERTER BASIC CIRCUIT

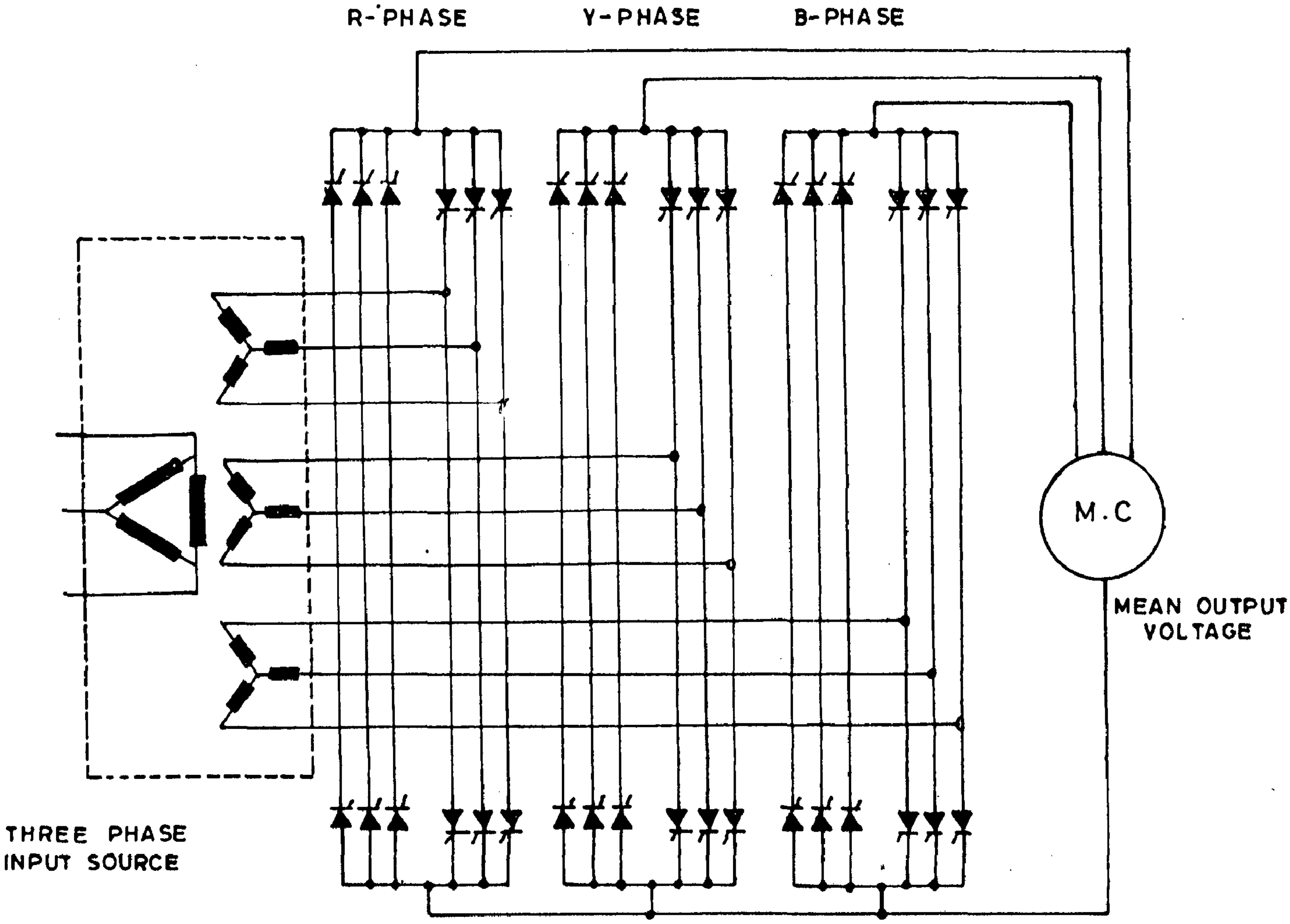


FIG. 2.7 THREE PHASE SIX PULSE CYCLOCONVERTER BASIC CIRCUIT

The waveform of output voltage given by cycloconverter is very much dependent upon the control logic that selects appropriate segments of the input voltage. Using converters of higher pulse number in each group(positive and negative), the waveform can approach close to the reference signal waveform. The exact waveshape of the output voltage mainly depends upon the following factors:

* Converter pulse number.
* Ratio of output to input frequencies.
* Relative level of the output voltage.
* Load displacement angle.
* Modulation techniques which controls the firing pulses of the thyristors.

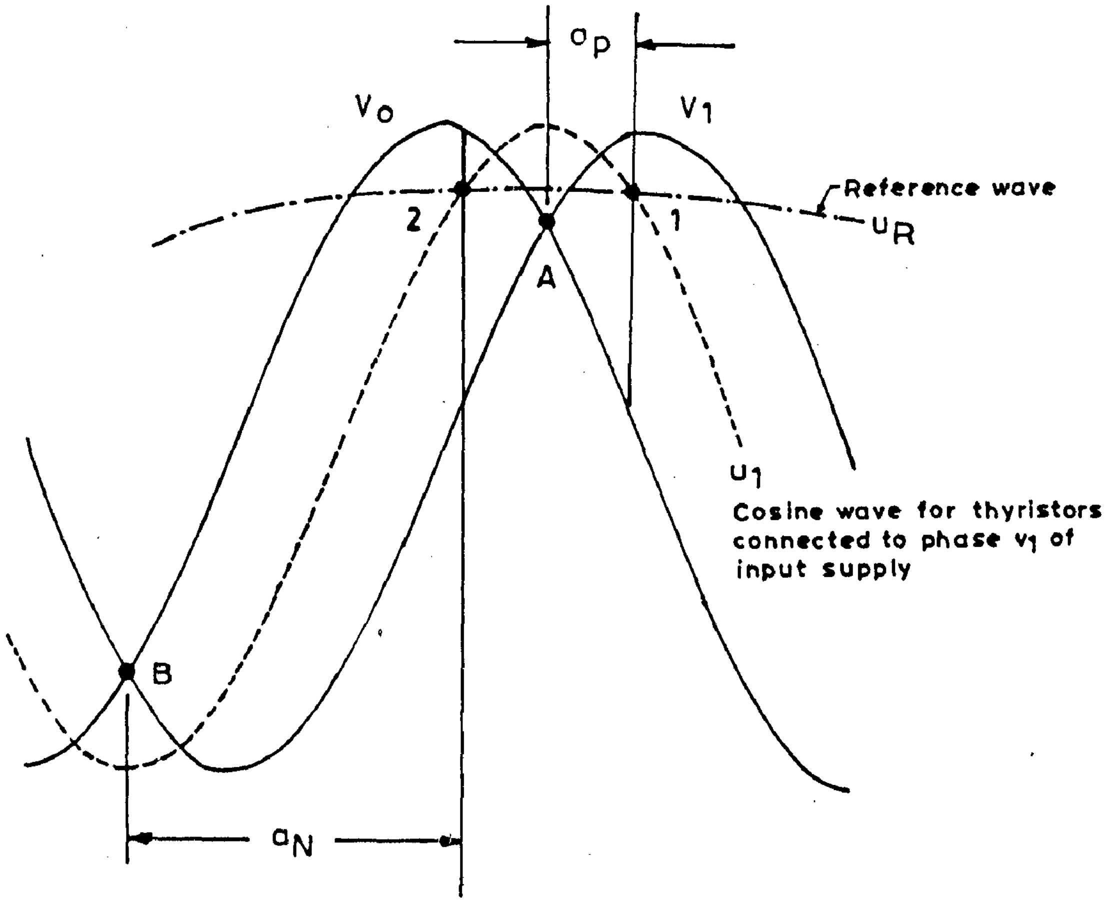
However the firing angle of the positive group can not be reduced to zero, as this corresponds to a firing angle of π in the negative group. Inverter firing can not be delayed by 180 degrees, since sufficient margin must be allowed for commutation overlap and thyristor recovery time. Therefore the delay angle of the positive group can not be reduced below a certain finite value α_{min}. The maximum output voltage is therefore

$$Vd_{max} = Vd_0 \cos \alpha_{min} = r \; Vd_0$$

In practice the output voltage is less than the theoretical value due to commutation overlap the circulating currents between positive and negative groups.

2.4 COSINE WAVE CROSSING CONTROL

In order to control the output voltage of the phase controlled cycloconverter, it is necessary to control the phase of the thyristors firing pulses. Out of various pulse timing control schemes ***"COSINE WAVE CROSSING"*** control principle for determining the firing instants gives excellent output waveform, i.e it produces



A – Zero firing angle instant for positive group thyristor connected to phase v_1

B – Zero firing angle instant for negative group thyristor connected to phase v_1

FIG. 2.8 COSINE WAVE CROSSING CONTROL

minimum possible overall rms harmonic distortion [1].

In "cosine wave crossing" scheme a firing instant is given by the point of intersection of a associated "cosine timing wave" and the reference voltage as shown in **Fig. 2.8**. The cosine firing wave is derived from, and synchronized to, the converter ac input voltage and its phase is such that its peak occurs at the earliest possible commutation angle(i.e. α=0 degree) of the associated thyristor.

According to this principle each firing pulse is initiated at the point at which the associated cosine timing wave becomes instantaneously equal to the reference voltage. That is, when

$$E \cos(\omega_1 t) = V \cos(\omega_2 t)$$

where

E- peak value of the cosine timing wave

V- peak value of reference voltage

ω_1- Angular frequency of timing wave

ω_2- Angular frequency of reference wave

At the intersection point $\omega_1 t = \alpha$ therefore

$$E \cos(\alpha) = v \cos(\omega_2 t)$$

Fig. 2.9 (a) shows supply phase voltage waveform of phase a,b and c and the earliest instants when the thyristors of positive and negative groups starts conduction for three phase three pulse cycloconverter. Cosine waves for positive thyristors T_A, T_B and T_C are e_a , e_b and e_c respectively as shown in **Fig. 2.9 (b)**. Starting from zero firing angle instant, 'cosine' waves are drawn for a period of 180^0 in each cycle. A positive group thyristor is fired at an angle α decided by the point of intersection of the corresponding 'cosine' wave and a reference sinusoidal voltage of a particular amplitude and frequency as shown in **Fig. 2.9(b)**. When the positive group thyristors are sequentially fired in this manner, the voltage waveform as shown in **Fig. 2.9 (c)** is obtained across the load.

The mean envelop of this waveform has the same frequency as that of the reference voltage waveform and its amplitude is proportional to the amplitude of the reference voltage waveform. Thus the frequency and amplitude of the load may be controlled by controlling the frequency and voltage respectively of the reference voltage waveform.

The cosine waves e_a' , e_b' and e_c' for negative group thyristors T_A' , T_B' and T_C' respectively are given in **Fig. 2.9(d)** along with the reference voltage waveform. The corresponding load voltage waveform is given in **Fig. 2.9(c)**. The mean envelop of this waveform is identical with respect to that contributed by positive group thyritors.

Fig. 2.9(f) shows supply voltage waveform and earliest instants when the thyristors of positive and negative groups starts conduction. Cosine waves for positive thyristors T_1, T_2, T_3, T_4, T_5 and T_6 are e_1, e_2, e_3, e_4, e_5 and e_6 respectively as shown in **Fig. 2.9(g)** and for negative thyristors T_1', T_2', T_3', T_4', T_5' and T_6' are e_1', e_2', e_3', e_4', e_5' and e_6' respectively as shown in **Fig. 2.9(h)**.

Firing instant for the different thyristors of positive group is given in **Fig. 2.9(g)**.

The waveforms of the two converters are not instantaneously identical and difference between the two leads to the circulating current when both groups conduct simultaneously. This circulating current can be limited by using a reacter or by suitable control of firing pulses in accordance with the direction of load current so as to "block" the idle converter or by a combination of both of these techniques.

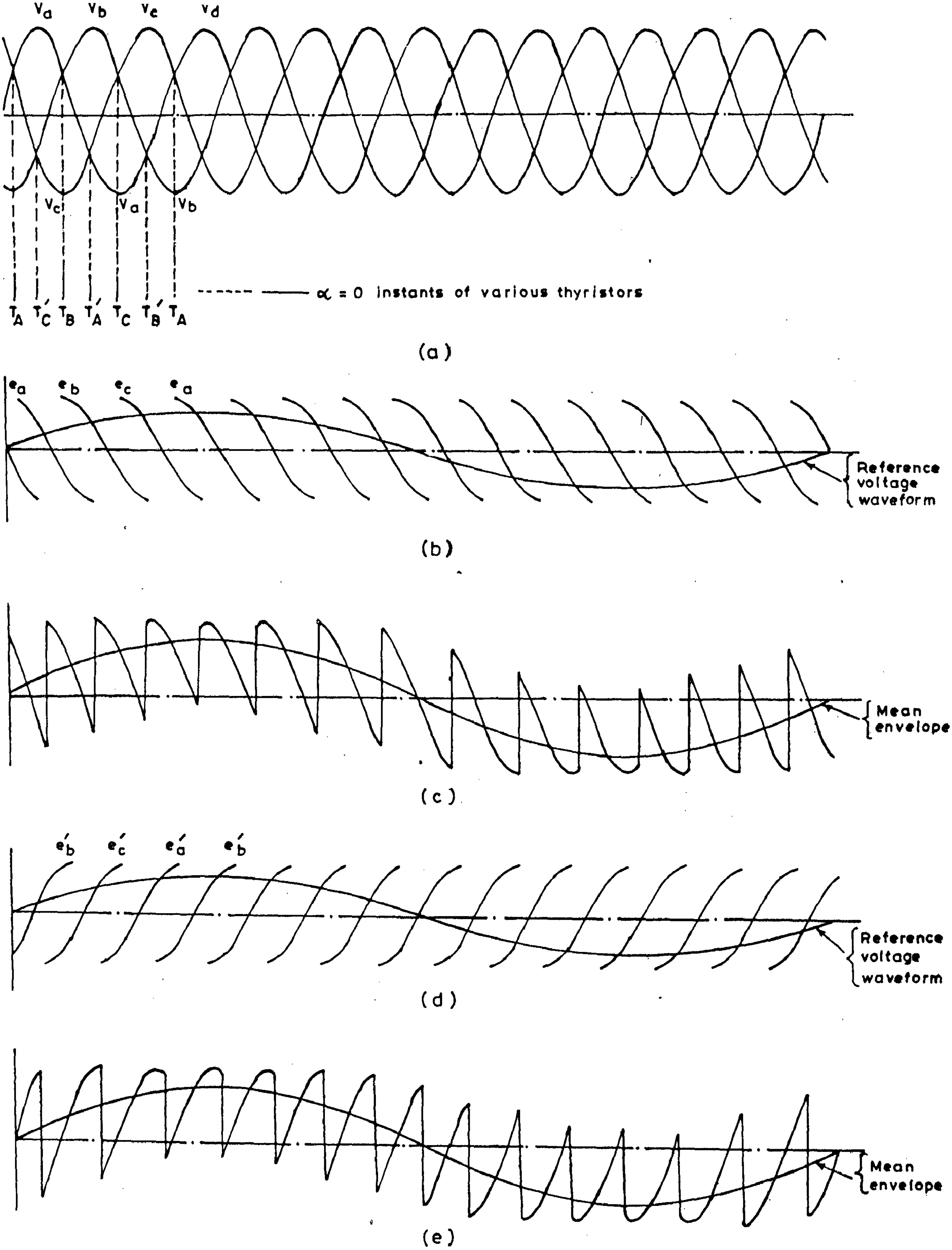


FIG. 2.9 COSINE CROSSING CONTROL OF CYCLOCONVERTER (Three pulse)

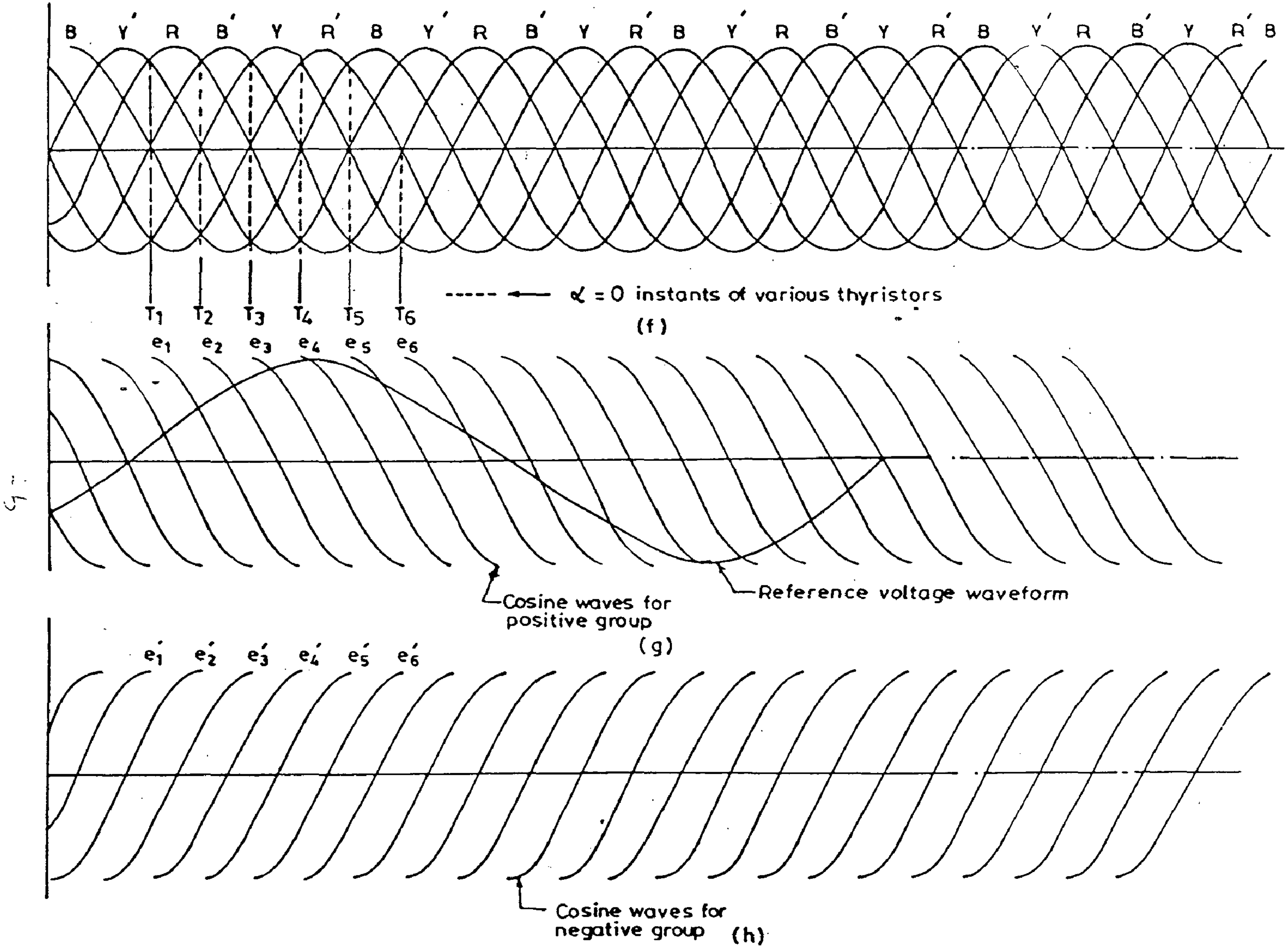


FIG. 2.9 COSINE CROSSING CONTROL OF SIX PULSE CYCLOCONVERTER

2.5 MODES OF OPERATION

There are two modes of operation of cycloconverter, these are:

1. The *"natural"* circulating current mode of operation.
2. The circulating current free mode of operation.

THE NATURAL CIRCULATING CURRENT MODE OF OPERATION

In this mode of operation of cycloconvertor both convertors conduct simultaneously. The ripple current circulates between the two converters. Suppose positive group has a delay angle α_p and delivers positive current to the load. The negative group has a delay α_n and permits current flow in the opposite direction. If on state voltage of thyristor is negligible the angle must be controlled so that $\alpha_p=180-\alpha_n$. In this manner, the average output voltage of the rectifier group is maintained equal to the average back emf of the inverter groups, and circulation of large low frequency currents between groups is avoided. However the instantaneous voltages of the two groups are not identical, and large harmonic currents will circulate unless they are limited.

These intergroup currents are limited using an intergroup reactor. A centre tapped reactor is connected between the two groups and load is connected to a centre tap. The low frequency output current of the cycloconverter is opposed by the reactance x due to one half of the intergroup reactor. If the two halves of the rector are tightly coupled, the flow of harmonic current between the groups is opposed by a reactance approaching 4Kx, where k is the order of the harmonic. A suitable choice of the inductance will restrict the flow of harmonic current without seriously affecting the fundamental output current.

In **Fig. 2.10**, the voltage and current waveforms are shown for the six pulse cycloconverter,assuming a highly inductive load. For the positive half cycle of output voltage positive group operates as a rectifier with a delay α_p, which is less than 90^0, while the negative operates in the inverter region with a delay angle $\alpha_n=180-\alpha_p$. Thus the average output voltage of the two groups are equal, but the instantaneous values are quite different. The voltage difference appears across the inter group reactor and has the waveform shown. The circulating current flows through the two series connected thyristor circuits and is limited only by the inductance of the intergroup reactor, assuming negligible circuit resistance. The circulating current waveform is therefore determined by the volt-second integral of the intergroup voltage and has the waveform as shown. During the interval when positive and negative thyristor groups have different instantaneous voltages, the intergroup reactor behaves as a potential divider and the output voltage at centre tap is average of the two group voltages.

This mode of operation therefore, suffers from following drawbacks

* Cost of converter becomes more.
* Input displacement factor is less.
* Size is comparatively large.
* Current loading on thyristors is more.
* Losses are more.

CIRCULATING CURRENT FREE MODE OF OPERATION

In this mode of operation circulating current is suppressed by blocking all thyristors in the rectifier group that is not delivering load current. Blockage is achieved by removing the gating pulses for the appropriate periods, and the intergroup reactors then be reduced in size or completely eliminated. A current sensing device is then incorporated in each output phase of the cycloconverter. This sensor detects the output current and feeds a signal to the control circuit to inhibit the gating of the thyristors in the nonconducting group. If an overload or fault current flows in the system, all the gating pulses are removed in order to protect the thyristors. Therefore

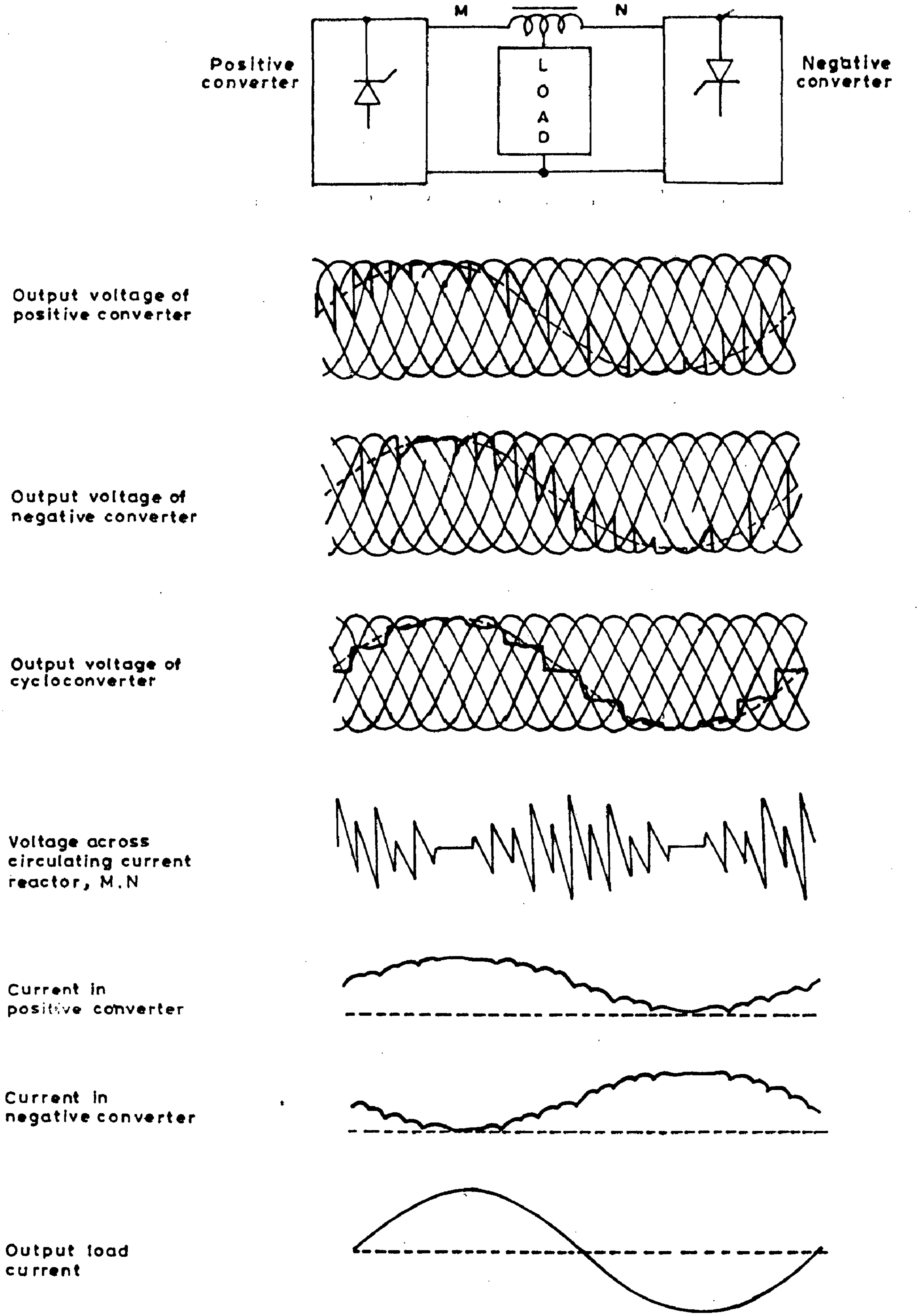


FIG. 2.10 WAVEFORMS FOR THE SIX-PULSE CYCLOCONVERTER IN THE NATURAL CIRCULATING CURRENT MODE

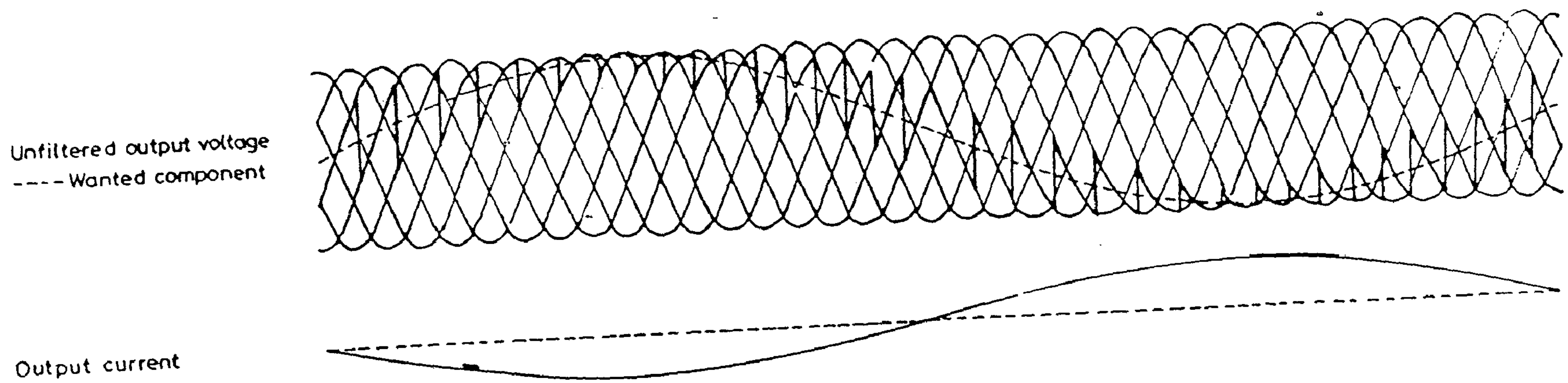


FIG. 2.11 WAVEFORMS FOR THE SIX-PULSE CYCLOCONVERTER IN THE CIRCULATING CURRENT FREE MODE

this mode of operation gives better efficiency and higher displacement factor of the cycloconverter. However, control of the cycloconverter in this mode of operation is complicated.

The operation of six pulse cycloconverter in circulating current free mode of operation is shown in **Fig. 2.11**. Here converter operates in their rectifying and inverting regions during specific period of each output cycle, according to the displacement angle of the load.

2.6 LOAD COMMUTATED CYCLOCONVERTER

The load commutated cycloconverter differs from the line commutated cycloconverter in that the thyristors can be commutated by the reversal of load voltage. Therefore load must posses a back emf independent of source voltage such as a permanent magnet synchronous machine. In this case, the load frequency can be equal to or greater than, the source and still allows the natural thyristor commutation. The thyristor gating depends upon two control signals. First with respect to the source voltage, to control the load voltage; and second with respect to the synchronous machine-generated emf, to ensure that current will flow in correct phase of load machine at correct time. In aircraft applications load commutated cycloconverters are used to start and accelerate a gas turbine through its high frequency synchronous ac generator operating as a motor. After the turbine has started and reached its operating speed the generator and cycloconverter deliver 400 hertz power to the aircraft.

2.7 FORCED COMMUTATED CYCLOCONVERTER

The line-commutated and load commutated cycloconverters have relied on the reversal of the source or load voltage to achieve natural commutation of the thyristors. Another approach to commutation is to provide additional circuit components to force commutate the thyristors independent of the source and load voltages. This independent turn-off technique allows the output frequency to be lower than, equal to, or higher than the input frequency. Two forms of forced, or impulse, commutations are used. These are reverse voltage commutation and reverse current commutation. In each method all thyristors of the cycloconverter needs to be connected to the forced commutating circuit or circuits, and there are many different locations for the commutating components. These components may include auxiliary thyristors, diodes, capacitors, reactors,transformers, and auxiliary power supplies. The added cost of these additional components has tended to limit the application of forced-commutated cycloconverters, but the advent of devices with self-turn-off capability may allow these types of cycloconvertes to be constructed without auxiliary components for commutation.

CHAPTER-3

LITERATURE SURVEY

When a microprocessor controlled cycloconverter is to be designed and tested, it is essential to know the facts from the experience of the past research work. Several investigation have been carried out on cycloconverter drives which concern one or more of the following aspects:

1. Different configurations in which cycloconverter is employed in ac drives
2. Improvement in control techniques.
3. Microprocessor based control.
4. Performance improvements.
5. Modelling and analysis of cycloconverter drives.

