DESIGN AND ANALYSIS OF A SINGLE PHASE DELTA MODULATED CYCLOCONVERTER

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Dated. 19.5.92 ....

Dedicated to My Parents

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Abstract

Cycloconverters are power converters used in the applications requiring a.c. to a.c. power conversion of variable frequency and magnitude. Usually these converters are used for large horse power a.c. motors, specially in the synchronous motor drives. Pulse width modulation (pwm) control is being used in these converters to reduce the size of input/output filters and to control output voltage and frequency. Pwm technique also reduces the low order harmonics of the output waveforms and thereby reduce the detrimental effects of harmonics on the applications, i.e., the harmonic losses, heating and torque pulsation in a.c. drives. The most common form of pwm technique used in power converters is the sine pwm technique. This technique has many advantageous features. Recently, computer implementation of various sine pwm techniques are becoming popular for static power converter controls, including the control of cycloconverters. One objection of sine pwm control is the tedious and difficult implementation procedure with constraints imposed by specific performance optimization. Such optimization invariably requires waveform synthesis by off-line mainframe computers and on-line microcomputer implementation. In the present thesis, an effort has been made to analyse and implement a delta modulation technique to control a single phase cycloconverter. One of the objectives of this work is to demonstrate the ability of this modulation technique to improve the performance of the cycloconverter on-line. Implementation of digital logic circuits for operating a cycloconverter has been built and tested successfully. Delta modulation provides equally good and in some respect better performance of the converter control compared with the sine pwm technique in the single phase cycloconverter application.

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List of Symbols

$A =$ slope of the estimated waveform in volts/second or volts/rad

$A_n =$ Fourier coefficients

$B_n =$ Fourier coefficients

$C_n =$ Fourier coefficients

$e(t) =$ error signal

$E_c =$ maximum magnitute of the carrier triangular wave

$E_r =$ maximum magnitude of the modulating wave

$e =$ modulating sine wave

$f =$ frequency in Hz

$f_c =$ frequency of the cycloconverter

$g(t, t_0, t_1) =$ gate function

$m =$ modulated signal

$N_p =$ number of pulses in half cycle

$sw_1 =$ switching function 1(one)

$sw_2 =$ switching function 2(two)

$T =$ period of the switching function sw_1. in sec.

$T_c =$ period of the cycloconverter in sec.

$u(t, t_o) =$ unit step function starting at t_o

$v =$ voltage in volts or in p.u.

$\Delta V =$ window width$involts$.

$v_i =$ input voltage in volts or in p.u.

$v_r =$ rectified voltage wave

$v_o =$ output voltage in volts or in p.u.

$v_R =$ maximum magnitude of ripple voltage

$v_l =$ lower envelope

$\omega = \frac{E_r}{E_c} =$ modulating index

$\omega_i =$ ith pulse position

$\omega_r =$ ripple frequney of the triangular wave

$\omega_s =$ frequency of the sine wave

$\omega_i =$ ith pulse position in radians

$\omega_1 =$ fundamental frequency

$\alpha =$ firing angle

$\delta_i =$ pulse width of ith pulse

$\theta_i =$ ith pulse mid position

$\Delta = \frac{\pi}{N} =$ distance between successive pulses

List of Abbreviations

AC = Alternating Current

BJT = Bipolar Junction Transistor

DC = Direct Current

DFT = Discrete Fourier transforms

DM = Delta Modulation

FET = Field effect transistor

FFT = Fast Fourier Transform

GTO = gate Turn off

MOSFET = Metal oxide Semiconductor FET

PWM = Pulse width modulation

RWDM = Rectangular wave delta modulation

SCR = Silicon controlled rectifier

SPWM = Sine pulse width modulation

VLSI = Very large scale integration

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CHAPTER - 1
INTRODUCTION

There has been significant advances in power electronics during the last few years. Several types of power converters are available which are mainly used for conversion of electrical energy from one form to a different form. The basic power converters are ac to ac voltage controllers, ac to dc controlled rectifiers, dc to ac inverters, dc to dc choppers, ac to ac voltage and frequency changers (Cycloconverters) and the switch mode power supplies. This research aims at the study of pulse width modultated cycloconverters which are usually used in applications which require direct frequency change at variable voltage. One of the main objective in this thesis is to investigate the possible use of delta modulation technique for the control of cycloconverters and the comparison of its performance with commonly used sine pulse width modulation (pwm) technique. In the recent past, Delta modulation technique (dm) has been successfully used for control of several other type of power converters like inverters, control rectifers and choppers. However, its application in the control of cycloconverters has not been carried out so far.

1.1 Introduction.

Cycloconverters are static power converters used for the transfer of energy from supply ac to ac of arbitrary frequency and voltage. Fig. 1.1(a) shows a single phase cycloconverter using two controlled rectifiers known as 'p' and 'n' converters. the function of the 'p' converter is to supply the load for certain time (half the period (T_c) of cycloconverter frequency). During 'p' converter operation the gating signals required for the switching devices of the converter are shown in Fig. 1.1(b). It is mentionable at this point that when the switching devices of the 'p' converter are turned ON and OFF, the switching devices of the 'n' converter are completely OFF (no gating signals are provided to the gates of the switching devices of this converter during this time interval). When half the period of the cycloconverter is over, all the 'p' converter switches are made completely OFF and 'n'

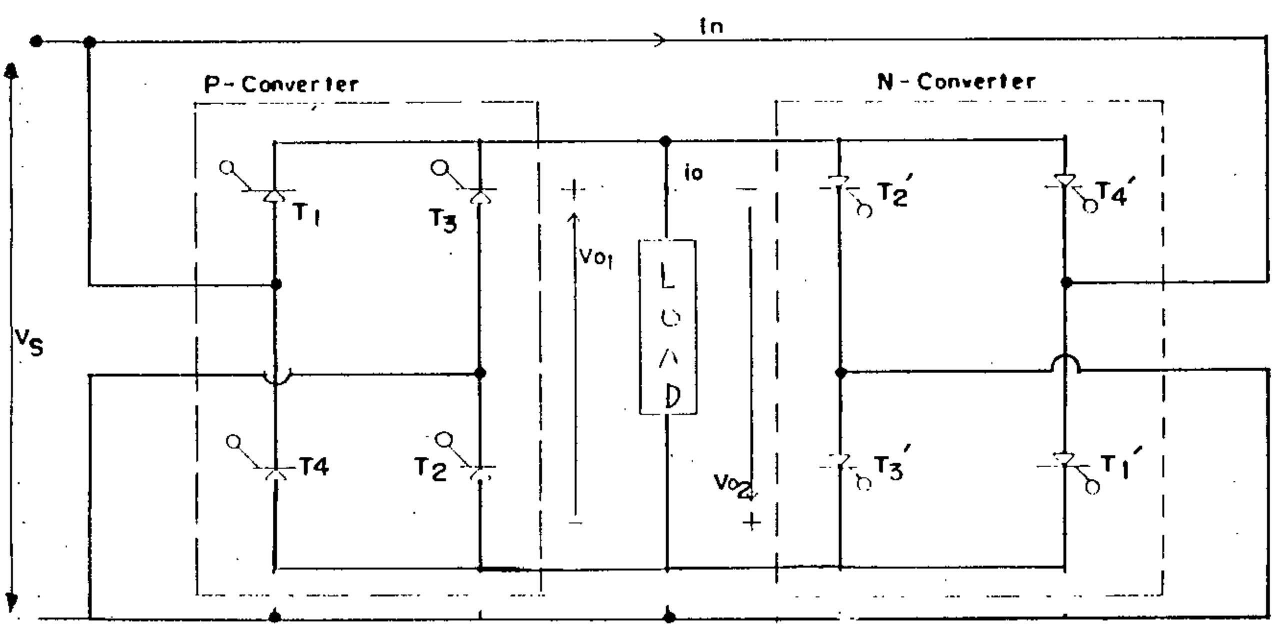


Fig:1.1(a) Basic single phase cycloconverter
(Fig 1.1(b) to 1.1(c) explains the operation of this converter)

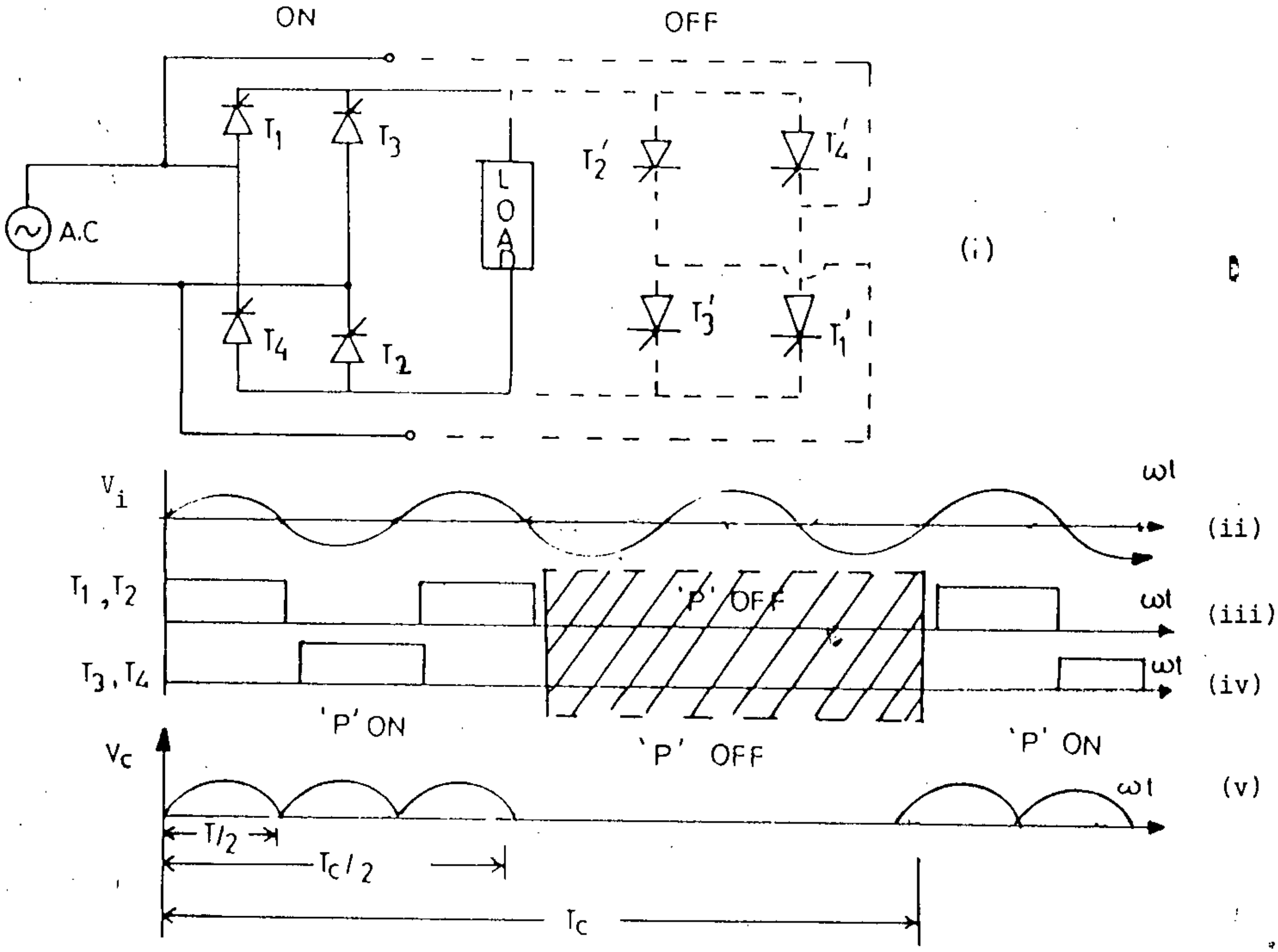


Fig: 1.1(b) operation of the 'p' converter while 'n' converter is OFF
i) 'p' converter ON, 'n' converter OFF
ii) input sine wave V_i
iii) gating signals of switch T_1&T_2 of 'p' converter
iv) gating signals of switch T_3&T_4 of 'p' converter
v) V_c cycloconverter output when 'p' converter is ON
T= period of supply sine wave
T_c= period of cycloconverter output

converter switches are activated by the gating signals as shown in Fig. 1.1(c). As a result negative voltage is applied to the load via 'n' converter. Hence, by alternate operation of the 'p' converter and 'n' converter, an a.c. of desired frequency can be obtained at the load side. The frequency of the cycloconverter is determined by the total duration of 'p' and 'n' converters ON OFF time. However, the average value of the converter's output is determined by the ON OFF time of the 'p' and 'n' converter switches during each half cycle of the supply voltage (of 50 cps as in the phase controlled cycloconverters). The gating signals of a phase controlled cycloconverter switches and the resultant output waveform of a phase controlled cycloconverter are shown in Fig. 1.2. This type of cycloconverters are naturally commutated. If force commutation technique is used, only one converter would perform the same job. Cycloconverters for polyphase are also in use for frequency changing purpose. Their main use is in adjustable speed drives. In non drive systems their use is very limited. Since the maximum output frequency of these converters are limited to the supply frequency (in naturally commulated converters) they are usually used in drive systems requiring frequency variation from 0 to the frequency of the supply voltage. In other words they are used in slow speed drive systems [1].

Various types of cycloconverter circuits have been developed so far. The variations were introduced by the requirements of load and cost effectiveness of the cycloconverters. In most of these converters, as mentioned earlier, it is necessary to control output voltage and frequency [27,28]. Since the output voltage and the input current of these converters, like any other static converter waveforms are nonsiousoidal, harmonic reduction schems are also desired. It has been the efforts of researchers to reduce the requirement of output/input filter requirements and improve the converter waveforms by various control strategies through a number of modulation techniques. Also the power circuits are also undergoing various modifications with the advent of different improved static devices. Usually SCRs precede all other static devices in the cycloconverter circuits because these converters are normally used in the high power drives requiring devices of high voltage and high current carrying capability. For medium and low power use converters with BJTs, GTOs, MOSFET and other static switches may be employed. However, such application has so far been nominal.

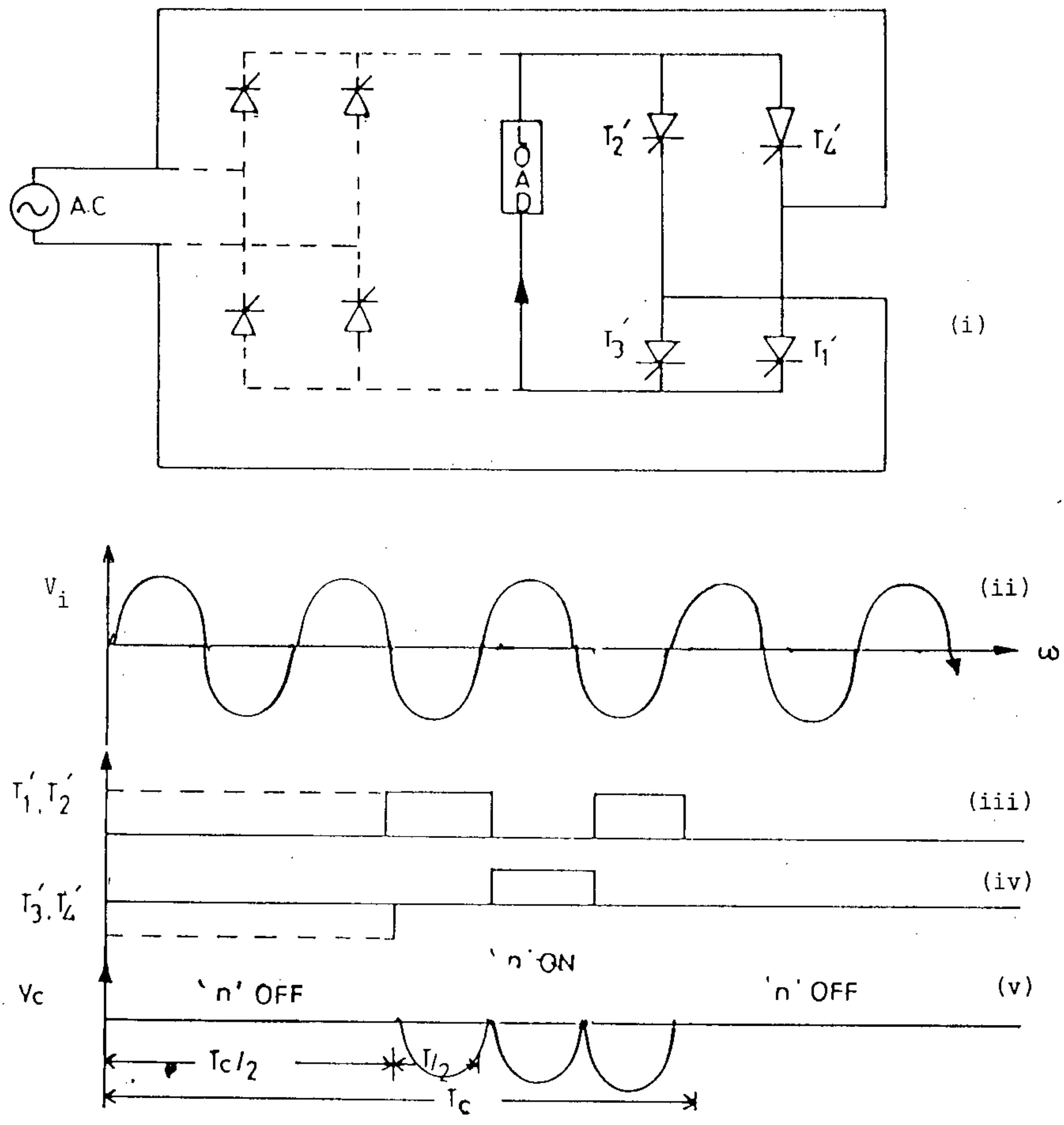


Fig: 1.1(c) operation of the 'n'n converter while 'p' converter is OFF

i) 'n' converter ON, 'p' converter OFF

ii) input sine wave V_i

iii) gating signals of switch T_1&T_2 of 'n' converter

iv) gating signals of switch T_3&$T_4$of 'p' converter

v) v_c-cycloconverter output when 'n' converter is ON

T= period of supply sinewave

T_c= period of cycloconverter output

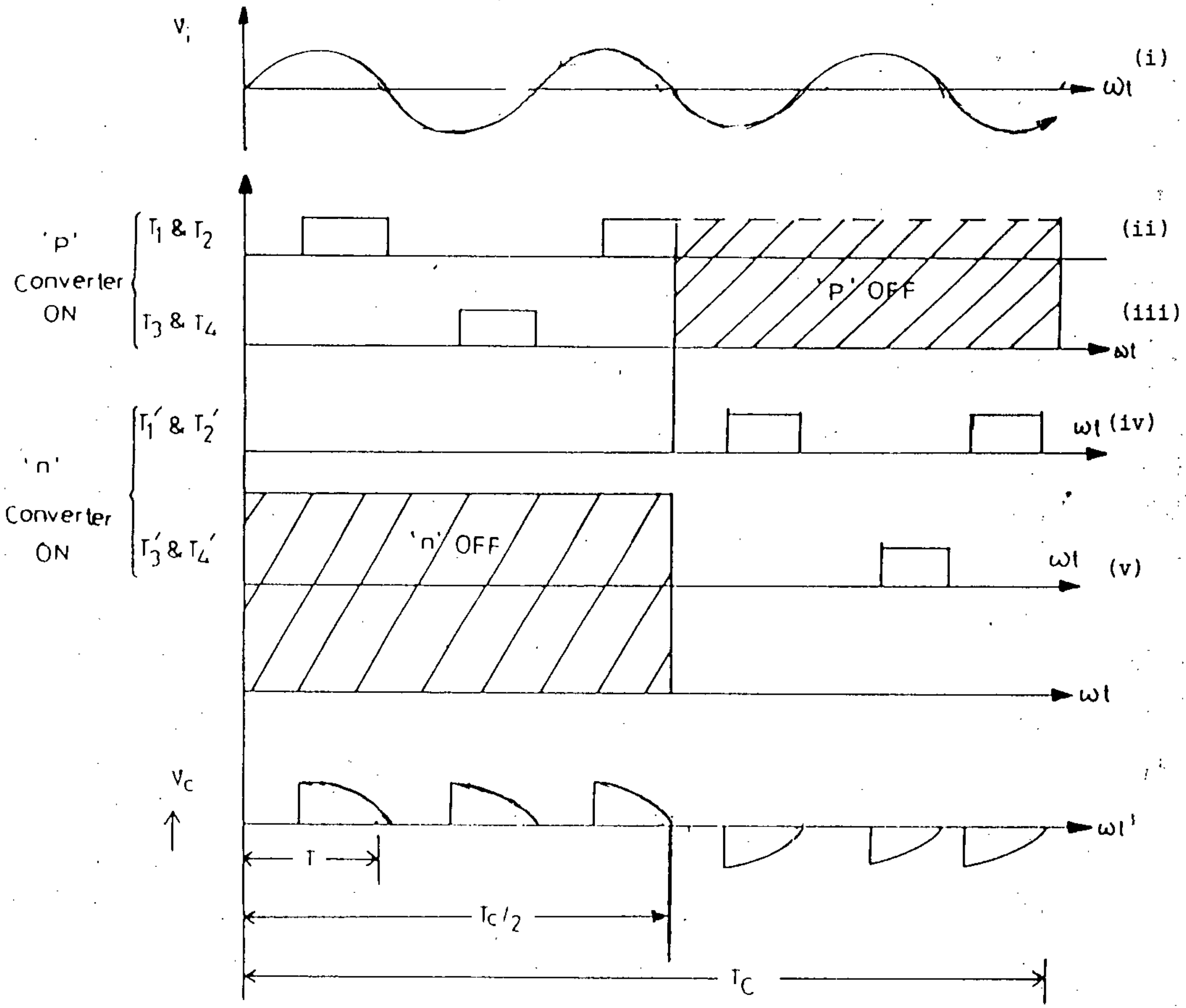


Fig: 1.2 Typical supply and the output waveforms of a single phase cycloconverter

i) input sine wave V_i
ii) gating signals of T_1&T_2 of 'p' converter
iii) gating signals of T_3&T_4 of 'p' converter
iv) gating signals of T_1'&T_2' of 'n' converter
v) gating signals of T_3'&T_4' of 'n'converter
T_c= period of the cycloconverter output
T= period of the input sinusoid.

The objectives of this research as mentioned is to investigate the possible use of delta modulation technique in the operation of a single phase cycloconverter and to compare the performance in terms of control and harmonic elimination with commonly used pulse width modulated (pwm) cycloconverters.

1.2 Pulse Width Modulated Cycloconverters.

Normal cycloconverters have the inconvenience of having output waveforms containing considerable amount of low order harmonics. They also need double power conversion or dual converter systems for simultaneous voltage and frquency control. These problems of normal cycloconverters can be reduced by incorporating pulse width modulation for the control purpose.

The objectives of typical cycloconveters disappear if the cycloconverter is supplied by a controlled rectifier and a forced commutated inverter operated at very high frequencies so as to chop the input for double purpose of voltage control and low order harmomic elimination [Fig 1.3]. Also the modulation process can be performed prior to the inverter as well [Fig.1.4] using a pwm switch. The operation of the converter of Fig. 1.3(a) is illustrated in Fig. 1.3(b) and 1.3(c), whereas the operation of converter of Fig. 1.4(a) is illustrated in Fig. 1.4(b) and 1.4(c) respectively.

Pulse width modulation (pwm) makes use of cycloconveter circuitry to permit variation of the ratio between input and output voltage of the converter. Pulse width modulation though being used in almost every static converter schemes these days, its earlier developements began with the control of inverter input/output. In an inverter pulse width modulation technique accomplishes both voltage and frequency regulation which otherwise needs dual converter schemes. In power inverter control the inverter section is arranged to switch the dc in such a manner that output line voltage consists of a series of pulses. Pulses are arranged in such a manner that the average output voltage leads to a sine wave. This technique is the most recent and involved process as used in static variable frequency drives. Three most commonly used modulation techniques in power schemes are [6].

1. Single pulse modulation
2. Multiple pulse modulation and

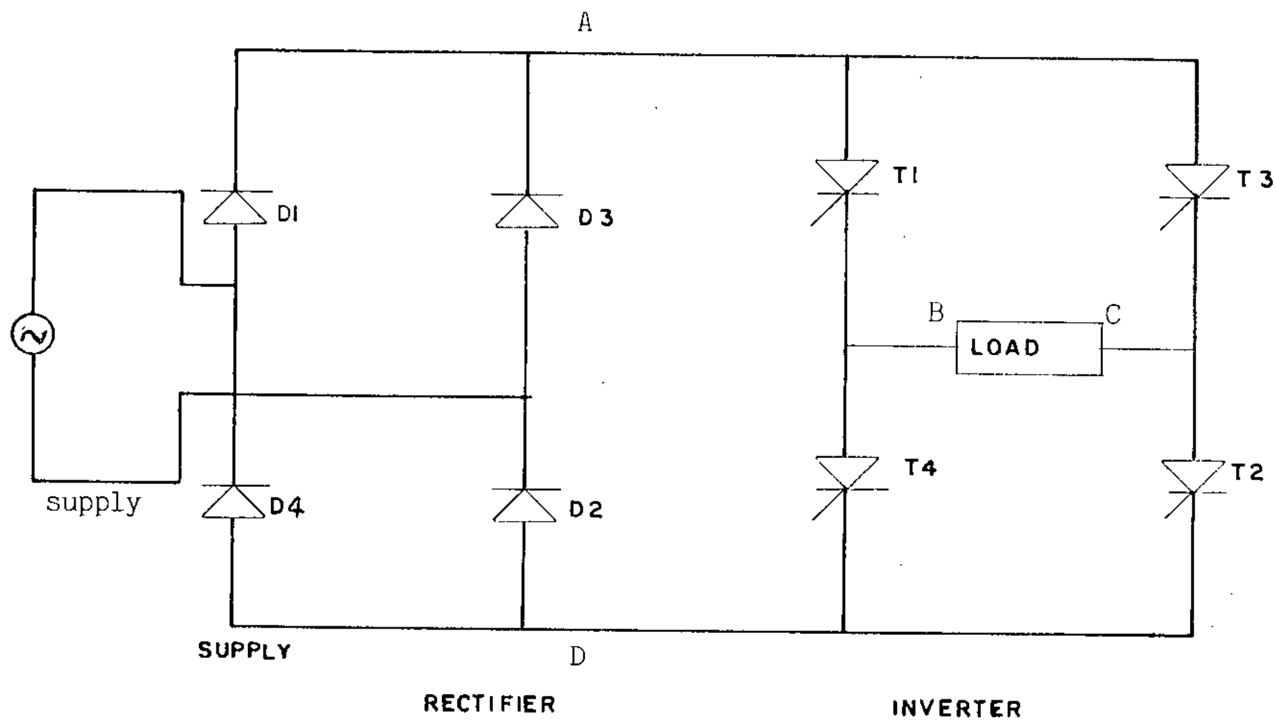


Fig:1.3(a) A cycloconverter with an uncontrolled rectifier and a forced commutated inverter. (operation of the circuit is explained in Fig 1.3(b) to 1.3(c))

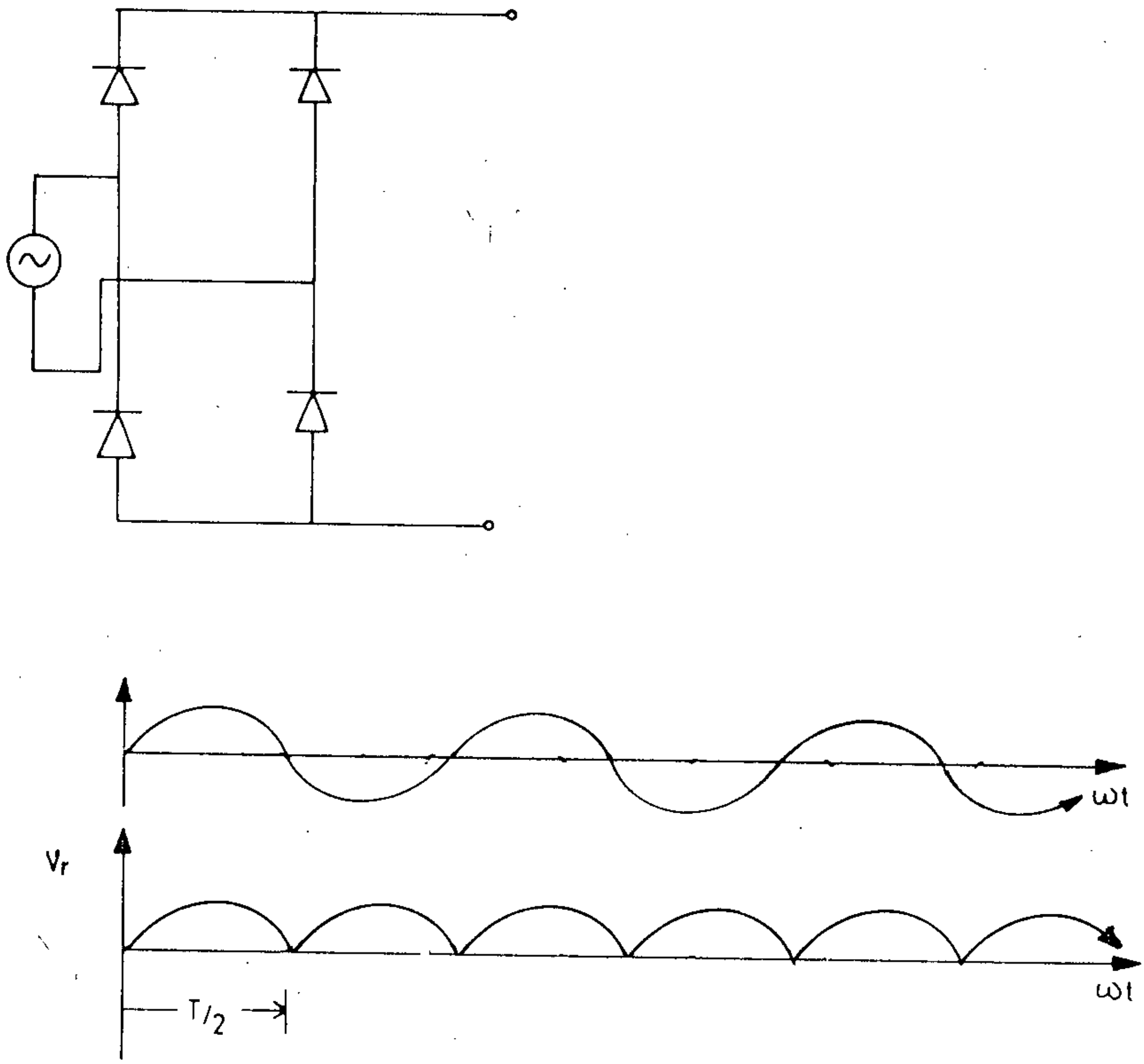


Fig: 1.3(b) The rectifier circuit of 1.3(a) and its output.
v_r= rectified output

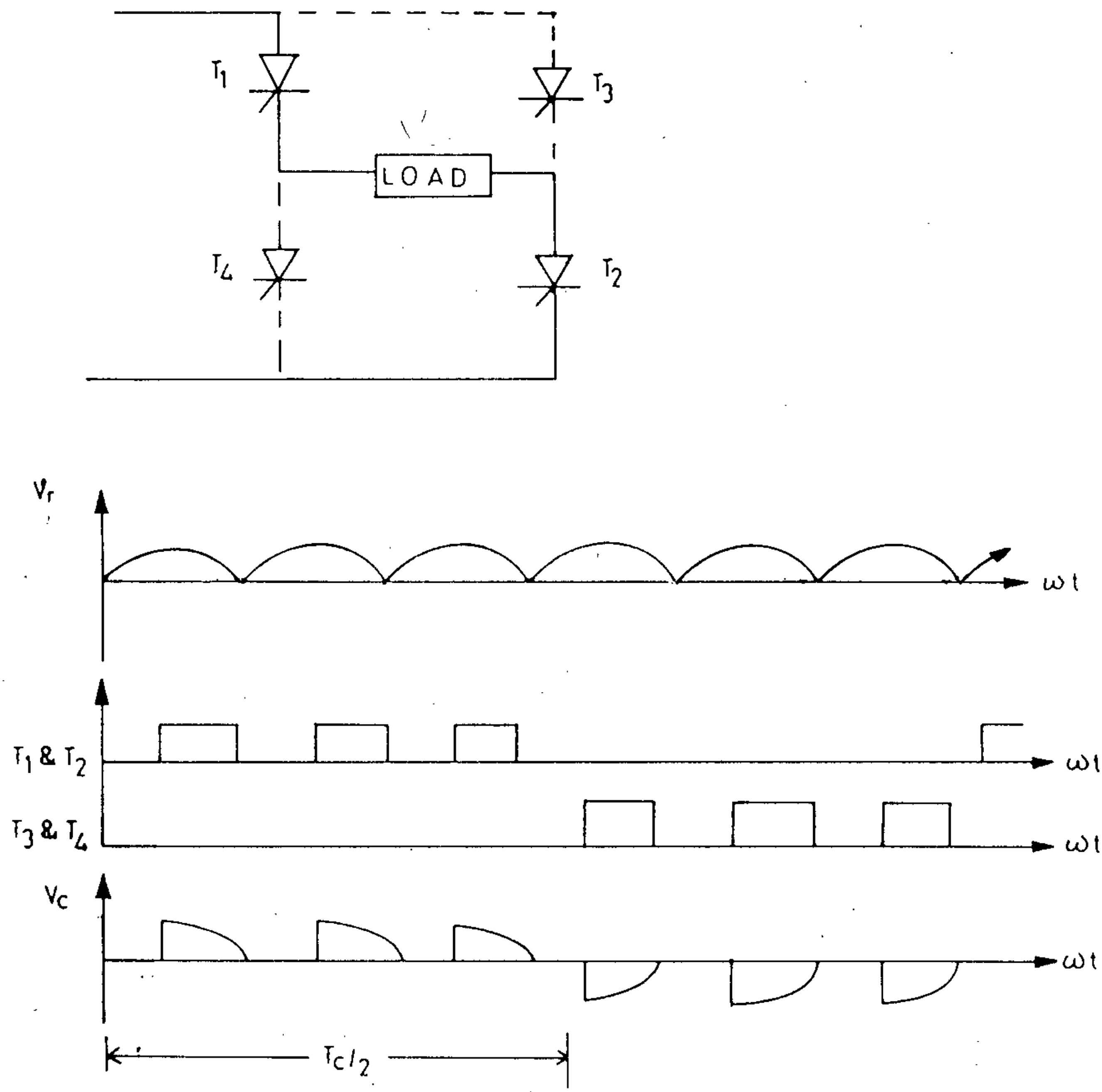


Fig: 1.3(c) input to the inverter part of the cycloconverter of Fig 1.3(a) and the corresponding output for gating signals as shown.

T_1&T_2 are gating signals of switches T_1&T_2

T_3&T_4 are gating signals of switches T_3&T_4

V_c cycloconverter output

$T_{c/2}$ half the period of cycloconverter wave form

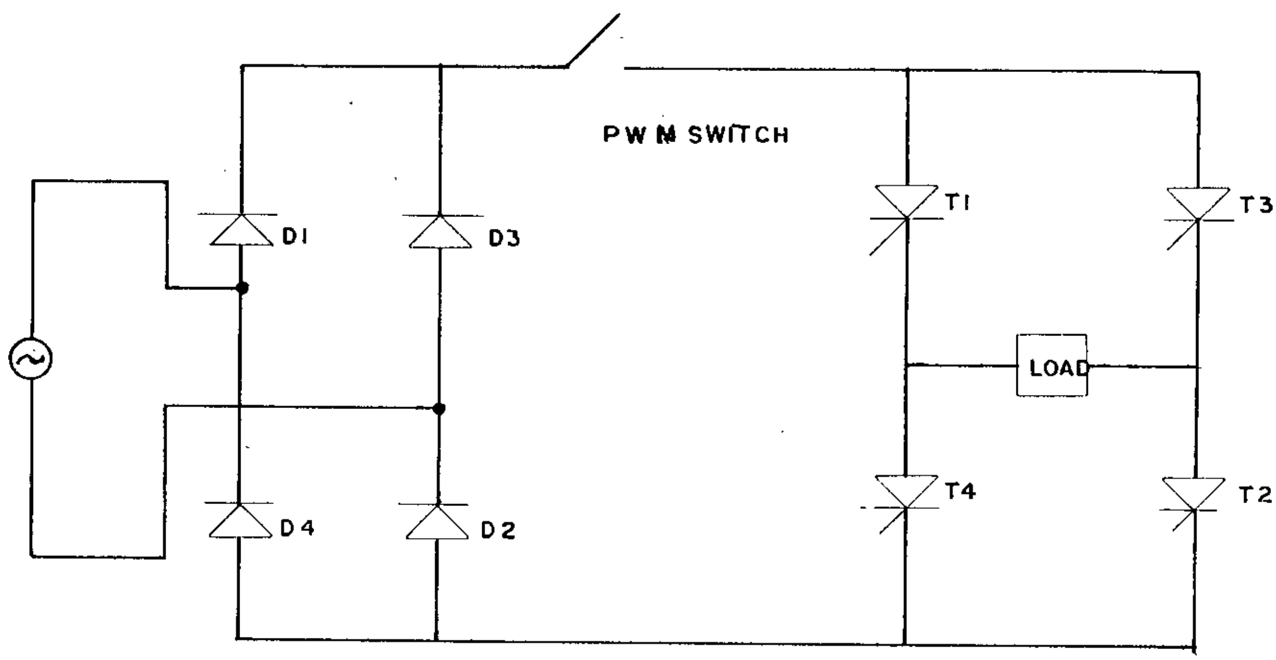


Fig: 1.4(a) Cycloconverter with a pwm switch.
(the operation is explained in Figs
1.4(b) and 1.4(c))

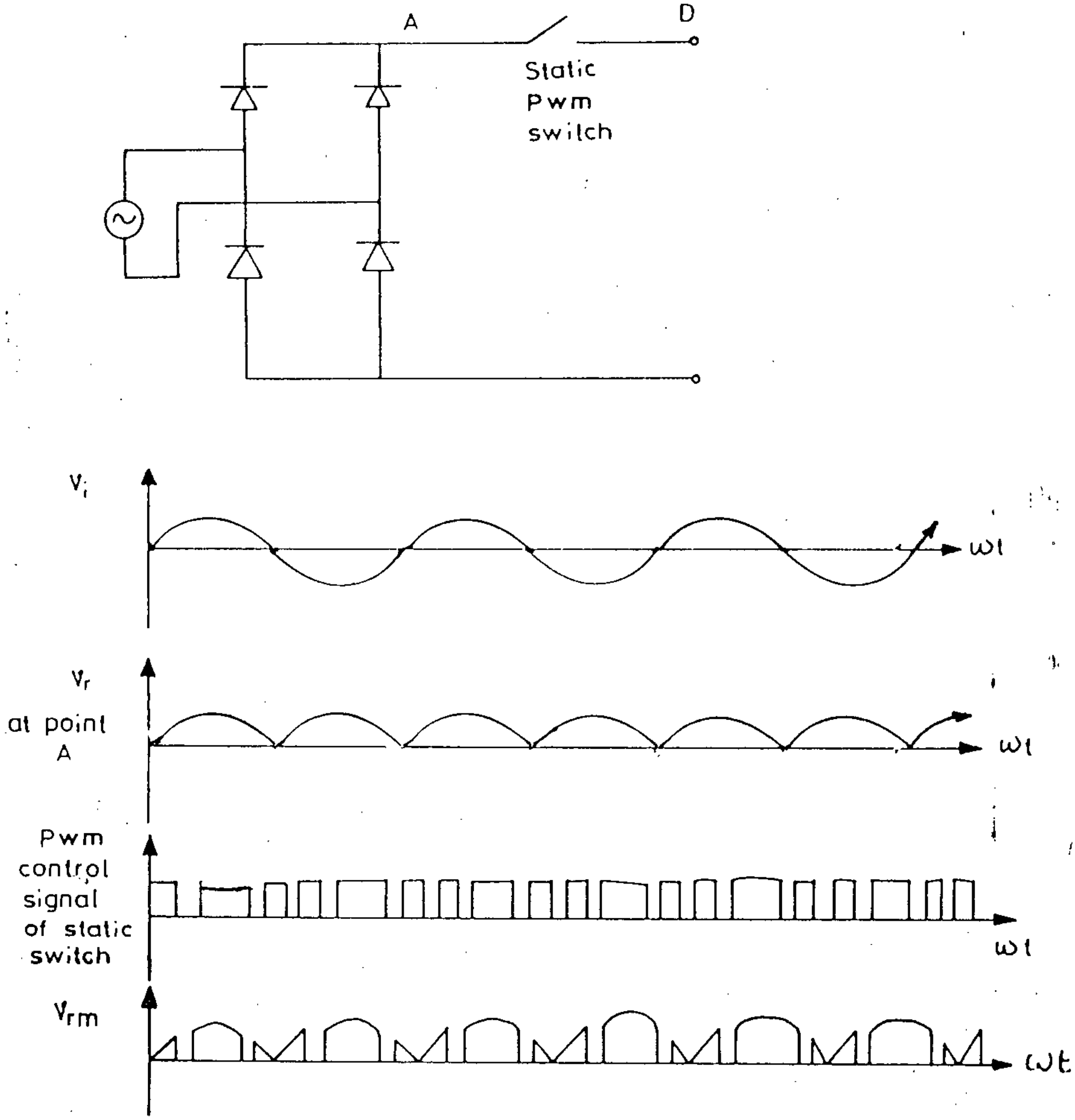
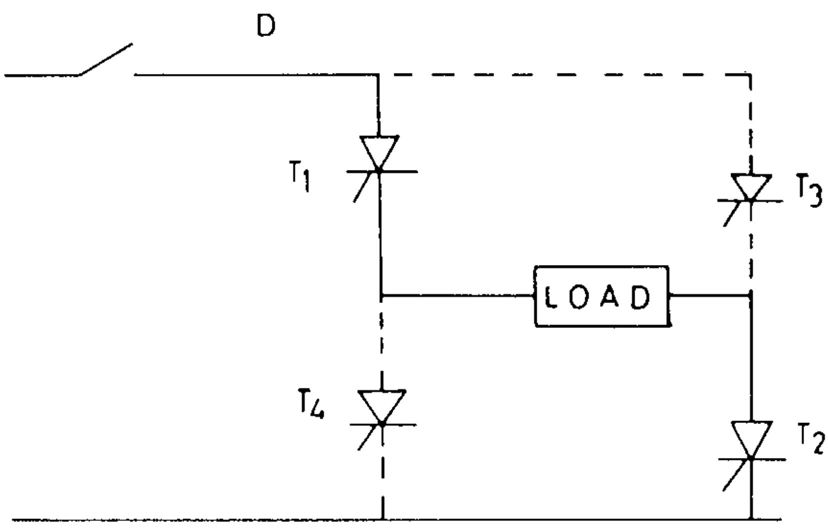


Fig: 1.4(b) The rectifier and pwm switch of the cycloconverter of Fig. 1.4

v_i input sine wave

v_r rectifier output

v_{rm} rectified pwm wave at point D



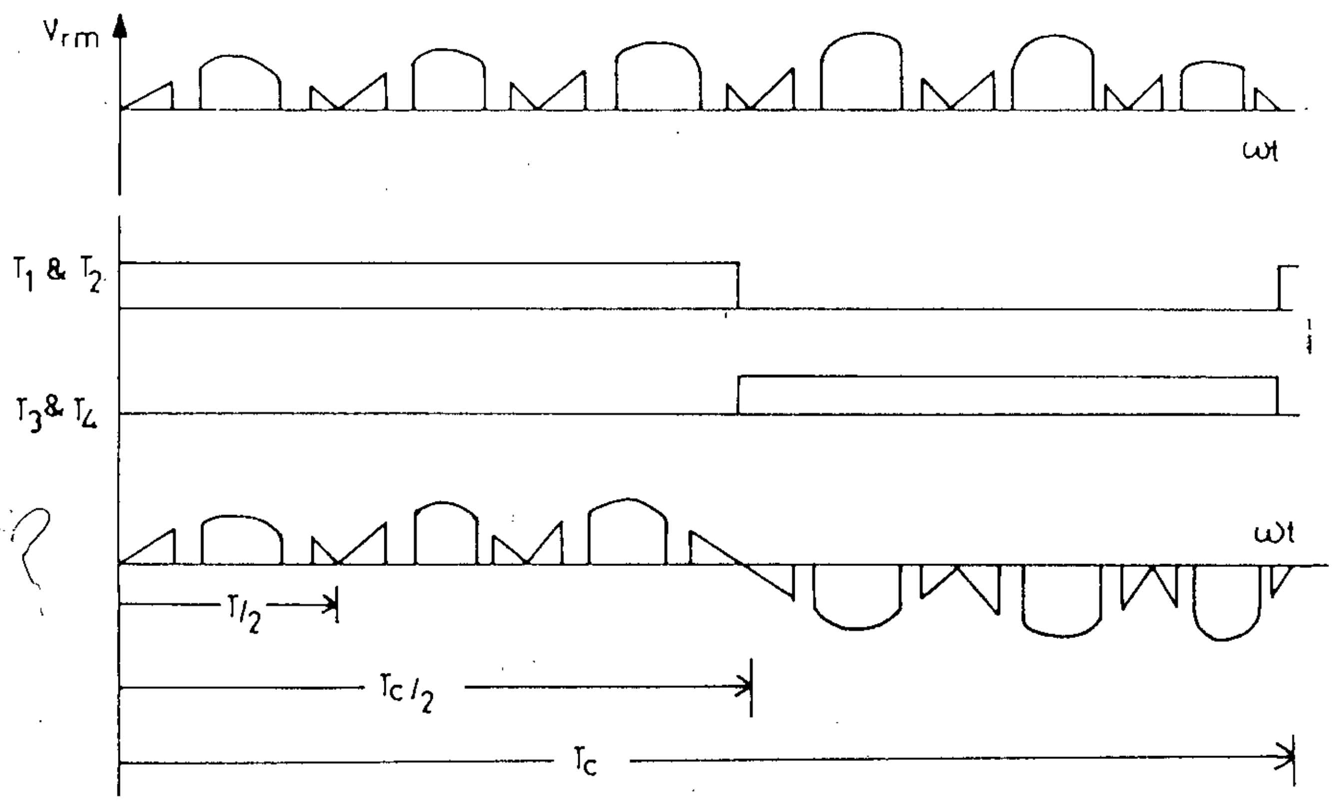


Fig: 1.4(c) The inverter operation of the cycloconverter of Fig 1.4

v_{rm} rectified input at point D of the inverter

T_1&T_2 gating signals of switching devices T_1&T_2

T_3&T_4 gating signals of switching devices T_3&T_4

3. Sinusoidal pulse width modulation

Among the three modulation processes ((Fig 1.5(a), 1.5(b), 1.5(c))used in converter control,the sine pulse width modulation Fig 1.5(c) technique is the most versatile one. In this method the switching waveform's pulse widths are sinusoidal function of each cycle. Good performance of this modulation technique depends precisely on the capability of the electronic control circuitry to define accurately the switching instants of the power converters in order to cause the output of the controller to be a train of pulses with a time average that approximates a sinusoid. Such control signal generation was introduced by the comparison of triangular wave known as carrier wave with the sinusoidal wave called modulating wave.

1.2.1 Brief Survey of PWM Technique [5].

The earliest modulation techniques for the control of power converters were the single pulse and multiple pulse modulation [2,3,4,5]. Eventually sinusoidal pulse width modulation superseeded these modulation technique in the control of power converters [4,7]. The first sine modulation technique used in power converters was the asynchronous spwm [8]. This method was problematic in maintaining integer ratio between modulating wave and carrier frequency which used to result in unwanted subharmonics at the output voltages of the converters.The problem was solved by synchronous spwm technique. However, several other problems were faced in this method [8,9,10]. With a view to overcome these problems, pulse width modulation with variable ratio scheme was introduced. In the variable ratio scheme, the carrier steps through a sequence of ratios as the operating frequency of the converter is increased.Currently three distint approaches are in use to formulate the pwm switching strategy [11,12,13]. These are,

a. Natural sampling technique [4,11]

b. Regular sampling technique [11,12,13,15]

c. Optimal switching strategy [16,17,18]

Detail descriptions of these modulation techniques and their advantages and disadvantages are given in the references.

Along with the implementation of various modulation techniques, the analysis of different converter waveforms have also been carried out from time to time. Attention has been

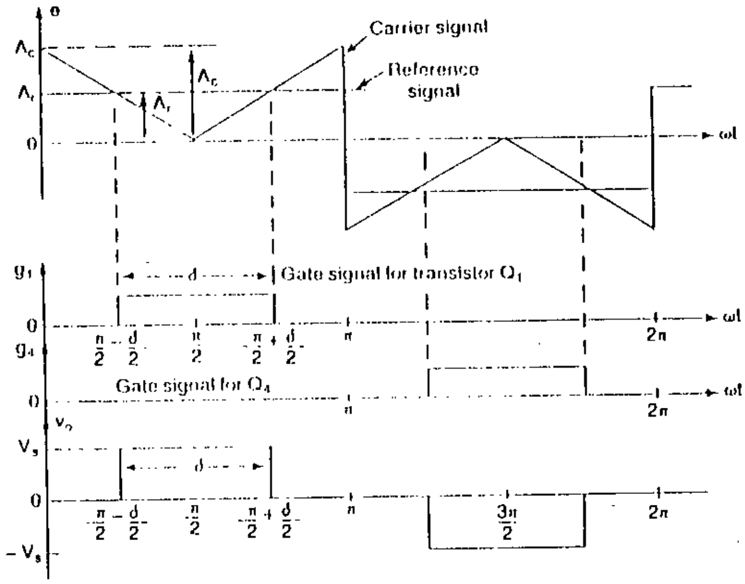


Fig: 1.5(a) Single pulse width modulation

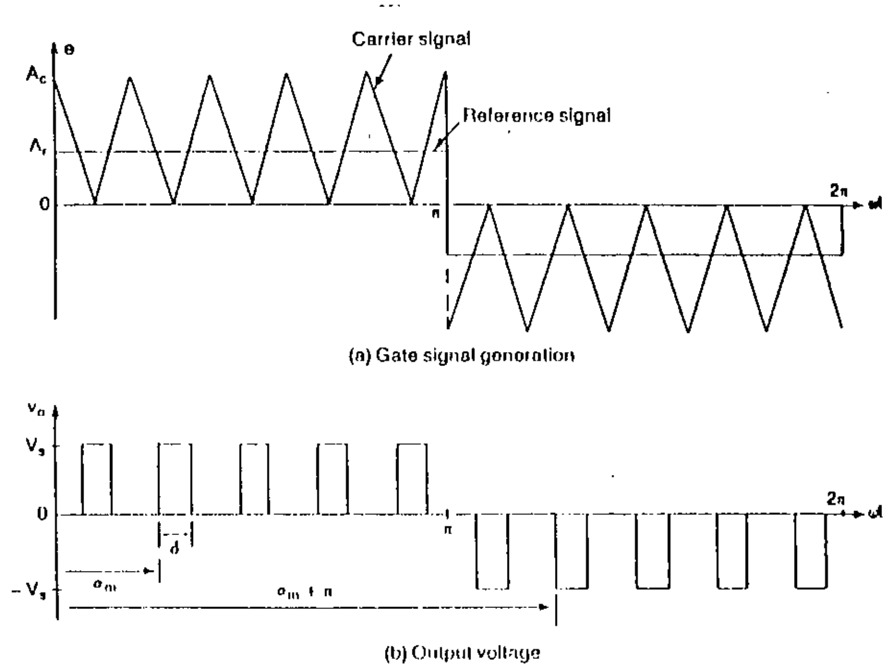


Fig: 1.5(b) Multiple pulse width modulation

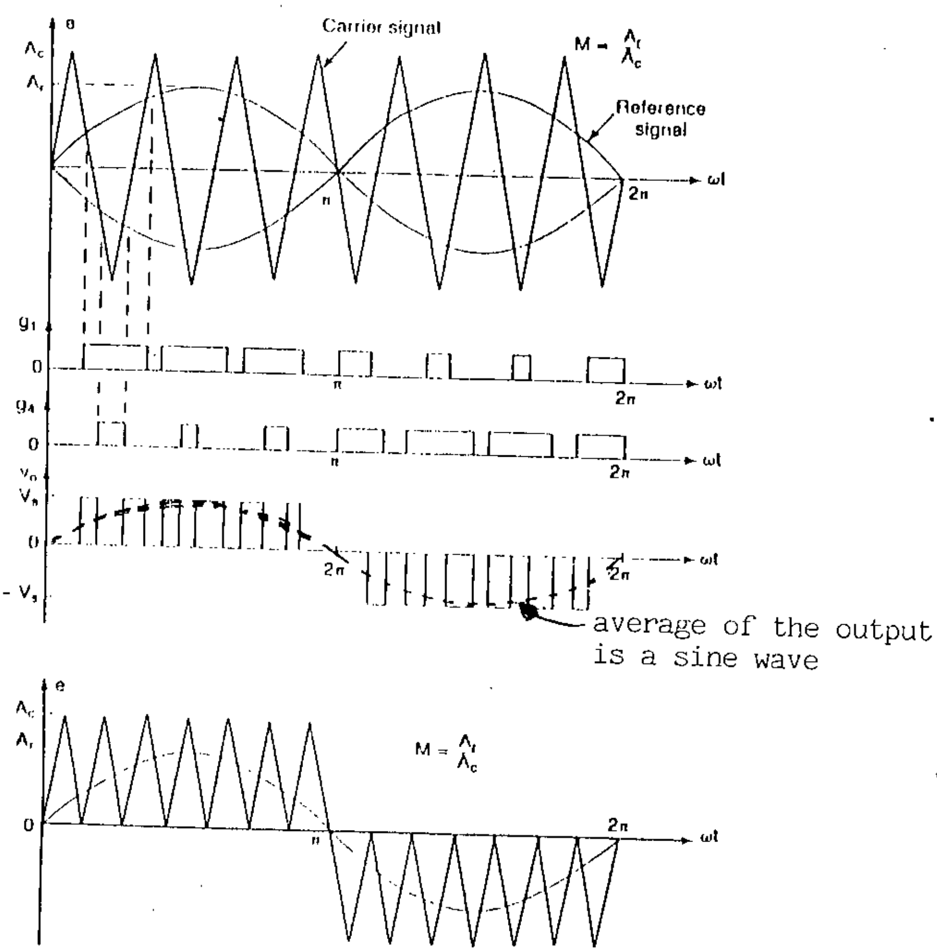


Fig: 1.5(c) Sinusoidal pulse width modulation focused mainly on the analysis of the output voltage and the input current. The usual method is to use Fourier series analysis [13,19,20]. Presently the harmonic determination of waveforms can also be carried out by available package programs which use discrete Fourier transform in analyzing nonsinusoidal waveforms. The analytical approach is drawing more attention due to the fact that the implementation of different modulation techniques, especially the optimum pwm require mathematical formulation of software developments for their implementation.

1.2.2. Delta modulation technique [21].

Delta modulation (dm) is one of the most simple technique of modulation of analog signals. In last few years its possible use in the control of vaious power converters like inverters and controlled rectifiers have been reported [16,21].This scheme is simple and easy to implement and has versatile controllability. Delta modulation is one form of asynchronous pulse width modulation. In the use of inverters and controlled rectifiers the properties of modulation circuit have been successfully used to obtain output waveform of low order harmonics and with fundamental voltage variation as required by the applications. As for examaple for inverter drive system the fundamental voltage variation with V/f= constant (i.e. the ratio of the fundamental voltage to inverter operating frequency = constant) was obtained without additional control circuitry.

Constant research in the possible use of delta modulation for controlling inverters in induction motor drive also focussed on the modulators capability of on-line waveform sysnthesis. This on-line waveform sysnthesis makes use of the modulator's filter and quantizer properties to achieve near optimum output waveforms which were previously obtained only by the complex computer implementation of involved mathematical procedures [22,23].It has been shown that implementation of dm controller either by analog circuits or by microprocessors are simpler than conventional pwm techniques [22,23].

The block diagram of a basic dm is shown in Fig.1.6. The components of this modulator are a quantizer, comparator and a low pass filter. For a single phase cycloconverter operation. the input to the modulator is a rectified sine wave and the output is the modulated wave. The integrator performs the signal estimation by integrating the output signal which is then compared with the input signal of the modulator to produce an error signal. The error signal is quantized by the qunatizer to produce the required modulated signal to turn ON/OFF the cycloconverters output waveform. Fig. 1.7 is a variation of the dm of Fig. 1.6. In the new circuit the quantizer is replaced by the hysteresis qunatizer and this type of modulator is known as rectangular wave delta modulator (rwdm). In the rwdm the hysteresis qunatizer limits the excursion of the error signal within a hysteresis band or a window. Such a limit provides useful hysteresis current control for inductively loaded inverters. In the past, simple techniques have also been proposed for harmonic reduction of pwm converter waveforms using dm [22,23]. In Fig.1.8 and Fig. 1.9 the block diagrams of tuned dm and variable step dm used for such purposes are shown. The integrator circuit generally used in the feeback circuit of the delta modulator is shown in Fig. 1.8(a). The integrator is a low pass filter and has the following transfer function,

$$\frac{e_o(s)}{e_i(s)} = \frac{k}{\tau s + 1} \tag{1.1}$$

where.k is the gain of the filter and τ is the time constant. $e_o(s)$ and $e_i(s)$ are the output and input signal of the integrator in frequency domain. In the tuned delta modulator this fixed cutoff frequency integrator is replaced by a tuned filter. The tuned filter is a combination of a linear analog multiplier and an integrator. The tuned integrator has the transfer function.

$$\frac{e_o(s)}{e_i(s)} = \frac{k}{\frac{10\tau}{E_c} s + 1} \tag{1.2}$$

where, the time constant is now $\frac{10\tau}{E_c}$ and $E_c$is a d.c command signal and the the time constant (i.e. the slope) is dependent on E_c. Hence, the time constant or the slope of such integrator can be made voltage controlled. In the case of converter control, the frequency control signal can also be used in changing the slope of the integrator in this manner. In the case of variable step delta modulator a voltage controlled reistance can be used for changing the hysteresis loop of the quantier. Fig. 1.10 shows a block diagram of a variable step tuned dm which incorporates the advantageous features of both the modulators in one. In such

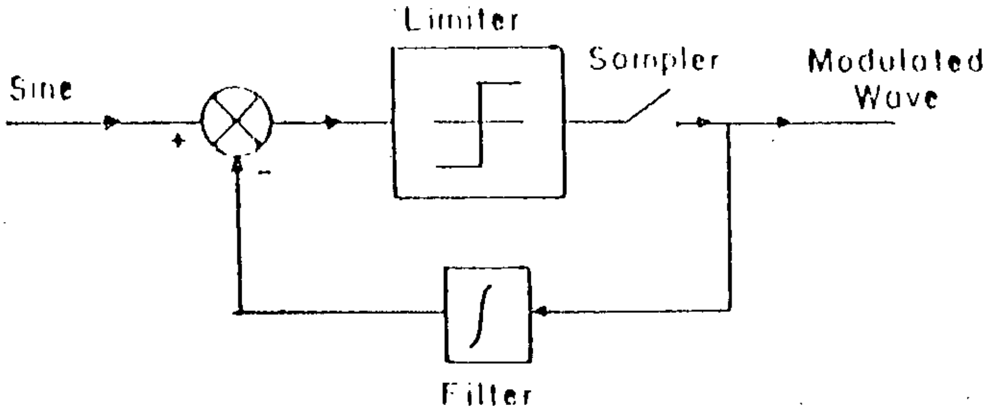


Fig: 1.6 The bolck diagram of a simple delta modulator

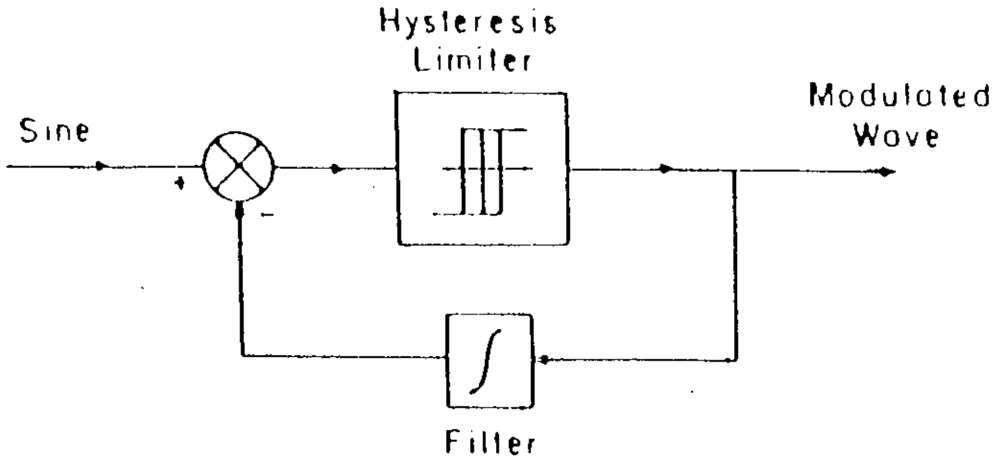


Fig: 1.7 The block diagram of a rectangular wave delta modulator

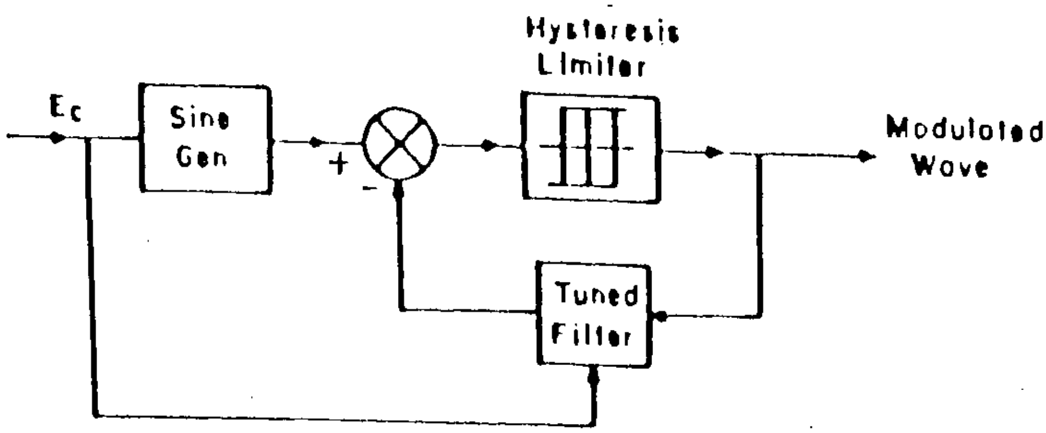
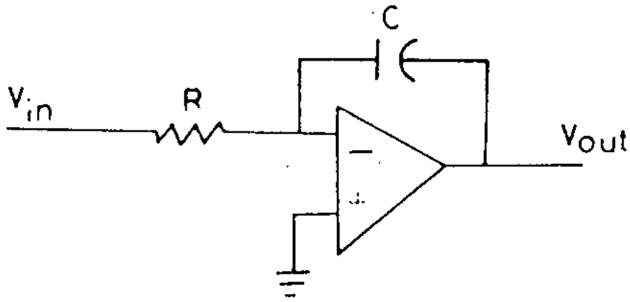
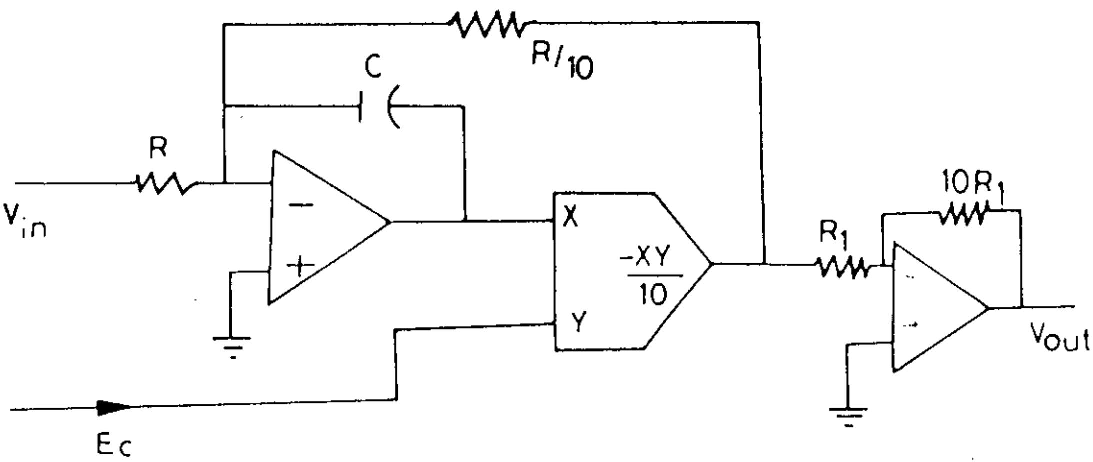


Fig: 1.8 The block diagram of a tuned rectangular wave delta modulator.



