ON-LINE OPTIMIZED CONVERTER WAVEFORM SYNTHESIS BY VARIABLE STEP DELTA MODULATION

BY

AHSAN HABIB CHOWDHURY

A THESIS

PRESENTED TO THE

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

OF

MASTER OF SCIENCE IN ENGINEERING (E.E.E.)

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING

AND TECHNOLOGY, DHAKA

AUGUST, 1990

Approval

Accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Electrical and Engineering).

1\. machondhury

Dr. Mohammad Ali Choudhury
Assistant Professor
Department of Electrical & Electronic
Engineering, BUET, Dhaka, Bangladesh.

Chairman
(Supervisor)

2\. M. A. Matin 27.8.1990.

Dr. Md. Abdul Matin
Professor and Head
Department of Electrical & Electronic
Engineering, BUET, Dhaka, Bangladesh.

Member
(Ex-officio)

3\. 27.8.90

Dr. Kazi Mohiuddin Ahmed
Associate Professor
Department of Electrical & Electronic
Engineering, BUET, Dhaka, Bangladesh.

Member

4\. Khan 27/8/90

Dr. Md. Rezwan Khan
Associate Professor
Department of Electrical & Electronic
Engineering, BUET, Dhaka, Bangladesh.

Member

5\. 27/8/90

Dr. A. M. Zahoorul Huq
391, Baitul Aman Housing Society
Road No. 7, Shyamoli, Dhaka.

Member
(External Member)

CERTIFICATE

This is to certify that this work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma.

Countersigned

Signature of the student

(Dr. Mohammed Ali Choudhury)

Supervisor

(Ahsan Habib Chowdhury)

Dedicated to My Parents

Acknowledgements

I acknowledge with gratitude and thanks the help and cooperation I received from my teachers, friends and colleagues during the research and preparation of this thesis. Special thanks are due to my supervisor, head of the department, Mr. Zahirul Alam of the department of EEE and Mr. Muniruzzan of the department of ME for their constant help and encouragements during the thesis work.

Abstract

Power inverters are devices used for conversion of dc electrical energy to ac electrical energy. The simplest semiconductor inverters are the square wave inverters which take dc in their inputs and produce square waves at their outputs of arbitrary phase and frequency, determined by the rate of switching of the power converters. With an aim to meet the requirements of simultaneous control of voltage, frequency and harmonics of the output voltage of inverters, pulse width modulation(PWM) is being used in inverter control. One of the commonly used pulse width modulation technique in inverter control is the sine PWM. Inverters have may uses in drives, uninterruptible power supplies, DC link for VDC transmission, and induction heating etc. One of the main distadvantage of inverters is the presence of harmonics at the output voltage and input current. It has been a constant effort of researchers to reduce the harmonics to desired level and hence minimize the filter requirements at the output and input side of the inverters. In the past such harmonic minimization technique was developed by set criteria on harmonics and determination of desired switching points by laborious computer solution of large number of simultaneous transcendental equations. After these switching points were determined, the modulated wave pattern was produced by micro-computer implementation, this process works well for single frequency operated inverters. However, for continuously variable frequency devices like in drives, such implementation would require large memory of very fast computers.

Recent studies reported delta modulation technique may be advantageously used for controlling various static power converters like controlled rectifiers, inverters and switch mode power supplies. Most advantageous feature of delta modulation is its simple implementation and easy controllability. It has been demonstrated in the recent past that rectangular wave delta modulation technique can be successfully used for waveform synthesis on-line. Towards this goal double integrator delta modulator and tuned delta modulator were used. The two techniques showed that the harmonic minimization of inverter output voltage is possible on-line. However, previous methods have the drawback of significant reduction of fundamental voltage during the on-line minimization process. With an aim to get rid or reduce such fundamental voltage reduction, this thesis proposes a new configuration for the delta modulation. The proposed modulation has a variable step hysteresis window in the feedforward path of modulator. In this thesis an attempt has been undertaken to analyze the performance of this newly proposed modulator with respect to inverter operation. It has been shown both analytically and experimentally that the proposed modulator has significant improvement in performance in terms of harmonic minimization than those reported earlier. To substitiate the validity of the claim, the analysis and experimental verifications were extended to the previously reported tuned rectangular wave delta modulator and the results thus obtained are compared and presented in the thesis.

CONTENTS

List of Figures

Page No.

Page No

Page No.

Page No.

List of Symbols

A_n = Fourier coefficents

B_n = Fourier coefficents

C_n = Fourier coefficients

$e(t)$ = error signal

E_c = control voltage of the modulator

E_m = amplitude of the modulating sine wave

f = frequency in Hz

f_r = ripple frequency

f_R = frequency of the reference wave

f_{idle} = idling frequency

$G(j\omega)$ = transfer function of the feed forward path of the modulator

$g(x)$ = gate function, $x = f(t, t_1, t_2)$

$H(j\omega)$ = transfer function of the feedback path of the modulator

m_n = n th harmonic component of the modulator output waveform

m_1 = fundamental component of the modulator output waveform

$m(t)$ = modulated wave

M_1 = fundamental component of the modulated wave

$m_T(t)$ = modulated wave of one cycle

$m(t + nT)$ = modulated switching waveform shifted by nT

N_p = number of pulses in one cycle

n = order of harmonics

S = slope of the estimated waveform in volts/seconds or volts/rad

t_i = i-th pulse termination time in second

T = period of a periodic wave in second

T_s = sampling frequency in Hz.

$u(x)$ = unit step function, $x = f(t, t_1)$

V = Voltage in volts or in p.u.

V_s = logic power supply voltage in volts.

V_n = Fourier voltage of inverter output in volts

V_{dc} = dc input to the inverter in volts

V_R = rms voltage of the reference sine wave in volts

$\bar{x}(t)$ = estimated signal of the delta modulator

$x(t)$ = input signal to the modulator

y_n = n th harmonic of estimated wave

Δ_R = step size of rectangular wave delta modulator

δ_i = window width

ω_i = i th pulse position in radians

ω_1 = fundamental frequency

ω_n = n-th harmonic frequency = $n\omega$ radians/sec

ω_r = ripple frequency radians/sec

ω_R = frequency of the reference wave radians/sec

τ = integrator time constant in volts/sec.

List of Abbreviations

CRT	Cathode ray tube
DFT	Discrete Fourier transforms
DPCM	Differential pulse code modulation
DM	Delta modulation
PWM	Pulse width modulation
PCM	Pulse code modulation

CHAPTER 1

Introduction

RWDM	Rectangular wave delta modulation
SCR	Silicon controlled rectifier
SPWM	Sine pulse width modulation
UPS	Uninterruptible power supply
VLSI	Very large scale integration

CHAPTER 1

Introduction

This chapter is devoted to an introduction to inverters and their applications. The advances in power electronics made it possible to the introduction of various types of inverters. The two basic types are the voltage source and the current source inverters. According to the need of the applications, various controls and modifications are incorporated in the basic circuits. One of the most versatile control techniques is the pulse width modulation (PWM) technique. Presently various PWM techniques are in use for inverters to drive motors. The aim of the present work is a detailed analysis and the implementation of a newly proposed variable step delta modulation technique for inverters.

1.1 Introduction.

Inverters are used to transfer energy from dc to an ac of arbitrary frequency and phase. More specifically, these are used in drive systems to provide power for adjustable frequency motors, to regenerate energy back to ac line from decelerating dc motors, and to pump rotor power back to the ac line from wound rotor induction motors. In non drive systems, these are used to supply uninterruptible ac power to computers and to convert energy between ac and dc at the terminal of high voltage dc power transmission line. Inverters are also used for standby power supplies and for induction heating[1].

Various types of inverter circuits have been developed so far, the variations were introduced by the requirements of load and cost effectiveness of inverters. In most inverters, it is necessary to control output voltage and frequency. As the inverter output is usually nonsinusoidal, harmonic reduction schemes are also desired.

In solid state inverters, both transistors and thyristors are used. Thyristor

(SCR) circuits take precedence where high power is involved. However, other things being equal, there is a general preference for the use of transistors. SCR circuits perform well wherever commutation can be successfully implemented and maintained. At present SCRs have greater power handling capability and find wide application in inverters of high power ratings. However, this may change eventually with the evolution of high power transistors in the future. Because of the present SCR capability of higher power handling, most inverters and converters for drive systems use the thyristors as the main controlling elements.

Inverter applications are wide and increasing in all types of applications. In fact, semiconductor devices have their greatest impact in the electric power industry, especially on the technology of electric motor drives. These led to the widespread use of adjustable speed drives, a radical change in the control and conversion of electric power for commercial and industrial use, and the development of new motor drive systems. Motor drives probably represent the largest market for power semiconductors. Thyristors as the means for controlled rectification was the instrument for the rapid development of motor drives of all types, sizes and applications. Like other power semiconductor circuits, inverters find their widest applications in adjustable ac motor drives. Variations of ac motors' speed can be achieved most effectively by variation of voltage and frequency of the supply. Presently static controllers for such variation are voltage controllers, cycloconverters and inverters. AC voltage controller control the speed to a very limited range by voltage variation only. The cycloconverter circuit is limited to the use of speed variation for low frequency operation because of its restrictions of the output frequency. As a result, static inverters take precedence over other types of converters in ac motor drives.

1.2 The Pulse Width Modulated Inverters.

It has been mentioned that static inverters are finding wide uses in ac motor drives. Two main inverter types using a dc link at one end are,

1. Voltage Source Inverters (VSI),

2. Current Source Inverters (CSI).

Classification is done by whether current or voltage at the dc link is the control parameter. Depending upon the control variability and commutation methods employed in SCR inverters, the invertes may be subgrouped in a variety of ways. Besides the main types, pulse width modulated inveters are very prominent in ac drive systems[2-6].

Normalvoltage source inverters and current source inverters have the inconvenience of generating square wave at the output of the inverter containing considerable amount of low order harmonics. These inverters also need double power conversion processes for simulataneous voltage and frequency control. Usually in ordinary inverters, voltage control is achieved with a controlled rectifier on the input side of the inverter. For simultaneous voltage control with frequency change, additional control circuit is necessary. However, these problems can be overcome using PWM operation of VSIs and CSIs. The objections to typical VSIs and CSIs disappear if the inverter is supplied by a fixed voltage dc link and switches are operated at higher frequencies so as to chop the output waves for the double purpose of voltage control and low order harmonic elimination. Basically PWM makes use of elaboration of the inverter control circuitry to permit variation of the ratio between dc input voltage and ac output voltage of the inveter itself.

Pulse width modulation technique accomplishes both the voltage and frequency regulation in the output of the inverter. The input ac supply is rectified and filtered at fixed full voltage. The inverter section is arranged to switch the dc in such a manner that the line to line voltage consists of a series of pulses. Pulses are arranged to be of varying width so that its average leads to a sine wave. This technique is the most sophisticated and complex in static variable frequency drives. It has advantages when full torque capability is required at low speeds. Three most commonly used modulation techniques in PWM inveters are,

1. Single Pulse Modulation,

2. Multiple Pulse Modulation, and

3. Sinusoidal Pulse Modulation.

In single pulse modulation, the usual positive and negative half cycle of a square wave at the output of the inverter are width modulated to vary the output voltage. Frequency change is also achieved in the same circuit (Fig.1.1(a)). In single pulse modulation, the harmonics at the output of the inverter increases as the pulse width of square waves are reduced. The harmonic contents at lower output voltages can be significantly reduced by using several pulses in each half cycle (Fig.1.1(b)), this method is known as multiple pulse modulation. The most versatile is the sine pulse width modulation technique. In this method, the switching waveform's pulse widths are a sinusoidal function of each cycle. Good performance depends principally on the capability of the electronic control circuitry to define precisely the switching instants of the power stage, in order to cause the output of the controller to be a train of pulses with a time average that approximates

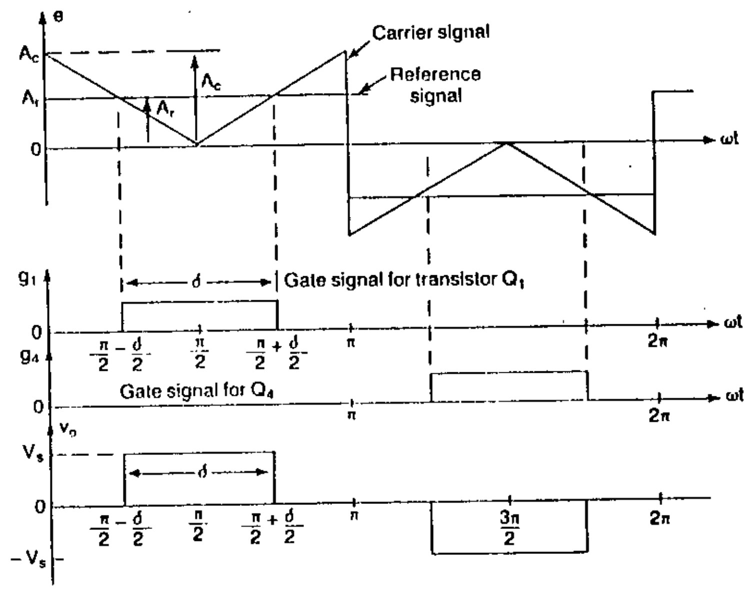


Fig. 1.1(a) Single-pulse-width modulation.

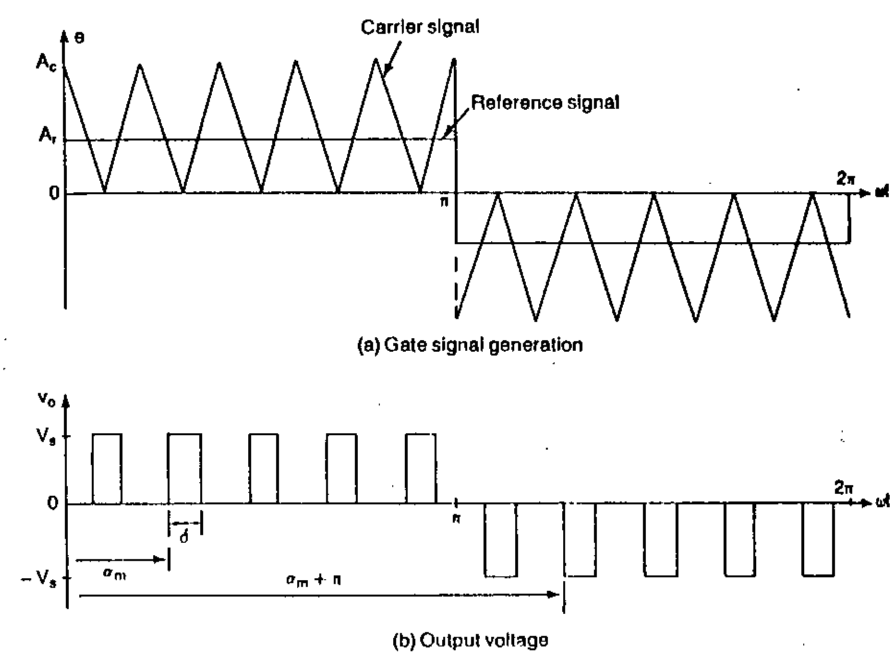


Fig. 1.1(b) - Multiple-pulse-width modulation.

a sinusoid. Complex logic is needed to perform this task and the conventional means for implementing the switching algorithm is the subharmonic or triangulation approach involving an electronic comparison between a reference sinusoid and a triangular carrier waveform as illustrated in Fig.1.1(c).

1.2.1 Survey of PWM Techniques.

PWM techniques of switching the inverters was introduced with a view to accomplish voltage and frequency control in one power stage and also to reduce harmonics at the output of the inverter. It is possible by surveying the literature over the last decade to trace the historical developments of PWM inverter control techniques and relate them to the changes in technology.

The foremost modulation technique in inverters were single pulse and multiple pulse modulation [1,2,3,4,17]. These modulation technique are capable of controlling inverter voltage and frequency in one power stage and capable of eliminating only selected harmonics at the output of the inverter. These modulation procedures were superseded by the introduction of the more complicated and versatile sine modulation [4,5]. Sine modulation is a variation of multiple pulse modulation where the pulse duration and numbers are determined by comparison of a modulating sine wave and carrier triangular wave. At first, sine moduation used the asynchronous PWM mode and subsequently the synchronous mode of PWM was introduced [9]. In the asynchronous mode, the sine wave is compared with a constant frequency carrier wave. The disadvantage of such operation is, with the constant frequency carrier the ratio of sine and triangular wave frequencies cannot be maintained to an integer value. This gives rise to subharmonics at the inverter output when the

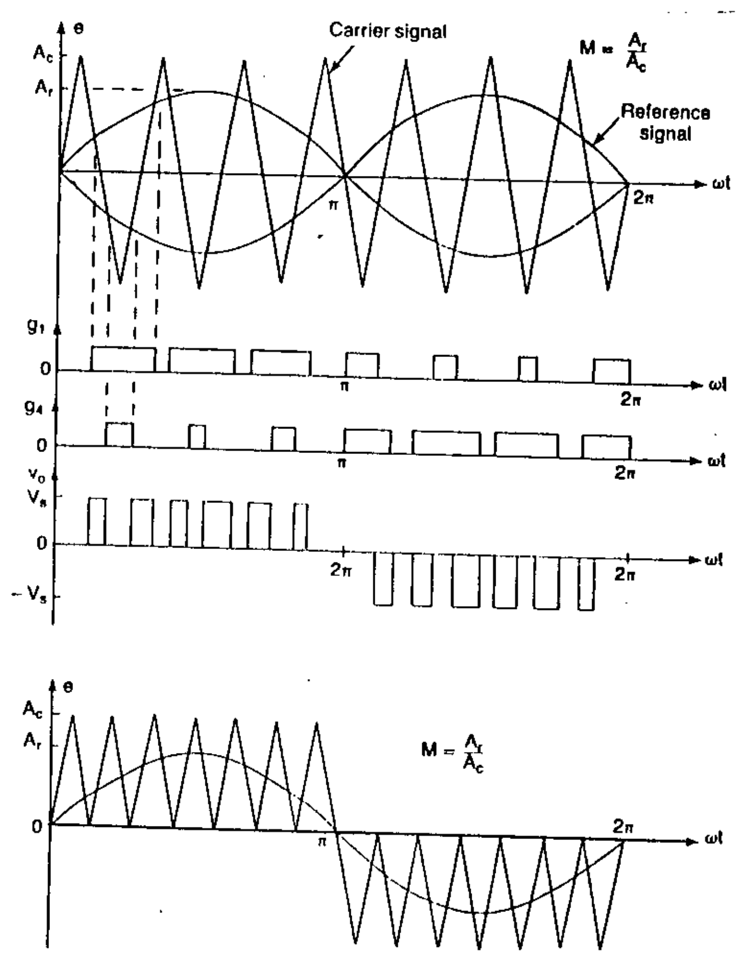


Fig.1.1(c) Sinusoidal pulse-width modulation.

ratio is not the desired integer value. The problem is overcome in synchronized sine PWM mode where the carrier wave frequency is varied with the modulating wave frequency so as to keep the ratio at the desired integer value. This, however, complicates the implementation of such techniques. The principal disadvantage of synchronous PWM method is that,as the modulating and carrier waves are synchronized, the carrier frequency must vary over a wide range with the change of output frequency . It is not usually practical, especially in inverters for ac motor drives, where the carrier frequency cannot be varied widelyBecause when the carrier frequency is too high, the commutation hazard increases as the number of commutations per second increases. Also, an increased number of commutations causes larger commutation losses in the power circuit of the inverter. For drives, a very low carrier frequency also creates problems, since, the motor constants are insufficient for adequate smoothing of current of the motor. To overcome this problem with the fixed ratio method [6], pulse width modulation with ratio changing at various operating frequencies was suggested [6,9,11]. In the variable ratio scheme, the carrier steps through a sequence of ratios as the operating frequency is increased. The later section maintains a high carrier frequency throughout the operating range thereby producing only high frequency harmonics at the output of the inverters which are easily filterable. The variability of types of sine PWM schemes are due to implementation involvements, types of applications and technical and economic feasibilities. Currently three distinct approaches are in vogue to formulate the PWM switching strategy [7,8,10]. The first, and the one which has been widely used because of its ease of implementation is based on natural sampling technique [4,7]. The recent trend is however, to generate the switching functions using microcomputers. The general tendency in microprocessor control is to use a new switching strategy known as 'regular sampling' [7,8,10,12,13]. In the regular sampling technique, the sine modulating wave is replaced by a sampled [stepped] sine wave and the switching points are determined from the crossover points of the carrier triangular wave with the stepped sine wave. In this method of control, the amplitude of the modulating signal at the sample instant is stored by a sample hold circuit operated at the carrier frequency and is maintained at a constant level during the intersample period until the next sample is taken. This produces a sample hold or amplitude modulated version of the modulated signal. As a result, the modulating wave has a constant amplitude while each sample is being taken, and the widths of the pulses are proportional to the amplitude of the modulating wave at uniformly spaced sampling time from where the terminology of uniform sampling or regular sampling came. It is an important characteristic of regular sampling that the sampling positions and smapling values can be defined unambiguously and the pulses produced are predictable both in width and position. In a natural smapling process no direct way of finding the pulse width and pulse positions is available other than solving transcendental equations or bessel function approximations. Since it is possible to calculate the pulse widths using simple trigonometric equations, the potential for real time PWM generation using the computing ability of the microcomputer is greater more with the regular sampling technique than with the natural sampling technique.