Short review of selected literature on these aspects is as follows

3.1 LITERATURE REVIEW

Factors affecting the operation of a three phase controlled cycloconverter have been discussed by ***Bland*** **[4]**. The output voltage functions obtained by using different combinations of control and modeling signals are deduced. An assessment is made of the factors affecting the magnitude, while as an alternative the logical conditions necessary for operation without circulating current has been formulated.

The control circuit of a cycloconverter essentially requires low level variable frequency variable voltage signals. Direct generation of these signals over a wide range of frequency is rather difficult and several techniques have been proposed in the literature.

Schonung and H. Stemmler **[5]**, **Datta[6]** employed hetrodyning using mixer circuits, This technique suffers from poor frequency stability of the output waveform.

Parsuram **et al. [7],** ***Kaplan*** **et al.** [8], ***Rahman*** [9] *and* ***Datta*** [10] have described the development of three phase sine wave reference generator using digital circuits. Independent control of amplitude and frequency of reference signal is obtained through separate dc control of amplitude and frequency of reference signal is obtained through separate dc control inputs. Phase sequence reversal is also possible. The oscillators are adaptable to closed loop control.

Clarke *and* ***Sen*** [11] have described development of another versatile three phase oscillator using digital cicuits. It was used in a cycloconverter powering a linear synchronous motor. In cycloconverter, use of a trapezoidal reference waveform can improve the input power factor at the expense of output harmonic content. This oscillator was designed to produce a variety of output waveforms such as triangular, square, trapezoidal and symmetrically clipped sine wave. Each wave is controlled for amplitude and frequency from separate control signals.

Pavitran *and* ***Perimelalagan*** [12] have suggested a new technique for the generation of adjustable frequency adjustable amplitude 5-phase reference sine wave using a multiplexing technique.Using this technique all the five waveforms are generated by subsequent demultiplexing. The technique is quite flexible and can be used to generate periodic waveforms of any shape and for any number of phases.

Hamblin **et al. [13]** have suggested use of the voltage biased cosine wave technique for phase control of non-circulating current cycloconverter. A new current zero detector is presented involving continuous monitoring of the voltage across each thyristor. Two types of circulating current elimination logic are used suitable for :

1. Resistive load and lagging load and

2. Leading resistive and lagging loads.

Chattopadhyay** and **Rao **[14]** have discussed the requirement of firing circuit suitable for cosine wave control. The circuit implementation and test results are presented and associated problem discussed.

Sonada, Veda, Irisa and ***Takata*** **[15]** and ***Veda*** **et al.[16]** have introduced a new method of detecting the output current zero point and polarity in a non-circulating cycloconverter of the continuous current type reverse polarity characteristics of series thyristor-diode network are used for this purpose. This method is based on the following two basic properties of a series thyristor-diode circuit

1. When a reverse polarity voltage is suddenly applied to the series circuit, the developed voltage at the diode terminals nearly equals the impressed voltage at first before gradually decaying to zero.

2. If a positive polarity triggering is applied to the thyristor gate at the time when series thyristor-diode is reversed, nearly all of this reverse bias voltage instantly appears across the diode terminals before gradually shifting back to the thyristor.

The method is very effective in correct selection without delay and eliminates the need of any equipment for preventing short circuit of the input power source.

With the advent of microprocessors, it is possible to simplify the complex control circuitary of the cycloconverter. The microprocessor based control of cycloconverter has been investigated in many ways. ***Nalin*** **[17]** have developed few general techniques for cycloconverter control. In developing the various techniques, accuracy of trigger timings and systems speed of response were used as performance criteria. But these techniques use large CPU timings and needs more memory space.

Chen **[18]** have suggested a control scheme for cycloconverter in which conventional cosine timing wave approach [1] is used in conjunction with sinusoidal reference voltages. The firing instants for the various thyristors are determined by comparing a series of cosine waves with an adjustable frequency and voltage reference signal for each output phase. As it is recognised that an actual digital implementation is to slow and impractical for the microprocessor, a numerical approximation is proposed which compromises to some extent the accuracy and control range achievable. The arithmatic processing is time consuming and entails a few multiplication steps.

Dalgit Singh **[19]** has tried to explore the possibility of using a microprocessor for controlling a single phase to single phase cycloconverter using square wave reference signal. While this no doubt simplifies computation and may be considered to certain restricted applications, the output voltage of the cycloconverter no longer approximates to a sinusoidal variation.

Robert E. Betz **et al. [20]** have suggested a new firing time algorithm by combining cosine and integral control algorithms. They have also applied this algorithm to construct a microprocessor controlled single phase cycloconverter.

Tso **[21]** gives a scheme for microprocessor control of cycloconverter to produce the desired output voltage waveform. Computation time algorithm for firing delay calculation is comparatively slow and requires large space in memory.

Ichida **et al. [22]** have suggested a new algorithm for determining the sub-divided interval of a 6-pulse digital control cycloconverter (DCC) output voltage waveform which in turn determines the firing angles. This method enables the maximum torque of the induction motor to be kept constant over the range of output frequency in addition the total distortion factor in output voltage is reduced.

Miyazawa **et al. [23][24][25]**, have suggested a new method for developing the control scheme of phase-controlled cycloconverters. In this method all the input cosine wave are transferred into a set of parallel lines by means of coordinate transformation. Two methods for simplifying the control algorithm of cycloconverter control are obtained from studies in a phase plane called a "time-process chart". One is a simple straight line approximation in which only arithmatic operations are involved, and one can avoid the use of trignometric or inverse trignometric functions. The other is also a straight line approximation, but some function tables are used in combination to improve the accuracy of approximation.

Vineeta **et al. [26]** have presented a novel microprocessor application for a single-phase to three phase cycloconverter. The algorithm is formulated for the cosine wave modulation such that it requires one reference wave to generate the trigger pulses for all three phases. This method has been implemented on 8085 microprocessor system. The results for the test performed has been presented.

Tso **et al. [27]** have presented the digital control strategies for obtaining sinewave output for a current-source cycloconverter with fast dynamic response. They have applied a convergence sequential least-squares parameter estimation algorithm, which is comparatively fast.

Vineeta **et al.[28]** have suggested an efficient algorithm to calculate intersecting points of a cosine wave and a reference wave in cycloconverter in order to reduce the processor time. The proposed algorithm requires a lesser number of comparisons to calculate the required intersections, and hence processor time is reduced.

***Goce Arsov* [29]** have presented an improved novel algorithm for a microcomputer-based digitally controlled naturally commuitated cycloconverter operating with variable-frequency input voltage. The author also presents the simulation results of the three-pulse single phase cycloconverter.

***Vineeta Agrawal* et al. [30]** have performed PSPICE simulations for a single phase to three phase cycloconverter. Results of the simulation for load voltage, load current of various semiconductor controlled rectifier (SCR) have been presented.

A high performance cross-current type cycloconverter configuration for induction motor drive has been suggested by ***Hiromi* et al. [31]** controlled by two 16-bit microprocessors, the cycloconverter output voltage waveform is built in stepped shape by simultaneously using positive and negative converters and allowing the mean voltage of the two converters to appear across the load. The advantage claimed are

* Output frequency can be raised to 60% or more of the input frequency, and
* Input power factor can be controlled constantly at a high level.

CHAPTER-4

DESIGN OF CYCLOCONVERTER

The microprocessor control of the power electronic devices reduces the system hardware. The block diagram for the microprocessor based three phase to single phase cycloconverter with no circulating current mode of operation is shown in **Fig.4.1**. An **8085** system interfaced with programmable peripheral interface **(PPI-8255)**, programmable interval timer **(PIT-8253)** programmable interrupt controller **(PIC)**, Analog-to-Digital Converter **(ADC)**, Erasable programmable read only memory **(EPROM)** is used. The complete cycloconverter circuit can be divided into two main groups -

1. Power Circuit
2. Control Circuit

To realise the proposed scheme, power circuit for three phase to single phase cyclocenverter is fabricated. Printed circuit board is designed for the synchronisation and phase crossing detection circuit, power amplification circuit, current sensing circuit and ADC interfacing circuit. Regulated power supplies of +5V, and ±12V required for IC'S is generated using three terminal IC regulators 7805, 7812 and 7912 respectively.

4.1 POWER CIRCUIT DESIGN

The cycloconverter power circuit consists of two six pulse converters connected in antiparallel and operated in non circulating current mode of operation. The design of the converter mainly depends upon the nature of the load. Power circuit for the proposed scheme is shown in **Fig. 4.1**

4.1.1 SELECTION OF THE THYRISTORS AND THEIR RATINGS

Three phase to single phase (6-pulse) cycloconverter requires two bridge converters. These can be realized using thyristors. Inverter grade thyristors have lower turn off time but they are relatively costlier. Also, the forced commutation required in

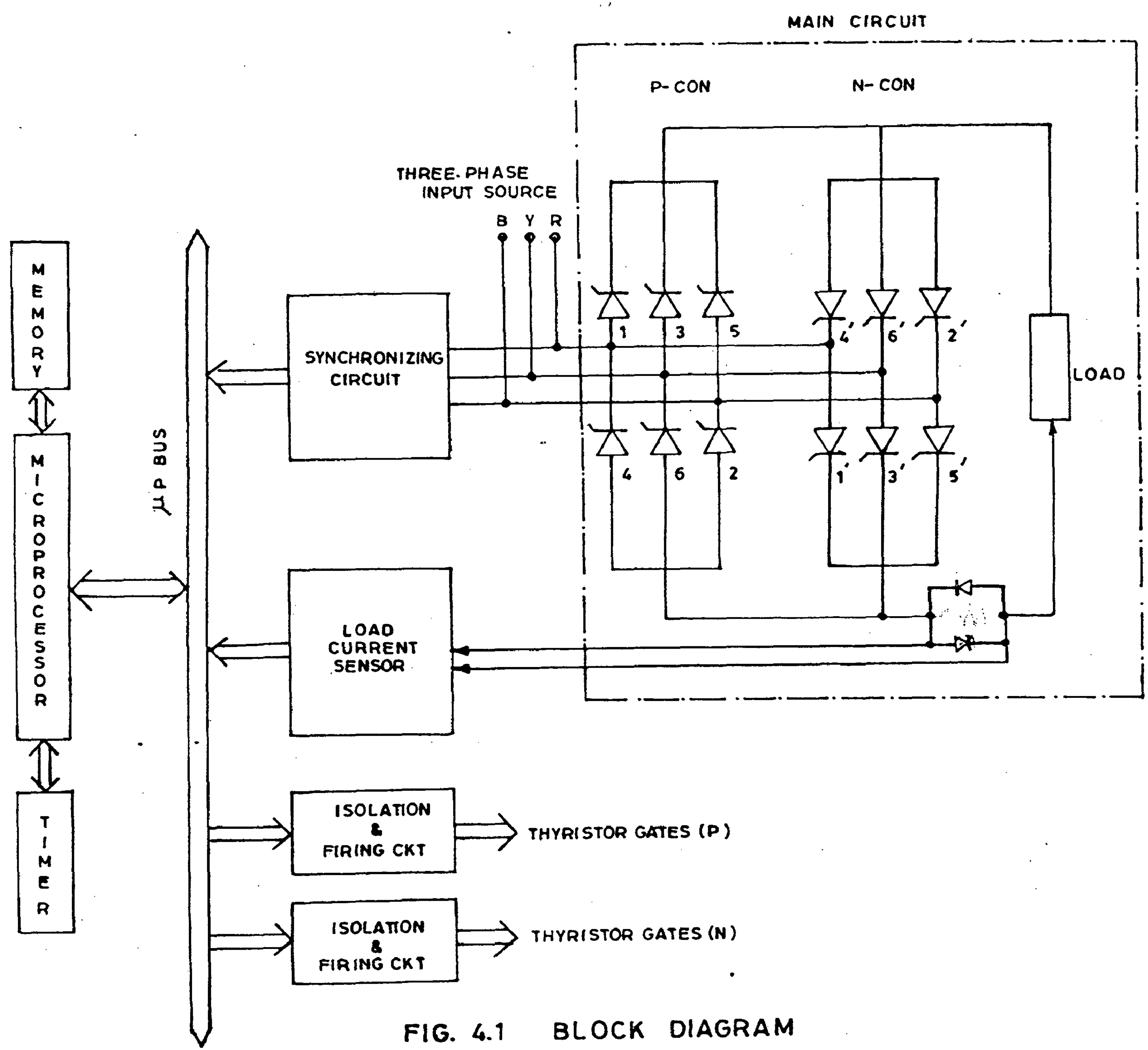


FIG. 4.1 BLOCK DIAGRAM

the case of thyristors increases the number of components and makes the circuit complex. The use of inverter grade thyristors increases the losses, the overall cost of the system and decreases the reliability. So converter grade thyristors are preferred over inverter grade thyristor with a natural commutating circuit for cycloconverter.

To select and use any thyristor successfully in any industrial circuit, none of its published ratings should be exceeded. One of the more critical factors involved in selecting the proper SCR is the current carrying capability of the devices. Nominal current rating for the thyristor can be decided by the circuit loading conditions and the cooling provided by the heat sink. For example, if a single phase bridge is supplying the current to an inductive load at 30A, then average current per arm is also 30A. The rms current can be calculated from average current and form factor of the output wave. Current rating of the thyristor should be selected approximately 40 to 60 percent more than the above calculated valve, taking into account the current transients. Peak inverse voltage rating of the thyristor may be taken 3 to 3.5 times the rms value of the input voltage of the circuit, which takes into account the reverse voltage across the thyristor and the voltage transients normally expected in practice.

Hence, the thyristors of rating 1200V 12A will be sufficient for the proposed scheme.

4.1.2 THYRISTOR PROTECTION

One of the several advantages of SCR is that they are small in size. However, from the stand point of protection small size is a disadvantage. SCR'S have low mass and less surface area and therefore low thermal time constant. These are very delicate devices, so following protections are necessary in the practical circuits.

I di/dt PROTECTION

When on SCR is forward biased and 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 the anode current is large, local hot spots will be created near the gate connection due to high current density. this localised heating may burn out the SCR. Therefore, the rate of rise of current (di/dt) at switch on must not exceed a specified limiting value.

Normally a small inductor called di/dt inductor is inserted in the anode circuit to limit the di/dt of the anode current. The typical di/dt limit in SCR'S is in the range of 20 to 500A/microseconds.

II dv/dt PROTECTION

When the forward voltage is applied across the thyristor a charging current flows. If the rate of application of the forward voltage is high, the charging current can be so high, that the thyristor 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 the thyristor against dv/dt turn on, a snubber circuit, which is a simple RC series circuit, is used across the thyristor. The rate of forward voltage dv/dt must be in the range of 20 to 500V/microseconds.

III HEAT SINK

When a thyristor is conducting, there is a voltage drop across the device. A large anode current flowing 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 given out to the atmosphere.

IV GATE PROTECTION

Gate can be protected against over voltage by connecting a diode across the

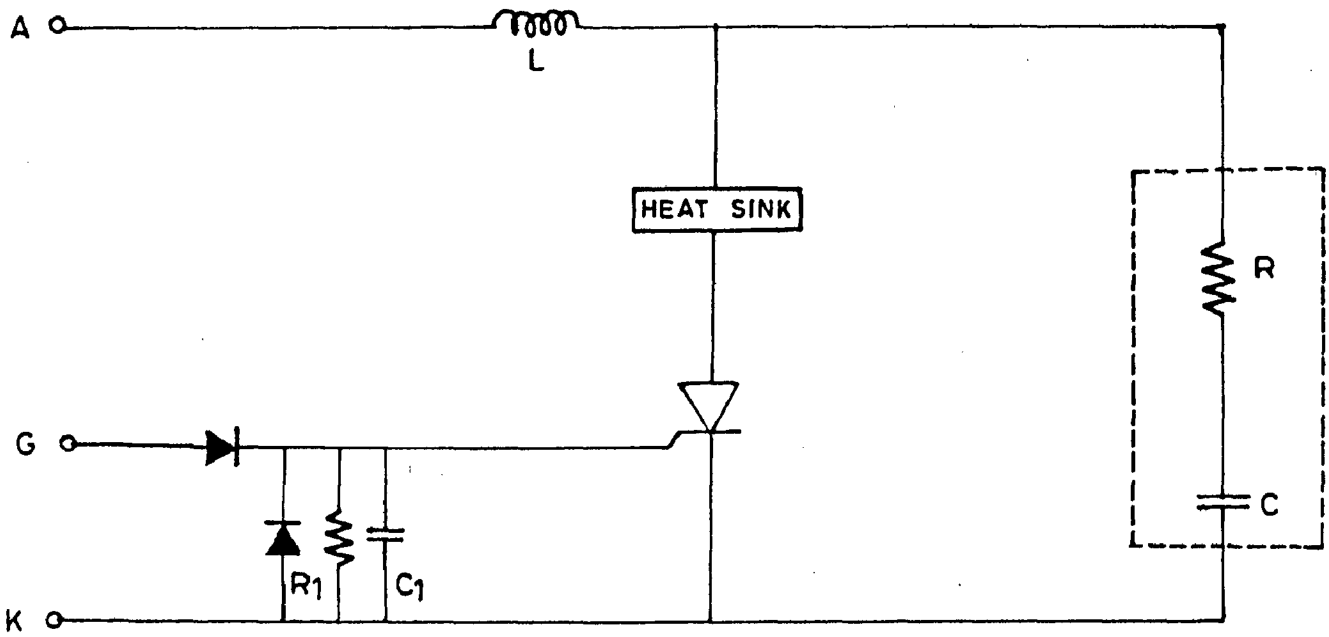


FIG. 4.2 THYRISTOR PROTECTION

gate. A common problem encountered in the thyristors circuitary is spurious firing of the device Trigger pulses may be induced at the gates due to turn on or turn off of a neighbouring thyristor or transients in the power circuit. These undesirable trigger pulses may turn on the device, thus causing improper operation of the circuit. A capacitor and a resistor are connected across the gate to bypass these undesired trigger pulses

4.2 CONTROL CIRCUIT

The gate turn on method is the most widely used method for triggering thyristors. SCR can be turned on even when anode to cathode voltage is less than the forward breakover voltage by injecting carriers into the gate region through gate. The performance capability of a thyristor will depend on the magnitude of the gate current. If the gate current is large enough the SCR will switch on as soon as the anode becomes positive with respect to cathode. The gate current may very from few mA to 250 mA SCR requires some time to attain full conduction when the device is turned on at the gate around 2-10/μ sec. When the SCR has attained full conduction gate has no control over it. But when the gate signal is reduced to zero before the anode current reaches the latching current, the SCR turn off again.

4.2.1 FIRING PULSE GENERATION

The generation of firing pulses required to control the cycloconverter are obtained by the microprocessor 8085, using the synchronisation and phase crossing detection circuit, PIC and relevant software. The pins of port A and B of **PPI1** have output pulses for the thyristors of positive converter and negative converter respectively. the pulses issued from port pins of **PPI (8255)** are not strong enough to turn on the thyristors. Besides this gate and cathode terminals of the SCR are at higher potentials of the power circuit and hence low voltage and low current pulse generation circuit should not be connected directly to the power circuit.

4.2.2 PULSE AMPLIFICATION AND ISOLATION

Pulse amplification and isolation circuit used for thyristors has been shown in **Fig. 4.3**. The firing signal from the output port of PPI and a high frequency signal generated by using IC-555 are ANDed (to avoid loading), amplified (using thyristor SL 100) and fed to the pulse transformer.

The pulse transformer is used to provide physical isolation between the power circuit and control circuit. A diode is connected across the pulse transformer primary to avoid the saturation of the pulse transformer and to protect the transistor against induced voltage. A diode is connected across the thyristor gate to protect against over voltages. A resistance is connected in series with the pulse transformer to limit the gate current therefore, provides protection against over current. A capacitor is connected across the gate to cathode to bypass the noise pulses. The circuit requires isolated ±5V and ±12V power supply. Therefore, 7805 and 7812 voltage regulation chips are used to generate ±5V and 12V respectively. **Fig. 4.3** shows complete details of the pulse amplification and isolation circuit.

4.2.3 SYNCHRONISATION AND PHASE CROSSING DETECTION CIRCUIT

Fig. 4.4. shows the details of the universal synchronising circuit. The "Phase interaction pulse generator" is a circuit used for generating a pulse at the intersecting point of two input phases. The firing pulses generated for each bridge converter used for designing the cycloconverter must be synchronised with the converter input. Basically synchronisation is achieved by sampling input signal as given to the converter. The input voltages are stepped down and isolated from electronic circuit using step down transformers. These ac signals are fed to the comparator **(IC 339)**. the output of the comparator remains high for 180 degree and goes low for next 180 since transformer introduces 180 degree phase shift, therefore an inverter circuit using **IC 7400** is constructed. The output of the inverter circuits is used as quantizer signals. The rising and falling edges of the comparator output signal is connected to the positive

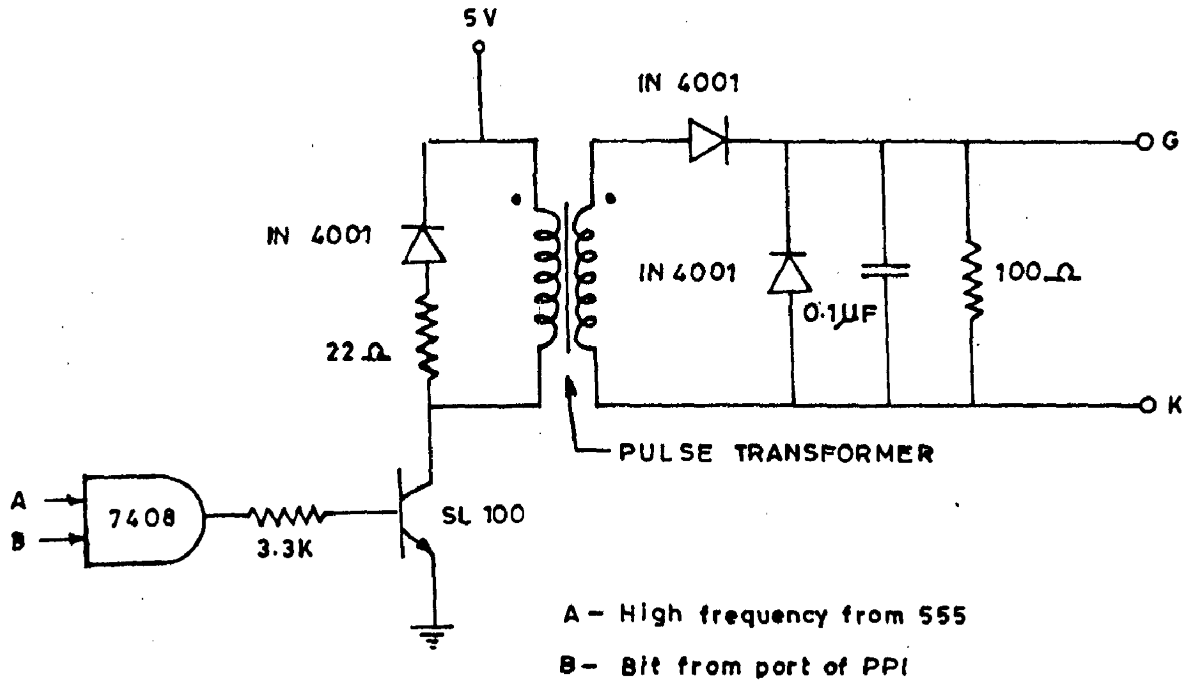


FIG. 4. 3 PULSE AMPLIFICATION AND ISOLATION CIRCUIT

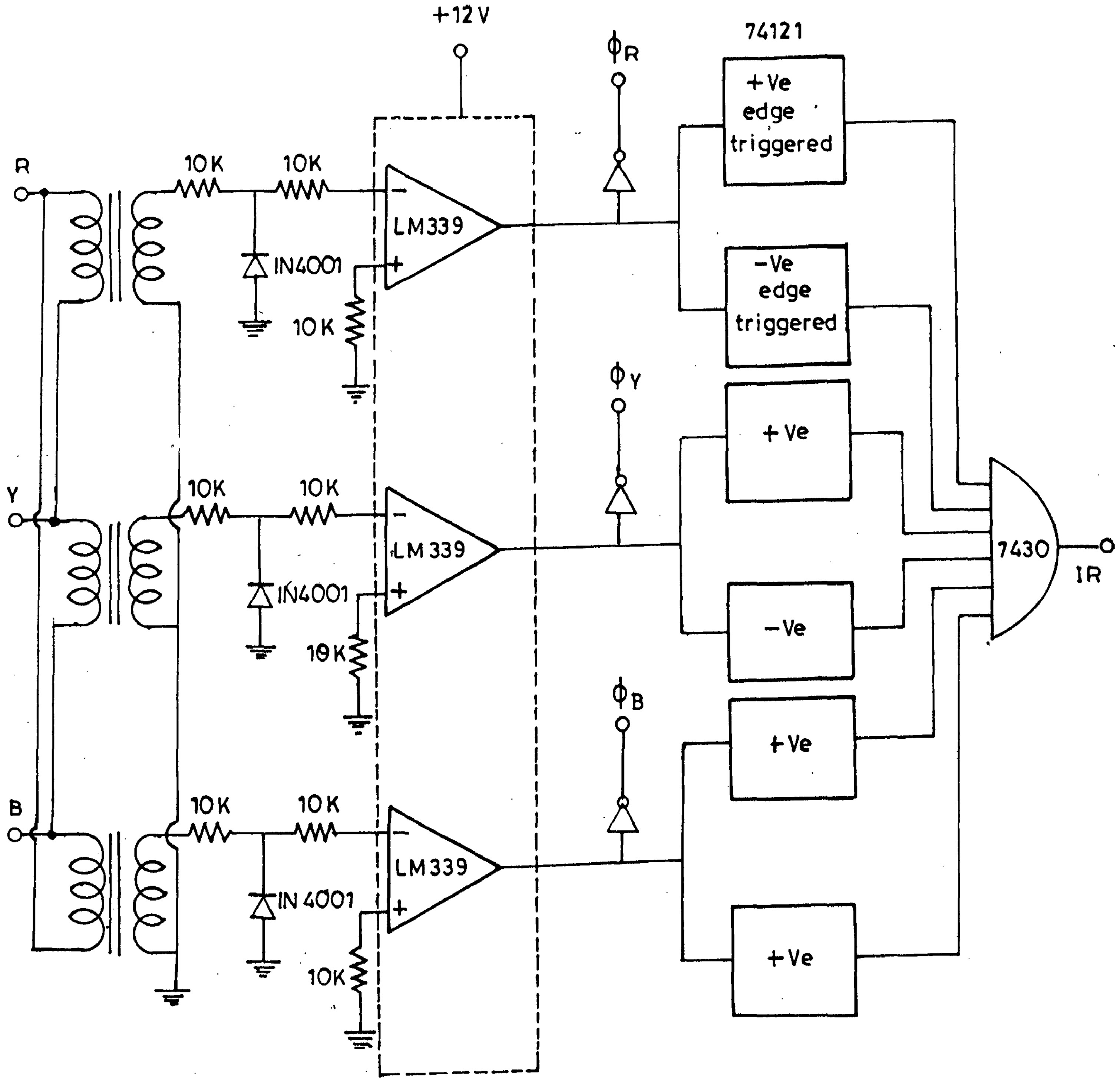


FIG. 4.4 SYNCHRONISING AND PHASE CROSSING DETECTION CIRCUIT

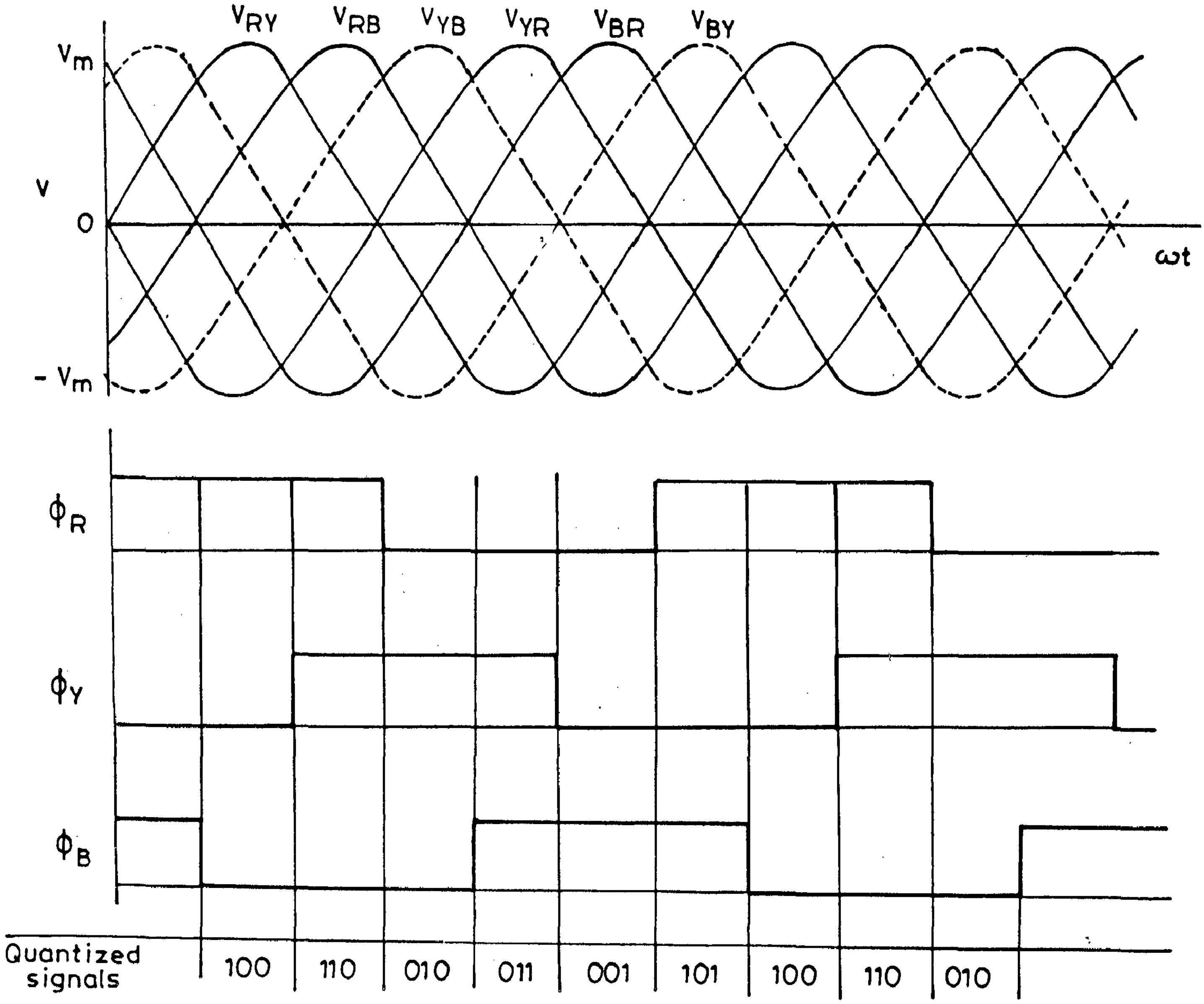


FIG. 4.5 QUANTIZER SIGNALS (THEORETICAL WAVEFORM)

triggered monoshot and the negative triggered monoshot **(IC 74121)**. The output of all monoshot is ORed to achieve 60^0 interrupts. The output pulse width of monoshot is decided by the external timing capacitor C and resistor R and is given by T_w = 0.69RC. Theoretical waveforms for the quantizer signals are shown in **Fig. 4.5.**

4.2.4 CURRENT SENSOR

The circulating current between the two converters is suppressed by withdrawing the firing pulses to all the thyristors in the rectifier group that is not conducting the load current. Positive converter. Conducts during positive half cycle of load current and negative converter conducts during negative half cycle of the load current. Therefore to sense the direction of the load current one separate circuit is interfaced to the **8085** system. to isolate the power circuit from low power electronic circuit opto isolators are used.