(a) Simple integrator Filter



(b) Tuned filter, tunable with signals E_c

Fig. 1.8 b: The filter part of the tuned delta modulator
a) ordanary integrator filter
b) the tuned filter using multiplier chip(XR2208) or AD538

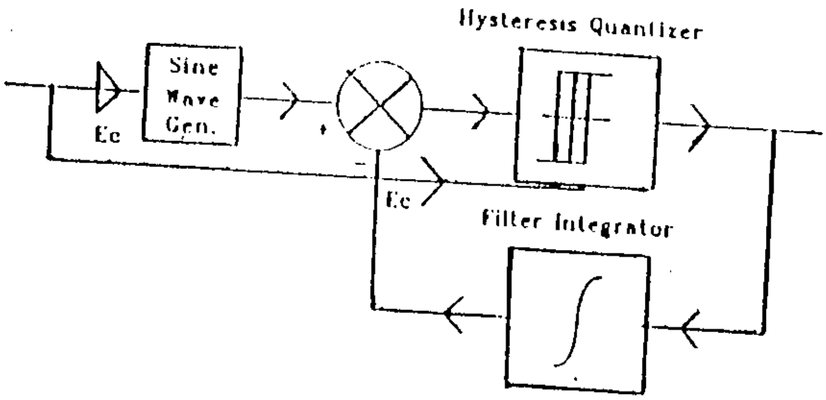


Fig. 1.9 Block diagram of a variable step dm

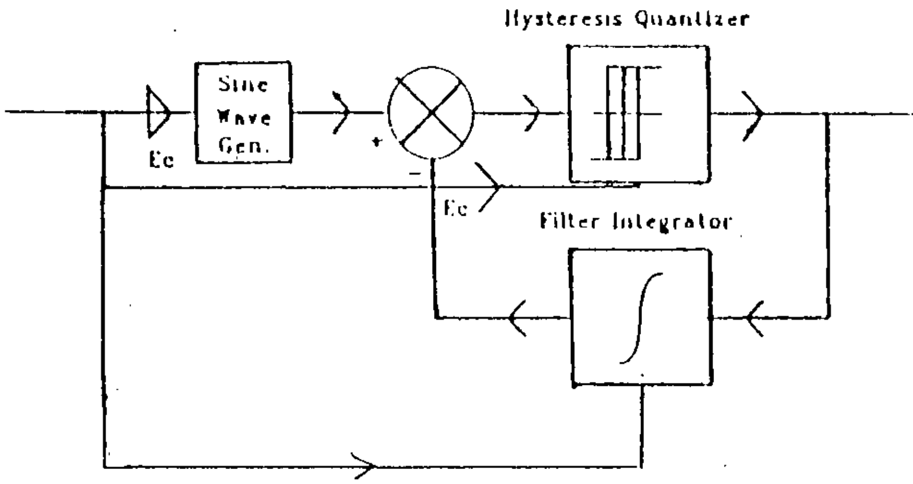


Fig: 1.10 Block diagram of a tuned variable step rectengular wave delta modulator

modulator's either the variation of slope (to a smaller value) or the variation of the step or window size (to a smaller size) would result in a better tracking of input signal and hence result in the harmonic reduction of the output waveform. Typical output waveforms of the cycloconverter for various conditions of the modulator are shown in Fig.1.11 to Fig. 1.14. The method of analysis and way to obtain these waveforms is described in later chapters. However, for a short outline the method can be described as follws.

In fig. 1.11(a), we have the input sine wave and a square wave of same frequency (known as the switching waveform sw_1). When these two waveforms are multiplied in time domain the rectified wave v_r of Fig. 1.11(b) results. In Fig. 1.11(b) another square wave of frequency that of the cycloconverter sw_2 is shown. When the waveforms v_r of Fig 1.11(b) is multiplied by sw_2 in time domain, we obtain the desired cycloconverter waveform v_c of Fig. 1.11(c). Fig. 1.11(d) is the spectrum of the waveform of Fig. 1.11(c) obtained by discrete Fourier transform.

1.3 Objective of the present work.

The analysis and design procedure for the application of delta modulation strategy in the control of cycloconverters is the main focus of this work. An attempt is being made to compare this modulation technique with the commonly used sine pulse width modulation technique in the control of cycloconveters. The study is the begining of investigation of dm's possible use in cycloconverters and hence involves the single phase cycloconveters as the starting point. The objective includes the analysis of dm cycloconveter and sine pwn cycloconverter waveforms using available softwares (to perform discrete Fourier transform (DFT)) and compare them. Attempt is being made to investigate the possible waveform synthesis in obtaining output waveforms with minimum low order harmonics and also to suggest a way of obtaining fundamental voltage variation such that ratio of fundamental voltage to the operating frequency of the cycloconverter (V/f = constant) as required by ac motors during variable frequency operation. Besides analytical investigation, objectives of research work also include the experimental verification of the results, specially a successful demonstration of dms control capability in the operation of a cycloconveter.

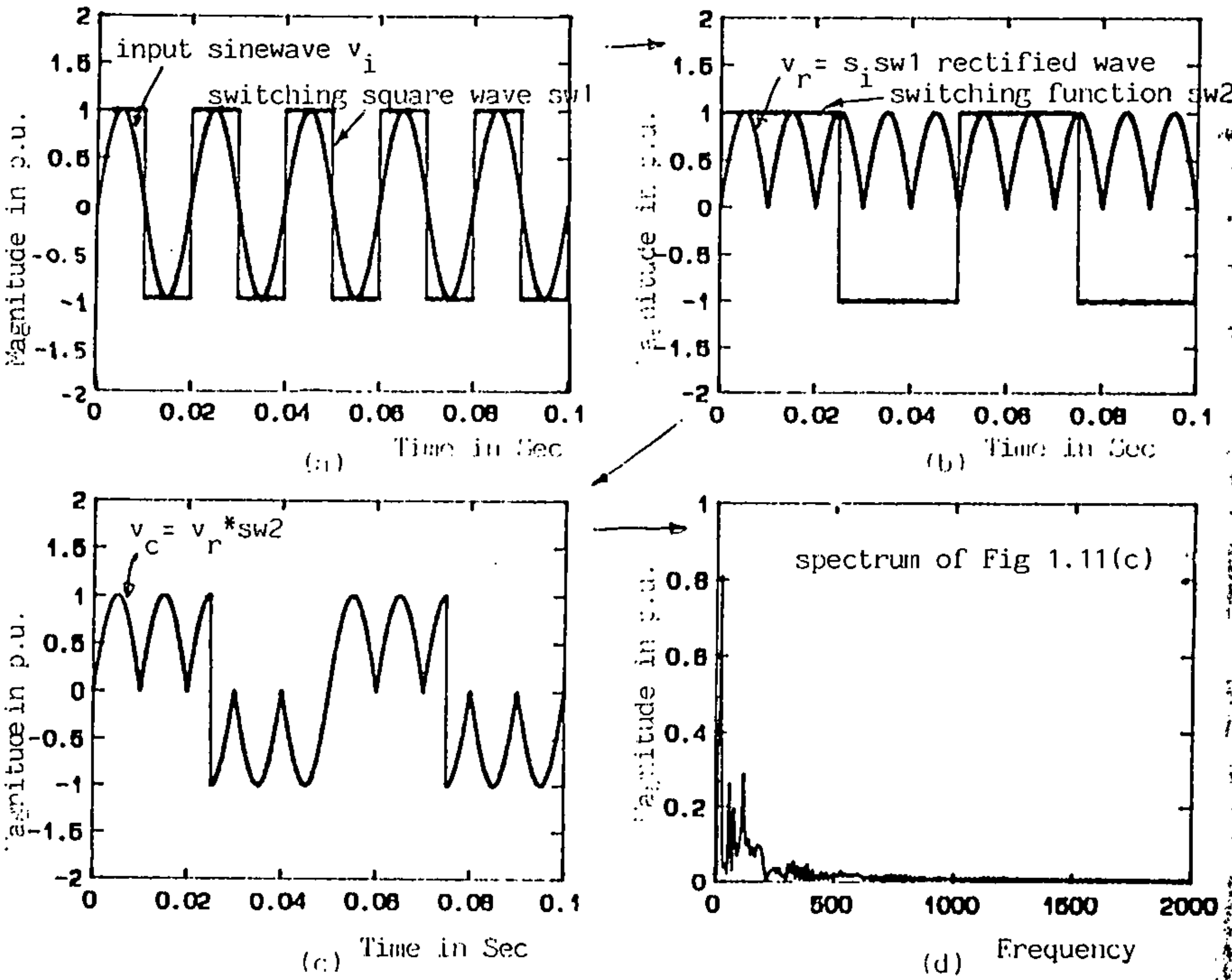


Fig: 1.11 Various waveforms of a 1-Ø cycloconverter and the output spectrum for $\alpha = 0$ where α = firing angle
a) Input sine wave and switching waveform sw1
b) Rectified sine wave and switching waveform sw2
c) Output of the cycloconverter
d) Spectrum of the waveform of (c)

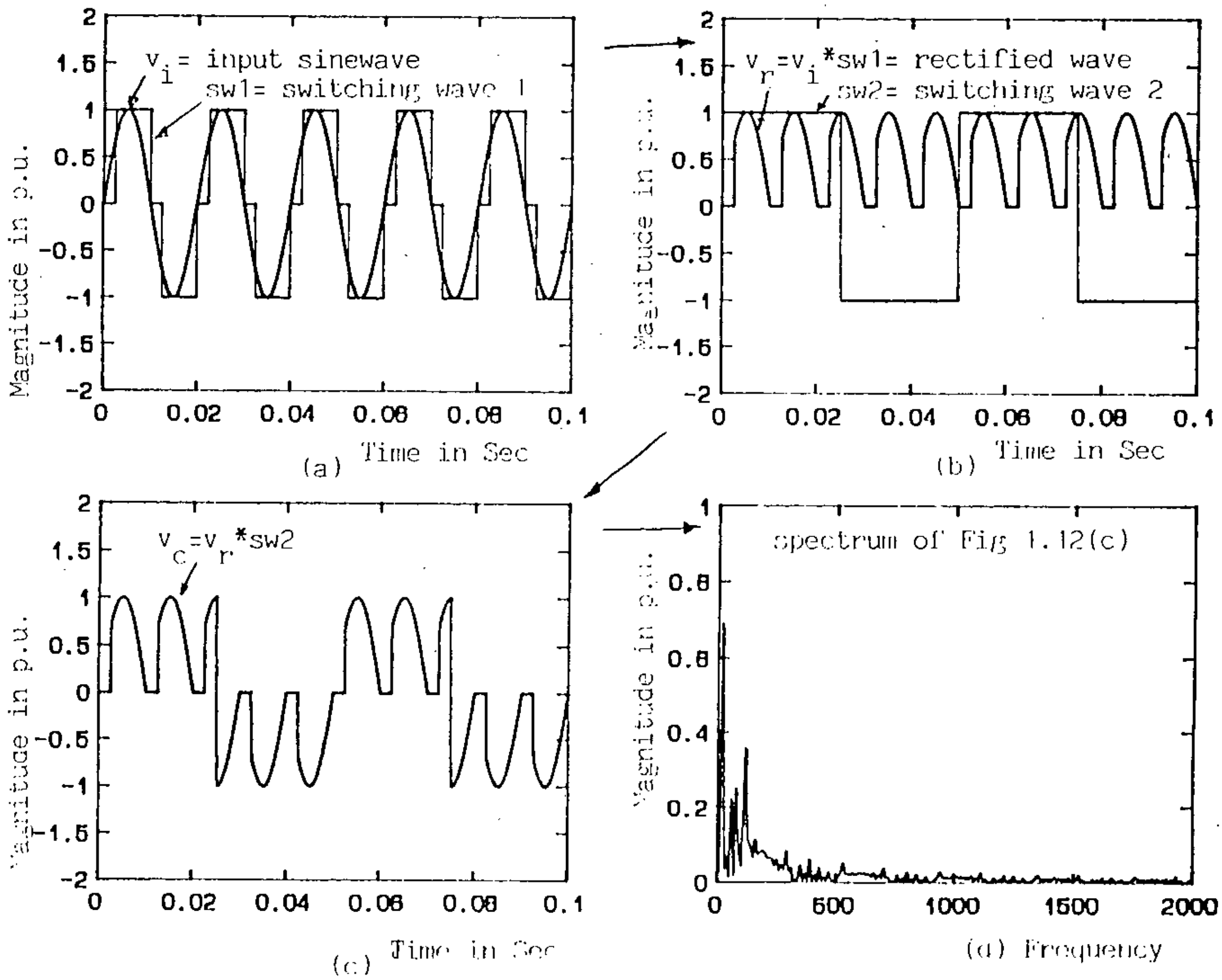


Fig: 1.12 Various waveforms of a 1-Ø cycloconverter and the output spectrum for $\alpha = 45^{\circ}$

a) Input sine wave and switching waveform sw1
b) Rectified sinewave and switching waveform sw2
c) Output of the cycloconverter
d) Spectrum of waveform of (c)

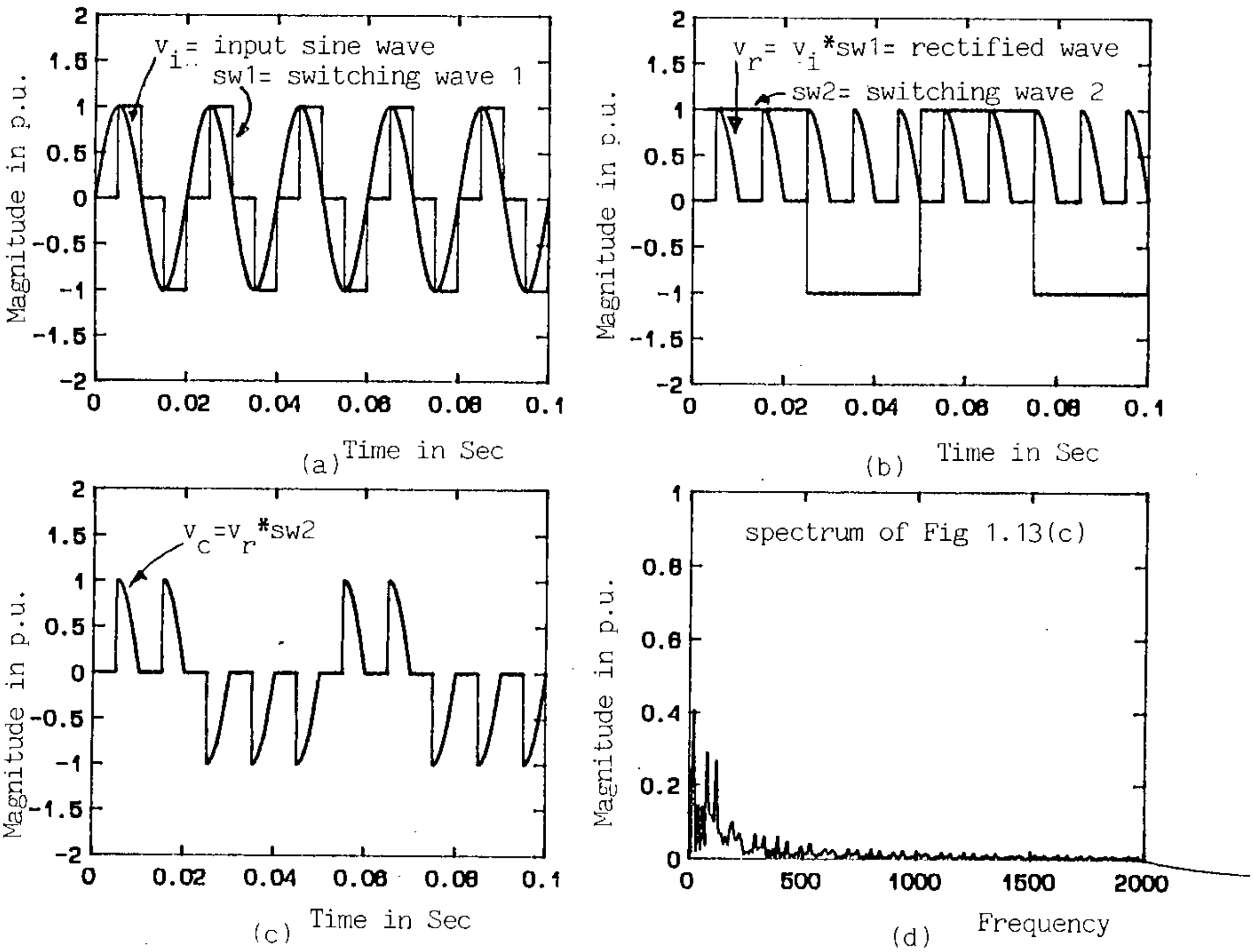


Fig: 1.13 Typical 1-Ø cycloconverter output and its spectrum for $\alpha=90^{o}$

a) Input sinewave and switching waveform sw1
b) Rectified sine wave and switching waveform sw2
c) Output of the cycloconverter
d) Spectrum of the waveform of (c)

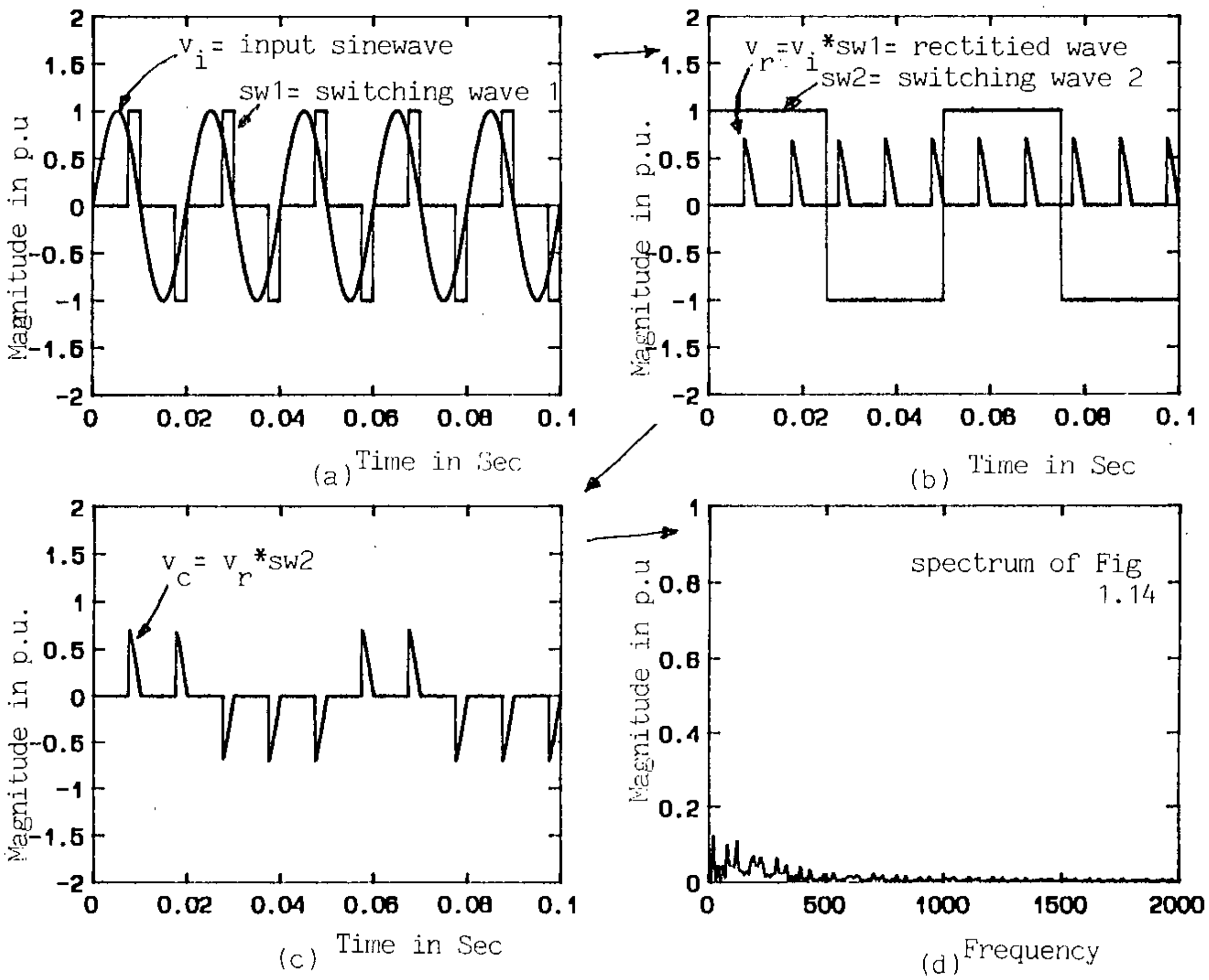


Fig: 1.14 Typical 1-Ø cycloconverter output and its spectrum for $\alpha = 135^{0}$

a) Input sine wave and switching waveform sw1

b) Rectified sine wave and switching waveform sw2

c) Output of the cycloconverter

d) Spectrum of the waveform of (c)

1.4 Outline of the Thesis.

Delta modulation technique has been proposed for cycloconverter operation in variable frequency applications. No significant work has been done in this area so far. The present work is aimed at a study and analysis of single phase pulse width modulated cycloconverters. In proposing delta modulation for the operation of cycloconverters, analysis has been undetaken to find the performance of sine pulse width modulated cycloconverters in chapter two. The method of analysis of finding the switching points of sine pulse width modulated cycloconverters are formulated.The results of harmonic analysis are reported in this chapter. In chapter three a brief review precedes the details of finding switching points of delta modulated cycloconverters. Results of harmonic analysis of output waveform of delta modulated cycloconverter with resistive load are also reported in this chapter. This chapter also includes the comparision between the two modulation technique in the operation of a single phase cycloconverter. Salient features of delta modulation is brought out in this chapter to focus its better controllability over the conventional sine pulse width modulation technique. In chapter four experimental design and implementation details are decribed. Results of actual operation of a single phase cycloconverter controlled by delta modulation technique are also included in this chapter. Experimental results are limited to the facilities available in the power electronics lab. Chapter five concludes on the overall research performed during this thesis work. This chapter also otlines the proposals for future work.

CHAPTER - 2
SINE PULSE WIDTH MODULATED CYCLOCONVERTER

2.1 Introduction.

This chapter deals with the description of a single-phase phase controlled and a sine pulse width modulated cyclconveters. The analytical technique used for finding the output waveform of both phase controlled and pulse width modulated cycloconverters is outlined. For the purpose of sine pulse width modulated cycloconverter, determination of switching points from the various condition of modulation is also needed. Effort has been made in this chapter to outline a technique to find the switching points using simple mathematics and few acceptable assumptions. Harmonic analysis of the waveforms has been performed by discrete Fourier transform (DFT). Fourier series analysis has been avoided for reasons outlined in the subequent sections. Since, DFT softwares are readily available these days, a commercial software (MATLAB) has been used for evaluation of the DFT of output waveforms of both the phase controlled and sine pulse width modulated cycloconveters. The results thus obtained is elaborated and is used for comparison in the following chapter to bring out the advantageous features of delta modulation technique in the operation of cycloconverters.

2.2 Phase Controlled single phase cycloconverter.

The operation of a phase controlled cycloconverter can be understood from the Figs. 2.1 through 2.6 Fig. 2.1 is a dual controlled rectifier circuit supplied from the same a.c. source and the load is connected between the converters as shown (the operation of Fig. 2.1 is described in chapter 1 in connection with the description of Fig. 1.1). For a resistive load and the gating signals of Fig 2.2, the converter works as a simple cycloconverter without phase control, i.e only the frequnecy of the converter can be controlled by the variation of time duration of the gating pulses. With such a gating sequence the output voltage control is not possible.

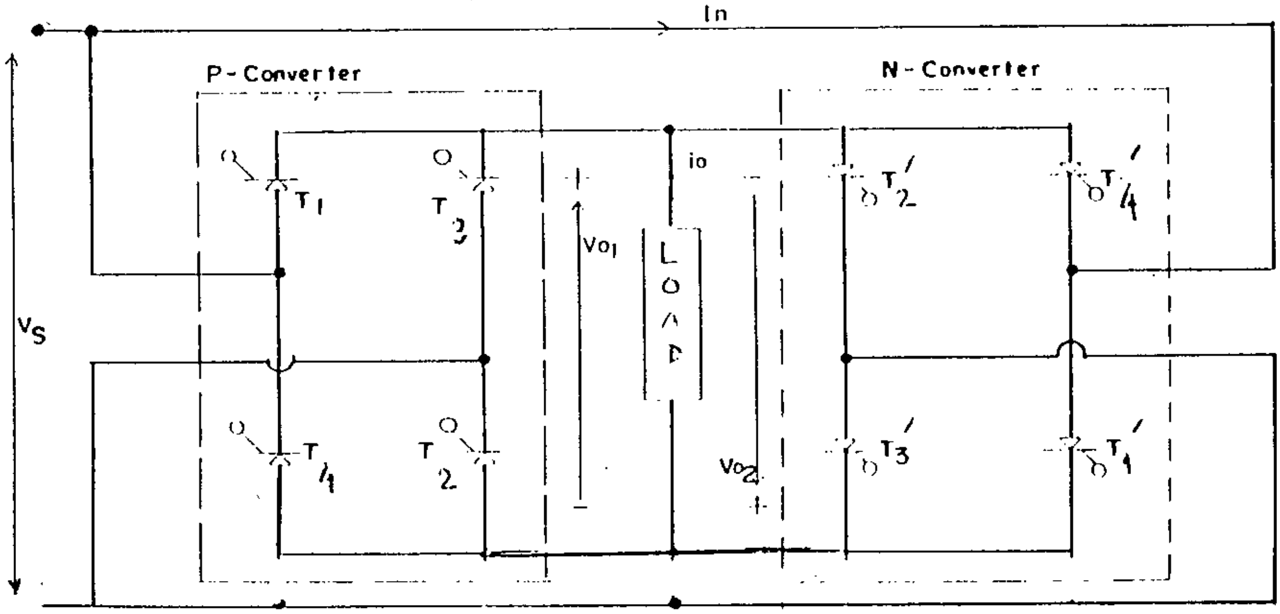


Fig: 2.1 A dual rectifier 1-Ø cycloconverter circuit

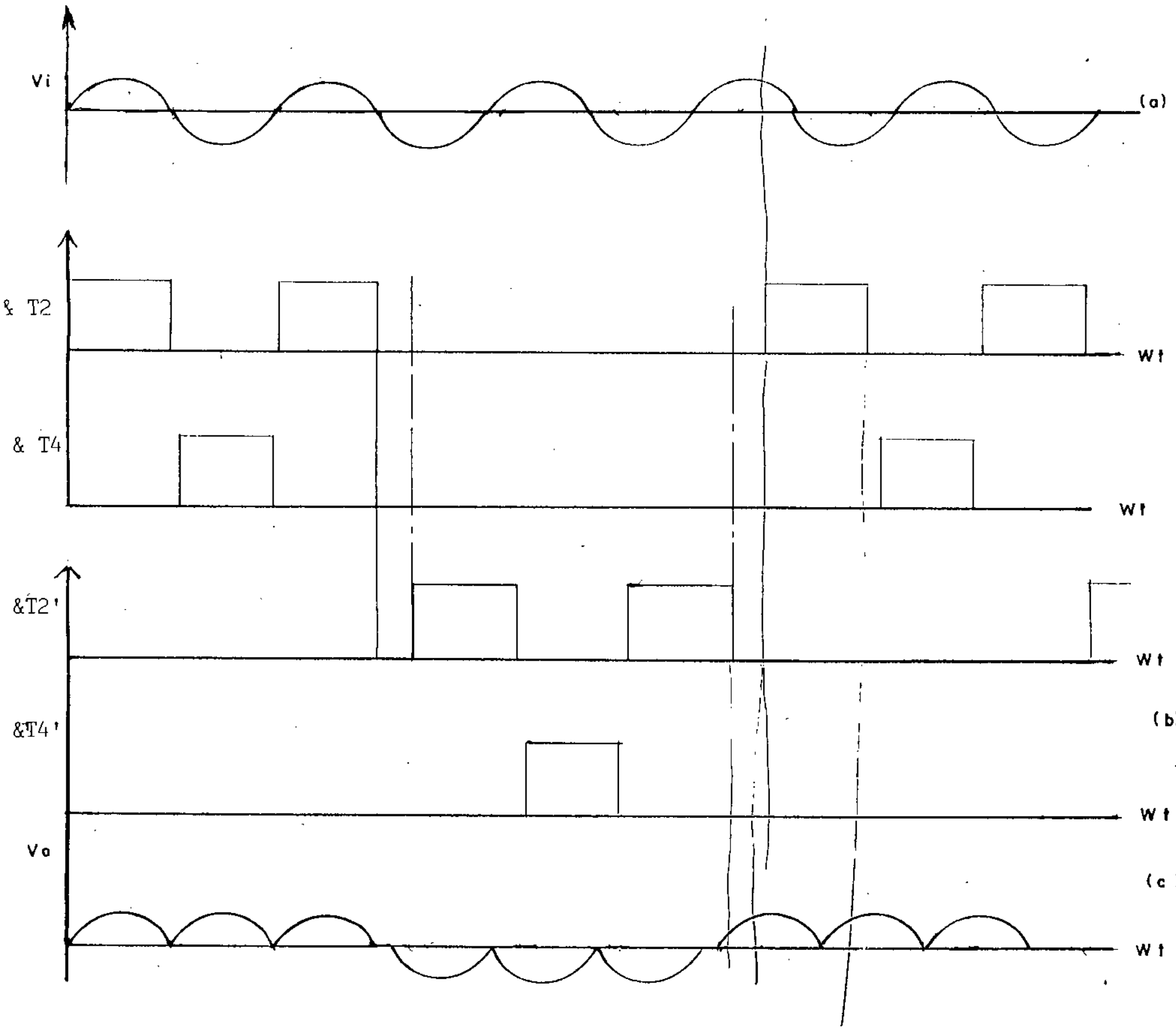


Fig: 2.2 Gating signals of a simple 1-Ø cycloconverter without phase control

a) Input to the cycloconverter

b) Gating signals

c) Output of the cycloconverter

To perform DFT analysis on the output waveform, it is necessary to define the output waveform interms of switching function (defined in terms of gating functions). Gating function can be defined as.

$$g(t, t_0, t_1) = u(t, t_0) - u(t, t_1) \tag{2.1}$$

where,

$$
\begin{aligned}
g(t, t_0, t_1) &= \textit{gate function starting at} \\
&\quad t_0 \textit{ and ending } t_1 \\
u(t, t_0) &= \textit{Unit step function starting at } t_0 \\
u(t, t_1) &= \textit{Unit step function starting at } t_1 \\
&= 1 \textit{ for } t \geq t_1 \\
&= 0 \textit{ elsewhere}
\end{aligned}
$$

The steps in obtaining the output waveforms can be described with the illlustration in Fig 2.3.

In the first step, input voltage v_i is multiplied by sw_1 in the time domain to obtain a rectified sine wave v_r, which is multiplied again by another switching function sw_2 to obtain the output voltage of the cycloconverter. The period of the first switching function sw1 is the same as the period of the supply voltage waveform's period .The period of the second switching function is the period of the cycloconverter output voltage waveform's period. The frequency of the output waveform can be varied analytically by the variation of the second switching waveform's period T_c. Different waveforms thus obtained can be expressed as,

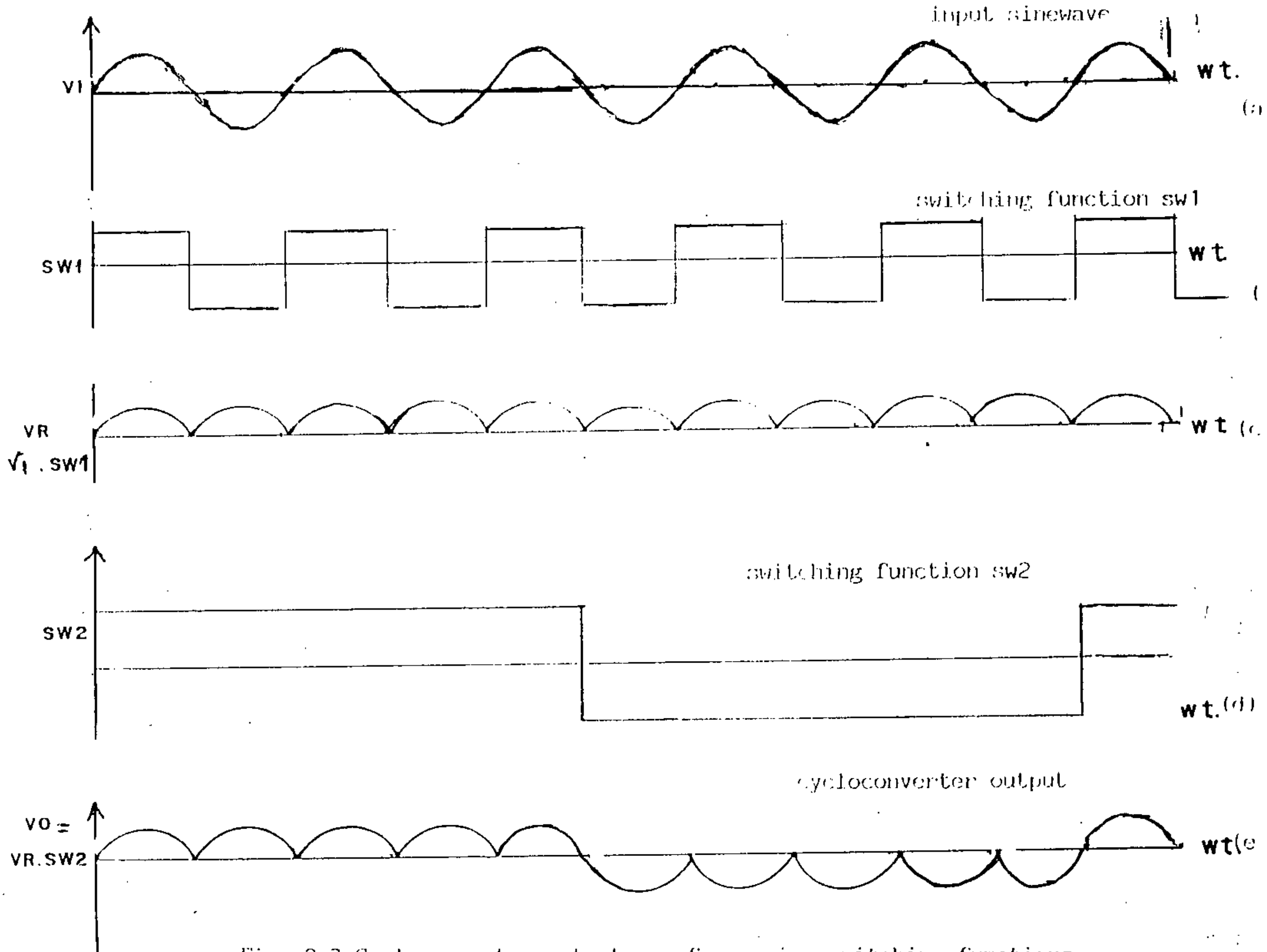


Fig: 2.3 Cycloconverter output waveform using switching functions
a) Input to the cycloconverter
b) Uncontrolled switching waveform sw1
c) Rectified sine wave
d) Switching waveform sw2
e) Cycloconverter output waveform

$$sw_1 = \sum_{n=1,2..}^{N} (-1)^{n+1} g \left\{ t, (n-1)\frac{T}{2}, \frac{nT}{2} \right\} \tag{2.2}$$

$$sw_2 = \sum_{n=1,2..}^{N} (-1)^{n+1} g \left\{ t, (n-1)\frac{T_c}{2}, \frac{nT_c}{2} \right\} \tag{2.3}$$

and

$$v_o = v_i .\ sw_1 .\ sw_2 \tag{2.4}$$

A typical spectrum of the output voltage waveform with resistive load is shown in Fig. 2.4. This type of cycloconverter control has no voltage control and Fig. 2.4 shows clearly that the output waveform contains significant amount of low order harmonics. In order to obtain voltage control of such cycloconverter, phase angle control can be incorporated into the firing of converter schemes. Fig 2.5 shows the firing scheme of the cycloconverter for phase control.

For analysis purpose, the technique described earlier can be used to formulate the output waveforms. Fig 2.6 shows the required switching function and the resultant output voltage waveform.

The switching waveforms of Fig 2.6 can be mathematically represented as,

$$sw_1 = \sum_{n=1,2..}^{N} (-1)^{n+1} g \left\{ t, \alpha + (n-1)\frac{T}{2}, \frac{nT}{2} \right\} \tag{2.2}$$

$$sw_2 = \sum_{n=1,2..}^{N} (-1)^{n+1} g \left\{ t, (n-1)\frac{T_c}{2}, \frac{nT_c}{2} \right\} \tag{2.3}$$

Typical waveforms for phase angle and frequency control are and also their.Spectra those are shown in Figs 1.11 to 1.14 [Chapter1] respectively. When both output voltage and frequency control is achieved it is evident that the output voltage is further corrupted by the low order harmonics. In these case low order harmonics will also appear in the input current waveshapes which would give rise to the requirement of large sized filters at both output and input side. Also in use many detrimental effect may apper in the form of

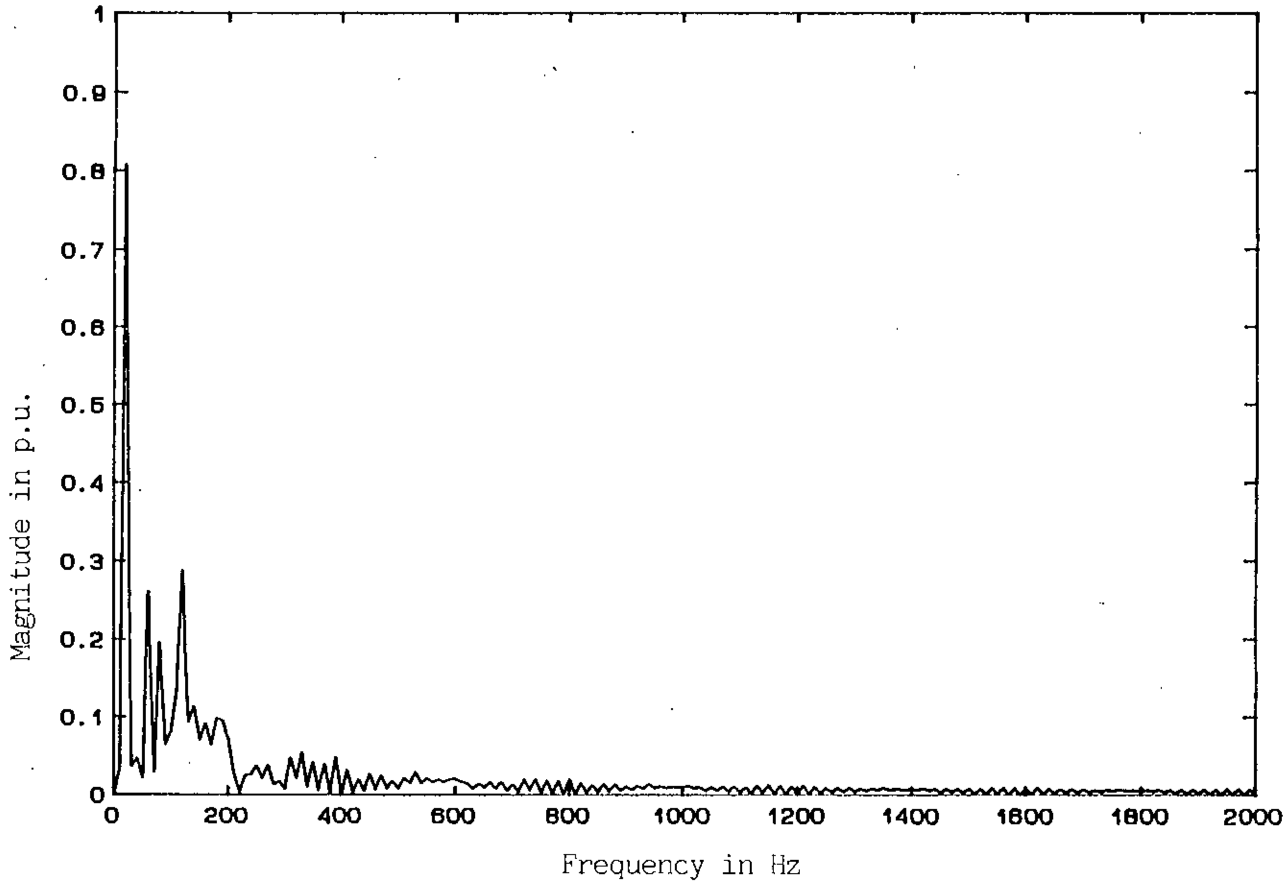


Fig: 2.4 Typical spectrum of a 1-Ø cycloconverter without phase control

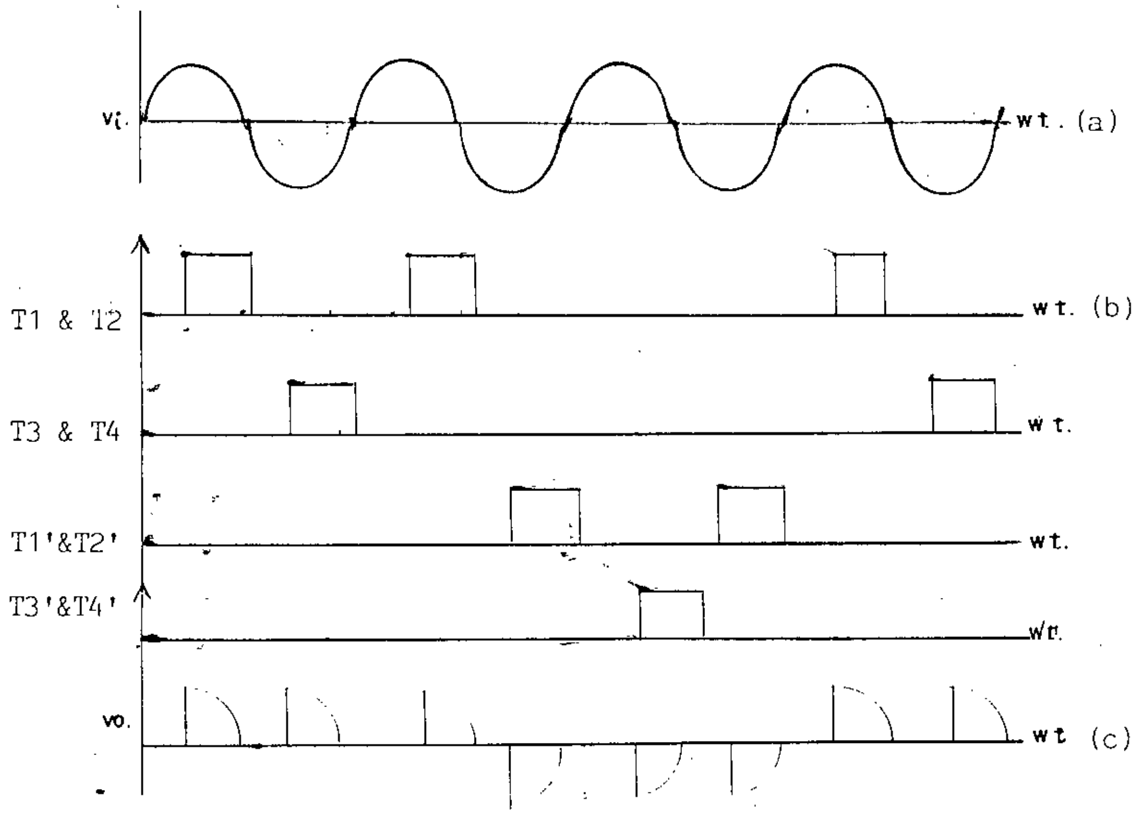


Fig: 2.5 Firing scheme of a 1-Ø cycloconverter with phase control
a) Input to the cycloconverter
b) Gating signals
c) Output of the cycloconverter

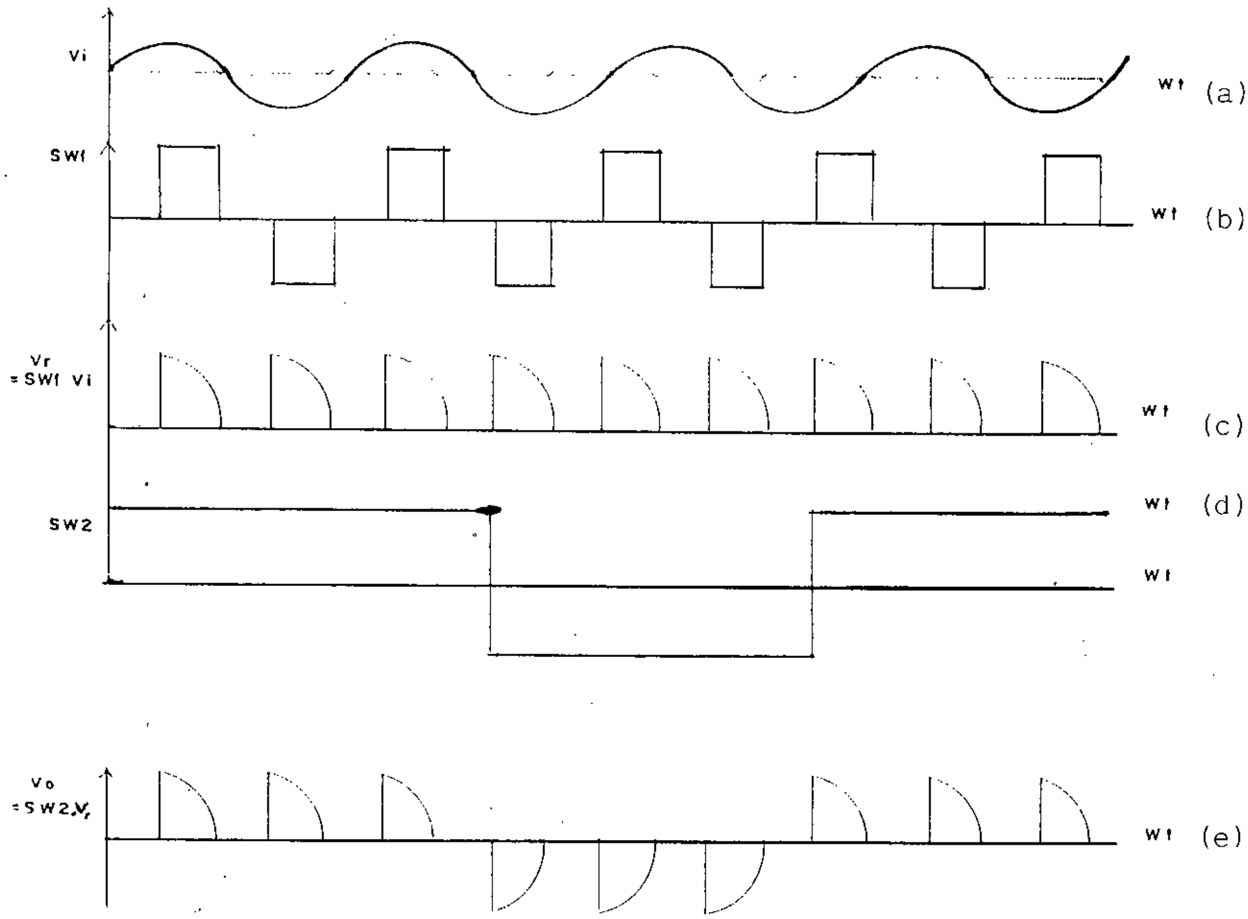


Fig: 2.6 Switching functions for the phase controlled cycloconverter and the resultant output voltage waveform
a) Input sine wave
b) Phase controlled switching waveform sw1
c) Phase controlled rectified sine wave
d) Switching waveform sw2
e) Output waveform of the cycloconverter

harmonics losses, noise, heating and vibration etc. To reduce these harmful effects pulse width modulation is used to improve the waveforms shape, reduce filter requirements and minimize harmonic losses.

It can be mentioned at this point that instead of using dual converter configuration, in simple applications the following two schemes can also be used as cycloconverter to achieve the same purpose with reduced gating signal involvements.Fig 2.7(a) shows a controlled rectifier at the front end and an inverter at the output side and 2.7(b) shows the waveforms of the cycloconverter configuration shown in Fig. 2.7(a) operation of the circuit is discussed in chapter 1 in connection with the description of Fig. 1.3(a) to Fig. 1.3(c). Fig 2.8(a) shows an uncontrolled rectifier and a chopper switch at the front end and an inverter at the output side to give the cycloconverter waveforms shown in Fig 2.8(b).In our case, we have used the scheme of Fig 2.8(a) for its simplicity. However, for power flow in all direction or a four quadrant operation of the converter only a dual controlled converter scheme can be practically used.

2.3 Sine Pulse Width Modulated Single Phase Cycloconverter.

The need for modulation technique in the control of various converter waveforms is emphasized in the previous section. Sine pulse width modulation is one of the common modulation process used in converter waveform generation. Fig 2.9 illustrates the technique of pwm waveform generation for a single phase cycloconverter. In this process the reference rectified sine wave is compared with a high frequency carrier triangular wave to produce the switching instants at the crossover of the two waveforms. The resultant waveform can be gated by required waves of desired duration to obtain the final gating signals for device switching. Output waveform's harmonic content, switching frequency and the magnitude of output voltage can be controlled by variation of either the carrier wave's frequency or the magnitude, resulting change in swicthing frequency and the pulse widths. This variation is usually measured interms of modulation index which can be defined as the ratio of the magnitude of modulating wave to that of the carrier wave.

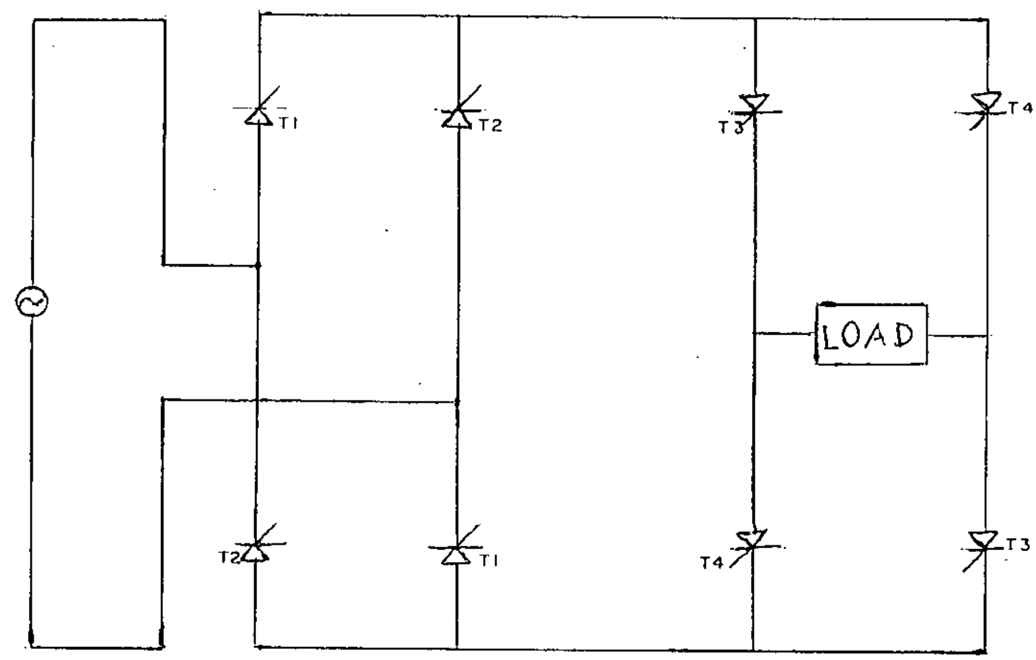


Fig: 2.7(a) A 1-Ø cycloconverter with a controlled rectifier at the front end and an inverter at the output side

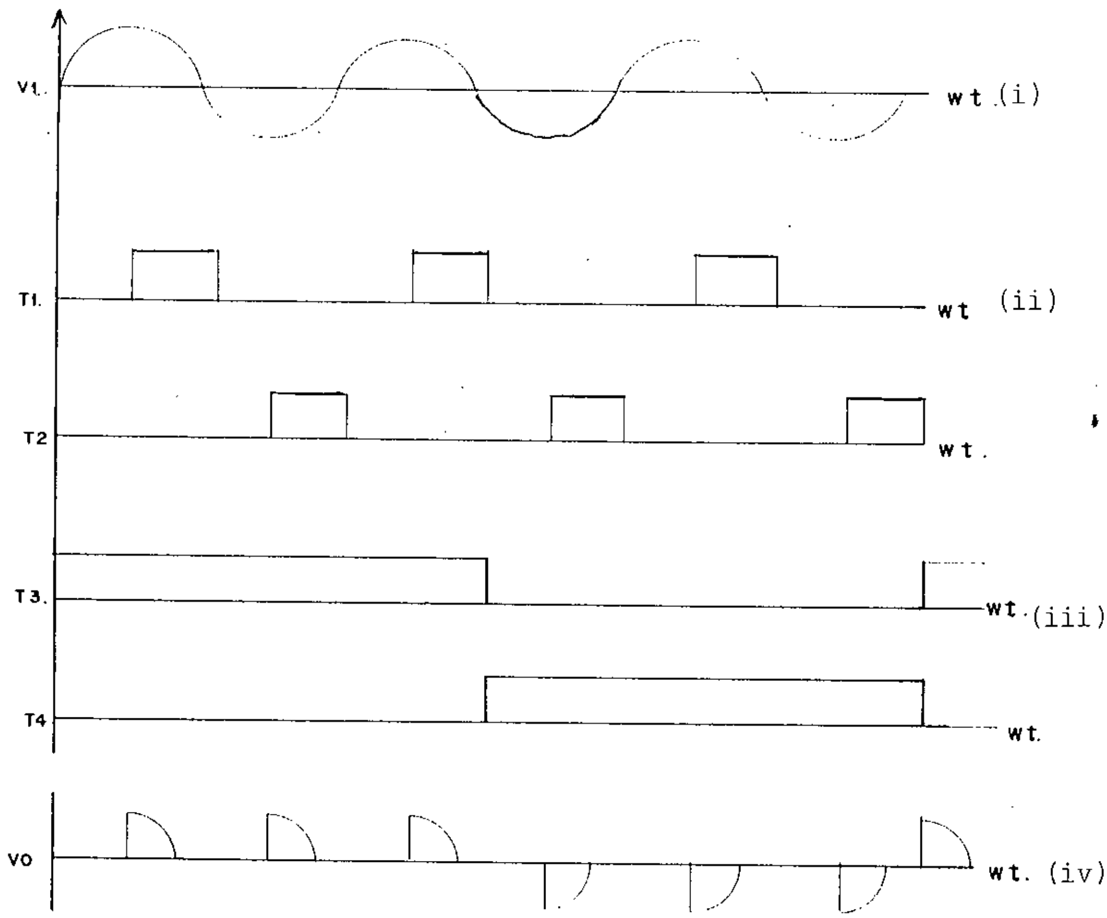


Fig: 2.7(b) The waveforms of the cycloconverter configuration shown in fig 2-7(a)

i) Input to the cycloconverter
ii) Rectifier gating signals
iii) Inverter gating signals
iv) Cycloconverter output waveform

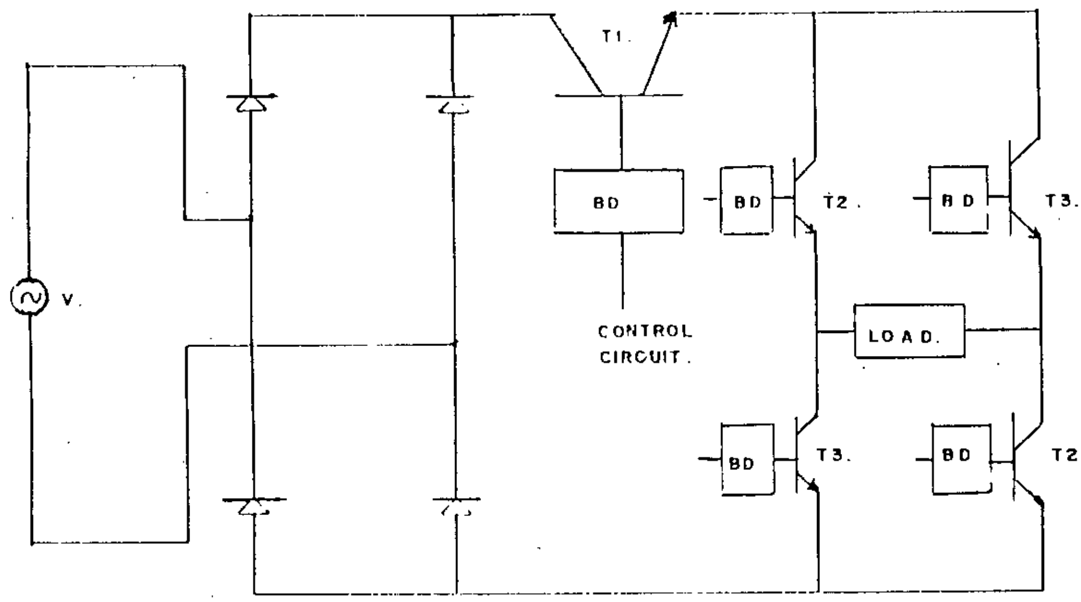


Fig: 2.8(a) A 1-Ø cycloconverter with an uncontrolled rectifier and a chopper switch at the front end and an inverter at the output side
In the diagram BDS are the base drives of the BJTS

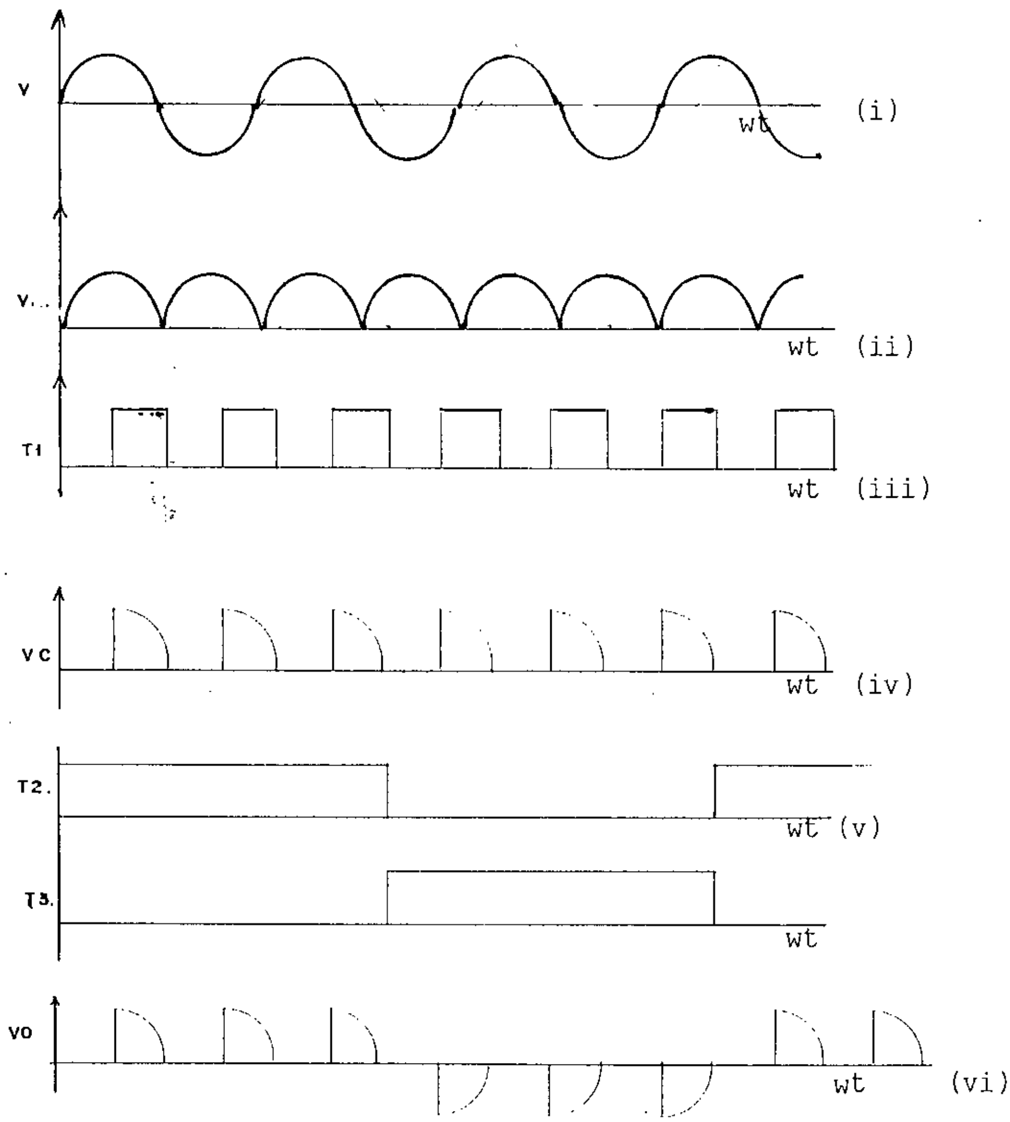


Fig: 2.8(b) The waveforms of the cycloconverter configuration shown in fig 2-8(a)

i) Input sine wave
ii) Rectified sine wave
iii) Swithcing pulses for phase controlled rectifier
iv) Phase controlled rectifier output
v) Inverter gating signal
vi) Cycloconverter output waveform

2.3.1 Method of Finding the Switching Points.

It is important in all modulated converters to find the modulated waveforms switching point so that the waveforms can be defined in terms of switching points. To find the switching points of the modulated signal generated for the control of a single phase cycloconverter. [Fig. 2.9] the following technique has been used in this thesis. The modulated wave's switching points are determined by the fact that whenever the carrier triangular wave crosses the reference rectified sine modulating wave. a pulse is produced and its duration is as long as the carrier wave's magnitude remains higher than the modulating wave.