The third approach used 'Optimal' PWM switching strategies which are based on the minimization of certain performance criteria [14,15,16], for example, elimination or minimization of particular harmonics, or the minimization of harmonic current distortion, peak current, torque ripple etc. These optimized PWM control strategies are currently receiving considerable attention. As a result of the developments in microprocessor technology, the feasibility of implementing these strategies has now become a real possibility [8,14,15,16,11,12]. In contrast to natural and regular sampling, it has been usual to generate optimised PWM by defining a general PWM waveform in terms of a set of switching angles and then to determine these switching angles using numerical methods and the mainframe computer.

Besides the types of modulation techniques mentioned already, there are several other modulation processes put forward from time to time, such as trapezoidal and square wave modulation [21]. However, these modulation processes did not find their way toward inverter voltage and frequency control.

Along with implementation of various modulation techniques in inverters, the analysis of such inverter have also been carried out by different authors at different times. Attention has been given to output voltage analysis and the input current harmonics. First attempts were made by the Fourier analysis method [10,20,21]. An approach to output voltage harmonic analysis based on double Fourier series expansion in two variables was also introduced later . This was necessary for the general case since there is no rational relationship between the modulating frequency and the carrier frequency. Presently, more emphasis is given to optimization techniques [18,21]. Availability of some packages [PWLIB] for general analysis of PWM inverter outputs are also reported [22]. Also, some new analytical methods for input current harmonic analysis of the inverter are rported. The analytical approach is drawing more attention due to the fact that the implementation of different modulation techniques, especially the optimum PWMs require a mathematical formulation of software development for their implementation.

However, due to the complexity of the modulation processes, no general approach has so far been standardized.

1.2.2 Sine PWM Inverter Strategy for Drives.

The merits of sine PWM in solving one set of problems bring back others. The first is the increasing commutation problems, and secondly the low utilization of dc power available. Since commutation is not a problem at higher voltages associated with higher speed, drive stability is more easily ensured. It is advantageous to combine the merits of the two systems by using the PWM mode at lower speeds and the pure square wave at higher speeds [23,24] with transitional stage from one system to another at medium speeds. The frequency encountered load characteristics, which transforms from a constant torque requirement at higher speeds makes such a hybrid system even more attractive. However such drive calls for a very complex control strategy for sine PWM inverters.

1.2.3 Delta PWM Inverters.

Recently a different modulation technique for inverters was put forward for drive applications [23]. The new scheme is simple to implement and it does not require additional circuit elements necessary for the sine modulation technique in order to give some of the characteristics required for an ac drive system. This modulation technique, known as delta modulation, uses similar triangular and sine wave comparison to produce switching waveforms of the inverters. However, the carrier triangular wave in delta modulation is generated by the modulating sine wave and has a variation which makes delta modulation capable of operating in both PWM and square wave modes without additional circuit elements. The technique also produces a modulation pattern with low harmonic content and a fundamental voltage variation which maintains an inherent constant voltage to frequency ratio. These features of delta modulation may make it very attractive for ac motor drives.

An induction motor's steady state performance is dependent on the harmonic voltages of the inverter output as well as on the fundamental voltage. The inherent characteristics of the delta modulation process, the linear fundamental voltage variation with frequency up to base frequency and constant voltage beyond the base frequency, provides required constant torque and constant power characteristics of ac motors.The harmonic contents in delta modulation are low and the dominent harmonics are at or near high carrier frequency. The harmonic contents, commutation timing and mode of operation can be changed easily by changing the amplitude of the modulating wave. All these features seems to be so attractive in ac motor drives that it may replace other modulations techniques for inverter fed ac drives.

1.2.4 Optimized PWM Inverter Waveforms Synthesis By Delta Modulators:.

As mentioned in previous section,recently, delta modulation (dm) schemes have been proposed for controlling the output waveforms of various pulse width modulated (pwm) converters. These schemes have the ability to optimize pwm converter waveforms on-line. The tuned and the multi integrator dm are the two schemes proposed for pwm waveform sysnthesis so far [48,49]. The methods were found useful for pwm inverter-fed ac drives. However, it was observed that during tuning and filtering process, fundamental output voltage of the inverters reduce. With an aim to overcome this effect, a new technique called the variable step dm is proposed.

The method has the capability to maintain a near constant fundamental voltage of the output waveform of the converters.

The advantages of dm for the control of various converter waveforms are their simple implementation and versatile performance. It has been shown that implementation of dm controllers by analog circuits or by microprocessors are simpler than the conventional pwm techniques [48,49]. It has been shown that these modulators are able to optimize the converter waveforms by adaptation of their filter properties in the feedback path. This method is simpler than conventional optimization techniques [14]. Specially, the optimization is realizable in the modulator without any computer processing.

The block diagram of a basic dm is shown in Fig.1.2. Two basic components of the modulator are the quantizer comparator and the filter. For inverter operation the input to the modualator is a sine wave, and the output is the modulated wave. The integrator performs the function of signal estimation from the output modulated wave by low pass filtering. At the input, this estimated signal is compared with the sine wave to produce an error singnal. The error signal is quantized by the quantizer producing the modulated output. In Fig.1.3 modulator has a hysteresis quantizer in the feedforward path. Such a modulator is known as a rectangular wave dm (rwdm). In rwdm the hystersis quantizer limits the excursion of the error signal within a hysteresis band or a window. This provides the very useful hystersis current control for inductively loaded inverters. In the past, simple techniques have been proposed for harmomic reduction of pwm waveforms using dm [48,49]. In Fig.1.4, the block diagram of a tuned dm is shown. In the tuned dm, the simple integrator of a dm is replaced by a tuned filter having the transfer function as [50]

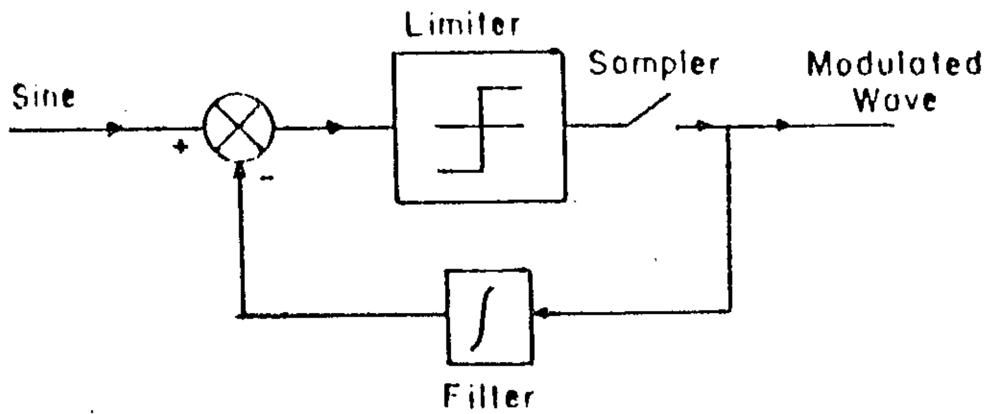


Fig.1.2 The block diagram of a simple delta modulator.

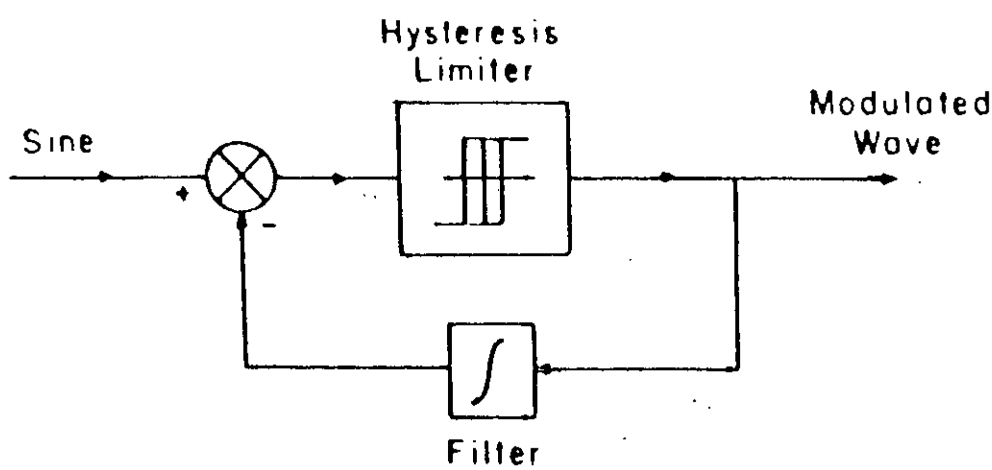


Fig.1.3 The block diagram of a rectangular wave delta modulator.

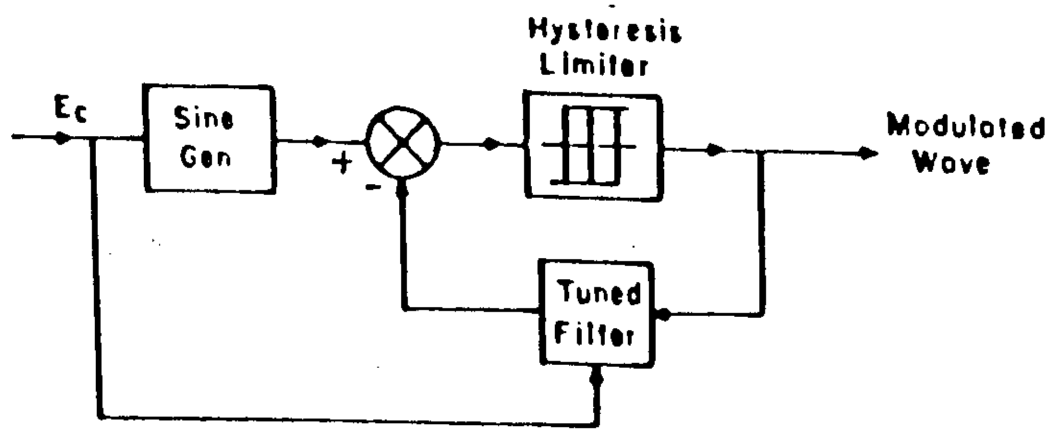


Fig. 1.4 The block diagram of a tuned rectangular wave delta modulator.

$$\frac{e_0(s)}{e_i(s)} = \frac{k_1}{\frac{k_2 s}{E_c} + 1} \tag{1.1}$$

$e_o(s)$ and $e_i(s)$ are integrator's output and input respectively, whereas, k_1 and k_2 are integrator constants.

Equation (1.1) shows that the integrator's time constant is variable with control voltage E_c. Since the cutoff frequency varies with E_c, it also varies with the frequency of operation of the inverter. This fact has been successfully used for harmonic reduction in variable frequency inverters. One drawback of this method is the reduction of fundamental component of the inverter output voltage. This thesis proposes a new scheme which controls the window of the quantizer to attain the same result and at the same time maintain a near constant magnitude of the fundamental component.

The block diagram of the new scheme is shown in Fig.1.5. It is named as variable step dm because the window size of the modulator is forced to change with the change of operating frequency of the inverter. In this type of modulators the hysteresis band of the rwdm is allowed to change with the command signal E_c which controls the frequency of the input signal. As the frequency of the input sine wave changes, the command signal E_c is also made to change the hysteresis band. For higher frequency operation, E_c changes the window in such a manner so as to increase the number of pulses of modulated wave. This results in the increase of the ripple frequency of the estimated wave. Hence, the dominent ripple frequency harmonics shift to higher values. The method uses a simple adaptive

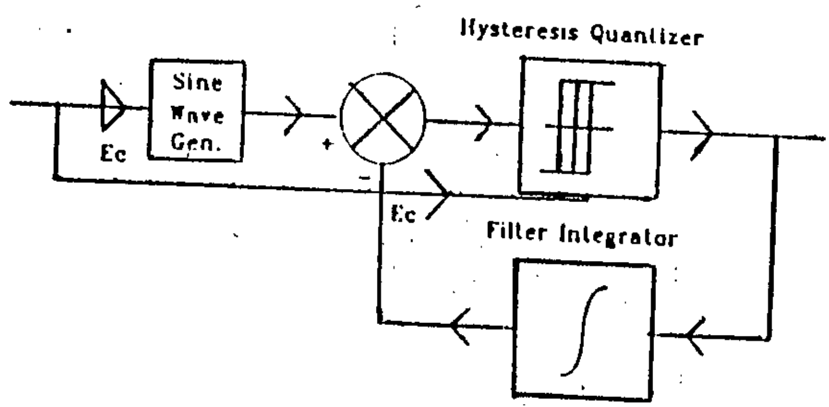


Fig. 1.5 Block diagram of a variable step dm

rwdm technique to provide optimized converter operations interms of harmonic contents. Typical estimated waves obtained from analysis of tuned dm and variable step dm are shown in Fig.1.6 and Fig.1.7 respectively. From the figures the variation of slope and window width are evident. The analysis of such waves are presented with their results in chapter 3.

1.3 Objective of Present Work.

Rectangular wave delta modulation (RWDM) is the main focus of this study. This type of modulation is suitable for on line optimization of the inverter waveforms with variable frequency operation. The block diagram of the rectangular wave delta modulator is shown in fig. 1.3. The harmonic contents of the modulated waveform (which will be used as gate signal of the inverter to dictate the output waveform of the inverter) can be controlled through the variation of several parameters in the rectangular wave delta modulator during on-line operation. Three of these parameters are i) Magnitude of the input wave ii) the window width and iii) the feed back filter characteristic.

This thesis proposes a noble technique of optimizqation of the output waveforms of the inverters during variable frequency operation by controlling the window width i.e. the width of the hystersis band of the rectangular wave delta modulator. This method of on-line optimization is simple, practically feasible, effective and eliminates the problem of reduction of the magnitude of the fundamental component of the inverter output voltage. Besides presenting the analysis for general ease in this thesis theoritical determination of variable step rw dm waves has been carried out. And the results have been verified exprimentally.

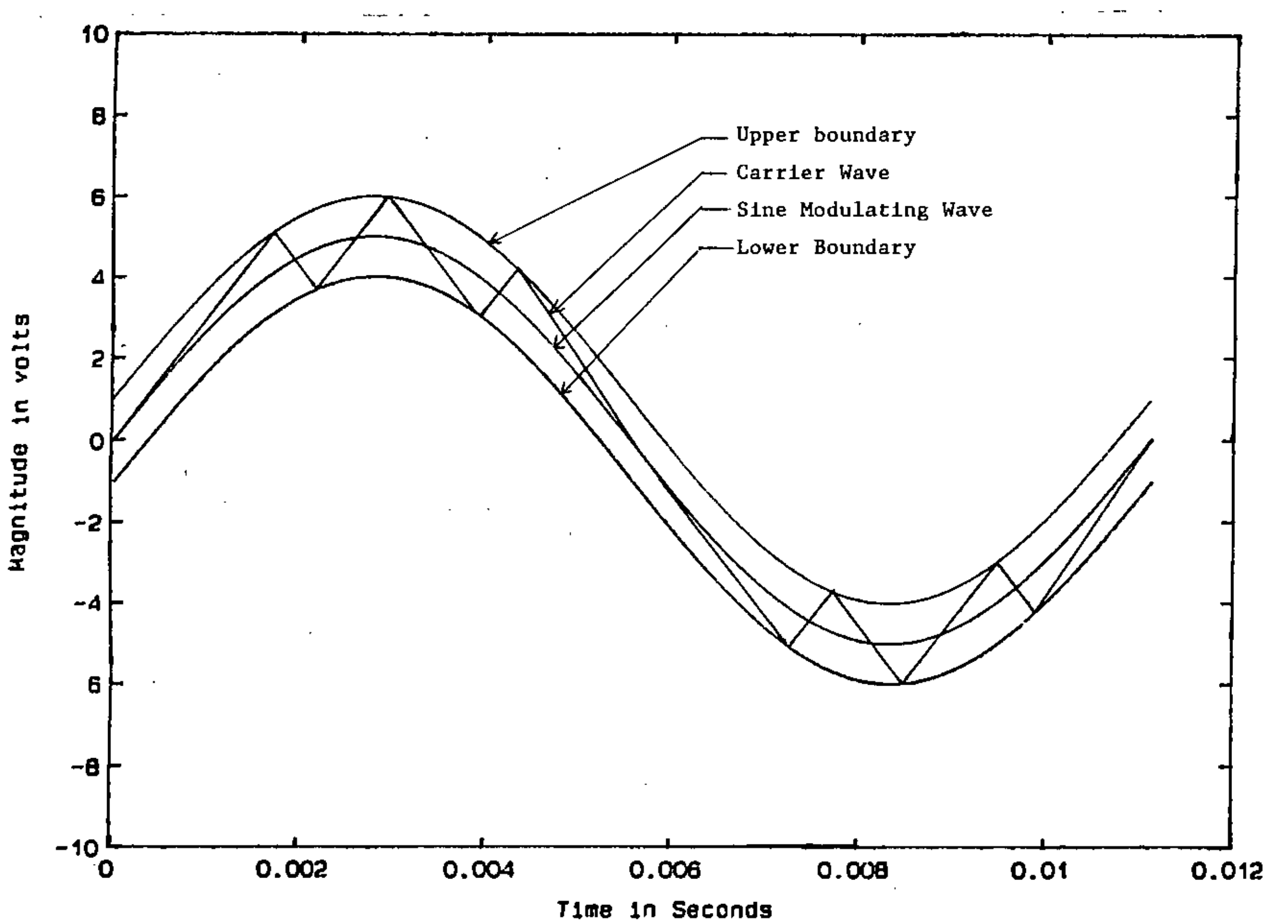


Fig. 1.6(a) Typical estimated wave forms of tuned rwdm.