Fig. 4.6 shows the current sensor circuit. Voltage drop in the diodes connected in series with the load is applied to the opto-isolators. When the signal arrives at photodiode of opto-isolator it conducts and hence optically coupled transistor also conducts. Opto-isolator number one conducts when the load current is positive and opto-isolator number two conducts when the current is negative thus outputs of these two opto-isolators gives the information about the direction of current.

4.2.5 ADC INTERFACING

The microprocessor processes digital signals whereas the real world physical quantities such as current, voltage, speed are all represented by analog signals. In order to couple the analog signals to the microprocessor, the analog to digital conversion is necessary, so, **ADC 0809** is interfaced with 8085 microprocessor to sense the output analog signals.

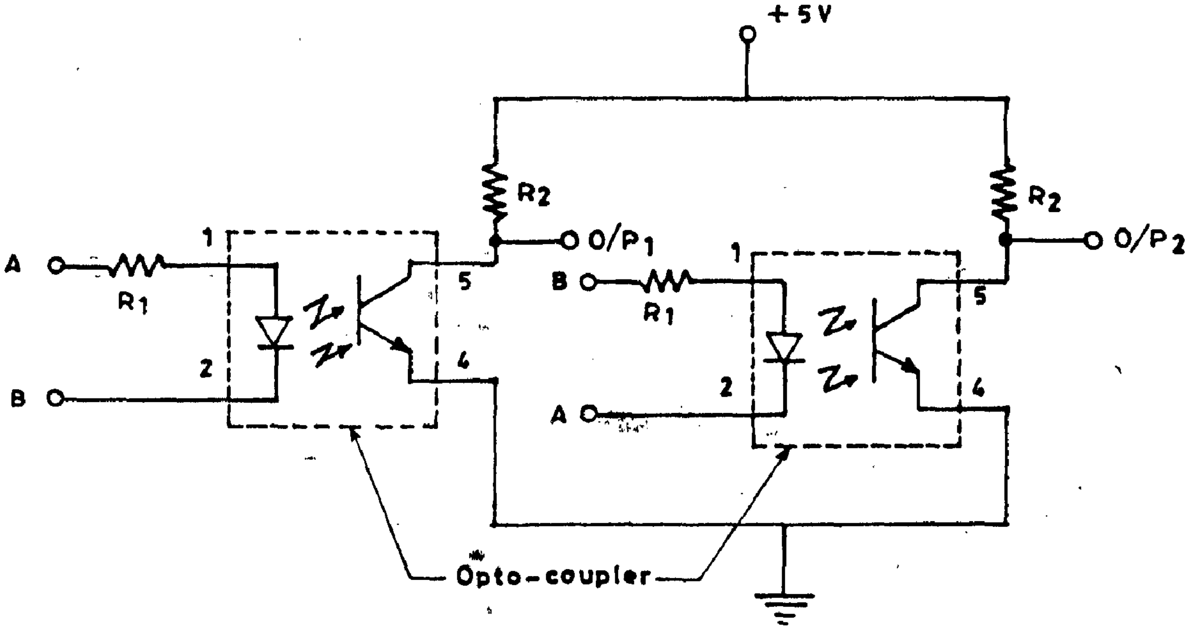


FIG. 4.6 CURRENT SENSOR CIRCUIT

Fig. 4.7 shows the interfacing diagram of the **ADC**. The CLK frequency required for **0809 ADC** lies in the range **10 KHZ** to **1280 KHZ**. The kit is about **3 MHZ**. Therefore it is reduced to a suitable value using I.C. package 7490, **IC 7490** is a decade counter.

An analog input is connected to **INO**, $5V_{d.c}$ (Vref.) which should be a precision voltage. The pin 9 and 11 are connected to 5 V_{dc} supply which is generated using voltage regulator 7805. Input channel select pins A, B and C are grounded.

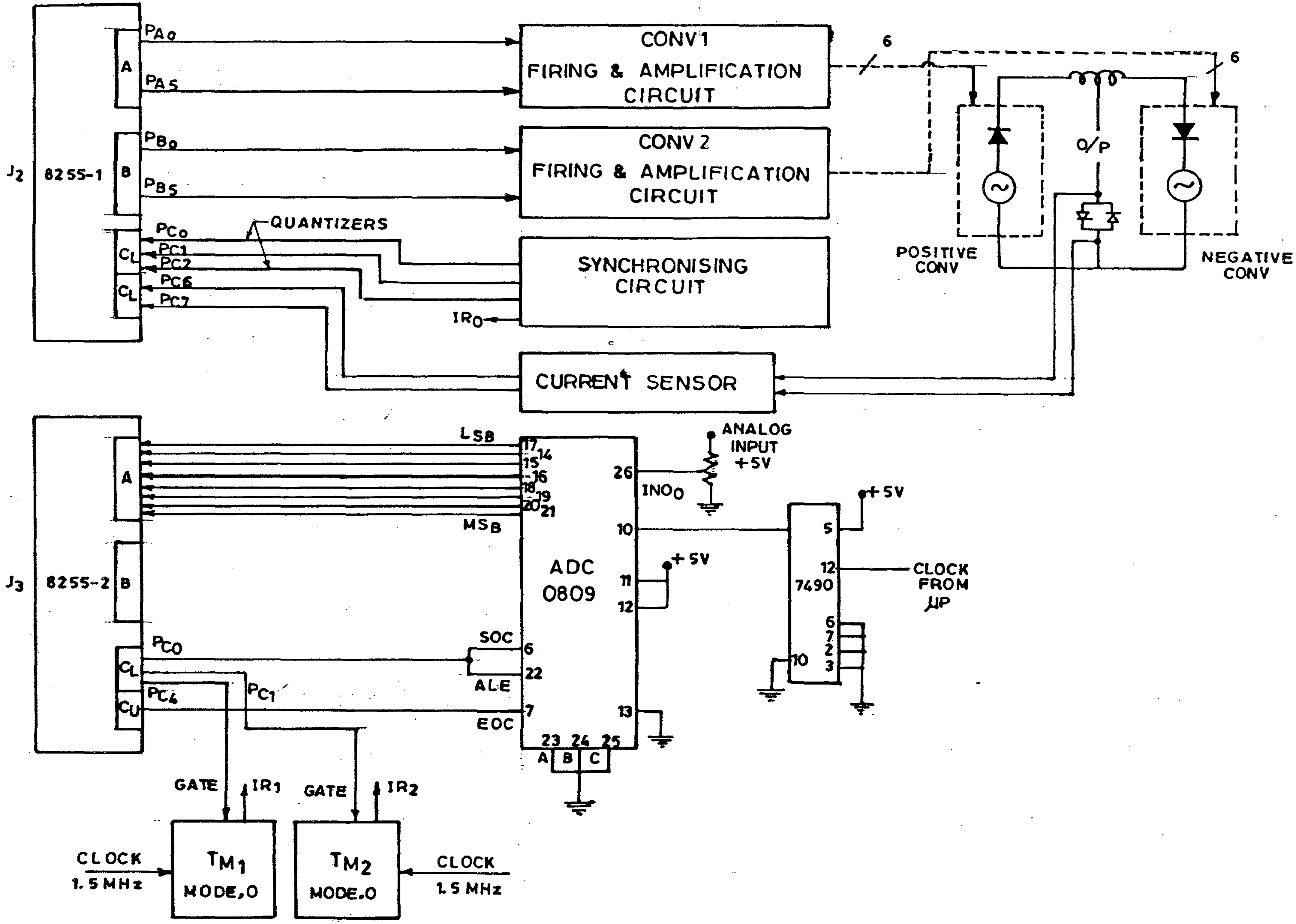


FIG. 4.7 ADC INTERFACING AND µP CONNECTION

CHAPTER - 5

SYSTEM SOFTWARE

The gating signals applied to the thyristors are obtained with the help of 8085 software. This drastically reduces the system hardware. The flowcharts for the control program are given in **Fig.5.1** to **Fig. 5.5**.

First we prepare three data tables (Appendix -I) table one gives firing delays for the positive converter, table two gives firing delays for the negative converter and table three gives value of variable `REF' which decides the converter to be operated under current zero condition.

5.1 MAIN PROGRAM

The flowchart for the main program is shown in **Fig.5.1** various peripheral chips such as **8255-1, 8255-2, 8253** and **8259** are initialised. Timer one is initialised in mode `zero' for generating interrupts at desired instants. The memory area is initialised with constants. All firing bits are made low. Frequency selection has been done through ADC. Analog signal which decides the frequency is read with the help of ADC. The digital output of ADC is stored in RAM. Depending upon the value of ADC, the no of steps for that particular freqency is read from the Table and stored n the RAM which is used by the interrupt routine IR_0 for resetting the pointer which is increamented after each IR_0 interrupt. After enabling the interrupts it waits for the IR_0 interrupt to come. After each `60^0' zero crossing interrupt (IR_0) come.

5.2 IR_0 INTERRUPT

The core of control program starts when the zero crossing intrrupt comes. After saving the registers firing command is issued to the appropriate thyristors. Since the cycloconverter has to operate in non circulating current mode, hence, possitive current must be supplied by P-converter and negative current must be supplied by N-

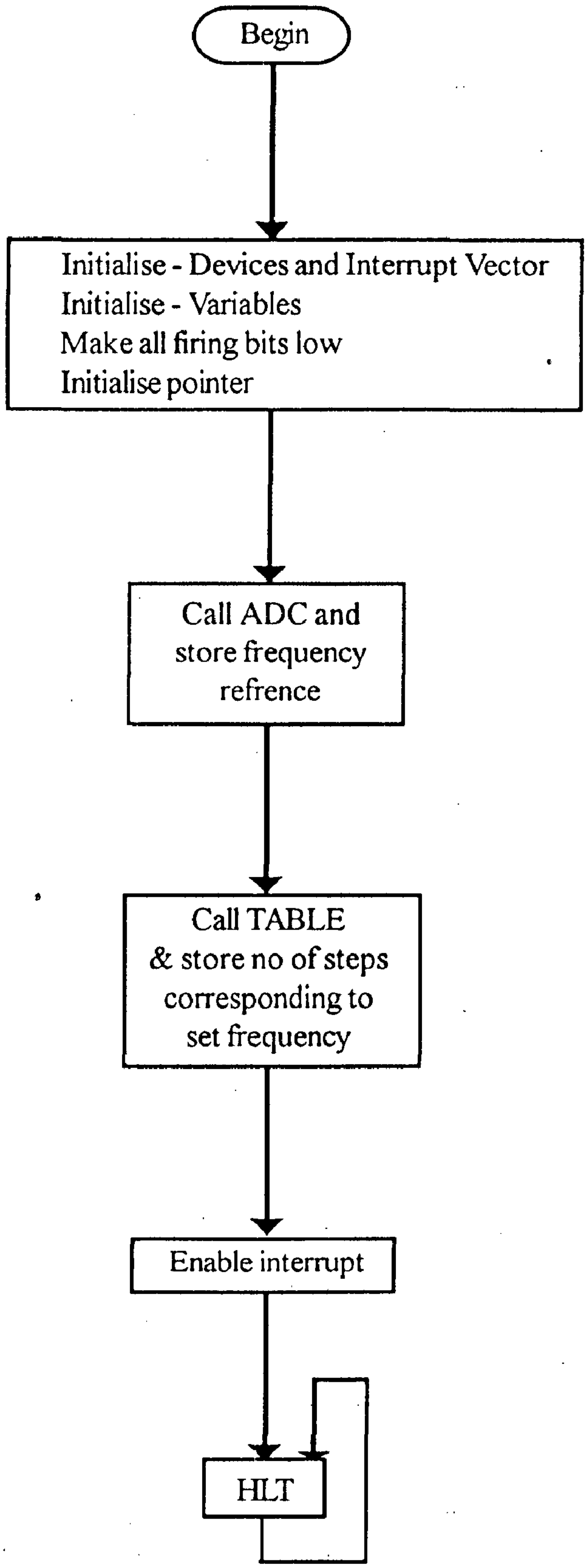


FIG. 5.1 MAIN FLOWCHART

converter. Current is read to decide the converter which is to be operated. Positive current selects positive converter and negative current selects negative converter. When current is zero the converter which is to be selected is decided by the variable 'REF'. When `REF' is `01' P-converter is slected and when it is `00' N-converter is selected. Need of reading `REF' arises only when current is zero.

Since firing delay is varying contineously within the range 0^0 to 180^0, hence there are three possible zones of operation.

Zone - I	$0 \leq \alpha < 60^0$
Zone - II	$60 \leq \alpha < 120^0$
Zone -III	$\alpha > 120^0$

Variable K is used to decide the zone of operation it is, initialised to 00 in the main program. It is set after reading each firing delay in the zero crossing interrupt. Memory one is used for storing the recent firing delay. Firing command is obtained for each converter and stored in the momory (RAM) named F_CMD_1 for positive converter and F_CMD_2 for negative converter. The flowchart for IR_0 interrupt and two converter routines are given in **Fig. 5.2 to Fig. 5.4**.

5.3 IR_1 INTERRUPT

This is the timer one interrupt. In this interrupt service routine after pushing the required registers the firing command is issued to the appropriate thyristors. Registers are recovered and interrupt is enabled again. The flowchart for this timer interrupt is shown in **Fig.5.5**.

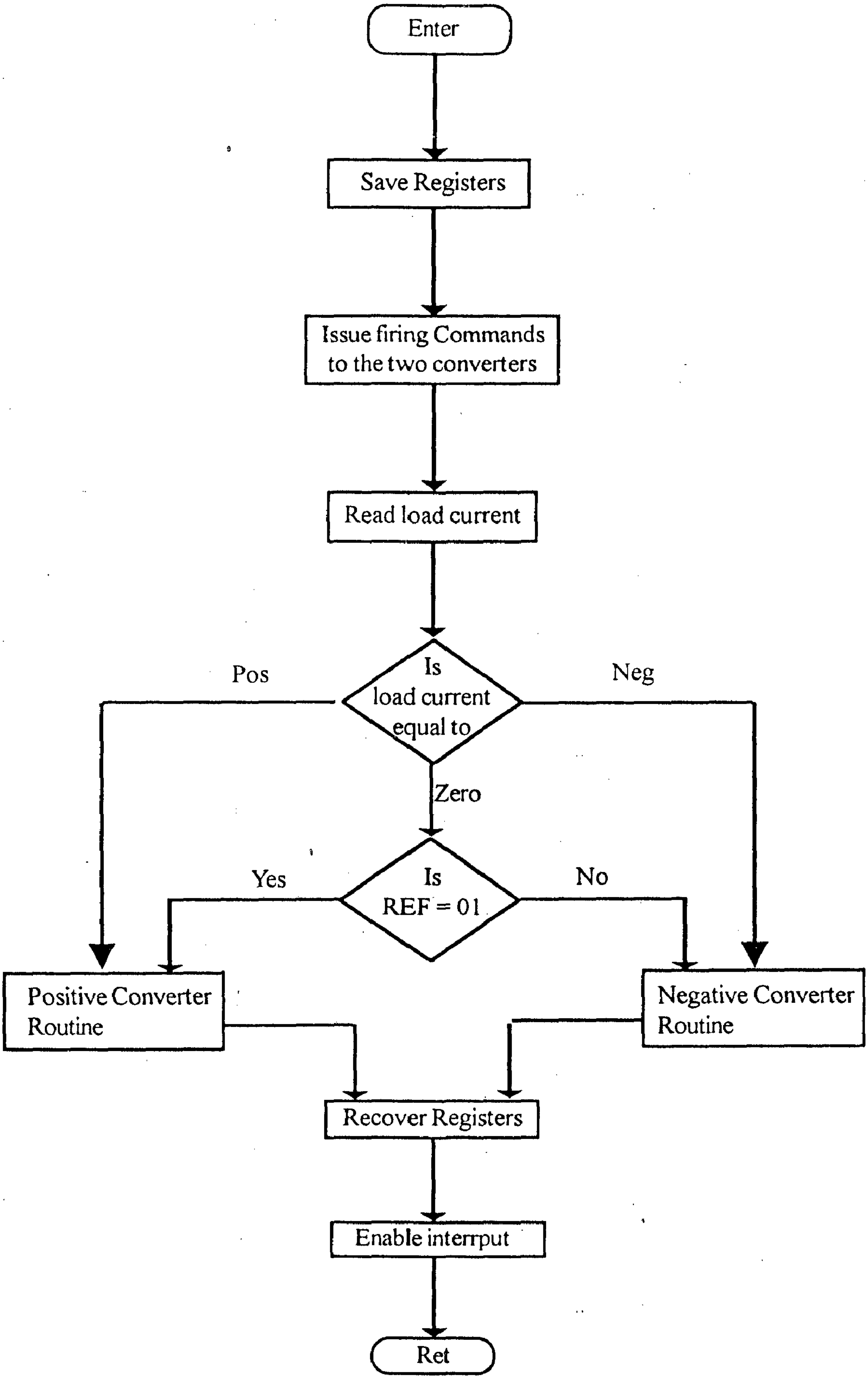


FIG. 5.2 FLOWCHART FOR IR_0

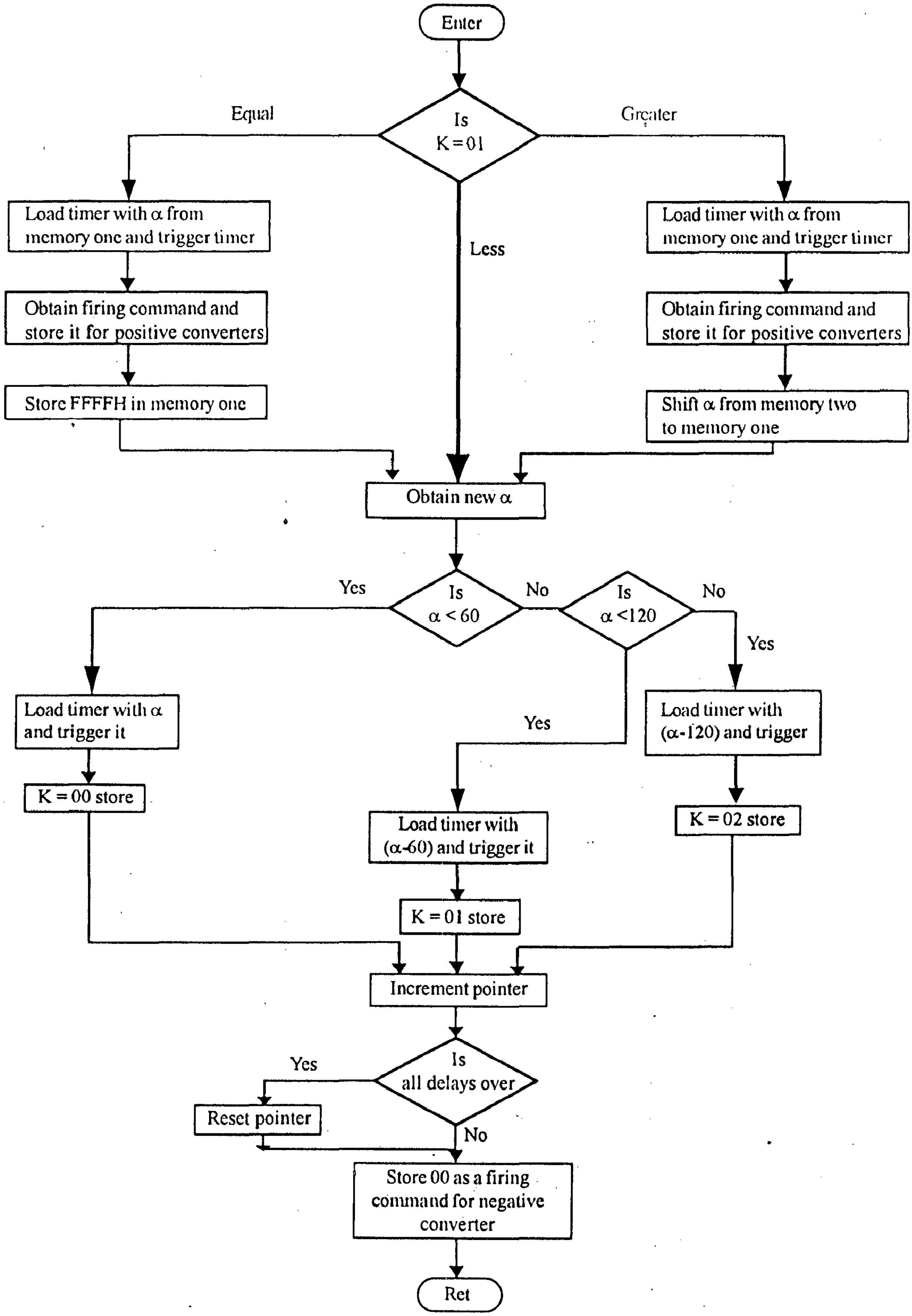


FIG. 5.3 : POSITIVE CONVERTER ROUTINE

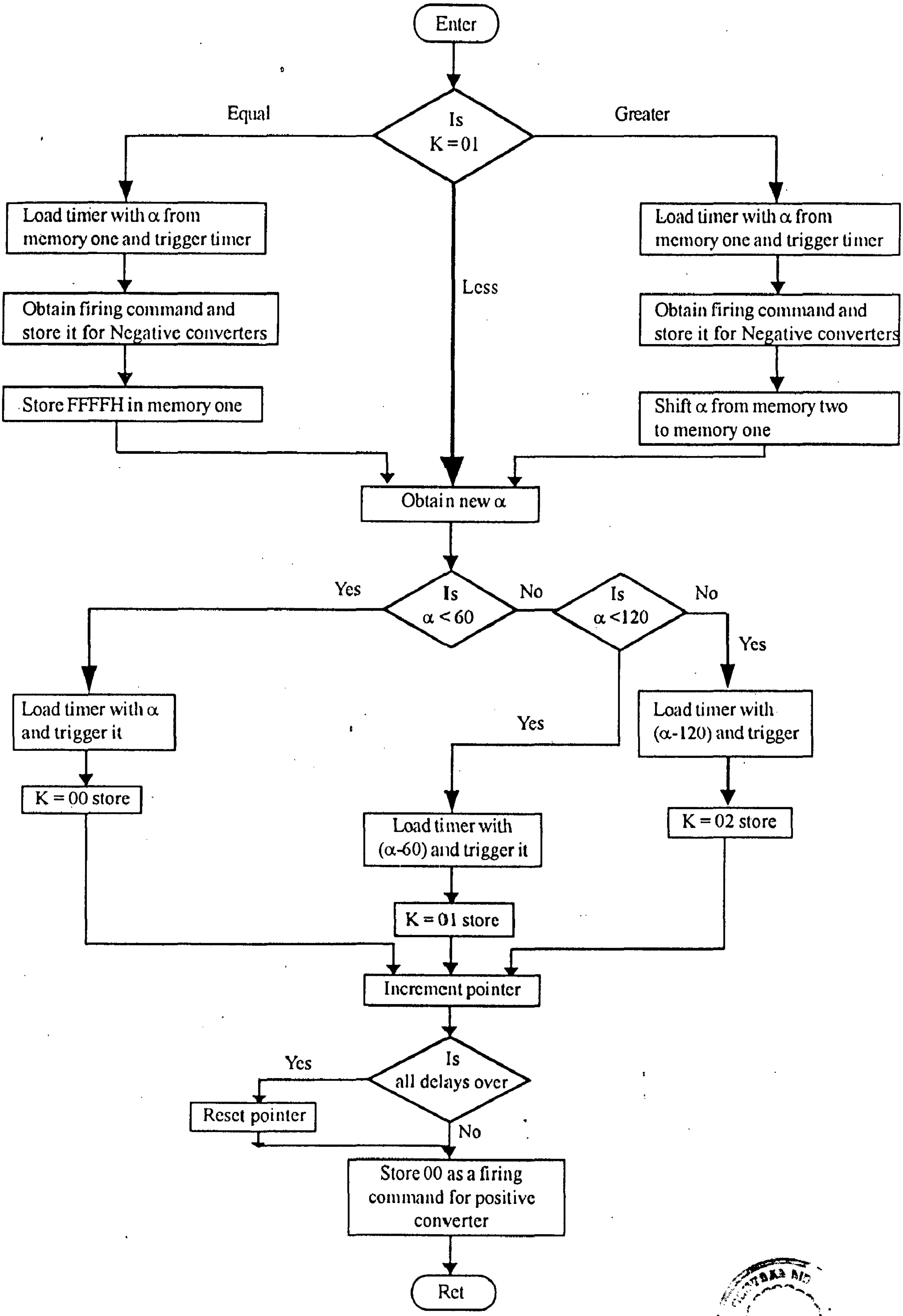


FIG. 5.4 : NEGATIVE CONVERTER ROUTINE

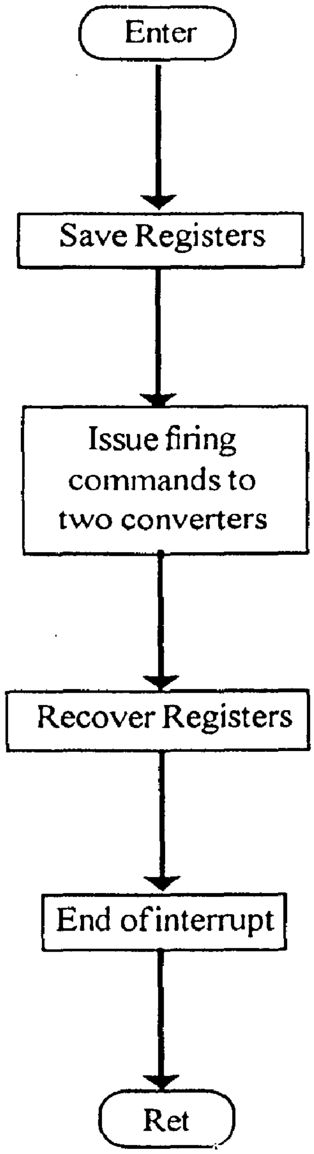


FIG. 5.5 FLOWCHART FOR IR_1

CHAPTER - 6

PERFORMANCE OF EXPERIMENTAL SETUP

A single phase cycloconverter has been fabricated for carrying out experimental investigations related to the present work. Pictorial view of the experimental set-up is shown in **Fig. 6.1 (A, B & C)**.

The experimental setup used for conducting the different invetigations is shown in **Fig. 6.2** and it consists of the following components.

6.1 INDUCTION MOTOR

A 1/2 HP, capacitor start Induction motor with following specifications.

0.5 H.P., 110 volts, 6 Amps, 1440 rpm, 50 Hz.

LOADING ARRANGEMENT

Brake drum type of load is used to load the induction motor.

6.2 THE EXPERIMENTAL RESULTS

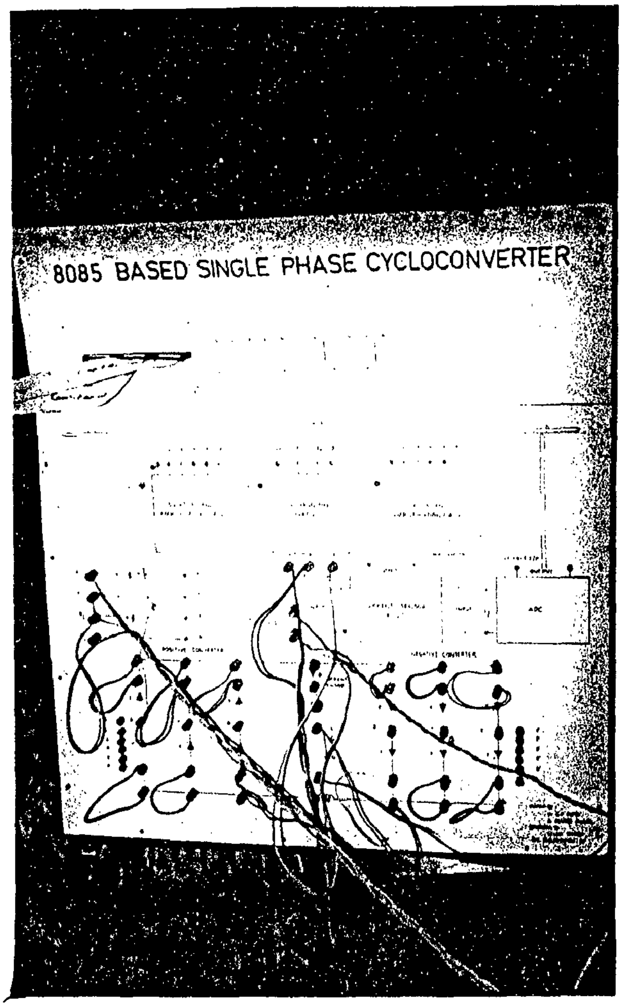
The experimental setup has been run for different types of loads (R-load, R-L load and motor load) for different settings of the frequency. V/f ratio is kept constant for Induction motor load by adjusting modulation index in same proportion with frequency. Following observations have been recorded

(i) Waveforms of voltage and current supplied to the load by the cycloconverter.