Pulse Width Determination

Let.

$$
\begin{aligned}
N &= \text{number of modulating pulses for each half cycle} \\
\delta_i &= \text{pulse width of the ith pulse} \\
&= \frac{\pi}{N} = \text{distance between successive pulses} \\
E_r &= \text{maximum magnitude of the modulating} \\
&\quad \text{rectified sine wave} \\
E_c &= \text{maximum magnitude of the} \\
&\quad \text{carrier triangular wave} \\
\theta_i &= \text{ith pulse's mid location} \\
w &= \frac{E_r}{E_c} = \text{modulating index}
\end{aligned}
$$

The modulating process ensures the following.

$$
\begin{aligned}
\delta_i &\propto e \\
\text{and } \delta_i &\propto \frac{1}{E_c}
\end{aligned}
$$

where. e is the modulating wave and $\propto$ is the sine of proportionality.

since.

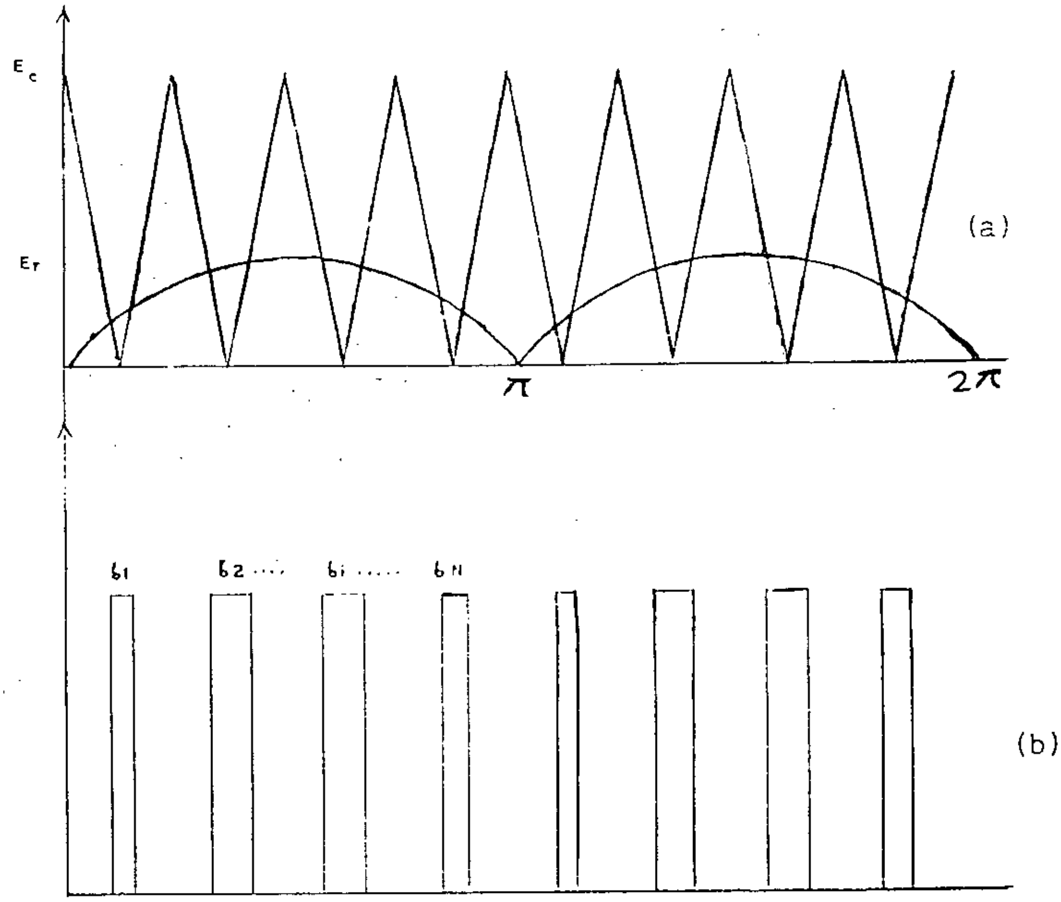


Fig: 2.9 PWM waveform generation for a single phase cycloconverter
a) Comparison between rectified sine wave with carrier triangular wave
b) Modulated wave

$$e = E_r \sin\theta_i$$

we can write by rearranging the following expressions.

$$
\begin{aligned}
e &= E_r \sin\theta_i \\
&= \frac{E_c}{E_c} E_r \sin\theta_i \text{ but} \\
\theta_i &= \frac{2i-1}{2N}\pi \\
\text{or, } e &= W E_c \sin\frac{2i-1}{2N}\pi
\end{aligned}
\qquad (2.6)
$$

From the conditions $\delta_i \propto e$ and $\delta_i \propto \frac{1}{E_c}$. We can write.

$$\delta_i = \frac{e}{E_c} \qquad (2.7)$$

which can be written as.

$$
\begin{aligned}
\delta_i &= \frac{W E_c}{E_c} \sin\frac{2i-1}{2N}\pi \\
&= W \sin\frac{2i-1}{2N}\pi
\end{aligned}
\qquad (2.8)
$$

which shows, when number of pulses are kept constant pulse widths vary with modulating index $W = \frac{E_r}{E_c}$ .When the modulating index is kept constant, pulse widths vary as a sinusoidal function of pulse number N. Once the pulse widths of all the pulses in the half cycle can be found by expression 2.8, the waveform can be represented interms of the pulse widths. For example, the pulse positions can be written as.

$\frac{1}{2}\frac{\pi}{N} - \frac{\delta_1}{2}$ *is the first rising edge*

$\frac{1}{2}\frac{\pi}{N} + \frac{\delta_1}{2}$ *is the first downward edge*

$\frac{3}{2}\frac{\pi}{N} - \frac{\delta_2}{2}$ *is the 2nd rising edge*

$\frac{3}{2}\frac{\pi}{N} + \frac{\delta_2}{2}$ *is the 2nd downward edge and so on*

in general the ith rising edge is.

$$\theta_{ir} = \frac{2i-1}{2}\frac{\pi}{N} - \frac{\delta_i}{2} \tag{2.9}$$

and the ith down going edge is.

$$\theta_{id} = \frac{2i-1}{2}\frac{\pi}{N} + \frac{\delta_i}{2} \tag{2.10}$$

These expressions can also be obtained in terms of time domain and can be used for waveform construction and Fourier series or Fourier transform analysis.

2.3.2 Spectrum Analysis.

The determination of switching points or the pulse widths of the modulated wave allows one to define the cycloconverter waveform interms of the modulated wave, rectified sine wave and the gating signal represented by switching waves as discussed in section 2.1. The modulated signal m of Fig 2.10 be can be represented by the following expression

$$m = \sum_{i=1,2,\ldots}^{N} (-1)^{i+1} g(t, t_i, t_{i+1}) \tag{2.11}$$

where, $g(t, t_i, t_{i+1})$ is the gate function starting at t_i and ending at t_{i+1}. The rectified sine wave V_r can be expressed as [section 1].

$$v_r = v_i . sw_1$$

where,

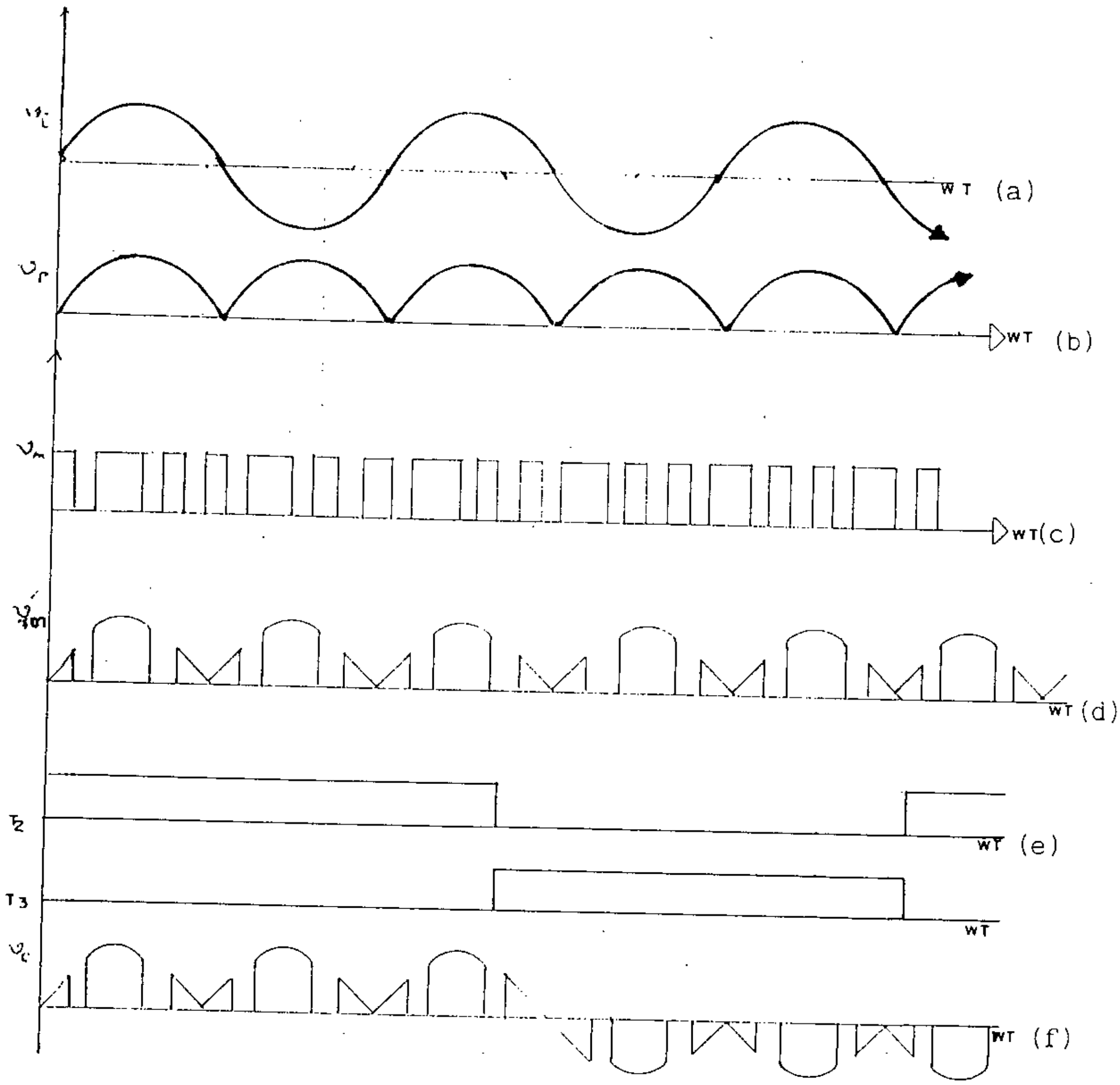


Fig: 2.10 PWM cycloconverter waveform generation
a) Reference sine wave (v_i)
b) Reference rectified sine wave (v_r)
c) Modulated wave (v_m)
d) Controlled rectifier waveform (modulated) (v_{rm})
e) Inverter gating signal
f) Modulated cycloconverter waveform (v_c)

$$sw_1 = \sum_{n=1,2..}^{N} (-1)^{n+1} g\left[t, (n-1)\frac{T}{2}, \frac{nT}{2}\right] \tag{2.12}$$

The second fuction sw_2 can be expressed as [section 2.1].

$$sw_2 = \sum_{n=1,2..}^{N} (-1)^{n+1} g\left[t, (n-1)\frac{T_c}{2}, \frac{nT_c}{2}\right] \tag{2.13}$$

where, T and T_c are the periods of supply voltage and the cycloconverter output voltage The expression for output voltage v_o can be obtained thus as [Fig. 2.10].

$$v_o = m.v_r.sw_2 \tag{2.14}$$

This output voltage in the first glance can be represented by a Fourier series as follows,

$$v_o = \sum_{n=1}^{\infty} [A_n sin(n\omega t) + B_n cos(n\omega t)] \tag{2.15}$$

where, A_n and B_n are the Fourier coefficients and the Fourier coefficient C_n can be expressed as,

$$C_n = \frac{1}{2}\sqrt{A_n^2 + B_n^2} \tag{2.16}$$

However, such Fourier series analysis would give erreneous result in the case of single phase cycloconverter waveform analysis, because for various duration of switching function sw_2, the output waveform will not be periodic as required by Fourier series representation. It may have periodicity other than the defined period due to unysmmetical nature of the waveform. Hence the subharmonics (harmonics which are the multiple of actual period of the cycloconverter) will be missed in such analysis. As a result, though this method was randomly used in the past in analysing converter waveforms, is gradually being replaced by DFT analysis. In DFT analysis, the analytical waveforms are sampled and analyzed with convenient fast Fourier transform (FFT) algorithm. In our research we have represented waveforms in their sampled forms and ?carried out DFT (FFT of radix 2) with the help of software MATLAB [24].

2.4 Results.

Fig. 2.9 and Fig 2.10 show the steps outlined in previous section to obtain the waveforms of single phase pulse width modulated cycloconverter. Figs 2.11 to 2.14 show the wave form construction of variable frequency operation of a sine pulse width modulated cycloconverter for constant modulation index = 0.5 and constant number of pulses =9 (carrier frequency constant). Spectra for these waveforms are shown in Figs 2.15 -2.18. From these spectra it is evident that the fundamental voltage of the output waveform gradually decreases with the increase of cycloconverter operation frequency. Similar analyses were also carried out for constant number of pulses (carrier frequency = constant) but with increasing modulation index. The waveforms for $N_p = 9$, w = .75 and 1.00 are shown in Figs. 2-19 to 2-22 and Figs. 2-23 to 2-26 respectively. The spectra of the waveforms for the same conditions are shown in Figs 2-27 to 2-30 and Figs. 2-31 to 2-34. The results are given in tabular form in Table 2.1 to 2.3 .

The variation of the fundamental voltage is seperately shown in Table 2.4. Table 2.4 shows that fundamental voltage can be increased by increasing the modulation index w. The low order dominant harmonic variation for same condition are shown in Figs. 2.35 to 2.37 corresponding to Table 2.1 to 2.3. Fig. 2.38 shows the fundamental voltage variation with change in frequency for number of pulses N_p = constant and modulation index w = variable. Similar analyses were also carried out as standard for variation of N_p (number of pulses) with constant modulation index. The waveforms for $N_p = 9, 11, 13$ and $W_p = .5$ are shown in Figs. 2.11 to 2.14, Figs. 2.39 to 2.42 and in Figs. 2.43 to 2.46 and the spectra of the waveforms are shown in Figs. 2.15 to 2.18, in Figs. 2.47 to 2.50 and in Figs. 2.51 to 2.54 respectively. The variation of dominant low order harmonics for the above conditions are shown in table 2.5 and 2.6 and in Figs. 2.55 and 2.56. The fundamental voltage variations with frequency for different N_p are given in table 2.7 and represented graphically in Fig 2.57. From table 2.7 and Fig 2.57 it is evident that with increase in the frequency of cycloconverter. the fundamental voltage reduces for particular N_p and w. However, if the number of pulses are varied by increasing the carrier frequency, the fundamental increases, but insignificantly.

The results of the sine pulse width modulated cycloconverter clearly indicates the advantage of reduced low order harmonics compared to those obtained for phase controlled cycloconverter.

2.5 Conclusions.

The operation of a single phase cycloconverter in phase and sine pulse width modulated control modes have been considered. It has been clearly outlined why pulse width modulated control is preperred over phase controlled cycloconverter. In sine pulse width modulated control, cycloconverter waveforms can be improved by variation of either modulation index W or by variation of carrier frequency f_C. In the variable frequency operation of cycloconverter, the effect of changing modulation index or the number of pulses N_p has been investigated seperately. In practical control scheme these variations require involved implementation technique. As a result such adaptive sine pulse width modulation is not implemented by normal analog and digital electronics technique, rather dedicated microcomputer and VLSI custom chips implementation are usual. In the following chapter a comparison is made between sine pulse width modulation and delta modulation control of cycloconverters. The features of delta modulators enable one to use normal analog implementation of modulated cycloconverter very easily.

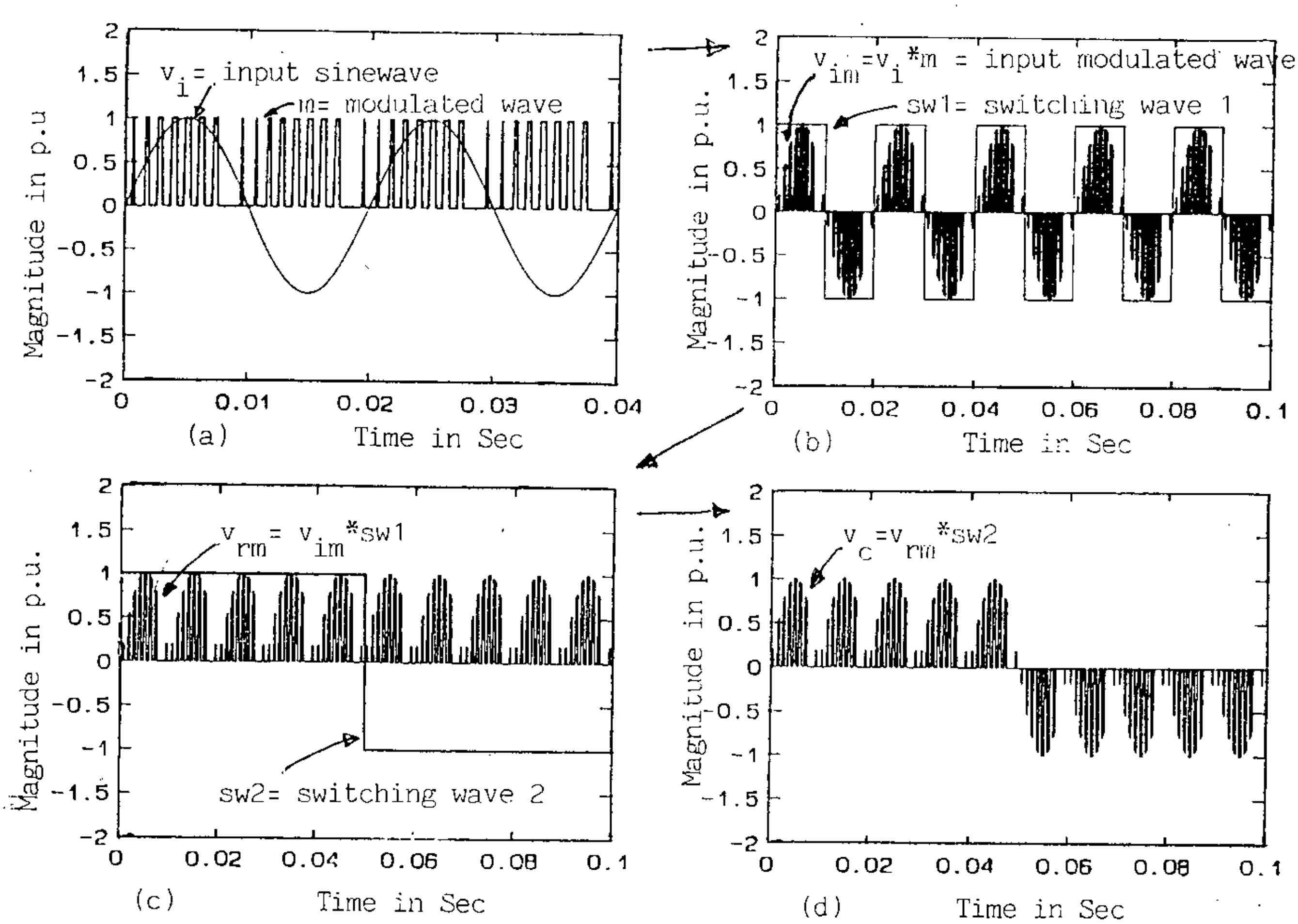


Fig: 2.11 Waveforms of a 1-Ø spwm cycloconverter for $W=.5, N_p=9$, $T_c=.1$ Sec where W is the modulation index, N_p is number of pulses, T_c is cycloconverter period

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switechng waveform sw2
d) Output of the cycloconverter

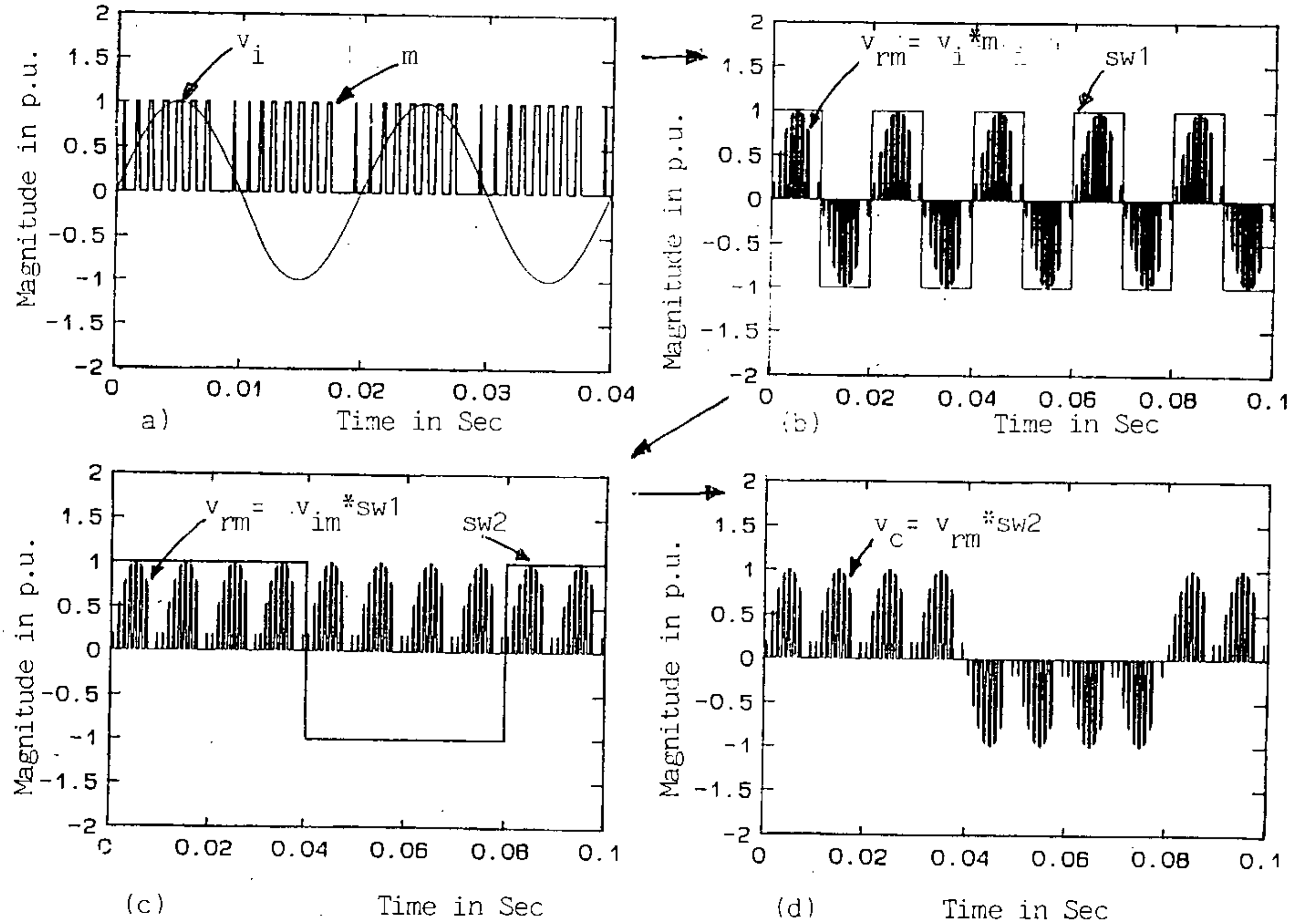


Fig: 2.12 Waveforms of a 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.08 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and swhtching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

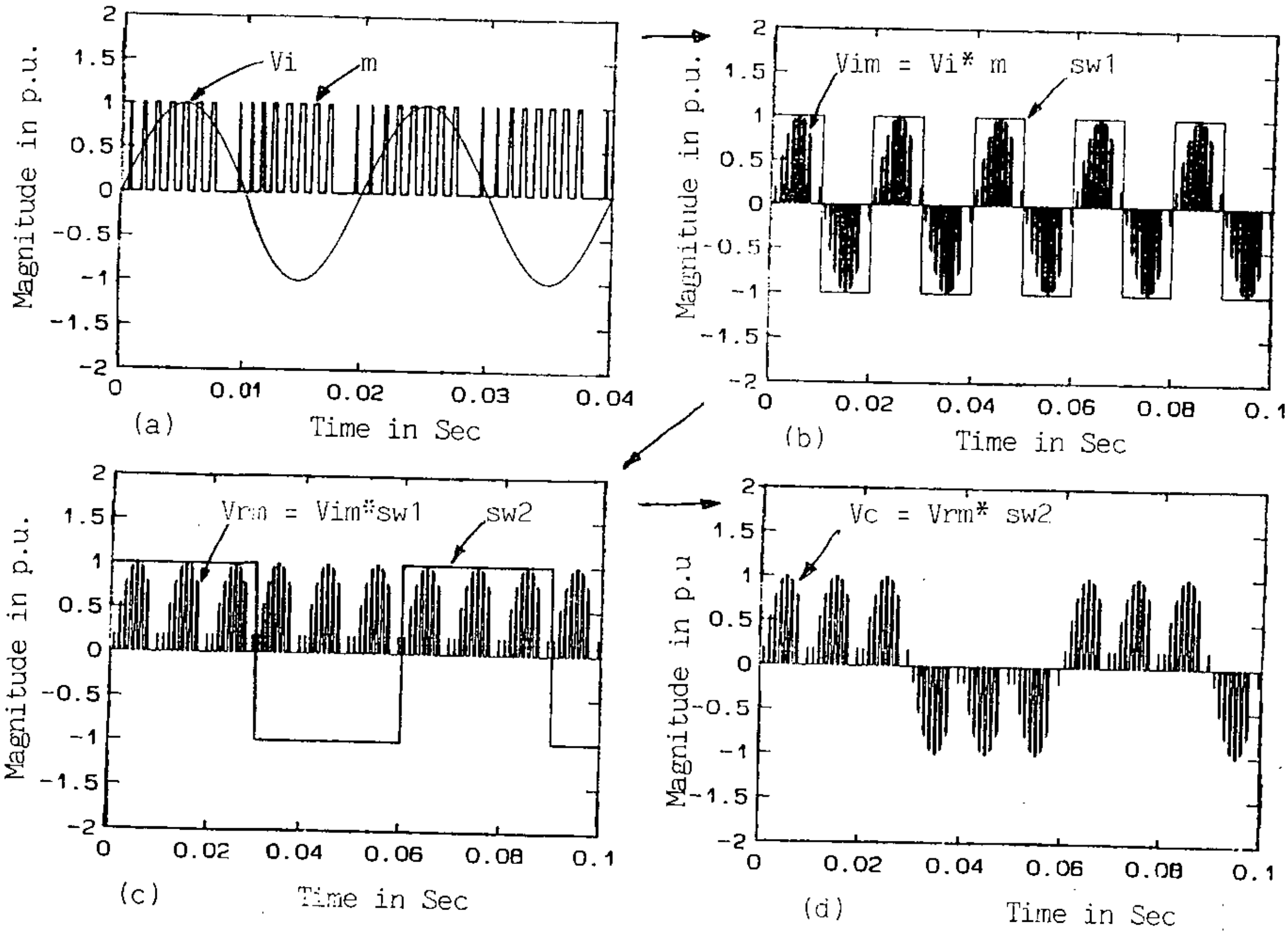


Fig: 2.13 Waveforms of a 1-Ø spwm cycloconverter for W=.5, N_p=9 T_c=.06 Sec

a) Reference input pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

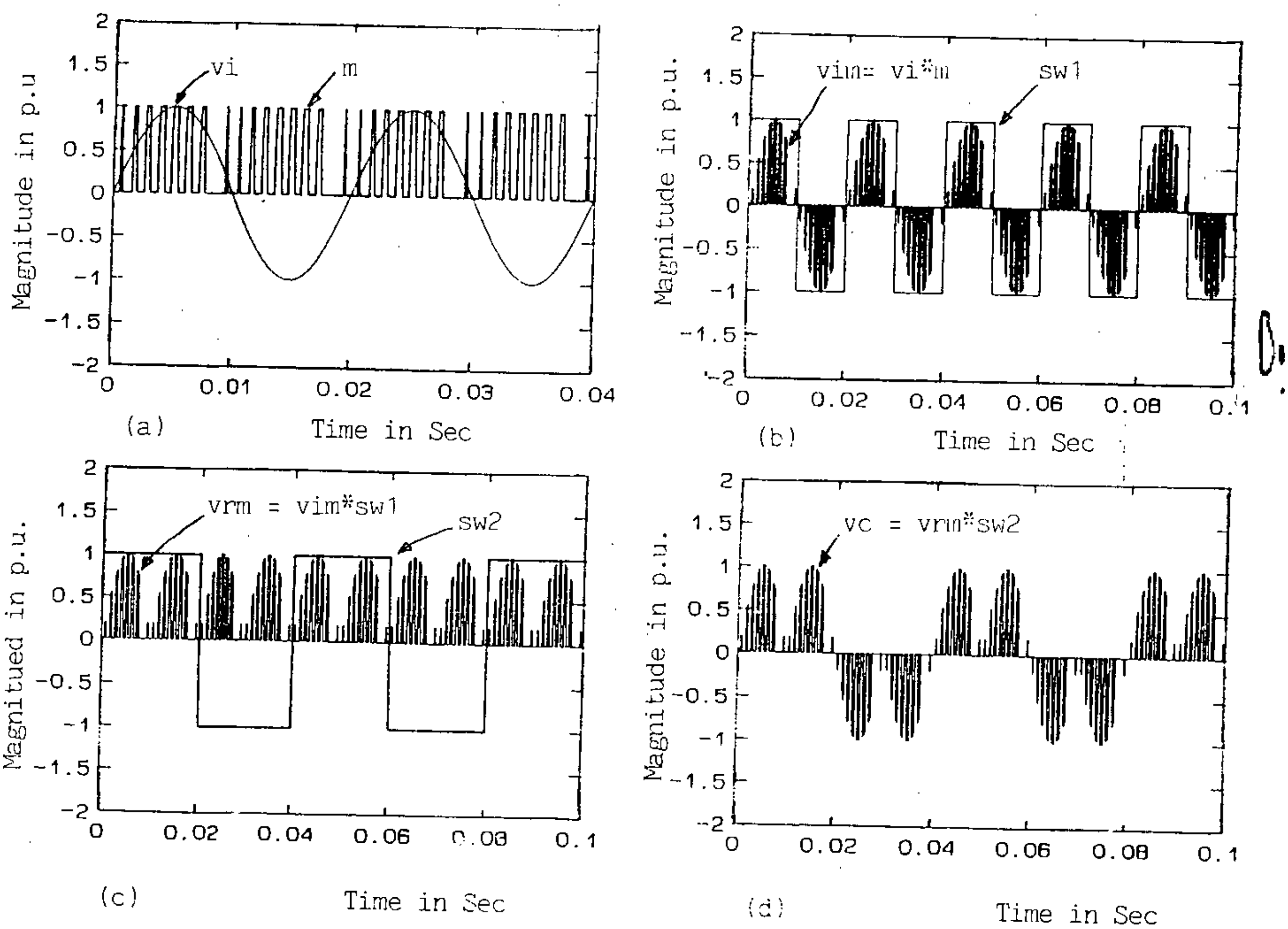


Fig: 2.14 Waveforms of an 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.04 Sec

a) Reference input and pwm waveform
b) Resultant modulated wave and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

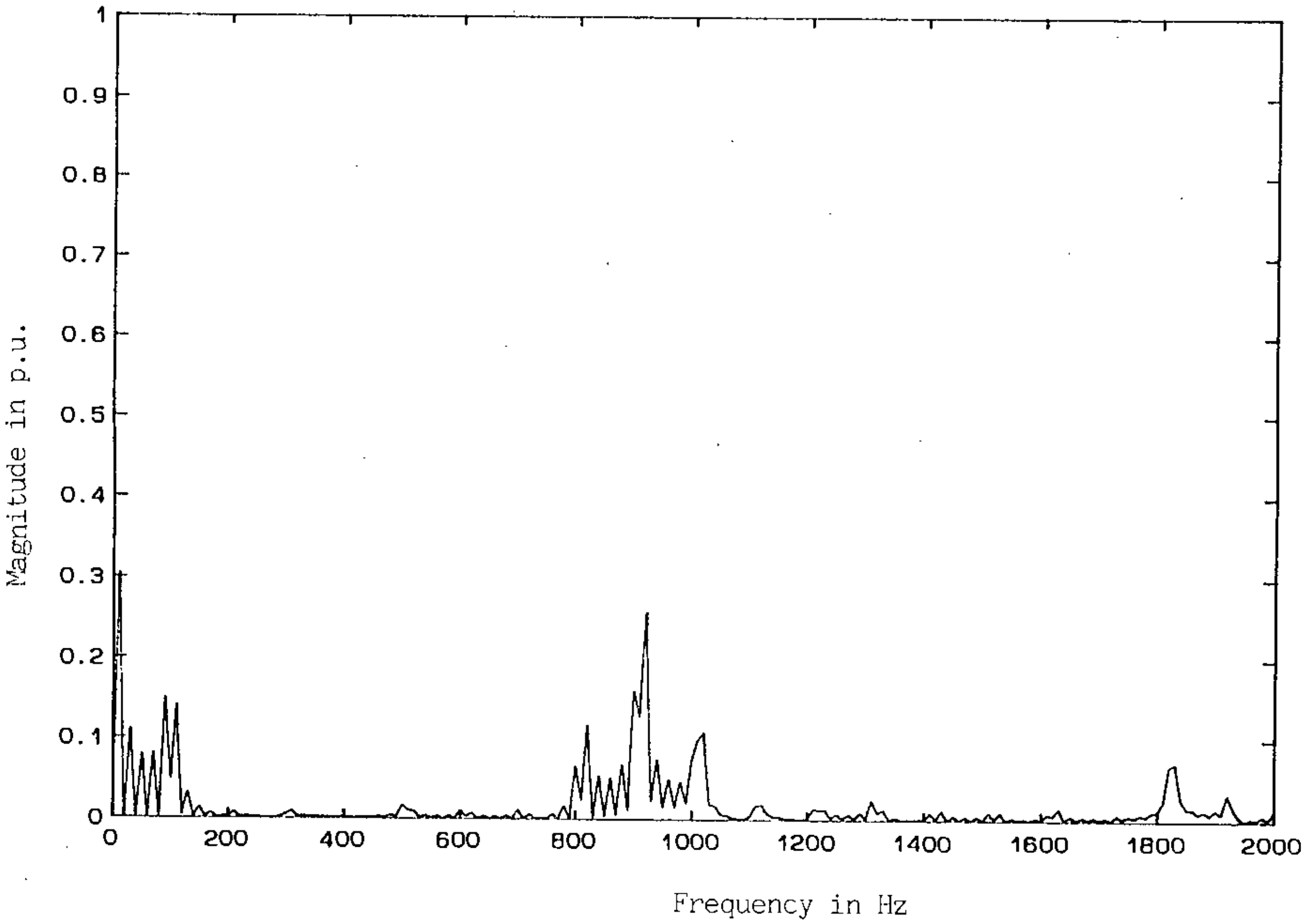


Fig: 2.15 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.1 Sec

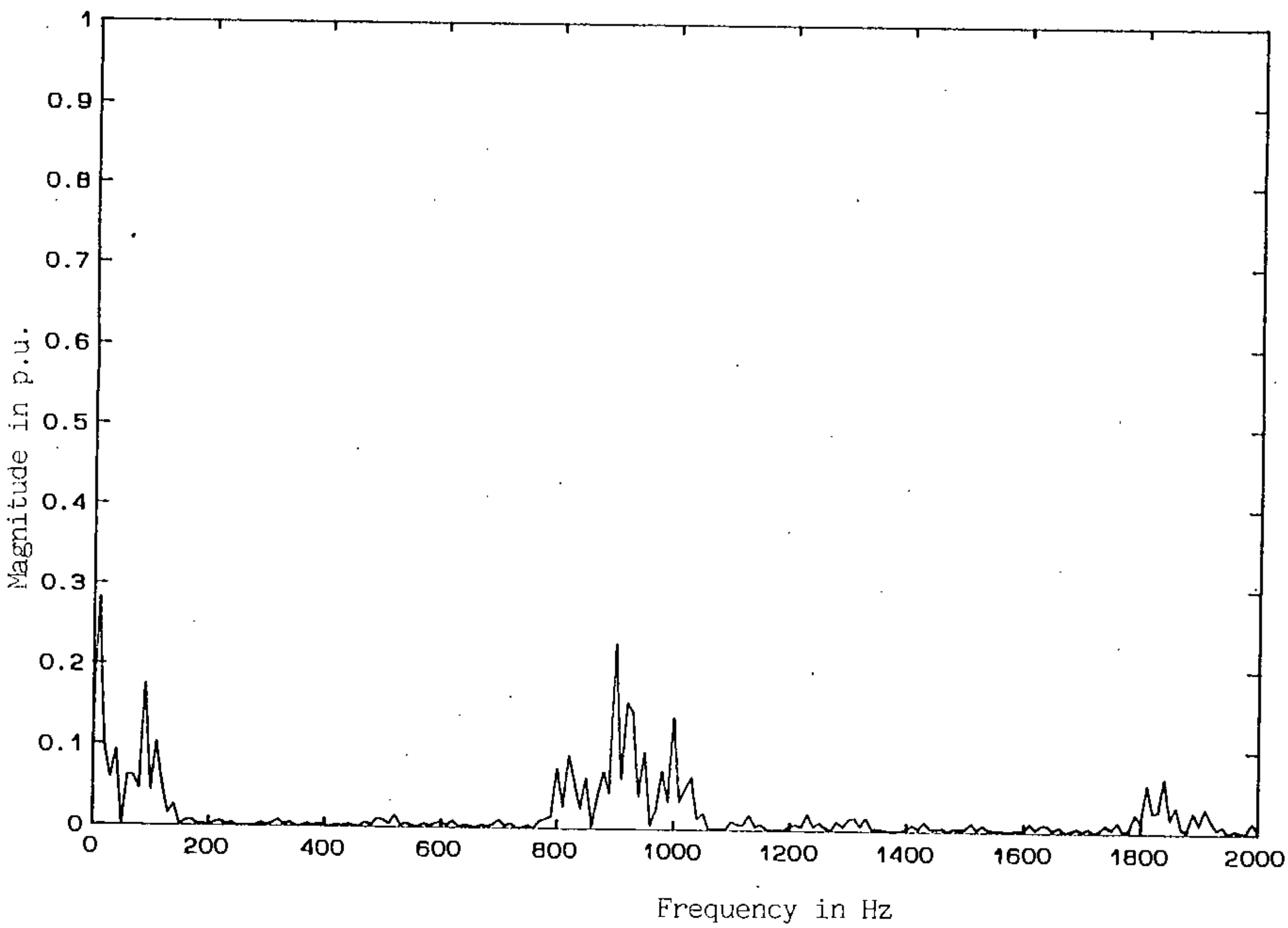


Fig: 2.16 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.08 Sec

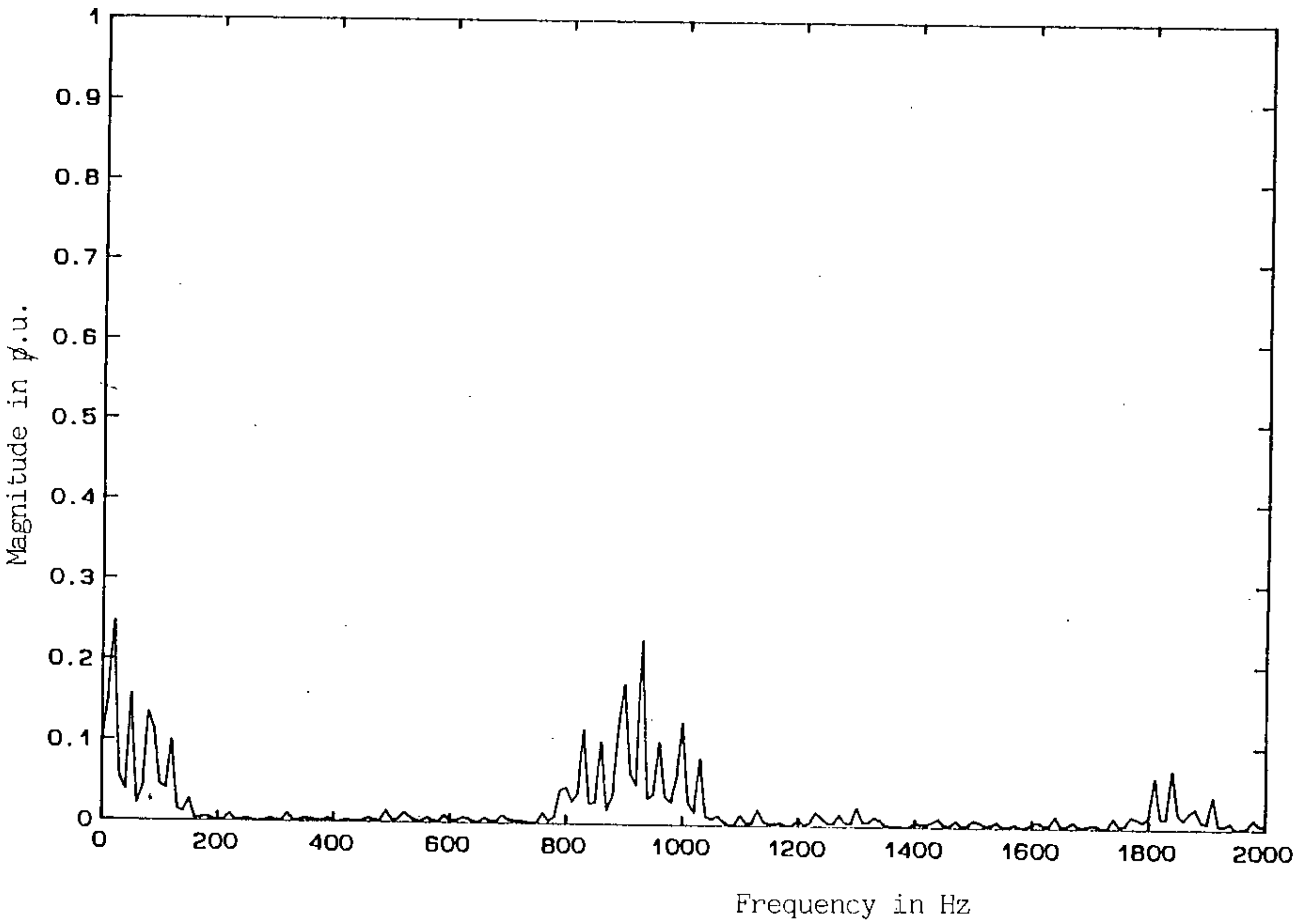


Fig: 2.17 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.06 Sec

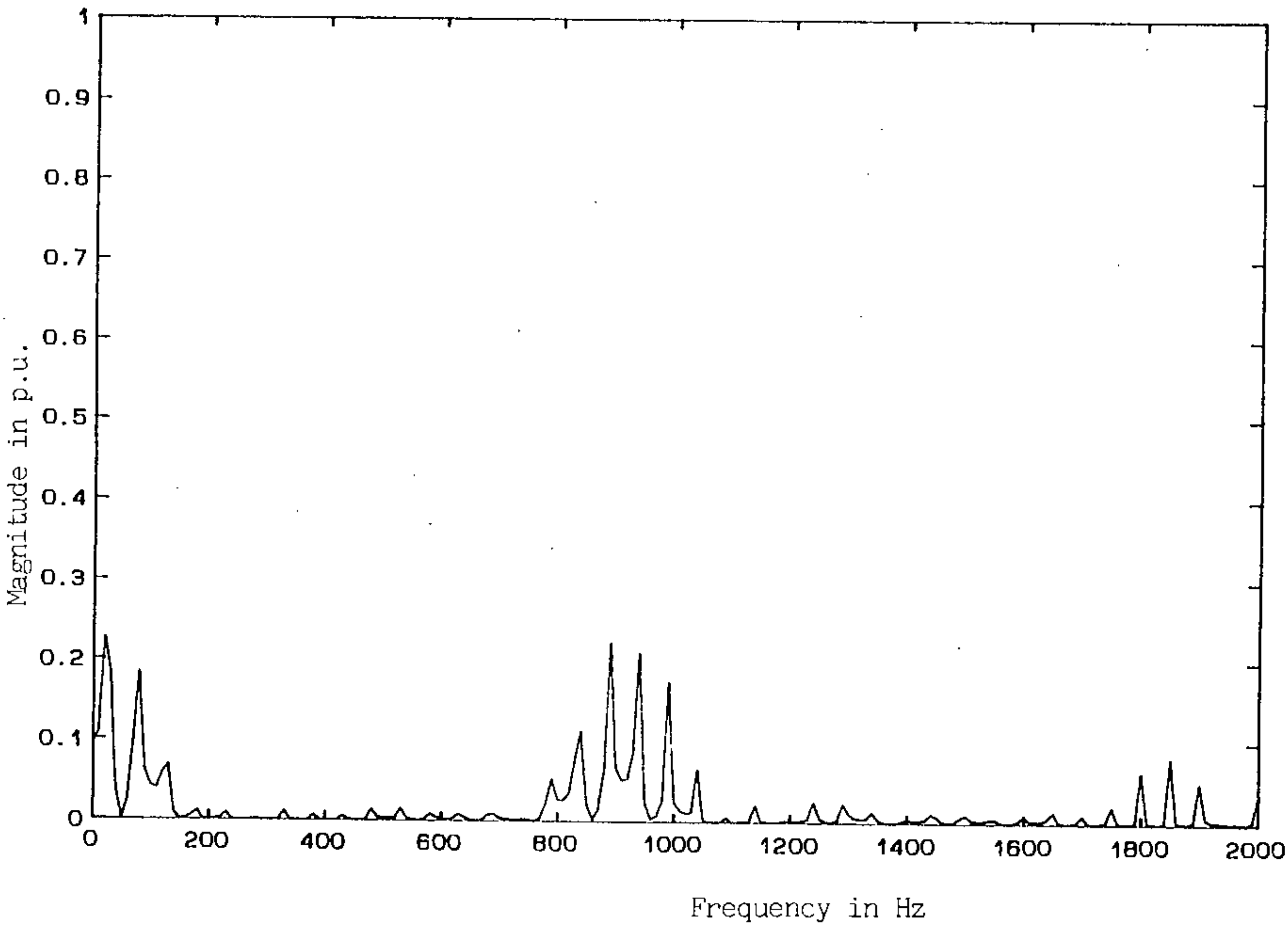


Fig: 2.18 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=9, T_c=.04 Sec

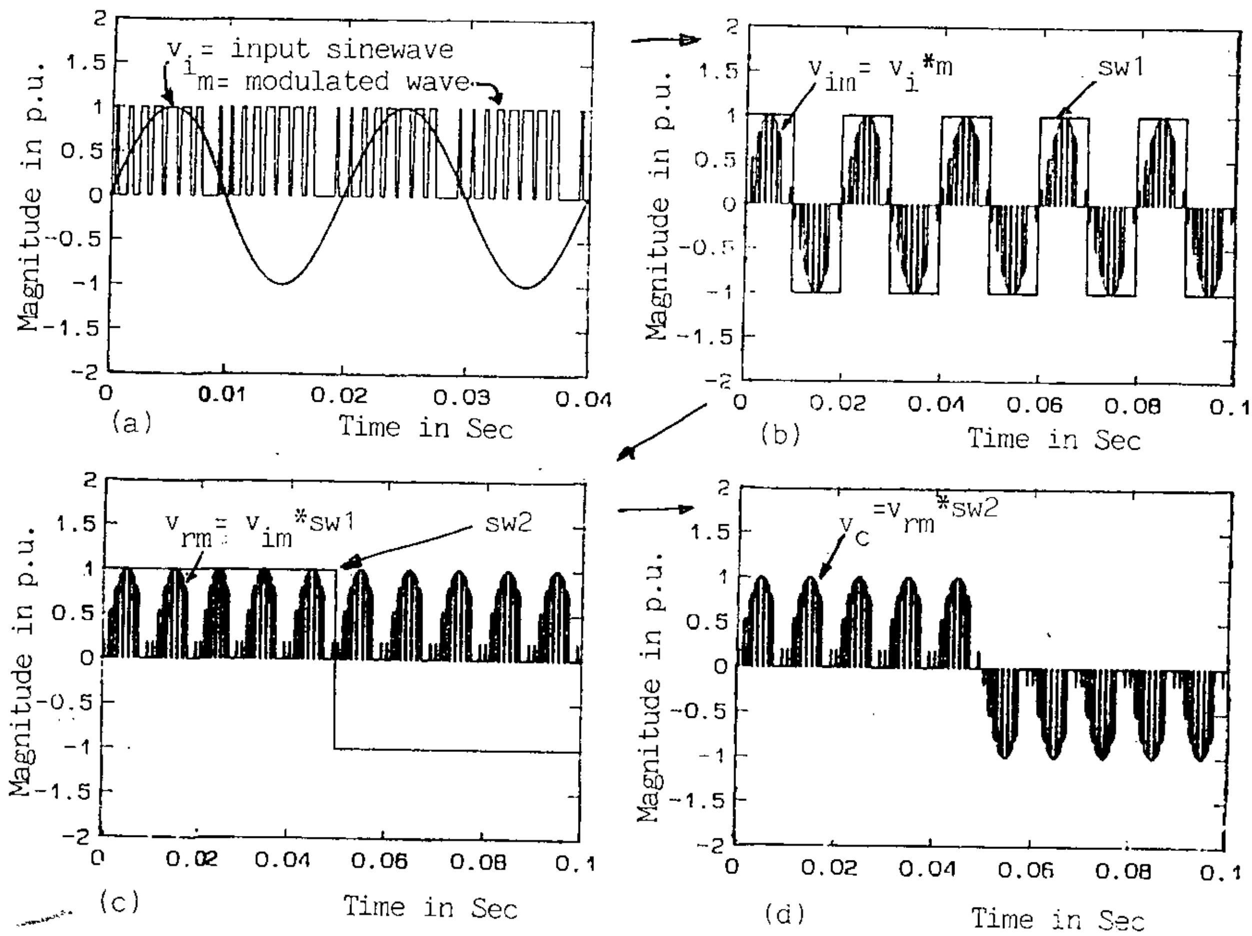


Fig: 2.19 Waveforms of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.1 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Out of the cycloconverter

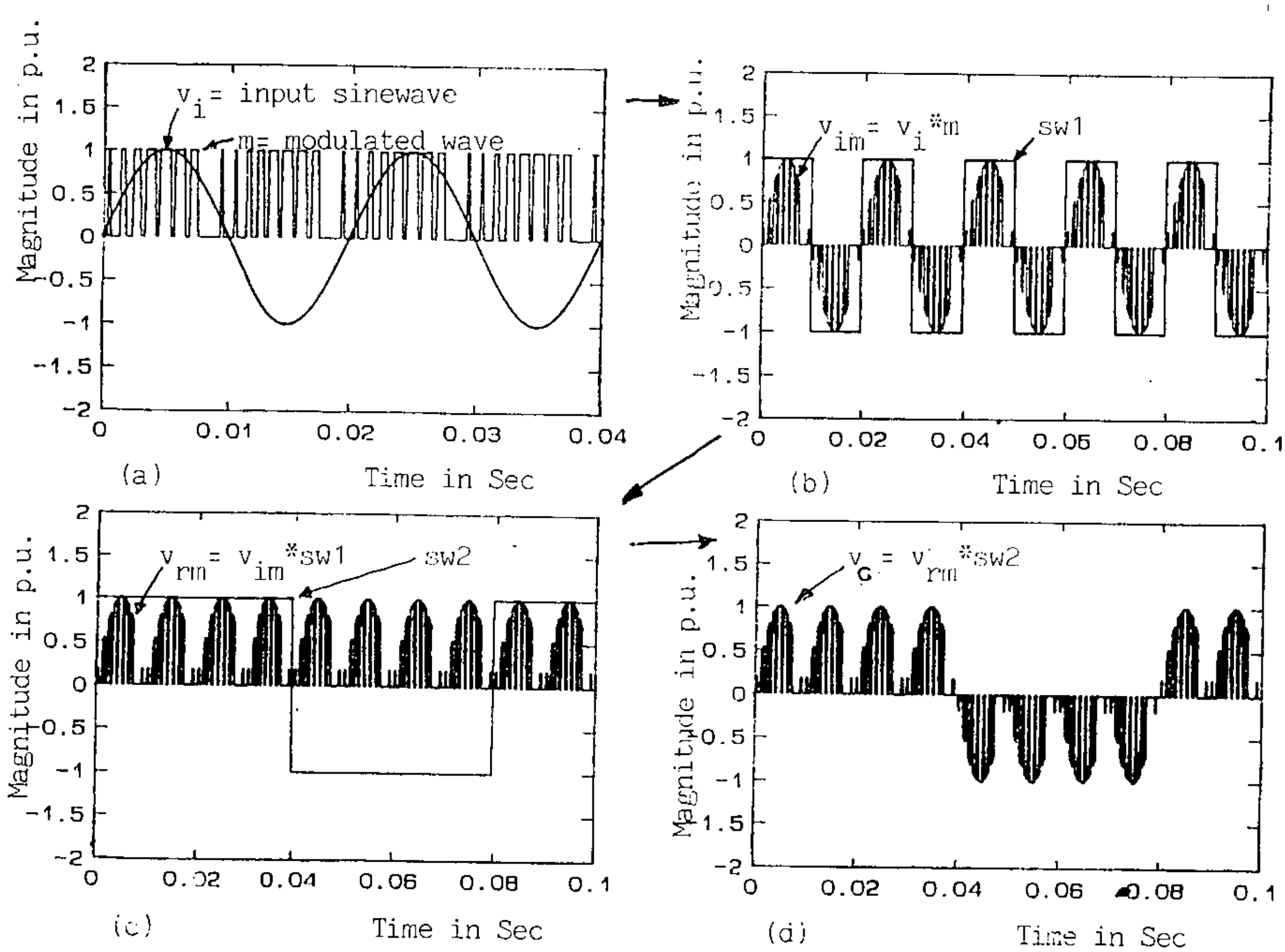


Fig: 2.20 Waveforms of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.08 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cylcloconverter