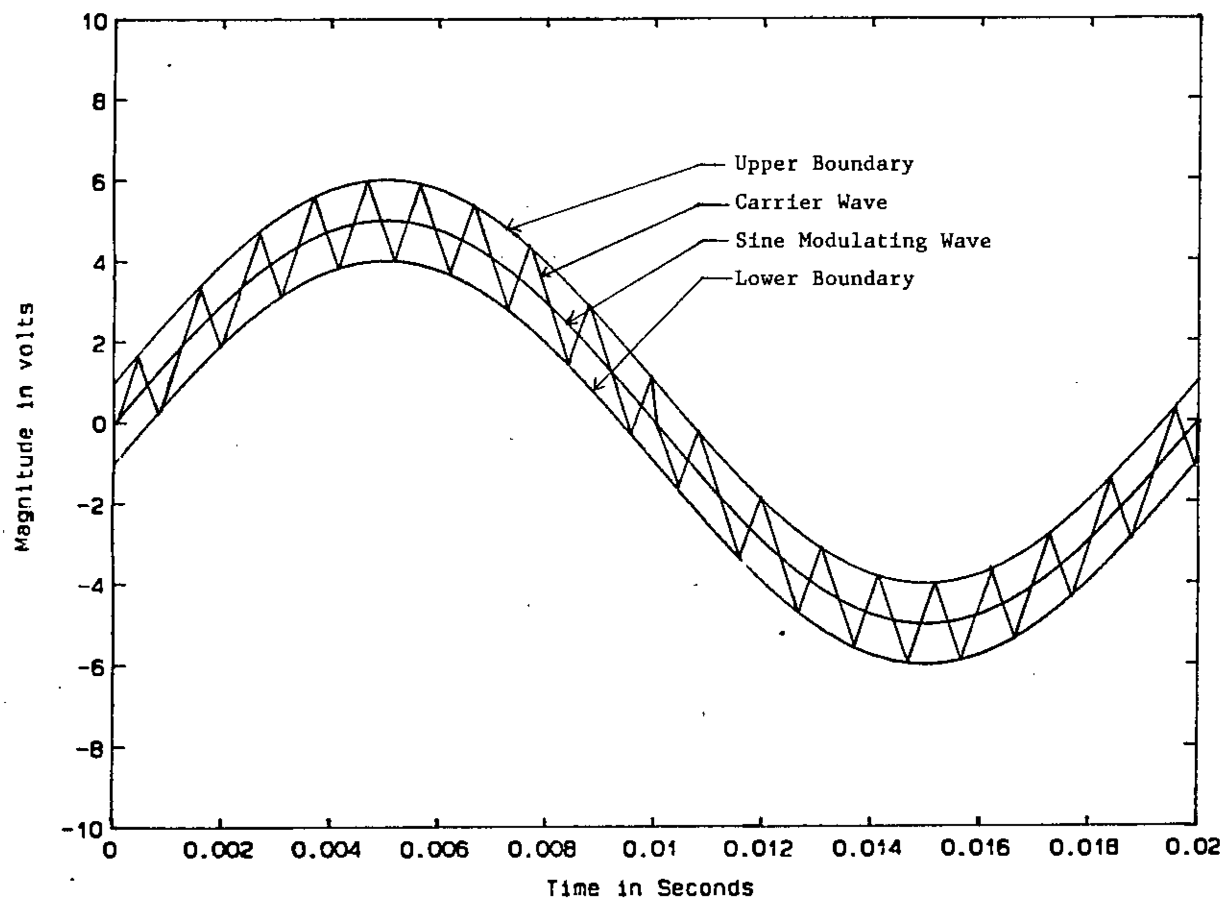


Fig. 1.6(b) Typical estimated wave forms of tuned rwdm.

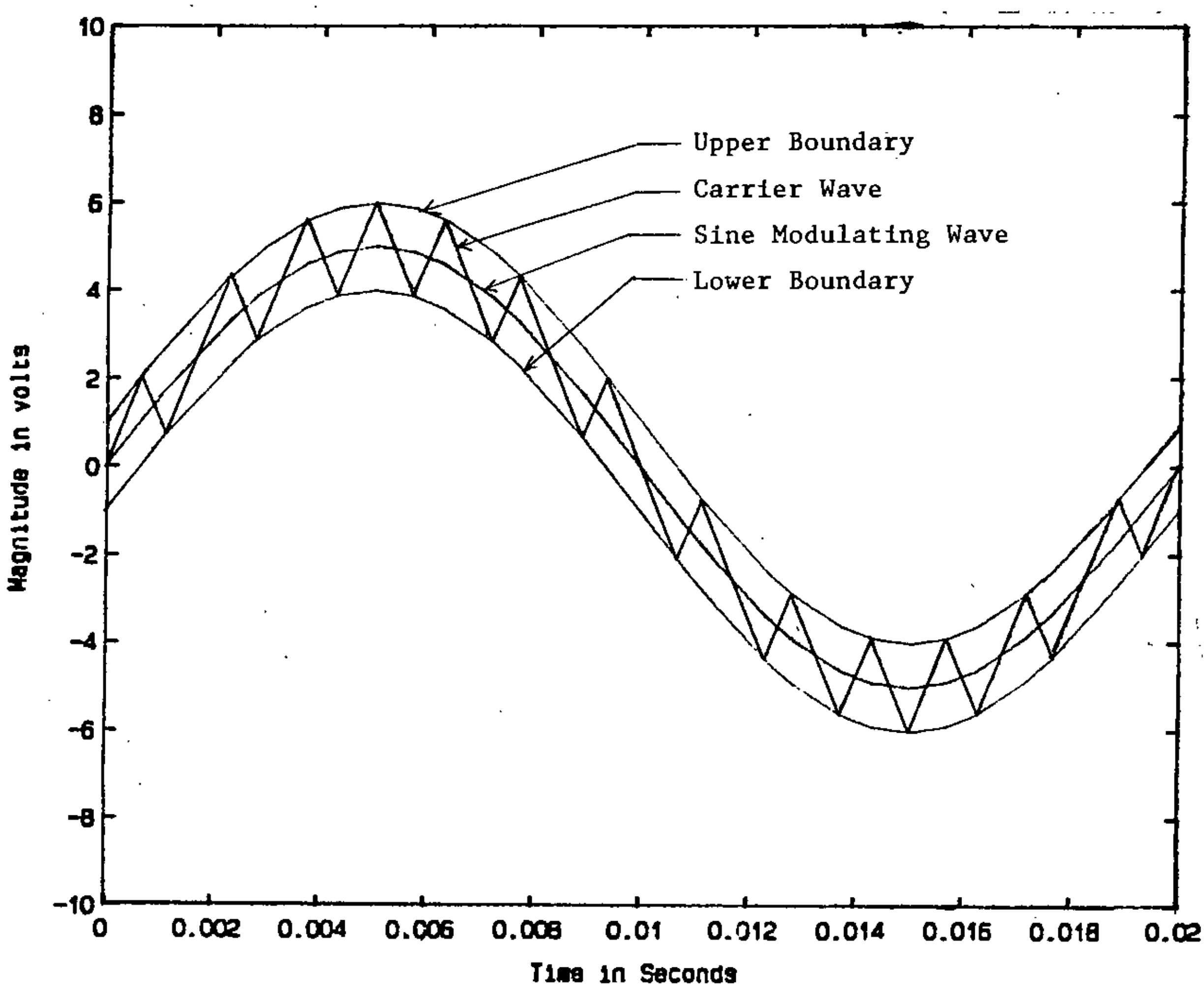


Fig. 1.7(a) Typical estimated wave forms of variable step rwdm.

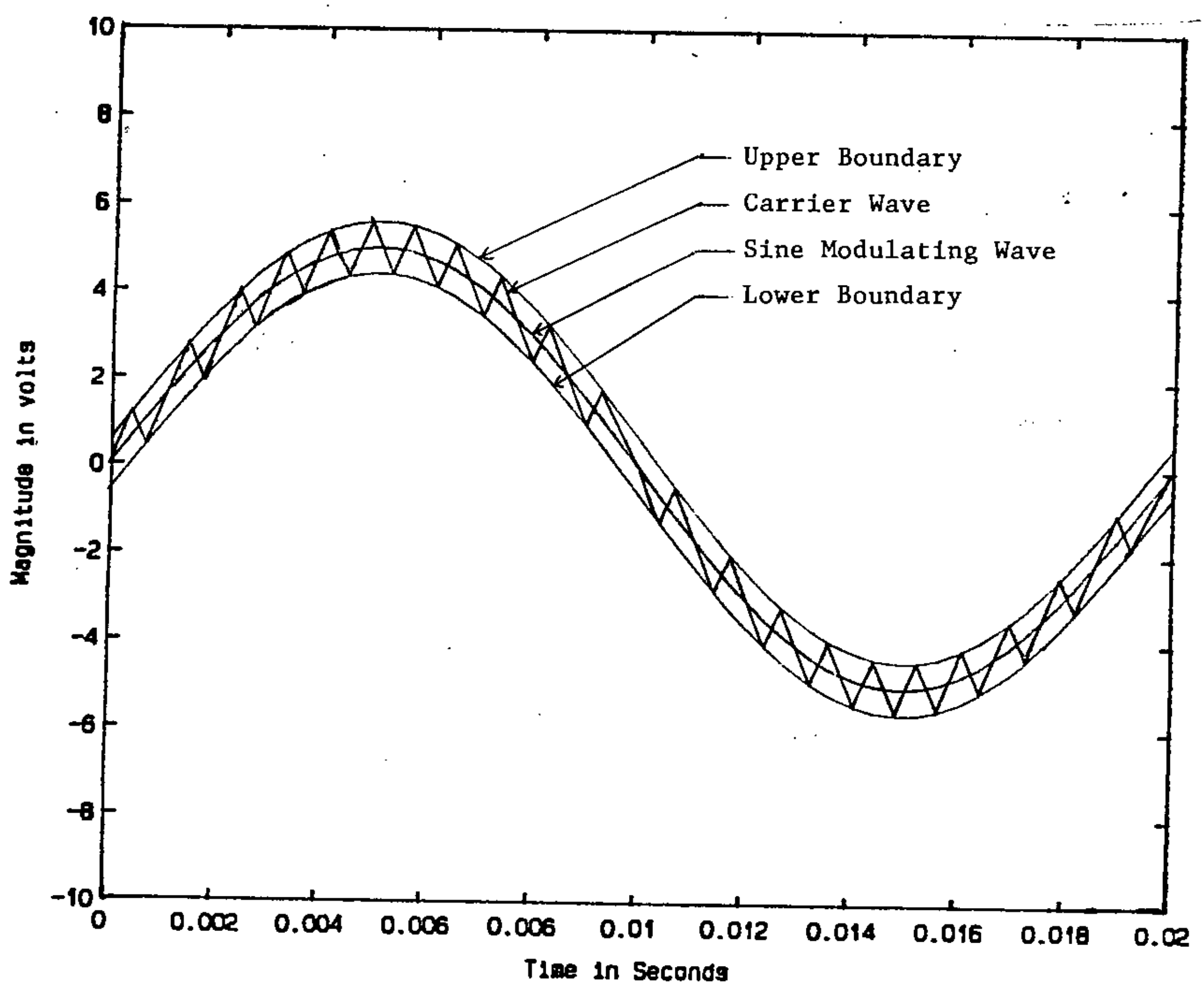


Fig. 1.7(b) Typical estimated wave forms of variable step rwdm.

CHAPTER 2

Delta Modulation Technique

2.1 Introduction.

The objectives of this chapter are to describe the delta modulation techniques, their important characteristics as well as their limitations with regard to inverter operation. At present, there are several types of delta modulators available. The variations stemmed from the need for and requirements of different applications and the necessity to improve the modulator performance. For inverter switching the modulation schemes adapted are restricted to the simpler ones. A brief review of the delta modulation technique is presented in this chapter.

2.2 Delta Modulation Technique.

Different forms of delta modulation (DM) have recently been used in inverters and other power converters. It has the advantage of retaining many of the features of currently used pulse width modulation (PWM) techniques. Delta modulation is known as the simplest method for modulating an analog signal to its digital form [25], without significant redundancy in encoding the signal. The basic delta modulator consists of a comparator quantizer and a filter (Fig.2.1). The comparator at the input of this block compares the input signal with the stepwise approximation of the input signal. The difference signal produced by the comparison is known as the error signal. The quantizer quantizes the error signal accroding to the sign of the error signal to produce the positive and negative pulses of the modulated wave. The function of the integrator in the modulator is to reconstruct the input signal from the output modulated signal. The input to the integrator is the modulated waveform. The integrator acts as a low pass filter and estimates the modulating signal. For digital conversion the digitized waveform is obtained by a sampler in the modulator block. Depending on the use of sampler, the estimated waveform may be stepped or triangular in nature (fig.2.2). The estimated waveform is also called the carrier waveform in delta modulation. The estimated waveform or the carrier waveform in delta modulation is a self-generated signal. If x(t), $\bar{x}(t)$, m(t) and e(t) are the input, the estimated, the modulated and the error signal respectively, the dm technique described above can be expressed as follows

For the modulator without sampler:

$$e(t) = x(t) - \bar{x}(t) \tag{2.1}$$

$$m(t) = sgn e(t) \tag{2.2}$$

$$\bar{x}(t) = \int m(t)dt \tag{2.3}$$

For modulator with sampler:

$$e(kT_s) = x(kT_s) - \bar{x}(kT_s) \tag{2.4}$$

$$m(t) = V_D\, sgn[x(kT_s) - \bar{x}(kT_s)]\delta(t - kT_s) \tag{2.5}$$

$$\bar{x}(t) = \int m(t)dt \tag{2.6}$$

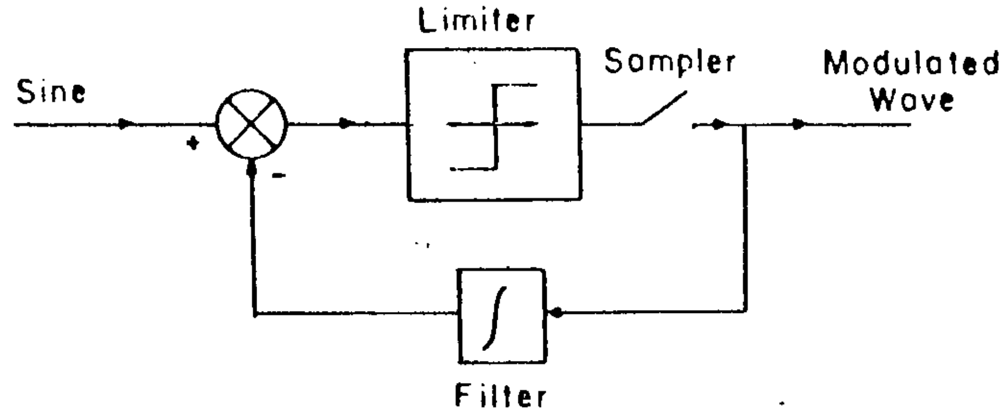


Fig. 2.1 The block diagram of a simple delta modulator.

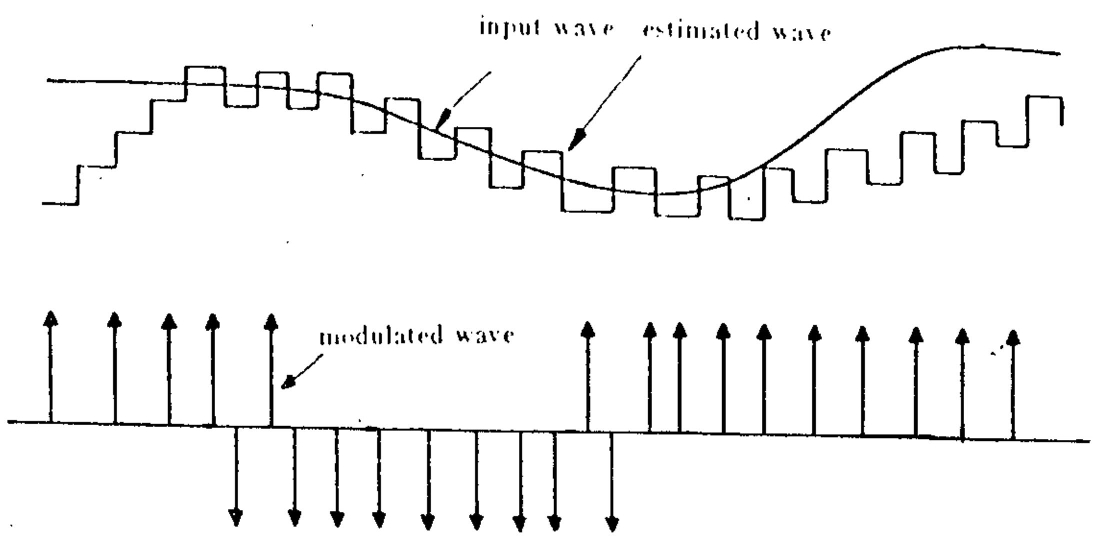


Fig. 2.2 Waveforms of the simple delta modulator.

where,

V_D is the level of quantization

sgn is the sign function

T_s is the sampling frequency.

In encoding a signal, delta modulation has two distinct restrictions. When the predicted signal $\bar{x}(t)$ is smaller than the actual signal x(t) at the beginning , the first impulse has the weight $+V_D$. When fed-back and integrated, that impulse produces a step wise change in e(t) and causes a negative impulse. If x(t) remains constant, $\bar{x}(t)$ follows it in steps until the rate of change is too rapid. If the rate of change is too fast slope overload takes place. This occurs when the window width Δ is too small to track a rapidly changing signal. Slope overload occurs due to the modulator's inability to track large changes of the input signal x(t) in a small time interval. Slope overload is considered to be a basic limitation in delta modulation schemes for communication systems. However, the same characteristic may be used to an advantage in switching power converters.

A variation of DM is the differential pulse code modulation (DPCM) with a multilevel quantier instead of two level quantization. Functionally, DPCM signal is a pulse code modulated (PCM) representation of the difference signal $[x(t) - \bar{x}(t)]$, where $\bar{x}(t)$ has a variable step size ranging from V_D to $QV_d/2$. Where Q is the number of quantization level. Signal $\bar{x}(t)$ follows x(t) more accurately when companding is used. This results in lower idling, fast start up and less chance of slope overload. The following section gives a brief review of the DM technique as it evolved for digital communications.