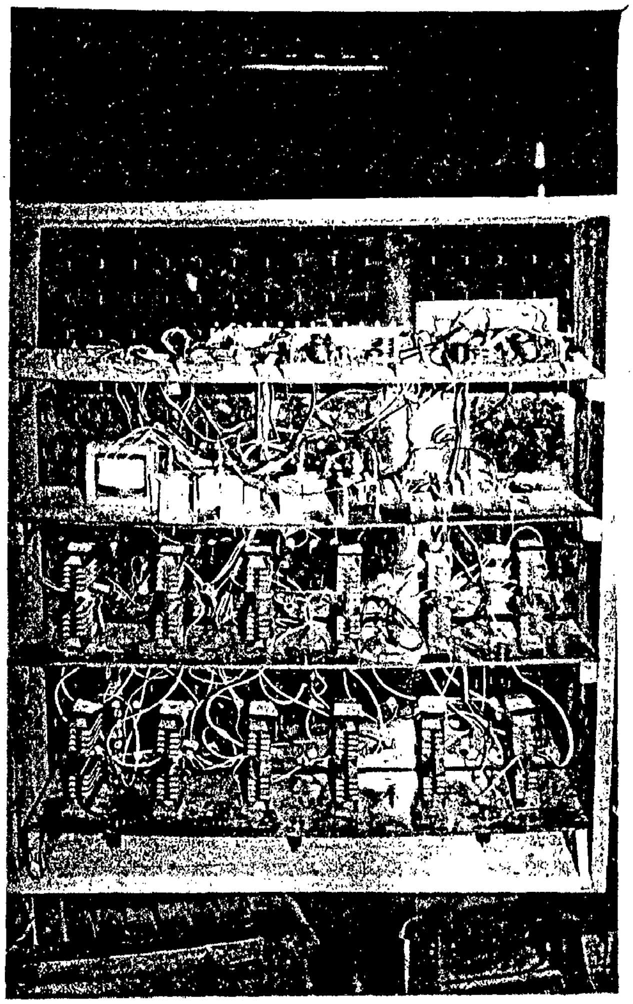
(ii) Using conventional measuring instruments (ammeters, voltmeters and watt meters) the following opservations have been made.

  (A) Power input to the load

  (B) Voltage and current in the load

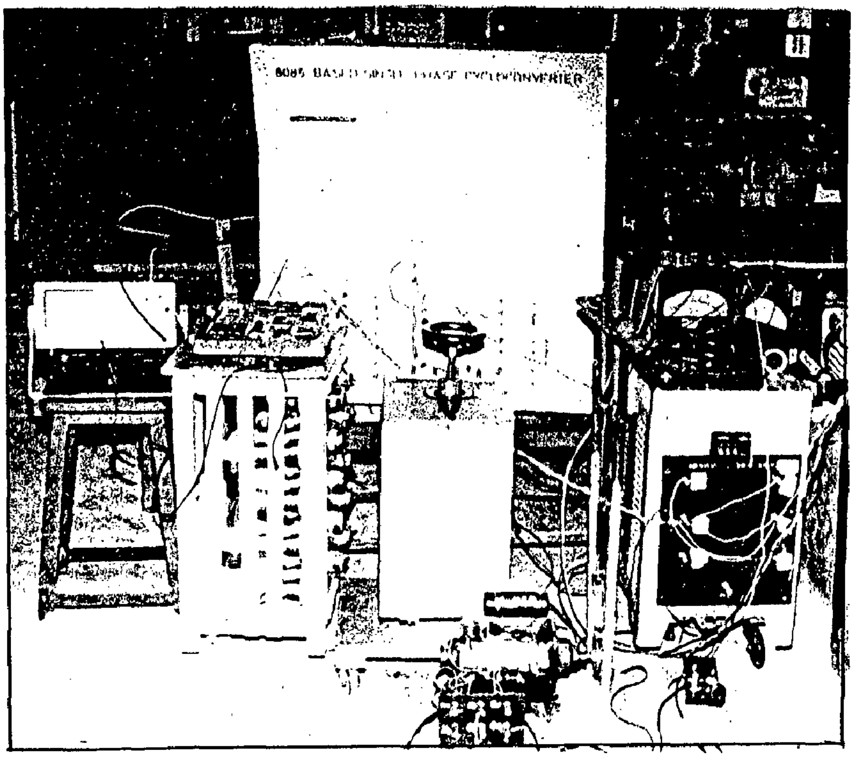


FRONT PANEL



Power circuit and control circuit

FIG. 6.1 : HARDWARE IMPLEMENTATION IN THE LABORATORY



OVER ALL VIEW OF THE DRIVE

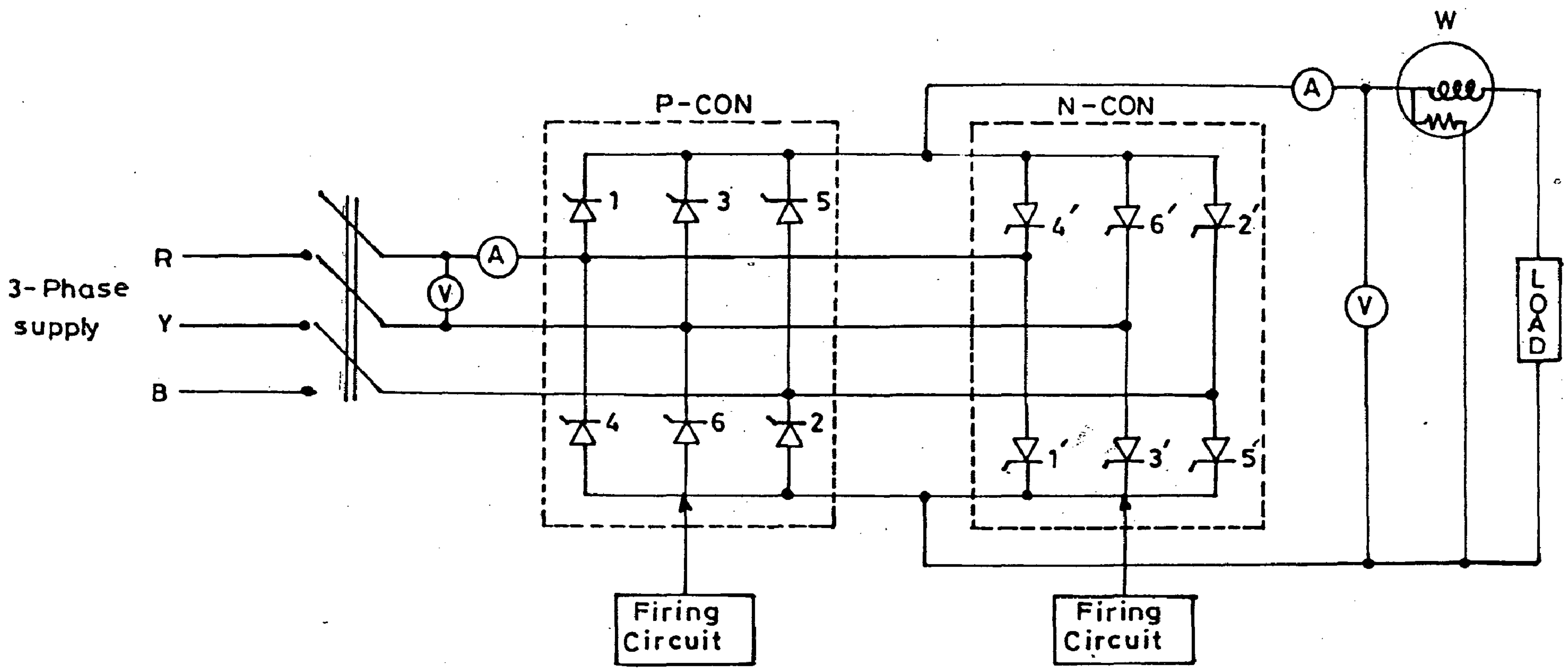


FIG. 6.2 EXPERIMENTAL SETUP

6.2.1 WAVEFORMS

The waveforms of voltage and current are recorded using GOULD make digital storage ascilloscope having integral plotter. The purpose of recording the waveforms is to gain qualitative knwoledge of the nature of these waveforms for the present drive.

(A) CONTROL CIRCUIT WAVEFORMS

The three sinusoidal inputs to the comparators of the synchronising and phase crossing circuit and the base interrupt signals are shown in **Fig. 6.3(A)**.

The comparator output is clipped using zener diode to generate the quantizer signals. The three quantizer signals are shown in **Fig. 6.3(B)**.

Fig. 6.3(C) shows one of the sinusoidal input to synchronising circuit, zero crrosings, timer output and firing signal going to the thyristor one (Th_1) of P-converter when operating at firing delay $\alpha' = 30^0$. This picture shows the period for which firing signal is going to thyristor one which is exactly 120^0 i.e. each thyristor conducts for 120^0.

Fig. 6.3(D) shows, one of the sinusoidal input to synchronising circuit, zero crossings, timer output, and firing signal going to the thyristor one (Th_1) of P-converter when operating at a frequency which is one third (16.67 Hz) of the input frequency when power circuit kept open i.e. not supplying the current to the load.

Fig. 6.3(E) to **(G)** shows one of the sinusoidal input going to the synchronising circuit, zero crossings, timer output and firing pulse going to the Th_1 of P-converter for three different settings of the frequency which are 1/4th, 1/5th and 1/10th of the input frequncy (50 Hz) i.e 12.5 Hz, 10Hz and 5Hz respectively when cycloconverter is not supplying power to the load.

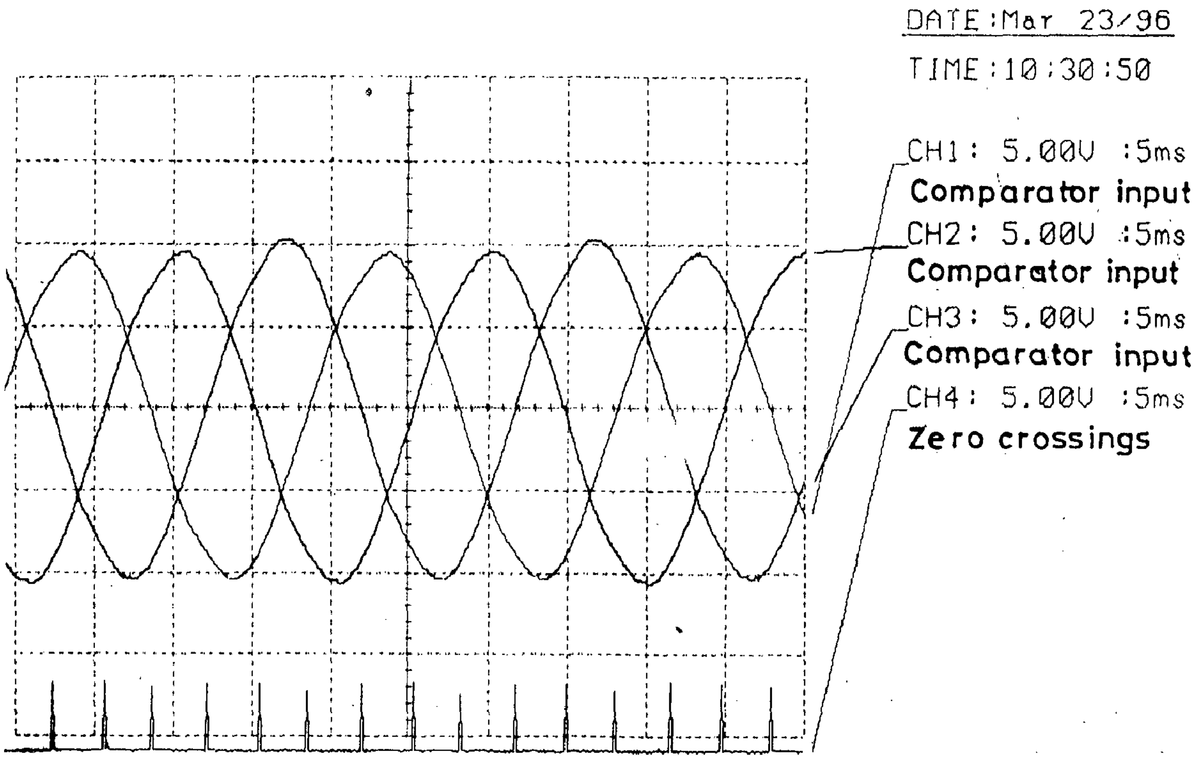


FIG. 6.3 (A)

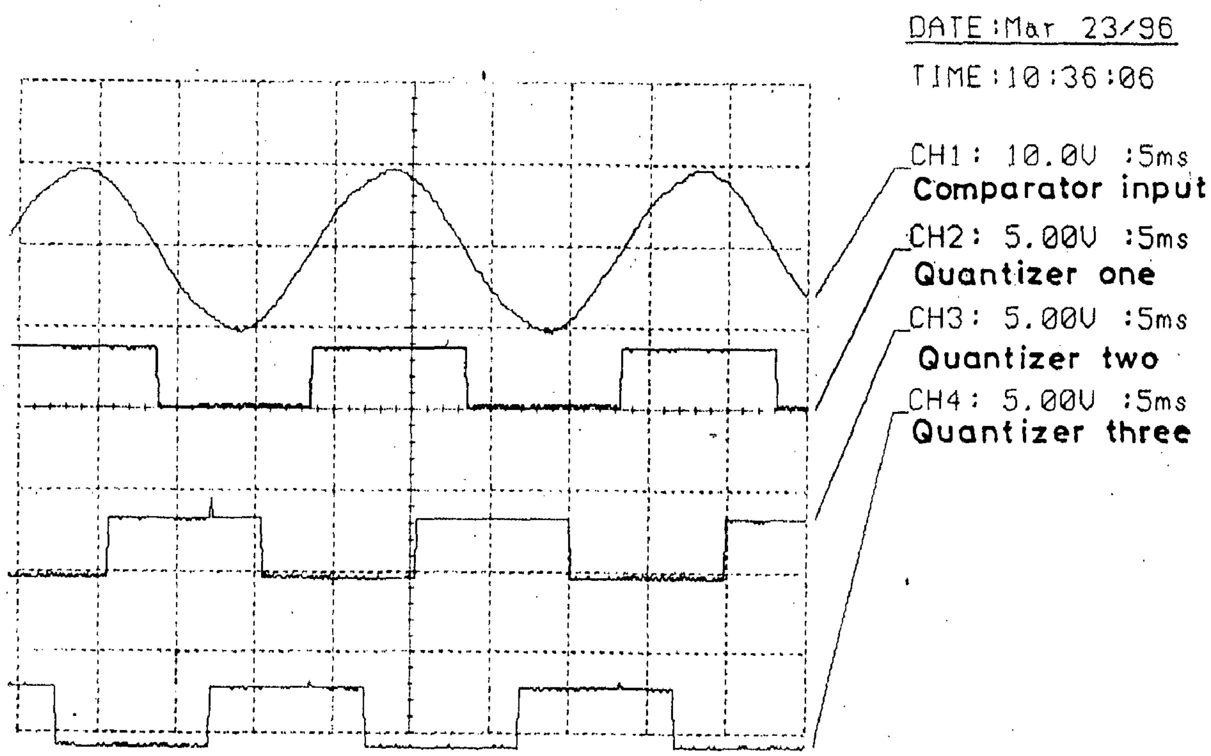


FIG. 6.3 (B)

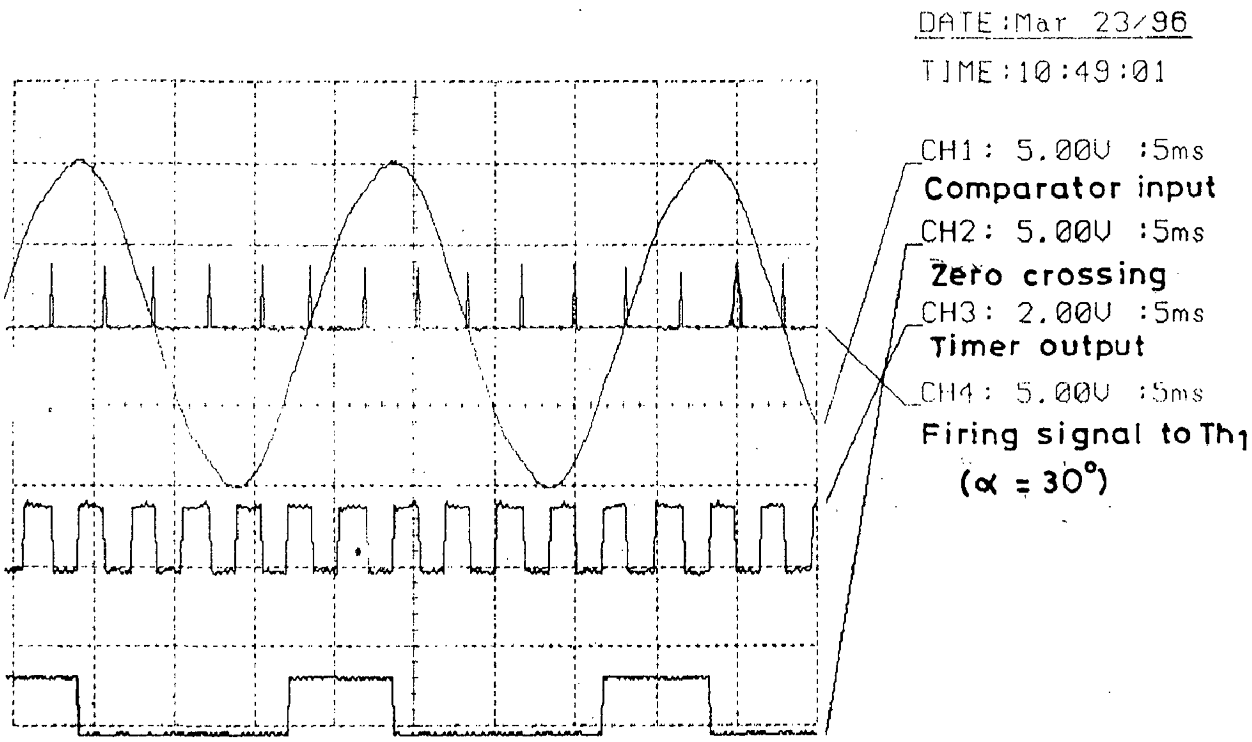


FIG. 6.3 (C)

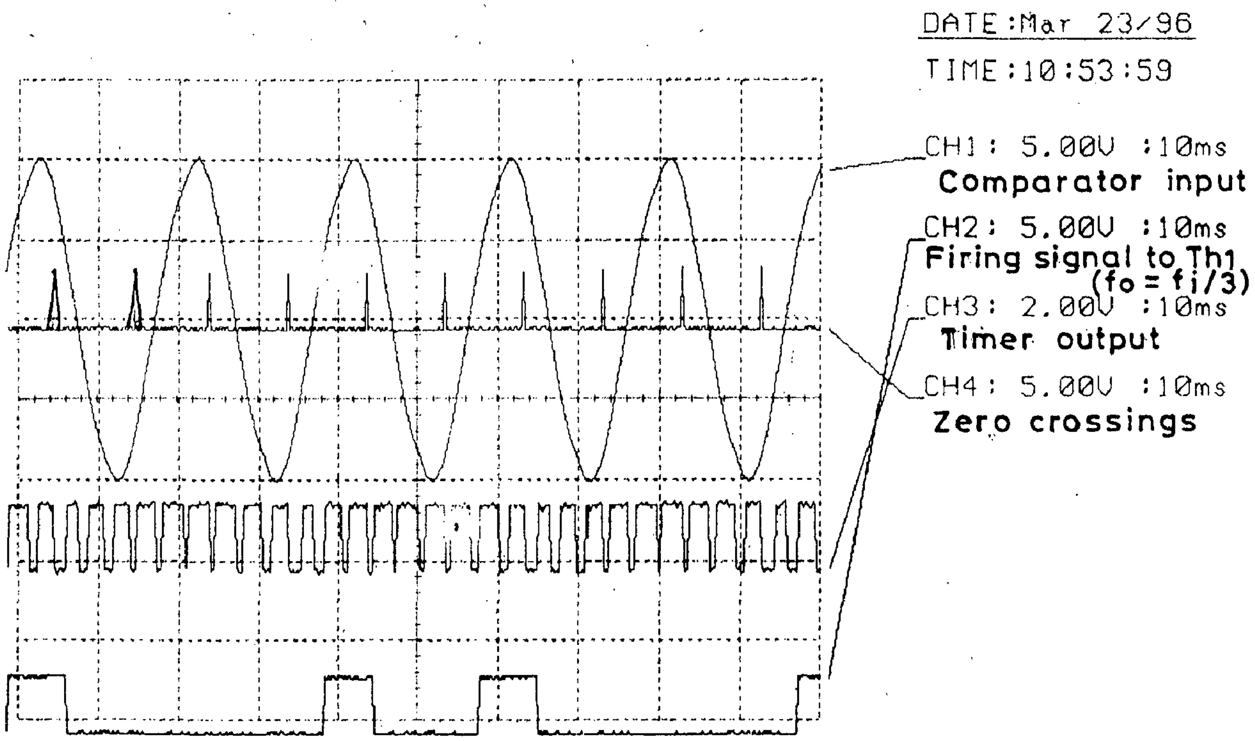


FIG. 6.3 (D)

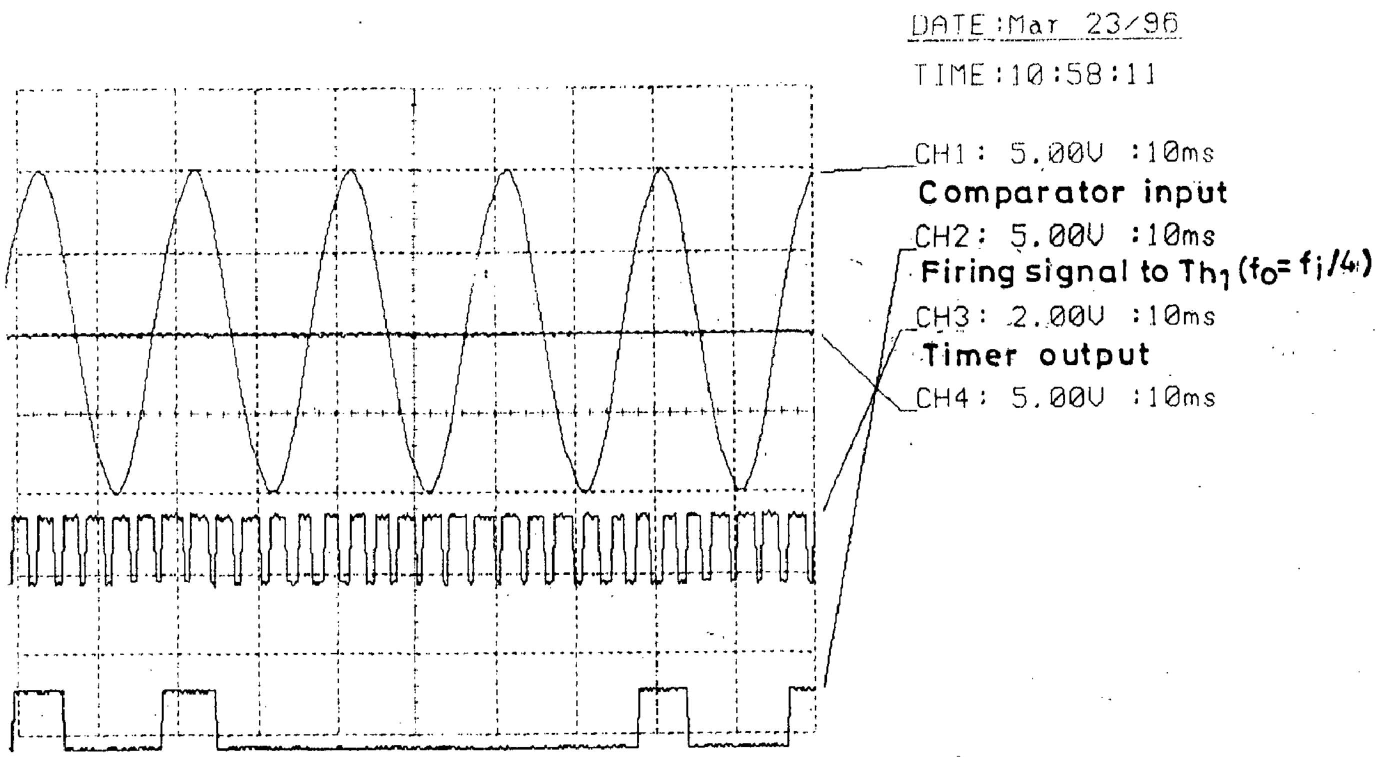


FIG. 6.3 (E)

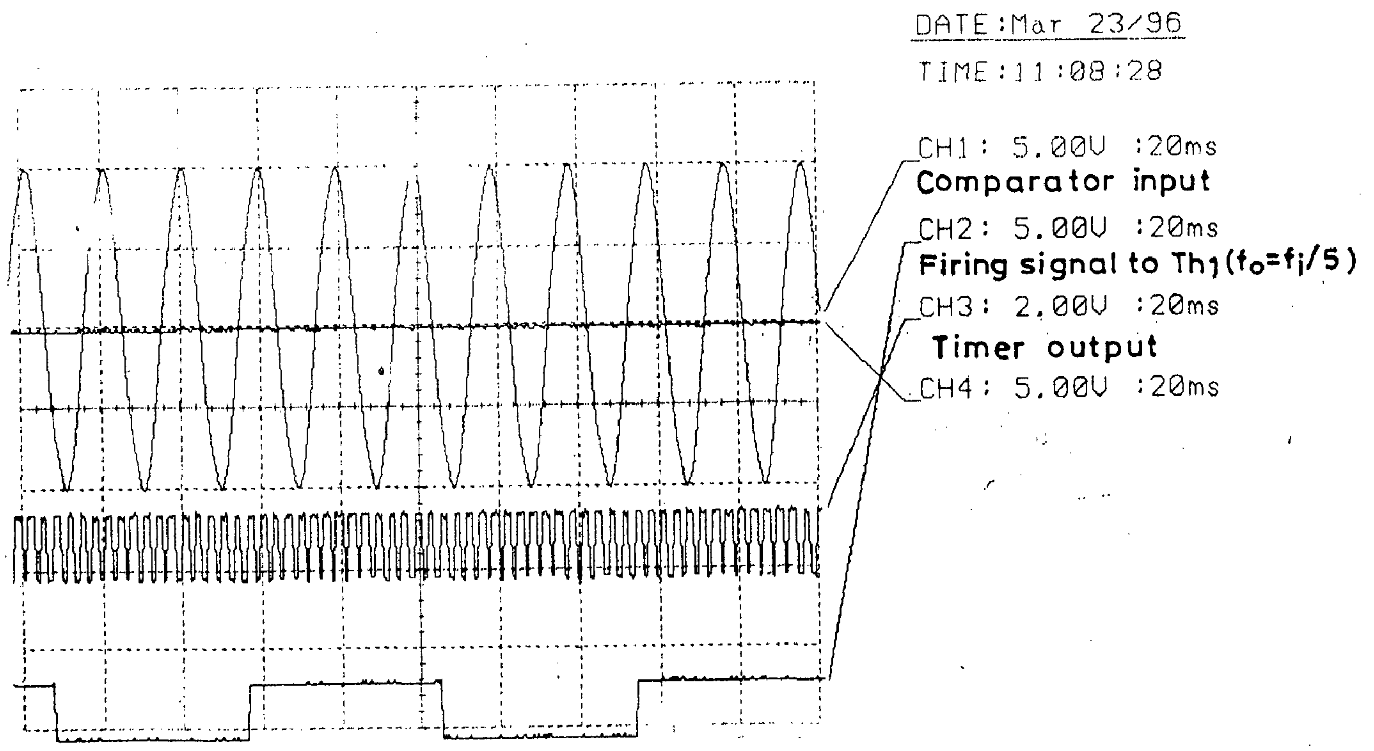


FIG. 6.3 (F)

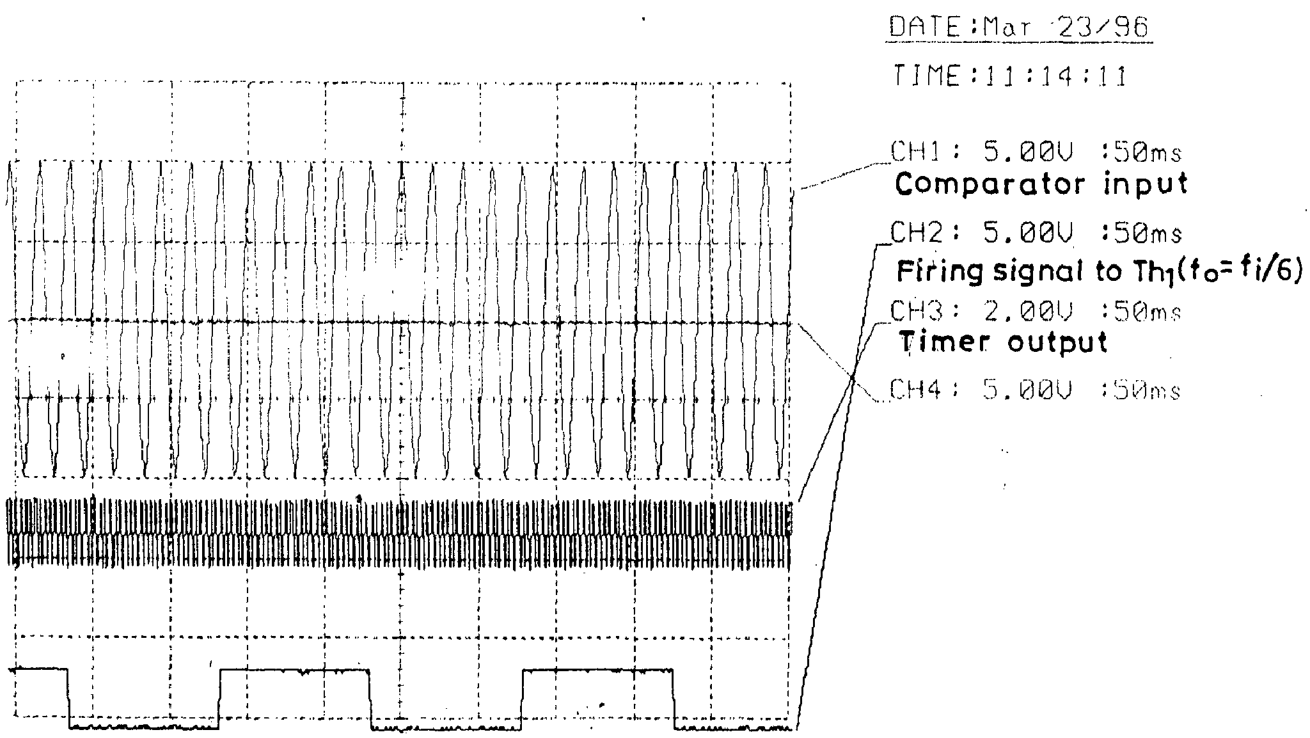

DATE:Mar 23/96
TIME:11:14:11
CH1: 5.00V :50ms
Comparator input
CH2: 5.00V :50ms
Firing signal to Th1(fo= fi/6)
CH3: 2.00V :50ms
Timer output
CH4: 5.00V :50ms

FIG. 6.3 (G)

(B) POWER CIRCUIT WAVEFORMS

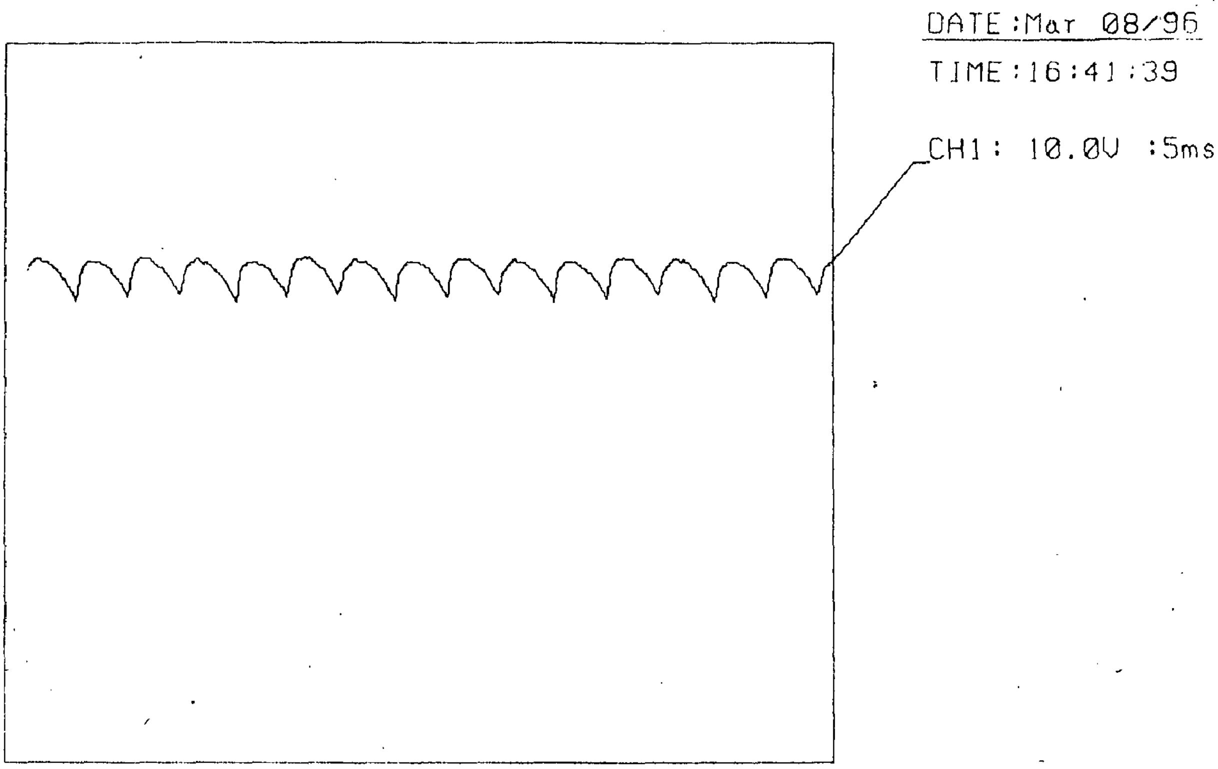
The two converters have been tested separately on resistive load. For this purpose they are operated one by one as controlled rectifiers by triggering the thyristors symmetrically at a given firing angle. The converters are supplied from three phase 50 HZ source.