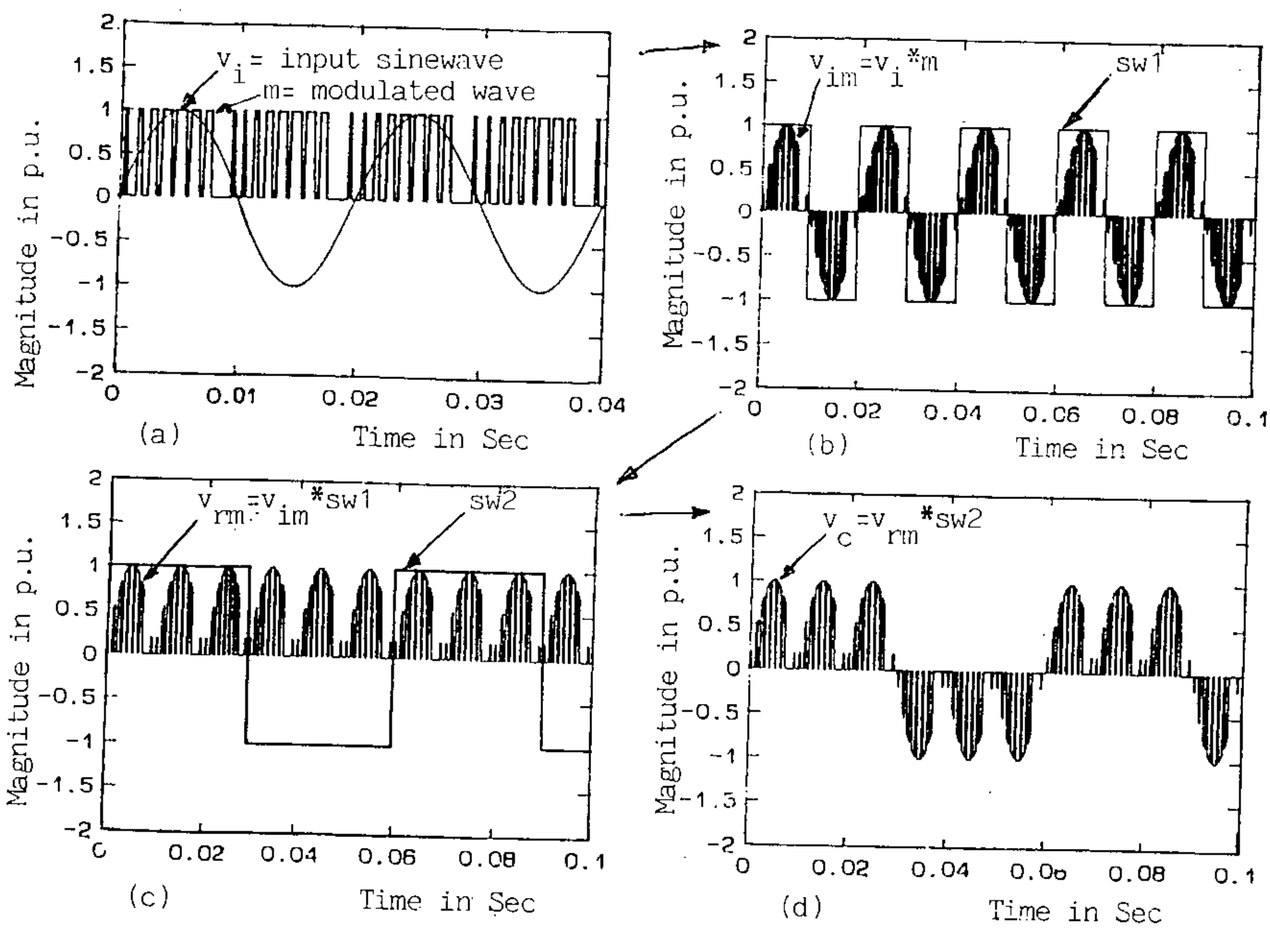


Fig: 2.21 Waveform of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.06 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

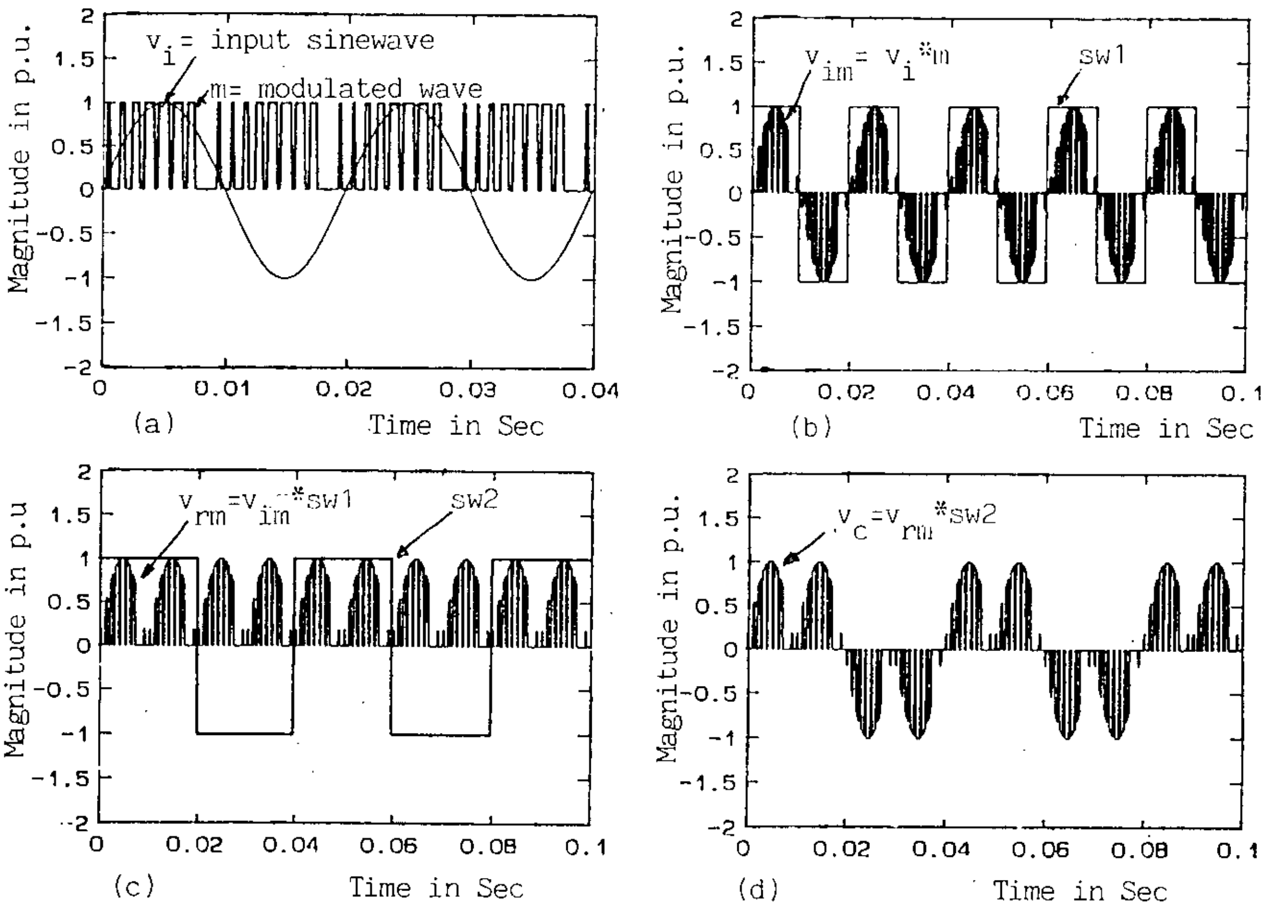


Fig: 2.22 Waveforms of a 1Ø cycloconverter for W=.75, N_p=9, T_c=.04 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveformsw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

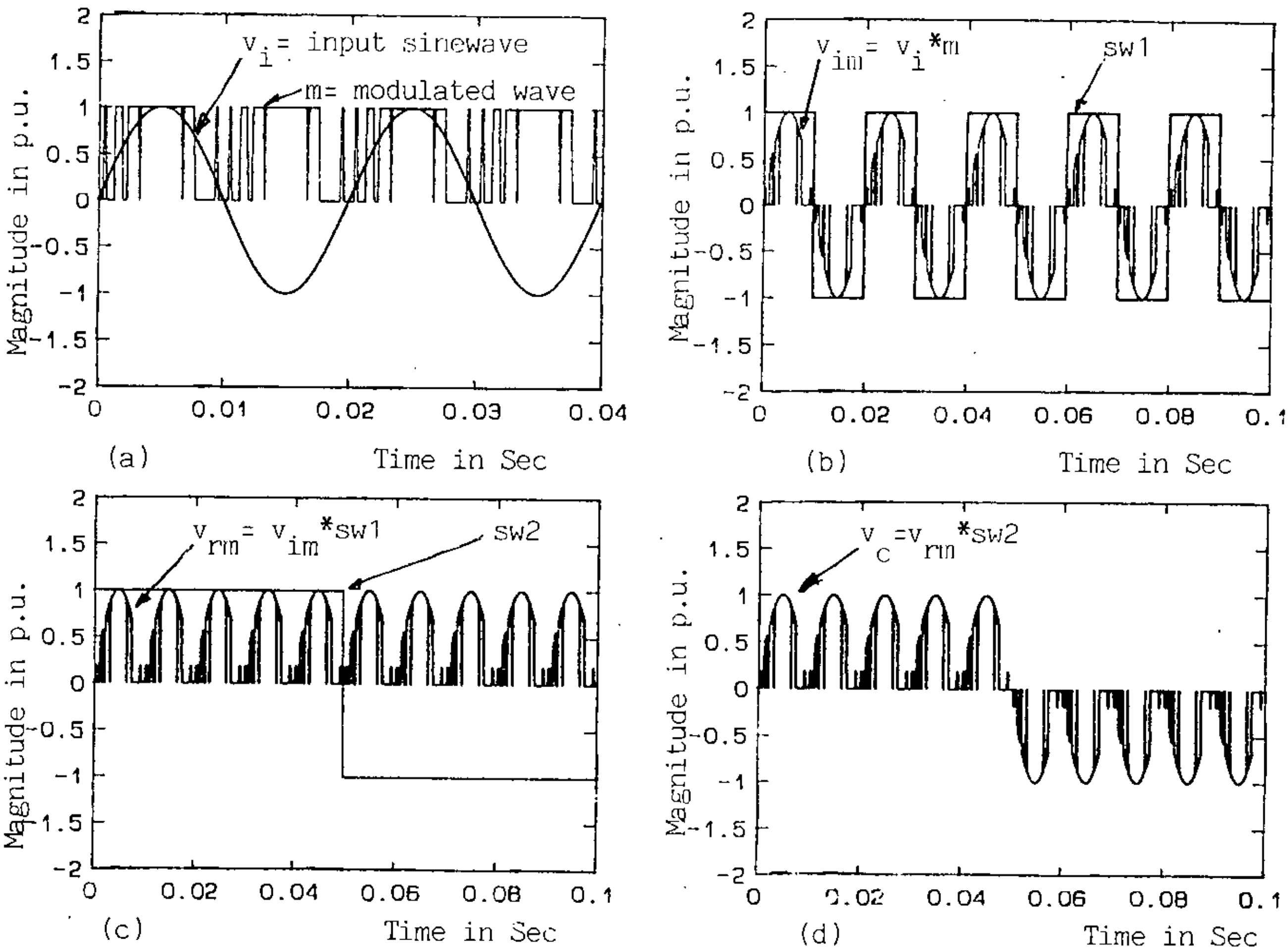


Fig: 2.23 Waveforms of a 1-Ø spwm cycloconverter for W=1.00, N_p=9, T_c=.1 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching wave-form sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

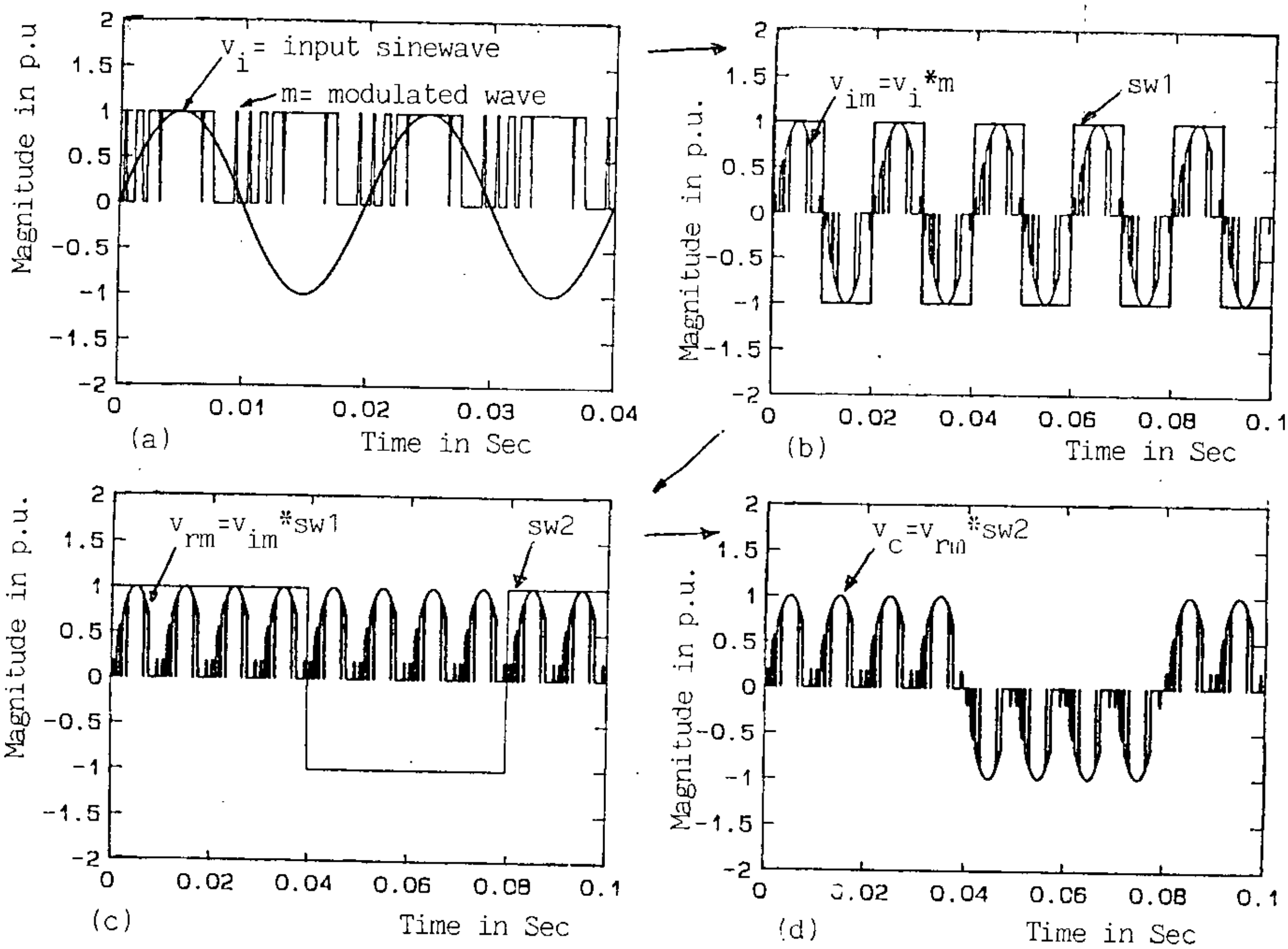


Fig: 2.24 Waveforms of a 1-Ø spwm cycloconverter for W=1.00, N_p=9, T_c=.08 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

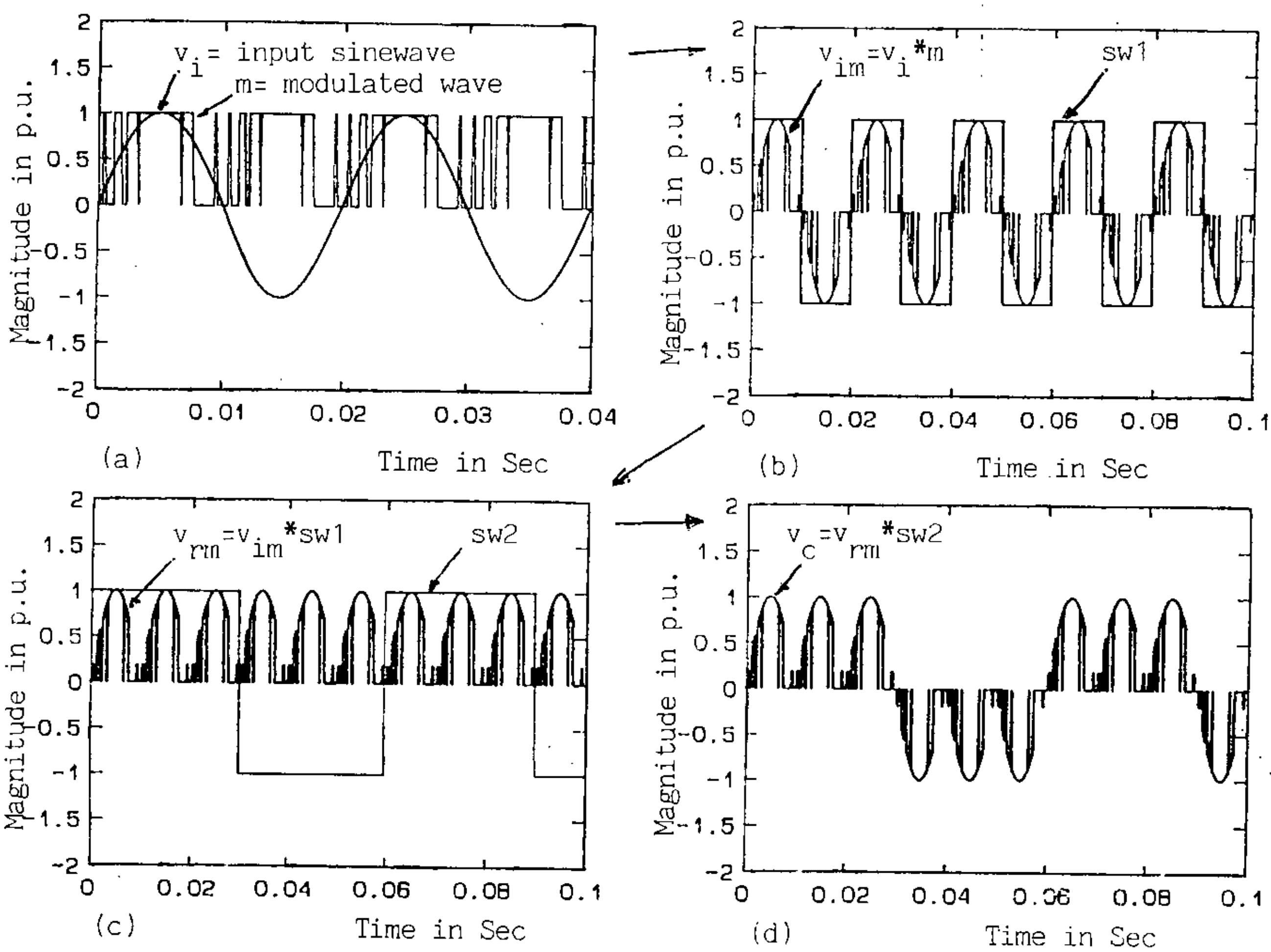


Fig: 2.25 Waveform of a 1-Ø spwm cycloconverter for W=1.00, N_p=9, T_c=.06 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

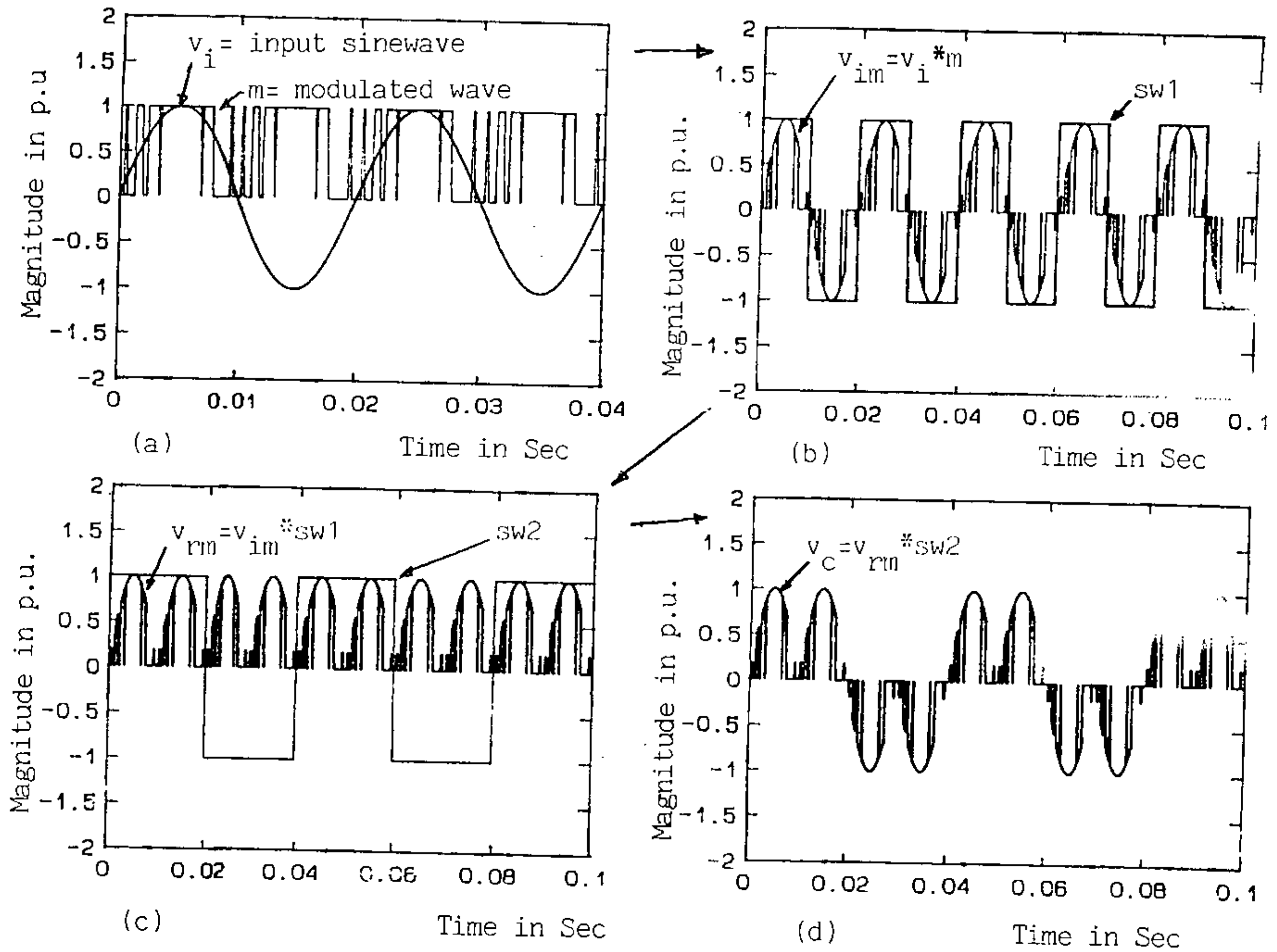


Fig: 2.26 Waveforms of a 1-Ø spWm cycloconverter for W=1, N_p=9, T_c=.04 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

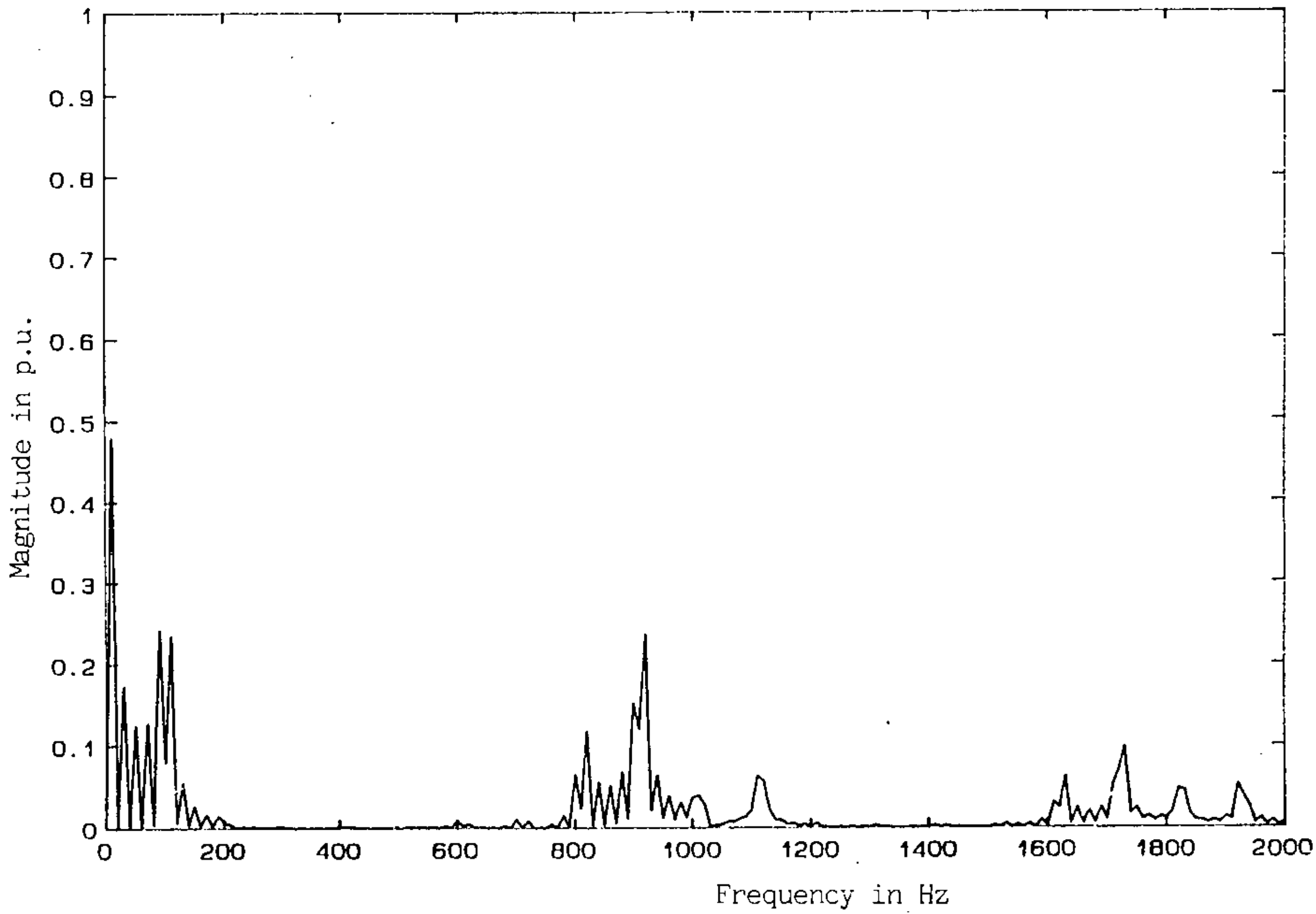


Fig: 2.27 Spectrum of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.1 Sec

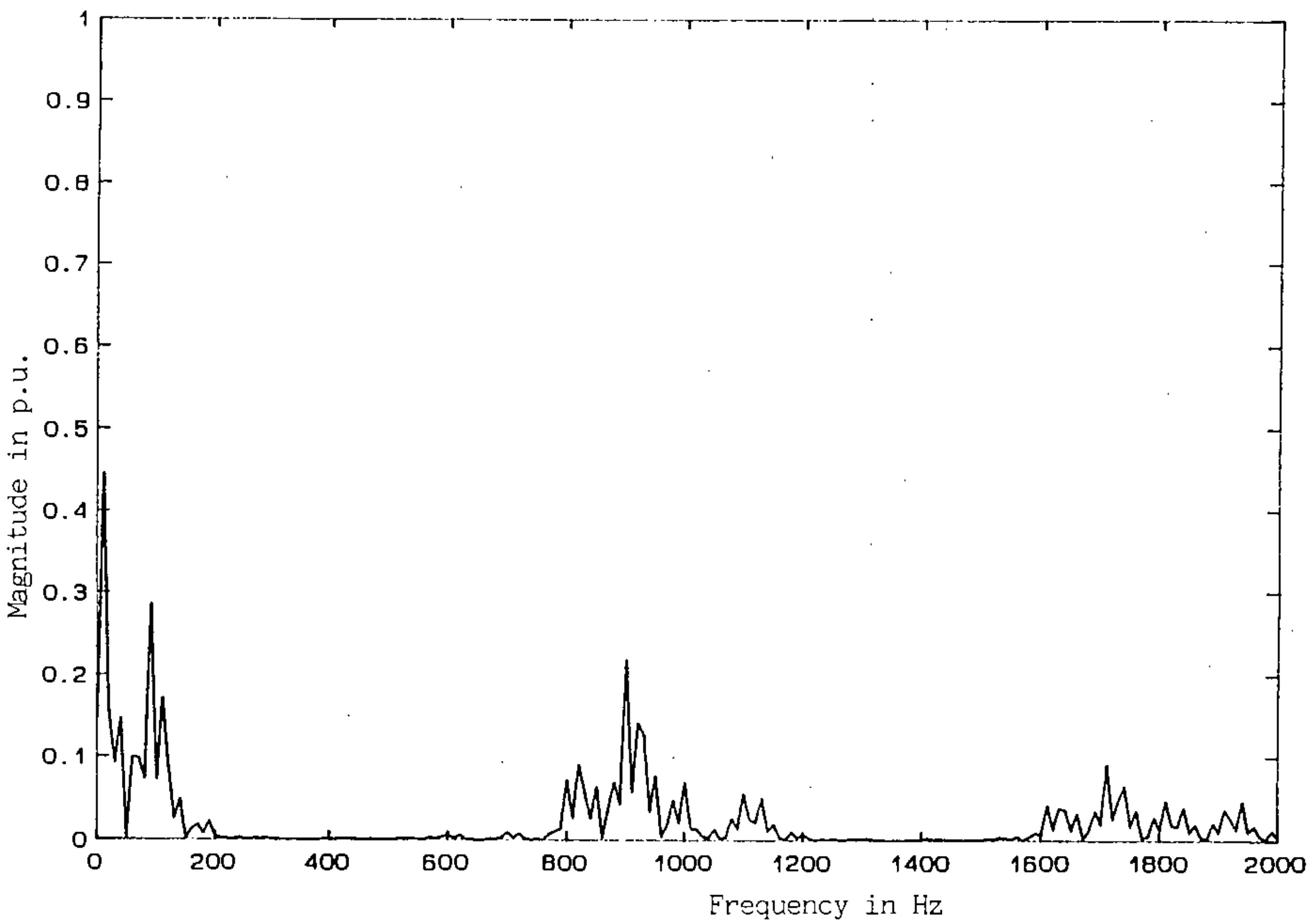


Fig: 2.28 Spectrum of a 1-Ø spwm cycloconverter for W=.75,N_p=9, T_c=.08 Sec

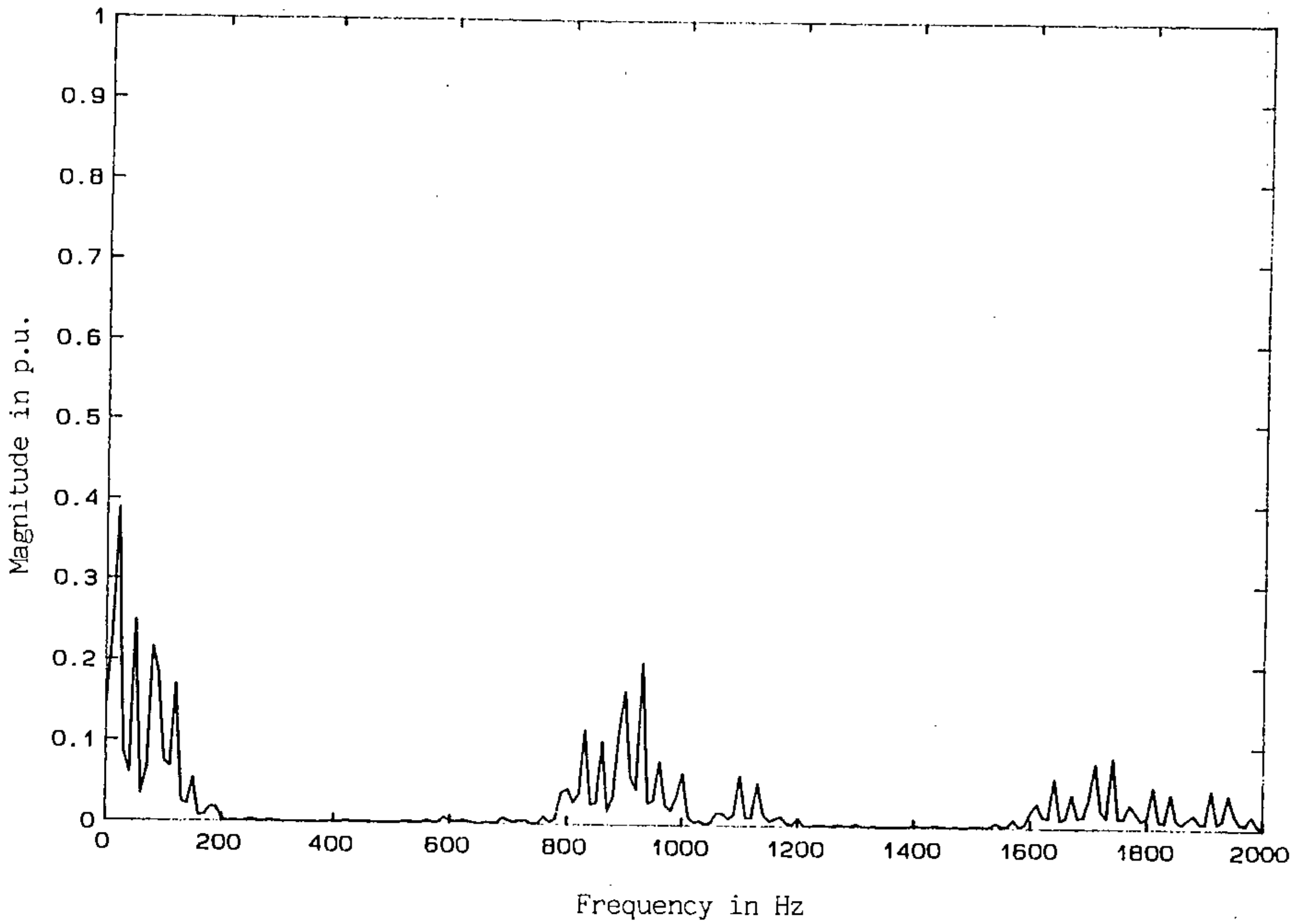


Fig: 2.29 Spectrum of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.06 Sec

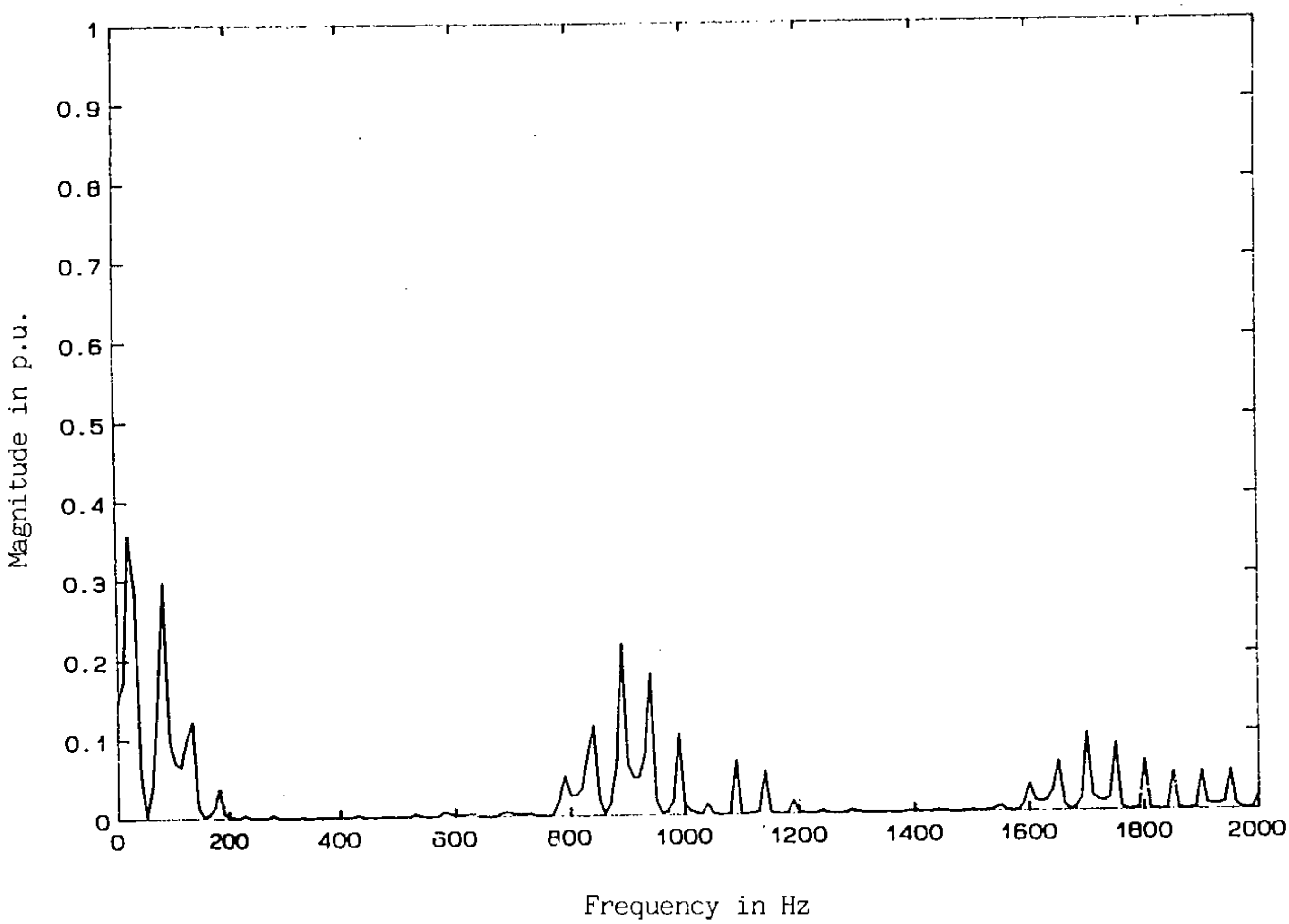


Fig: 2.30 Spectrum of a 1-Ø spwm cycloconverter for W=.75, N_p=9, T_c=.04 Sec

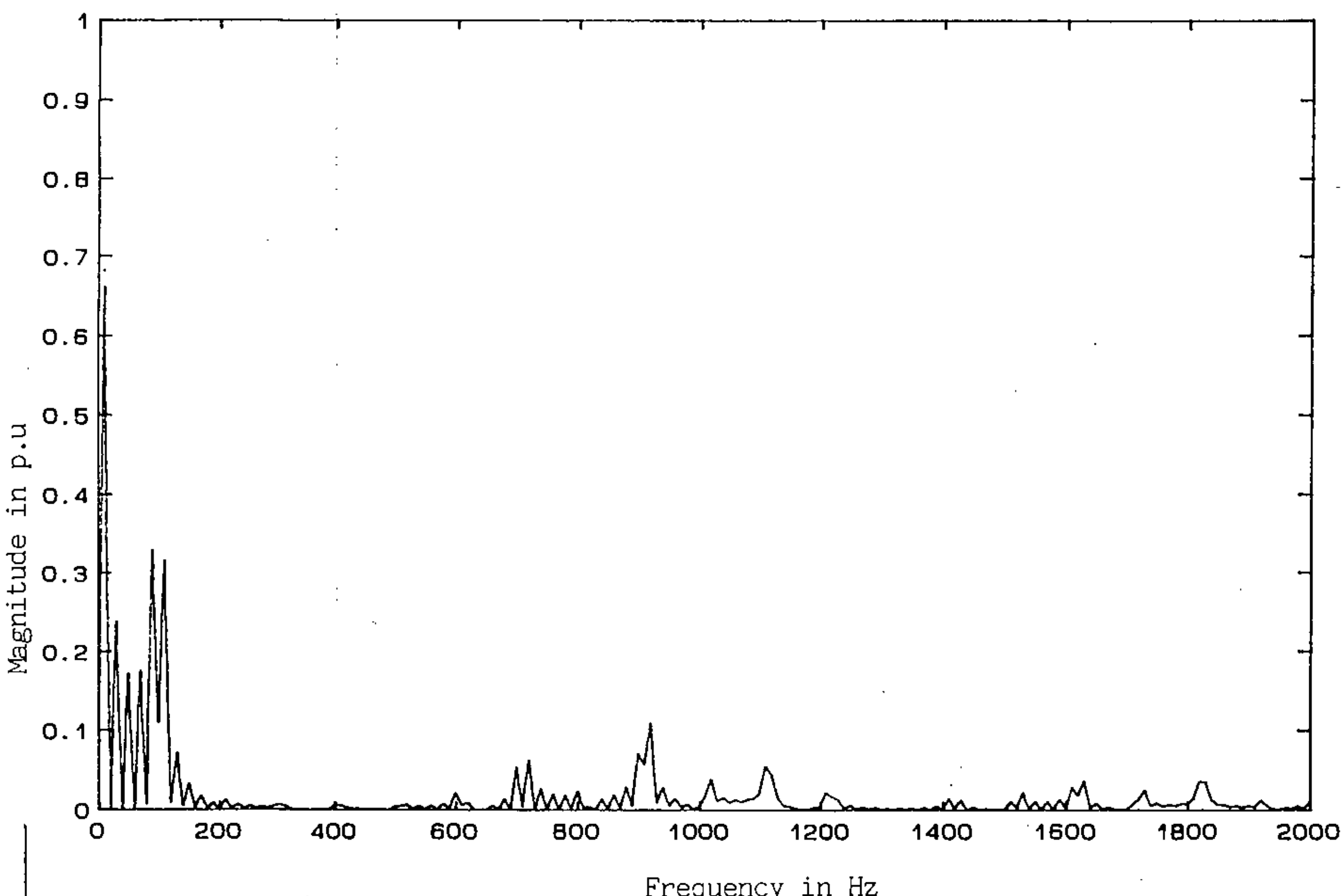


Fig: 2.31 Spectrum of a 1-Ø spwm cycloconverter for W=1.00, N_p=9, T_c=.1 Sec

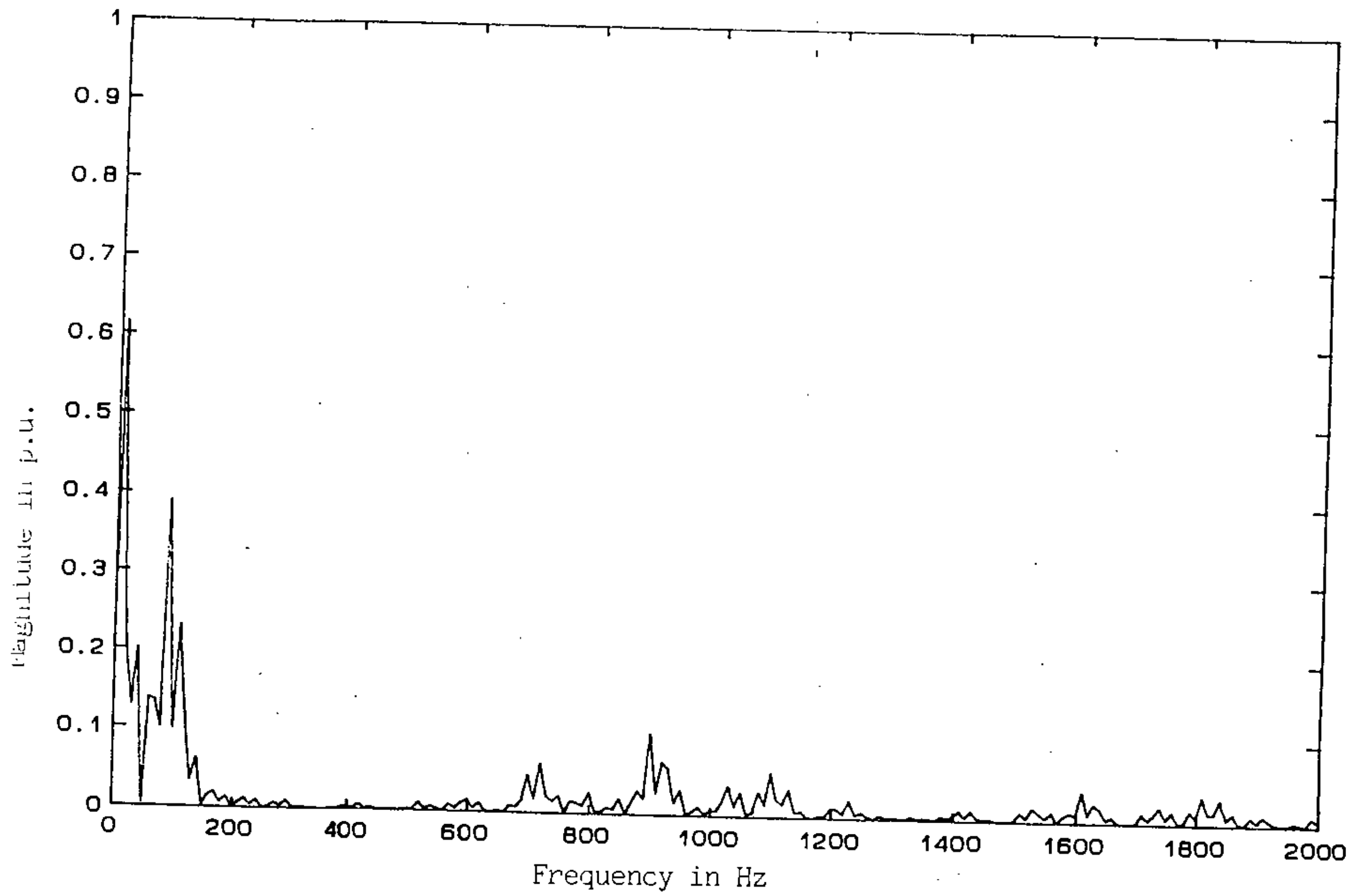


Fig: 2.32 Spectrum of a 1-Ø spwm cycloconverter for W= 1, N_p=9, T_c=.08 Sec

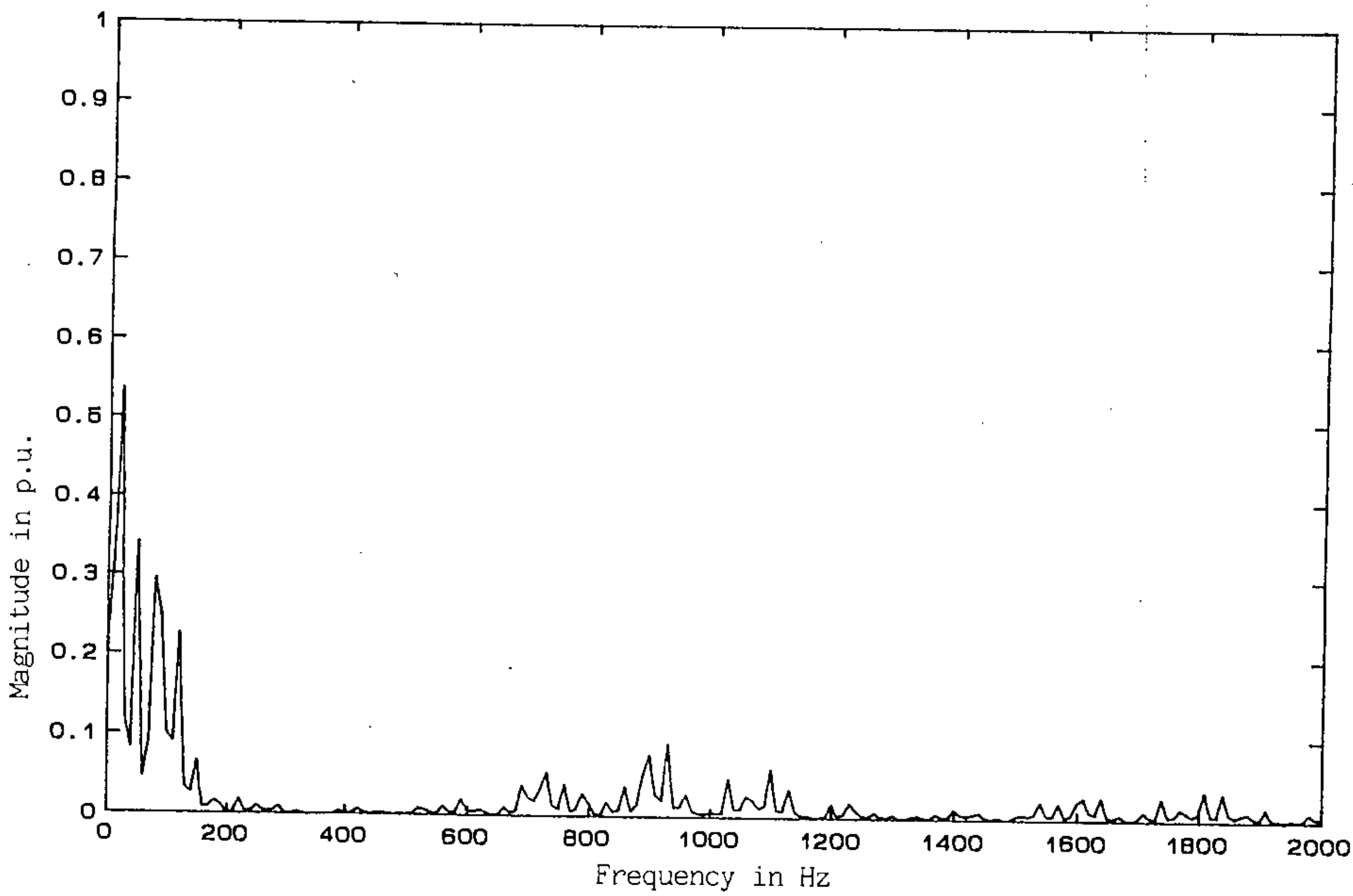


Fig: 2..33 Spectrum of a 1-Ø spwm Cycloconverter for W=1, N_p=9, T_c=.06 Sec

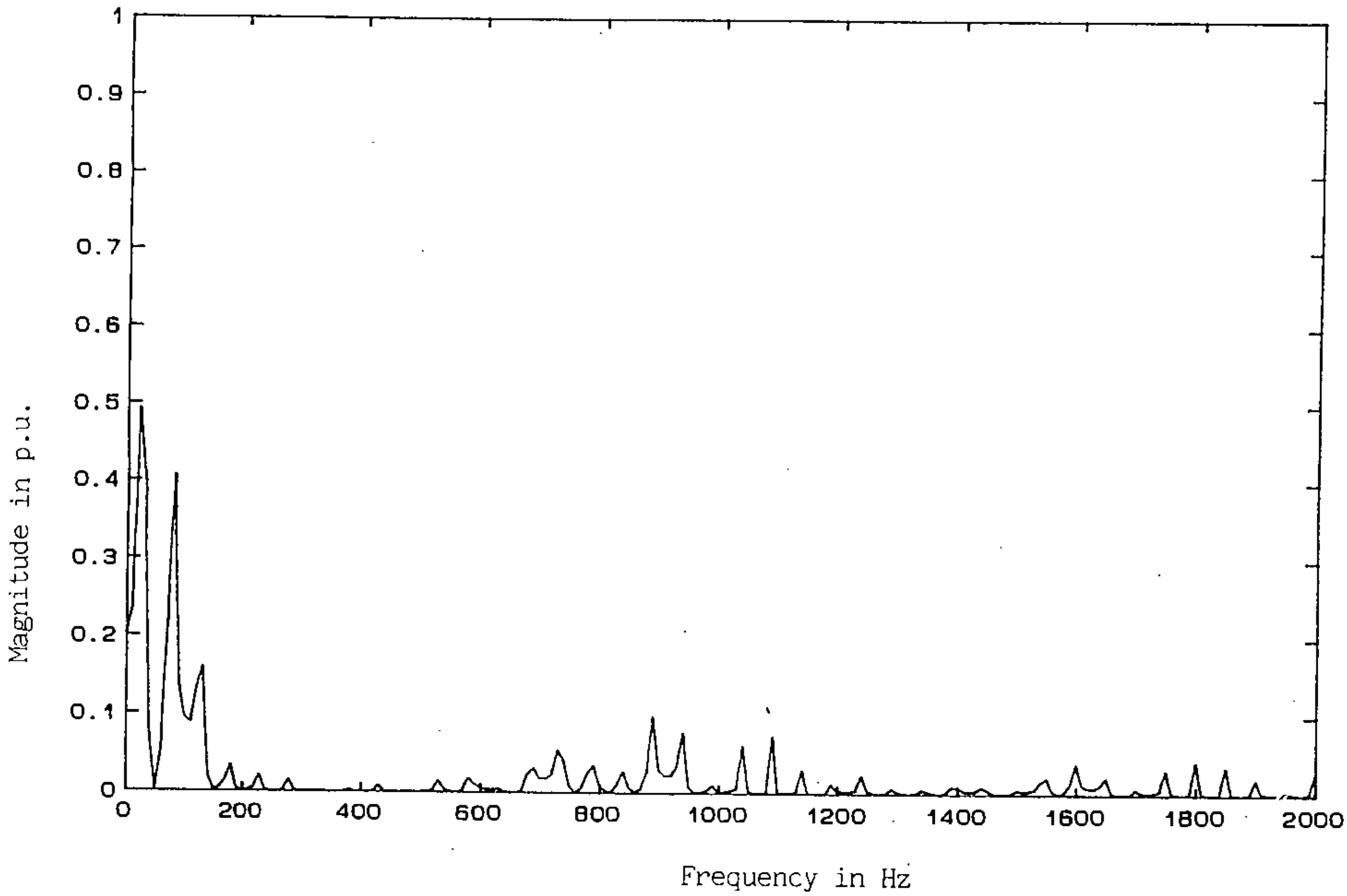


Fig: 2.34 Spectrum of a 1-Ø spwm cycloconverter for W=1.00, N_p=9, T_c=.04 Sec

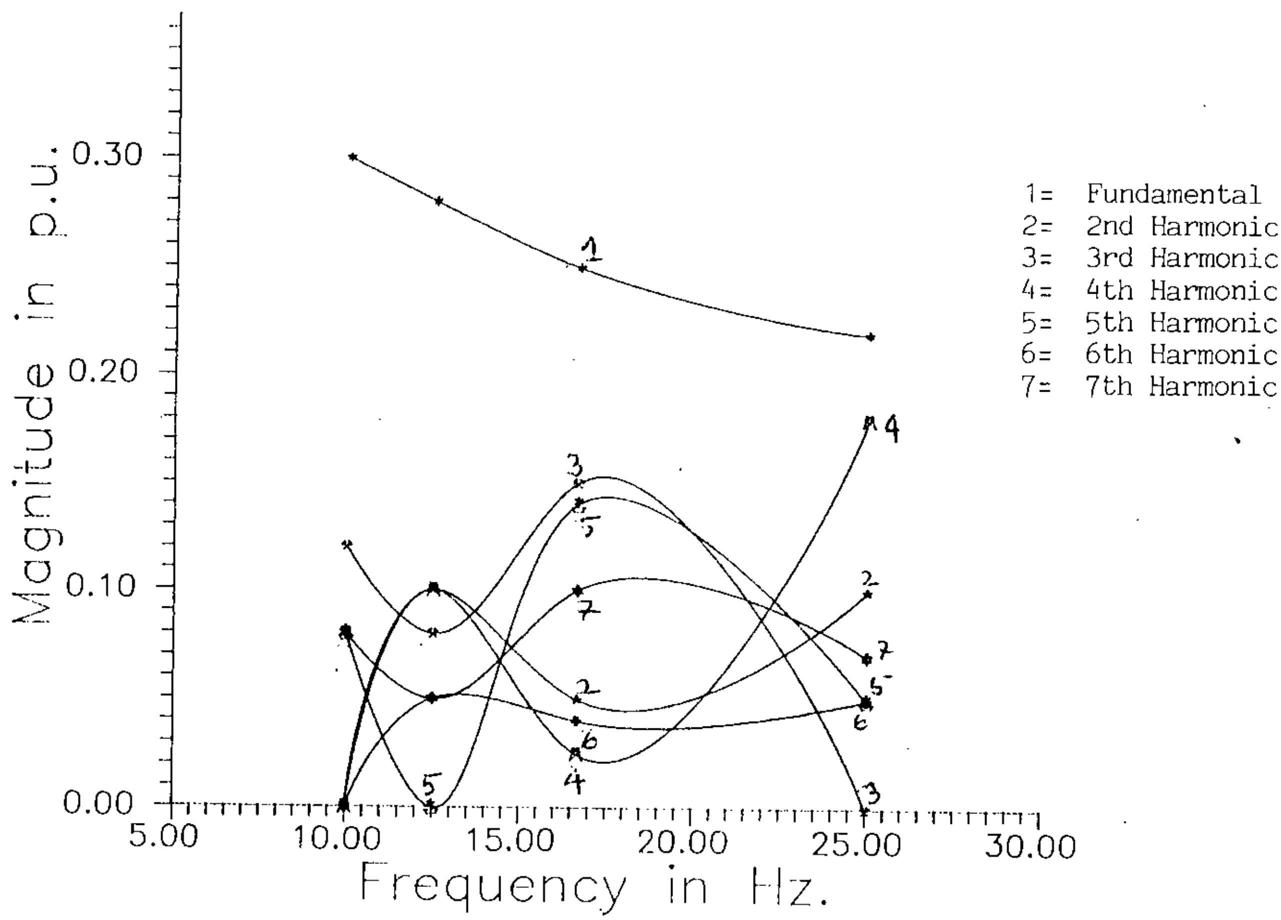


Fig: 2.35 Result of spectral analysis of a 1-Ø spwm cycloconverter for W=.5, N_p=9

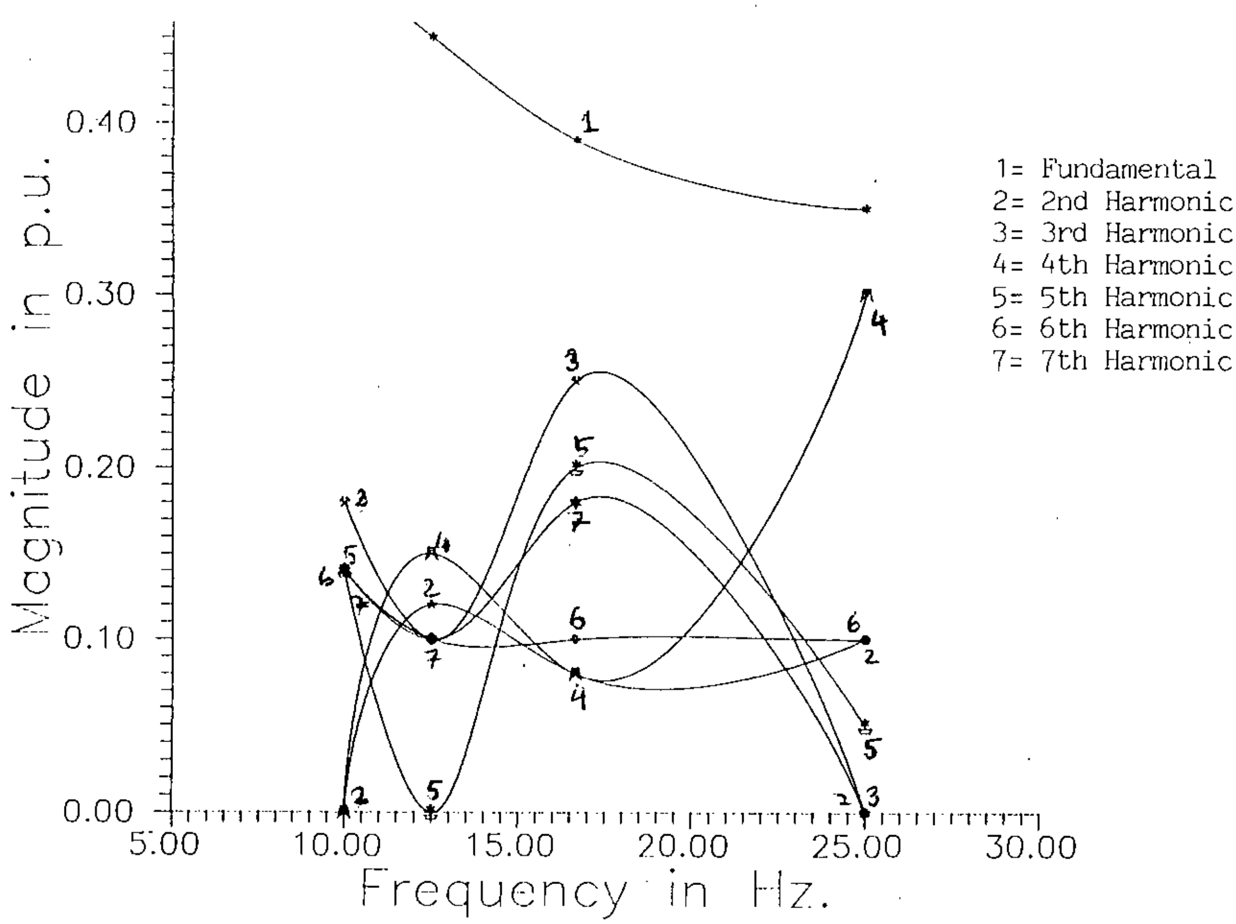


Fig: 2.36 Result of spectral analysis of a 1-Ø spwm cycloconverter for W=.75, N_p=9

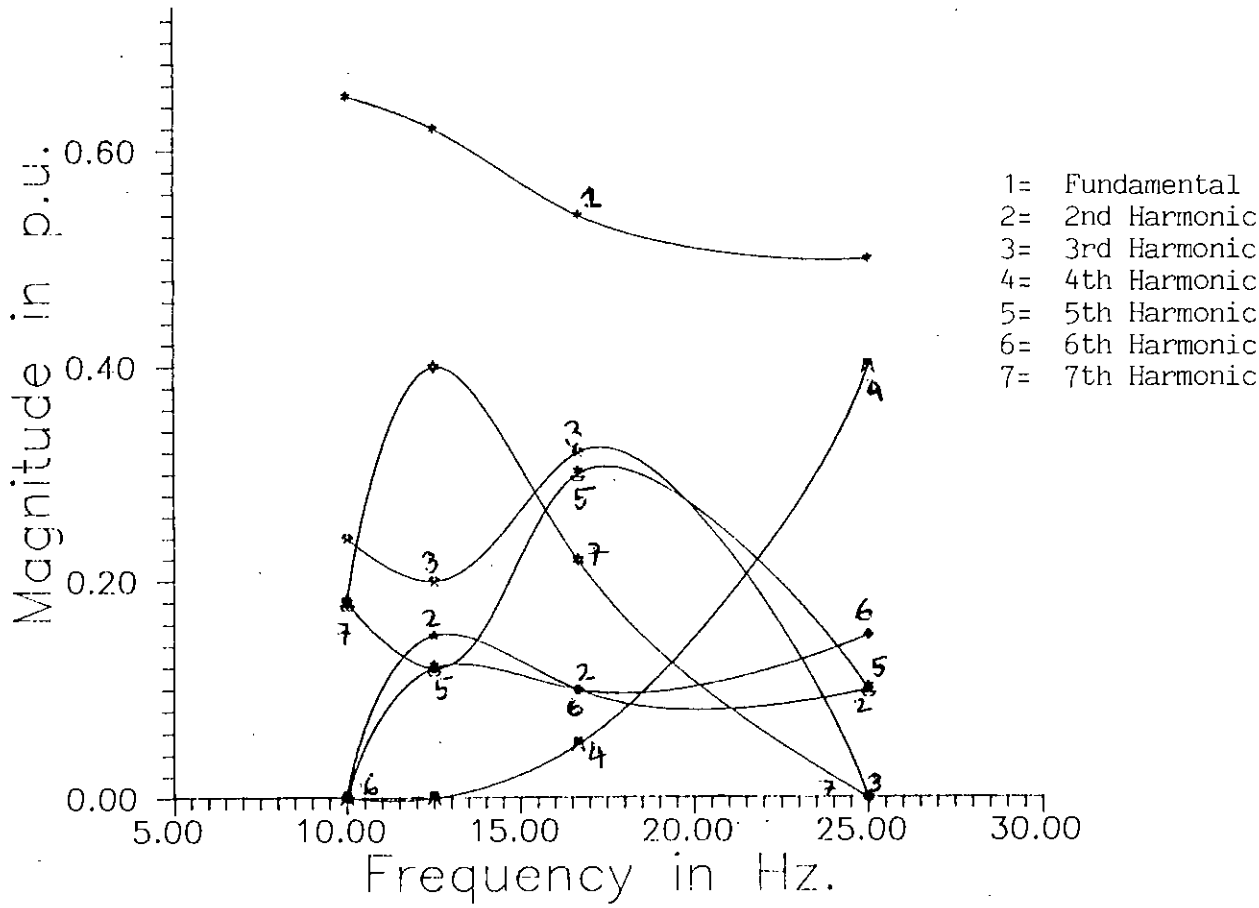


Fig: 2.37 Result of spectral analysis of a 1-Ø spwm cycloconverter for W=1, N_p=9.