2.3 A Brief Review of Delta Modulation Technique.

The linear delta modulation was first reported in 1946 and its early description emerged in the 1950s [26,27]. In linear delta modulation the modulator receives a band limited analog signal at the input and produces a binary output signal. The output of the modulator is also locally decoded by the integrator in the feed-back path and subtracted from the input signal to form an error which is quantized to one of two possible levels depending on the polarity of the error signal. The closed loop arrangement of the DM encoder ensures that the polarity of the pulses is adjusted by the sign of the error signal. This ensures that the locally decoded waveform will track the input signal. This type of delta modulator is known as a linear modulator because the decoder at the receiving end is a linear network. Despite the attractive simplicity of the delta modulation coders, initial drawbacks had prevented their wide-scale use at the start [28].Delta modulation remained an interesting field for theoretical studies in communication systems for decades. This situation began to change when more refinements were suggested [29] and today development of delta modulation is in full progress. At present, many communication research institutions are engaged in in-depth exploration of the technique and its applications [30,31,32]. The simplicity of delta modulation has inspired numerious refinements and variations since its basic invention in 1946 by De Loraine and Derjavgotch [28]. Most of these DM systems have received impetus from the applications of digitization of audio and video signals. The initial DM coder consisted of a single integrater (analog) or a first order predictor (digital) in its feedback path. Subsequently, the DM coder with double integrator and multiple integrator (or their substitutes, the predictors in the digital domain) were used in the feedback path for more precise signal tracking [33]. Some investigators replaced the integrator of the feedback loop with RC network by introducing the concept of exponential delta modulators [34]. In order to suit the technique for uncorrelated signals, sigma delta modulation was introduced in 1962 [35,36]. In the initial sigma delta modulators, the input signal was passed through an integrator prior to coding. Subsequent modification replaced the feedback integrator and the integrator at the front with a single integrator at the feed-forward path. This pre-emphasizes the low frequency input signal thereby increasing the sample correlation. To keep pace with pulse code modulation several researchers suggested an adaptive delta modulation (ADM) scheme [36,37]. In adaptive delta modulation the value of the signal at each sample time is predicted to be a non-linear function of the past value of the quantized signal. In literature, two other DM schemes frequently encountered are the companded and the asynchronous delta modulation schemes [38,39]. The companded DM technique uses compression of large signal levels as compared to the smaller ones. Compression is done prior to encoding using compressor circuits, and expansion of the signal is done at the decoder side to recover the signal. The asynchronous delta modulation system has digital output quantized in amplitude but not in time. The rectangular wave delta modulation (RWDM) is one of the asynchronous delta modulation techniques. In rectangular wave delta modulation, the memory-less quantizer of the modulator circuit is replaced by a non-linear element whose characteristics are that of a hysteresis loop or a bang-bang ON/OFF controller. Also, smaplers of ordinary modulators are permanently closed. This form of delta modulation was first reported by Sharma [40,41].

In addition to the modulators already mentioned, there are various other delta modulators which have been sporadically suggested by different researchers [28]. Nonetheless, their operations are basically similar to the modulators already discussed.

2.3.1 Typical Use of Delta Modulators Outside Communication Field.

Since delta modulation is the simplest of all the available modulation techniques it is being used extensively in communication applications. However, it has applications in other fields as well. At present instrumentation rely increasingly on digital techniques. Delta modulators offer attractive applications in such areas. Due to very large scale integration (VLSI), the cost of implementation is no longer a reason for choosing delta modulation over other modulation techniques. It is the simple encoding process and the requirements of a simple decoder which are the most advantageous features of the DM techniques. Some of the important uses of delta modulation technique in instrumentations are measurement of noise, time scaler (transient) display of cathode ray tubes (CRTs) and recorders, peripherals for hybrid computers, and in power measurements by delta sigma wattmeters [42,43]. Also, delta modulation strategy plays an important role in the design and fabrication of digital filters [44,45,25]. In addition, speed control of a small ac motor using delta modulated class D low power amplifier was suggested during early days of DM developments [46,25]. This idea of speed control of small motors can be extended and adopted for high power voltage source ac drive scheme.

2.4 Delta Modulation Scheme For Inverter.

Inverters are functionally power amplifiers used for the frequency and voltage control of the supply to a device. Inverters are also used for high frequency links between utilities and in high frequency induction heating. In induction motor drives modulation is used for the translation of sinusoidal reference voltage to a stream of positive and negative pulses. The pulses of unequal widths, carry the voltage and frequency information from the low power control side to the high power load side through the inverter. It is desirable that the low power control sinusoidal wave be conveyed to the load without much distortion. In applications such as the uninterruptible power supplies (UPS) and in high frequency link inverters, the output waveforms of the inverters are filtered to obtain sine waves at the load side. For ac drives, the motors themselves work as the low pass filters, thus additional filters are not required. The choice of a modulation scheme and the control system for the ac drives are however, dictated by the type of drives, their requirements and applications.

In inverters, the modulation process to produce the switching signals for the thyristors determines the frequency and voltage at the output of the inverter. The delta modulation technique for generating such switching logic utilizes a sine reference waveform and a stepped shaped carrier waveform to determine the switching frequency of the inverter switches (the SCRs).

The stepped carrier waveform is allowed to oscillate within the defined window extending equally above and below the reference wave. The minimum window width and the maximum carrier slope determine the maximum switching frequency. For inverter switching the modulation is prime object and no attempt of sampling the modulated wave to produce a binary signal is taken. The signal to be modulated is sine wave. The carrier wave acts as quantizing the reference wave in two levels. It also determines the widths of the switching pulses. The key waveforms associated with this technique are shown in Figs.2.3(a) and 2.3(b). The switching waveform oscillates between $\pm V_s$ and can be expressed as

$$V_I(t) = V_s sgn[x(kT_s) - \bar{x}(kT_s)] \quad (2.7)$$

and bounded by ΔV.

where,

ΔV = quantization level

V_s = level of switching pulses

$x(kT_s) = sin\omega(kT_s)$ = modulating signal in this case at kT_s

$\bar{x}(kT_s)$ = Predicted signal at kT_s

T_s = Sampling time

In implementing the DM technique to produce the necessary switching function for inverters, the switching pulses are generated by the interaction of reference sine wave and stepped triangular carier wave. Whenever the carrier reaches the upper or lower window boundary, it reverses its slope and changes the switching waveform V_I from $+V_s$ to $-V_s$. This process continues to generate a train of switching pulses. The switching frequency can be altered in three different ways, by changing the amplitude of reference wave V_R or by changing the slope of the triangular carrier

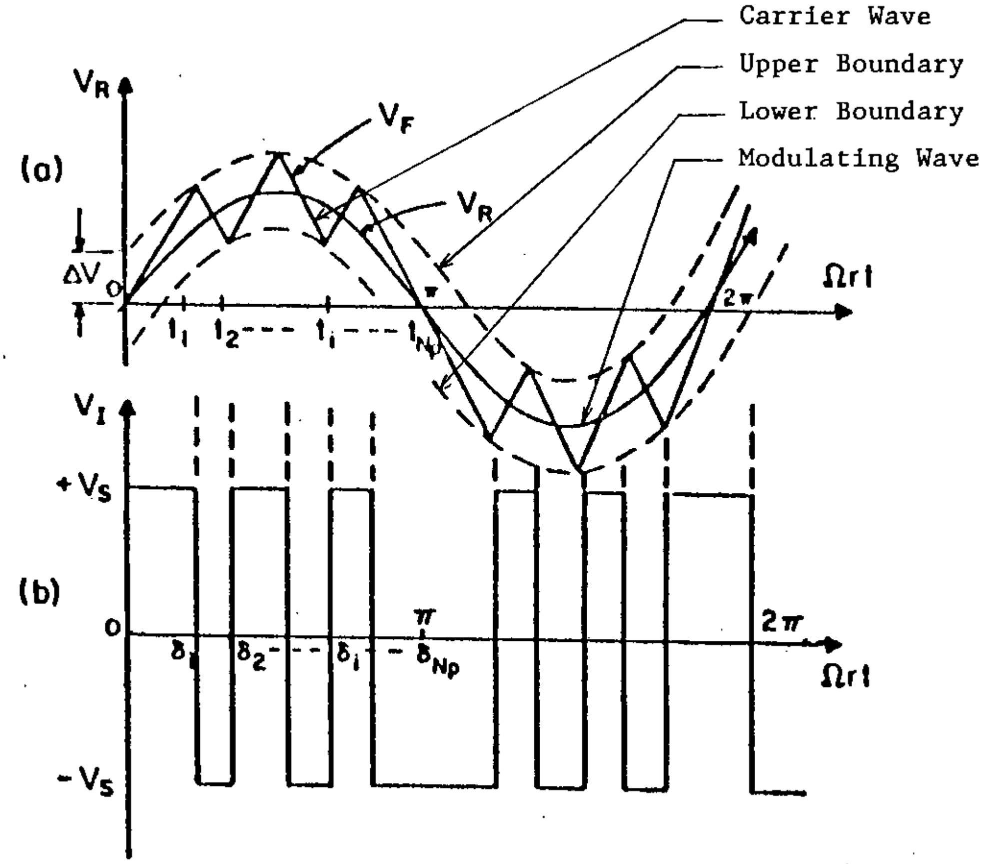


Fig. 2.3 **Graphical illustration of DM technique for inverters**

wave or by changing the window width (quantization level) ΔV. Thus it is important to set these values such that sufficient time is provided for proper turn ON and turn OFF of SCRs. If a single phase full bridge inverter is to be switched by the modulated wave, the sequence of the thyristors to be fired is shown in Figs.2.3(b) and 2.4. Fig.2.4 illustrates the basic single phase full bridge inverter circuit.

In practice, the slope of the carrier frequency and sampling rate are kept constant in implementation by circuit parameters. So it is obvious that overload error described earlier takes place, as the frequency is changed to higher value. This phenomenon is however useful for inverter operation. As the sampling rate is kept constant, sampling per cycle is kept constant as frequency of operation (sine modulating wave frequency) is increased. As the result of overload error in modulation, a transition from PWM to single pulse mode operation takes place when the modulating wave and carrier wave frequencies are equal. The modulated output continues to be single pulse square wave beyond that frequency.

2.5 Characteristics of Three Simple Delta Modulators.

Three simple delta modulators which have been used in the past for generating inverter switching waveforms are shown in fig.2.5. The linear delta modulator (LDM) consists of a quantizer- comparator in the feed-forward path and an integrator in the feedback path. In addition it has a sampler to digitize the output waveform. In the sigma delta modulator (SDM) the integrator is placed in the feed-forward path before the quantizer block. The rectangular wave delta modulator (RWDM) has a hysteresis quantizer. The sampler in the rectangular wave delta modulator is permanently closed. The output of the linear and the sigma

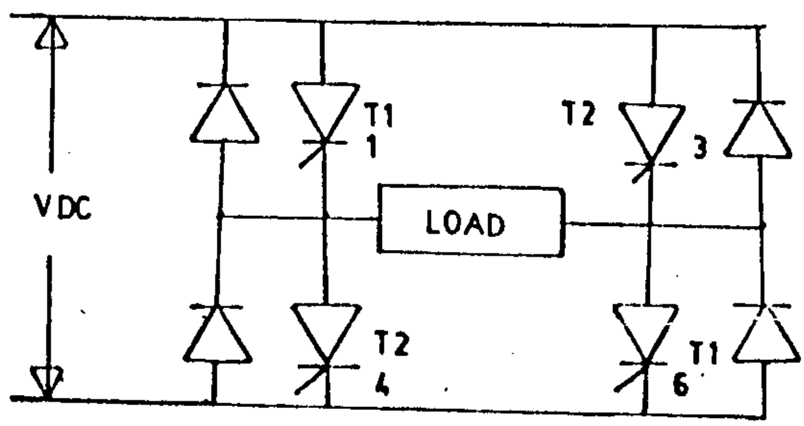


Fig. 2.4 **Basic single phase bridge inverter circuit**

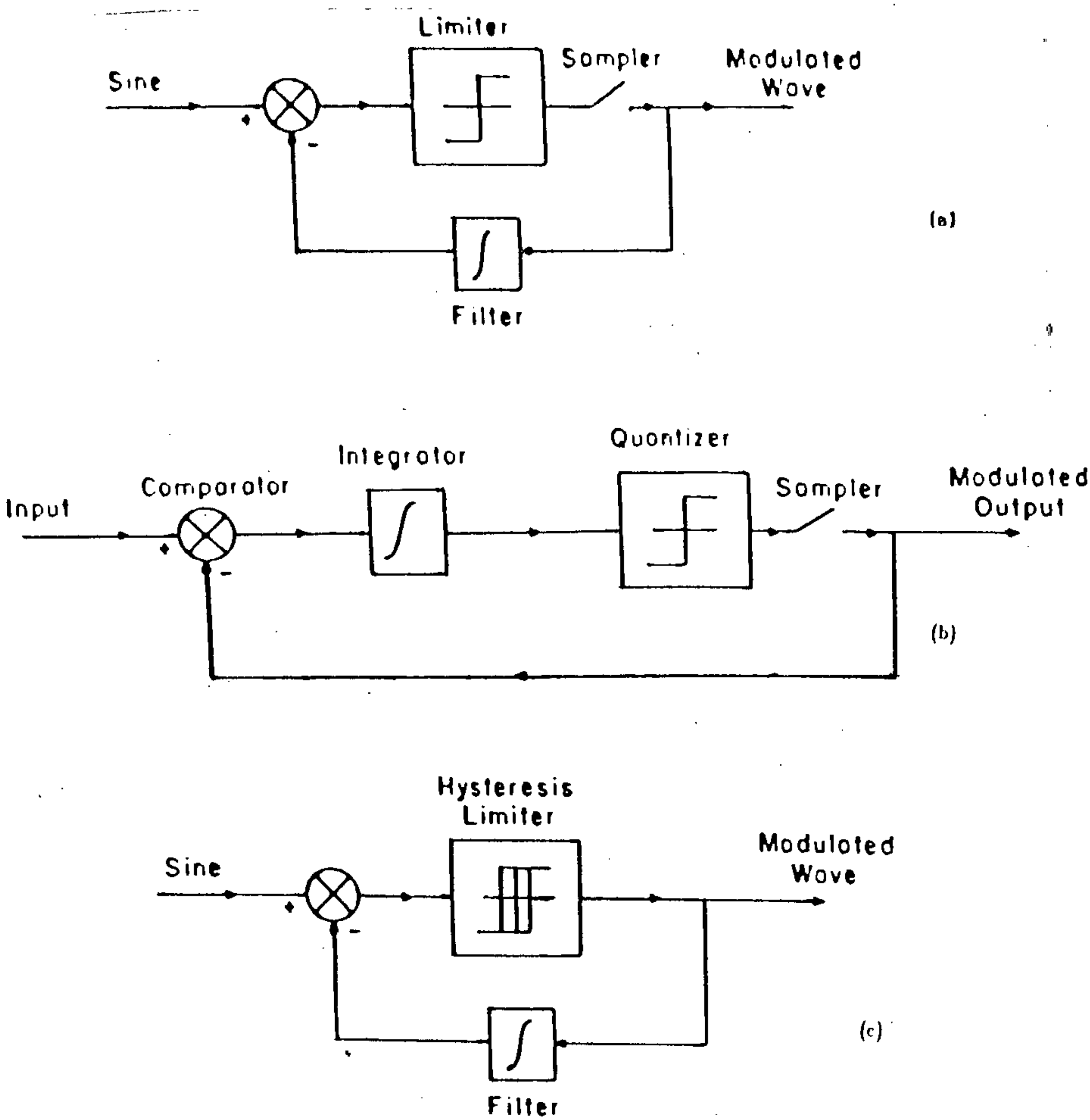


Fig. 2.5 Block diagrams of the linear, the sigma, and the rectangular wave delta modulators.
(a) The linear delta modulator.
(b) The sigma delta modulator.
(c) The rectangular wave delta modulator.

delta modulators are digitized and appear in the form of pulses. In contrast, the output of the rectangular wave delta modulator is in pulse width modulated form. The tracking signals of the linear and the rectangular wave delta modulators are the integrated output (stepped in the LDM and triangular in the RWDM). For the sigma delta modulator (SDM) the tracking signal is the output waveform itself.

The characteristics of these three modulators are examined with respect to the drive requirements. The modulator performance in ac drives depends on many factors. The basic characteristics examined for each modulator are:

1. The idling characteristics.

2. The overload characteristics.

3. The availability of fundamental voltage with change in operating frequency.

4. Stability of the modulator.

5. Step response of the modulator.

6. Current tracking capability in the open loop control of drives.

Table 2-1 contains both a summary and a comparison of features of the three delta modulators discussed. The comparison shows that the RWDM should be the choice of the modulator for inverter switching. Besides the advantageous features already mentioned the rectangular wave delta modulator was considered to be the best among the simple delta modulators because of its lowest signal to noise ratio, and low quantization error [25]. It was also suggested for industrial uses particularly in transmitting signals over short distances for instrumentations.

Table 2-1

Summary and Comparison of LDM, SDM and RWDM

	LDM	SDM	RWDM
Idling output	Square wave output of high frequency	Square wave output of high high frequency	Square wave of high frequency
Overload	Depend on step size and frequency of input	Depend on step size only	Depend on step size and frequency of input
Fundamental voltage availability	moderate ramp characteristics in PWM mode	moderate ramp characteristics	ramp in PWM mode and constant voltage in square wave mode
Step response	slower response than the SDM and RWDM	response is fast	response is inherently faster due to hysteresis quantizer
Stability	Inherently stable	Inherently stable	Stability depends on the frequency and the gain of overall modulator
Current limiting capability	Absent	Absent	Present
On-line optimization	Possible with tuned	Possible but difficult	Possible with variable step rwdm

The other significant reason for choosing rectangular wave delta modulator for inverter switching is the ability of on-line optimization of the inverter output waveform by variable window quantiser width. A unique method of optimizing the modulator waveform using a variable step rwdm is discussed in section 3.3.

2.6 Conclusions.

The delta modulation technique is proposed for the switching of inverters in drive applications. The criteria for the modulator and the drive requirements have been established. On the basis of the requirements for drive applications, the characteristics of three simple delta modulators have been discussed to select the best suitable delta modulator for switching an inverter. The three modulators discussed for possible use in inverters are the linear, the sigma and the rectangular wave delta modulators. It has been established that the rectangular wave delta modulator is the most suitable of the three which can advantageously be used for on line optimization of inverter output waveform

CHAPTER 3

Analysis and Optimization of The Rectangular Wave Delta Modulator

3.1 Introduction.

A novel waveform synthesis and an on-line harmonics minimization of the inverter output voltage using delta modulation technique are described in this chapter. The proposed on-line harmonic reduction method uses a hystersis quantizer with variable window width in the feed forward path of the delta modulator. An investigation into the conventional way of defining the switching points and their analytical determination for harmonics using the Fourier series has been conducted.

Based on the analysis, the features of the delta modulation technique as applied to the operation of inverter are summarized. Realization of a practical modulator circuit, its operation, and the performance are also discussed. The operational limitations of inverters using DM switching are briefly discussed.

3.2 Rectangular Wave Delta Modulator.

Based on the selection criteria discussed in Chapter 2, the rectangular wave delta modulation (RWDM) has been selected for switching of an inverter . The intrinsic features of rectangular wave delta modulators are proved and verified. A novel method of optimization of inverter waveforms using variable step $_{RW}$DM is suggested in this section.

3.2.1 The Simple Rectangular Wave Delta Modulator.

The following are the intrinsic features of rectangular wave delta modulators

1. Upto the base frequency the fundamental voltage to frequency ratio remains constant

2. Beyond the base frequency, the modulator operates in the square wave mode of operation. The available fundamental component of the voltage is constant in this region.

3. Low order harmonics in the carrier and the modulated waves are small in magnitudes.

4. For fixed window width the number of commutations of the modulated wave decreases with increase in operating frequency.