Fig. 6.4 (A), (B), (C), and **(D)** show the ouput voltage waveform of P-converter and **Fig. 6.5 (A), (B), (C)** and **(D)** show the output voltage waveform of N-convertor for four different settings of the firing angle; 10^0, 30^0, 75^0 and 105^0 respectively.

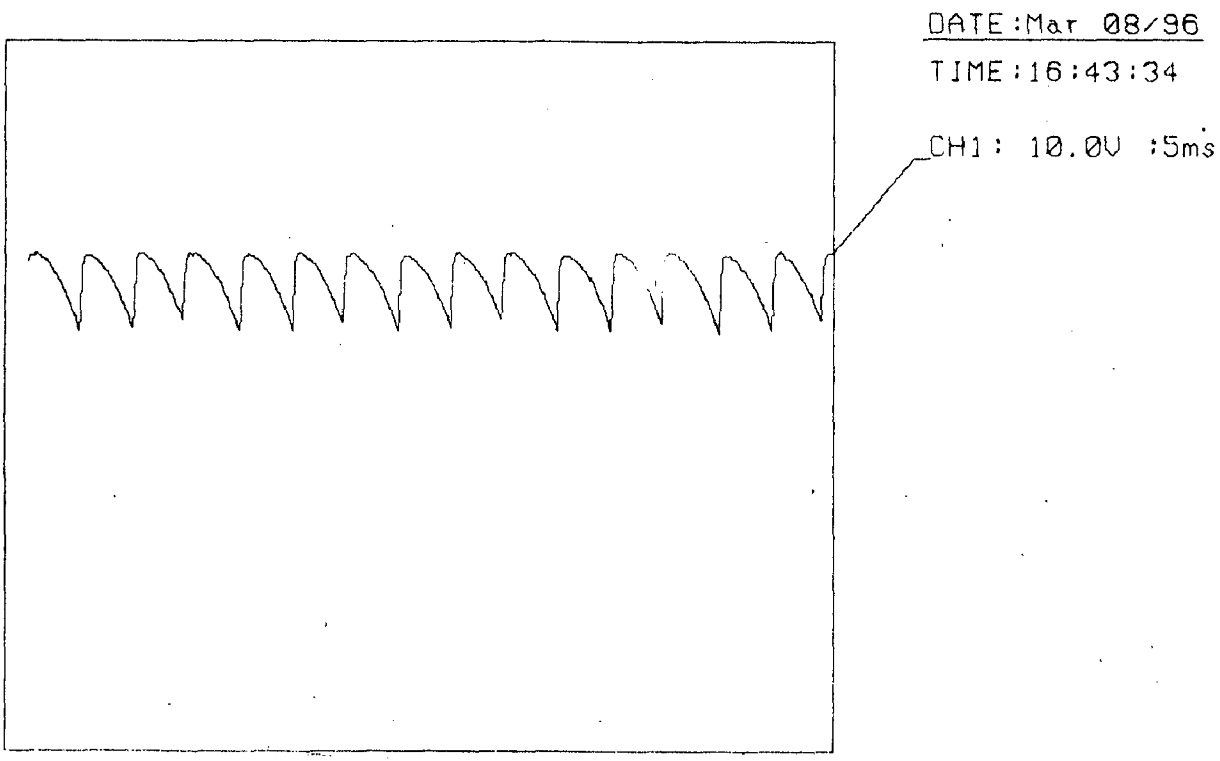
Fig. 6.4 (A) (B) and **(C)** reval that all the six thyristors are symmetrically responding to the trigger commands. In **Fig. 5.4(D)** which shows the output voltage at $\alpha = 105^0$, some thyristors are found nonconducting. The reason possibly lies in the fact that all thyristors used are not identical. However, when input voltage is raised to 200 volts the converter operates satisfactorily at the same firing angle as shown in **Fig. 6.4 (E)**. It is noted that the thyristors of present converter respond erratically at high firing angles when the input voltage is low.

. **Fig.6.5 (A)** to **(D)** are the corresponding load voltage waveforms for negative converter (N-converter). Although the performance of N-converter is satisfactory it is not identical with respect to p-converter for similar operating conditions (compare **Fig. 6.4(C)** and **Fig. 6.5(C)**. This is again due to non-similar thyristors used in present setup.

Fig. 6.6 shows the voltage across anode and cathode of a thyristor of p-converter when operating at $\alpha = 30^0$. It is noted that whereas the input phase voltage is 80 volts the peak voltage which appears across the thyristor when it is not conducting is the peak line-to-line voltage which in present case is 196 volts.

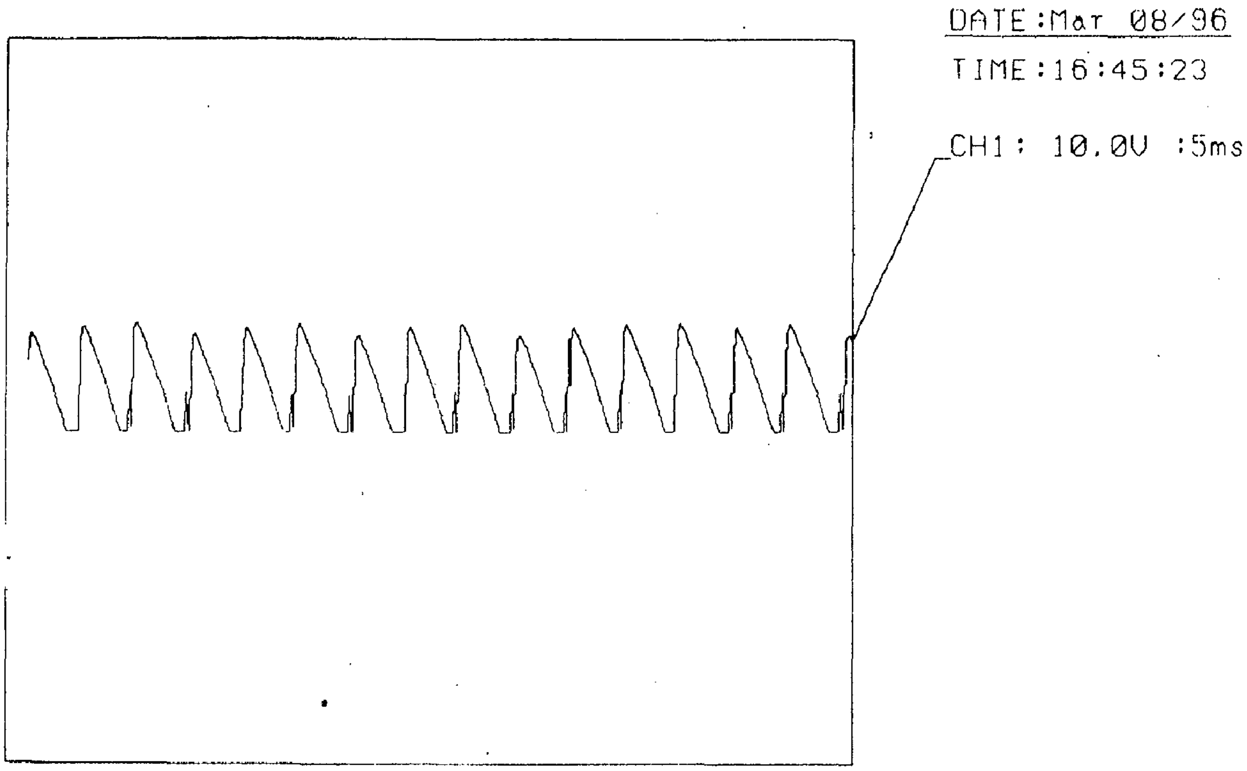


(A) $\alpha = 10^0$

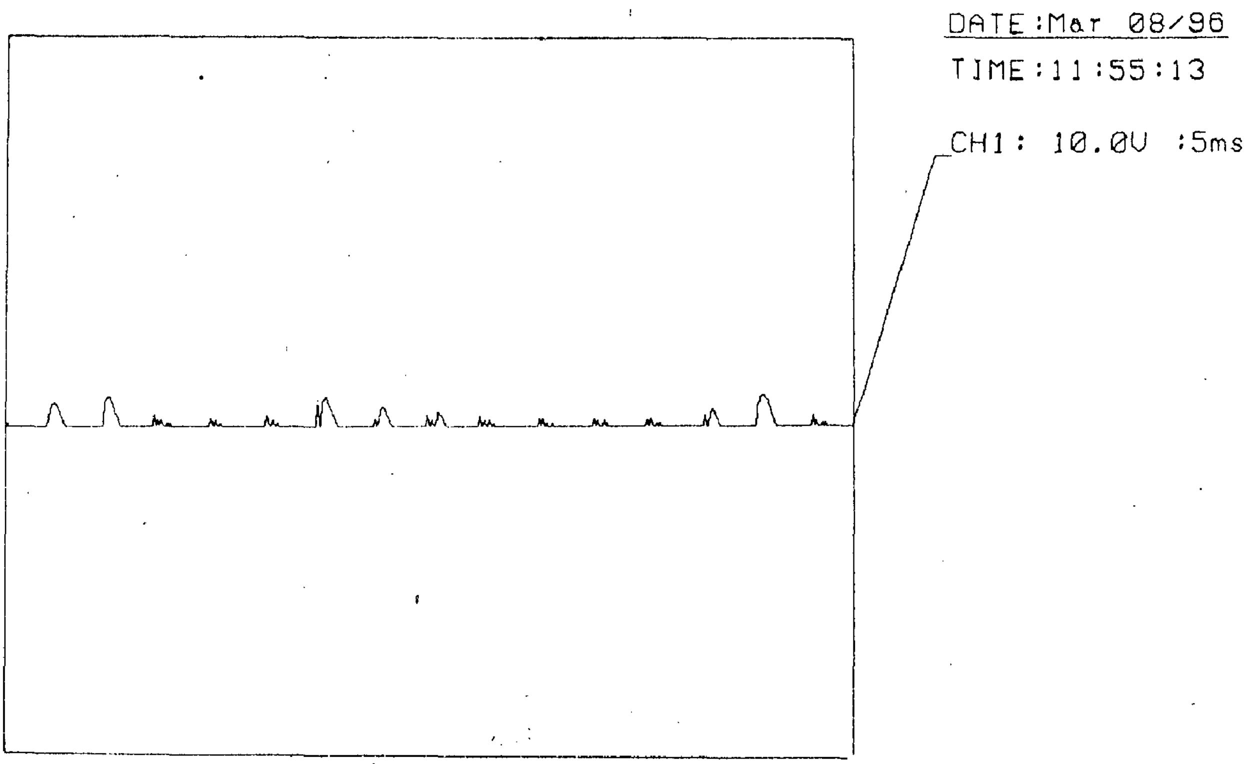


(B) $\alpha = 30^0$

FIG. 6.4 VOLTAGE WAVEFROM AT OUTPUT OF P- CONVERTER
(R-LOAD, $V_i = 80V$)

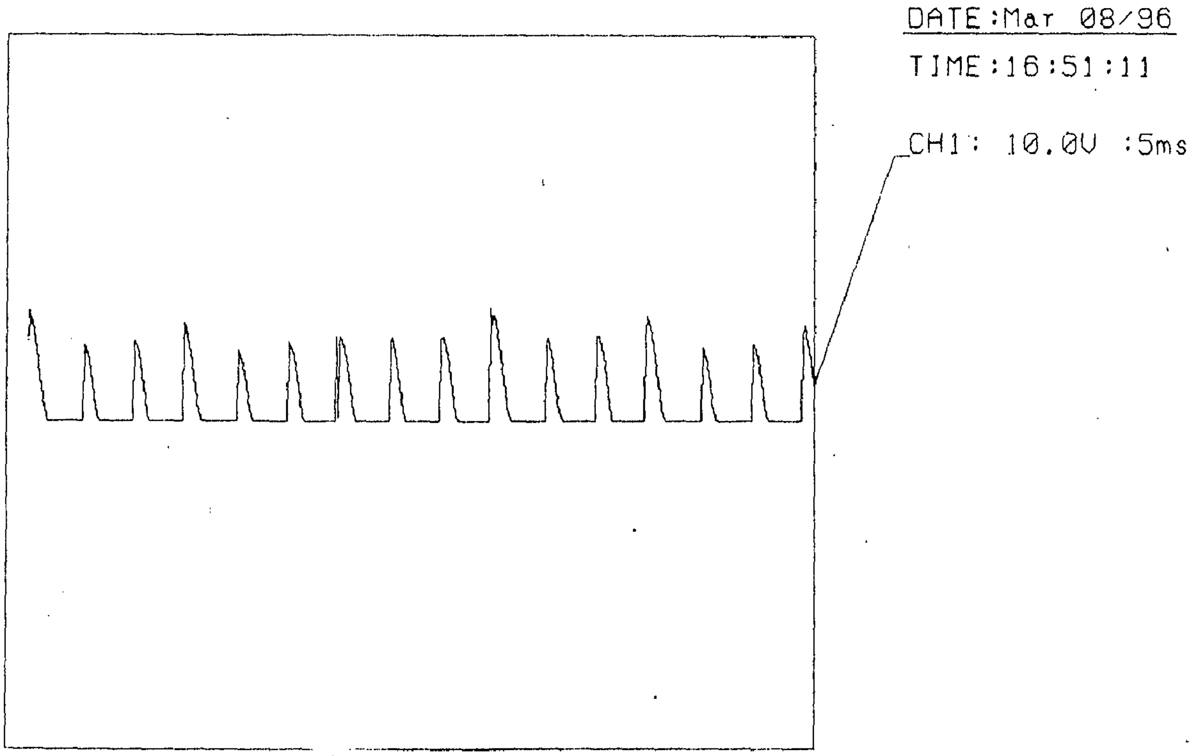


(C) $\alpha = 75^0$



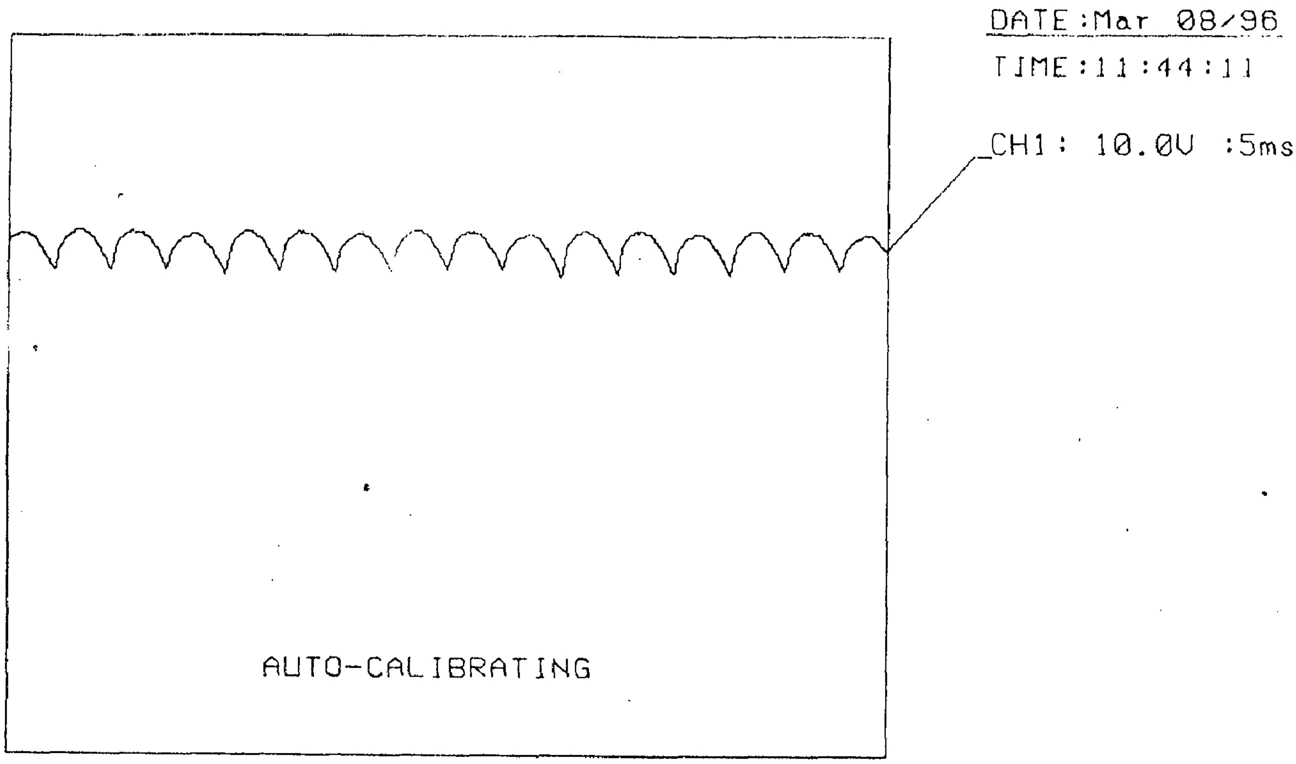
(D) $\alpha = 105^0$

FIG. 6.4 VOLTAGE WAVEFROM AT OUTPUT OF P- CONVERTER (R-LOAD, $V_i = 80V$)

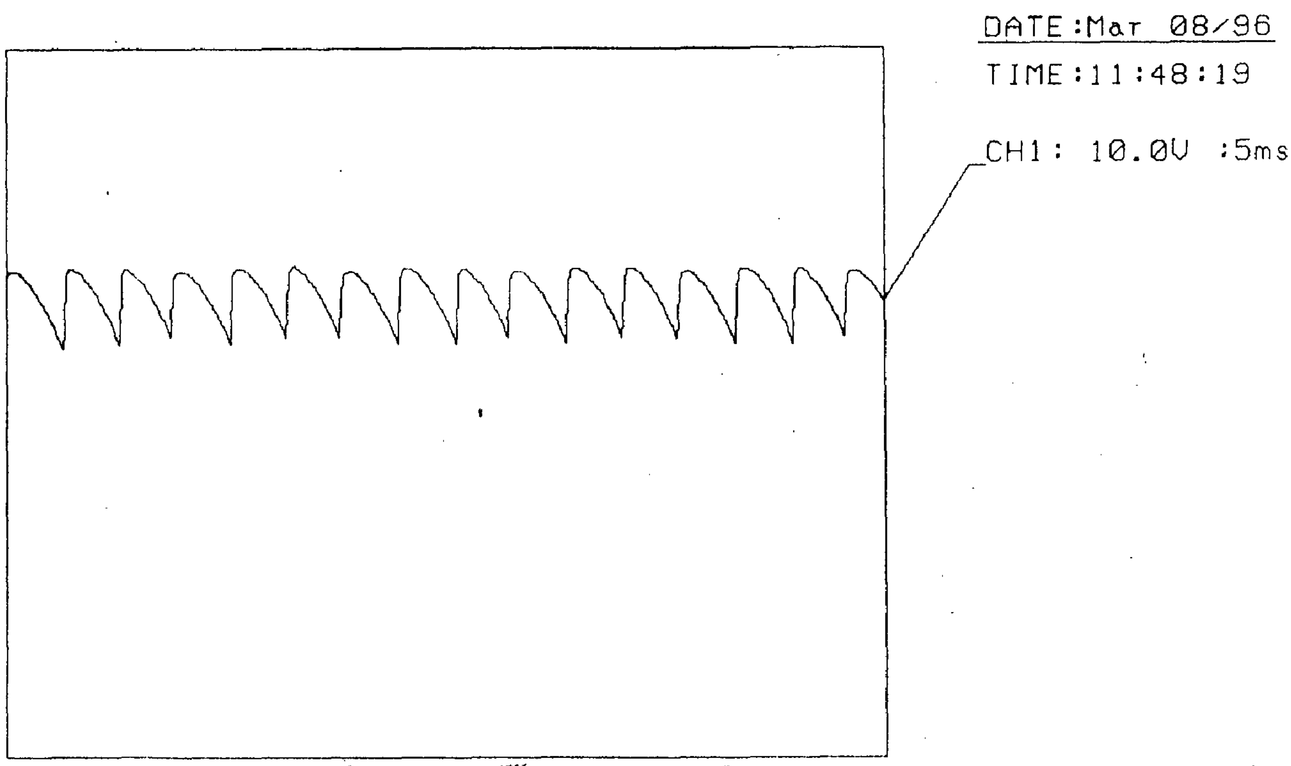


(D) $\alpha = 105^0$, $V_i = 200$ V

FIG. 6.4 VOLTAGE WAVEFROM AT OUTPUT OF P-CONVERTER

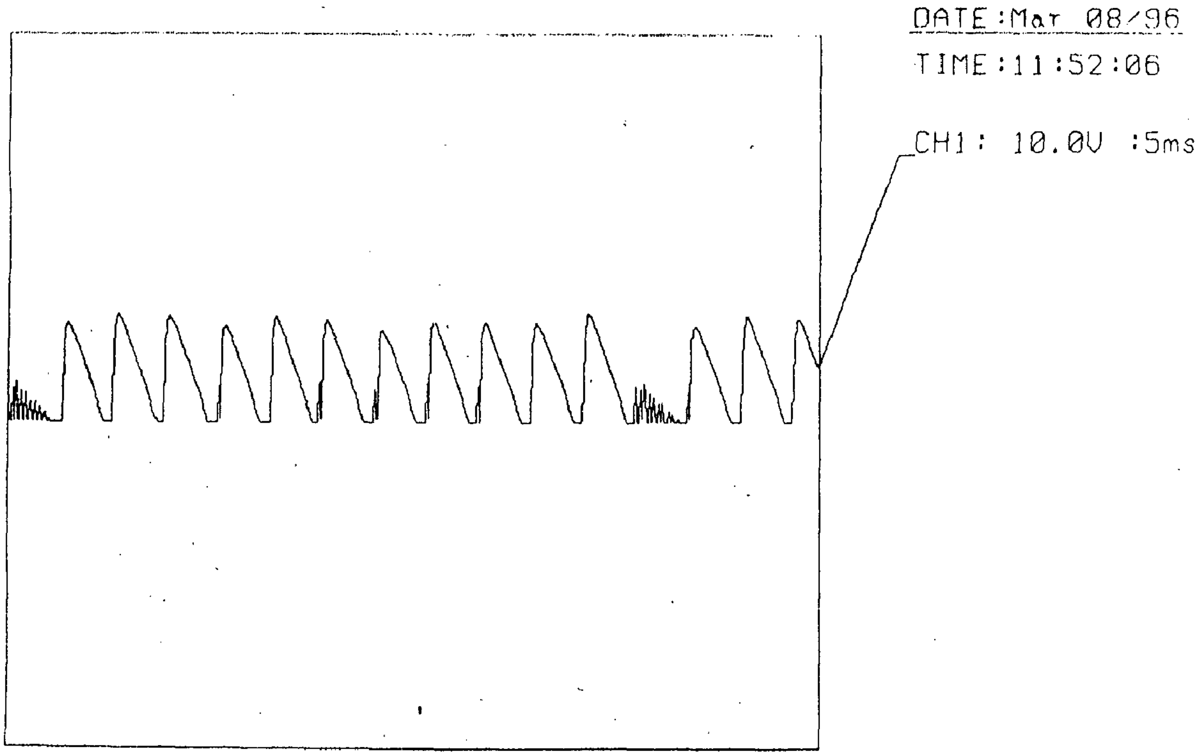


(A) $\alpha = 10^0$

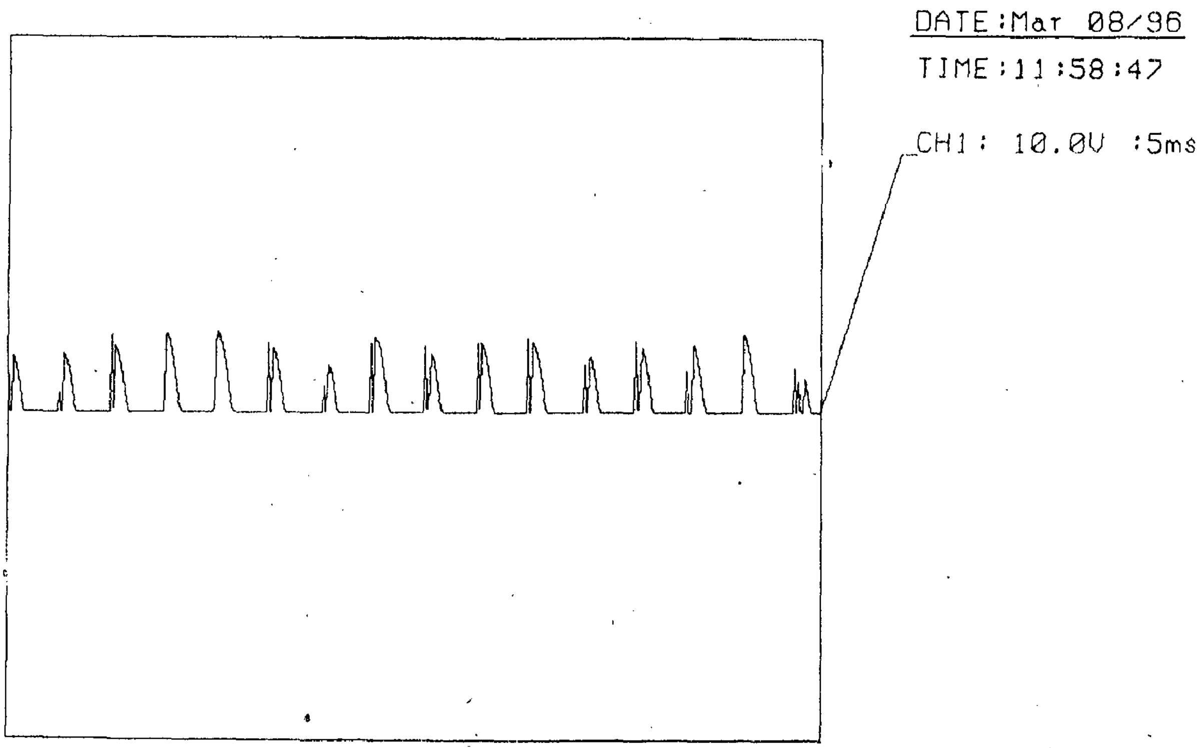


(B) $\alpha = 30^0$

FIG.6.5 VOLTAGE WAVEFROM AT OUTPUT OF N-CONVERTER
(R-LOAD, V_i=80V)



(C) $\alpha = 75^0$



(E) $\alpha = 105^0$, $V_i = 200$ V

FIG.6.5 VOLTAGE WAVEFROM AT OUTPUT OF N-CONVERTER

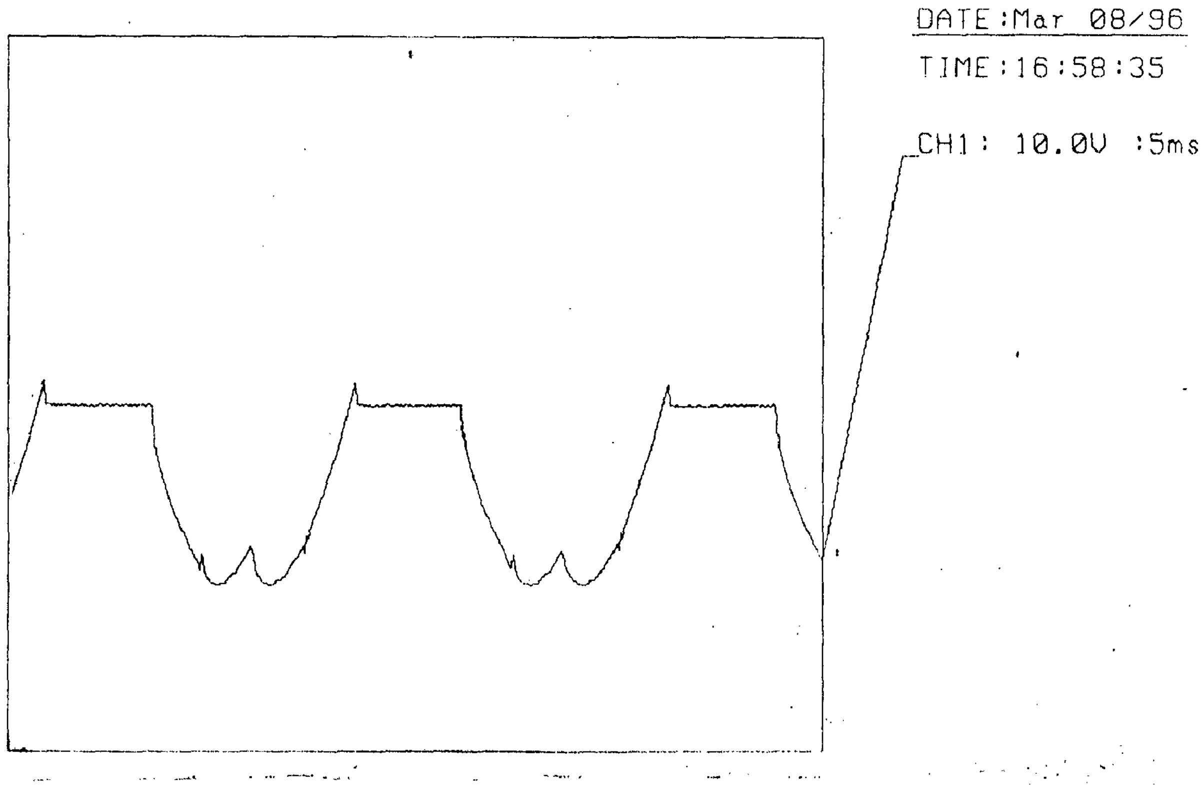


FIG. 6.6 ANODE TO CATHODE VOLTAGE OF Th_1
($V_i = 80V, \alpha = 30^0$)

Fig. 6.7 (A) shows output voltage waveform of cycloconverter for resistive load for a frequency which is one third of input frequency. since modulation index is set to 1/3, the output voltage is set according to the modulation index = 1/3. Frequency of the output voltage waveform is seen to be exact one third (time period = 60 m secs). Both positive and negative half cycles are almost symmetrical. Since cycloconverter is operating in non-circulating current mode positive half cycle is contributed by p-converter and negative half cycle is contributed by N-converter.