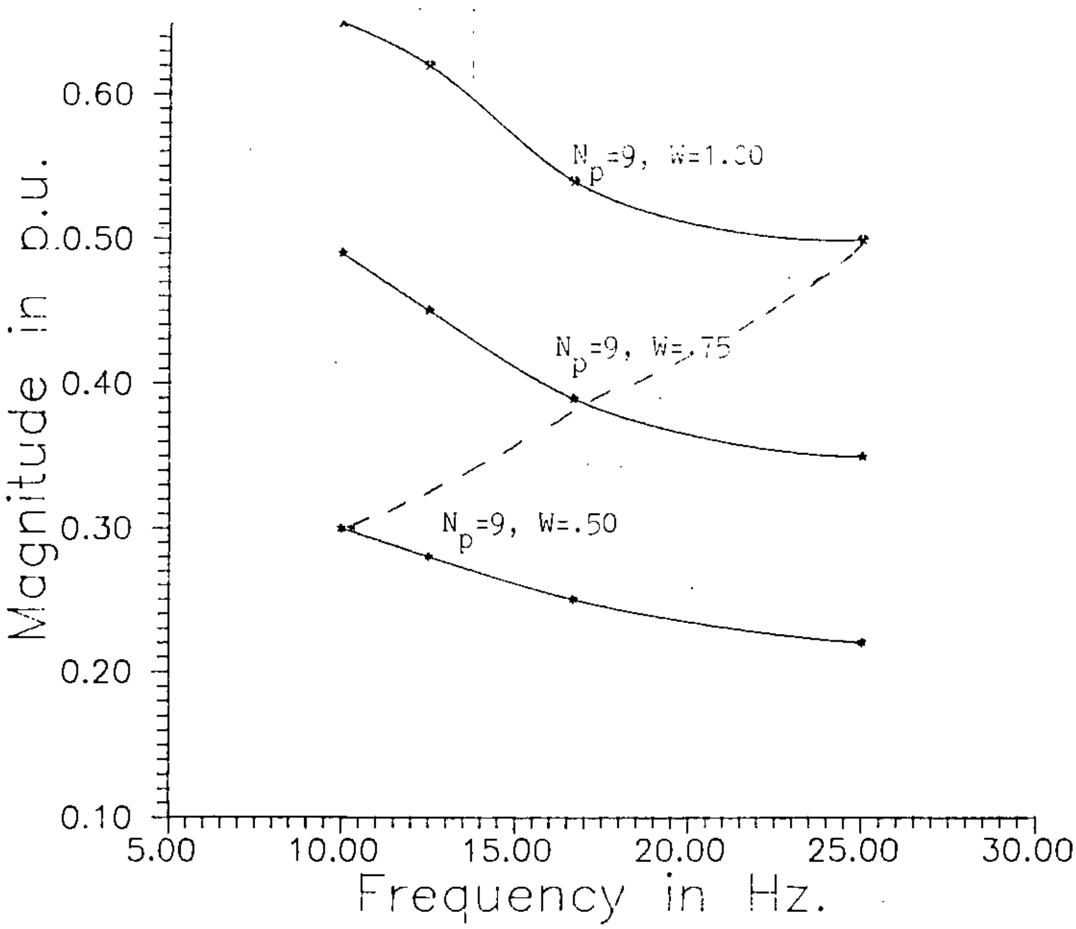


Fig: 2.38 Fundamental voltage variation for 1-Ø spwm cycloconverter with N_p constant, W= variable

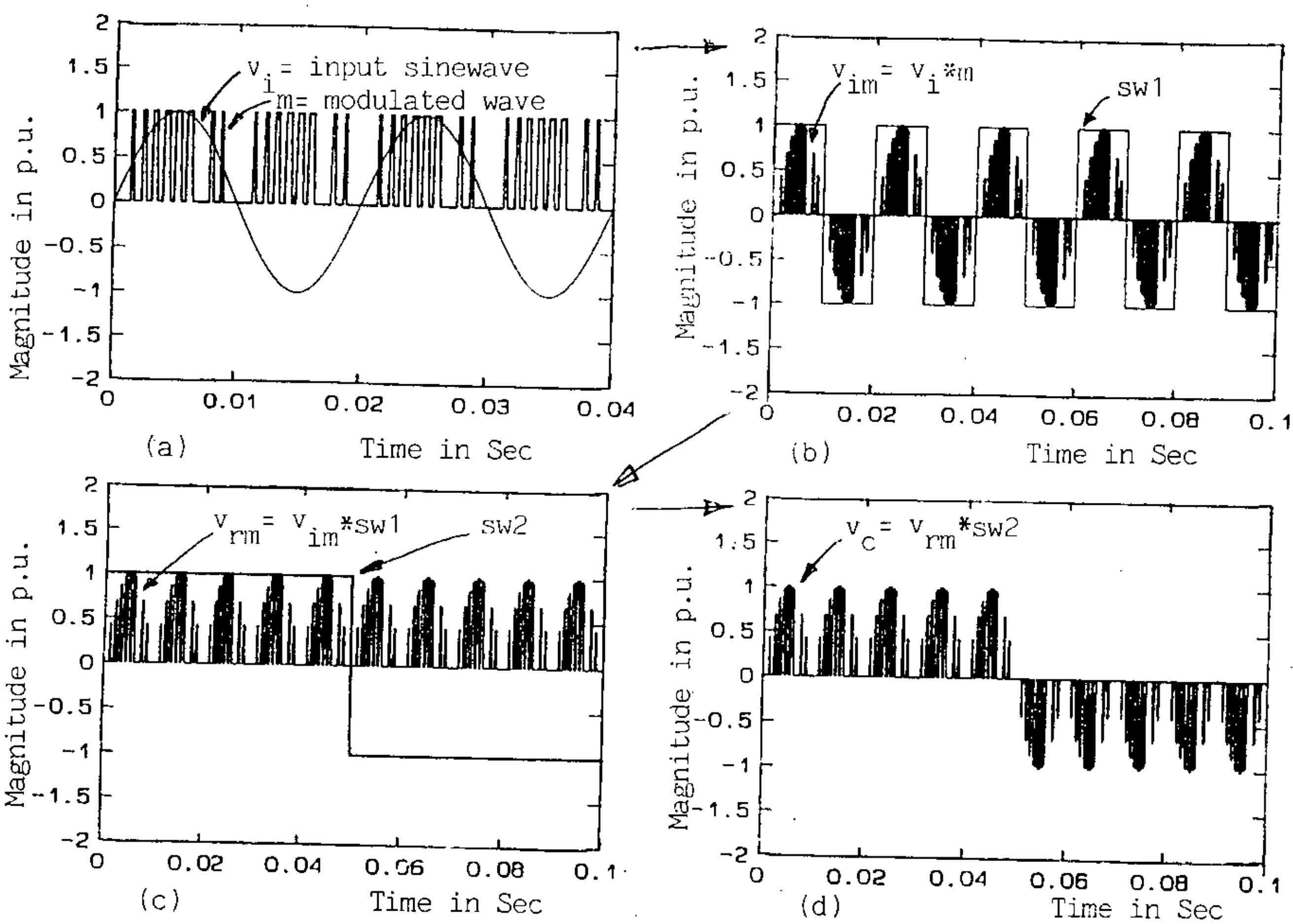


Fig: 2.39 Waveforms of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.1 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

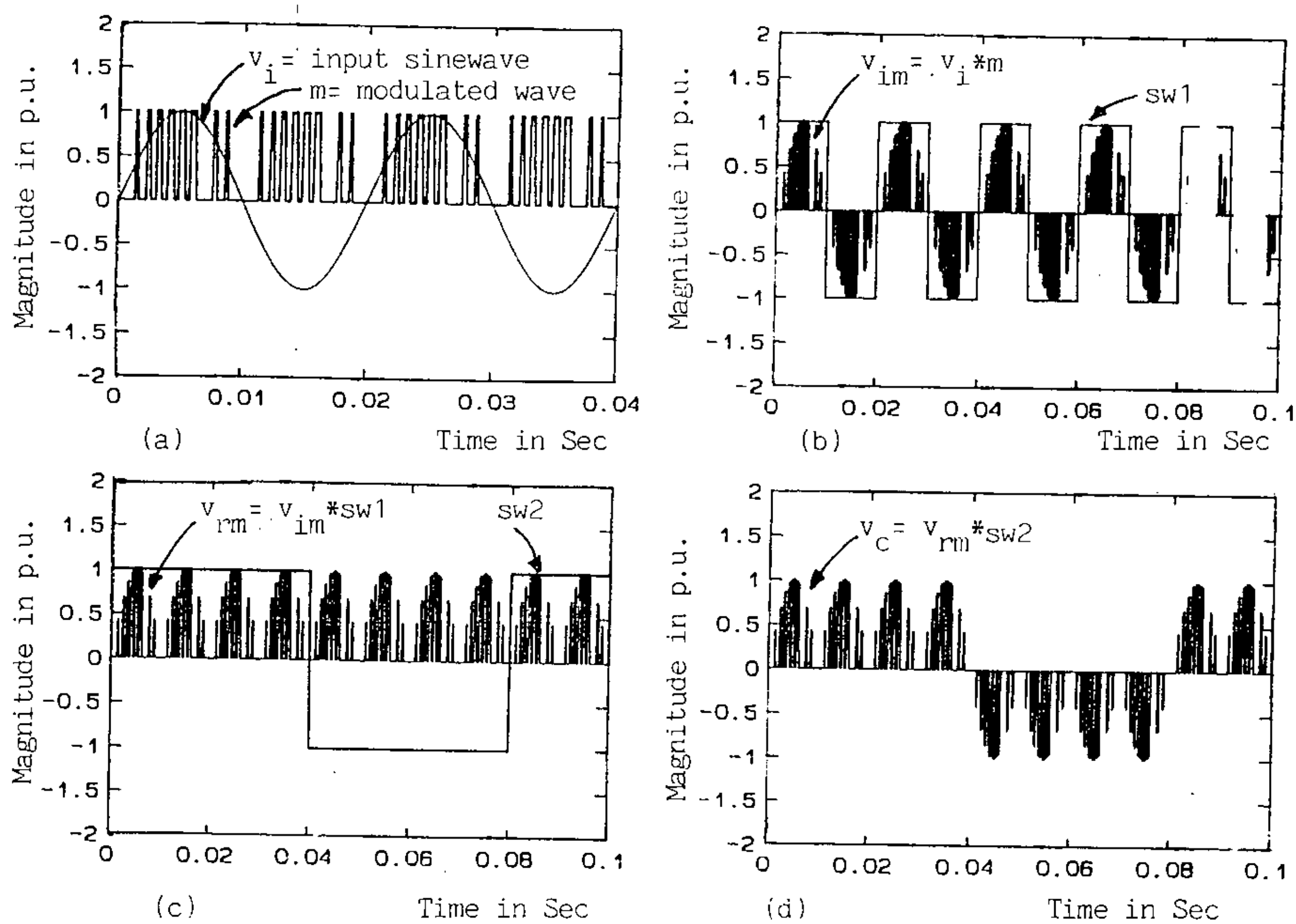


Fig: 2.40 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.08 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

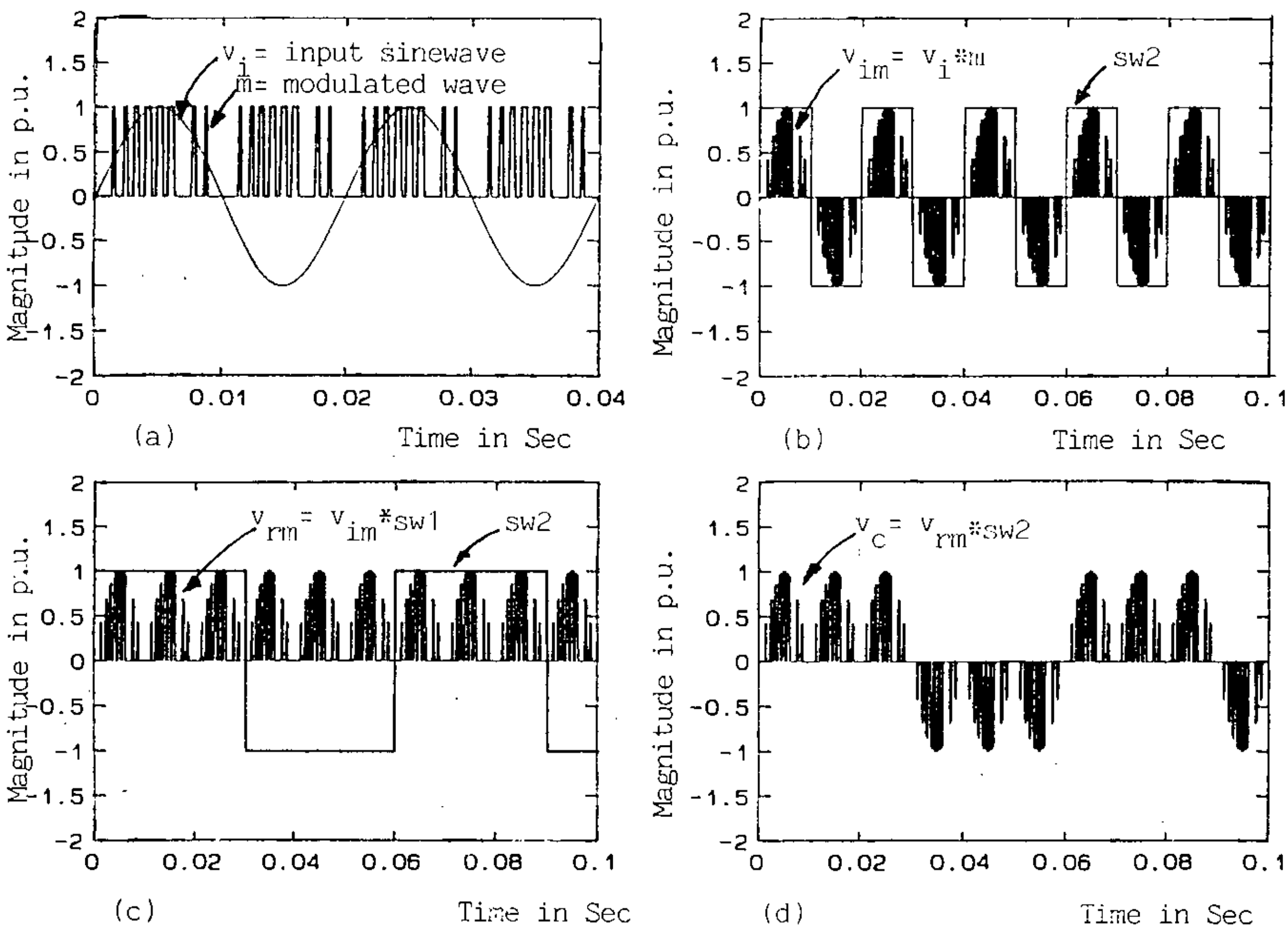


Fig: 2.41 Waveform of a 1-Øspwm cyclcconverter for W=.5, N_p=11, T_c=.06 Sec

a) Reference input npwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulataed rectified wave and switching waveform sw2
d) Output of the cycloconverter

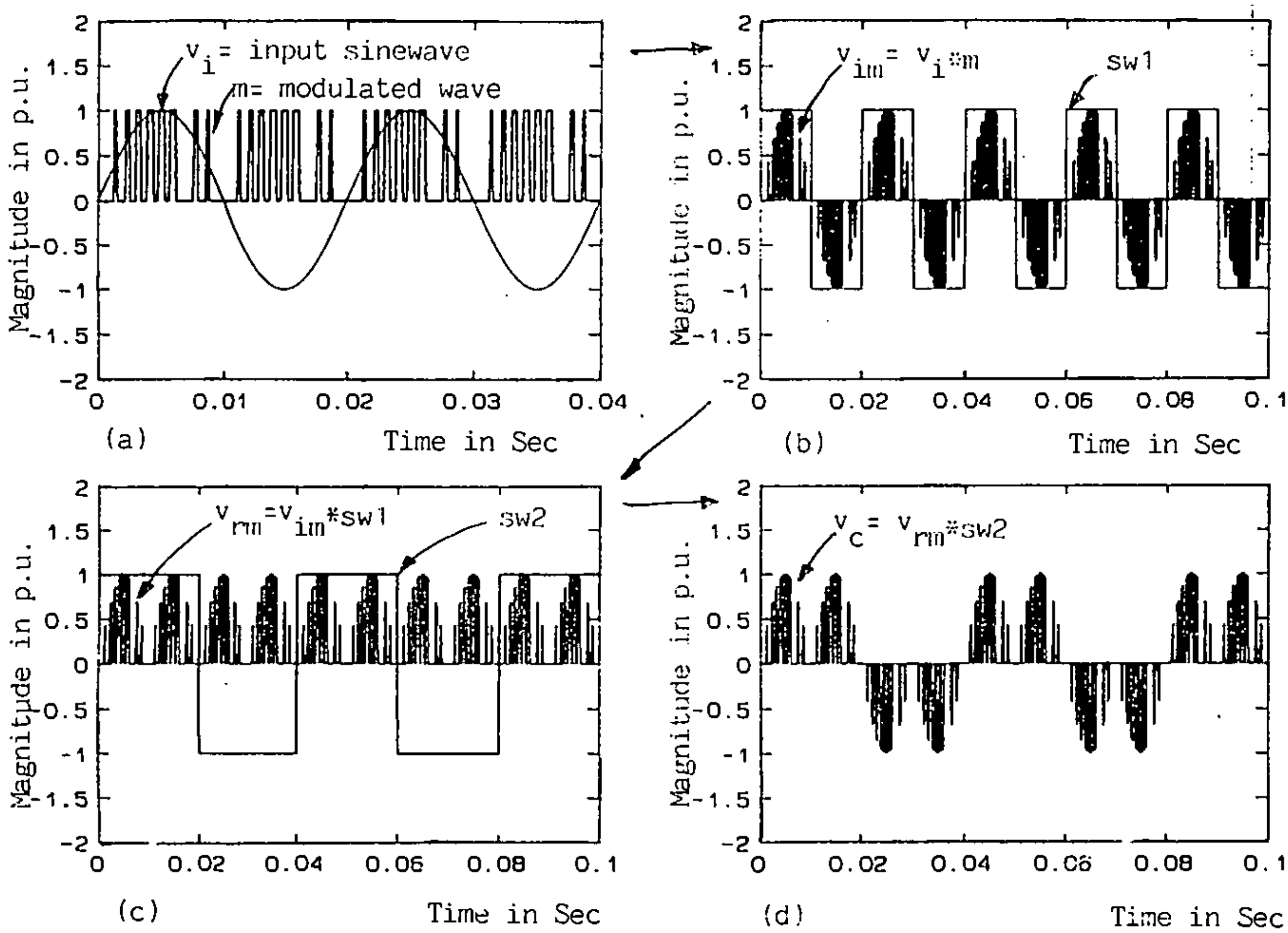


Fig: 2.42 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.04 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

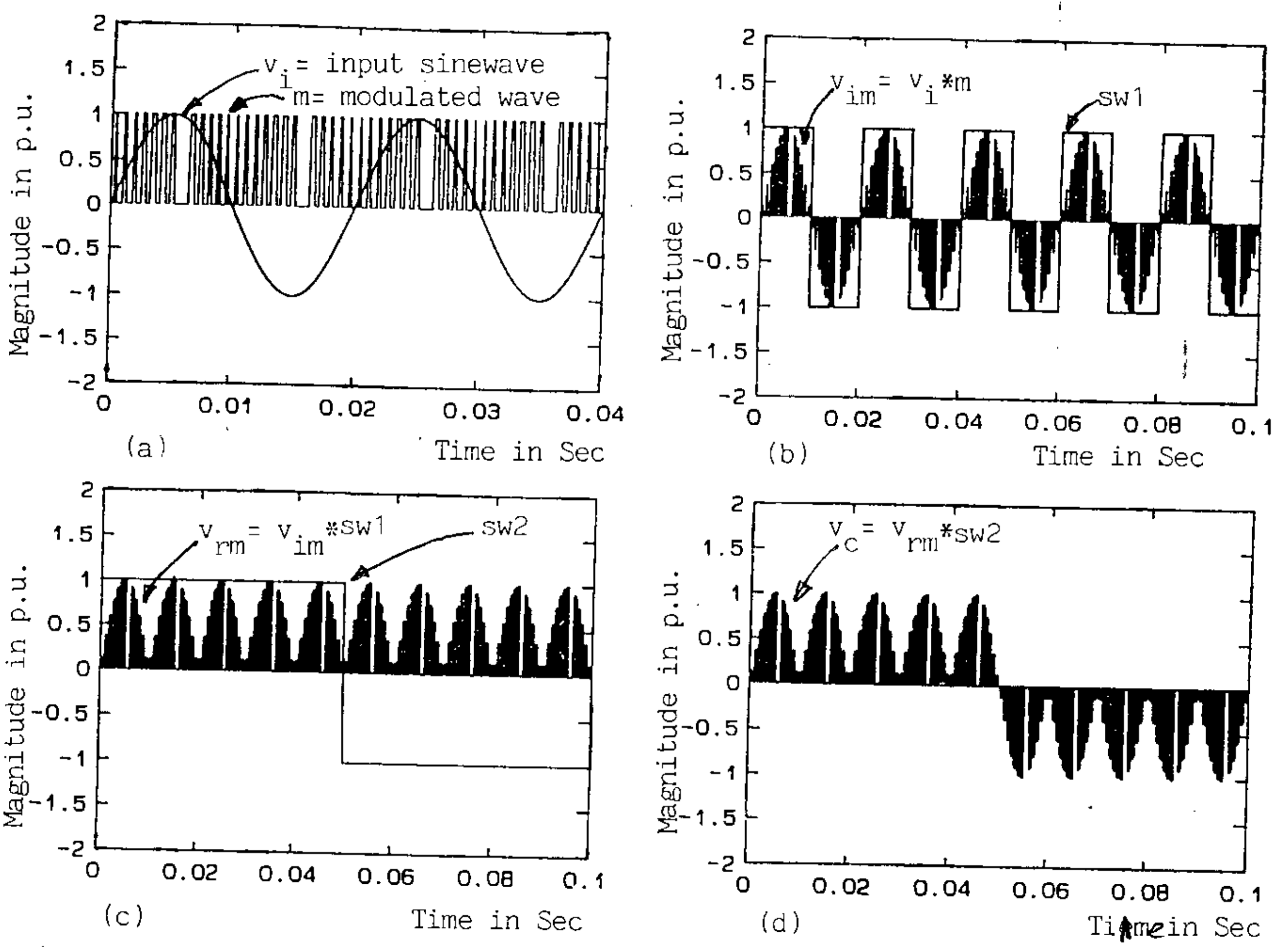


Fig: 2.43 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=30, T_c=.1 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

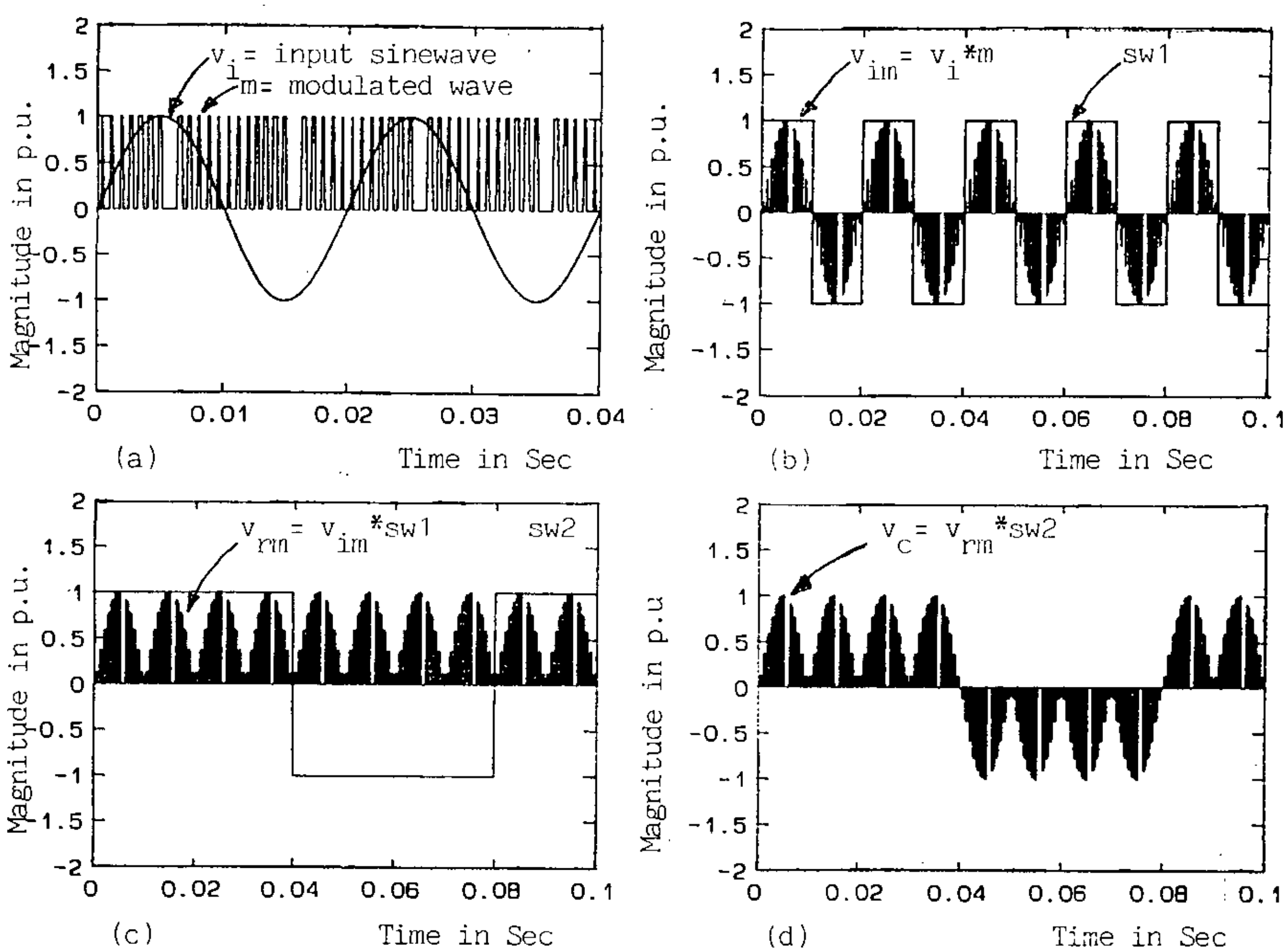


Fig: 2.44 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=30, T_c=.08 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

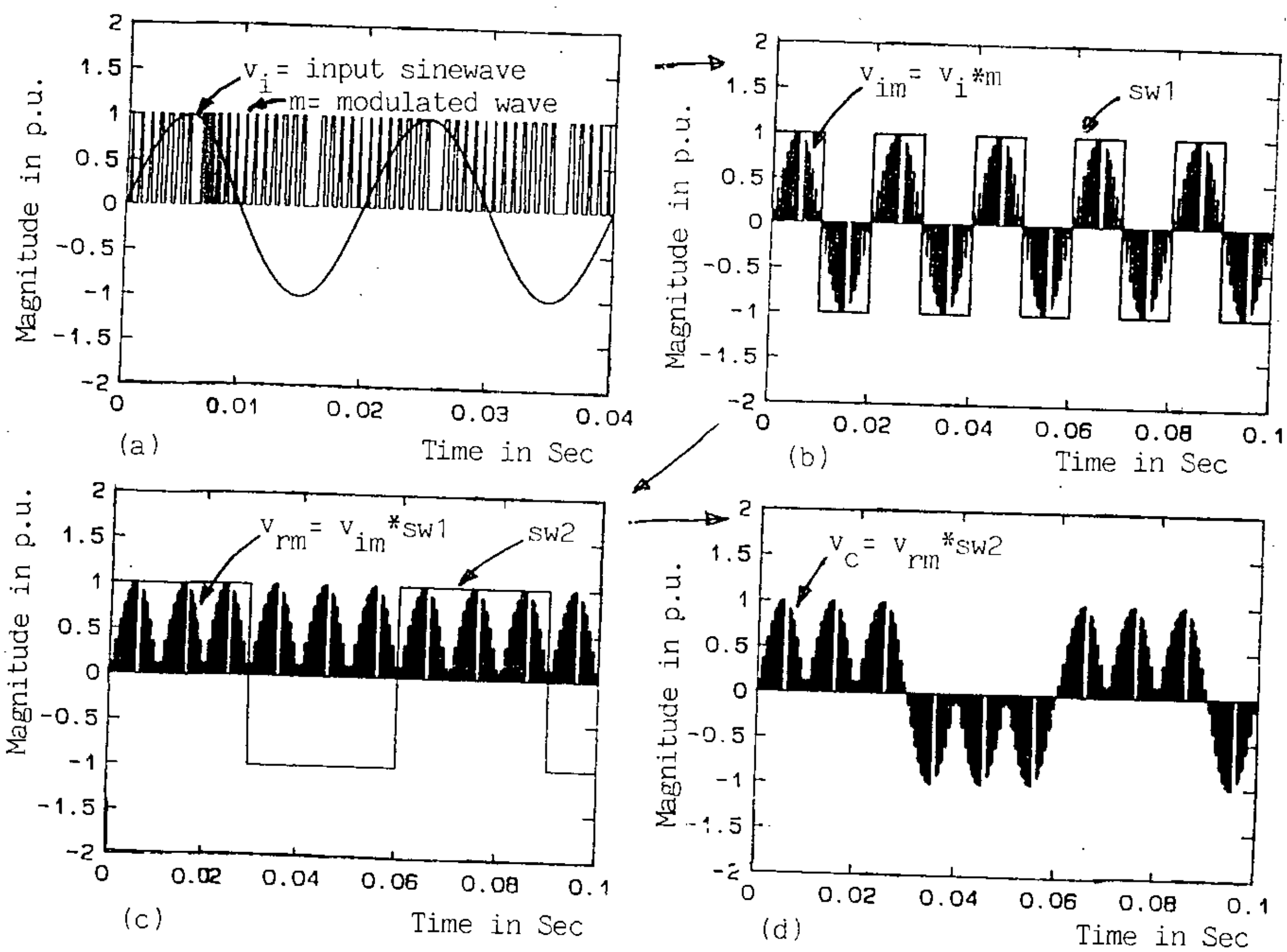


Fig: 2.45 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=30, T_c=.06

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

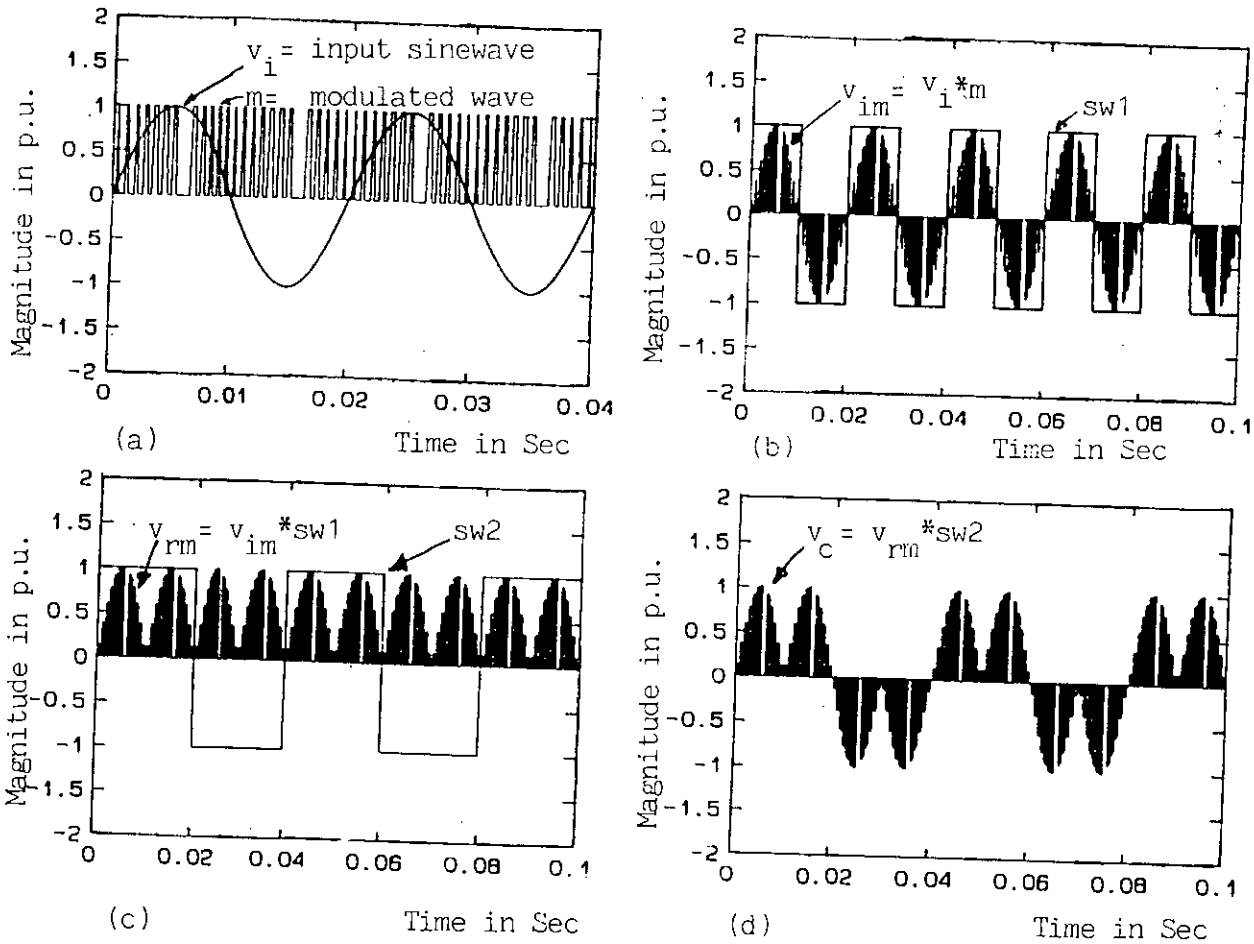


Fig: 2.46 Waveform of a 1-Ø spwm cycloconverter for W=.5, N_p=13, T_c=.04 Sec

a) Reference input and pwm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

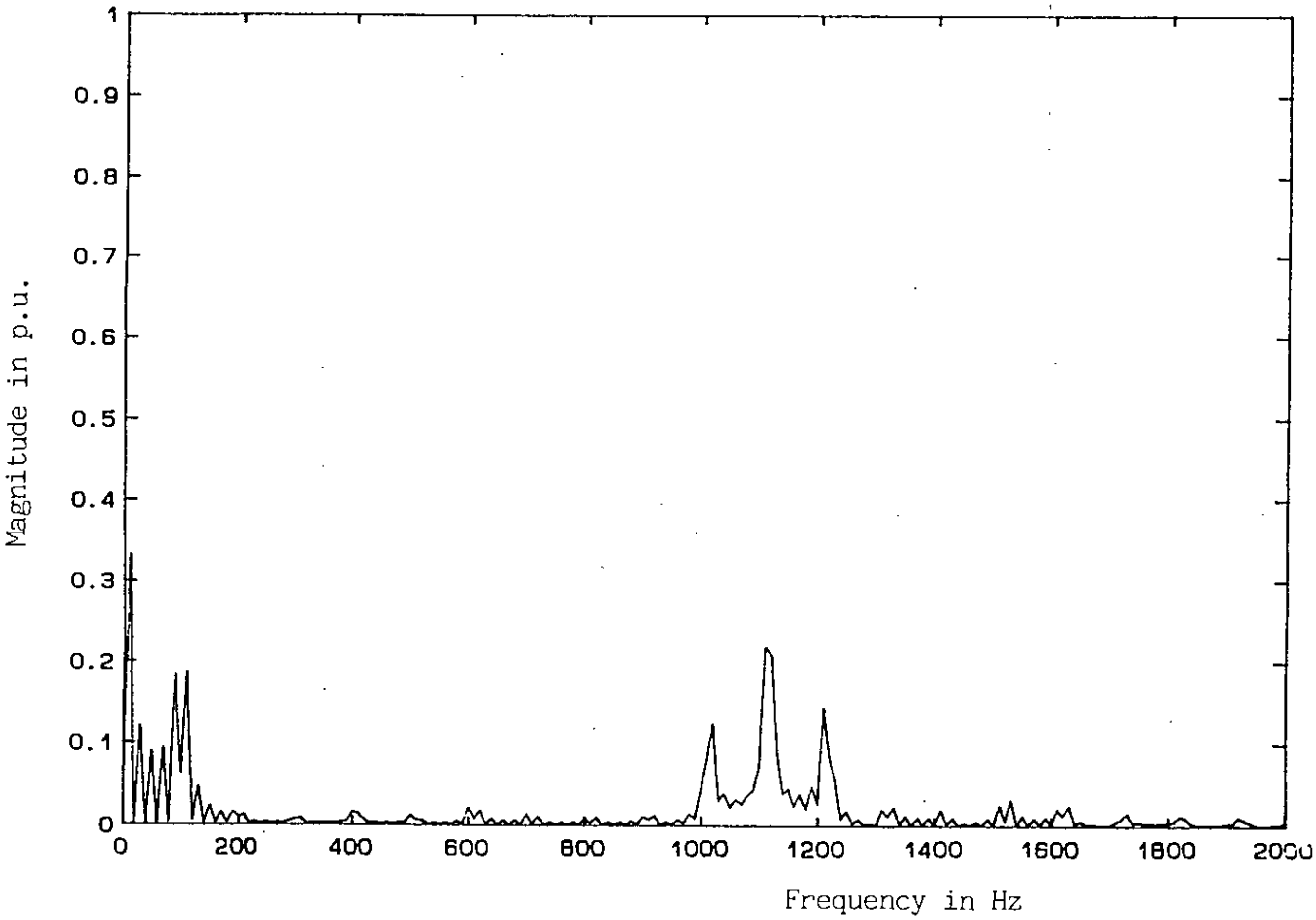


Fig: 2.47 Specthum of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.1 Sec .