5. Modulator performance can be changed by changing the window width or the filter characteristic.

6. The modulator is stable, and it has a fast response to any step change in its input.

The basic rectangular wave delta modulator is shown in fig.3.1. With a sinusoidal input to this block, the output waveform is a modulated waveform as shown in fig.3.2(b). The integrator in the feed-back path of this modulator is a low pass filter having an approximate transfer function of $1/\tau_s$. The output of this integrator is, therefore, a high frequency triangular wave having an average shape of a sine wave. This waveform is also known as the estimated waveform. The comparator at the front of the modulator compares the input sine wave with the estimated wave. An error signal e_i is generated from the difference. The hysteresis comparator quantizes the error signal to give the modulated signal. Due to the presence of the hysteresis comparator, the error signal is bounded between $\pm\Delta V$ of the reference signal. As a result, whenever the error signal reaches any of the hysteresis boundaries the modulated signal is forced to change its polarity. This in turn changes the direction

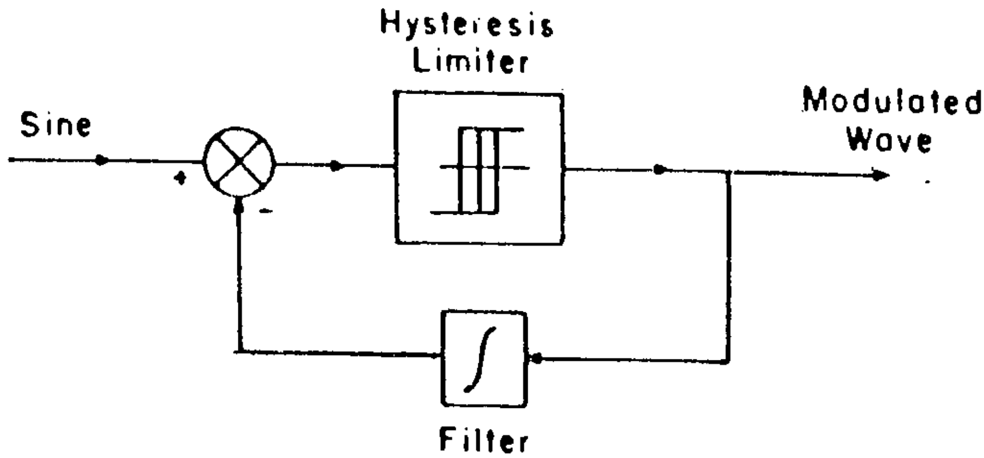


Fig. 3.1 The block diagram of a rectangular wave delta modulator.

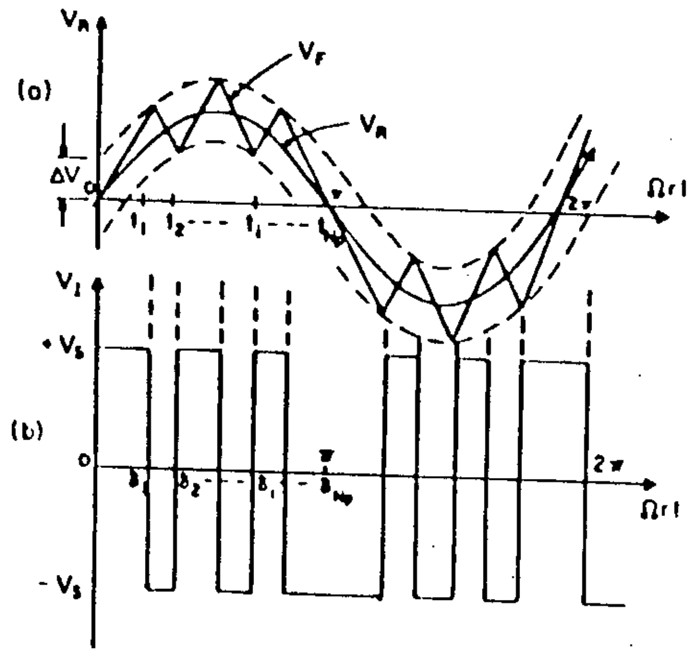


Fig. 3.2 Expected waveforms of a rectangular wave delta modulator.
(a) The input sine wave and the estimated triangular wave.
(b) The modulated wave.

of the excursion of carrier triangular wave. The excursion of the carrier triangular wave is also bounded above and below the input sine wave by a window $\pm\Delta V$. The various waveforms of the rectangular wave delta modulator are shown in fig.3.2.

3.2.2 Analysis of the Rectangular Wave Delta Modulator.

The analysis of the rectangular wave delta modulator requires the knowledge of switching points of the modulated waveforms. To find the switching points of typical output waveforms of a rectangular wave delta modulator of fig.3.2, the following basic equations are used.

Termination of the first pulse position is governed by the relationship

$$\frac{\Delta V}{S} + \frac{V_R}{S} sin\omega_R t_1 = \omega_R t_1 \tag{3.1}$$

Where,

ΔV = half the window width as shown in fig.3.2.

S = Slope of the triangular carrier wave

t_1 = first pulse termination time

$V_R sin\omega_R t$ = input sine reference wave

ω_R = the frequency of the input sine wave in radians/sec.

With the knowledge of the first pulse termination time, the successive switching points of the modulated wave can be obtained by numerical solution of the output equation (3.2)[47]

$$t_i = \frac{2\Delta V + St_{i-1}}{S} + \frac{V_R sin\omega_R t_{i-1} - V_R sin\omega_R t_i}{(-1)^i S} \tag{3.2}$$

In the PWM mode of operation a knowledge of the switching points of the modulated wave allows one to write the equation of the modulated wave in terms of gate function as

$$m(t) = \sum_{A=0,T,2T..}^{ZT} \sum_{i=0}^{N_p} (-1)^{i+1}[g\{t, A + t_i, A + t_{i+1}\}] \tag{3.3}$$

Where,

N_p is the number of pulses in one cycle

T is the period of one cycle

(Z-1) is the number of cycle of the input signal simulated

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

m(t) is the modulated wave

g(t,v,w) is the gate function and defined as

$$g(t, v, u) = u(t - v) - u(t - w) \tag{3.4}$$

u(t-v) and u(t-w) are the unit step functions which are given as

$$u(t-v) = 1 \ for \ t > v$$
$$= 0 \ for \ t \leq v \tag{3.5}$$

$$u(t-w) = 1 \ for \ t > w$$
$$= 0 \ for \ t \leq w \tag{3.6}$$

The waveforms of the rectangular wave delta modulator were defined using the switching points obtained from solution of equation (3.1) to (3.6). The ordinary Fourier series technique was initially carried out. The modulated wave can be expressed in terms of Fourier series. The Fourier coefficients of modulated waveforms in terms of switching points can be written as

$$A_n = \frac{2V_{dc}}{n\pi} \sum_{i=1,2,..}^{Np} (-1)^{i+1}(sinn\delta_i - sinn\delta_{i-1}) \tag{3.7}$$

$$B_n = \frac{2V_{dc}}{n\pi} \sum_{i=1,2,..}^{N_r} (-1)^{i+1}(cosn\delta_{i-1} - cosn\delta_i) \tag{3.8}$$

where,

$\delta_i = \omega_R t_i$ is the i-th pulse position in radians.

V_{dc} is the dc supply voltage

n is the order of harmonics

A_n andB_n are the n-th order Fourier coefficients.

For the pulse width modulated mode of operation, the fundamental voltage of the switching waveform can be obtained from equations (3.7) and (3.8) as

$$A_1 = \frac{2V_s}{\pi} \sum_{i=1,2,..}^{N_p} (-1)^{i+1}(sin\delta_i - sin\delta_{i-1}) \tag{3.9}$$

$$B_1 = \frac{2V_s}{\pi} \sum_{i=1,2,..}^{N_p} (-1)^{i+1}(cos\delta_{i-1} - cos\delta_i) \tag{3.10}$$

Fundamental voltage is given as

$$V_1 = \sqrt{(A_1^2 + B_1^2)} \tag{3.11}$$

The fundamental voltage variation of the modulated wave can also be obtained from the modulator's characteristics as follows:

If y and m are the estimated and the modulated waveform of rectangular wave delta modulator respectively, then for a simple integrator circuit with transfer function $1/S\tau$ the input/output relationship of the integrator is

$$|\frac{y_n}{m_n}| = |\frac{1}{\tau\omega_n}| \tag{3.12}$$

Where y_n and the m_n are the nth harmonics of the two waveforms and $\omega_n = 2\pi f_R n$. For fundamental of the voltage, equation (3.12) can be expressed as

$$|\frac{Y_1}{M_1}| = |\frac{1}{\tau\omega_1}| = |\frac{1}{\tau\omega}| \tag{3.13}$$

Assuming the fundamental voltage of the estimated wave to be equal to the magnitude of the input sine wave V_R, equation (3.13) can be written as

$$|\frac{V_R}{m_1}| = |\frac{1}{\tau\omega}| \tag{3.14}$$

$$|\frac{m_1}{V_R}| = |\tau\omega| \tag{3.15}$$

Since V_R remains constant, the fundamental component of voltage varies almost linearly with frequency. When the modulator operates in the square wave mode of operation, its voltage variation can be obtained from the slope overload condition.

The modulator reaches its slope overload condition when the following condition prevails:

$$\tau = \frac{V_R sin 2\pi f_R T/2 + 2\Delta_R}{T/2} \tag{3.16}$$

where, Δ_R = is the window width of the hysteresis limits.

Equation (3.16) can be simplified to

$$f_R = \frac{\tau}{4\Delta_R} \tag{3.17}$$

In the square mode of operation during the slope overload the harmonics of the modulator output waveform are given as

$$V_n = \frac{4V}{n\pi} \tag{3.18}$$

The fundamental voltage variation is given as

$$V_1 = \frac{4V_s}{\pi} \tag{3.19}$$

A typical fundamental voltage relationship of rectangular wave delta modulated waveform with variation of operating frequency is shown in fig.3.3. Figure 3.3 shows that, for pulse width modulation mode of operation of the modulator, the fundamental voltage increases almost linearly with frequency, and in the square wave mode of operation the fundamental voltage remains constant over an increased range of the frequency.

The theoretical harmonic analysis is carried out using the expressions obtained in this section and the results are shown in fig 3.4 . The theoretical result shows that during low frequency operation of the modulator the significant harmonics of the output waveforms are of higher orders. As the operating frequency of the modulator is increased the lower order harmonics start appearing. Once the modulator reaches square wave mode of operation the magnitudes of the harmonics remain constant. The study revealed that the harmonic contents of a delta modulator can be changed by variation of different parameters like the window width ΔV, the integrator time constant τ and the amplitude V_R of modulating wave.

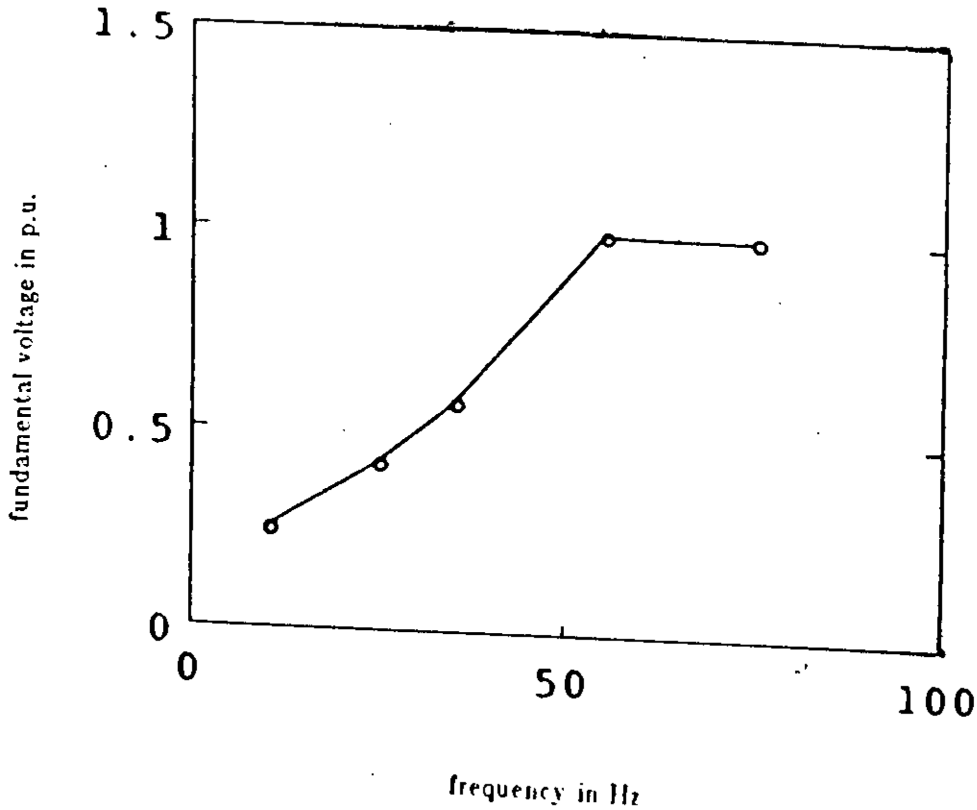


Fig. 3.3 Fundamental voltage variation of rectangular wave delta modulated waves with change in operating frequency. (p.u. value of the output voltage is the ratio of the output voltage to the fundamental voltage of a square wave of the same frequency)

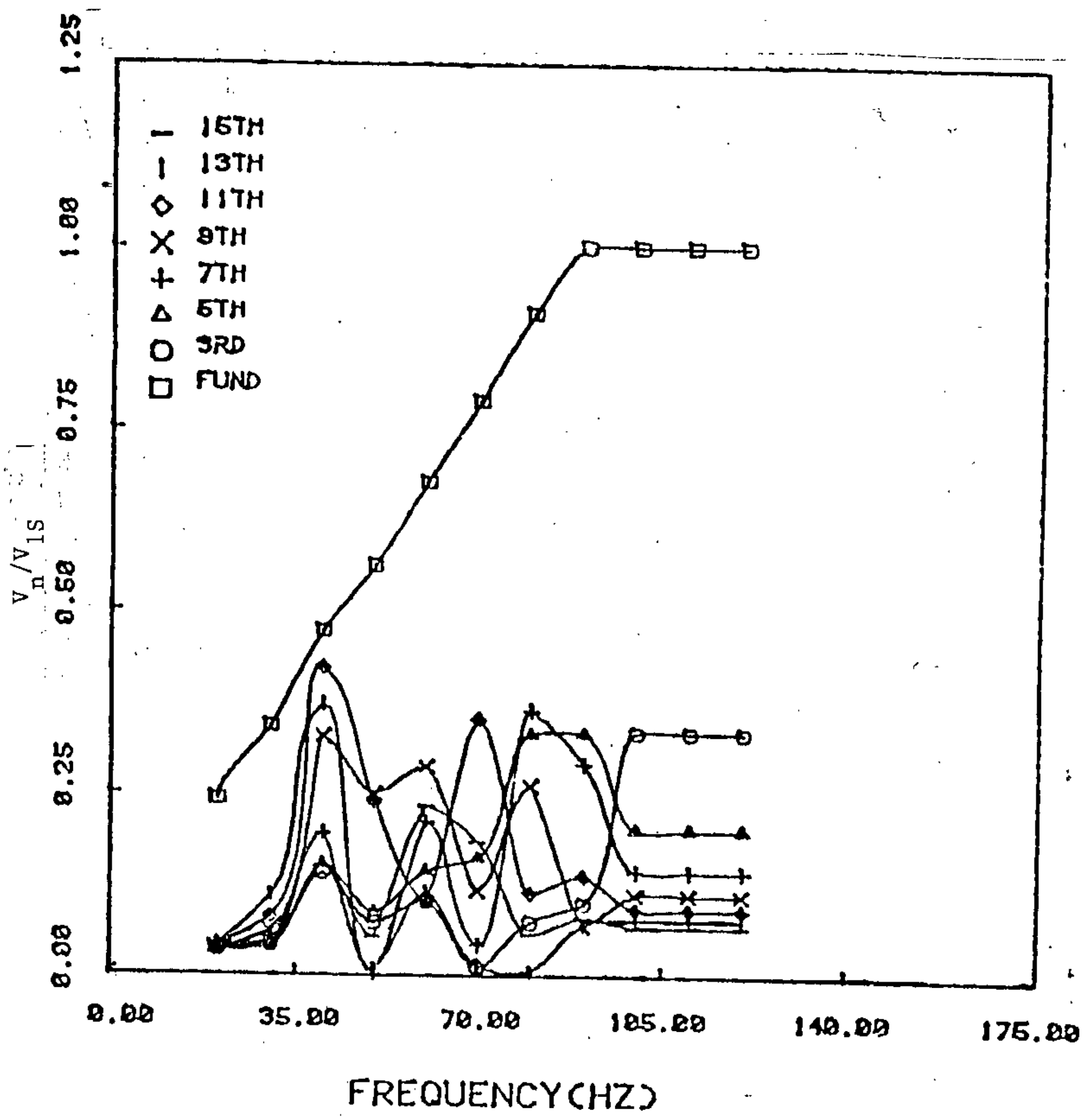


Fig. 3.4 **Harmonics of DM inverter output at various operation frequencies**

V_n - Magnitude of nth harmonic

V_{1s} - Magnitude of fundamental of Square Wave having same voltage level.

Variation of Number of Switching in RWDM Waveform.

The number of commutations in any inverter is an important feature. The increase in commutation results in increased commutation losses in the inverter. Some applications require that this loss be kept at a minimum level. The amount of switching has to bekept at a minimum for perfect commutation of the switching devices of the inverter as well. The number of pulses/half cycle of the modulator output waveform can be determinedby using the analysis for termination of switching points.

The i-th pulse termination is the modulator output voltage in RWDM mode of operation is given by

$$\delta_i = \omega_R t_i \tag{3.20}$$

where t_i is the i-th pulse termination time. Solution of the equation (3.20) for δ_i at $\delta_i = \pi$ gives the number of pulses per half cycle of the modulating wave as

$$i = N_p \tag{3.21}$$

The number of switching per cycle is given as

$$N_c/cycle = 2N_p \tag{3.22}$$

The number of commutation/sec can be obtained as

$$N_c/sec = 2N_p f_R \tag{3.23}$$

Equations (3.20) to (3.22) are solved for different frequencies of operations. The results are shown in fig.3.5 for various values of modulating signal level V_R. The results show that without any other change, the number of switching of modulated wave decreases with the increase in operating frequency. This is a desired characteristic for the safe operation of inverters.

Idling Characteristic.

The idling characteristic of RWDM is mentioned in relation to the selection criteria in section 2.5. The idling frequency of RWDM is given by

$$f_{idle} = \frac{\tau}{4\Delta} \tag{3.24}$$

The output of the modulator during idling is a square wave. The harmonics of this idling output waveform are given by

$$V_n = \frac{4V_s}{n\pi} \tag{3.25}$$

Since the fundamental frequency of the idling wave is very high, other harmonics which are the odd multiples of the fundamental frequency are high also.