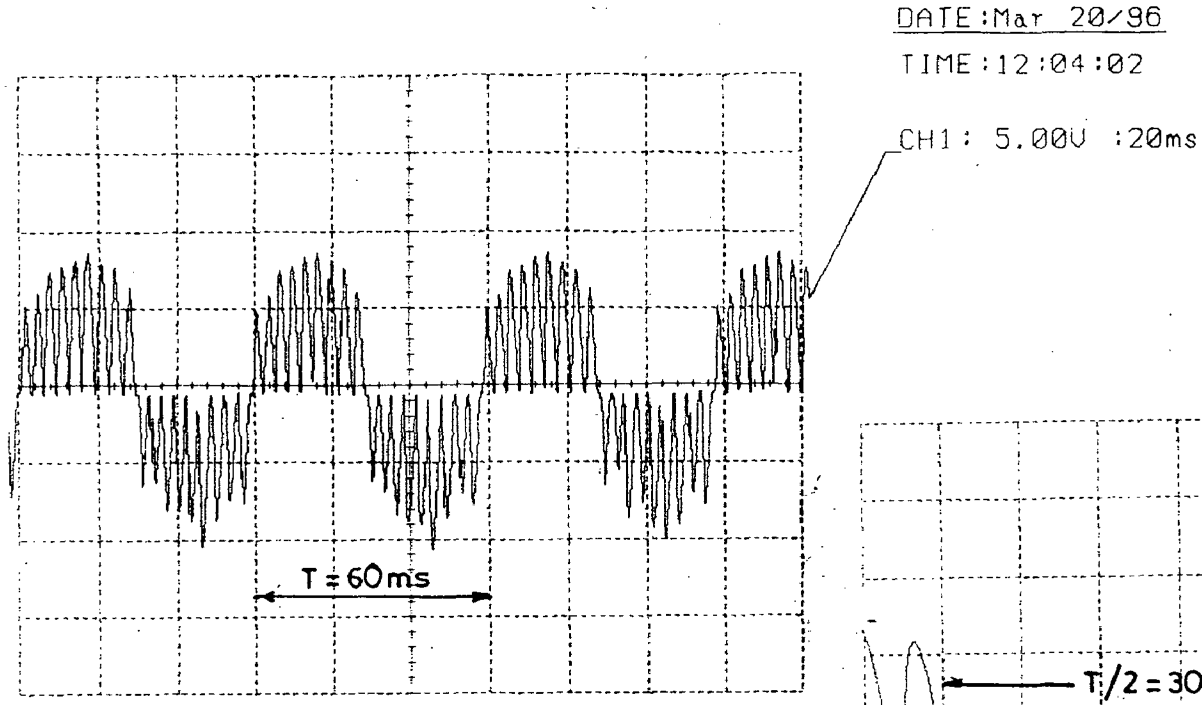
This is further seen more clearly in **Fig. 6.7 (B)** which is obtained at reduced time base setting of 10 ms/div and **Fig. 6.7(C)** obtained at 5 ms/div.

Fig. 6.8 to **6.12** show the cycloconverter output voltage wave form for resistive load for the different frequency setting from 50/3 Hz to 50/10 Hz, that is, 16.66 Hz to 5 Hz. During these observations the input phase voltage has been set throughout to 100 volts through a three phase autotransformer.

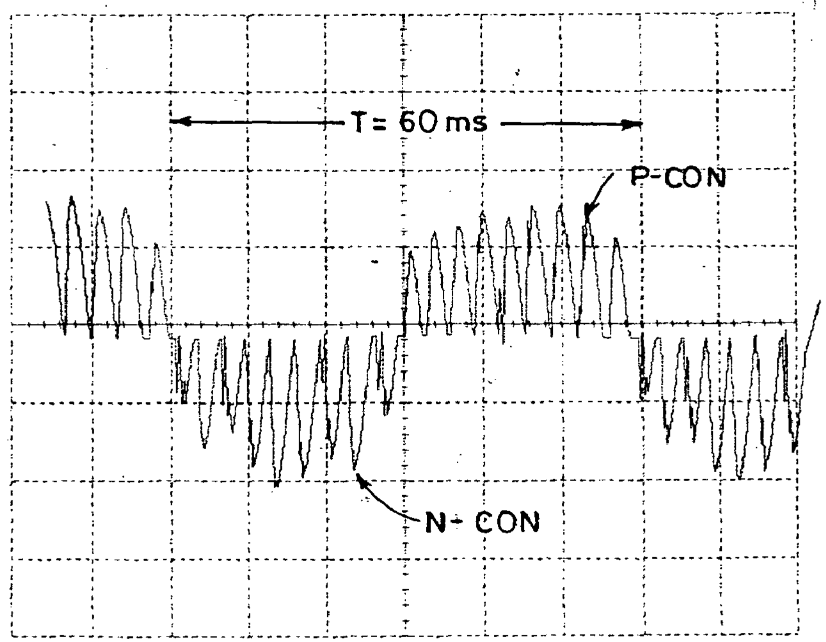
These waveforms show that the frequency of the output voltage is exactly equal to the set frequency.

It is also confirmed that the trigger commands for a desired frequency setting are being faithfully implemented by the control circuit and the response of the power circuit to these commonds is fairly satisfactory. The response would have been more superior if all devices were identical.

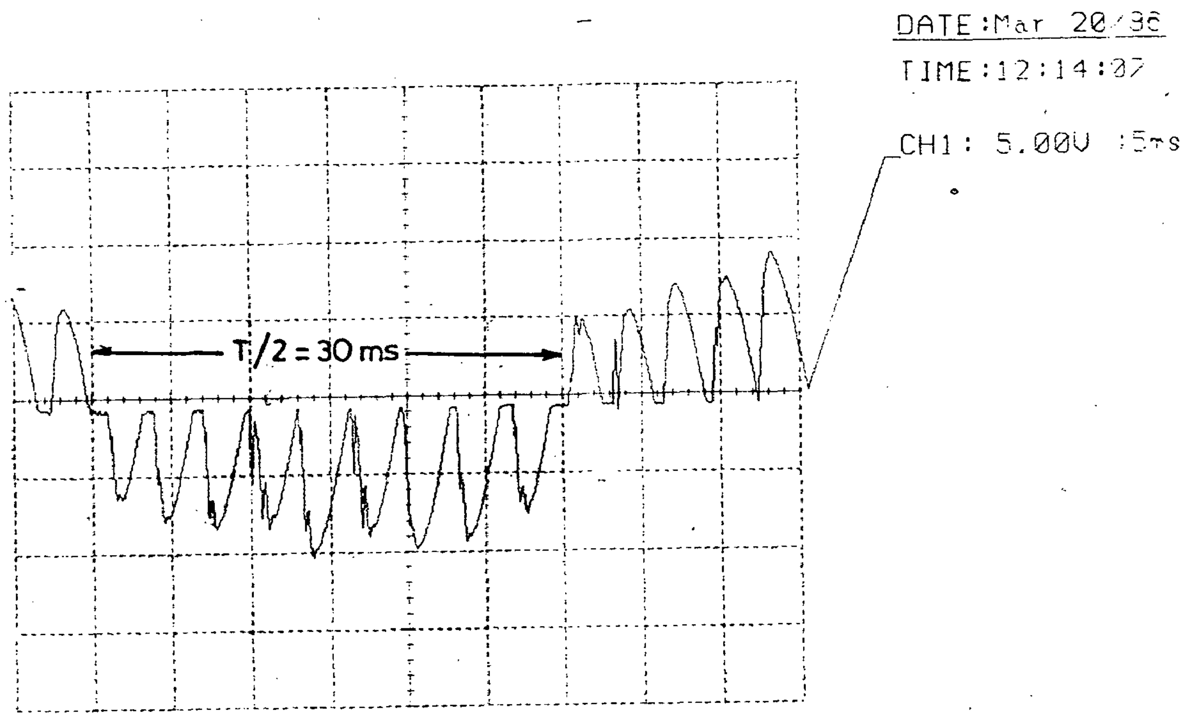
In order to determine harmonic components in these waveforms harmonic spectrums have been obtained experimentally with the help of FFT analyser facility of the storage oscilloscope. The output voltage waveform of the cycloconverter and their harmonic spectrum spectrum have been obtained and printed through the integral plotter of the oscilloscope for the three different settings of output frequncies which



(a)



(b)



(c)

FIG.6.7 LOAD VOLTAGE WAVEFROM R-LOAD

(A) $V_i = 70V$, $f_i = 50$ Hz, $f_0 = fi/3$
$m = 1/3$, $I_L = 0.5$ AMP

(B) SAME CONDITIONS AS (A) TIME BASE = 10 ms

(C) SAME CONDITIONS AS (A) TIME BASE = 5 ms

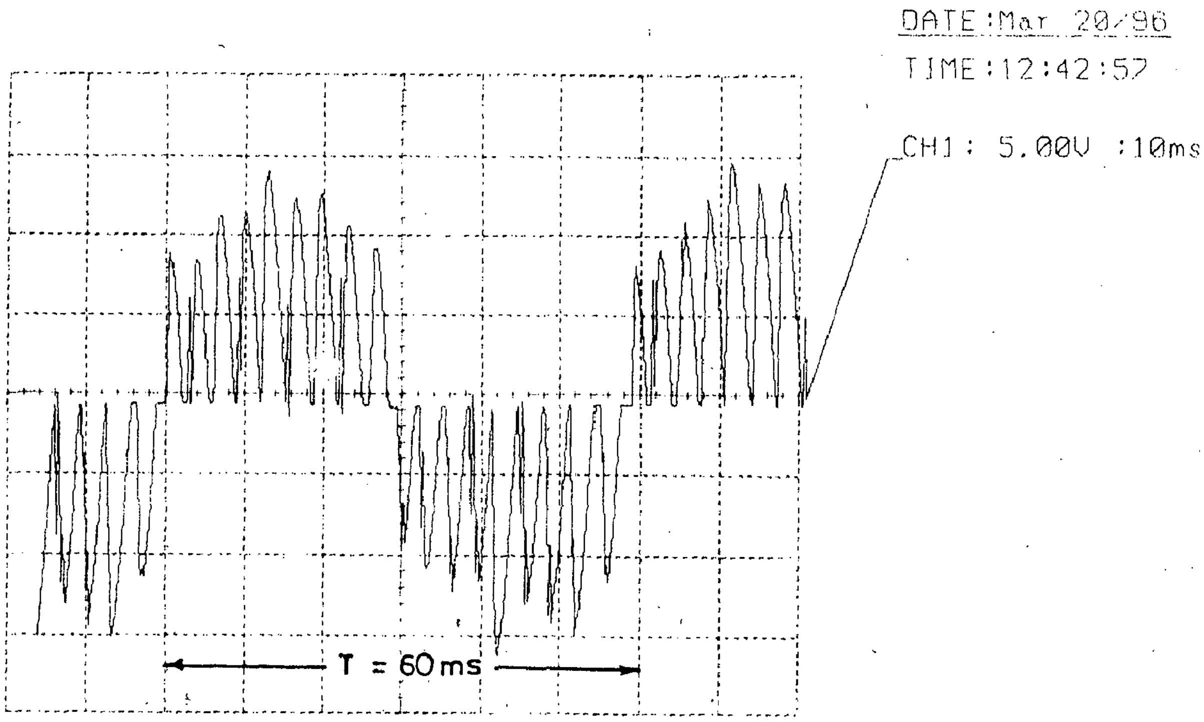


FIG. 6.8 LOAD VOLTAGE WAVEFROM R - LOAD
(A) $V_i = 100V$, $f_i = 50$ Hz, $f_0 = fi/3$
$m = 1/3$, $I_L = 0.5$ AMP

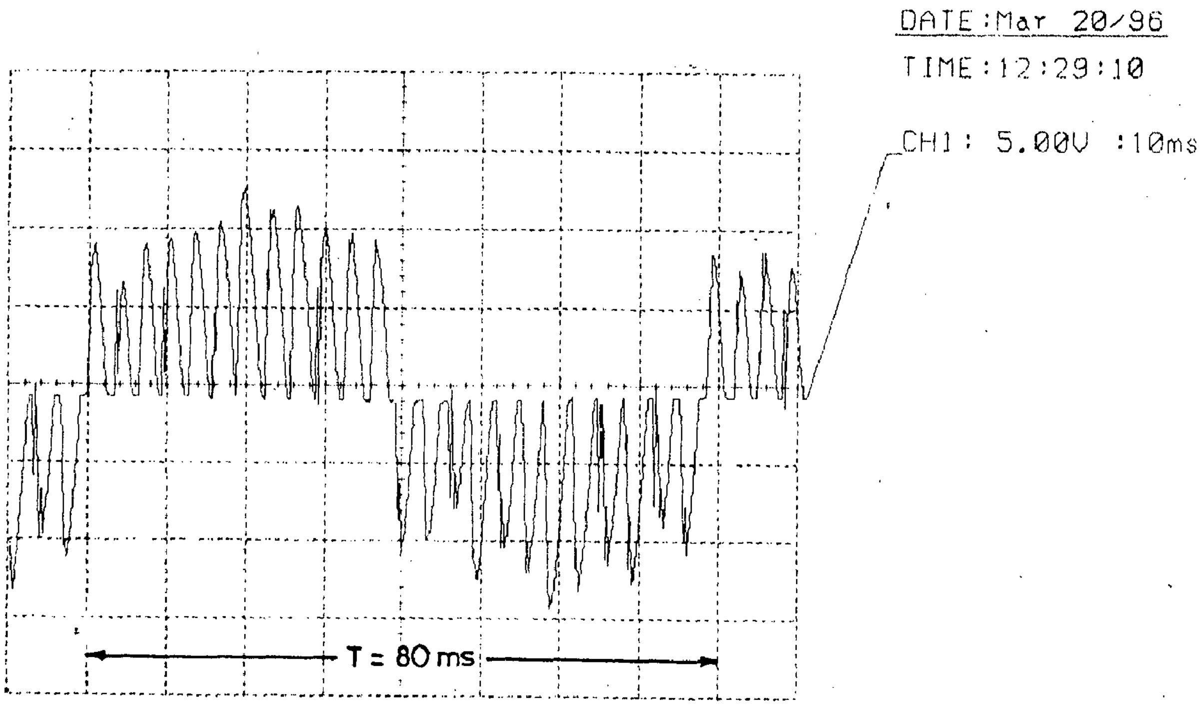


FIG. 6.9 LOAD VOLTAGE WAVEFROM R - LOAD
(A) $V_i = 100V$, $f_i = 50$ Hz, $f_0 = fi/4$
$m = 1/4$, $I_L = 0.45$ AMP

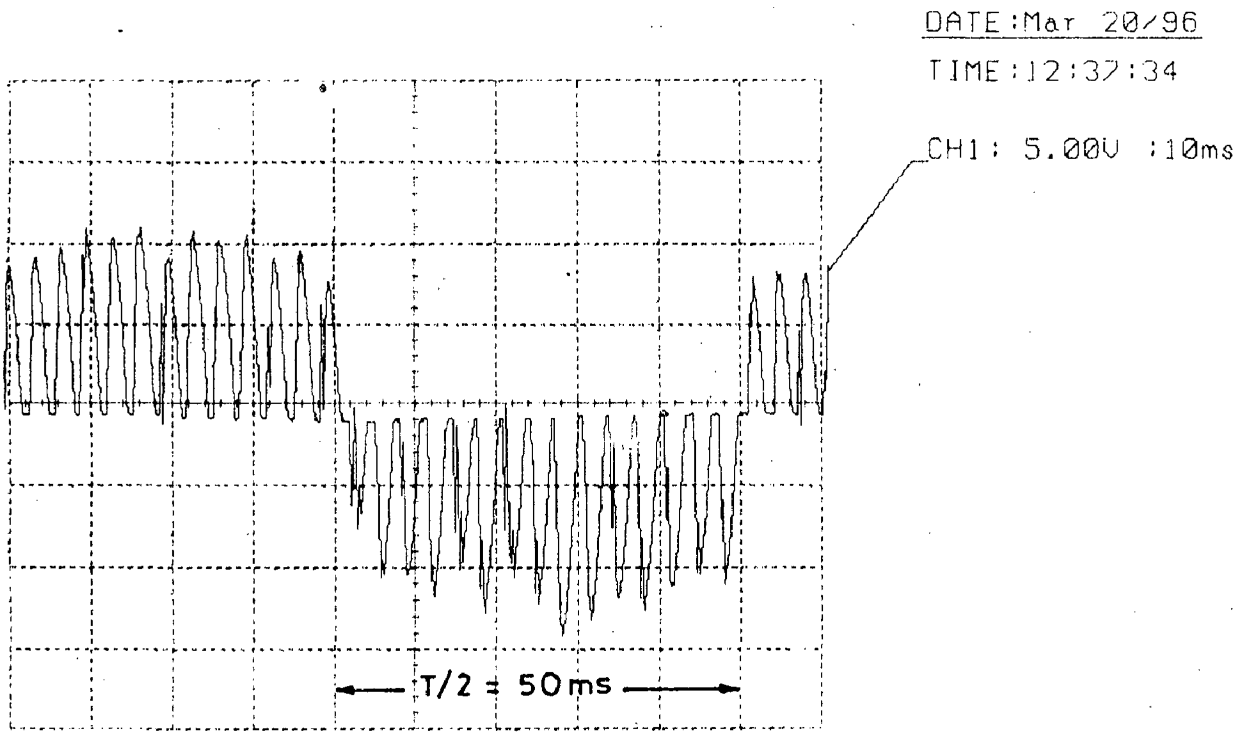


FIG.6.10 LOAD VOLTAGE WAVEFROM R - LOAD
(A) $V_i = 100V, f_i = 50$ Hz, $f_0 = fi/5$
$m = 1/5, I_L = 0.4$ AMP

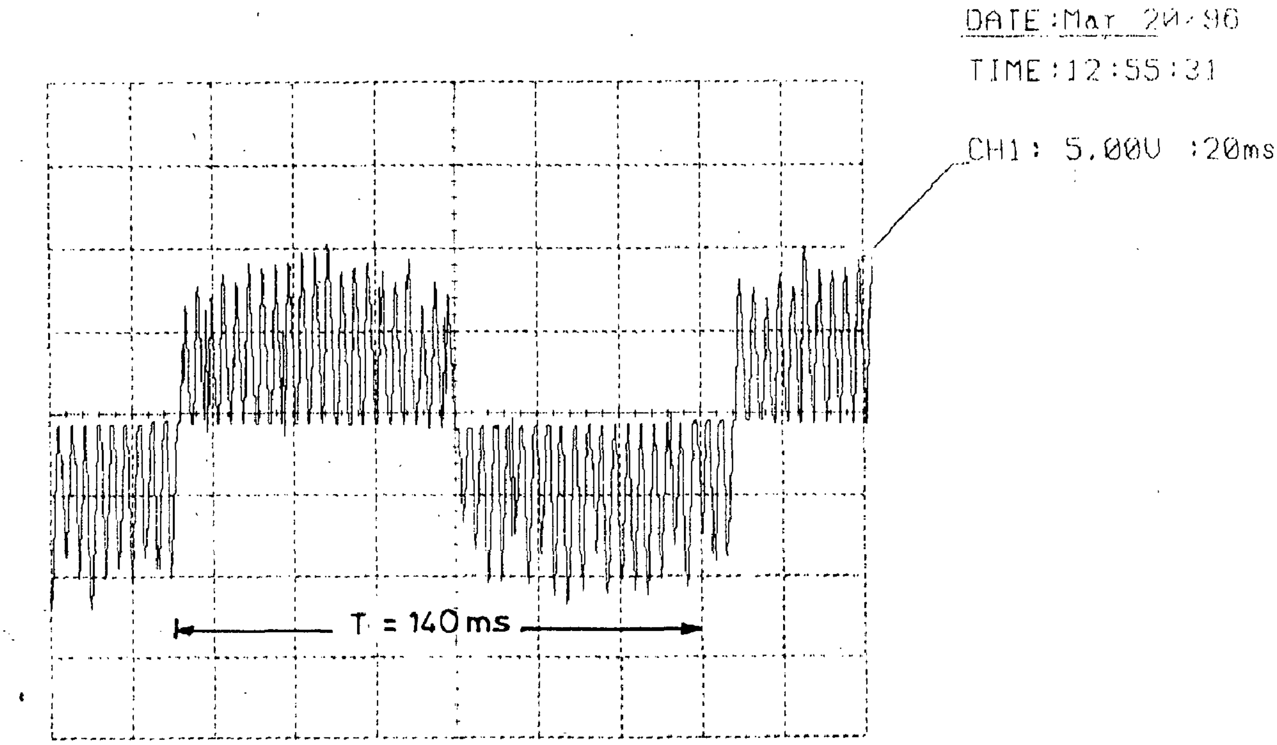


FIG.6.11 LOAD VOLTAGE WAVEFROM R - LOAD
(A) V_i = 100V, f_i = 50 Hz, f_0 = fi/7
m = 1/7, I_L = 0.35 AMP

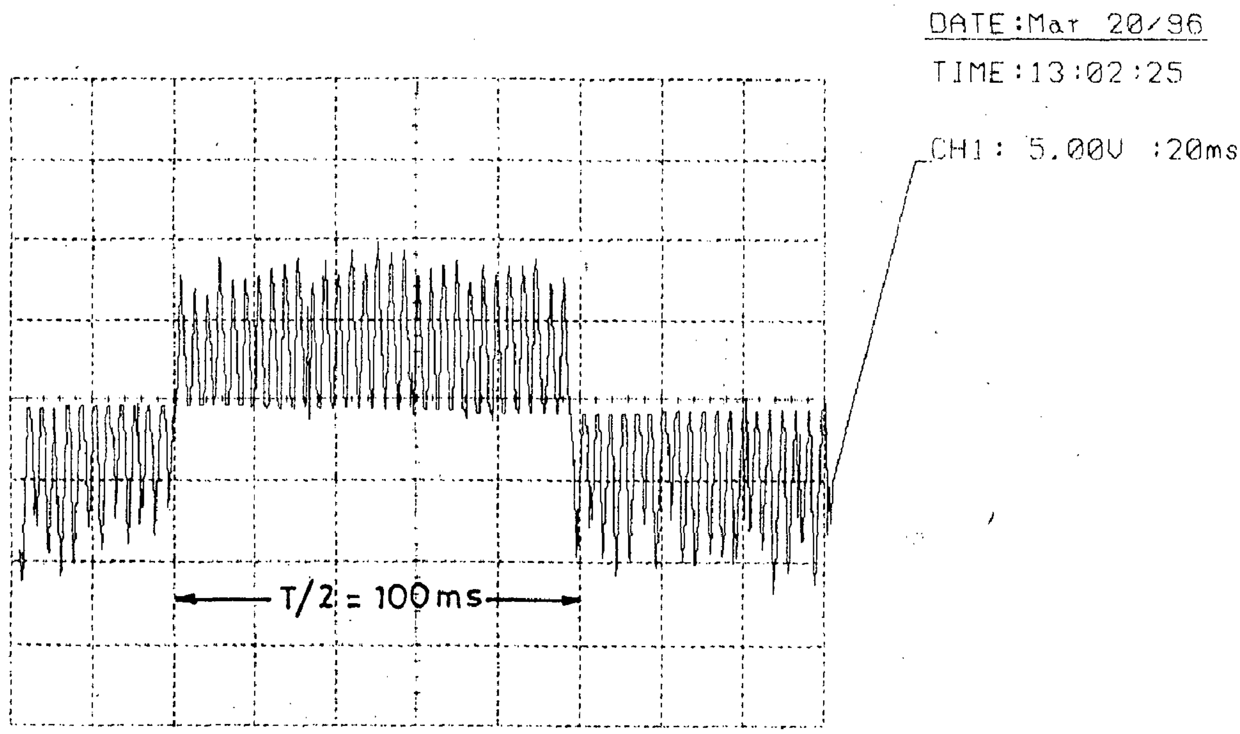


FIG.6.12 LOAD VOLTAGE WAVEFROM R - LOAD
(A) V_i = 100V, f_i = 50 Hz, f_0 = fi/10
m = 1/10, I_L = 0.3 AMP

are 1/3rd, 1/7 th and 1/10th of the input frequncy (50 Hz).

For 1/3rd frequncy setting, that is, 16.67 Hz only odd harmonics 13th, 15th, 17th and 19th are present and all triplens are absent as shown in **Fig. 6.13 (B)** which is harmonic spectrum of **Fig. 6.13 (A)**. It may be noted that the converter is now operated at increased voltage level of 150 volts. the sagments formed in positive and negative half cycles are almost similar, confirming the observation made earlier that performance of the present setup improves at higher voltages. The harmonic spectrum of **Fig. 5.13 (B)** clearly brings out the merit of a cycloconverter for obtaining reduced frequency. The absence of lower order harmonics makes the voltage waveform ideally suitable for drive applications.

Fig. 6.14(A) shows cycloconverter output voltage for the 1/7th frequency setting that is 7.14 Hz corresponding to 50 Hz input. It's harmonic spectrum is shown in **Fig. 6.14(B)** In this case the lowest significant harmonics are of 41st, 43rd and 45th order which is a considerable improvement over 16.66 Hz operation.

Fig. 6.15 (A) shows cycloconverter output for a frequency equal to 5 Hz which is 1/10th of the input frequency corresponding to 50 Hz input frequency. It's harmonic spectrum is shown in **Fig. 5.15(B)** which shows still better performance as compared to the above two cases. In this case lowest significant harmonics are of 61st, 63rd and 65th order.

Fig. 6.16 to **Fig. 6.19** show the output voltage waveforms of the cycloconverter when it is supplying R-L load for four different frequency settings which are 16.67 Hz, 10 Hz, 7.12 Hz and 5 Hz respectively. During all these four test records input phase voltage have been kept constant to a fixed value that is 75 volts.