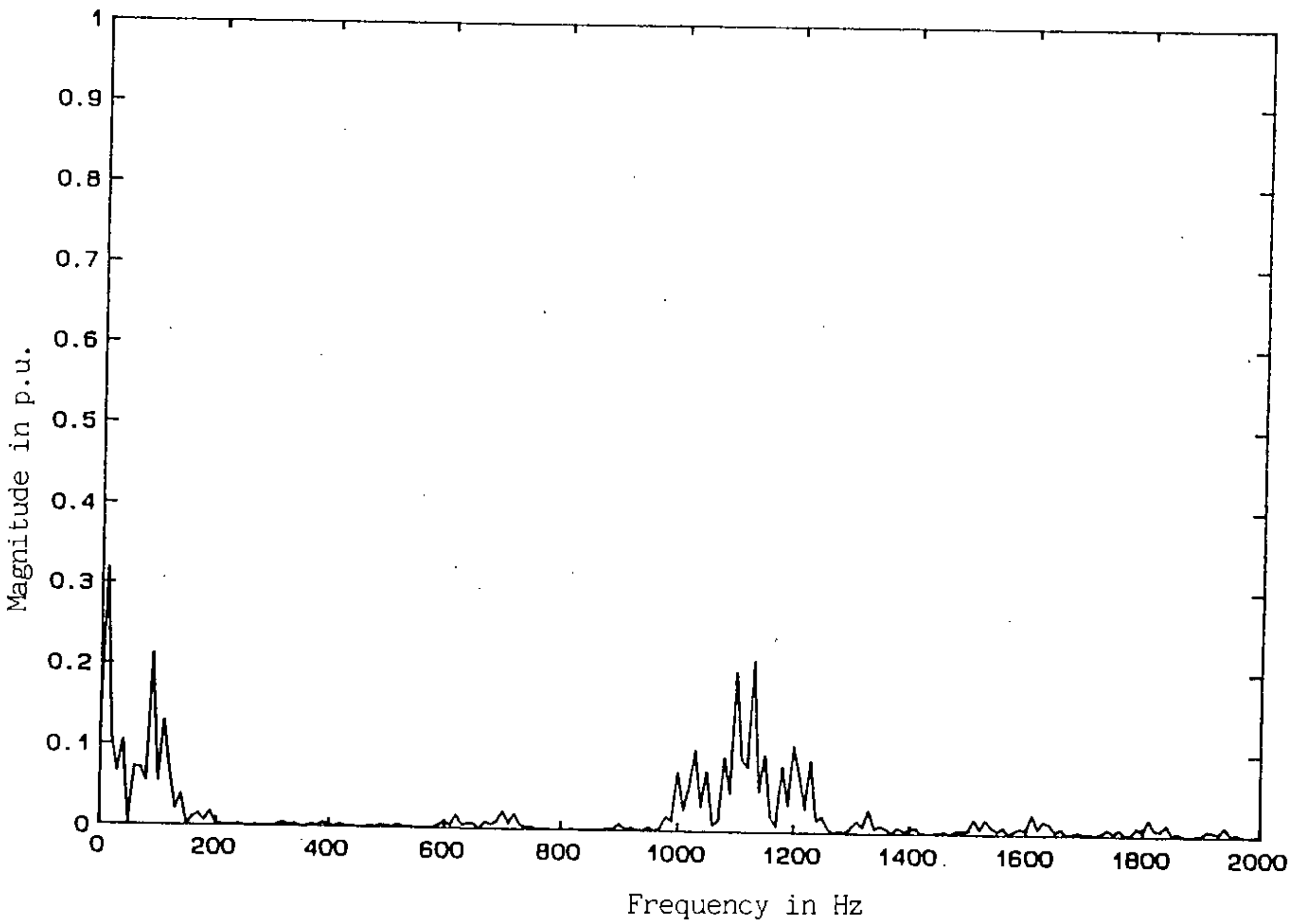


Fig:2.48 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.08 Sec

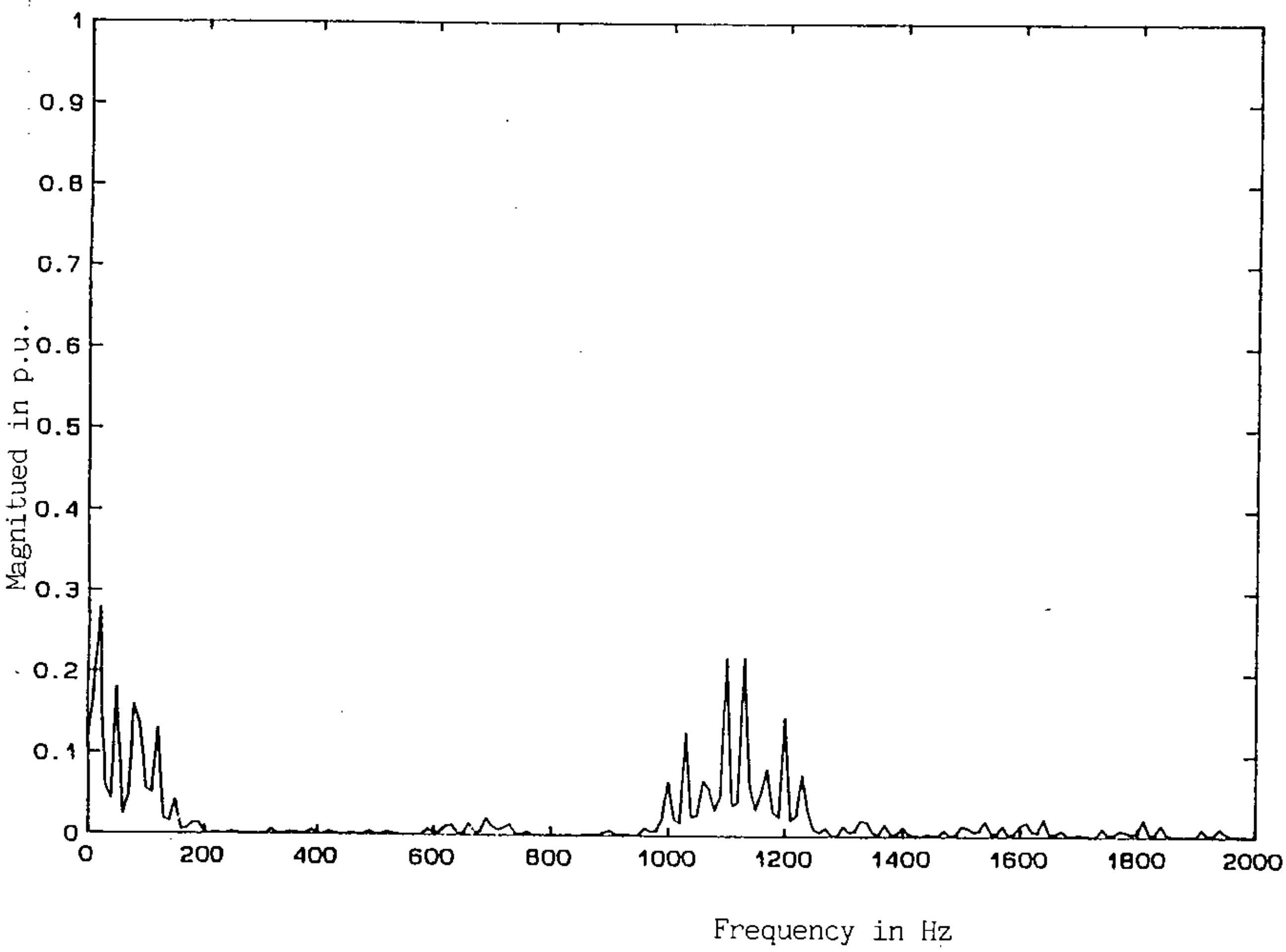


Fig: 2.49 Spectrum of a 1-Ø spwm cycloconverter for W= .5, N_p=11, T_c=.06 Sec

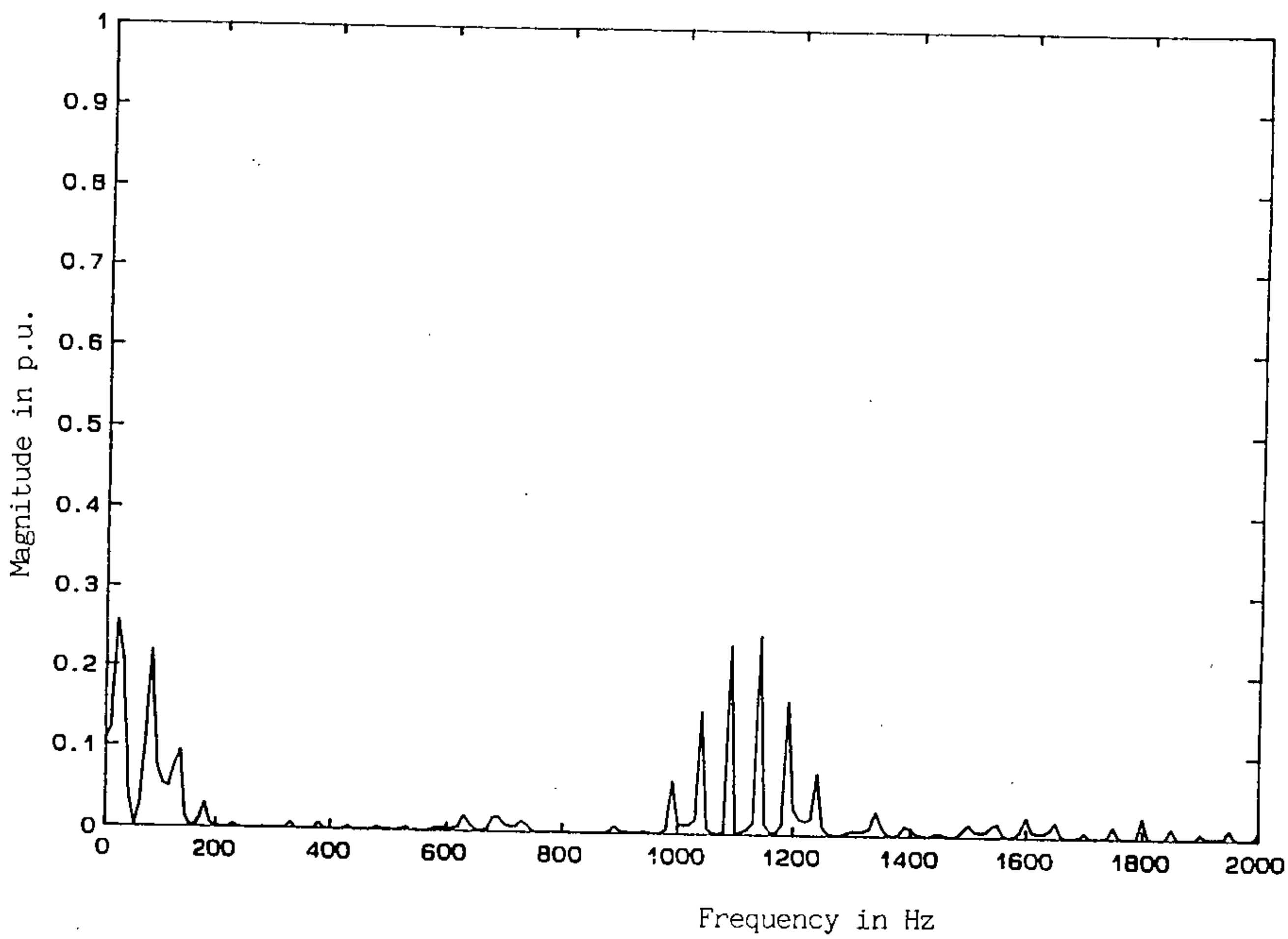


Fig: 2.50 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=11, T_c=.04 Sec

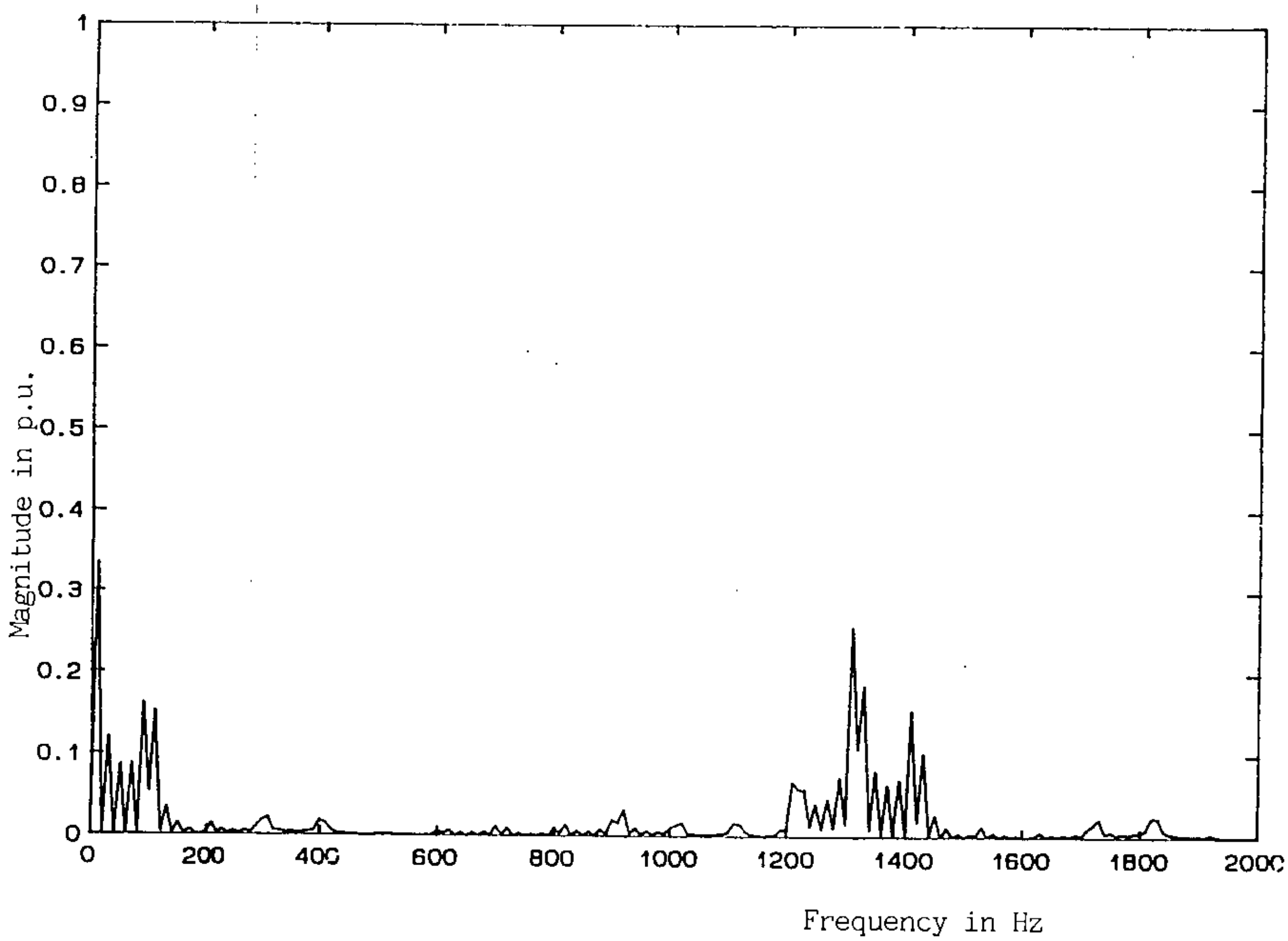


Fig: 2.51 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=13, T_c=.1 Sec

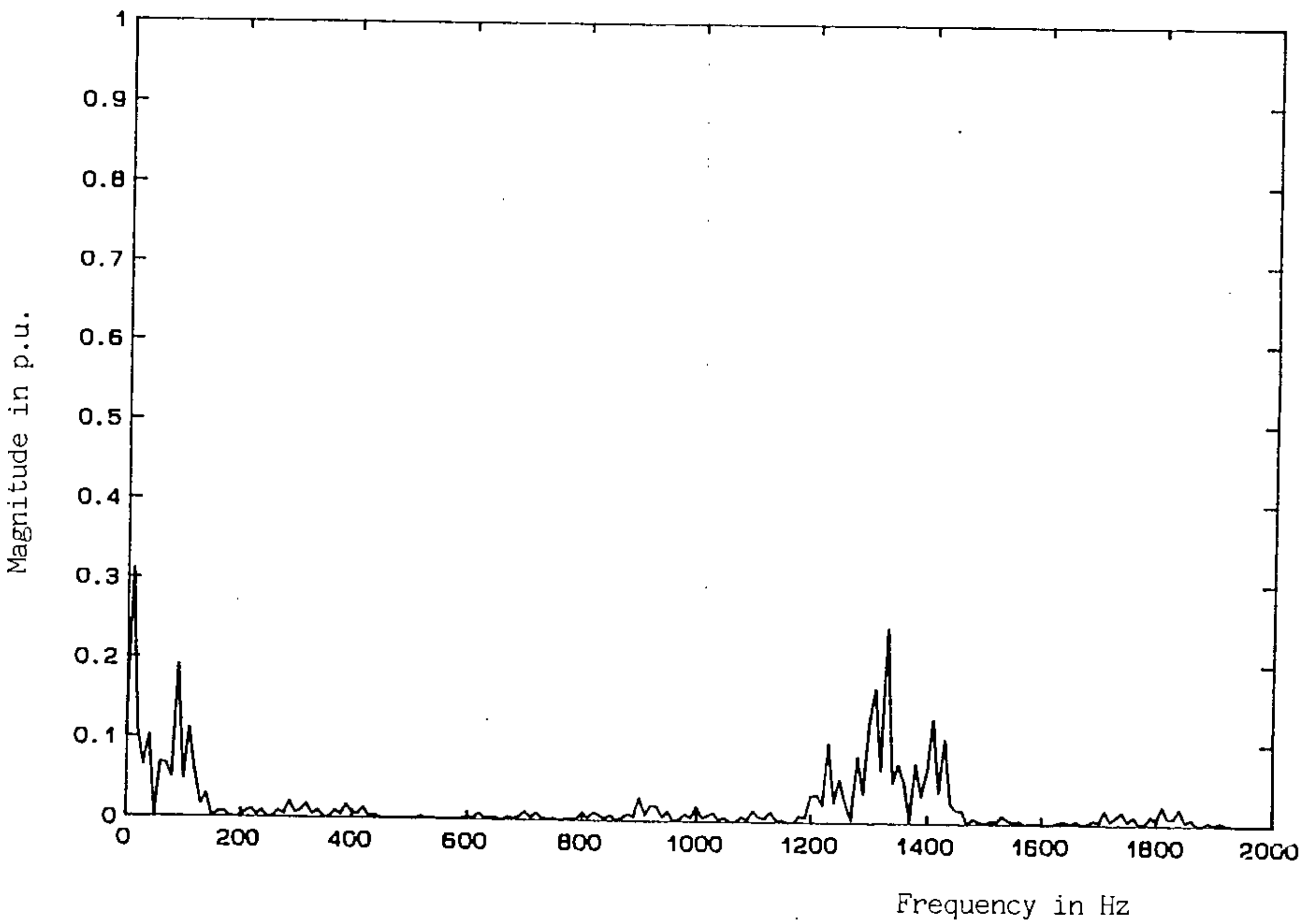


Fig: 2.52 Spectrum of a 1-Ø spwm cycloconverter for W=.5, N_p=13, Tc=.08 Sec

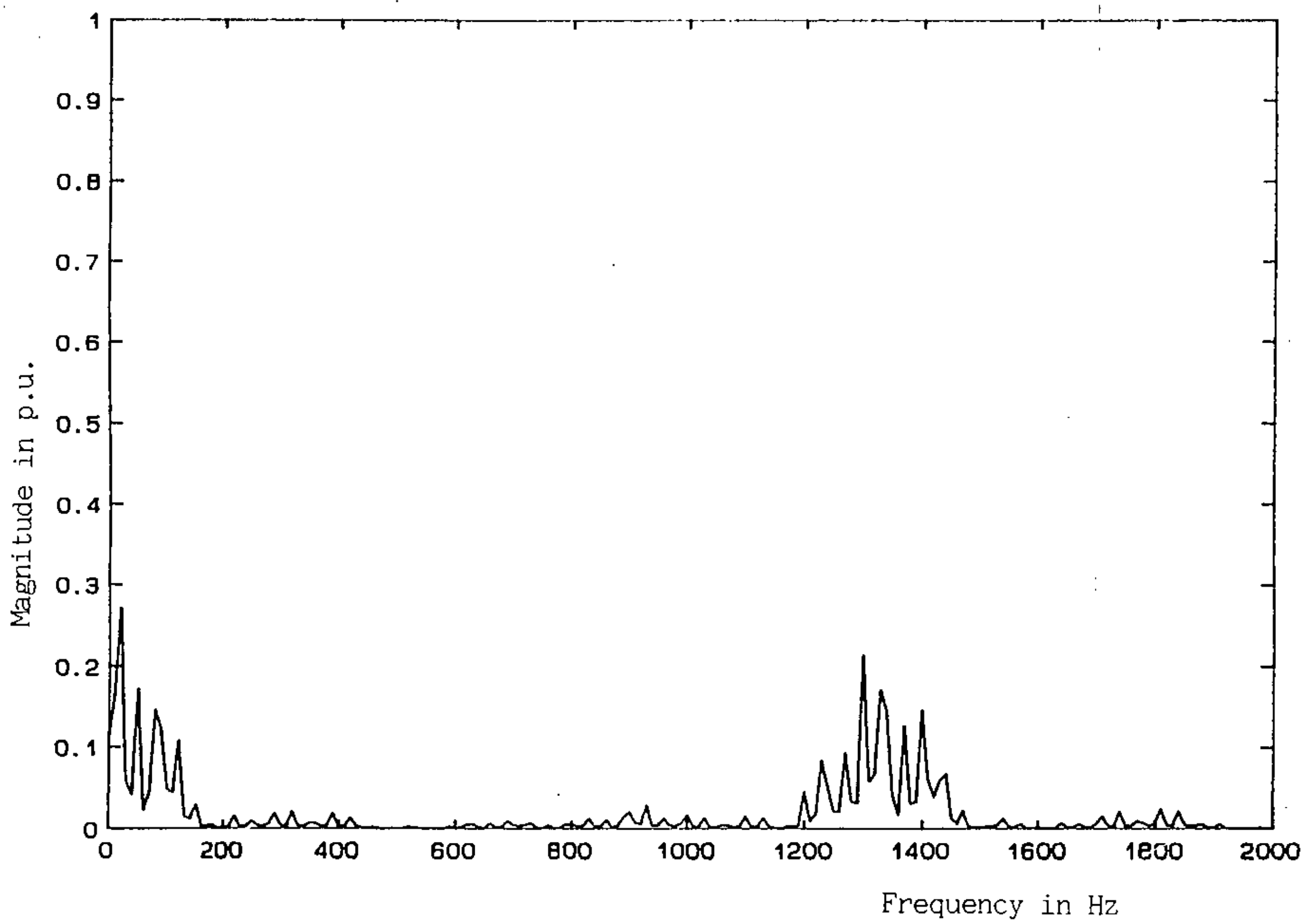


Fig: 2.53 Spectrum of a 1-Ø spwm cycloconverter for W=.5, Np=13, Tc=.06 Sec

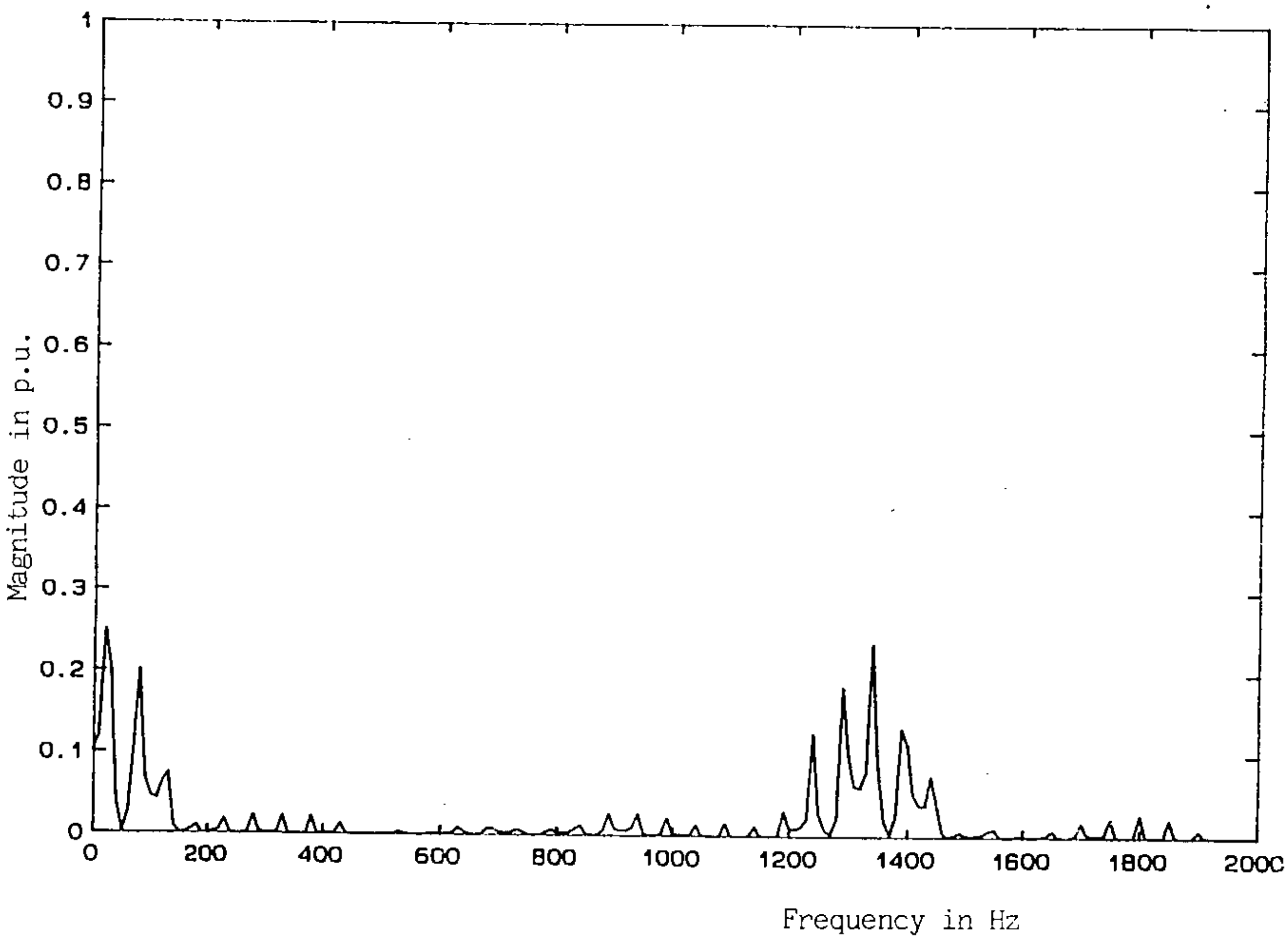


Fig: 2.54 Spectrum of a 1-Ø spwm cycloconverter for W=.5, Np=13, Tc=.04 Sec

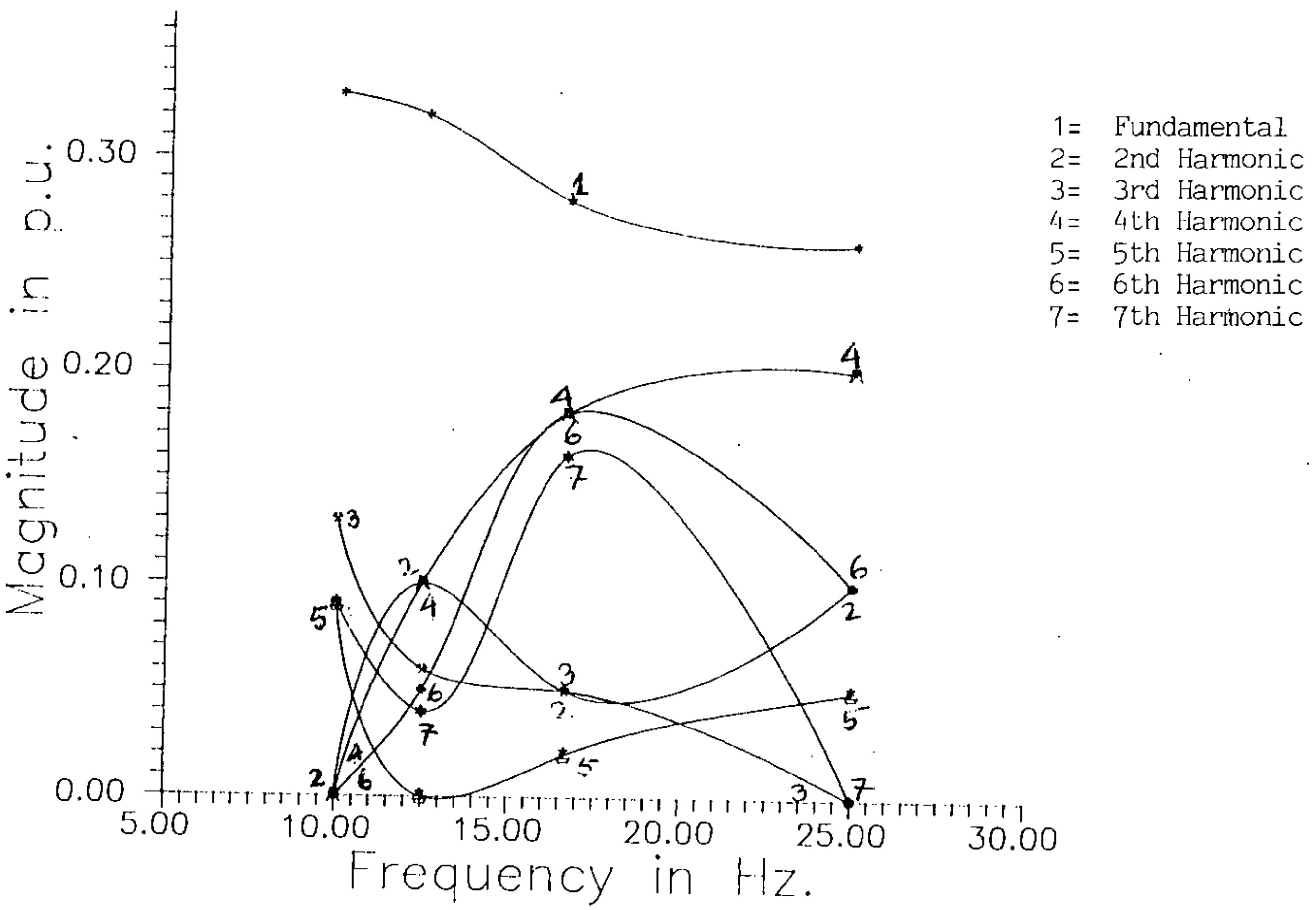


Fig: 2.55 Result of spectural analysis of a 1-Ø spwm cycloconverter for W=.5, Np=11,

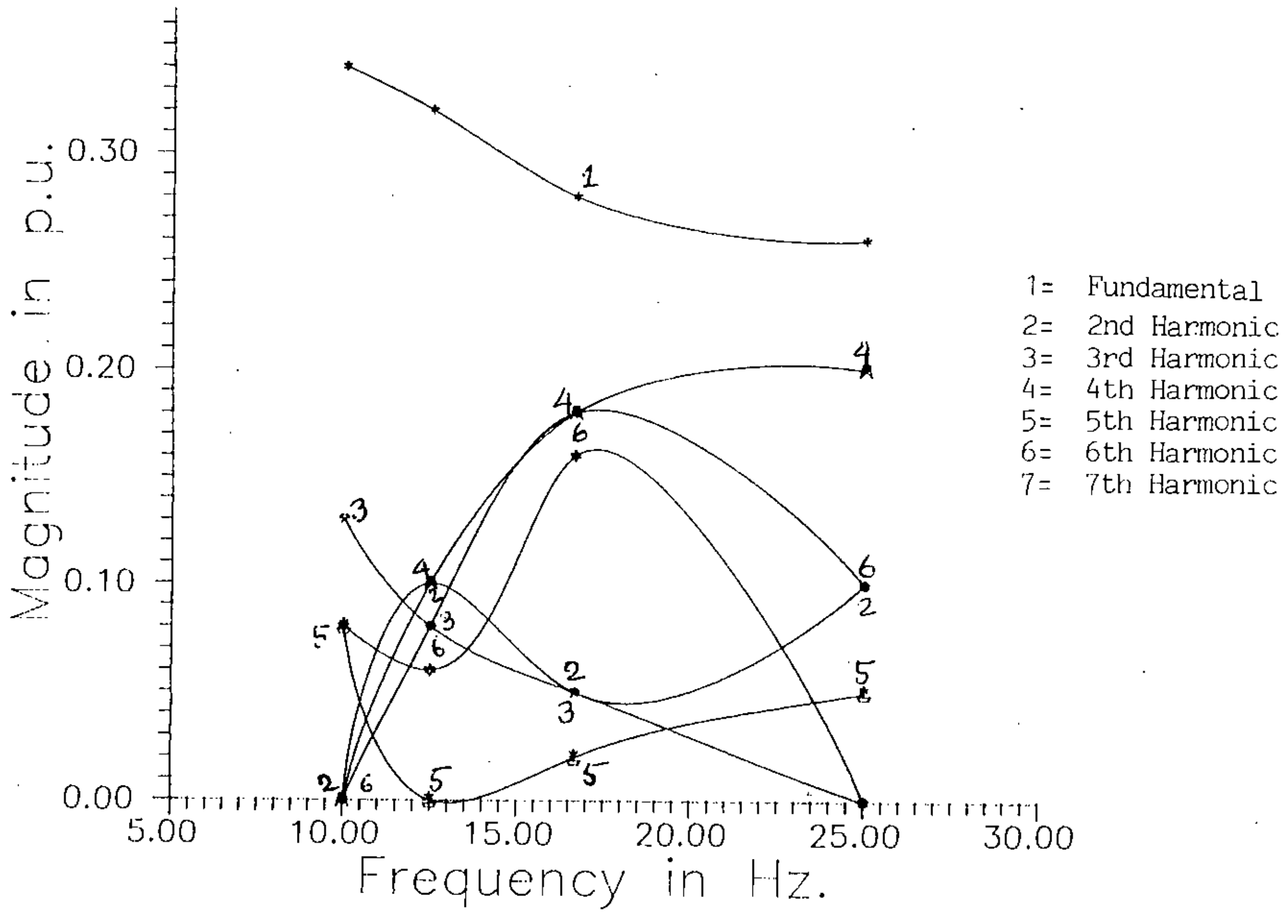


Fig: 2.56 Result of spectral analysis of a 1-Ø spwm cycloconverter for W=.5, Np=13

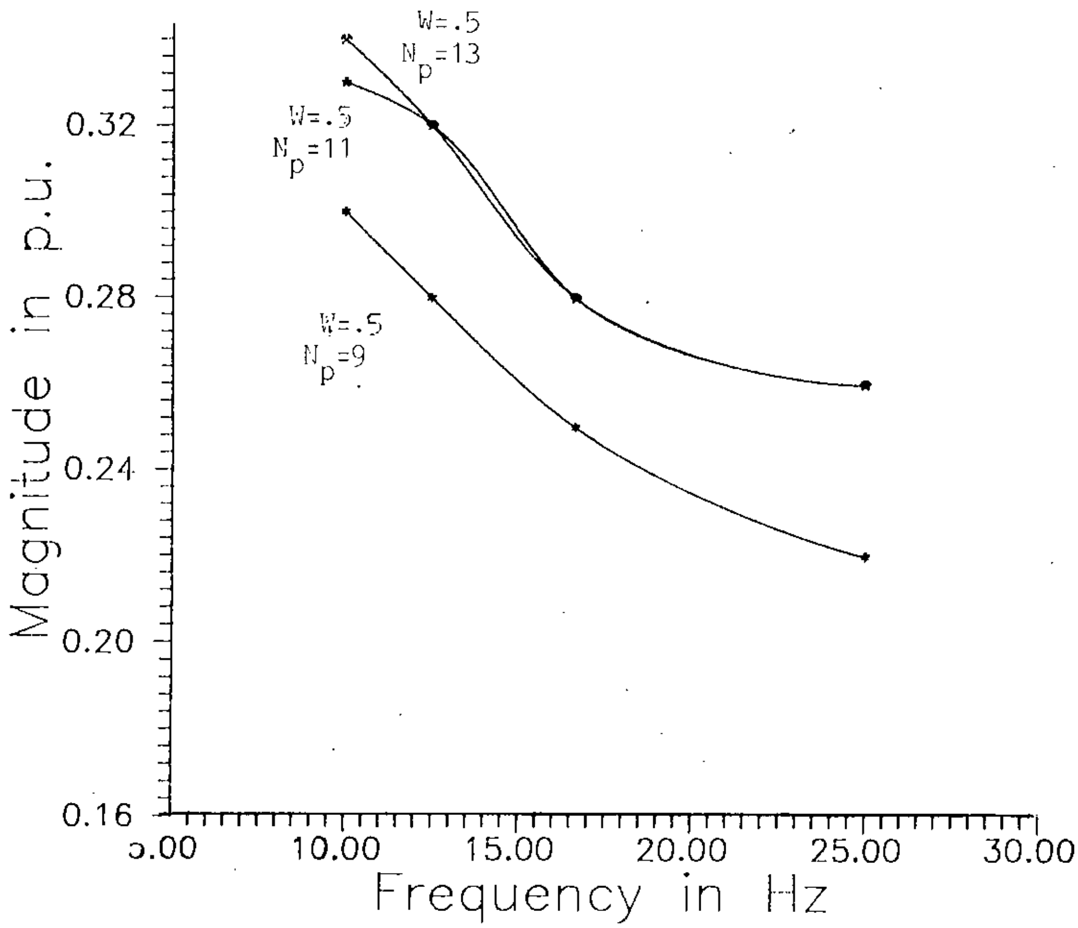


Fig: 2.57 Fundamental voltage variation for 1-Ø spwm cycloconverter with W= constant, Np= variable

Table 2.1

Results of spectral analysis of spwm waves for W= 0.5 and N_p = 9 where W=modulation index, N_p= no of pulses per half cycle

frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
10	03	0	.12	0	.8	.8	.8
12.5	.28	.1	.08	.1	0	.05	.05
16.67	.25	.05	.15	.025	.14	.04	.1
25	.22	.1	0	.18	.05	.05	.07

Table 2.2

Results of spectral analysis of spwm waves for W= .75 and N_p = 9

Frequency in Hz	Harmonics						
	1	2	3	4	5	6	7
10	.49	0	.18	0	.14	.14	.14
12.5	.45	.12	.1	.15	0	.1	.1
16.67	.39	.08	.25	.08	.2	.1	.18
25	.35	.1	0	.05	.1	0	0

Table 2.3

Results of spectral analysis of spwm waves for W= 1.00 and N_p = 9

Frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
10	.65	0	.24	0	.18	0	.18
12.5	.62	.15	.2	0	.12	.12	.4
16.67	.54	.1	.32	.05	.3	.1	.22
25	.5	.1	0	.4	.1	.15	0

Table 2.4

Fundamental voltage variation for spwm waves for W=variable N_p= 9 (constant).

Frequency	W=.5	W=.7	W=1.00
10	.3	.49	.65
12.5	.28	.45	.62
16.67	.25	.39	.54
25	.22	.35	.5

Table 2.5

Results spectral analysis of spwm waves for W=0.5 and N_p = 11

Frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
10	.33	0	.13	0	.09	0	.09
12.5	.32	.1	.06	.1	0	.05	.04
16.67	.28	.05	.05	.18	.02	.18	.16
25	.26	.1	0	.4	.05	.1	0

Table 2.6

Results spectral analysis of spwm waves for W=0.5 and N_p = 13

Frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
10	.34	0	.13	0	.08	0	.08
12.5	.32	.1	.08	.1	0	.08	.06
16.67	.28	.05	.05	.18	.02	.18	.16
25	.26	.1	0	.2	.05	.1	0

Table 2.7

Fundamental voltage variation for spwm waves for W= 0.5 (constant) and N_p= variable

frequency	N_p = 9	N_g = 11	N_p = 13
10	.3	.33	.34
12.5	.28	.32	.32
16.67	.25	.28	.28
25	.22	.26	.26

Chapter - 3

DELTA MODULATED CYCLOCONVERTER

3.1 Introduction.

This chapter deals with the dscription of simple delta modulation technique that may be used for modualted cycloconverter control. The analysis of the modulator and a single phase cycloconverter waveforms similar to the technique described in chapter -2 has been carried out. The modulator and waveform analyses would bring out the advantageous features of delta modulation (dm) technique for converter control. A comparison of the results obtained for sine pulse width modulated cycloconverter will be made with that of dm cycloconverter.

3.2 Delta Modulation Technique [21,25].

Delta modulation is the simplest known method for modulating an analog signal to its digital form. The basic modulator consists of a comparator quantizer and a filter [Fig 3.1]. The comparator at the input compares the input signal with stepwise approximation of the input signal. The difference signal produced by the comparison is the error signal and is quantized by the qunatizer and sampled to produce the sampled modulated signal. The integrator in the feedback path filters the output modulated signal to reconstruct or estimate the input signal from the output signal. Many variations of the simple delta modulator described in the preeding paragraph were reported from time to time and a detailed review is availabe in reference [26].

3.3 Delta Modulation Scheme for Cycloconverter.

Cycloconverters are power converters used for the energy conversion from ac to ac at arbitrary frequency and voltage. Pulse width moduation is used in such converters to effectively control the harmonics of the output voltage and the input current waveshapes. It is desirable that the low power control signal can be conveyed to the load side without much distortion and to produce the switching signals for controlling the output voltage and frequency. Delta modulation technique can be used for such purpose by using a rectifed sine wave as a modulating wave at the input of a delta modulator. The stepped shape carrier waveform (or the estimated waveform) determines the switching points of the cycloconverter [Fig. 3.2] . Fig 3.2 is a rectangular wave delta modulator (rwdm) and the typical waveforms of this modulator at various points are shown in Fig 3.3. Rectangular wave delta modulator is a variation of a simple linear delta modulator in which the ON/OFF quantizer is replaced by a hysteresis ON/OFF quantizer. Such a quantizer limits the excursion of carrier estimated wave within a window width allowing modulator to track the input signal more precisely. In converter application, such a window limitation also satisfy the hysteresis current control of inductive load. As a result, such controllers achieve hysteresis current control without any closed loop arrangement.

It has been shown in previous works that a rwdm has several intrinsic features for advantageously operating inverters [26]. However, all these intrinsic features are not available for cycloconverter operation. Only the following features of rwdm are observable for operation of cycloconverters,

1. With the change of operating frequency, increase of fundamental voltage is inherent, but this increase may not be linear without extra control.
2. Low order harmonics are small
3. Modulator performance can be changed on-line by varying slope and window width to change the output harmonic characteristics.
4. The modulator is stable and has fast step response.

3.4 Analysis of the Rectangular Wave Delta Modulator.

As shown in the analysis of sine pulse width modulated cycloconverter, the analysis of delta modulated cycloconverter requires the knowledge of switching points of the modulated signal obtained from the modulator and other switching signals used for obtaining the proper gating signals of cycloconverter switches. To find the switching points of the typical modulator output waveform of rwdm as shown in Fig 3.3, the following method has been used.

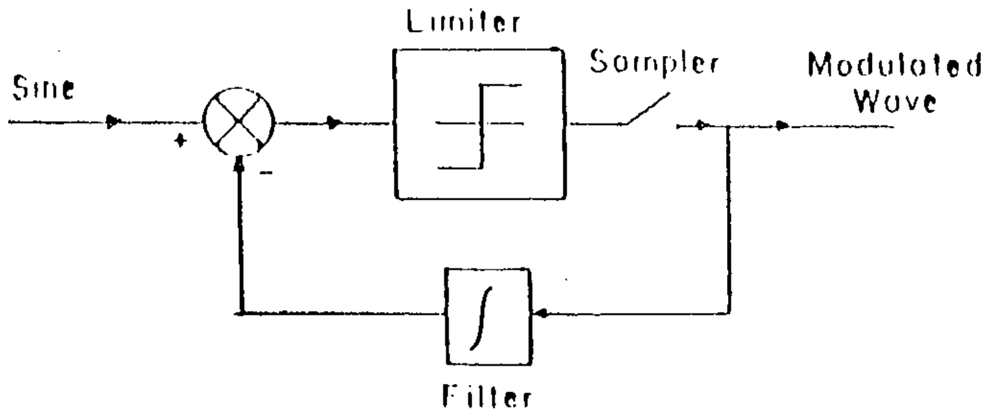


Fig: 3.1 Basic delta modulator (dm)

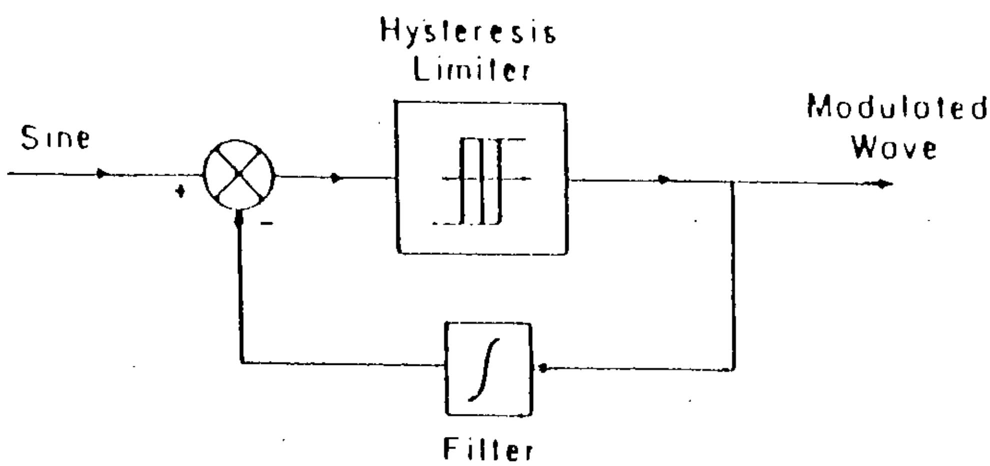


Fig: 3.2 Basic rectangular wave delta modulator (rwdm)

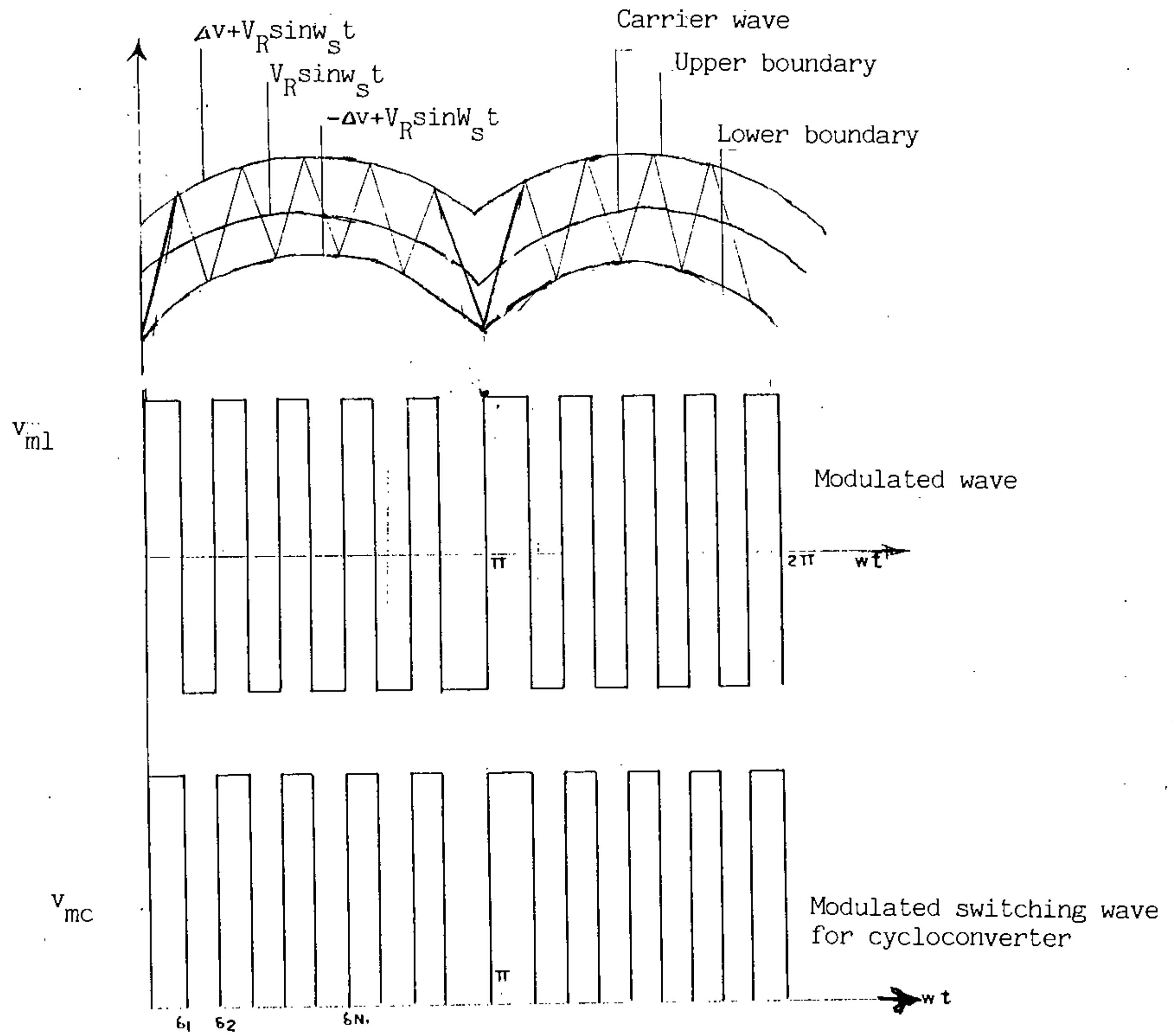


Fig: 3.3 Typical waveforms at various points of a rwdm

Defining,

$$A = \text{slope of trangular wave } V/Sec$$
$$\Delta V = \text{window width in volts}$$
$$\omega_s = \text{frequency of the sine wave (which is rectified and used as the modulating wave)}$$
$$\omega_r = \text{ripple frequency of the triangular wave}$$

Equation of the modulating wave, upper envelope and lower envelope are obtained as,

$$V_r = V_R sin\omega_s t \tag{3.1}$$
$$V_u = \Delta V + V_R sin\omega_s t \tag{3.2}$$
$$V_l = -\Delta V + V_R sin\omega_s t \tag{3.3}$$

where, V_r, V_u, V_l, are the instantaneous value of modulating wave, upper envelope and lower envelope and $\omega_s = 2\pi f_s$. First switching point t_1 can be found as below,
since,

$$\Delta V + V_R sin\omega_s t_1 = At$$
$$t_1 = \frac{\Delta V + V_R sin\omega_s t_1}{A} \tag{3.4}$$

subsequent switching point t_2 can be found as,
since,

$$\frac{\Delta V + V_R sin\omega_s t_1 - (-\Delta V + V_R sin\omega_s t_2)}{t_1 - t_2} = -A \tag{3.5}$$

$$\text{or,} t_2 = \frac{2\Delta V + V_R sin\omega_s t_1 - V_R sin\omega_s t_2 + At_1}{A}$$
$$\text{or,} t_2 = \frac{2\Delta V + At_1}{A} + \frac{V_R sin\omega_s t_1 - V_R sin\omega_s t_2}{A}$$
$$\text{similarly,} t_3 = \frac{2\Delta V + At_1}{A} - \frac{V_R sin\omega_s t_1 - V_R sin\omega_s t_2}{A} \tag{3.7}$$

An investigation into these equation gives a general form of these equation for any pulse i(t_i) as,

$$t_i = \frac{2\Delta V + At_i}{A} + \frac{V_R sin\omega_s t_{i-1} - V_R sin\omega_s t_i}{(-1)^i A} \tag{3.8}$$

The above equation is a transcendental equation and also each switching point requires the position of the previous pulse. In terms of radians, the pulse positions can be obtained as,

$$\delta_1 = \omega_s t_1$$

$$\delta_2 = \omega_s t_2$$

$$\delta_i = \omega_s t_i$$

$$\delta_\pi = \omega_s t_\pi$$

and $(\delta_i - \delta_1)$ gives the last pulse termination position within half cycle. Solving equation (3.8) for particular ΔV(window width) and A (slope), a set of switching points can be obtained, which can be used for waveform construction of the cycloconverter.

In the pwm mode of modulator operation, the knowledge of the switching points of the modulated wave allows one to write the equation of the modulated as,

$$m(t) = \sum_{A=0,T/2,T,..}^{ZT} \sum_{i=0}^{N_p} (-1)^{i+1} \left[g(t, A + t_1, A + t_{i+1})\right] \tag{3.9}$$

where,

$N_p =$ *is the number of pulses in one half cycle*

$T =$ *is the period of one cycle of the input sine wave*

$Z - 1 =$ *is the number of cycles of simulated signal*

$t_{i+1} =$ *is the* $(i+1)$ *th pulse position*

$m(t) =$ *is the modulated wave*

$g(t, t_1, t_2) =$ *is the gate function starting at* t_1 *and ending at* t_2

where,

$$g(t, t_1, t_2) = u(t - t_1) - u(t - t_2) \tag{3.10}$$

and,

$$\begin{aligned} u(t - t_1) &= 1 \; for \; t \geq t_1 \\ &= 0 for \; t \leq t_1 \end{aligned} \tag{3.11}$$

$$\begin{aligned} u(t - t_2) &= 1 \; for \; t \geq t_2 \\ &= 0 for \; t \leq t_2 \end{aligned} \tag{3.12}$$

To obtain a single phase cycloconverter waveform, few other switching functions are necessary.

If the $v_i = v_m sin\omega t$ is the input to the cycloconverter with period T, and the cycloconverter output frequency has a period T_c, then let us define two switching functions,

$$sw_1 = \sum_{t_i=0,T/2,T..}^{A} g(t, t_i + \frac{T}{2}, t_i + T) \tag{3.13}$$

$$sw_2 = \sum_{t_i=0,T_c/2,Tc..}^{B} g(t, t_i + \frac{T_c}{2}, t_i + T_c) \tag{3.14}$$

Sw_1 of equation 3.13 is a square wave of period T and sw_2 of equation 3.14 is a square wave of period T_c. A rectified sine wave may be defined as,

$$v_r = v_i.sw_1 \tag{3.15}$$

When multiplied by the modulated signal m(t), equation 3.15 would result is a rectified modulated wave,

$$\begin{aligned} V_{rm} &= V_r.m(t) \\ or V_{rm} &= V_i.sw_i.m(t) \end{aligned} \tag{3.15}$$

The single phase cycloconverter output voltage can now be obtained as,

$$V_o = V_{rm}.sw_2$$
$$or, V_o = V_i.sw_1.sw_2.m(t) \quad (3.17)$$

Equation 3.16 can be used for simulating different single phase cycloconverter output waveforms for rwdm modulation. Typical waveforms obtained from such analyses are shown in Fig 3.4 to 3.5 for cycloconverter frequency $f_c = 10$ $f_c = 25$ respectively.

3.5 Spectral Analysis of Delta Modulated Single Phase Cycloconverter Waveforms.

The waveforms obtained by analyses outlined in the previous section can be subjected to Fourier analysis to determine the harmonic contents of the waveforms. The Fourier series method require well defined periodicity for such analysis. But as in sine pwm cycloconverter, the output waveforms of delta modulated cycloconverter also do not have any well defined perodicity. So any attempt to apply Fourier series technique would result in erreneous result. Importantly any presence of subharmonics (harmonics which are not multiples of the operating frequency of the cycloconverter) will not be detected in such analysis. Hence, as before, discrete Fourier transform (DFT) has been carried out can the waveforms with the help of commercially available MATLAB program. MATLAB uses fast Fourier transform (FFT) of radix 2 to find the DFT of the sampled waveforms.

Fig. 3.4 and 3.5 show two waveforms obtained for a delta modulated cycloconverter at two cycloconverter frequencies. The spectra for $\Delta V = .25$ V and slope A = 3000 V/sec. at frequencies 25, 16.6, 12.5 and 10 Hz are shown in Figs 3.6 to 3.9 respectively. The spectra reveals that the fundamental voltage of the output waveforms gradually decreases with the increase in operating frequency. And the low order harmonics gradually reduces with the increase in operating frequency.

Result of spectrum analysis for the dm waves are shown in table 3.1 and in Fig 3.10. Spectra for $\Delta V = .5V$ and slope A=3000 V/S spectra are shown in Fig 3.11 to 3.14 and the result are shown in table 3.2 and in fig 3.15. The two sets of spectra have similar characteristics.

However, simultaneous increase of ΔV with operating frequency increases the fundamental voltage substantially. In previous works slope variation of delta modulators were also used for waveform improvement. An investigation to this for cycloconverter waveform shows that, though low order harmonics reduces substantially, the fundamental reduces with variation of operating frequency. However, simultaneous charge of operating frequency and slope gives an increasing fundamental voltage variation. Spectra for $\Delta V = .5V$ and slope A= 2500 V/Sec. are shown in Figs. 3.16 to 3.19 and the result of spectrum analysis are shown in table 3.3 and in Fig. 3.20. Similarly spectra for $\Delta V = .7V$ and slope 3000 V/sec. are shown in Fig. 3.21 to 3.24 and the results of the spectrum analysis are shown in table 3.4 and in Fig. 3.25. The figures and tables verify the above features of dm cycloconverter. The variation of fundamental voltage with increase of operating frequency for changing ΔV is shown in table 3.5 and in Fig. 3.26, where as variation of fundamental voltage for changing slope is shown in table 3.6 and in Fig. 3.27. From these figures, it can be seen that delta modulation can be easily used for cycloconverter to achieve the feature of increasing fundamental voltage with the increase of operating frequecny either by having window width ΔV variable or by having slope of the filter variable.

3.6 Comparison of Delta PWM Technique with Sine PWM Technique..

In chapter 2 the analysis of sine modulation technique for operating a single phase cycloconverter has been presented. Similar analyses are presented in this chapter for delta modulated single phase cycloconverter. Comparing the results of the two, several distinction between the two techniques and the superiority of delta modulation in controlling a cycloconverter in pulse width modulation mode can be observed.

a. Sine pwm technige uses the comparison between a sine modulating signal with a carrier triangular wave to produce modulating signal. The generation of modulating signal by such comparison for cycloconverter and other power converters are not easy when many factors like synchronization of triangular wave with modulating wave and clear definition of switching point etc are considered.

Whereas, in delta modulation the carrier wave (also known as estimated wave) is a self generated wave. Delta modulation technique itself is simple and easy to implement.

b. To achieve increased fundamental voltage with increase in operating frequency, the modulation index or the carrier frequency may be varied in spwm technique. However, such implementation is not easy and may become very complex with other control requirements of the application.

In delta modulation technique either the change of window width or of slope may result in fundamental voltage increase at the output of a cycloconverter. Such change may be incorporated into the modulator by active networks to control the ΔV or slope with a control signal E_c which would also change the frequency of the cycloconverter.

c. In drive applications, the modulator characteristics or rwdm restricts the excursion of the load current beyond a certain boundary. This is due to the hysteresis band which limits the excursion of the modulator's estimated wave between boundaries. In spwm, such control requires external logic implementation.

d. The characteristics of delta modulators described in b) c) above is equivalent to on-line waveform synthesis. In spwm technique the optimization of waveforms require off- line waveform synthesis and the switching strategy has to be implemented by dedicated micro-computers.

The comparison described above is inferred on the basis of theoretical results obtained and detailed in chapter 2 and 3. The experimental verifications of these observation are limited according to present facilities available at our labs. However, a small scale implementation of the delta modulation in controlling a cycloconverter has been undertaken and the procedures followed and the results obtained from the experiments are presented in brief in chapter 4.

3.7 Conclusions.

The operation of a single phase cycloconverter by delta modulation technique is shown in this chapter. A comparison between delta modulation and sine pulse width modulation (spwm) is also made. From the discussion it is clear that delta modulation has superiority over sine pulse width modulation. Cycloconverter waveforms can be improved by variation of either window width ΔV or by variation of slope A in the dm technique. In the following chapter, practical dm cycloconverter waveforms are considered with our limited lab facilities.

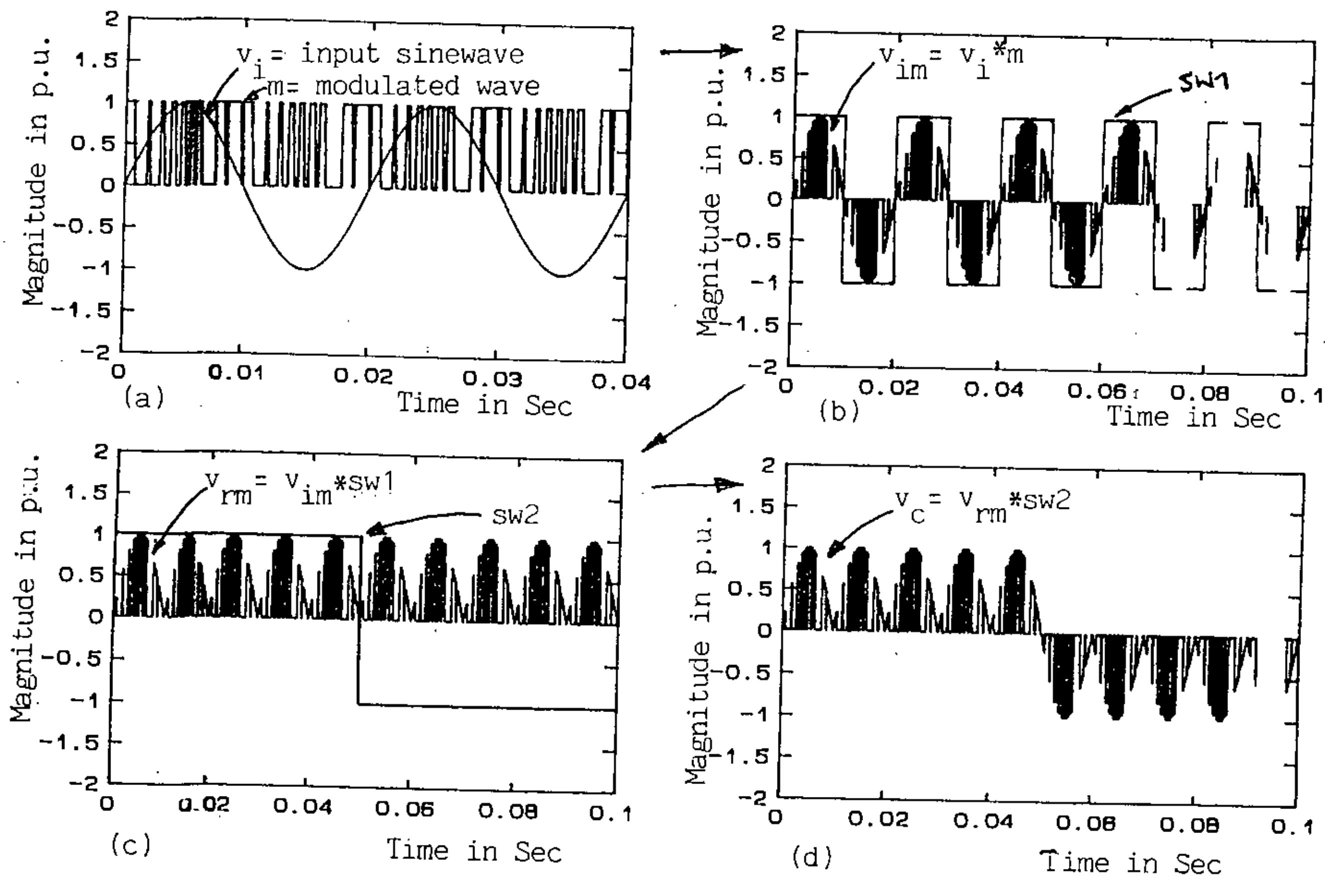


Fig: 3.4 Waveforms of a 1-Ø dm cycloconverter for Δv=.5, A=2500, Tc=.1 where Δv is the window width, A is the slop and Tc is the period of the cycloconverter.

a) Reference input and dm waveform
b) Resultant modulated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

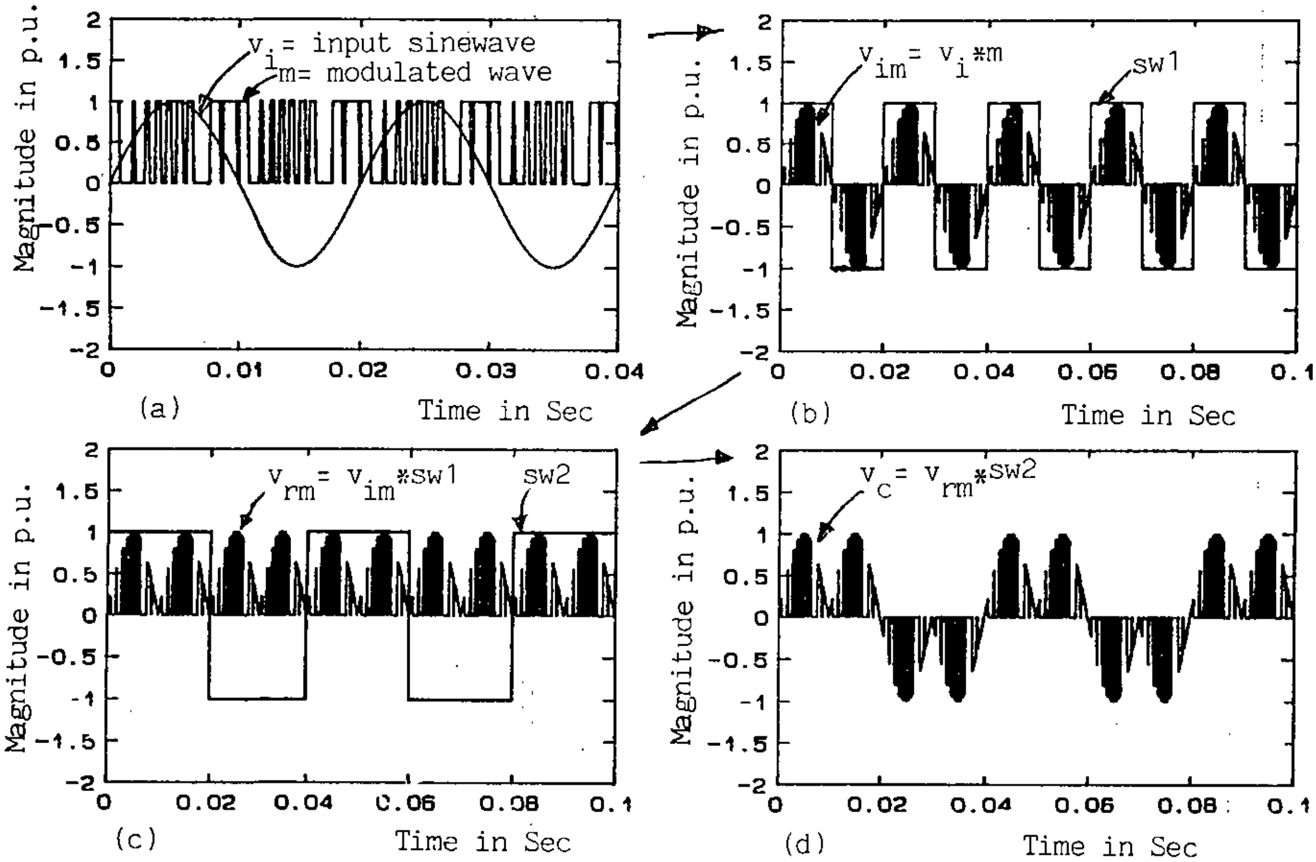


Fig:3.5 Waveforms of a 1ϕ dm cycloconverter for $\Delta v=.5$, $A=2500$, $T_c=.04$ Sec

a) Reference input and dm waveform
b) Resultant movudated waveform and switching waveform sw1
c) Modulated rectified wave and switching waveform sw2
d) Output of the cycloconverter

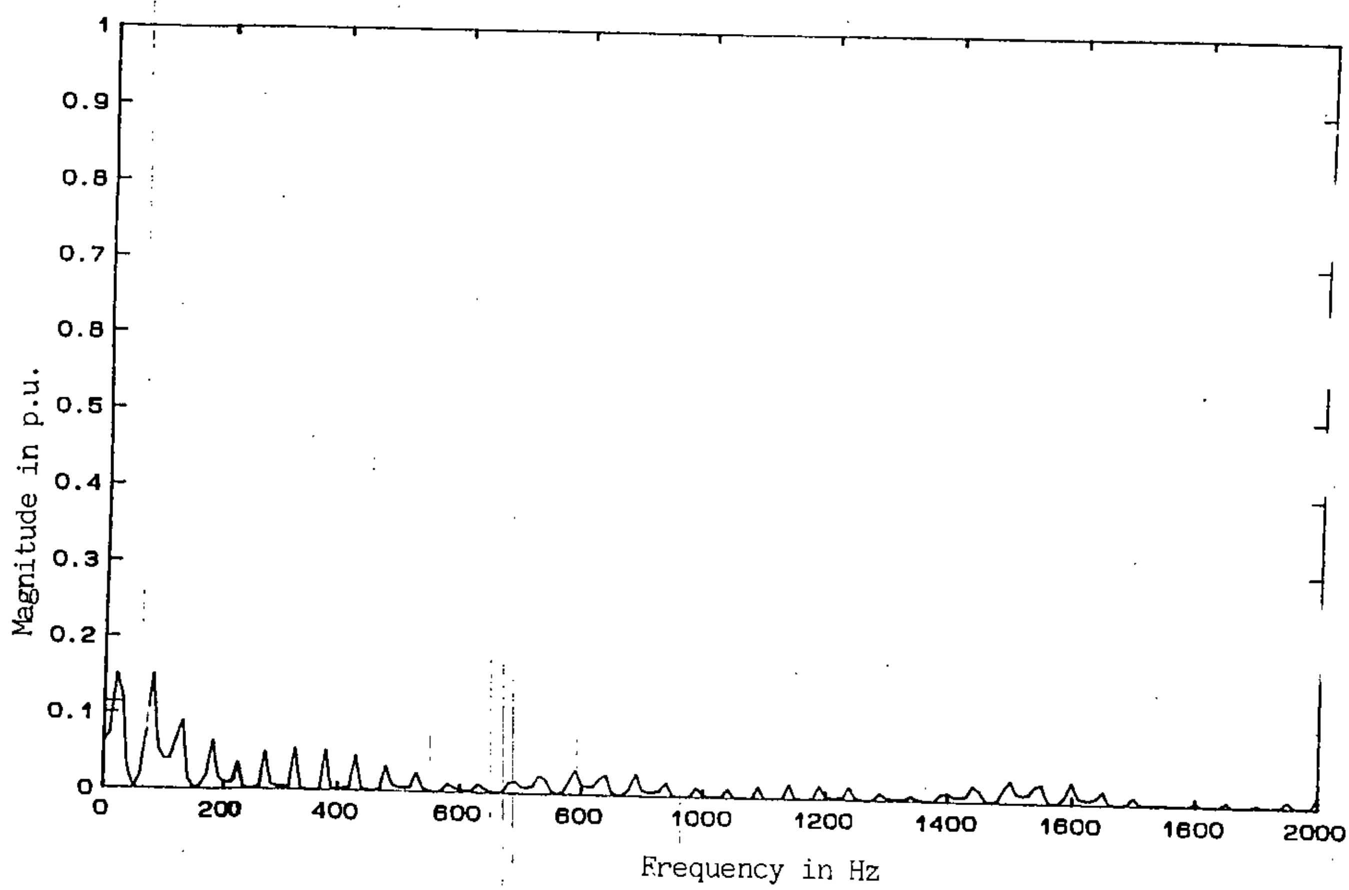


Fig: 3.6 Spectrum of a 1-Ø dm cycloconverter for Δv=.25, A=3000, Tc=.04

Δv in v, A in v/Sec, Tc in Sec

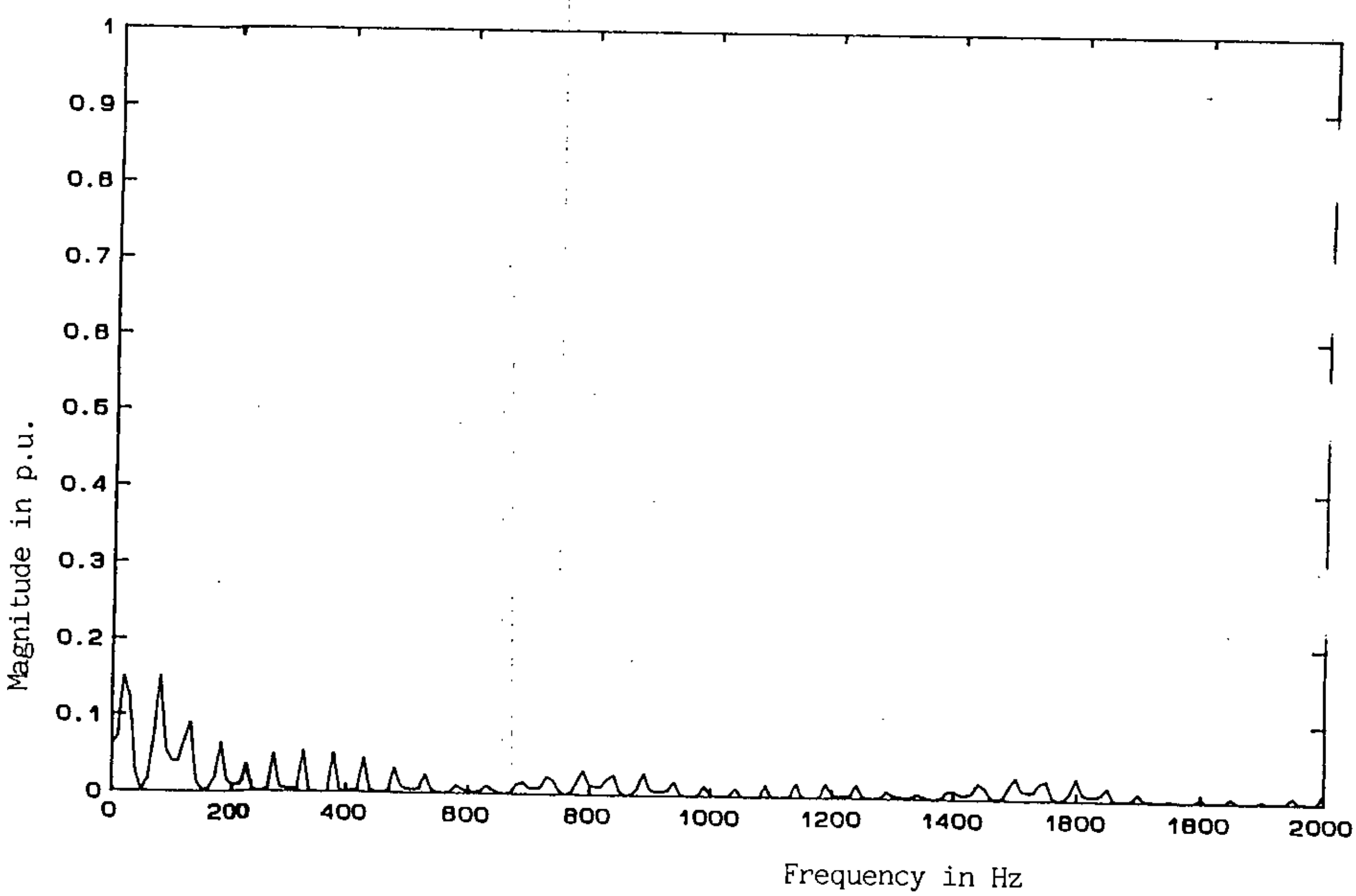


Fig:3.7 Spectrum of a 1-Ø dm cycloconverter for Δv= .25, A=3000, Tc=.06

Δv in v, A in v/Sec, Tc in Sec

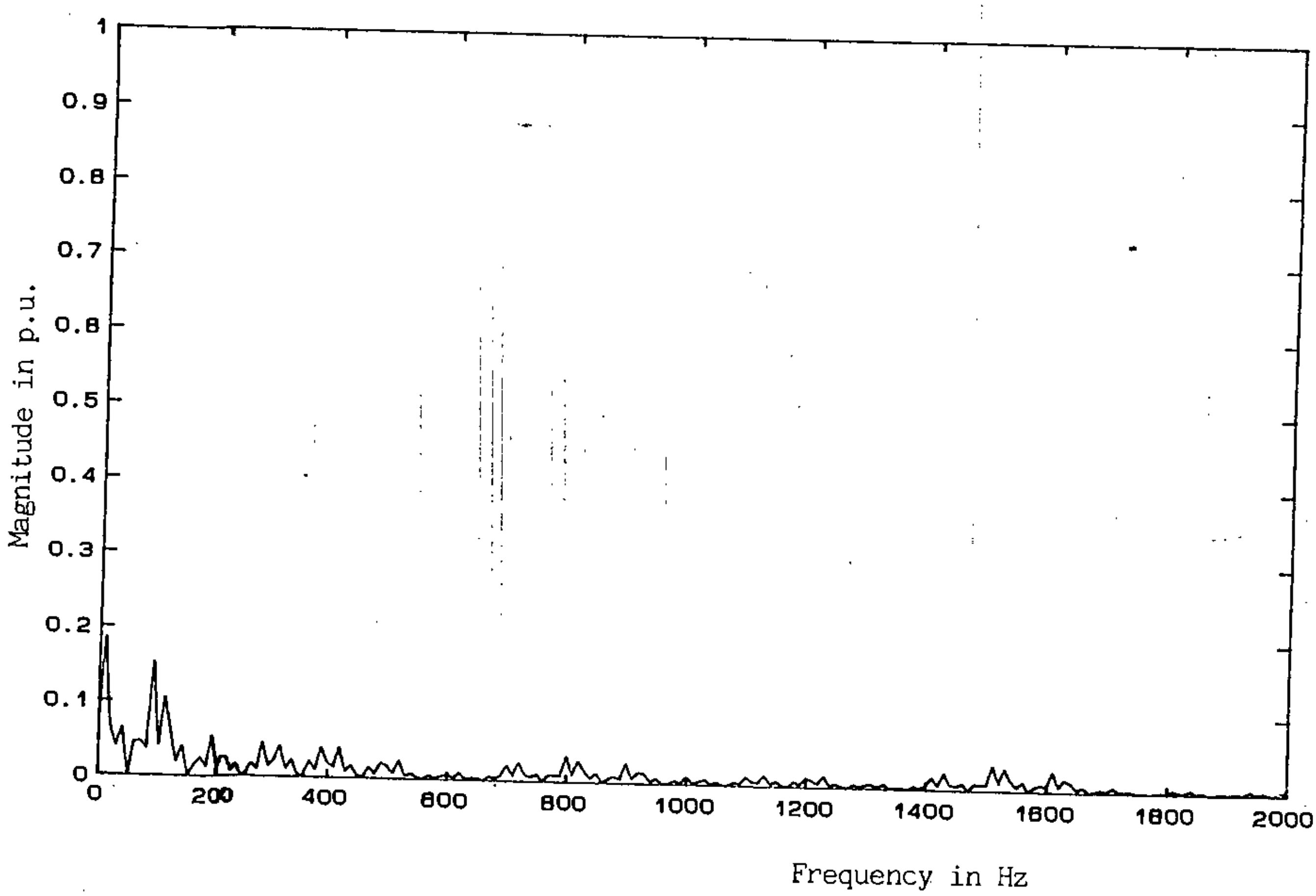


Fig: 3.8 Spectrum of a 1-Ø dm cycloconverter for Δv=.25, A=3000, Tc=.08
Δv in v, A in v/Sec, Tc in Sec