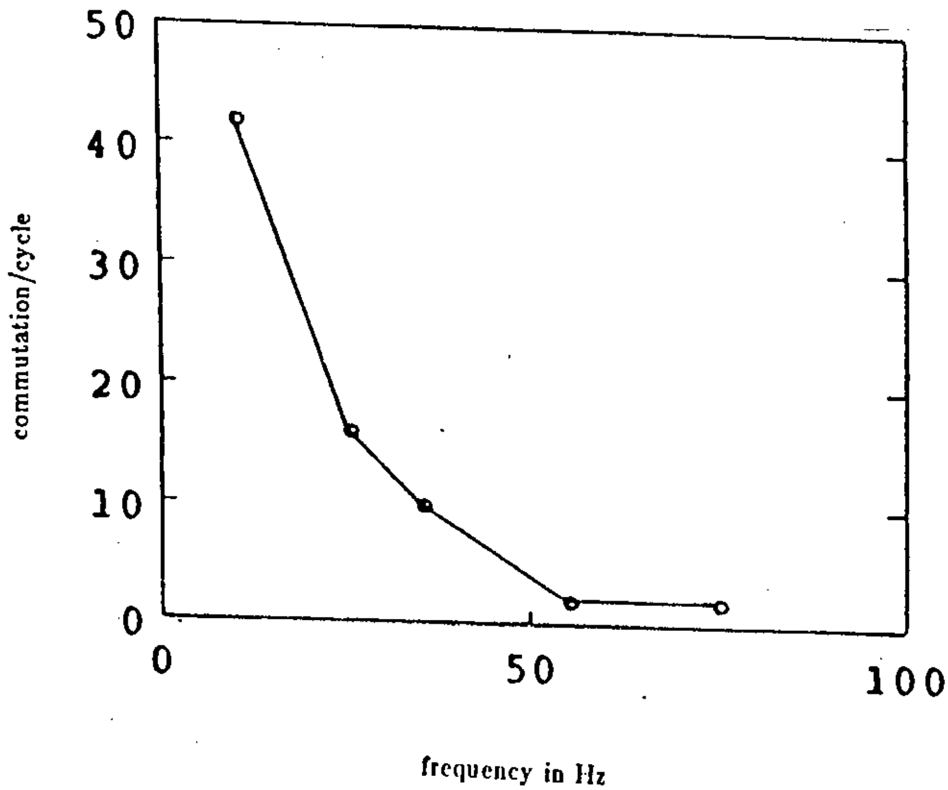


Fig. 3.5 Variation of the number of commutation of output waveforms of a rectangular wave delta modulator versus frequency.

3.3 Variable Step Rectangular Wave Delta Modulation for Inverter Operation.

Delta modulation offers the possibility of on-line harmonic minimization of pulse width modulated inverter output without resorting to conventional optimization processes. Conventional harmonic minimization includes selective harmonic elimination and harmonic weighting technique [52,53]. They attempt to modify the harmonic contents of the inverter output voltage in a desired fashion. These are normally achieved by waveform synthesis methods. Harmonic minimization through waveform synthesis are computationally intensive because they require the solution of sets of transcendental equations. The preferred technique has been to determine the switching instances by off- line computation with a main-fram computer. The switching points are stored in the erasable programmable read only memory (EPROM) of a micro computer for use during the inverter operation. For fixed frequency inverter operations this works well. However for continuously variable frequency operation of an inverter it requires numerous look-up tables in EPROMs. The recently proposed, simplest technique of PWM inverter waveform synthesis for on line optimization is delta moduation (dm) schemes. The tuned and multi integrator dm are the two schemes proposed for PWM waveform synthesis so far. Brief discussion on tuned RWDM is already done in art 1.2.4. The integrator for circuit generally used in the feedback path of the tuned delta modulation is shown in fig. 3.6. The main objection to this method lies in the fact that due to inherent property of the filter, fundamental component of the inverter output voltage is reduced with the change of intergrator constants.

In this research an easy but versatile method of improving the harmonic con-

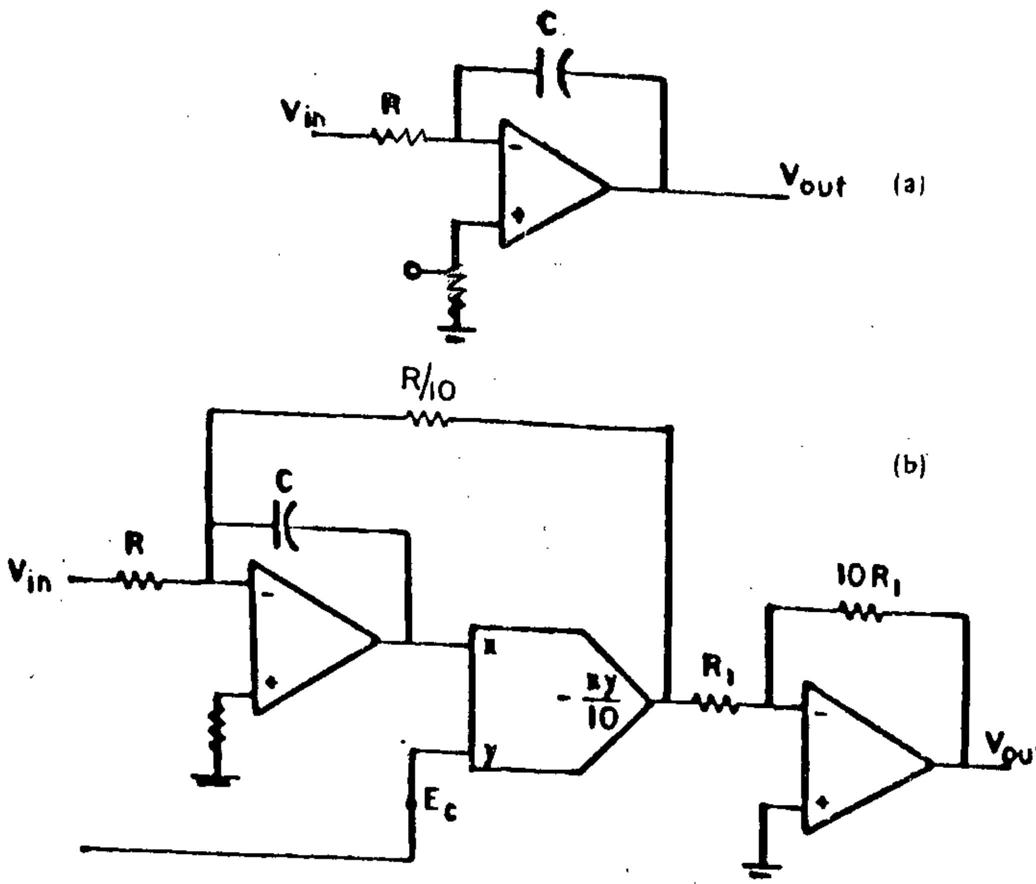


Fig. 3.6 The simple integrator and the tuned integrator circuits.
(a) The simple integrator circuit.
(b) The tuned integrator circuit.

tents of inverter by using a variable step RWDM is proposed and implemented. The new scheme controls the window of the quantizer to attain the same result and at the same time maintain a near constant magnitude of the fundamental component.

3.3.1 Operation of the Proposed Scheme.

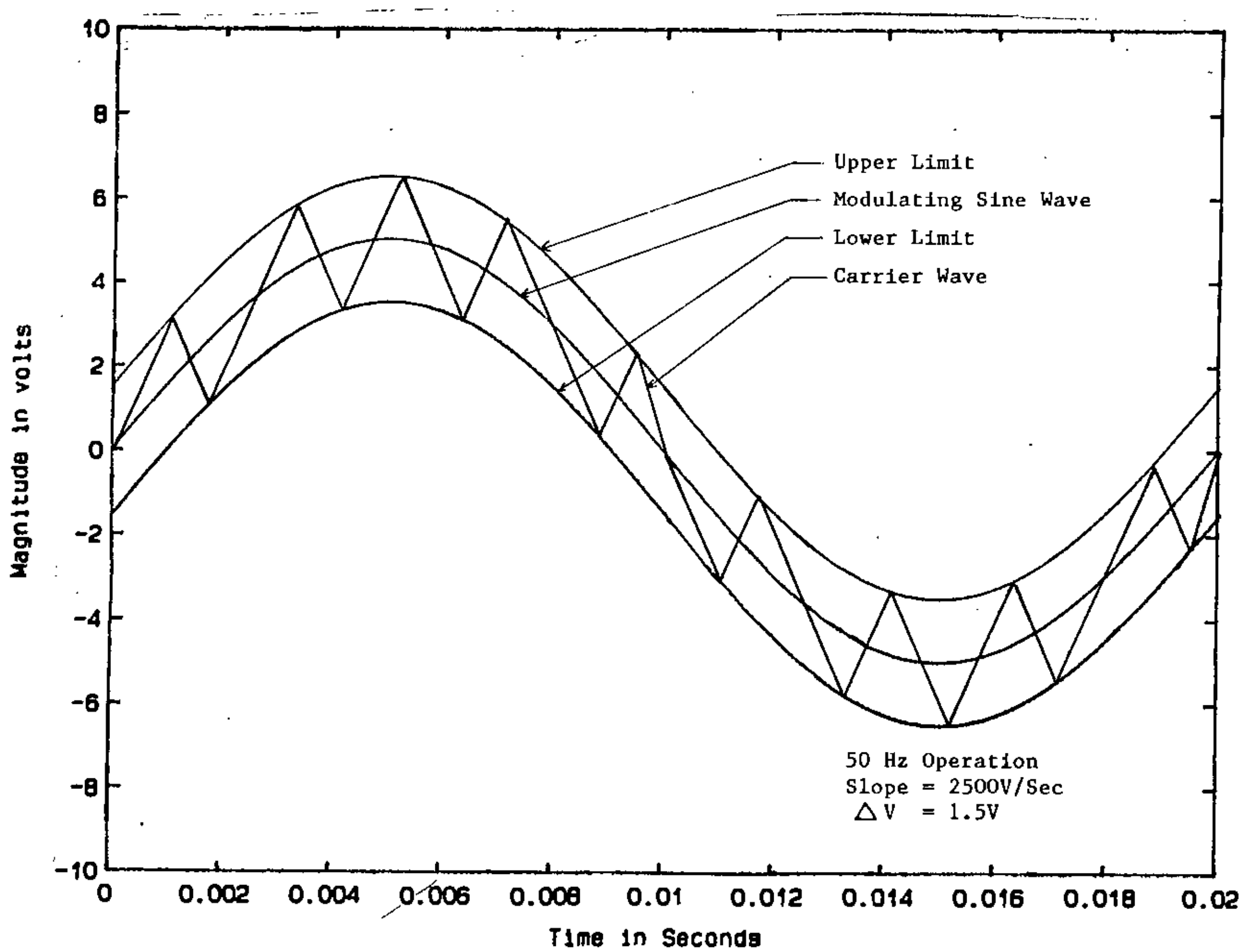
The block diagram and wave shape of the variable step RWDM is shown in figs 3.1 and 3.2. As the input frequency increases with other parameters (window width, slope) constant, number of switching point decreases i.e number of pulses per cycle decrease. This results domination of lower order harmonics. So to eliminiate or reduce these dominating lower order harmonics or in other words to send the dominating harmonics in high frequency position i.e far away from fundamental, number of switching points should be changed with frequency variation. This can be done by changing the window width. As the window width is reduced the carrier frequency is changed and thus the switching points are increased resulting higher number of pulses per cycle with variable width. This phenomenon is demonstrated in figs. 3.7 and 3.8.

3.3.2 Analysis.

The switching points of the variable step RWDM can be obtained from the generalized equation (3.2). Let us recollect the equation.

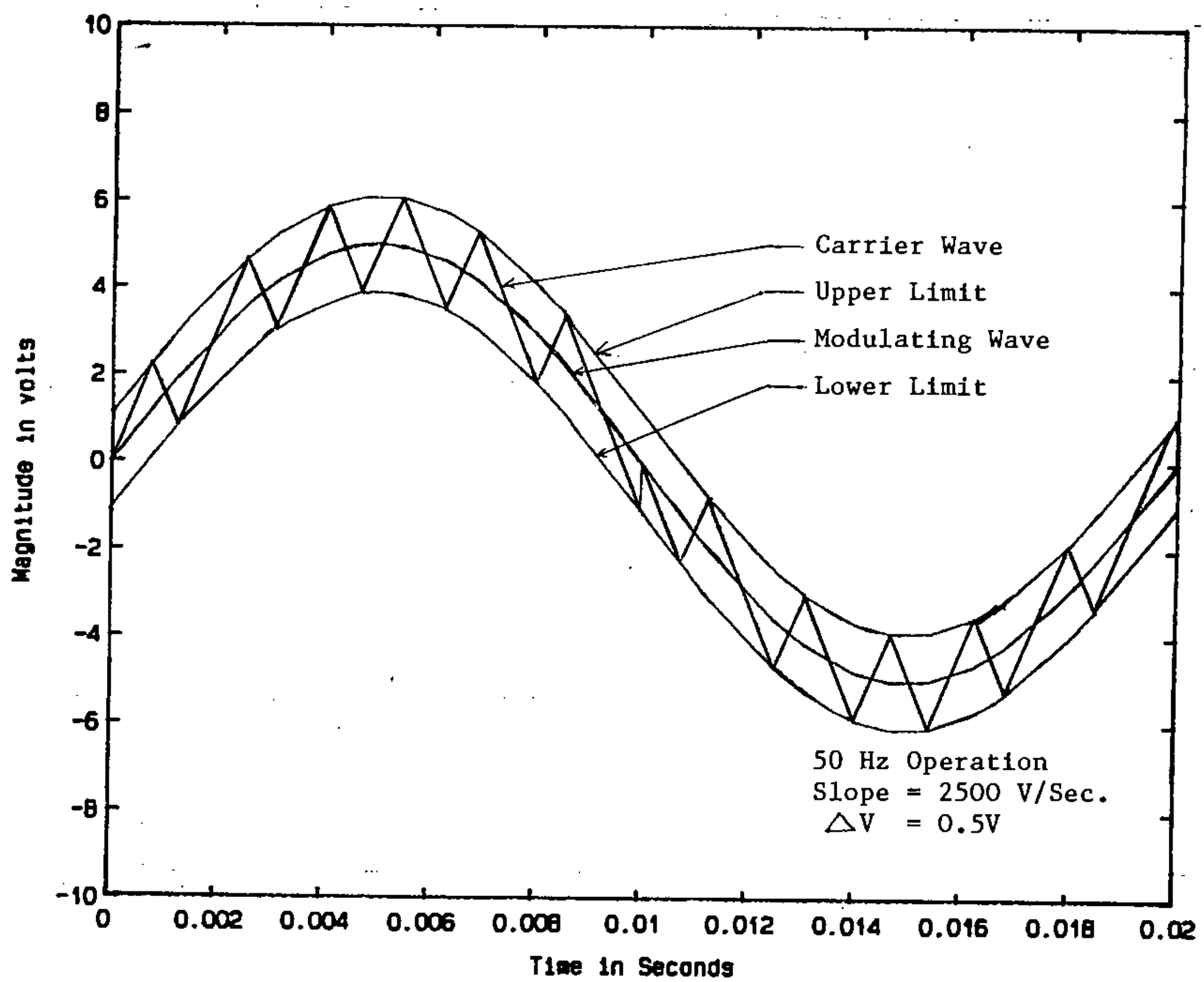
$$t_i = \frac{2\Delta V + St_{i-1}}{S} + \frac{V_R sin\omega_R t_{i-1} - V_R sin\omega_R t_i}{(-1)^i S} \qquad (3.26)$$

Replacing the various value of ΔV we shall get required switching points t_i.



10
8
6
4
2
0
-2
-4
-6
-8
-10
Magnitude in volts
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Time in Seconds
Upper Limit
Modulating Sine Wave
Lower Limit
Carrier Wave
50 Hz Operation
Slope = 2500V/Sec
△V = 1.5V

Fig. 3.7 (a)



Carrier Wave
Upper Limit
Modulating Wave
Lower Limit
50 Hz Operation
Slope = 2500 V/Sec.
△V = 0.5V
Magnitude in volts
Time in Seconds
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02

Fig. 3.7 (b)

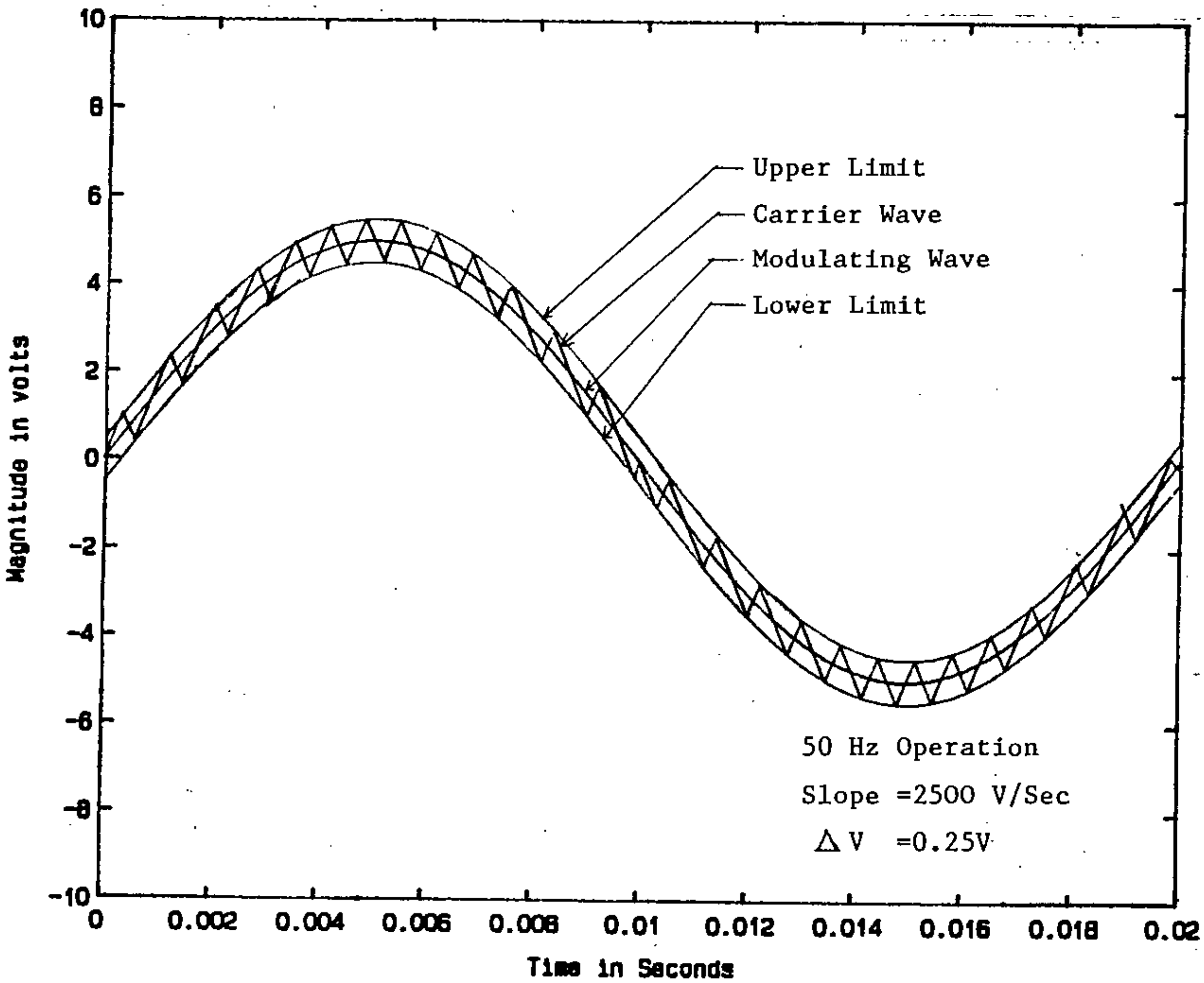
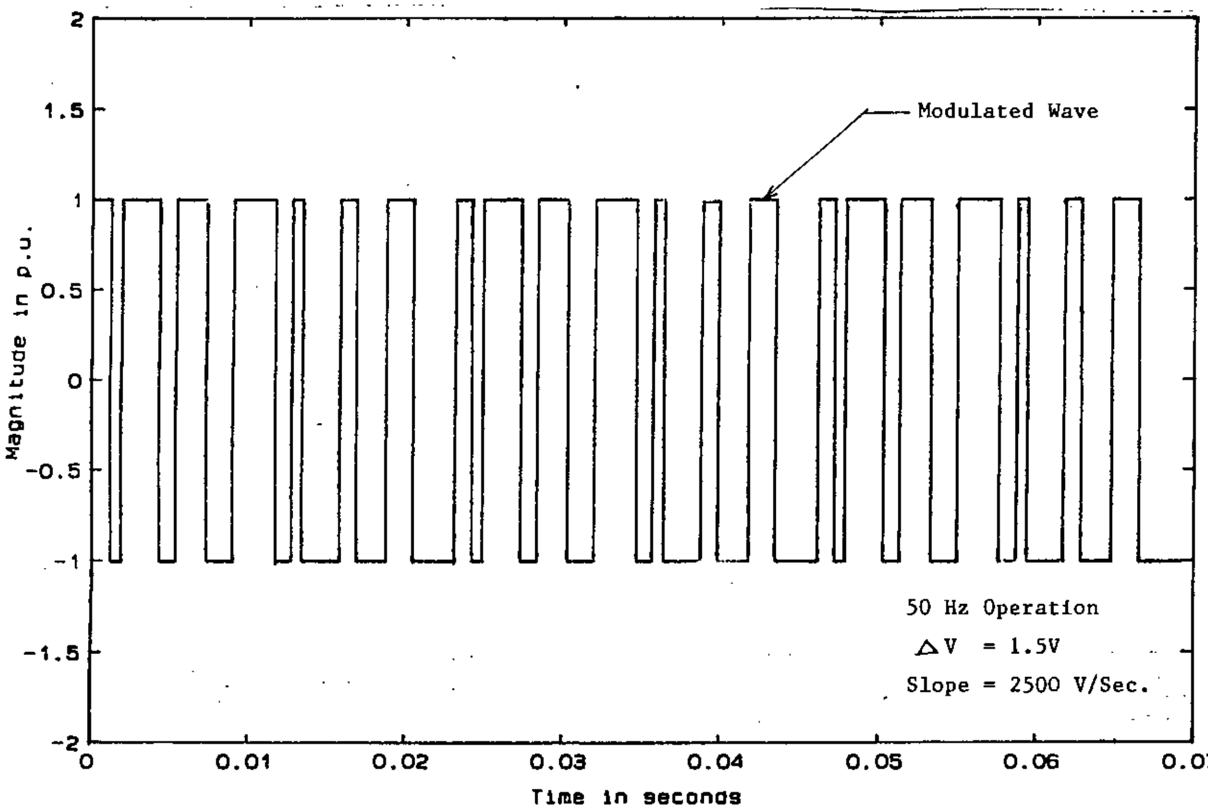