These pictures show that the performance of cycloconverter deteriorates as the

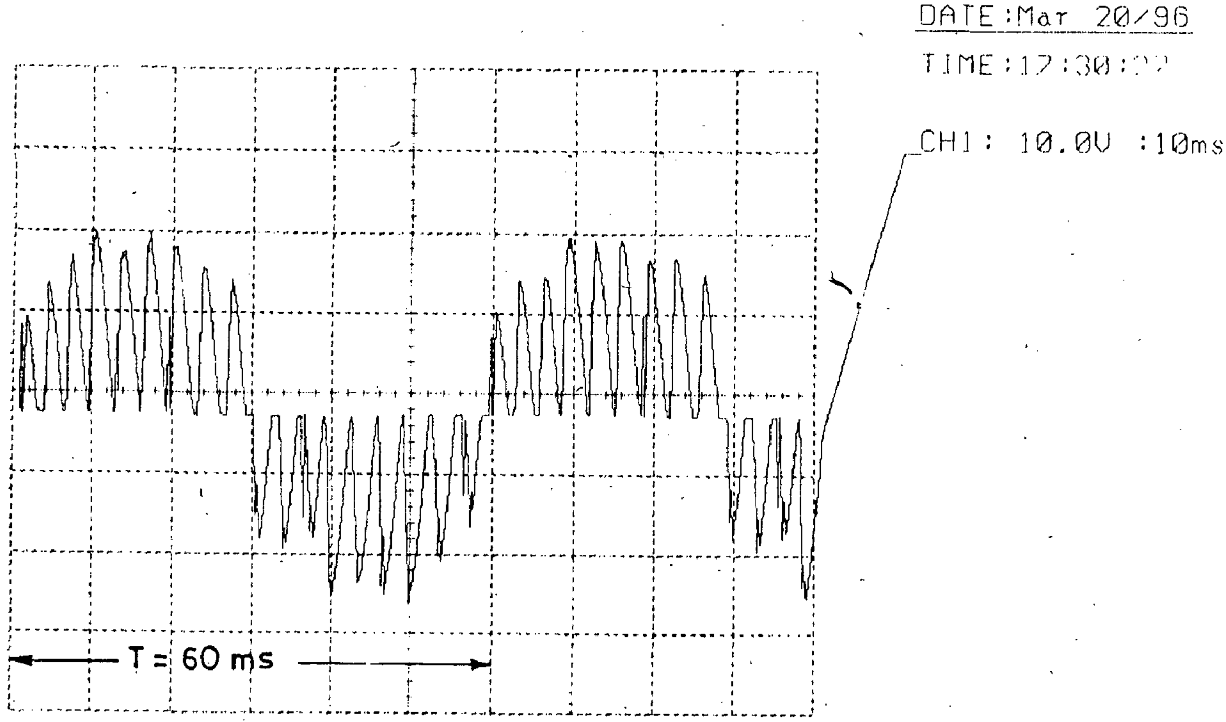


FIG.6.13 (A) LOAD-VOLTAGE WAVEFROM R-LOAD
(A) $V_i = 150V, f_i = 50$ Hz, $f_0 = f_i/3$
$m = 1/3, V_0 = 100V, I_L = 1.4$ AMP

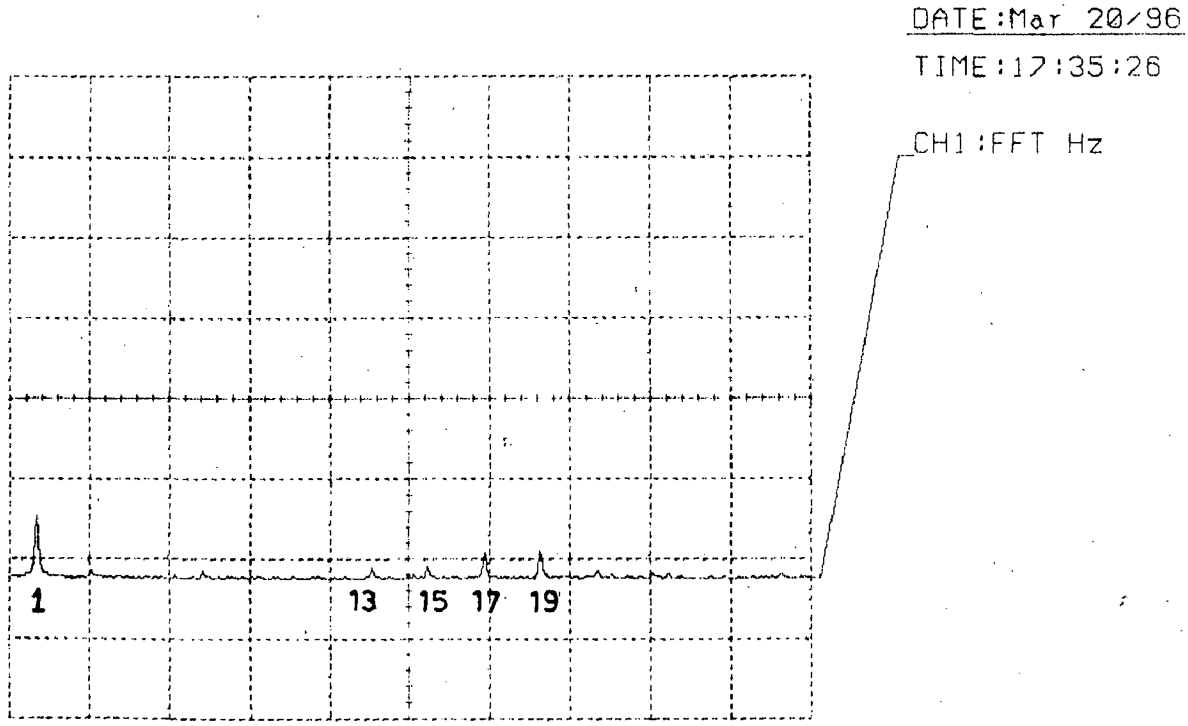


FIG.6.13 (B) HARMONIC SPECTRUM OF FIG.6.13 (A)
SCALE - 51 Hz/DIV

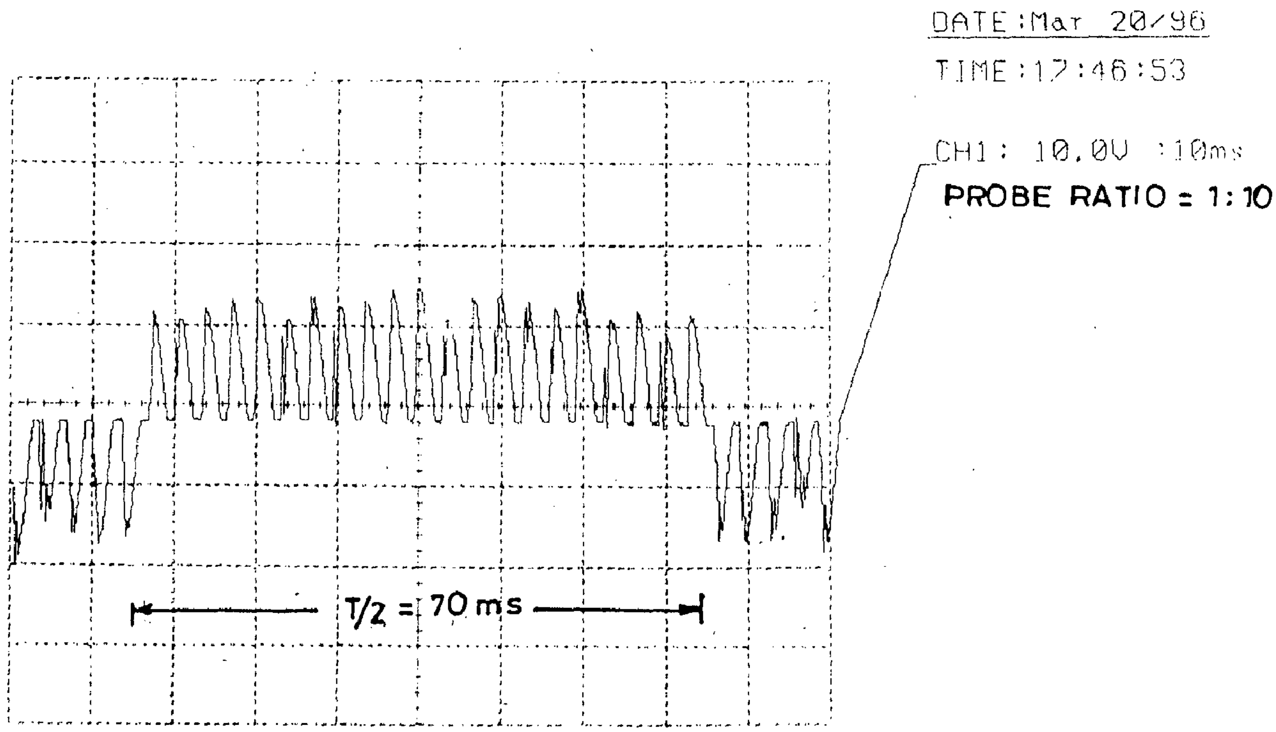


FIG.6.14 (A) LOAD VOLTAGE WAVEFROM R-LOAD
(A) $V_i = 150V, f_i = 50\ Hz, f_0 = fi/7$
$m = 1/7, V_0 = 70V, I_L = 1.2\ AMP$

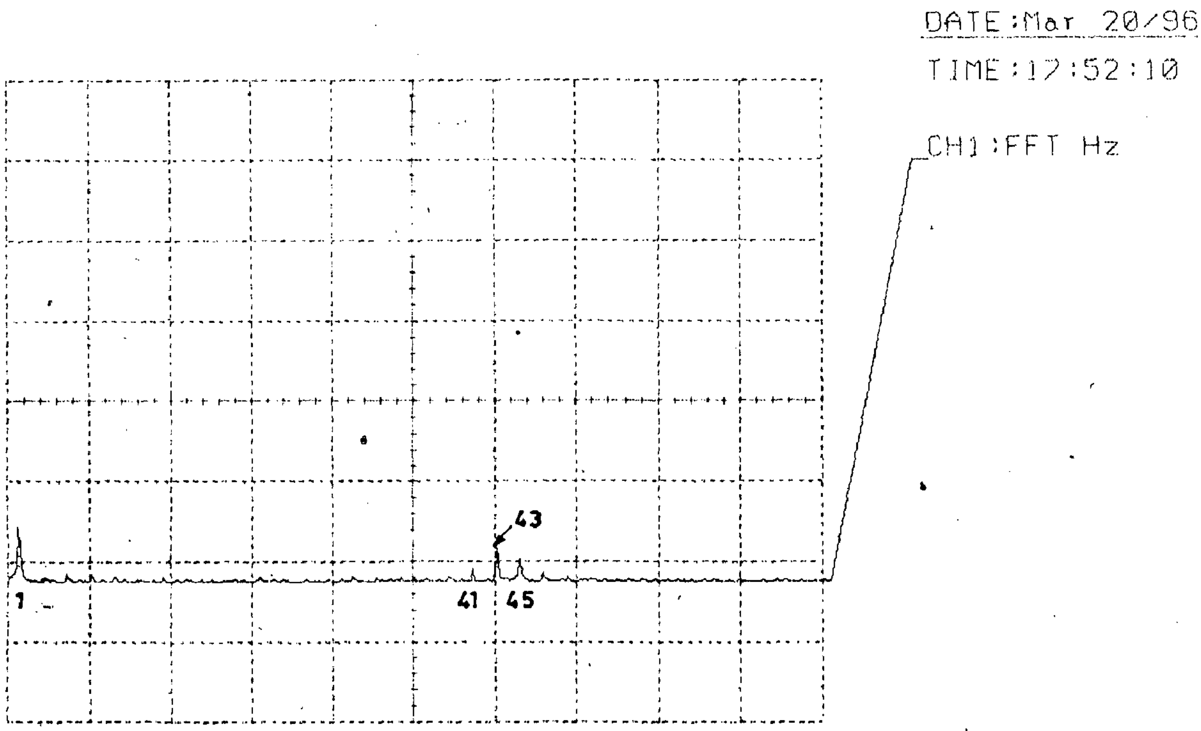


FIG.6.14 (B) HARMONIC SPECTRUM OF FIG.6.14 (A)
SCALE-51 Hz/DIV

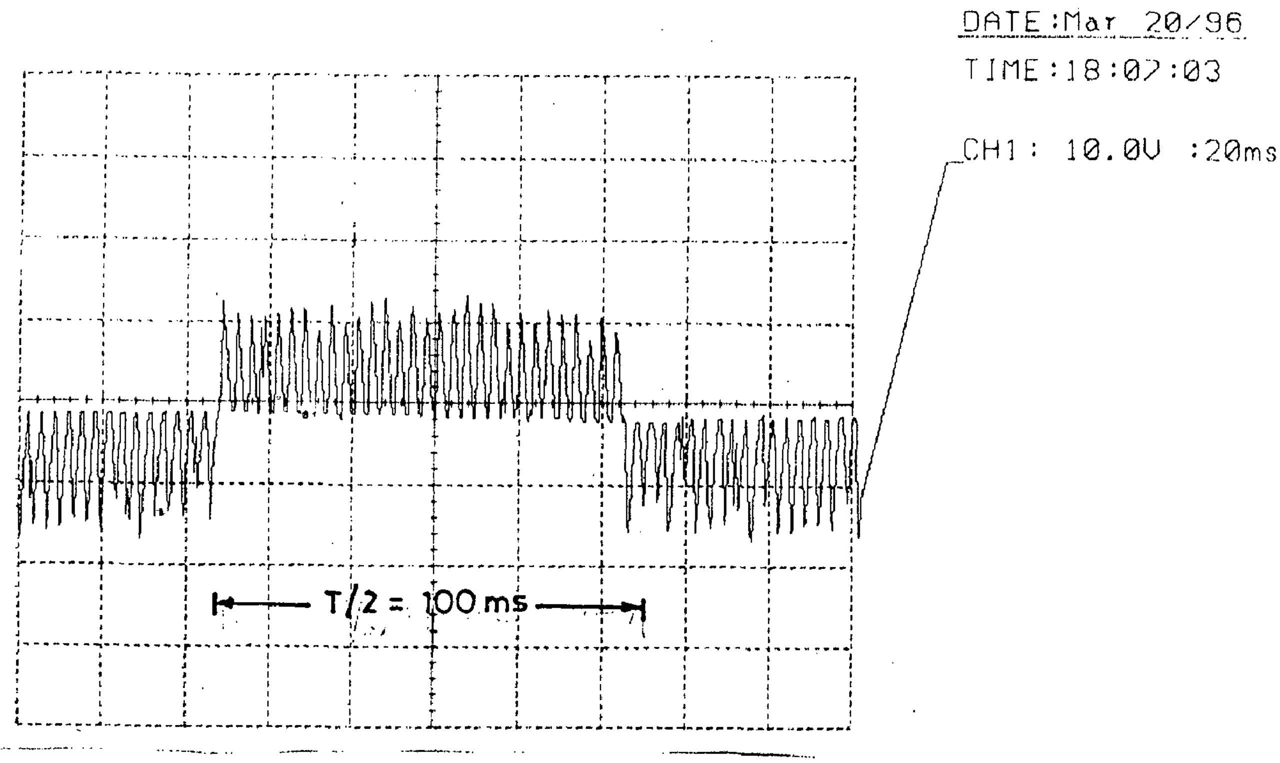


FIG. 6.15 (A) LOAD VOLTAGE WAVEFROM R - LOAD
(A) $V_i = 150V$, $f_i = 50$ Hz, $f_0 = fi/10$
$m = 1/10$, $V_0 = 50V$, $I_L = 1$ AMP

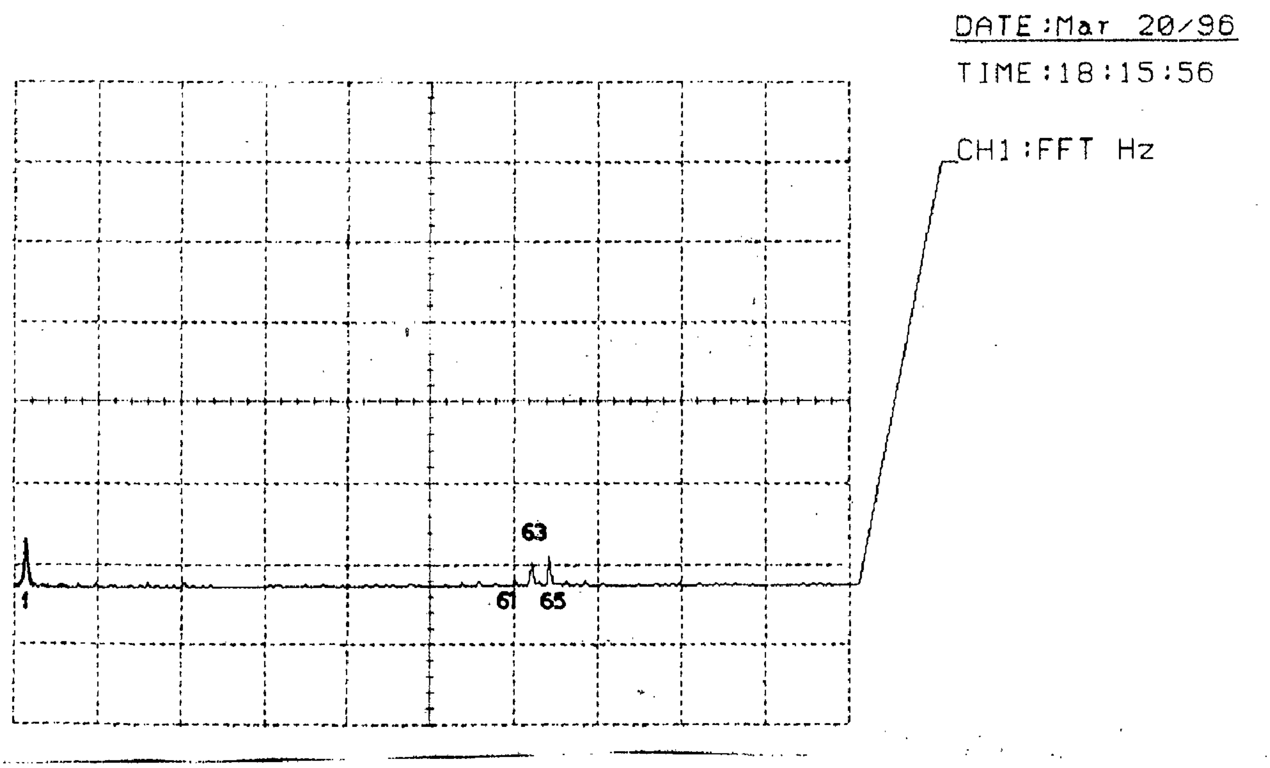


FIG. 6.15 (B) HARMONIC SPECTRUM OF FIG. 6.15 (A)
SCALE - 51 Hz/DIV

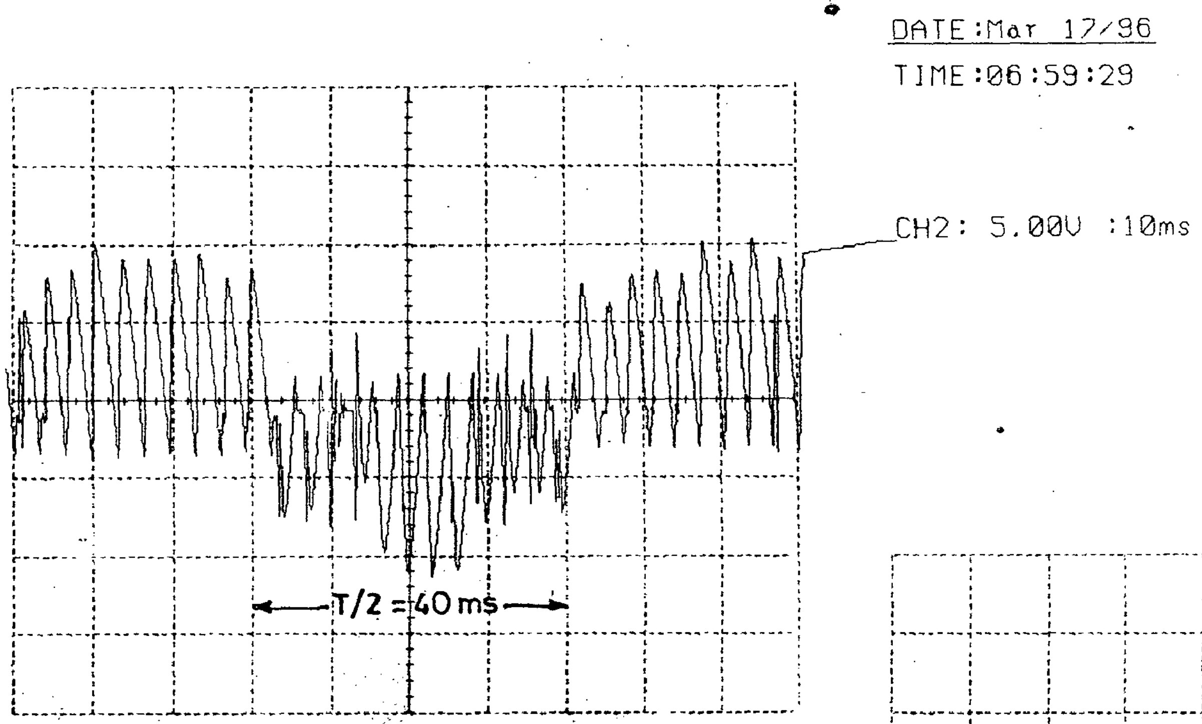


FIG. 6.17 LOAD VOLTAGE WAVEFROM R - L LOAD
(A) $V_i = 75V$, $f_i = 50$ Hz, $f_0 = fi/4$, m = 1/4

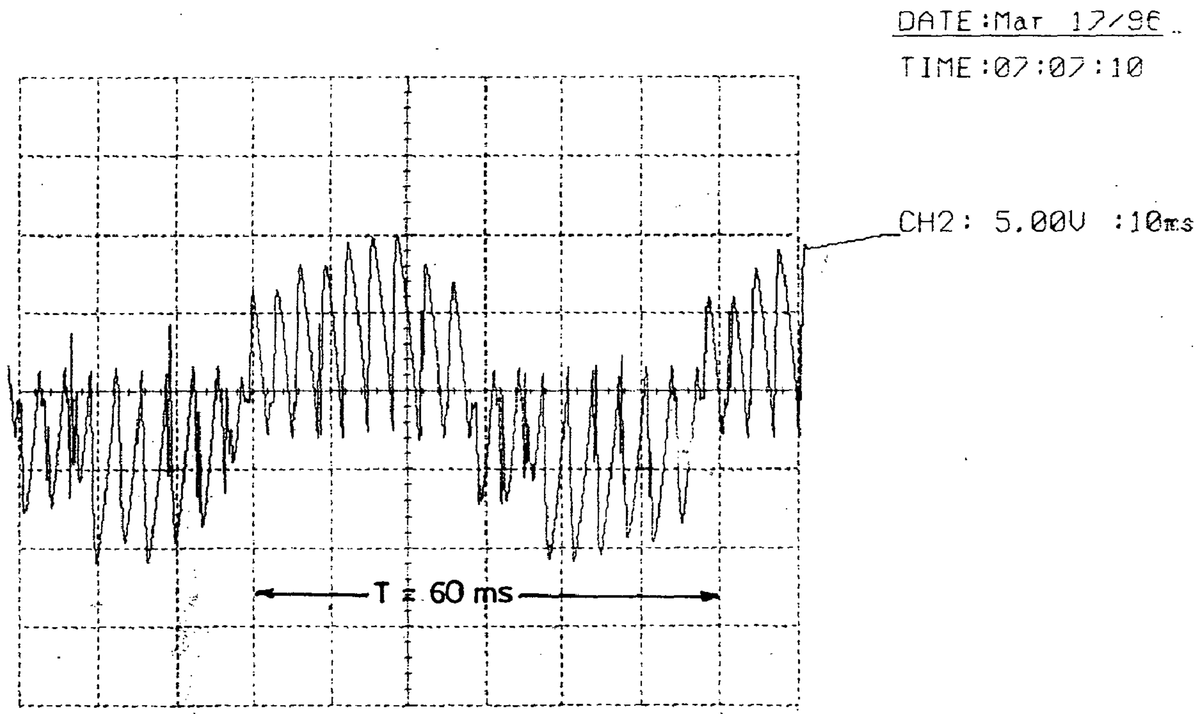


FIG. 6.16 LOAD VOLTAGE WAVEFROM R - L LOAD
(A) $V_i = 75V$, $f_i = 50$ Hz, $f_0 = fi/3$, m = 1/3

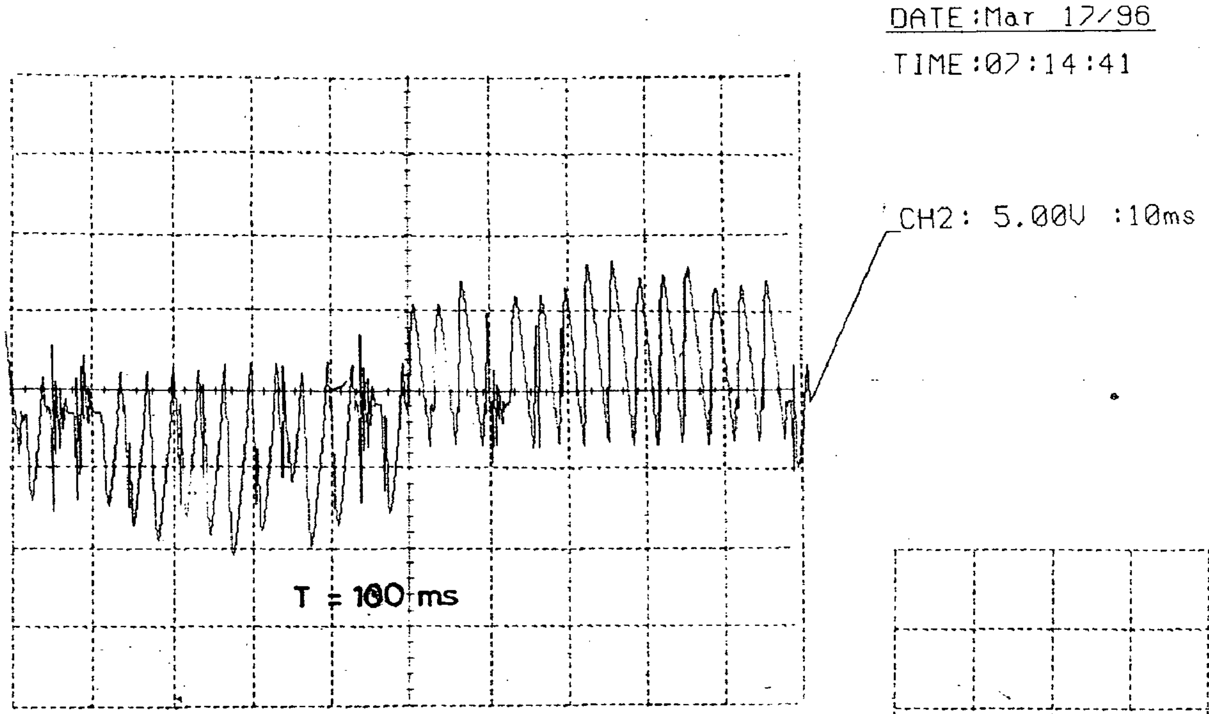


FIG. 6.18 LOAD VOLTAGE WAVEFROM R - L LOAD
(A) $V_i = 75V, f_i = 50$ Hz, $f_0 = fi/5$, $m = 1/5$

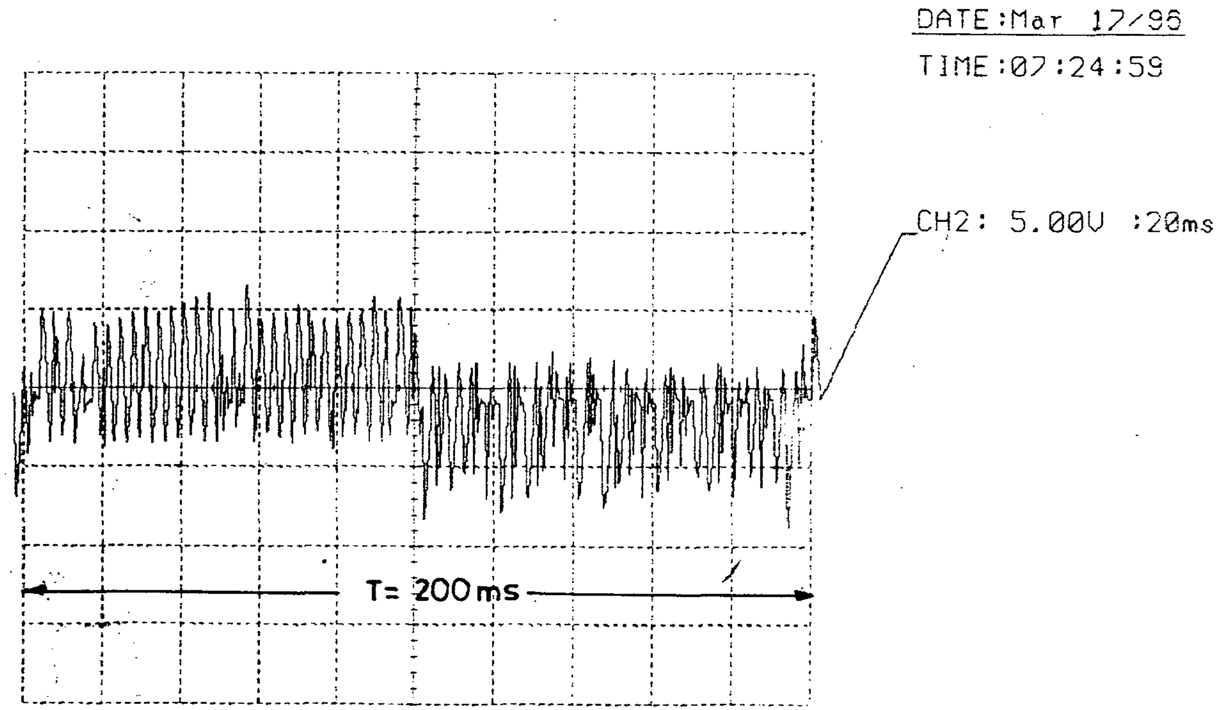


FIG. 6.19 LOAD VOLTAGE WAVEFROM R - L LOAD
(A) $V_i = 75V, f_i = 50$ Hz, $f_0 = fi/10$, $m = 1/10$

frequency goes down a modulation idex is also adjusted along with frequency. Hence with lower frequency voltage also goes down. On such lower voltage range few thyristors are not working satisfactorily.

Voltage and current waveforms for the motor load are now presented.

Fig. 6.20 (A) shows the motor voltage waveform when it is fed with the cycloconverter at one thrid frequency of the input frequency. Modulation index is adjusted to 1/3 to keep V/f ratio constant.

Fig. 6.20 (B) shows harmonic spectrum of **Fig. 6.21(A)**. It has been observed that with motor load also only odd harmonics are present.

Fig. 6.21 (A) shows motor current waveform for the same conditions as in **Fig. 6.20 (A)**.

Fig. 6.21(B) shows harmonic spectrum of the motor current corresponding to **Fig. 6.21(A)**. In current waveform performance is better than its corresponding voltage waveform.