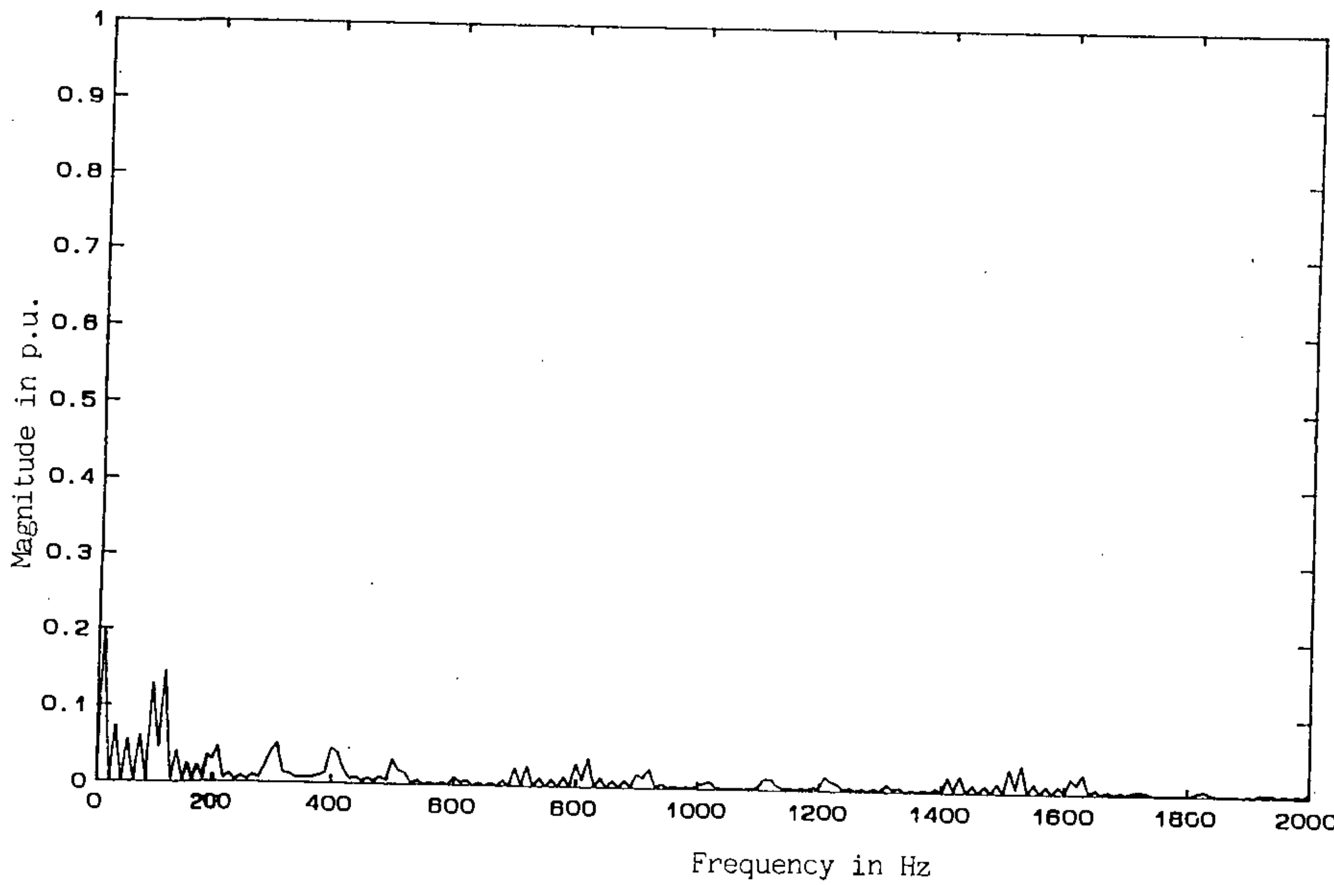


Fig: 3.9 Spectrum of a 1-Ø dm cycloconverter for Δv=`.25, A=3000, Tc=.1

Δv in v, A in v/Sec, Tc in Sec

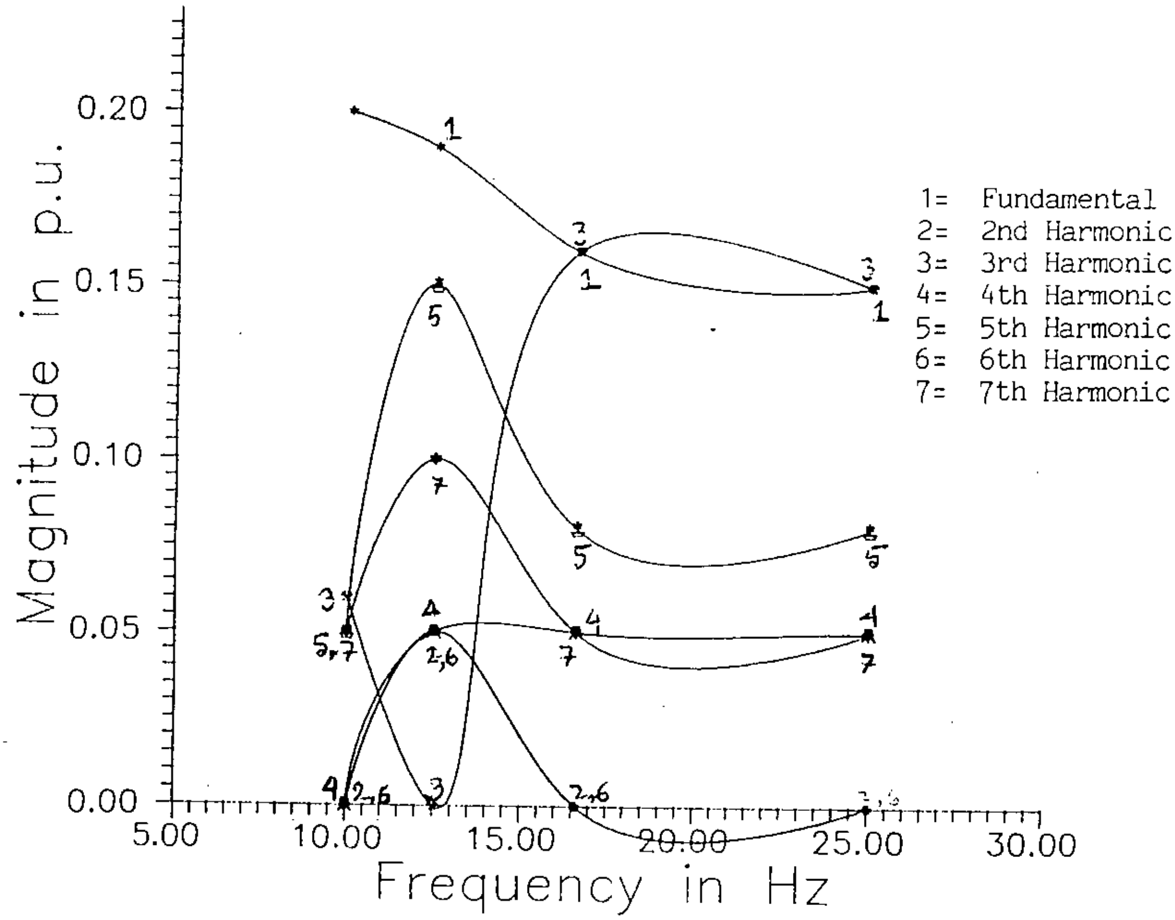


Fig: 3.10 Result of spectrum analysis of a 1-Ø dm cycloconverter for Δv= .25, A=3000,

(Δv in v, A in v/Sec)

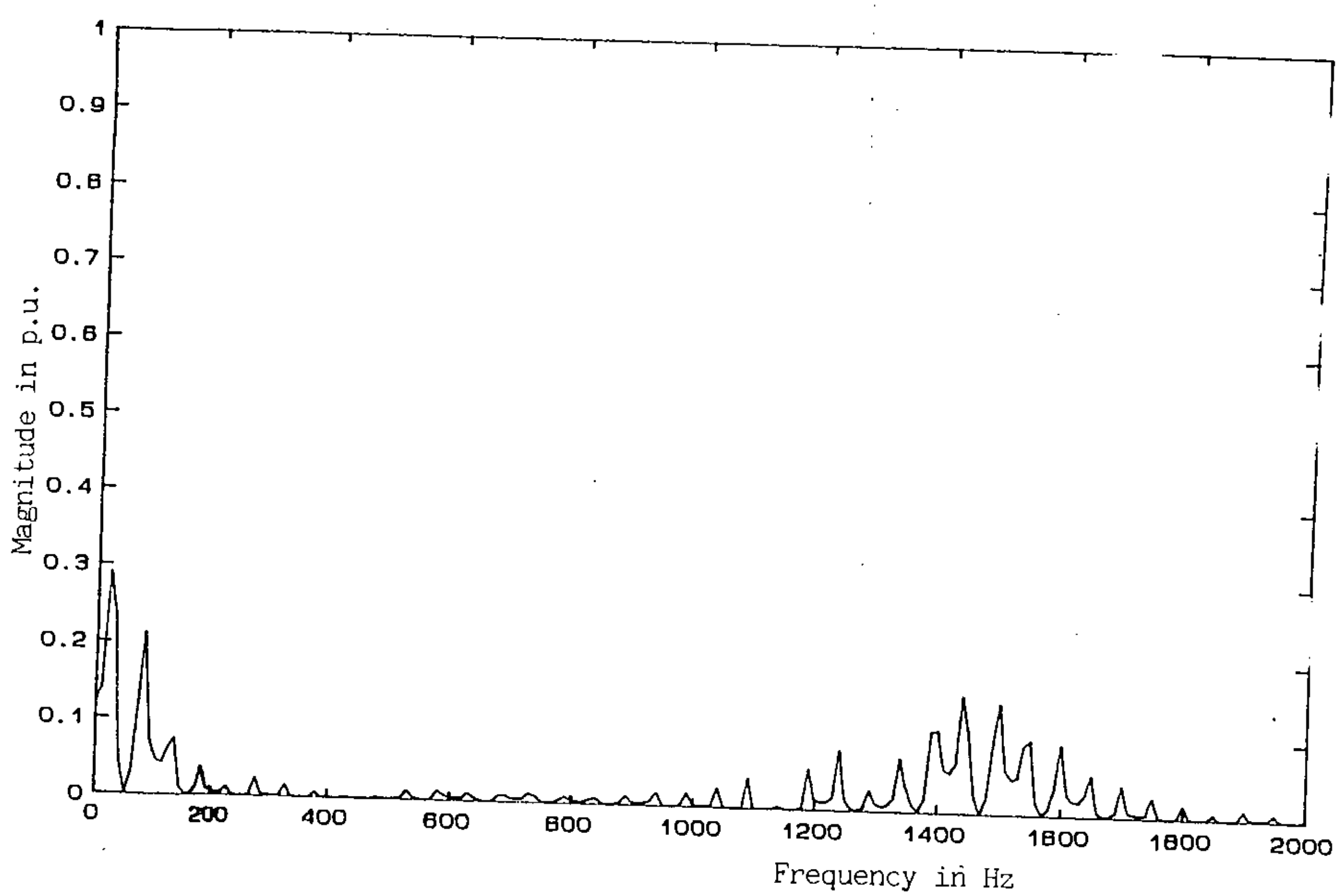


Fig: 3.11 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=3000, Tc=.04

Δv in v, A in v/Sec, Tc in Sec

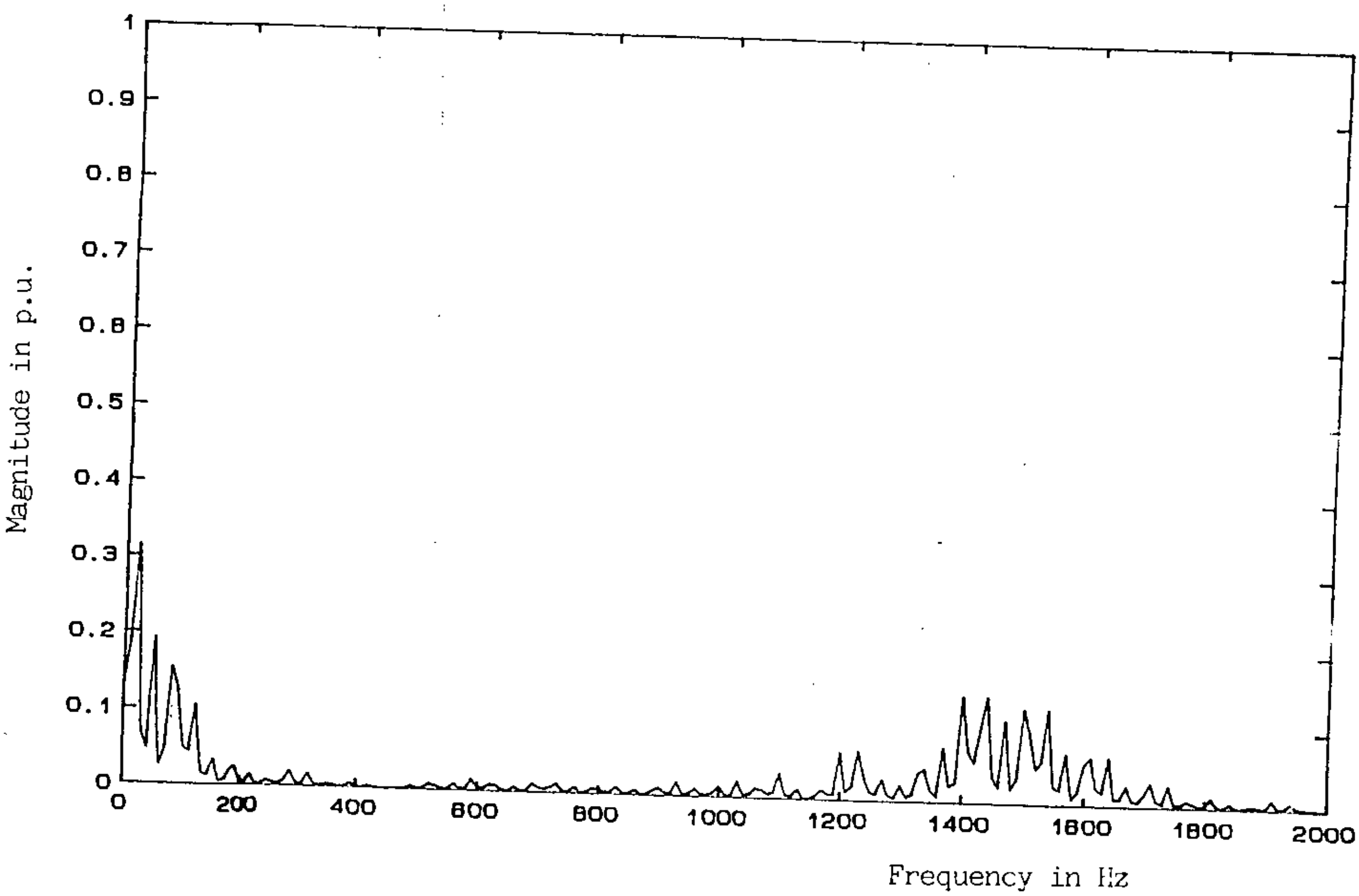


Fig:3.12 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=3000, Tc=.06

Δv in v, A in v/Sec, Tc in Sec

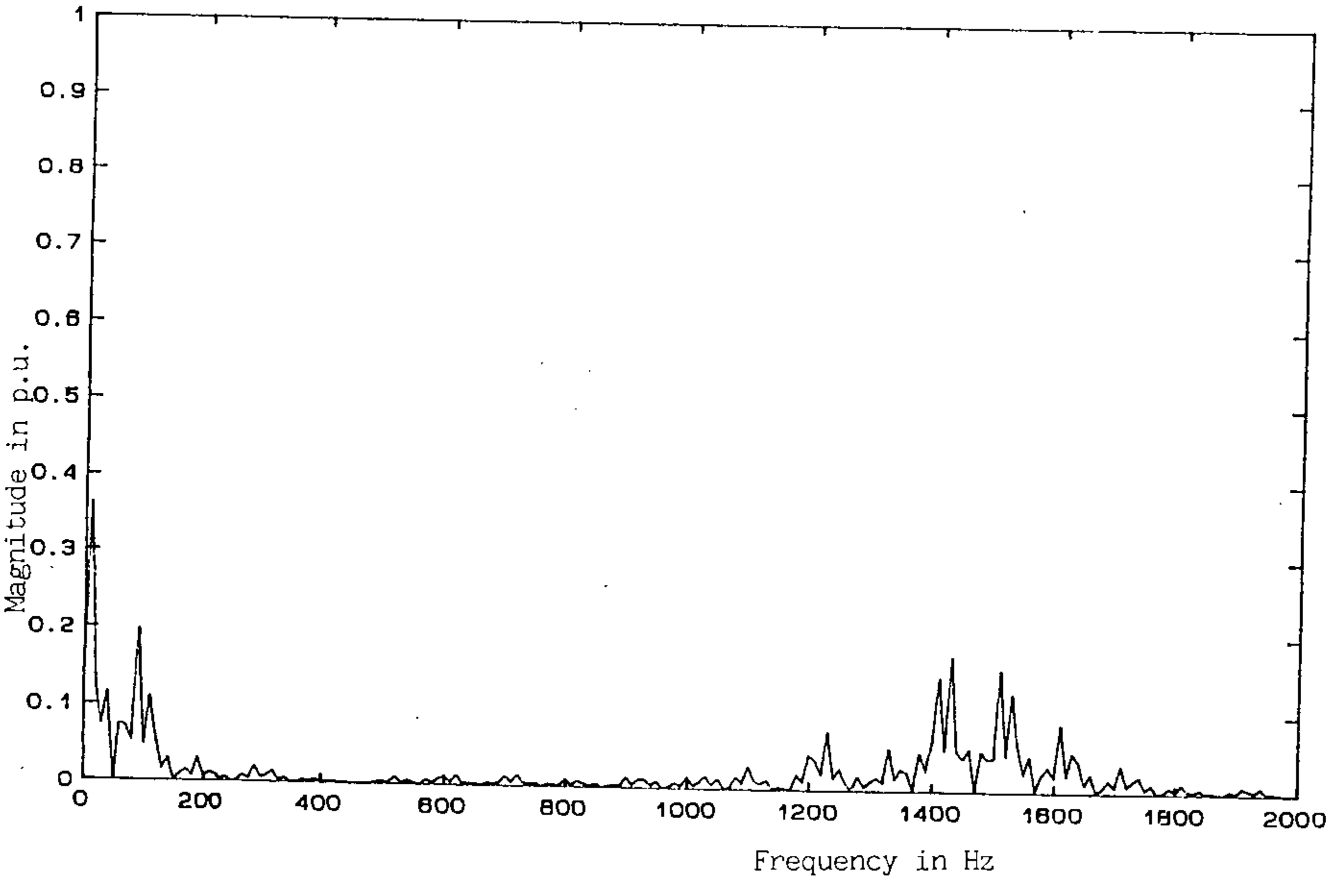


Fig: 3.13 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=3000, Tc=.08
Δv in v, A in v/Sec, Tc in Sec

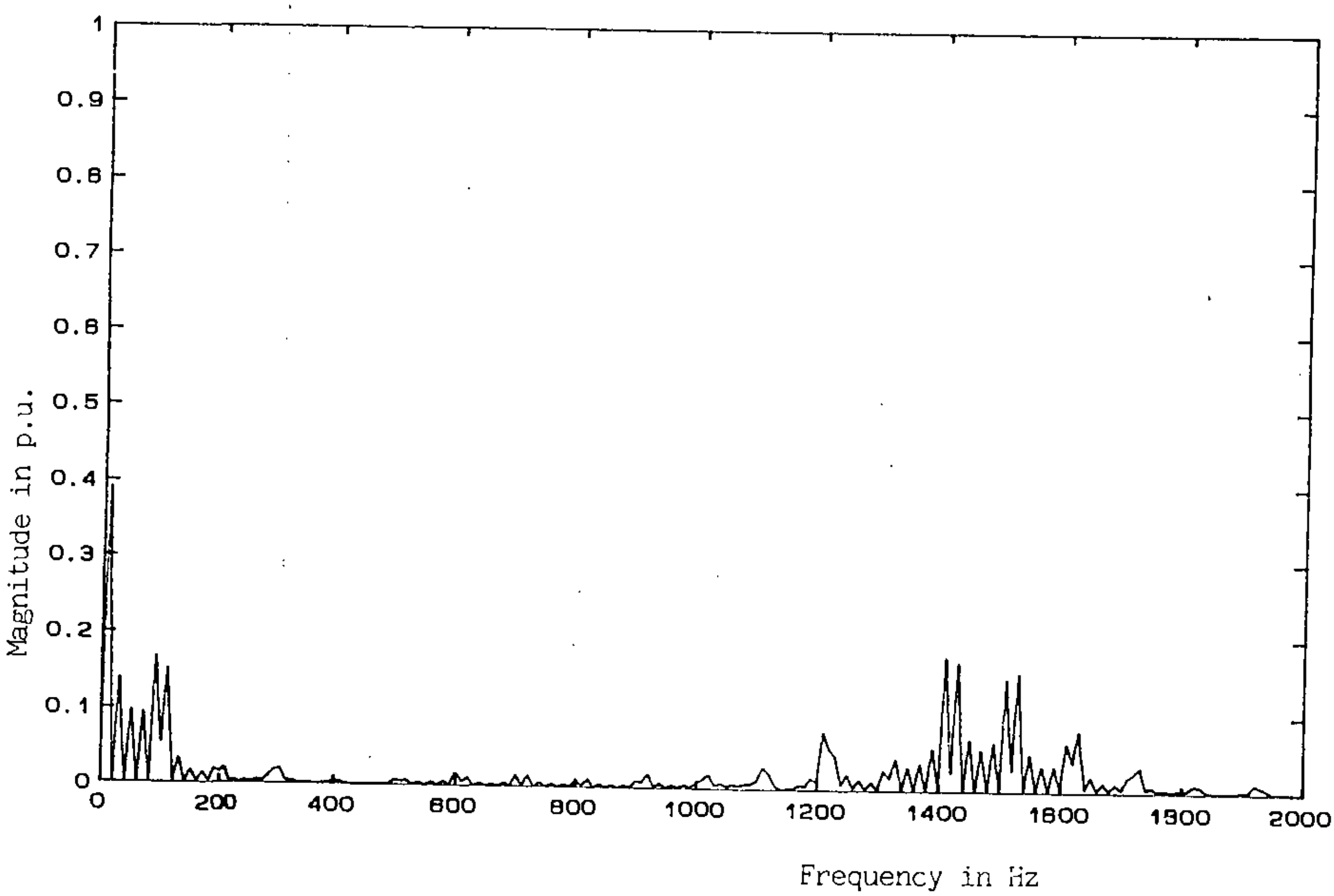


Fig:3,.14 Spectrum of a 1-Ø dm cycloconverter for △v=.5,A=3000, Tc=.1
△v in v, A in v/Sec,Tc in Sec

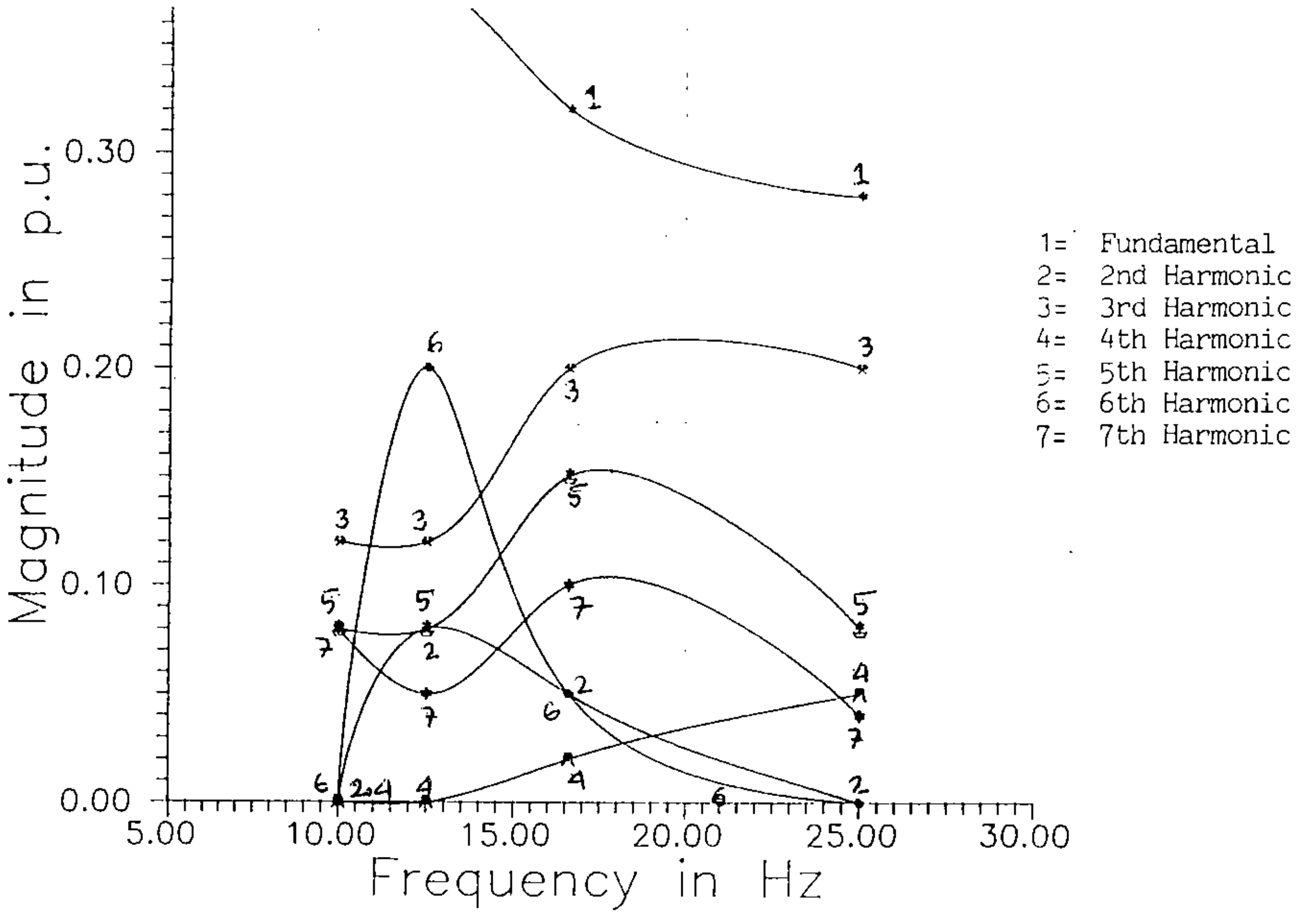


Fig: 3.15 Result spectral analysis of a 1-Ø dm cycloconverter for Δv=.5, A=3000.

(Δv in v, A in v/Sec)

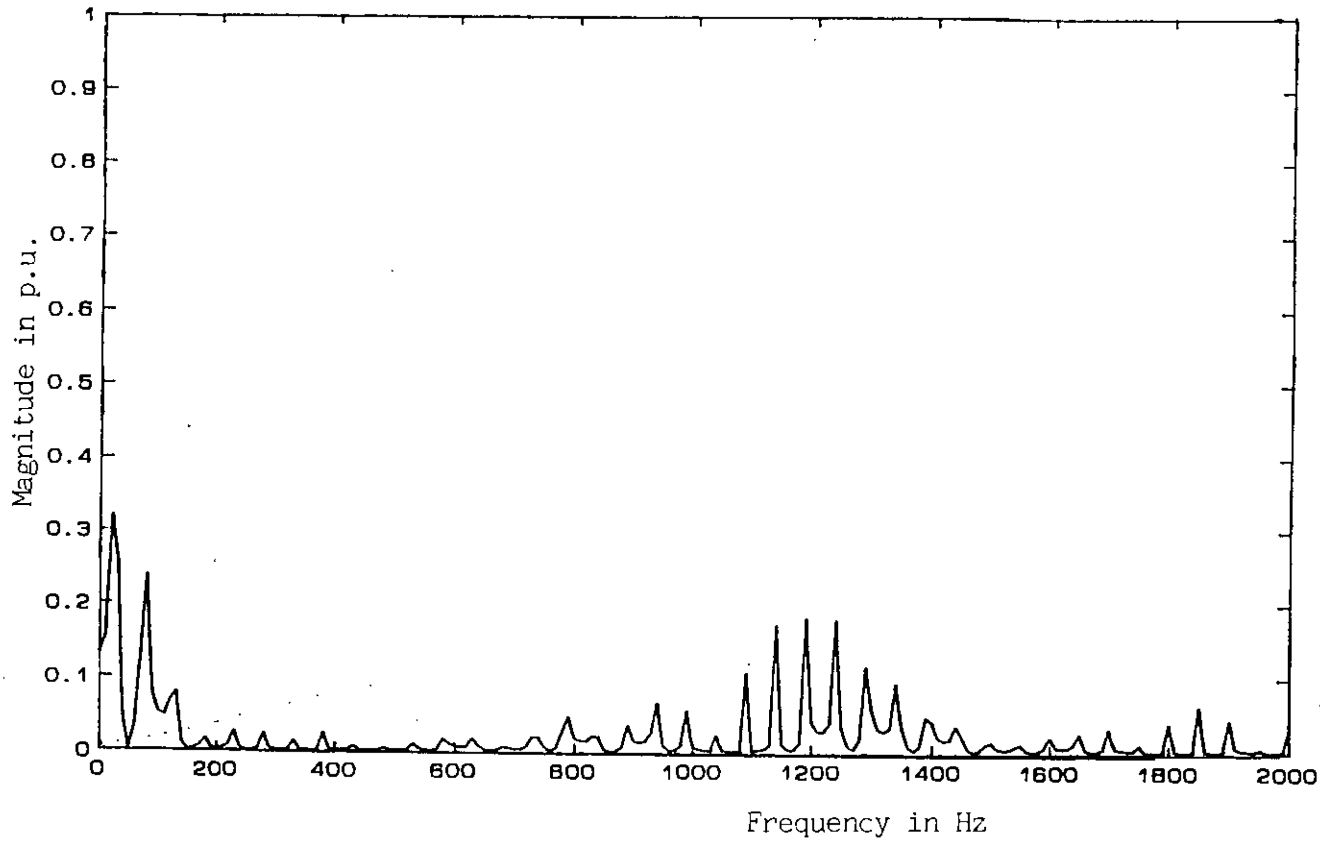


Fig: 3.16 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=2500, Tc=.04

Δv in v, A in v/Sec, Tc in Sec

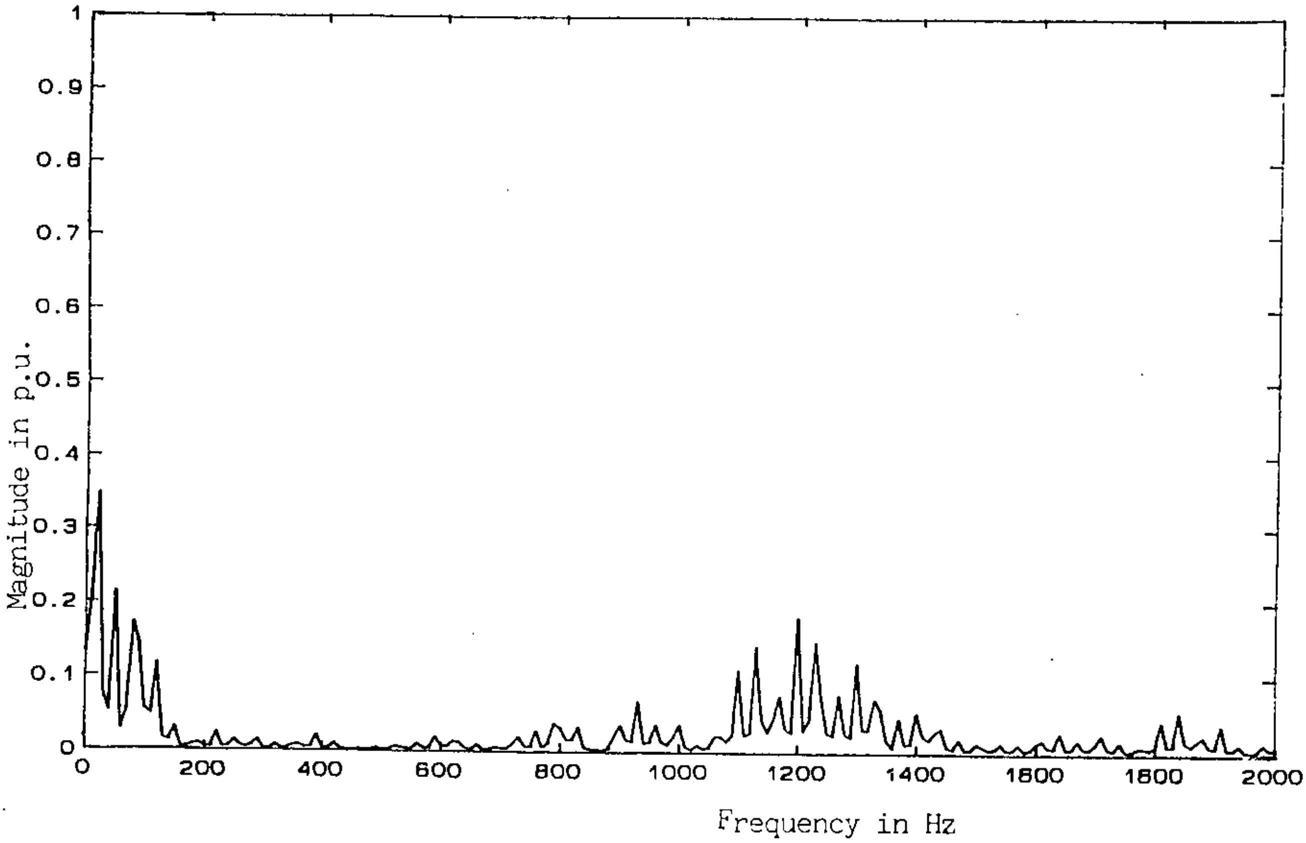


Fig: 3.17 Spectrum of a 1-Ø dm cycloconverter for $\Delta v=.5$, A=2500, Tc=.06

Δv in v, A in v/Sec, Tc in Sec

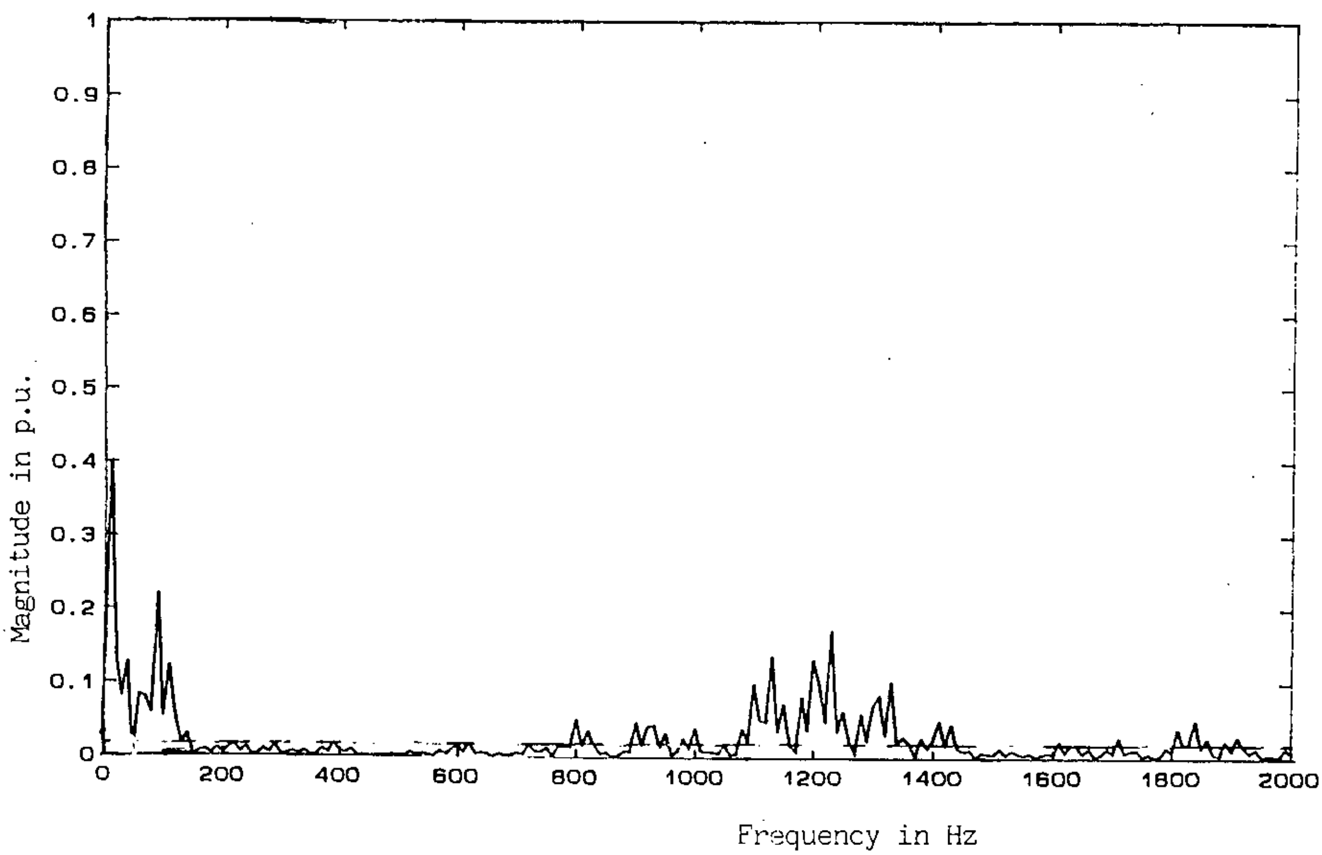


Fig: 3 .18 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=25000, Tc=.08

Δv in v, A in v/Sec, Tc in Sec

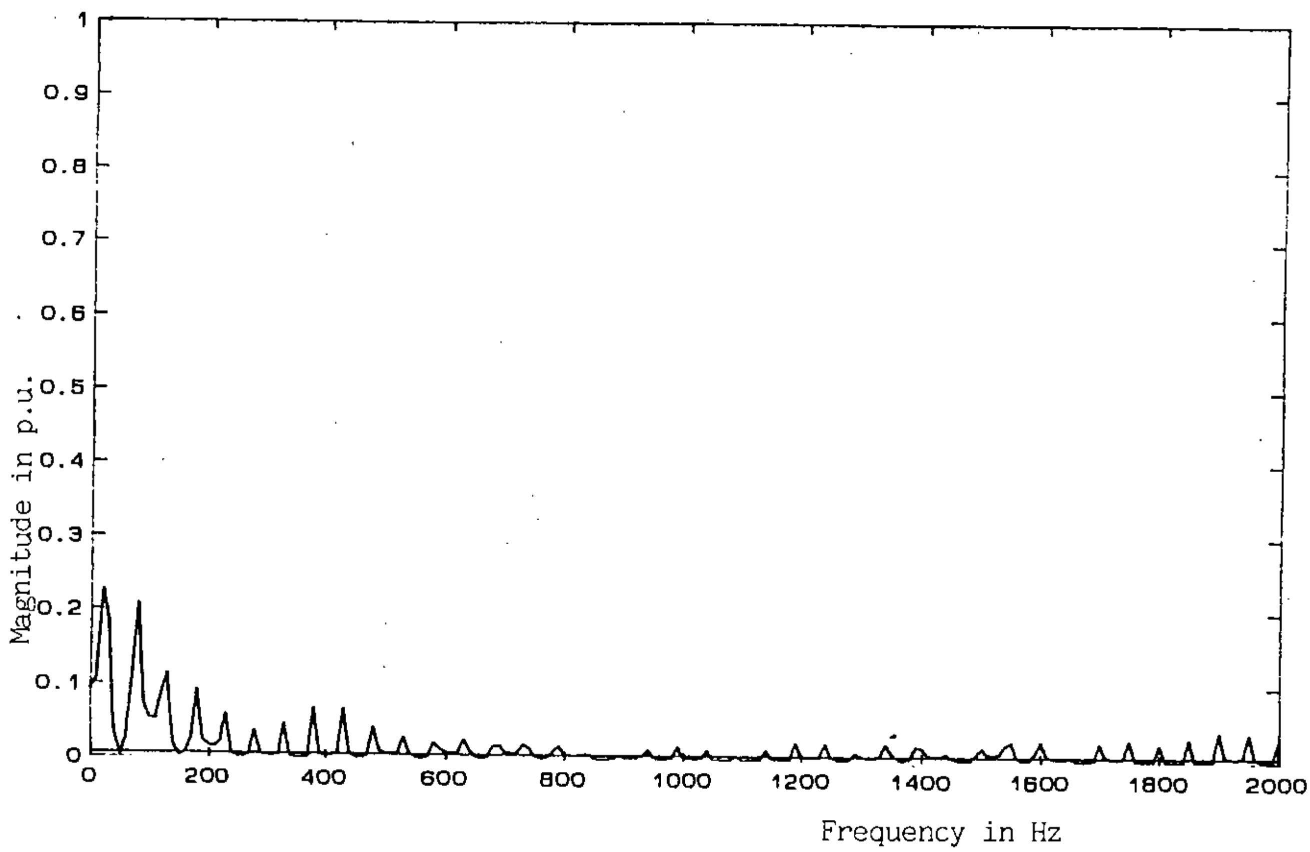


Fig: 3.19 Spectrum of a 1-Ø dm cycloconverter for Δv=.5, A=2500, Tc=.1

Δv in v, A in v/Sec, Tc in Sec

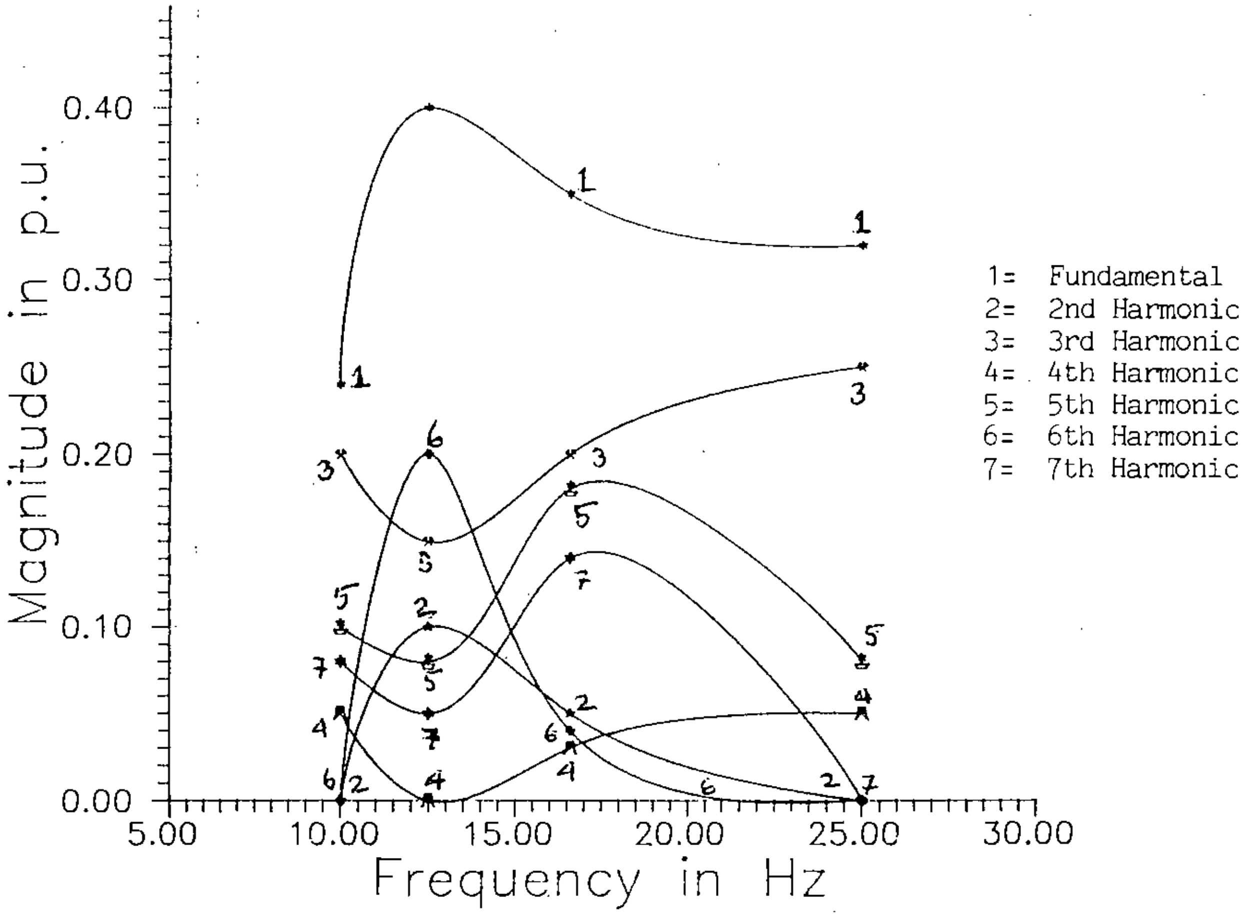


Fig: 3.20 Result of spectral analysis of a 1-Ø dm cycloconverter for Δv= .5, A=2500,

Δv in v, A in v/Sec, Tc in Sec

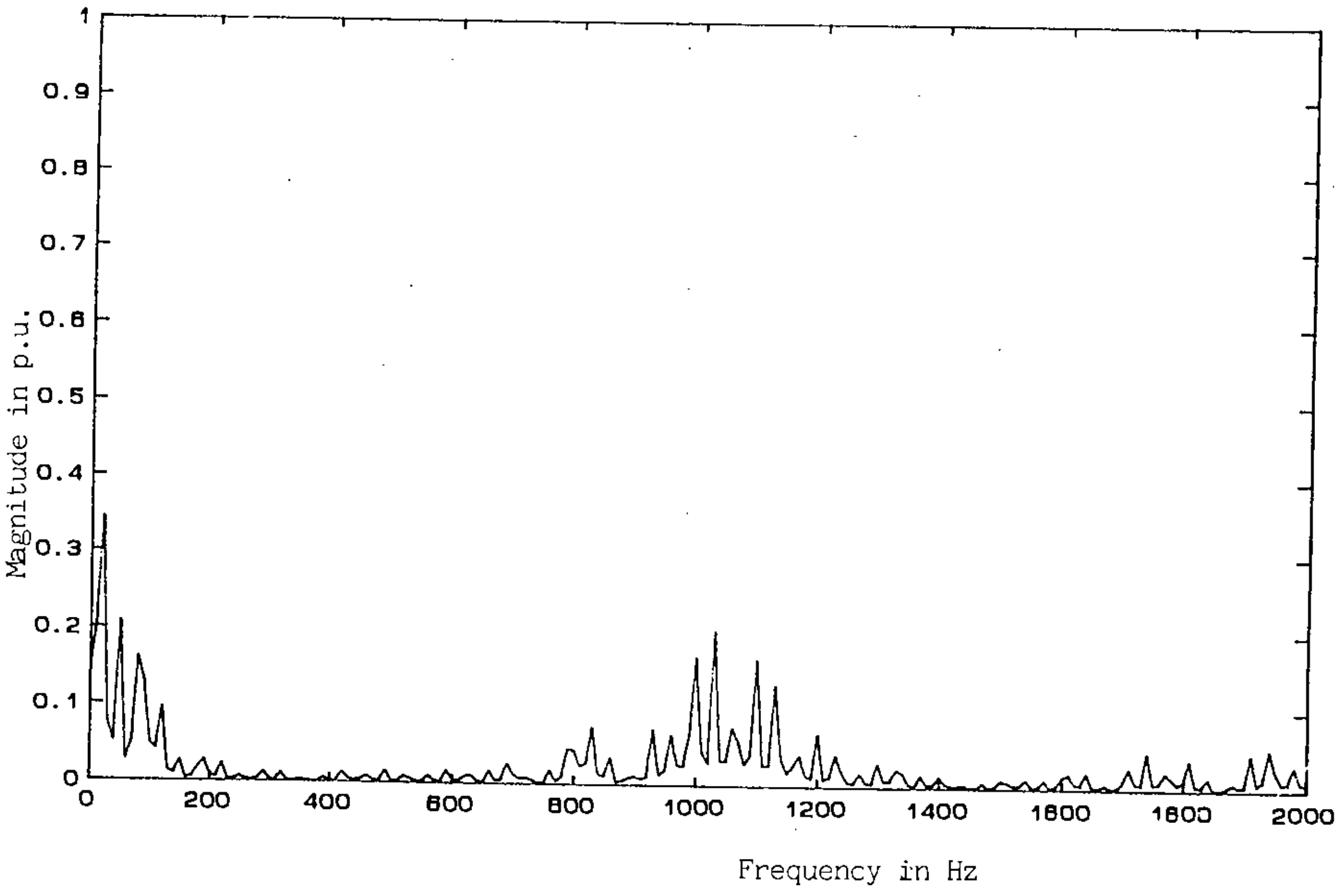


Fig: 3.21 Spectrum of a 1-Ø dm cycloconverter for Δv=.7, A=3000, Tc=.04
Δv in v, A in v/Sec, Tc in Sec

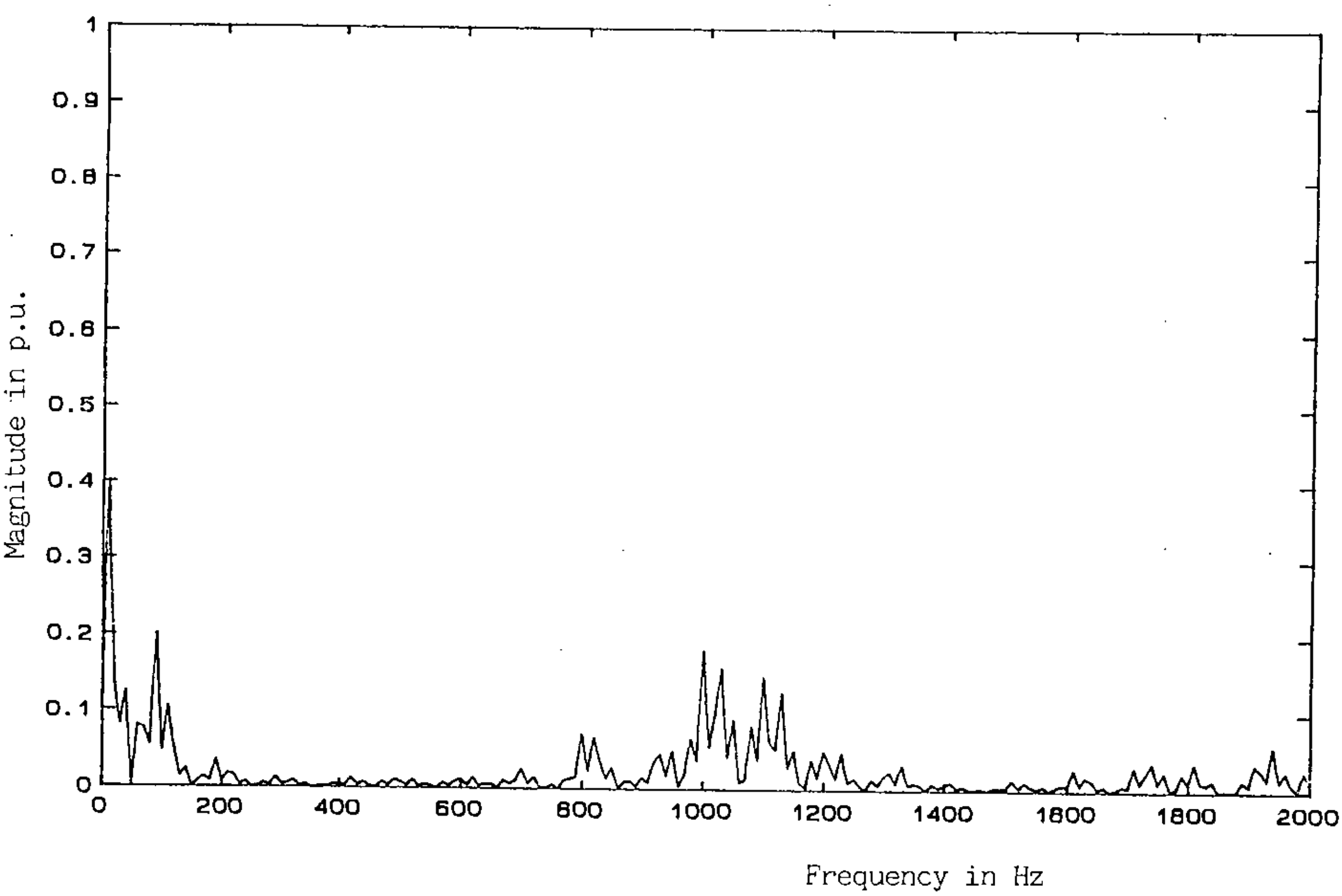


Fig: 3.22 Spectrum of a 1-Ø dm cycloconverter for Δv=.7, A=3000, Tc=.06
Δv in v, A in v/Sec, Tc in Sec

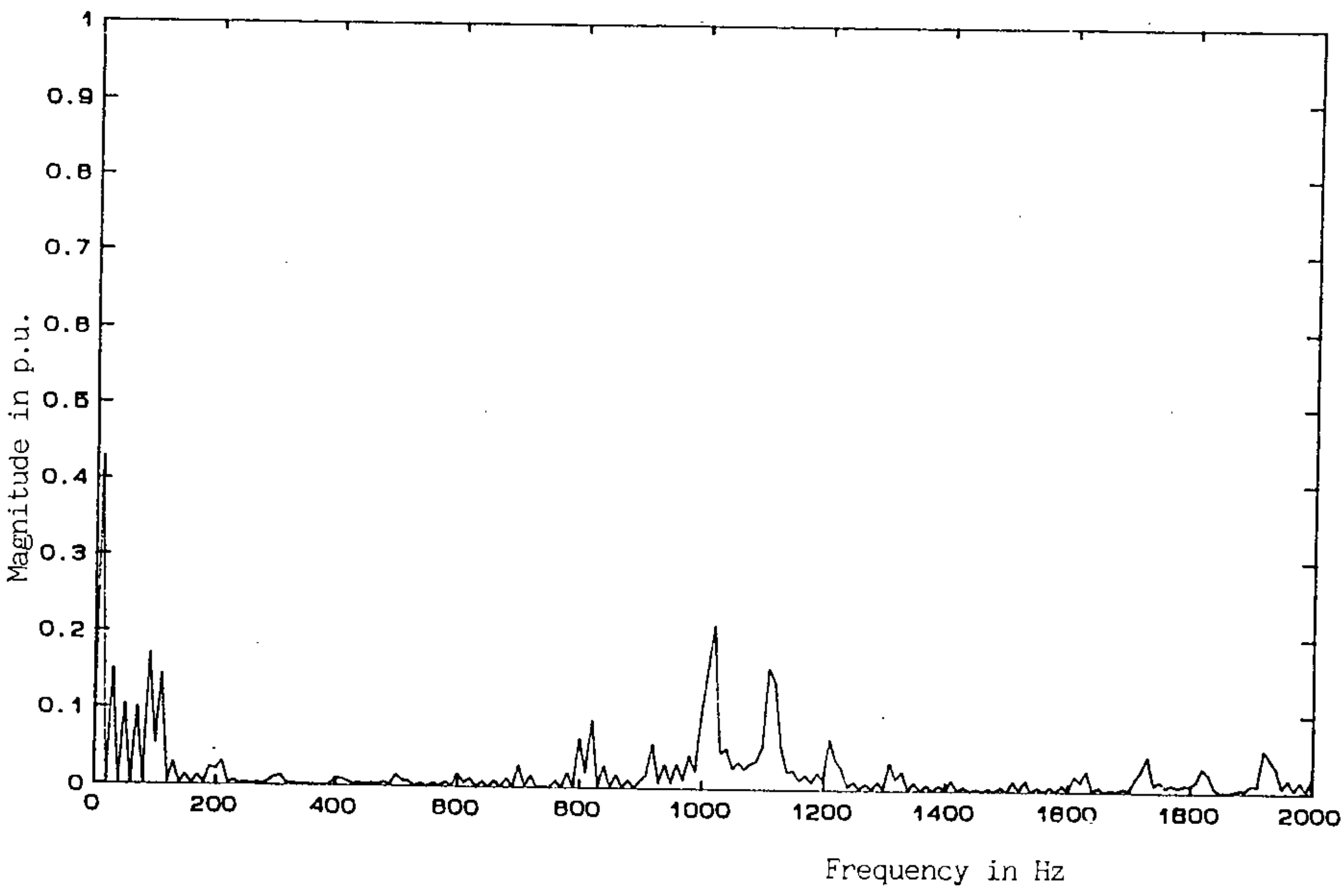


Fig:3.23 Spectrum of a 1-Ø dm cycloconverter for Δv=.7, A=3000, Tc=.008
Δv in v, A in v/Sec, Tc in Sec

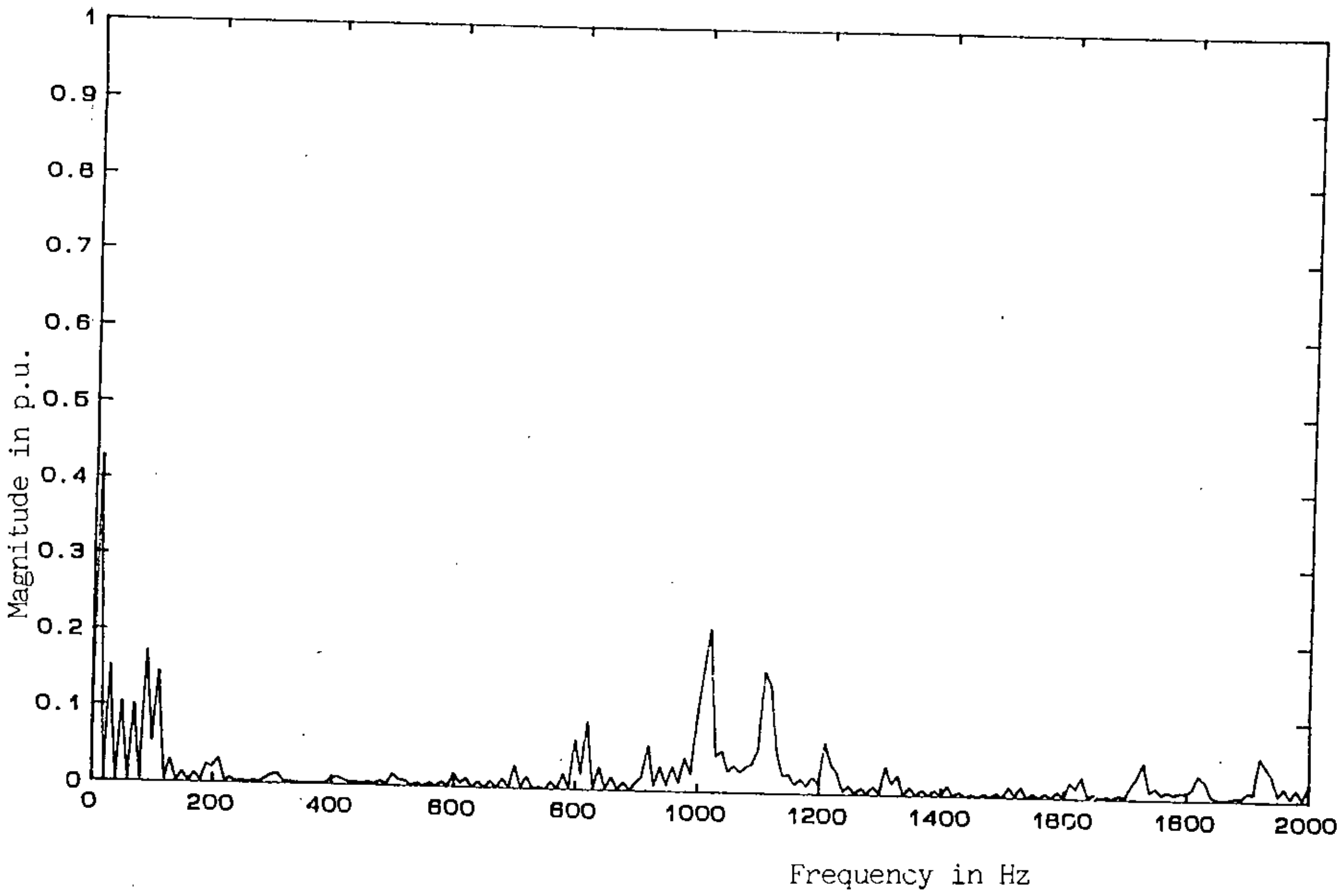


Fig: 3.24 Spectrum of a 1-Ø dm cycloconverter for $\Delta v=.7$, $A=3000$, $Tc=.1$
Δv in v, A in v/Sec, Tc in Sec

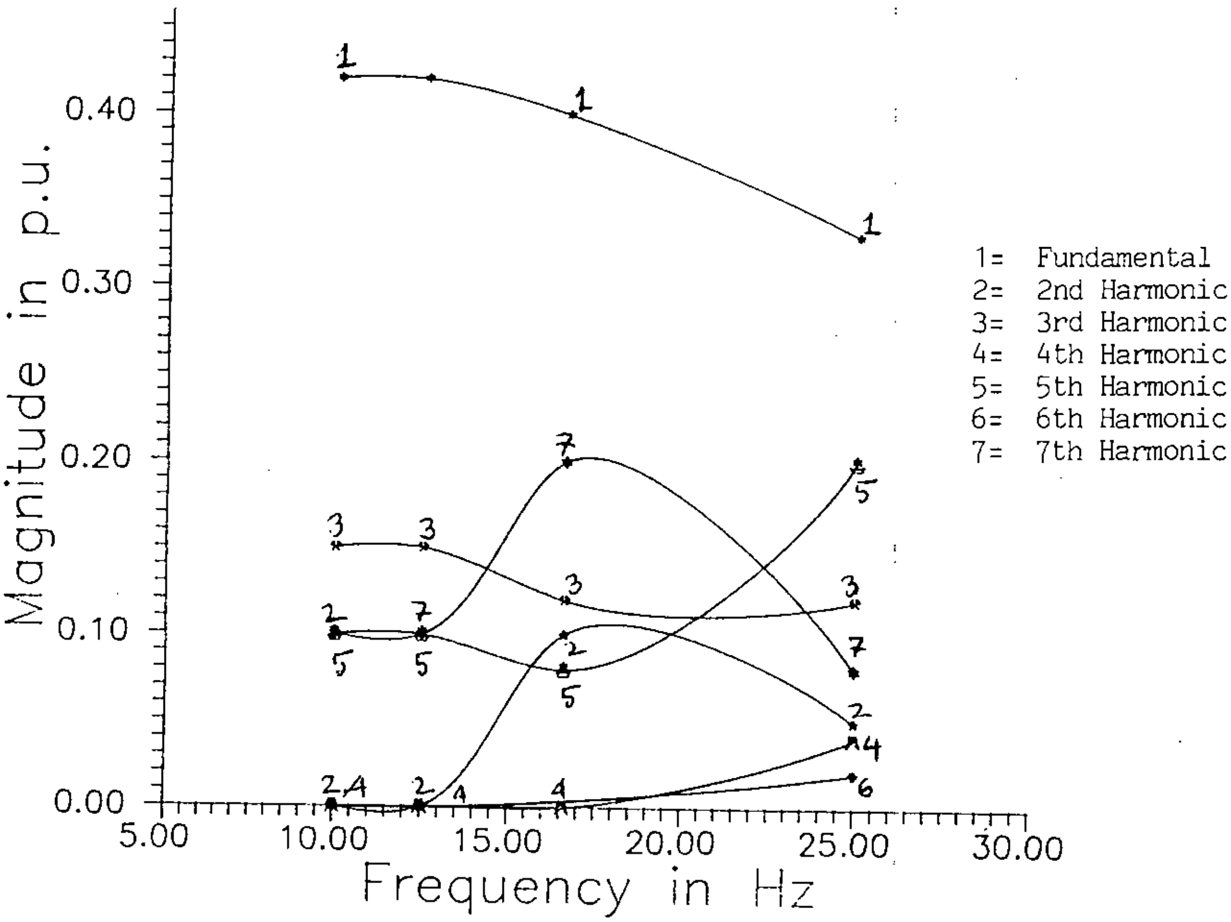


Fig:3.25 Result of spectral analysis of a 1-Ø dm cycloconverter for Δv=.7, A=3000,

(Δv in v, A in v/Sec)

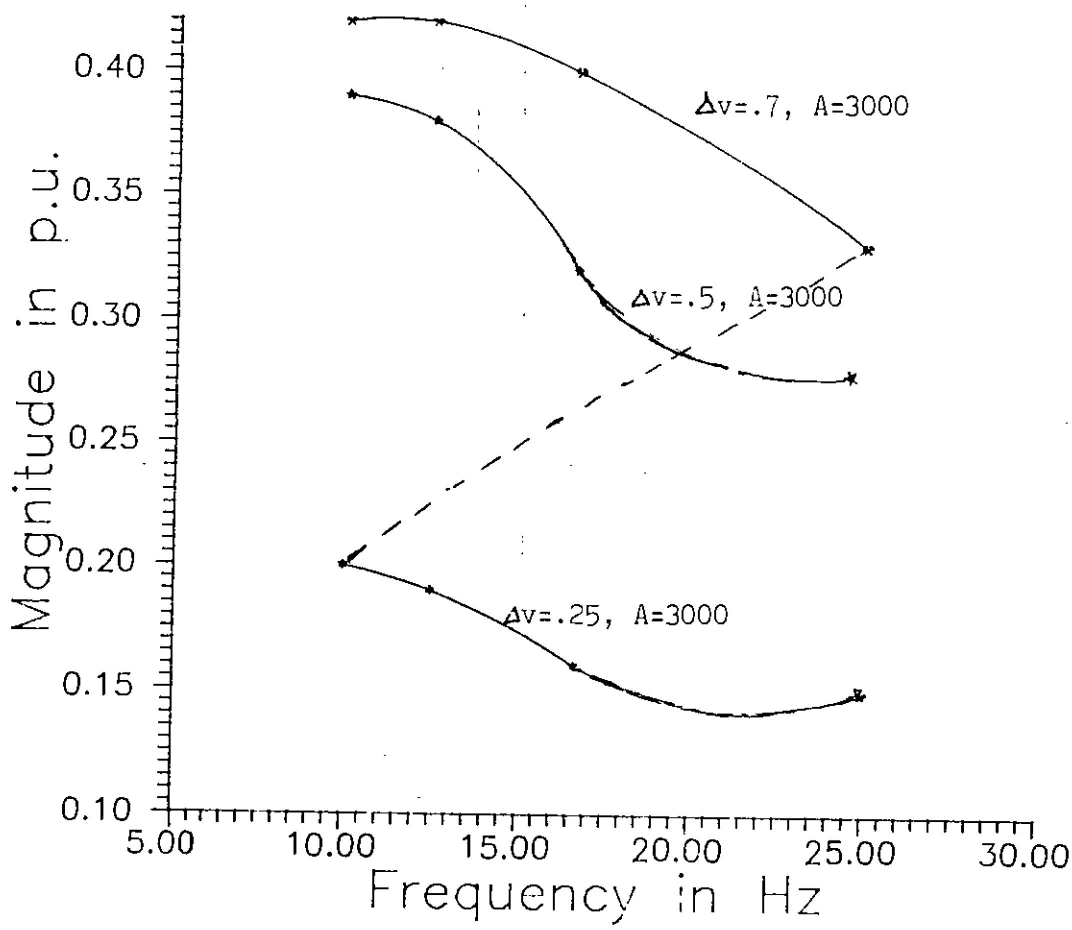


Fig: 3.26 Fundamental voltage variation with frequency for Δv= variable, A= constant.