Fig. 3.7 (c)

Fig. 3.7 Typical estimated waveforms of variable step rwdm as the window width is decreased.



Modulated Wave
50 Hz Operation
ΔV = 1.5V
Slope = 2500 V/Sec.
Magnitude in p.u.
Time in seconds
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

Fig. 3.8 (a)

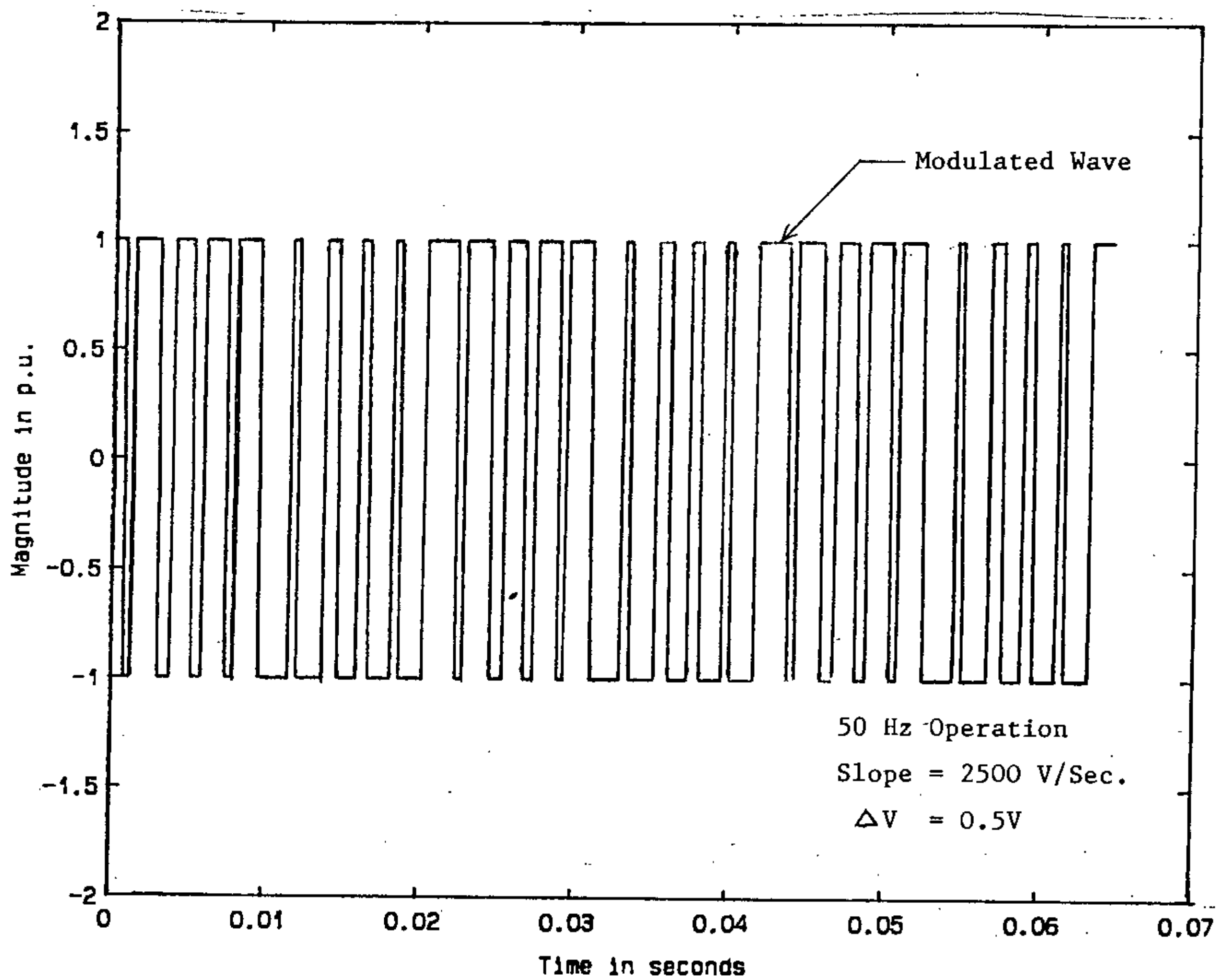

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Magnitude in p.u.
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Time in seconds
Modulated Wave
50 Hz Operation
Slope = 2500 V/Sec.
ΔV = 0.5V

Fig. 3.8 (b)

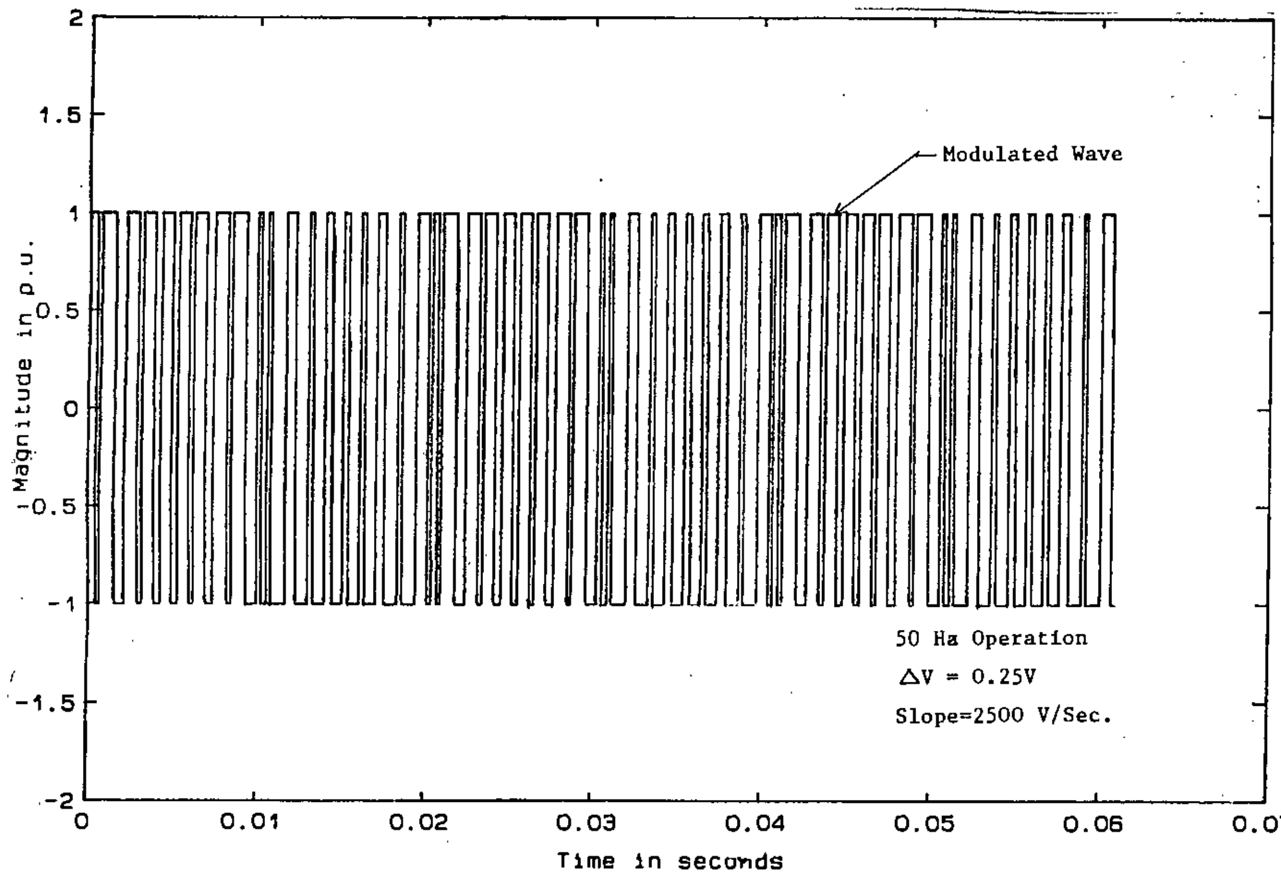


Fig. 3.8 (c)

Fig. 3.8 Typical modulated waveforms of variable step rwdm as the window width is decreased.

After the switching points are known the modulated waveform can be obtained from the equation (3.3). Let us rewrite it as follows

$$m(t) = (-1)^{i+1} \sum G(t, t_{i-1}, t_i) \tag{3.27}$$

The Fourier co-efficient of the above modulated wave can be obtained from the equations 3.7 and 3.8. Let us recall these equations.

$$A_n = \frac{2V_s}{n\pi} \sum_{i=1,2,..}^{N_p} (-1)^{i+1}(sinn\delta_i - sinn\delta_{i-1}) \tag{3.28}$$

$$B_n = \frac{2V_s}{n\pi} \sum_{i=1,2,..}^{N_p} (-1)^{i+1}(cosn\delta_{i-1} - cosn\delta_i) \tag{3.29}$$

$$V_{on} = \sqrt{A_n^2 + B_n^2} \tag{3.30}$$

For Fourier series analysis the waveform is assumed to be symmetrical. In practical circuits this has been achieved by resetting the modulators at every half cycle of the input sine wave.

Fig 3.9(a), (b) and (c) show three spectra of a tuned dm waves for 50 Hz operation with window width 1v and slopes of 2500, 3250 and 4000 v/s respectively. These spectra show that due to slope variation, the harmonics between 3rd and 17th have been reduced substantially, however, the fundamenal is gradually reduced from 0.43 P.U. to 0.27 P.U. with the increase of slope. The spectra for similar variation of window width from 1.5v to 0.5v through 1v for a slope of 3000 v/s at 50 Hz have been shown in figs. 3.10(a), (b) and (c). The spectra show that the harmonics

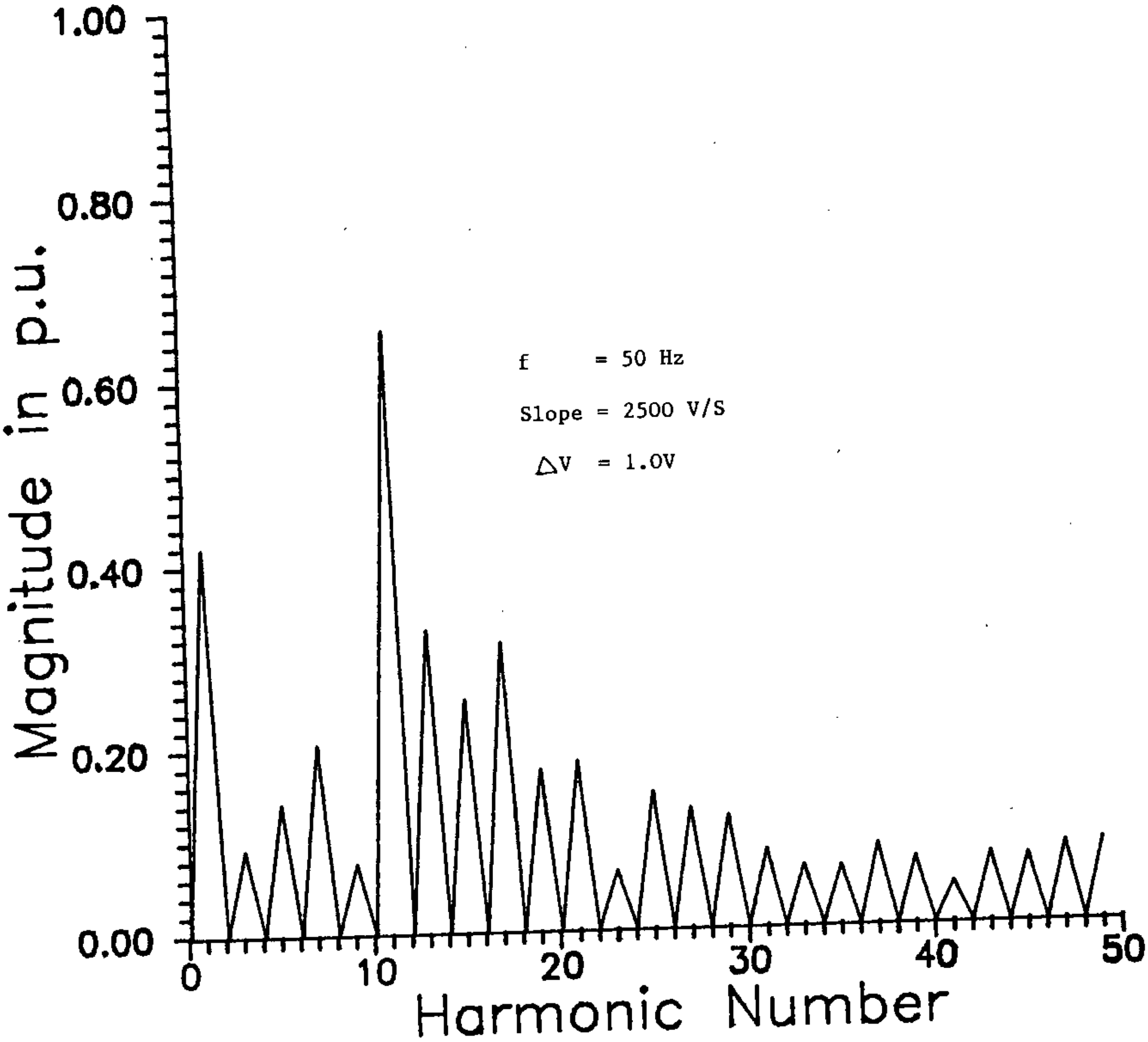

1.00
0.80
0.60
0.40
0.20
0.00
Magnitude in p.u.
0
10
20
30
40
50
Harmonic Number
f = 50 Hz
Slope = 2500 V/S
ΔV = 1.0V

Fig. 3.9 (a)

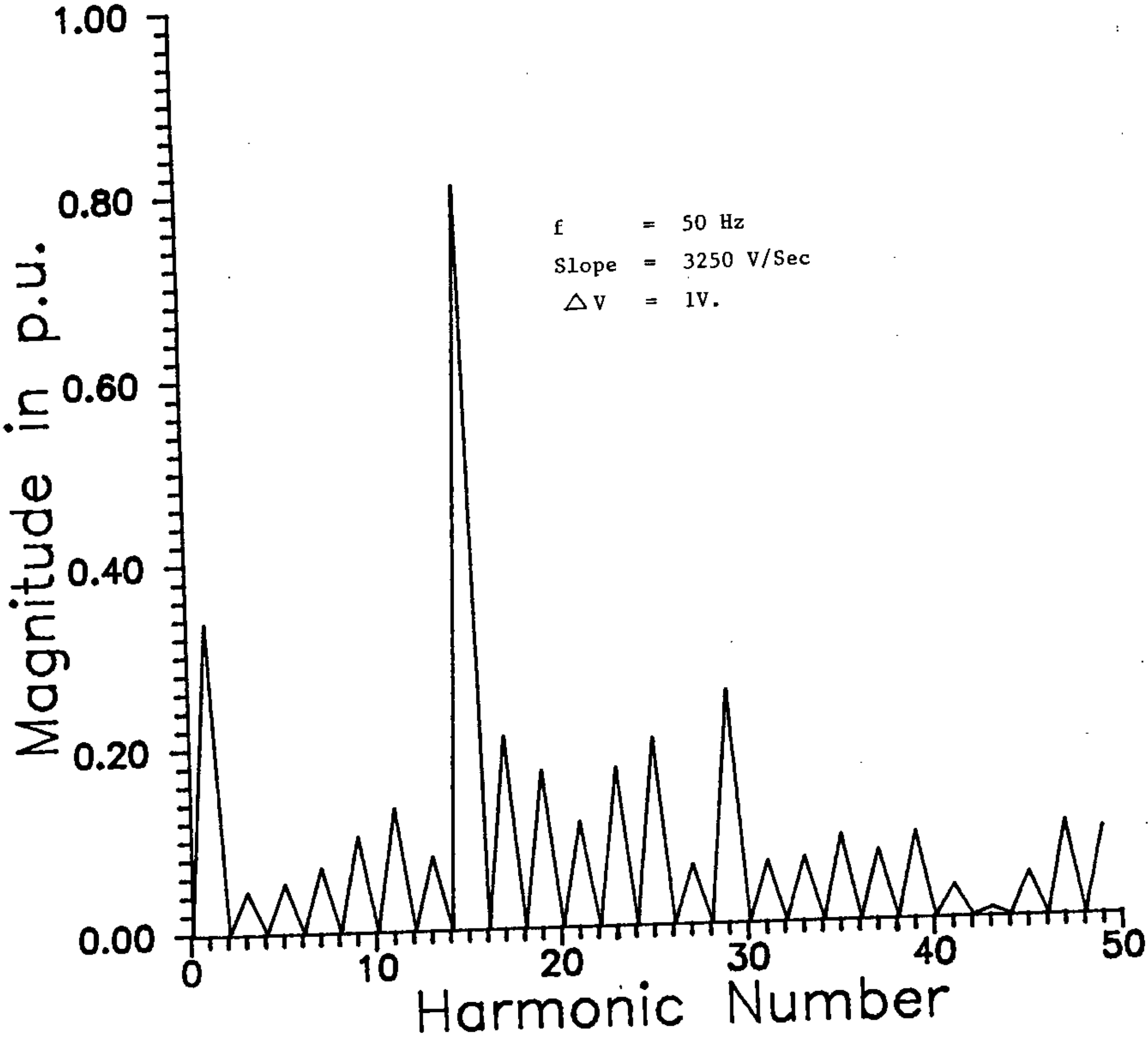

1.00
0.80
0.60
0.40
0.20
0.00
Magnitude in p.u.
0
10
20
30
40
50
Harmonic Number
f = 50 Hz
Slope = 3250 V/Sec
△V = 1V.