Fig. 6.22(A) shows motor current at 5 Hz which is one tenth of the input frequnecy (50 Hz) and modulation index is set to 1/10. For this particular frequency the rated current for the motor under test is 11 volts. On such reduced voltage thyristor perfornance further deteriorates, therefore only current waveform has been considered. **Fig. 5.22 (B)** shows harmonic spectrum of **Fig. 6.22(A)**

6.2.2 POWER INPUT TO LOAD

Table 1 gives comparison of the different results obtained when induction motor dirve is fed with sinusoidal supply with those obtained when it is fed with

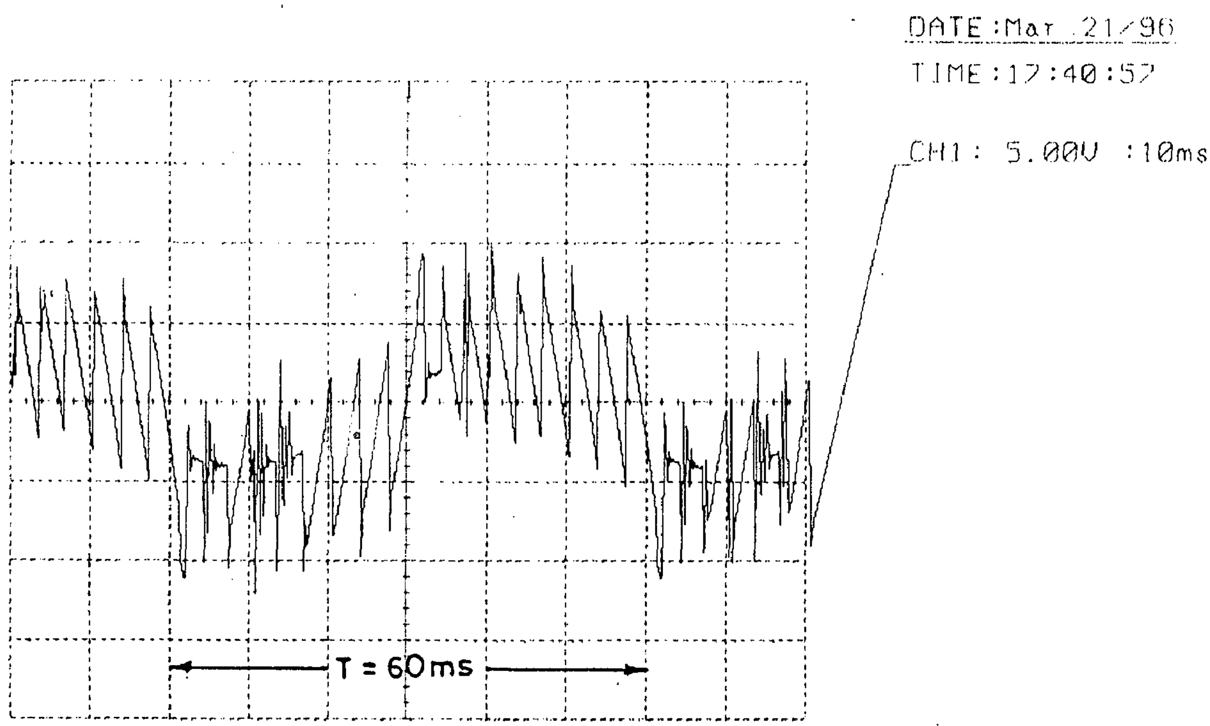


FIG. 6.20 (A) VOLTAGE WAVEFROM OF MOTOR LOAD
(A) $V_i = 45V$, $f_i = 50$ Hz, $f_0 = fi/3$, $m = 1/3$
$V_0 = 36V$, $I_L = 3.25$ AMP

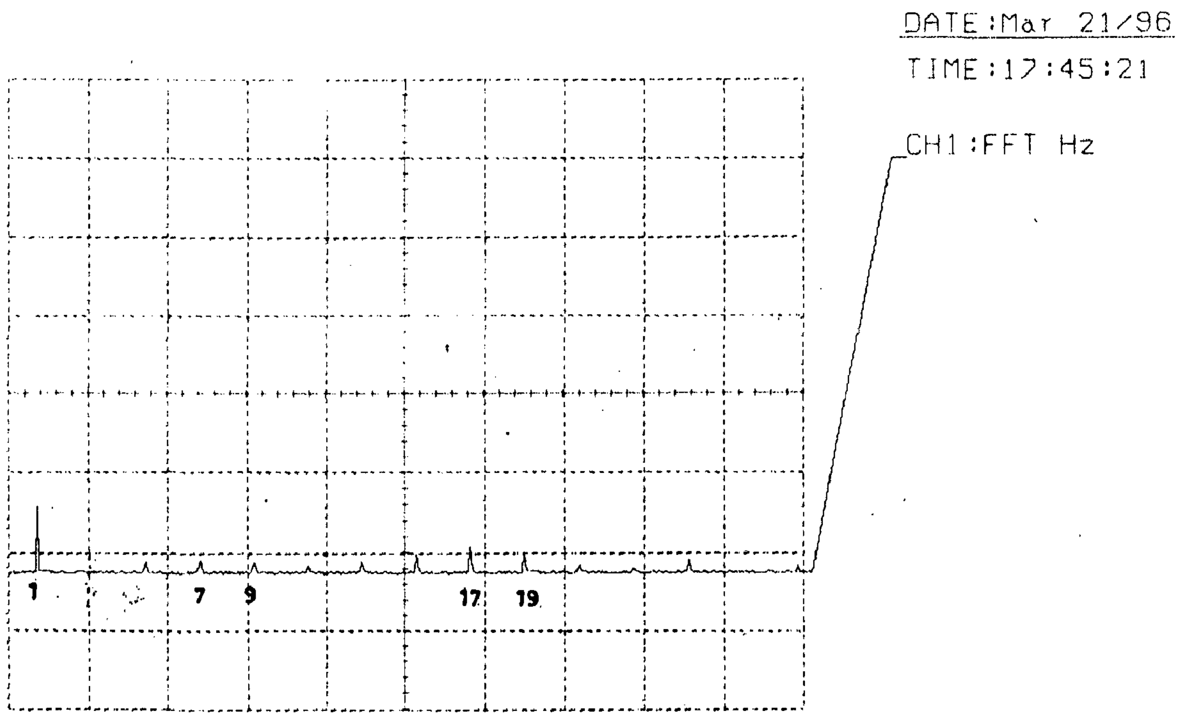


FIG. 6.20 (B) HARMONIC SPECTRUM OF FIG. 6.20 (A)
SCALE - 51 Hz/DIV

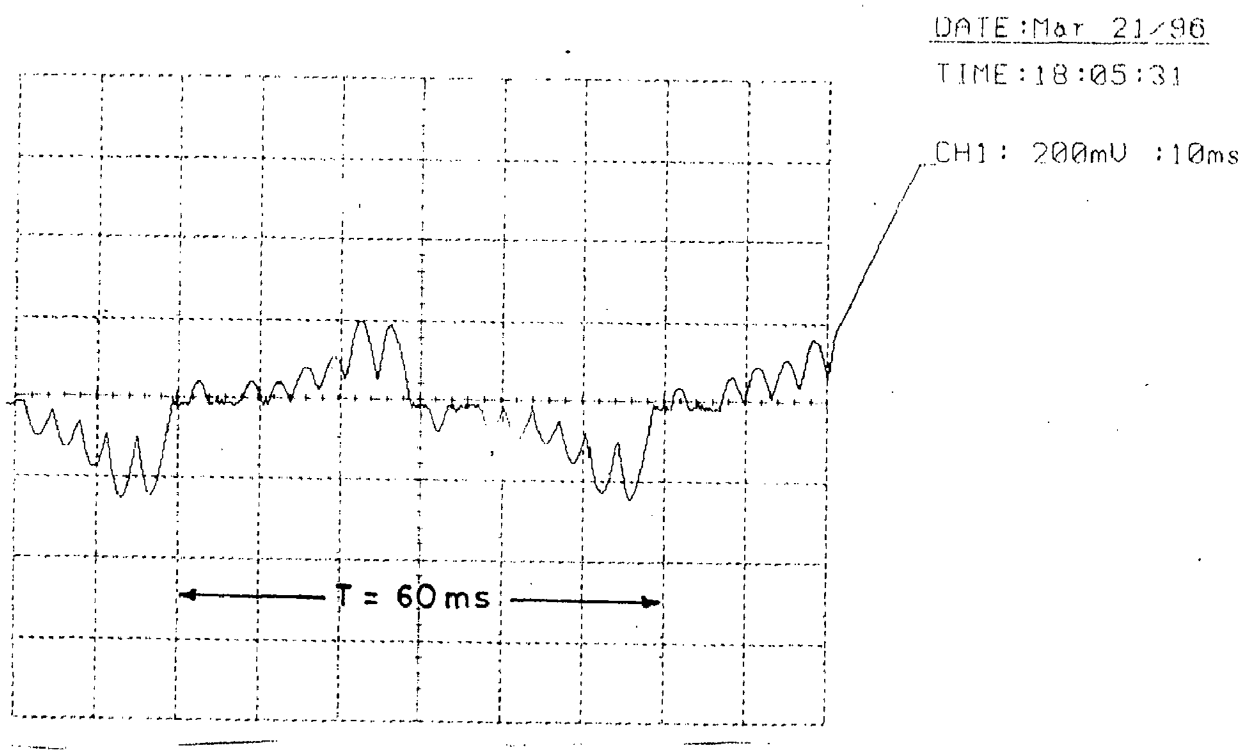


FIG.6.21 (A) CURRENT WAVEFROM OF MOTOR LOAD
(A) $V_i = 45V, f_i = 50$ Hz, $f_0 = fi/3, m = 1/3$
$V_0 = 36V, I_L = 3.25$ AMP

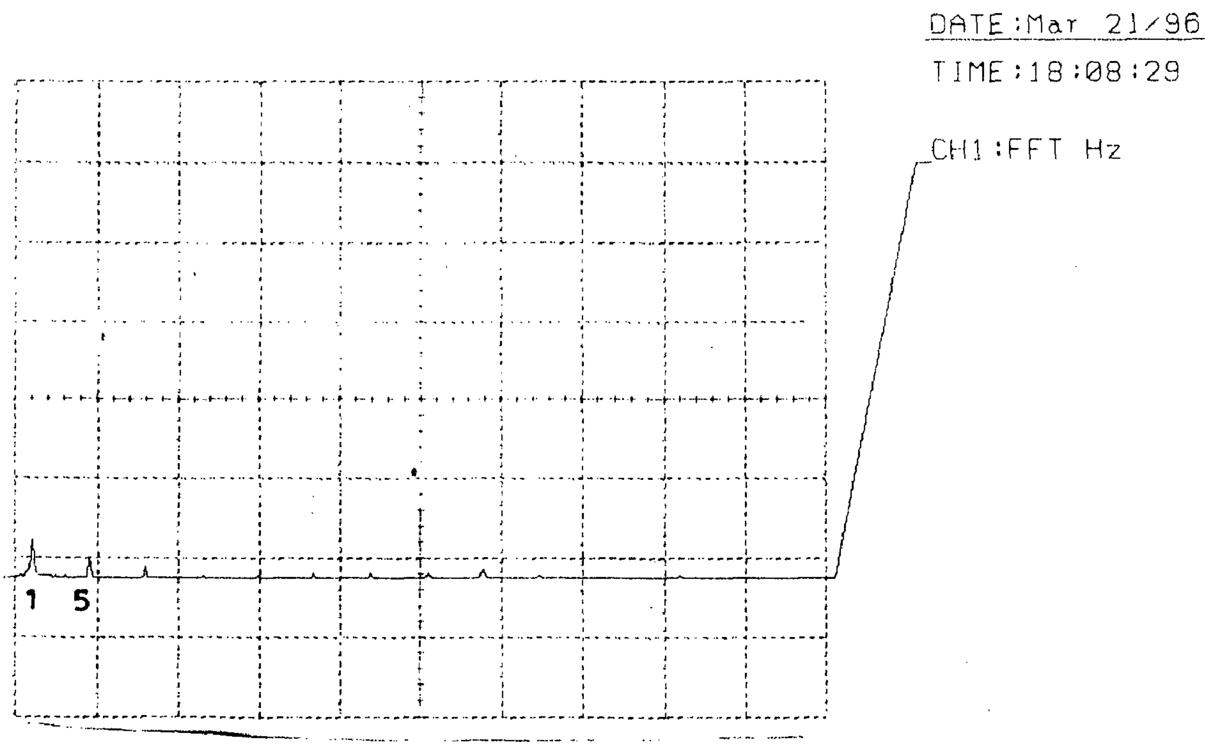


FIG.6.21 (B) HARMONIC SPECTRUM OF FIG.6.21 (A)
SCALE - 51 Hz/DIV

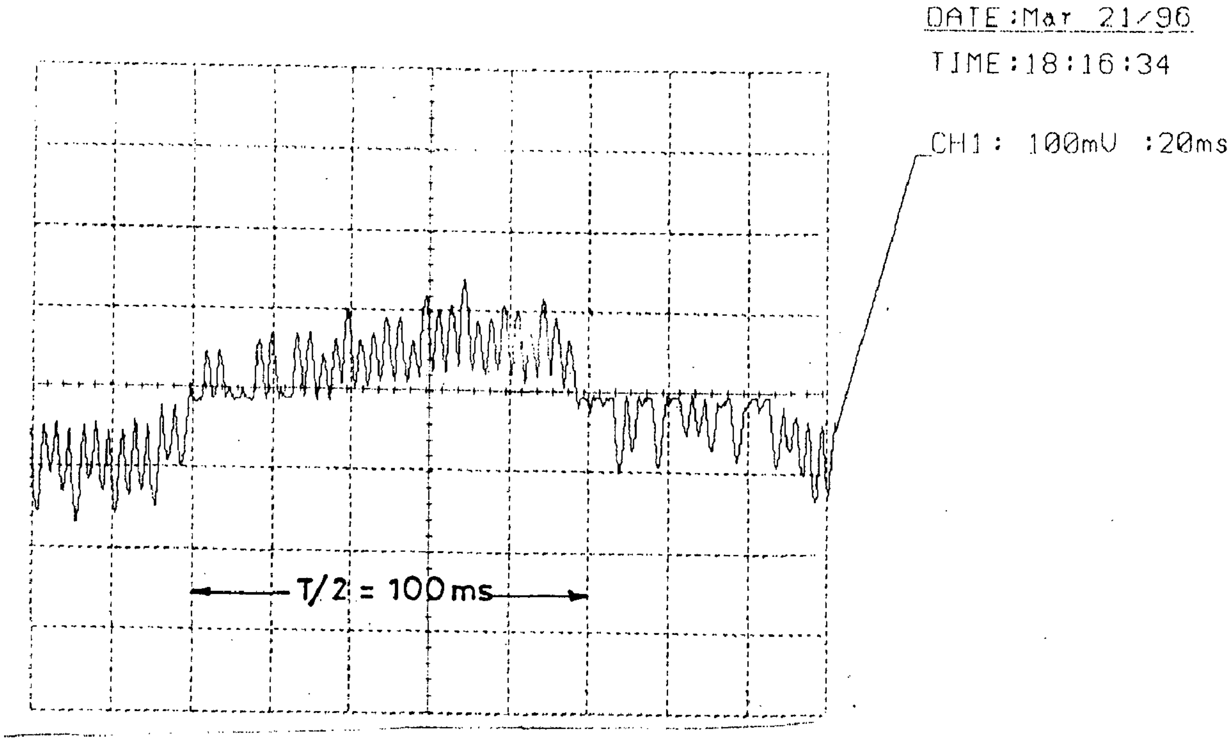


FIG. 6.22 (A) CURRENT WAVEFROM OF MOTOR LOAD
(A) $V_i = 45V$, $f_i = 50$ Hz, $f_0 = fi/10$, $m = 1/10$
$V_0 = 11V$, $I_L = 2.5$ AMP

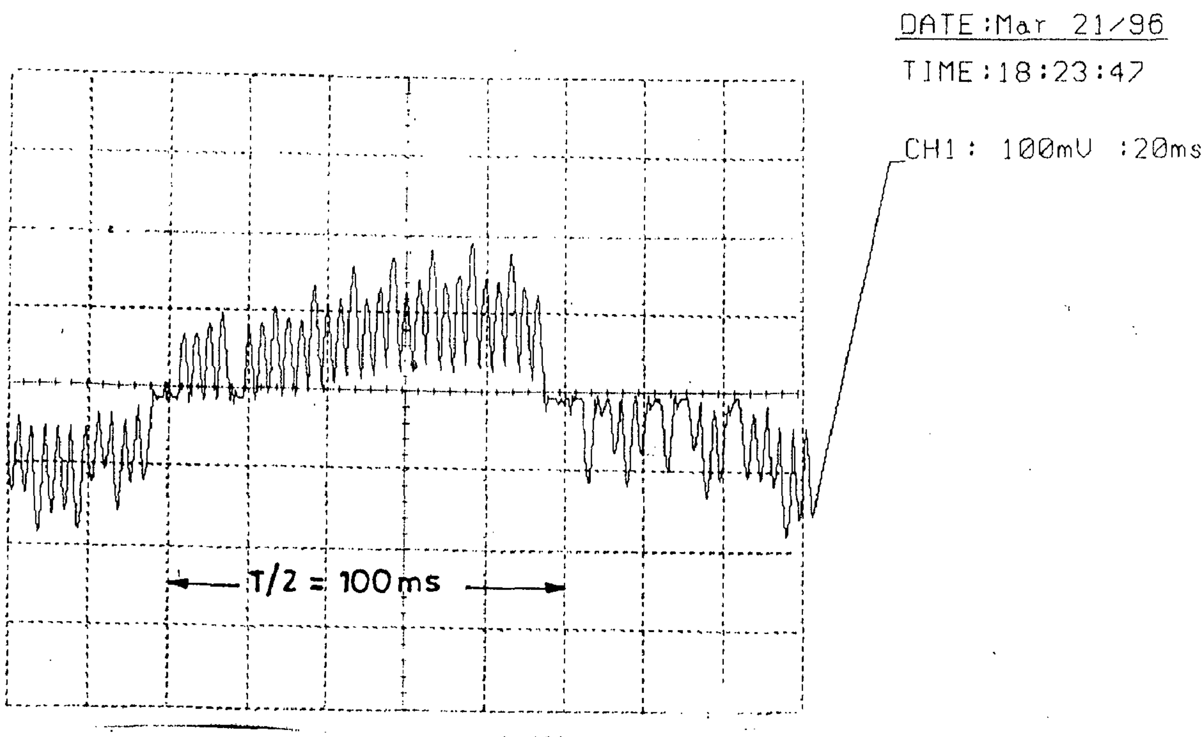


FIG. 6.22 (B) SAME CONDITIONS AS IN FIG. 6.22 (A)
EXCEPT $V_0 = 16V$

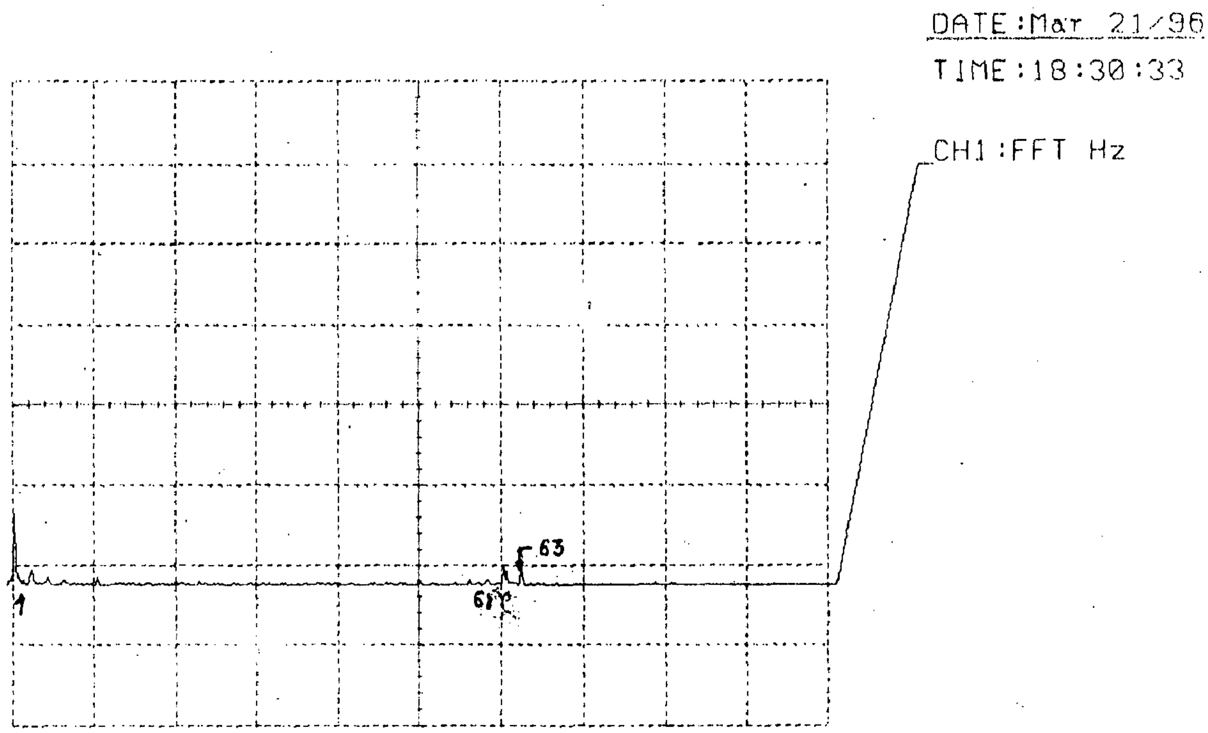


FIG. 6.22 (C) HARMONIC SPECTRUM OF FIG. 6.22 (B)
SCALE - 51 Hz/DIV

cycloconverter supply for the 16.67Hz operating frequency and voltage keeping v/f ratio at rated value of motor.

Observations are recorded for three settings of load. The resuls clearly indicates that the performance with cycloconverter supply is almost as good as on sinusoidal supply.

TABLE -1

Comparative performance of motor on cycloconverter supply with sinusoidal supply

	Operating frequency	Motor voltage	Input phase voltage to cyclo-converter	Motor speed	motor Input power	Motor current
Motor fed with sinsusoidal supply	16.67	36	-	490	26	2.9
	16.67	36	-	450	80	3.75
	16.67	36	-	440	100	4.00
Motor fed with cyclocon-verter supply	16.67	36	45	490	38	3.25
	16.67	36	55	450	81	3.75
	16.67	36	60	435	100	4.00

CHAPTER - 7

CONCLUSIONS AND SCOPE OF FURTHER WORK

7.1 CONCLUSIONS

The objective of this dissortation work was to develop three phase to single phase cycloconverter operating in non - circulating current mode of operation useful for induction motor drive. The development of the successful control circuit and the power circuit of the cycloconverter has been described. The software of the working system have also been described.

The application of the microprocessor serves a worthwhile objective of achieving important circuit simplification and enhancing overall reliability. The technique uses offline calculation of delay angles. The software developed uses an optimum number of instructuions to handle IO's within the time slots decided by the input signal.

Besides R-load, the cycloconverter has been tested on a .5HP single phase induction motor at several frequencies in the low frequency range maintaining V/f constant.

A comparision of motor performance on both cycloconverter and sinusoidal supply have also been presented.

7.2 SCOPE OF FURTHER WORK

It is generally assumed that the input is three phase and that either a single or three phase output is required. Usually the cycloconverter is required to deliver a three phase output from a three phase input. A three phase to three phase system could be made using the developed three, three phase-to-single phase controllers with appropriate phase synchroisation.

The experience gained from the present exercise indicates that for successful development of the cycloconverter drive it is highly desirable that all power switching devices (thyristors) be identical.

The apporach adopted for the generation of firing commands can be extended for :

1. A cycloconverter with higher pulse number and
2. For a six pulse three phase cycloconverter.

As for as excecution time is concerned 8-bit processor is slow, better results can be obtained with the help of higher order processor and multiprocessor system.

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APPENDIX

Firing Delays to get one cycle of output

Output Frequency = Input frequency / 3, m = 1/3

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
Count. Low	F4	A5	01
Count. High	16	23	01
	78	1F	01
	17	23	01
	DE	B9	01
	18	21	01
	EB	AC	01
	1A	IF	01
	4A	9F	01
	1D	1D	01
	AC	4F	00
	1F	1B	00
	B9	8D	00
	21	19	00
	1F	27	00
	23	18	00
	28	3E	00
	23	17	00
	A5	F4	00
	23	16	00
	1F	78	00
	23	17	00
	B9	DE	00
	21	18	00
	AC	EB	00
	1F	1A	00

Output Frequency = Input frequency / 3, m = 1/3

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
9F	4A	00
1D	1D	00
4F	AC	01
1B	1F	01
8D	B9	01
19	21	01
27	1F	01
18	23	01
3E	28	01
17	23	01

Output Frequency = Input frequency / 4, m = 1/4

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
Count. Low	93	04	01
Count. High	18	22	01
	C5	DA	01
	18	21	01
	53	44	01
	19	21	01
	2C	6C	01
	1A	20	01
	40	59	01
	1B	1F	01
	7B	1C	01
	1C	1E	01
	C9	DF	00
	1D	1C	00
	0E	C4	00
	1F	1B	00
	31	B9	00
	20	1A	00
	18	D8	00
	21	19	00
	B9	29	00
	21	19	00
	FC	B5	00
	21	18	00
	04	93	00
	22	18	00
	DA	C5	00
	21	18	00

Output Frequency = Input frequency / 4, m = 1/4

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
44	53	00
21	19	00
6C	2C	00
20	1A	00
59	20	00
1F	1B	00
1C	7B	00
1E	1C	00
DF	C9	01
1C	1D	01
C4	0E	01
1B	1F	01
B9	31	01
1A	20	01
D8	18	01
19	21	01
29	B9	01
19	21	01
D5	FC	01
18	21	01

Output Frequency = Input frequency / 5, m = 1/5

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
Count. Low	8D	0A	01
Count. High	19	21	01
	9E	F9	01
	19	20	01
	E9	AE	01
	19	20	01
	55	42	01
	1A	20	01
	B1	B4	01
	1A	1F	01
	92	0F	01
	1B	1F	01
	52	46	01
	1C	1E	01
	F8	9F	01
	1C	1D	01
	F2	B6	00
	1D	1C	00
	BA	FE	00
	1E	1B	00
	72	58	00
	1F	1B	00
	10	B9	00
	20	1A	00
	8E	3C	00
	20	18	00
	E0	D8	00
	20	19	00
	0A	9E	00
	21	19	00

Output Frequency = Input frequency / 5, m = 1/5

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
0A	8D	00
21	19	00
F9	9E	00
20	19	00
AE	E9	00
20	19	00
42	55	00
20	19	00
B4	B1	00
1F	1A	00
05	92	00
1F	1B	00
46	52	00
1E	1C	00
9F	F8	00
1D	1C	00
B6	F2	01
1C	1D	01
FE	BA	01
1B	1E	01
58	72	01
1B	1F	01
B9	10	01
1A	20	01
3C	8D	01
1A	20	01
D8	E0	01
19	20	01
9E	0A	01
19	21	01

Output Frequency = Input frequency / 7,
m = 1/7

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
Count. Low	A0	F7	01
Count. High	18	1F	01
	A9	EF	01
	1A	1F	01
	C2	D5	01
	1A	1F	01
	E3	B4	01
	1A	1F	01
	1D	7A	01
	1B	1F	01
	60	37	01
	1B	1F	01
	AB	EC	01
	1B	1E	01
	07	90	01
	1C	1E	01
	62	35	01
	1C	1E	01
	C6	D1	01
	1C	1D	01
	2A	6D	01
	1D	1D	01
	96	04	00
	1D	1D	00
	FE	A1	00
	1D	1C	00
	5F	43	00
	1E	1C	00

Output Frequency = Input frequency / 7,
m = 1/7

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
BA	ED	00
1E	1B	00
0D	9A	00
1F	1B	00
57	50	00
1F	1B	00
93	15	00
1F	1B	00
C5	E3	00
1F	1A	00
E4	B6	00
1F	1A	00
F5	A8	00
1F	18	00
F7	A0	00
1F	18	00
EF	A9	00
1F	1A	00
D5	C2	00
1F	1A	00
B4	E3	00
1F	1A	00
7A	1D	00
1F	1B	00
37	60	00
1F	1B	00
EC	AB	00
1E	1B	00

Contd...

Output Frequency = Input frequency / 7,
m = 1/7

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
90	07	00
1E	1C	00
3F	62	00
1E	1C	00
D1	66	00
1D	1C	00
6D	2A	00
1D	1D	00
04	96	01
1D	1D	01
A1	FB	01
1C	1D	01
43	5F	01
1C	1E	01
ED	BA	01
1B	1E	01
9A	0D	01
1B	1F	01
50	57	01
1B	1F	01
1F	93	01
1B	1F	01
E3	C5	01
1A	1F	01
BC	E4	01
1A	1F	01
A8	F5	01
1A	1F	01

Output Frequency = Input frequency / 10, m = 1/10

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
Count. Low	60	37	01
Count. High	1B	1F	01
	68	2F	01
	1B	1F	01
	70	26	01
	1B	1F	01
	81	16	01
	1B	1F	01
	9A	FD	01
	1B	1E	01
	B3	E4	01
	1B	1E	01
	CC	CB	01
	1B	1E	01
	ED	A9	01
	1B	1E	01
	0F	88	01
	1C	1E	01
	38	5E	01
	1C	1E	01
	64	35	01
	1C	1E	01
	94	03	01
	1C	1E	01
	BE	D9	01
	1C	1D	01
	F0	A7	01
	1C	1D	01

Output Frequency = Input frequency / 10, m = 1/10

Table1 Converter 1	Table2 Converter 2	Table3 Ref.
22	75	01
1D	1D	01
54	43	00
1D	1D	00
8E	11	00
1D	1D	00
C0	DD	00
1D	1C	00
ED	AD	00
1D	1C	00
1C	83	00
1E	1C	00
48	58	00
1E	1C	00
71	30	00
1E	1C	00
99	06	00
1E	1C	00
BA	E5	00
1E	1B	00
DB	C4	00
1E	1B	00
F4	AB	00
1E	1B	00
08	95	00
1F	1B	00
18	81	00
1F	1B	00

Contd...

Output Frequency = Input frequency / 10, m = 1/10		
Table1 Converter 1	Table2 Converter 2	Table3 Ref.
24	79	00
1F	1B	00
29	70	00
1F	1B	00
37	60	00
1F	1B	00
2F	68	00
1F	1B	00
26	70	00
1F	1B	00
16	81	00
1F	1B	00
FD	9A	00
1E	1B	00
E4	B3	00
1E	1B	00
CB	CC	00
1E	1B	00
A9	ED	00
1E	1B	00
88	0F	00
1E	1C	00
5E	38	00
1E	1C	00
35	64	00
1E	1C	00
03	94	00
1E	1C	00

Output Frequency = Input frequency / 10, m = 1/10		
Table1 Converter 1	Table2 Converter 2	Table3 Ref.
D9	BE	00
1D	1C	00
A7	F0	00
1D	1C	00
75	22	00
1D	1D	00
43	54	01
1D	1D	01
11	8E	01
1D	1D	01
DD	C0	01
1C	1D	01
AD	ED	01
1C	1D	01
83	1C	01
1C	1E	01
5A	48	01
1C	1E	01
30	71	01
1C	1E	01
06	99	01
1C	1E	01
E5	BA	01
1B	1E	01
C4	DB	01
1B	1E	01
AB	F4	01
1B	1E	01

Contd...

Output Frequency = Input frequency / 10,
m = 1/10

	Table1 Converter 1	Table2 Converter 2	Table3 Ref.
	95	08	01
	1B	1F	01
	81	18	01
	1B	1F	01
	79	24	01
	1B	1F	01
	70	29	01
	1B	1F	01