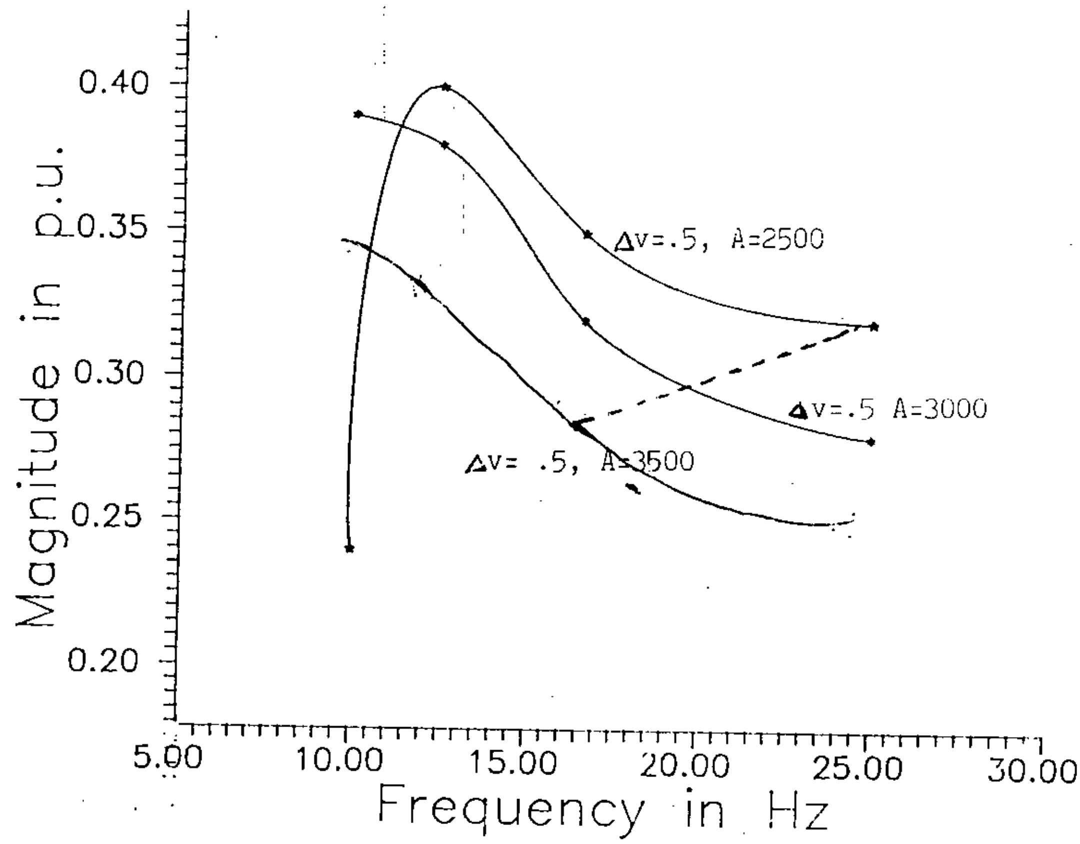


Fig: 3.27 Fundamental voltage variation with frequency for
Δv= constant, A= variable.

Table 3.1

Results of spectral analysis of dm waves for ΔV=.25 A = 3000 where V is the window width & A is slope V/sec.

frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
25	.15	0	.15	.05	.08	0	.05
16.6	.16	0	.16	.05	.08	0	.05
12.5	.19	.05	0	.05	.15	.05	.1
10	.2	0	.06	0	.05	0	.05

Table 3.2

Results of spectral analysis of dm waves for ΔV=.5, A = 3000 V/sec.

frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
25	.28	0	.2	.05	.08	0	.04
16.6	.32	.05	.2	.02	.16	.05	.1
12.5	.38	.08	.12	0	.08	.2	.05
10	.39	0	.12	0	.08	0	.08

Table 3.3

Results of spectral analysis of dm waves for $\Delta V=.5V$ A = 2500 V/sec.

Frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
25	.32	0	.25	.05	.08	0	0
16.6	.35	.05	.2	.03	.18	.04	.14
12.5	.4	.1	.15	0	.08	.2	.05
10	.24	0	.2	.05	.1	0	.08

Table 3.4

Results of spectral analysis of dm waves for $\Delta V=.7V$ A = 3000V/sec.

Frequency in Hz.	Harmonics						
	1	2	3	4	5	6	7
25	.33	.05	12	.04	.2	.02	.08
16.6	.4	.1	.12	0	.08	.08	.2
12.5	.42	0	.15	0	.1	0	.1
10	.42	0	.15	0	.1	0	.1

Table 3.5

Fundamental voltage variation with frequency for ΔV=variable and slope A=3000 v/sec = constant

frequency	V = .25	V = .55	V =.7
25	.15	.28	.33
16.67	.16	.32	.4
12.5	.19	.38	.42
10	.2	.39	.42

Table 3.6

Fundamental voltage variation with frequency for A=variable and constant ΔV = constant = .5 v/sec

frequency	A= 3000V/sec	A=2500V/Sec
25	.28	.32
16.67	.32	.35
12.5	.38	.4
10	.39	.24

Chapter - 4
PRACTICAL RESULTS

Introduction.

With a view to demonstrate the practicablity of the dm technique for operating a single phase cycloconverter, an experiment was set up and syccessful operation of a single phase cycloconverter was performed. In this chapter details of the experimental circuits are discussed with the results obtained during the operation of the cycloconverter.

4.1 Impementation of the Control Circuit Using dm.

The delta modulation technique requires relatively simple circuitry to obtain swithching waveform for a 1- cycloconverter. Fig 4.1 is an analog circuit that is capable of producing the modulated signal.

The operation of the circuit can be described as follows, Rectified sine wave is supplied to the input of the comparator A_1 and carrier V_F is generated in the following manner; whenever the output voltage of A_2 exceeds the upper or lower window boundary (present by $\frac{R_2}{R_1}$ ratio), the comparator A_1 reverses the polarity of V_I at the input of A_2. This rverses the polarity of V_F at the output of A_2.Itforces carrier wave to oscillate about the reference waveform. Once this switching waveform is obtained, the signals for the switching devices of the cycloconverter can be obtained by logic circuit implementation. In our case we have used to cycloconverter configuration of Fig 4.2, where the front and switch was a power MOSFET triggered by the modulated signal obtained by dm modulator. The inverter section with thyristor switches were simulated in the lab by two dual dc-dc converter connnected in bridge configuration. The inverter was used to converter the modulated rectified wave to the required ac of desired frequency. The timing diagram of the inverter logic circuit to trigger the main and commutation circuit SCRS are shown in Fig 4.3. The cycloconverters frequency control signal was generated by a timer circuit using 555 chip. Actual circuit for producing the signals of Fig 4.3 is shown in Fig 4.4 [25].

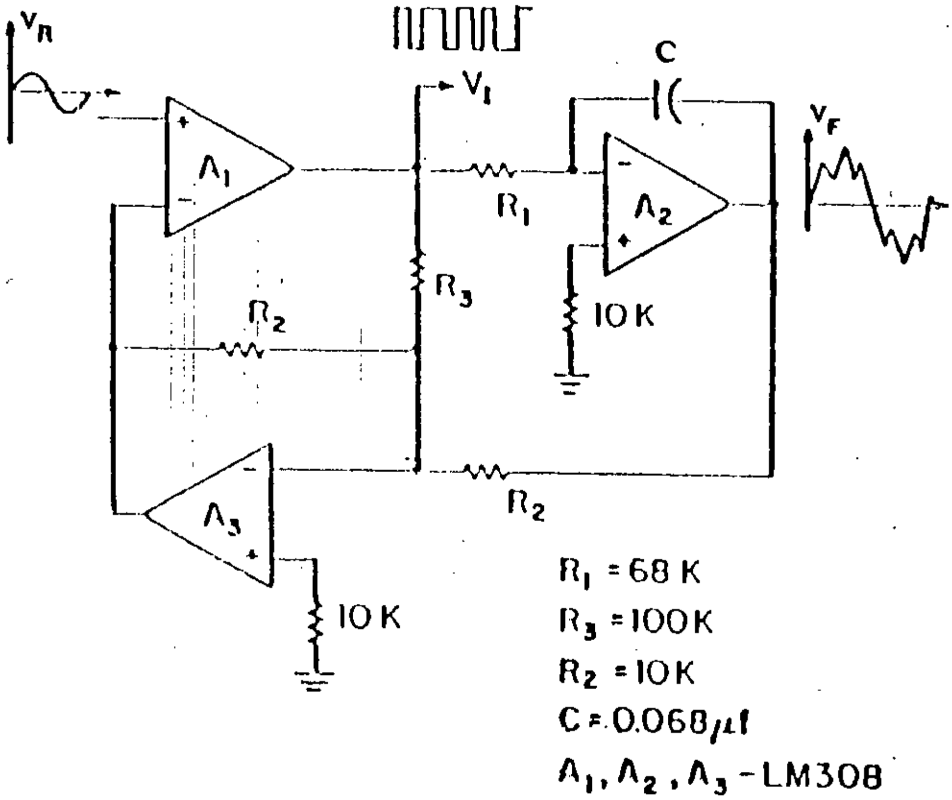


Fig. 4.1 A practical circuit for producing switching waveform of delta modulated cycloconverter

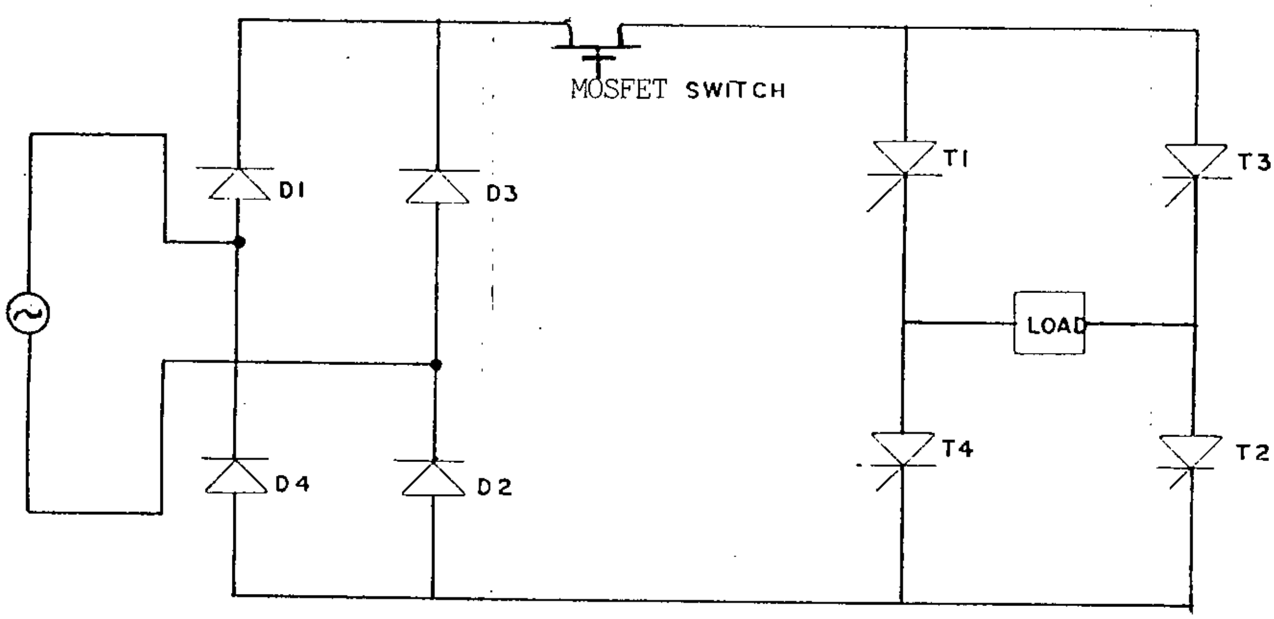


Fig: 4.2 Cycloconverter with a mosfet switch

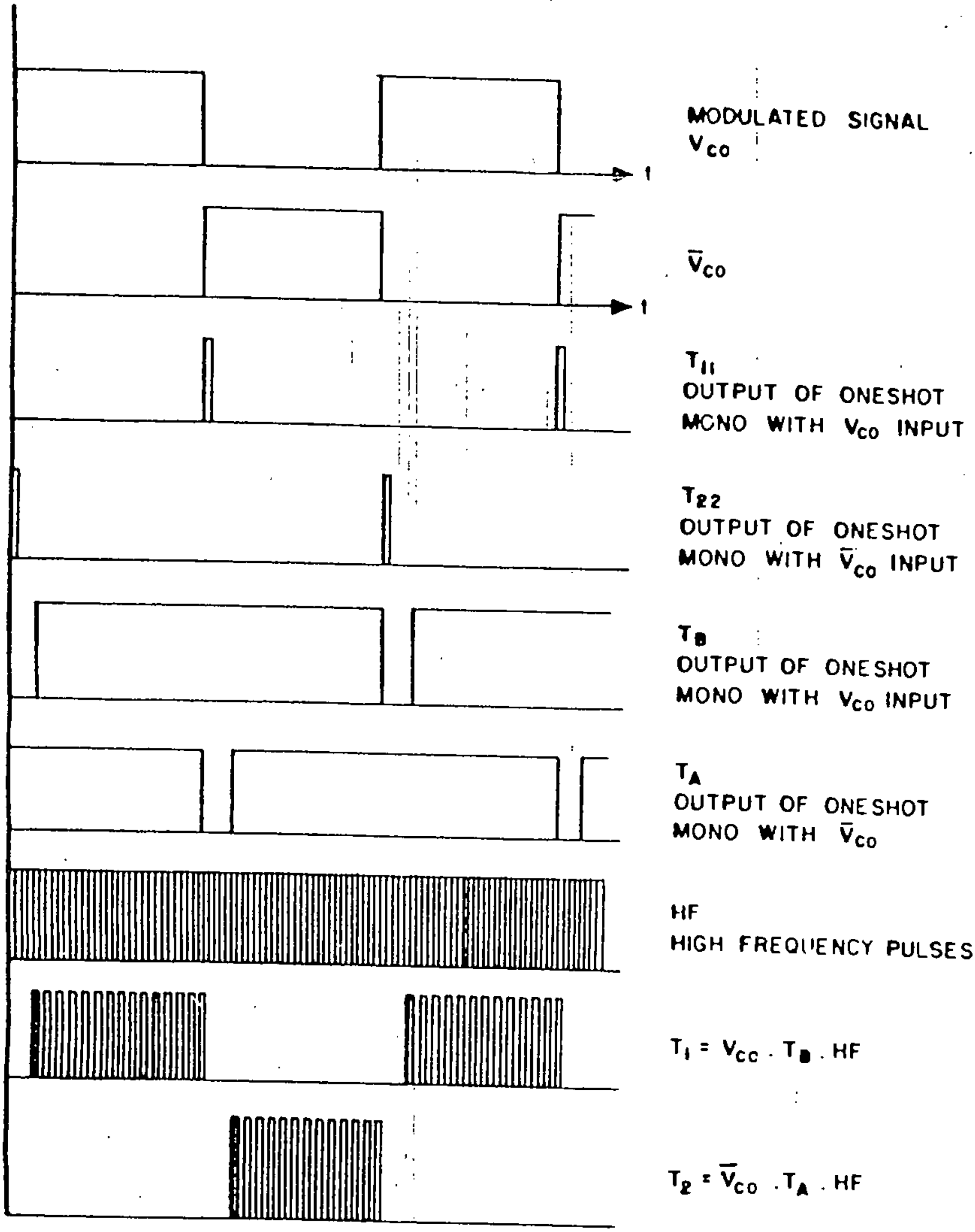


Fig: 4.3 Timing diagram of 1-phase inverter section of the cycloconverter gating signals.

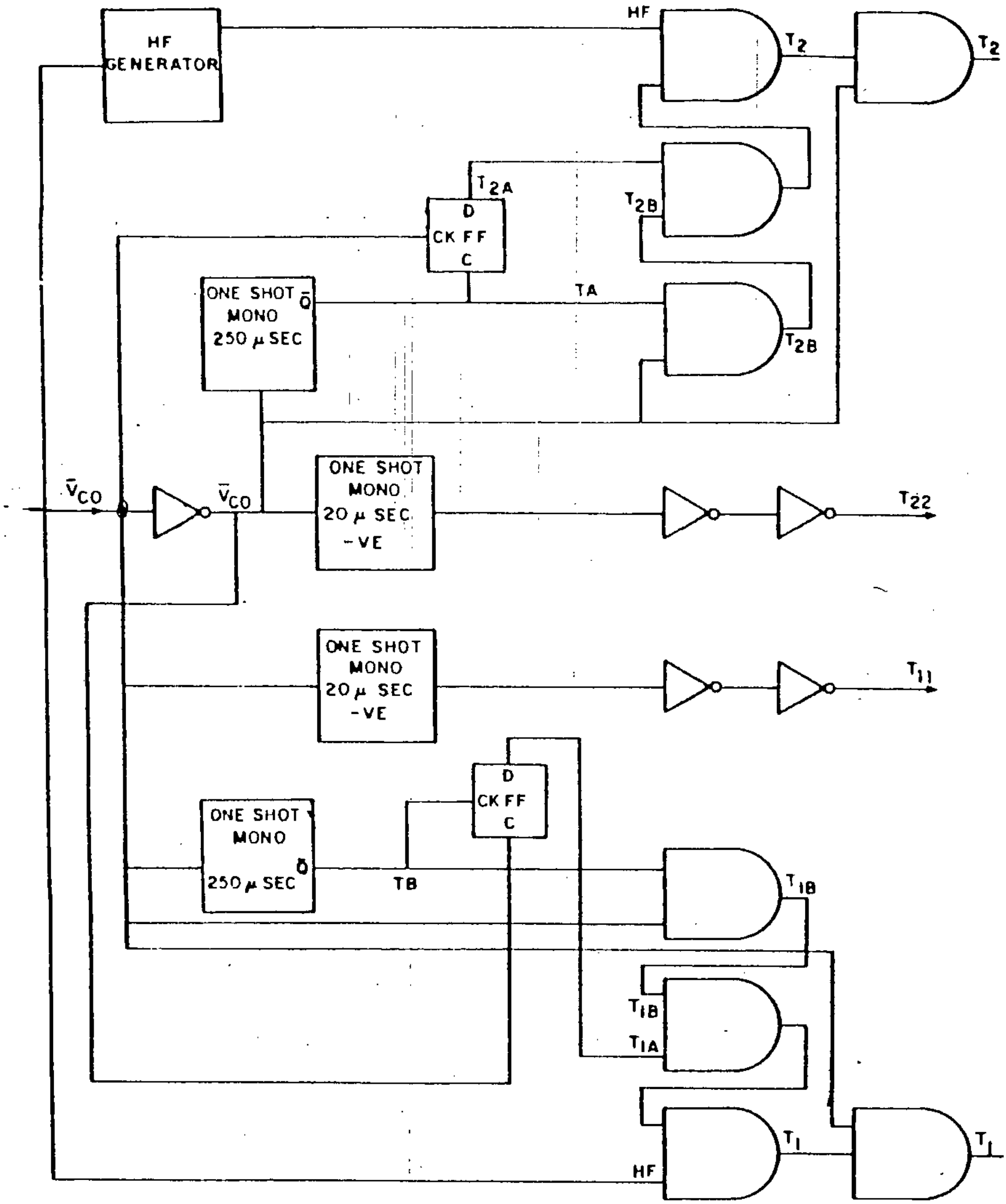


Fig. 4 .4 Block diagram of logic circuit to produce the signals of the timing diagram for the switching signals of the single phase DM cycloconverter (inverter section)

4.2 Experimental Results.

This section deals with the description of the experiments performed. Fig 4.5 are the oscilloscope pictures of the reference wave(sine) the carrier wave and the modulated waves, generated by the practical circuit with a sine input. The same waveforms for a different slope of the carrier wave are shown in Fig 4.6. It is observed that as the slope is increased by changing the resistance of the integrating circuit, the number of swithcing points are increased. Similar waveforms of variable window width with constant slope are shown in Fig 4.7. In the case of decreasing the window width also the swithcing frequency of the modulated wave increases.

In the experimental study, finally a single phase cycloconverter was run successfully by the dm switching strategy. Typical waveform obtained at the MOSFET switch after the rectifier is shown in Fig 4.8. These oscilloscope pictures show the output voltage waveform at the top and the current waveform at the bottom of the trace when the output of the MOSFET switch is Ωconnected to a resistive load. The two traces show the affect of varying modulation parameters on the waveforms. In Fig 4.8(a) the number of pulses are more than in the waveforms of Fig 4.8(b). Fig 4.9 illustrates the waveforms of the delta modulated single phase cycloconveter for a particular condition of the modulator. Waveforms of the cycloconverter is shown for three different operating frequencies 16.66 Hz, 25 Hz and 50 Hz in Figs 4.9(a), 4.9(b) and 4.9(c) respectively.

4.3 Conclusions.

In the experimental part of this research work only the successful operation of the cycloconverter has been demonstrated. However, the performance of the cycloconverter could not be evaluated experimentally in terms of harmonic contents due to the unavailability of a spectrum analyses. Also the on- line optimization circuit of the cycloconverter could not be realized in time for reporting in this thesis work.

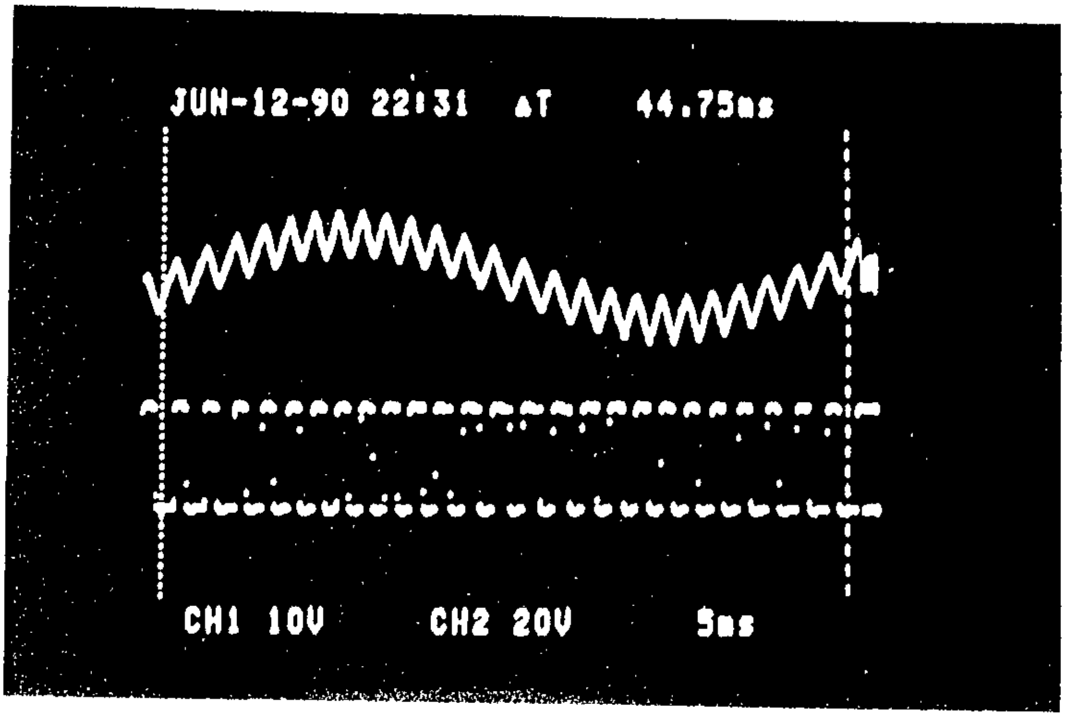


Fig. 4.5 (a)

20 Hz
VR=10V
ΔV=3V

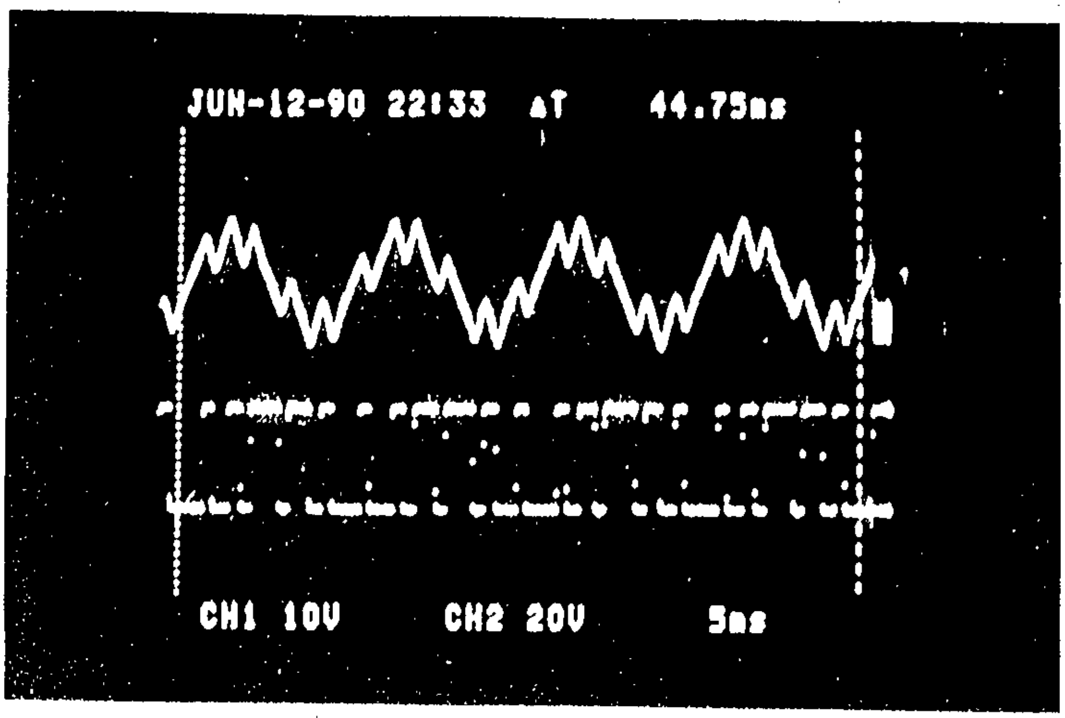


Fig. 4.5 (b)

20 Hz
VR=10V
ΔV=3V

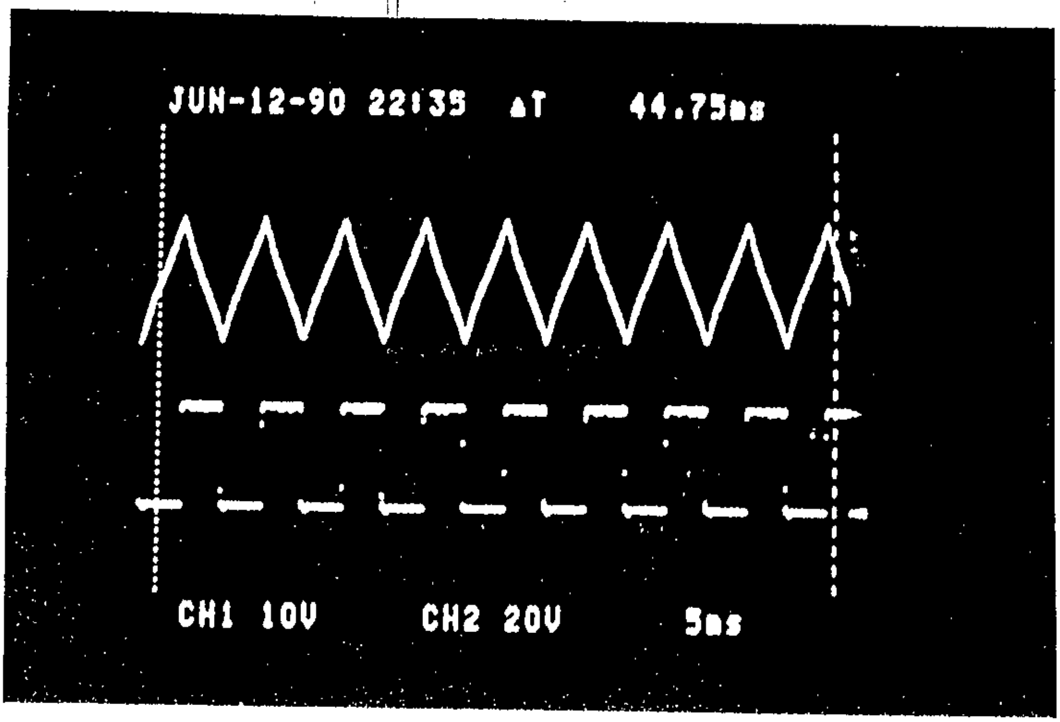


Fig. 4.5(c)

180 Hz
VR= 10V
ΔV= 3V

Fig. 4.5 Waveforms of variable step rwdm as the frequency of the modulating wave is increased.

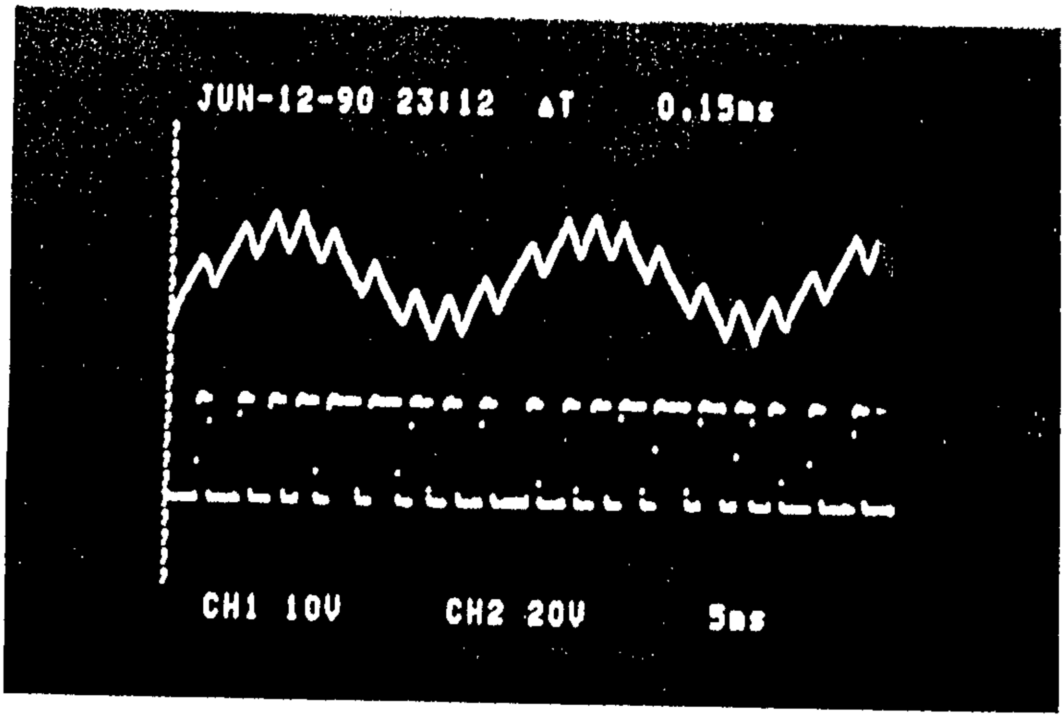


Fig. 4.6 (a)

40 Hz
A=2000 V/Sec
ΔV=3V

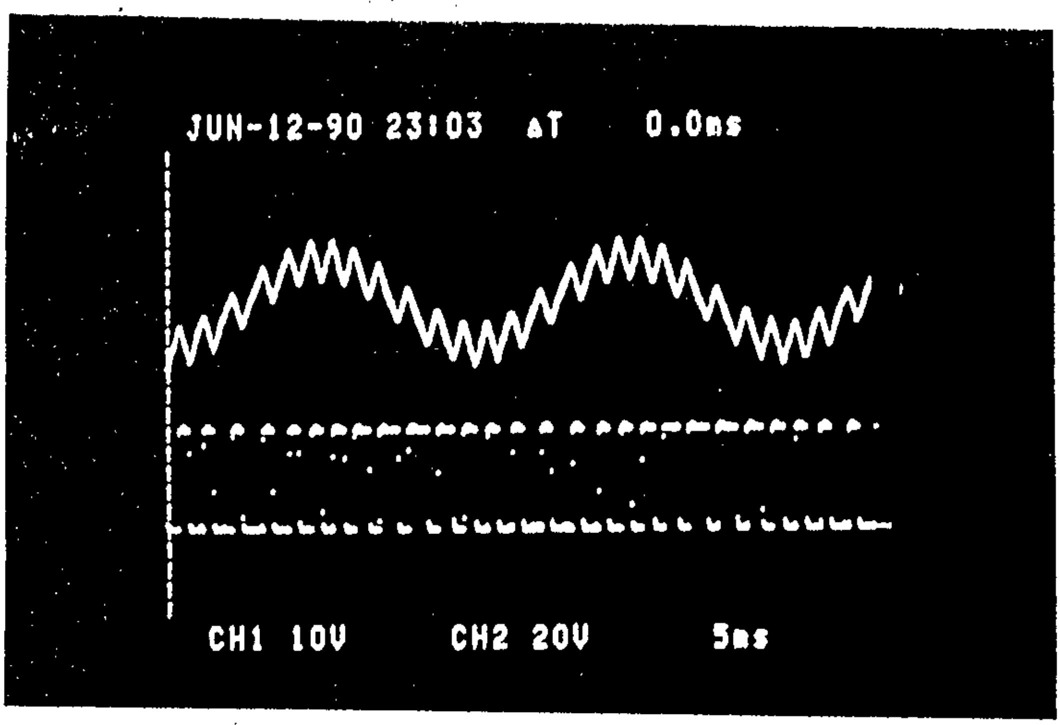


Fig. 4.6 (b)

40 Hz
A=4500V/Sec
ΔV=3V

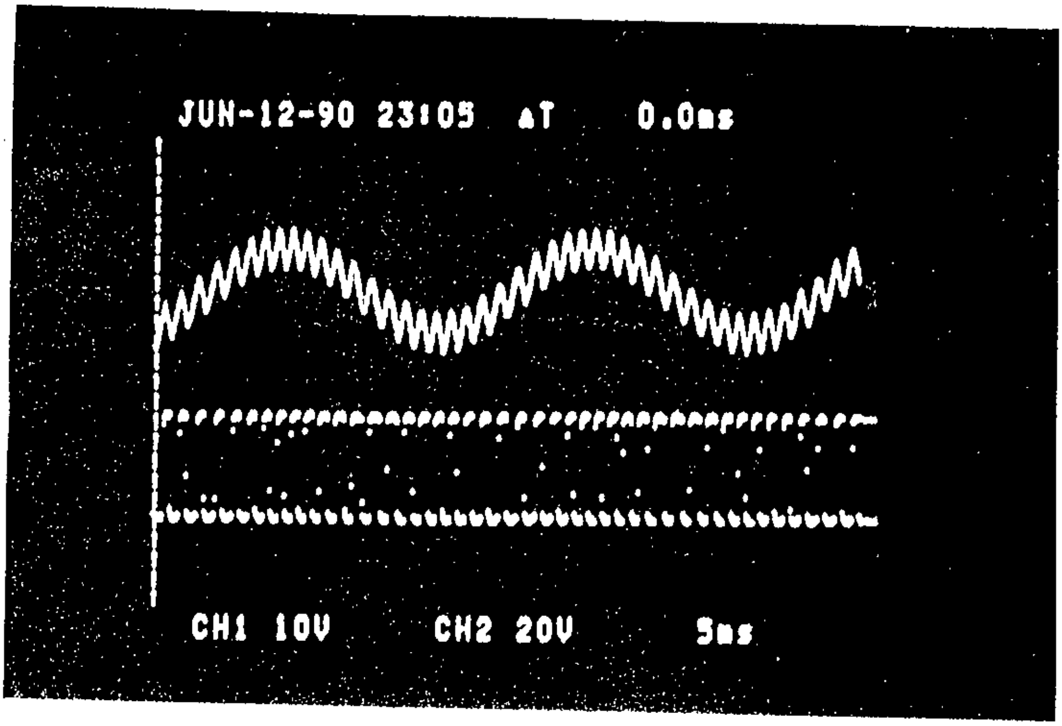


Fig. 4.6 (c)

40 Hz
A=6500 V/Sec
ΔV=3V

Fig. 4.6 Waveforms of tuned rwdm as the slope of the carrier wave is increased.

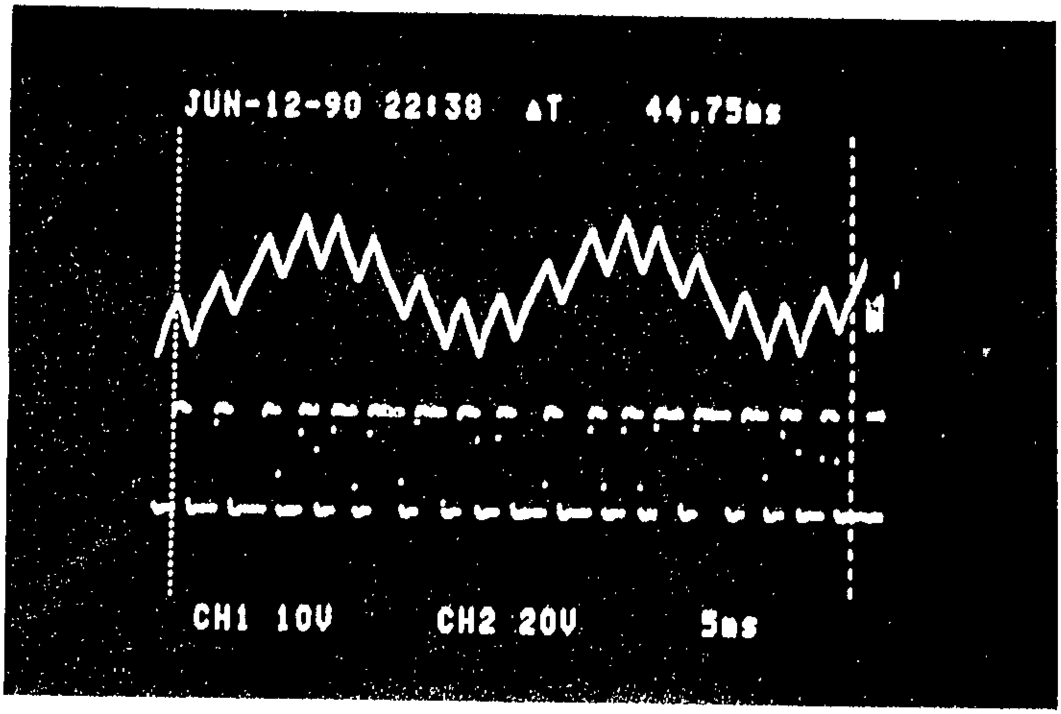


Fig. 4.7 (a)

40 Hz
ΔV=3V
A =2500V/Sec

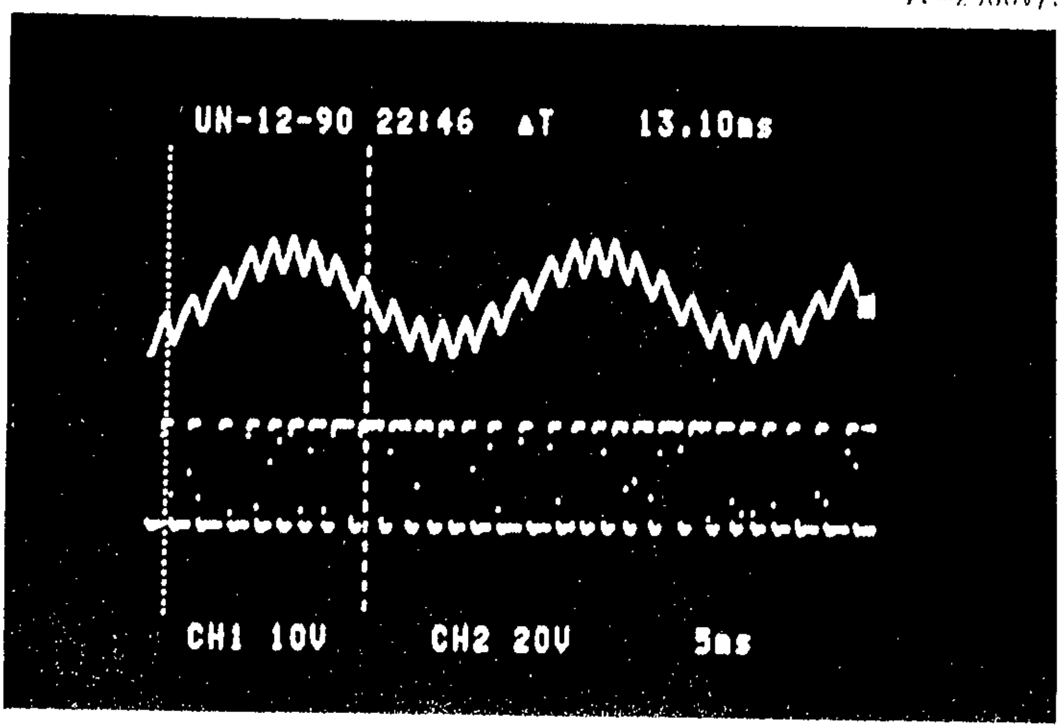


Fig. 4.7 (b)

40 Hz
ΔV=1.5V
A =2500 V/Sec.

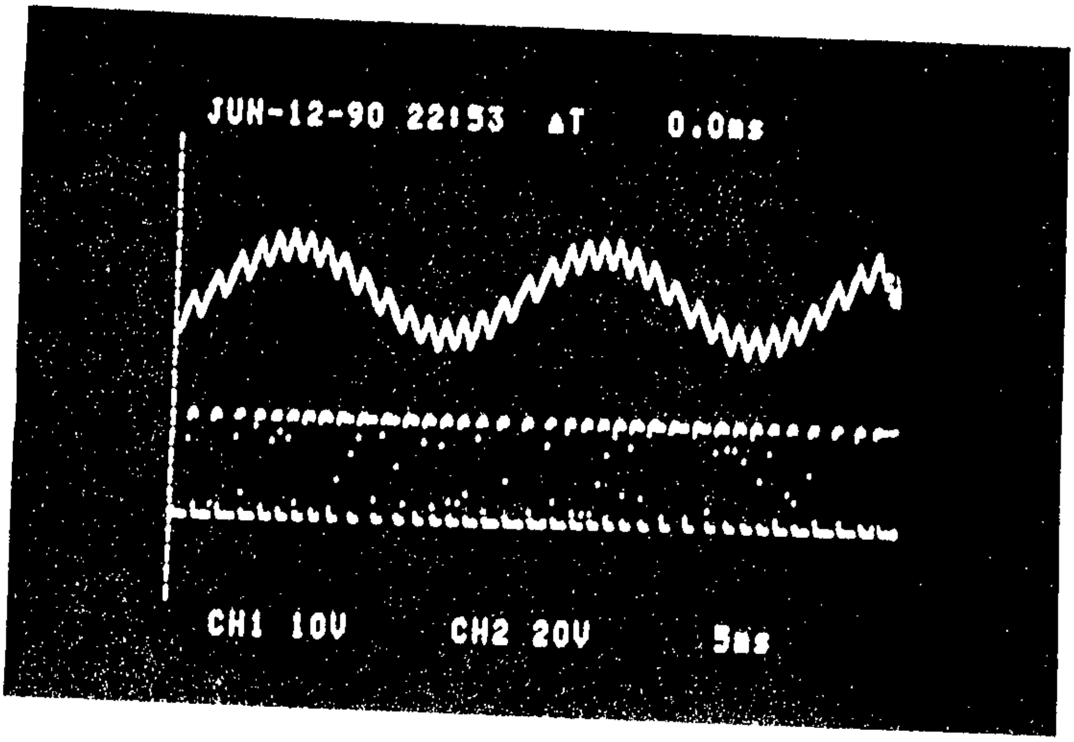


Fig. 4.7 (c)

40 Hz
$\Delta V = .75$
$A = 2500 V/Sec$

Fig. 4.7 Waveforms of variable step rwdm as the window width is decreased.

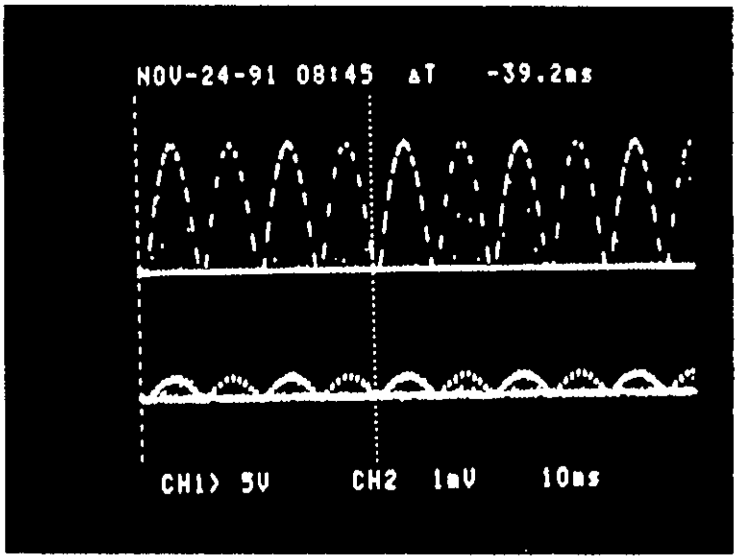


Fig: 4.8(a)

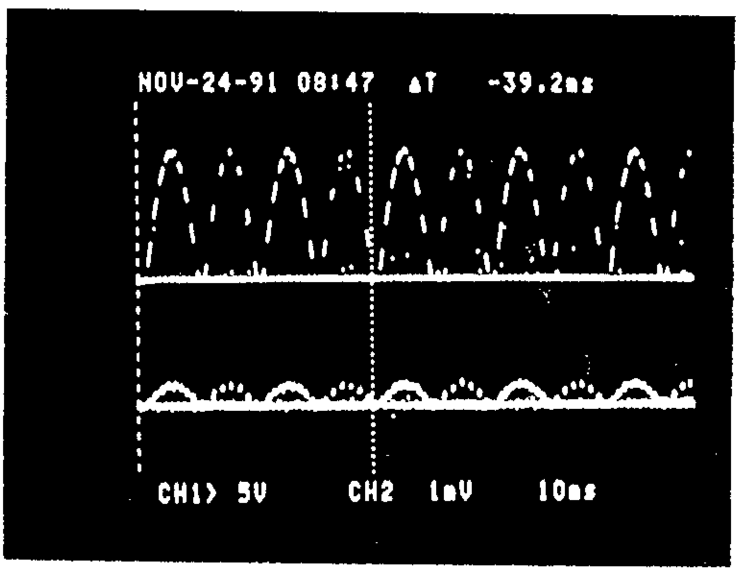


Fig: 4.8(b)

Fig: 4.8 Waveforms of modulated rectified wave at the output of MOSFET switch at the front end of the cycloconverter

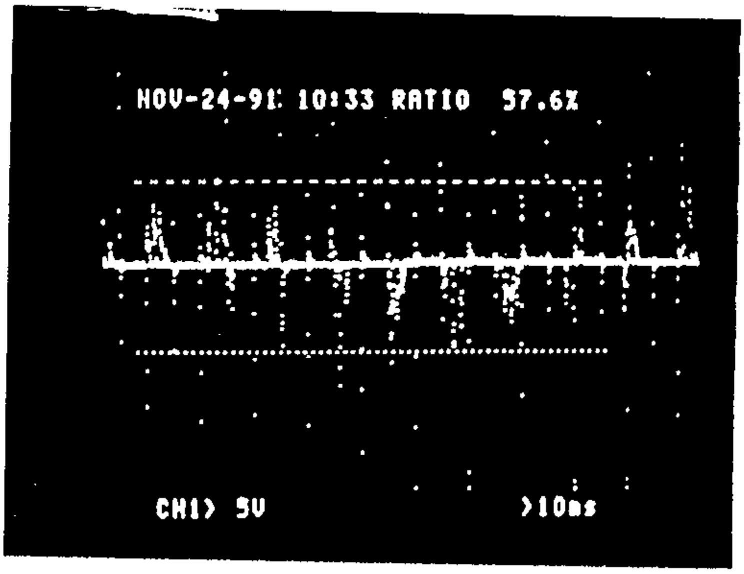


Fig: 4.9(a) Modulated cycloconverter waveform for f= 16.66 Hz

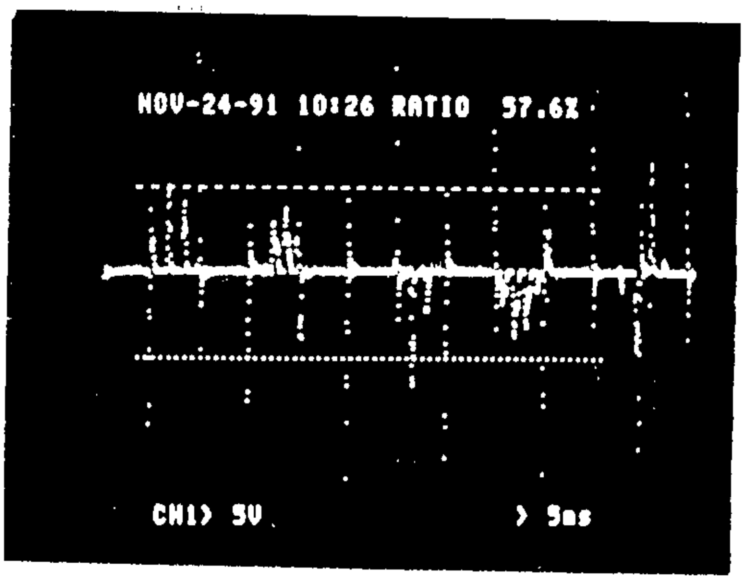


Fig: 4.9(b) Modulated cycloconverter waveform for f= 25 Hz

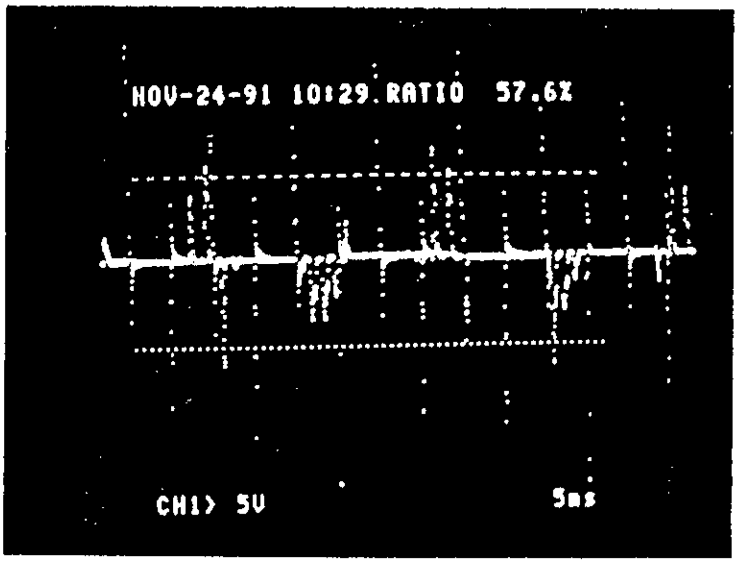


Fig: 4.9(c) Modulated cycloconverter waveform for f=50 Hz

Chapter - 5

Summary and Conclusions

The objectives set at the begining to investigate the use of delta modulation technique for a single phase cyclocoverter has been satisfactorily realized during this research. Simple analyses have been carried out on phase controlled and sine pulse width modulated single phase cycloconverter waveforms. These results were compared with those obtained for single phase delta modulated cycloconverter. Delta modulation proved its better performance in-terms of controllability and implementation over the other techniques. A method of on-line waveform sysnthesis of pulse width modulated cycloconverters using variable step rectangular wave delta modulation has been proposed. Compared with conventional cycloconverter waveform sysntheis, computer implementation of this technique is not mandatory, instead easy hardware implementation is possible.

The features of delta modulation in the operation of a single phase cycloconverter, namely easy implementation, small low order harmonics at the output, pulse dropping with frequency increase and easy fundamental voltage control have been verified. The analytical tools used for these purposes were determination of delta modulated waveforms from the switching points and package FFT. The results signifies the following,

a. Delta modulation technique is easy to implement.

b. This technique gives small low order harmonics at the output of the cycloconverter

c. It allows on-line waveform synthesis possible by hardware implementation. The features of controlling window width ΔV and slope of the filter can be used for this purpose. However, controlling ΔV with frequency change gives a better performance.

d. For a.c drive applications, cycloconverters are usually used in slow speed applications. In slow speeds, a.c. drives require constant flux in the air gap to achieve constant torque operation. Such a control is possible with delta modulated cycloconverter without additional control. It requires the variation of ΔV or slope as needed for waveform sysnthesis mentioned in C above.

e. Rectangular wave delta modulated cycloconverter limits the excursion of output current waveform for inductive loads. Such a feature achieves hysteresis current control of such loads without additional control.

f. Delta modulators, specially the rectangular wave delta modulators are efficient and their responses to step changes are fast [25].

g. Switching points or the number of pulses vary automatically in delta modulation allowing the commutation requirements of converters.

All the features mentiond above are also obtainable by conventional pulse width modulation technique. However, they can be incorporated into the system with much complication of the control circuitry and at times with additional closed loop control.

Future Work:.

Delta modulation technique has been previously reported for controlling rectifier, inverter and voltage controllers. However, its application in cycloconverter control did not appear in literature so far. This research effort is the first step towards this goal. Future work may include the implementation of dm technique in the control of a polyphase cycloconverter. Future work may also include the performance of induction and synchronous motors run from a delta modulated cycloconverter. Now-a-days it is also very common to implement various switching techniques with the help of microcomputers. Microcomputer generation of single and three phase switching waveforms using dm technique approach can be undertaken in future works. In the waveform synthesis area, simultaneous variation of window width and slope can be examined extensively.

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