Fig. 3.9 (b)

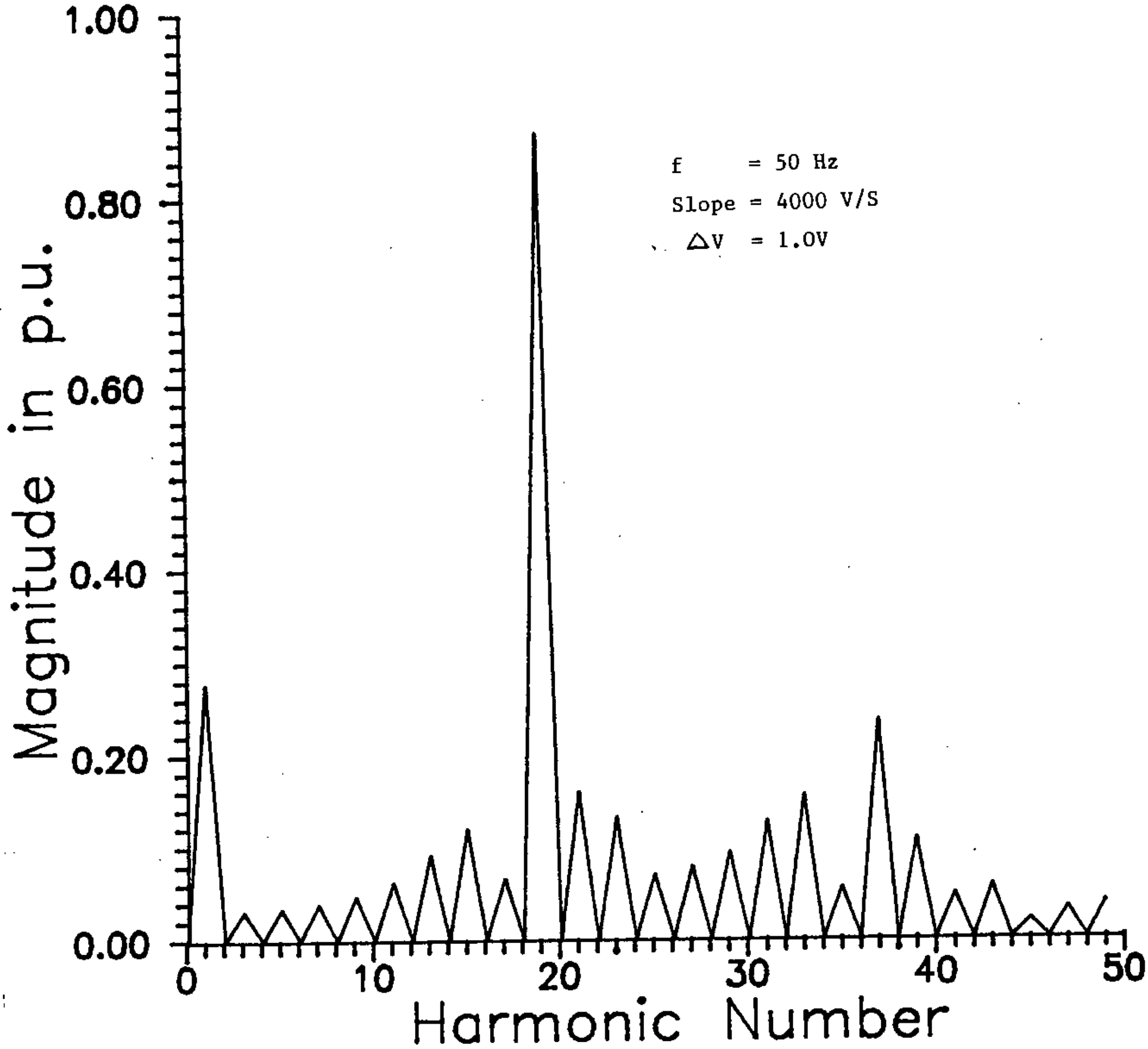


Fig. 3.9 (c)

Fig. 3.9 Spectra of tuned rwdm waves with frequency = 50 C/S and window width = 1v

(a) Slope = 2500 V/S
(b) Slope = 3250 V/S
(c) Slope = 4000 V/S

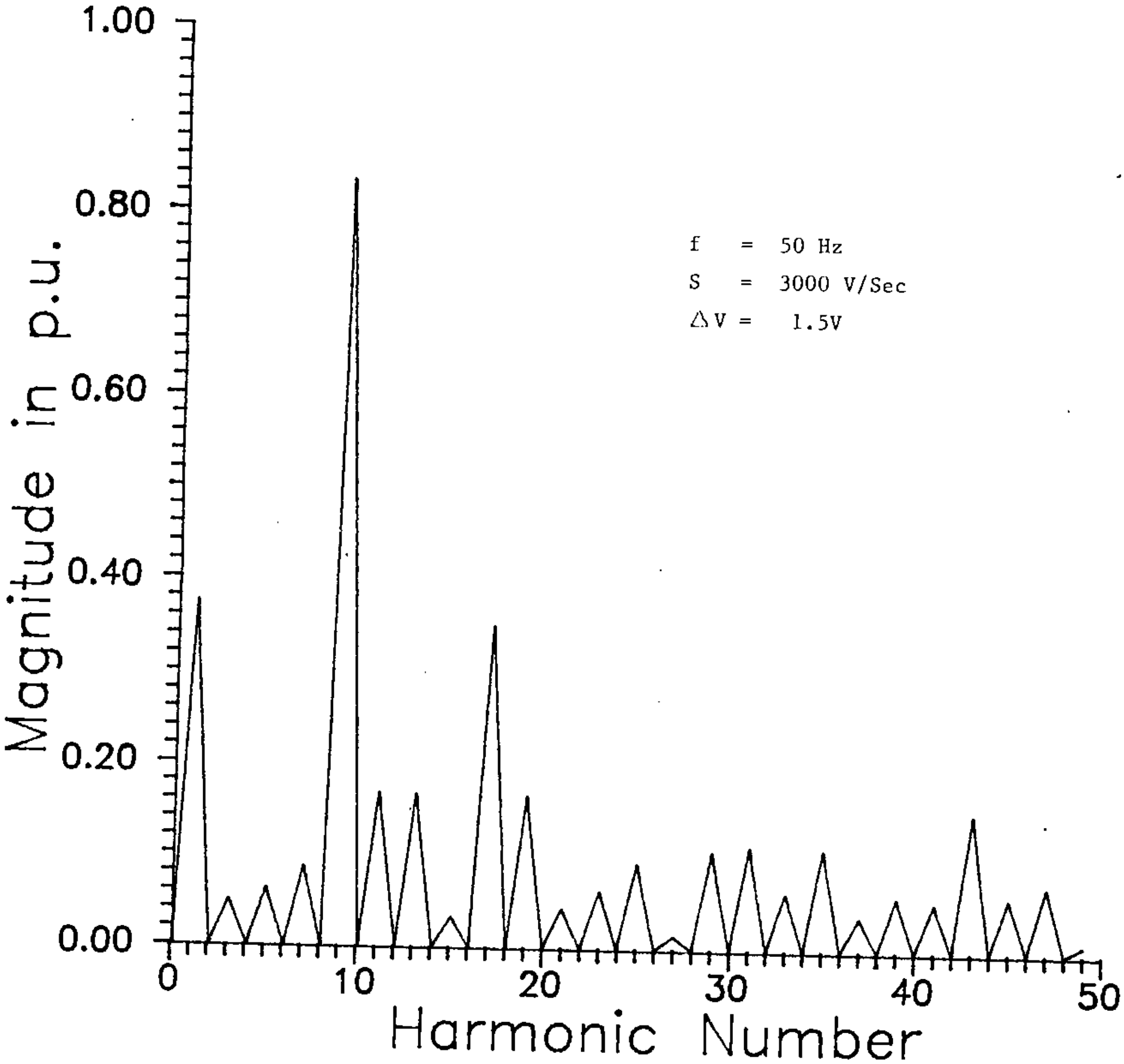

1.00
0.80
0.60
0.40
0.20
0.00
Magnitude in p.u.
f = 50 Hz
S = 3000 V/Sec
△V = 1.5V
0
10
20
30
40
50
Harmonic Number

Fig. 3.10 (a)

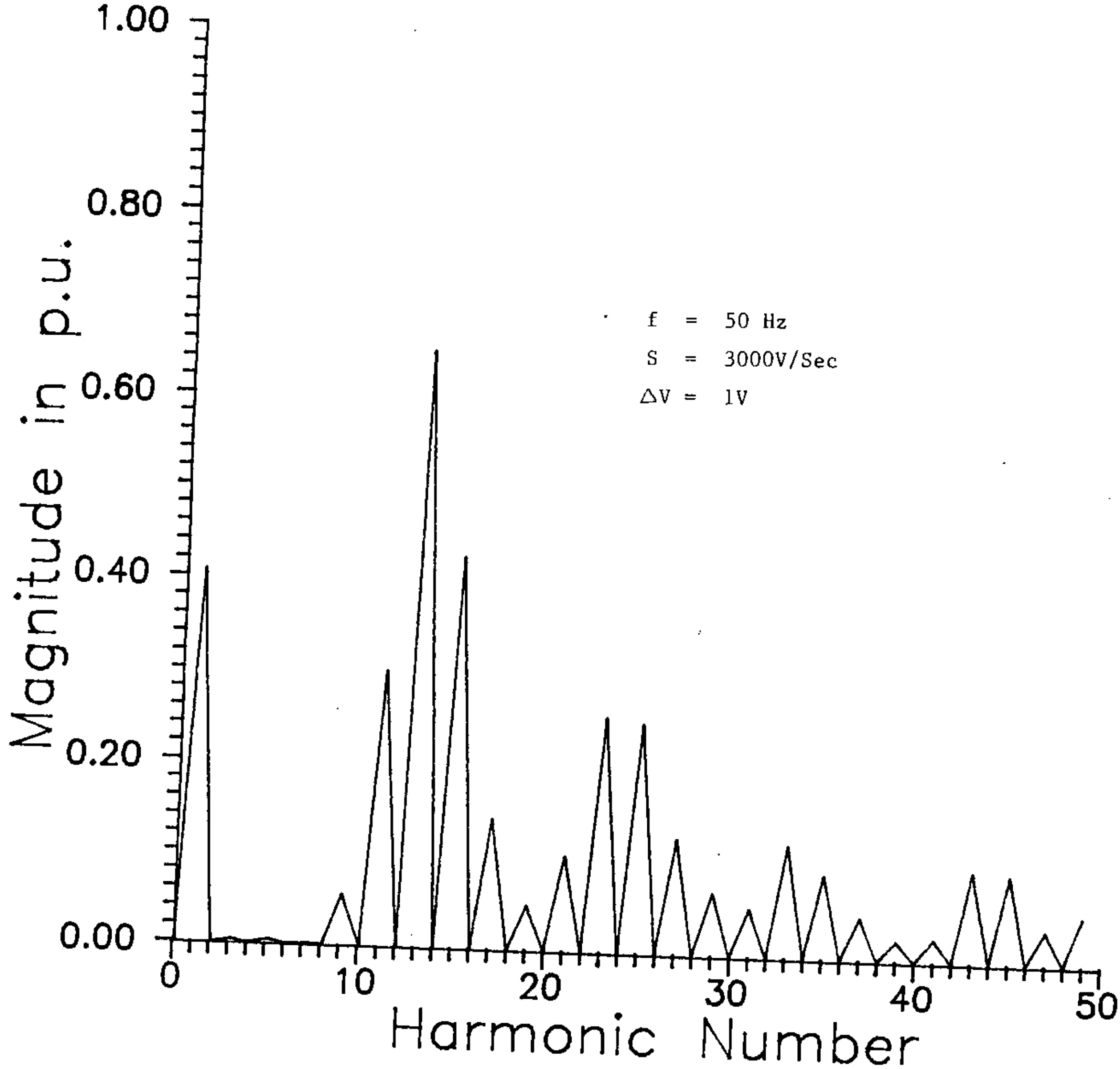

1.00
0.80
0.60
0.40
0.20
0.00
Magnitude in p.u.
f = 50 Hz
S = 3000V/Sec
ΔV = 1V
0
10
20
30
40
50
Harmonic Number

Fig. 3.10 (b)

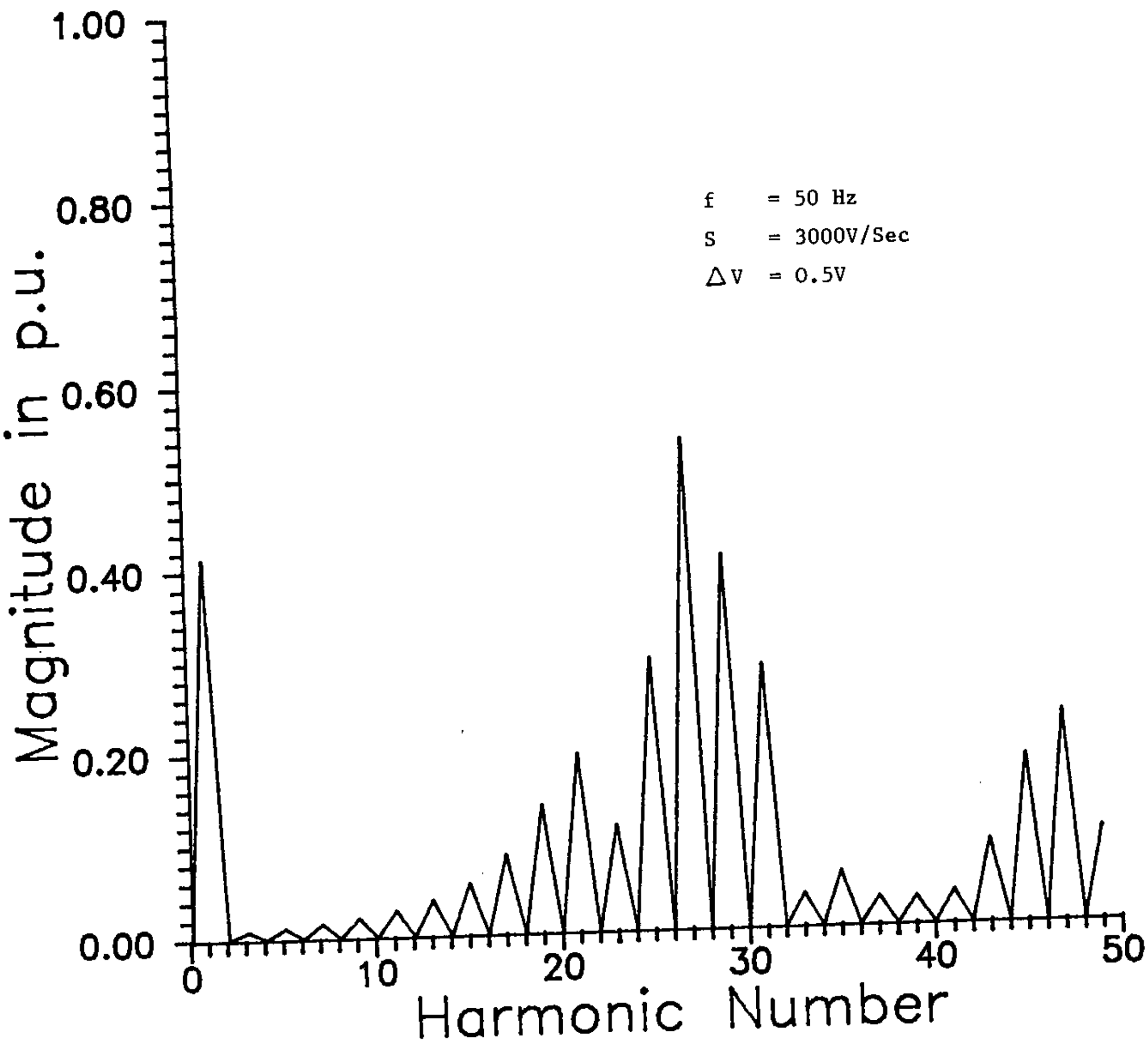


Fig.3.10 (c)

Fig. 3.10 Spectra of variable step rwdm waves width frequency
= 50 C/S and slope = 3000 V/S
(a) Window width = 1.5V
(b) Window width = 1V
(c) Window width = 0.5V

between 3rd and 17th have been reduced due to window width variation where as the fundamental remains almost constant at 0.4 P.U. The three dinensional spectral representation for dm modulated waves are shown in figs. 3.11 - 3.13. Fig. 3.11 is for window width = 1.25v slope 2000 v/s and frequency of 20-120 Hz. This shows that at low frequency operation, the magnitude of low order harmonics are small whereas, at high frequency operation the low order harmonics have higher amplitudes. Also the fundamental increases to a certain value in PWM mode of operation. With the increase in frequency the waveforms attain square waveform and magnitude of the fundamental remain constant there on. Fig. 3.12 is for frequency of operation of 100 Hz, window width 1.25v and slope of 200-3500 v/s. From the figure it is clear that as the slope increases, magnitude of lower order harmonics decreases. At the same time the magnitude of fundamental voltage decreases. Fig. 3.13 represents the variation of window width from 0.5v to 1.25v at 100 Hz and slope of 3500 v/s. From these spectra it can be observed that as the window width decreases the magnitude of lower order harmonics reduces. The magnitude of the fundamental, however, remains constant, except for the transition window width of 0.75v.

3.4 Conclusions.

A novel method of on-line inverter output waveform optimization using variable step RWDM circuit has been described. The method eliminates the necessity of pre-programmed waveform synthesis and use of micro-computers for optimized wave from generation. The performance of the proposed method is analysed in detail with the help of various waveforms and spectra which are obtained from theoritical calculations. The results show that the variable step RWDM technique has eliminates the major draw back of reduction of fundamental voltage of tuned

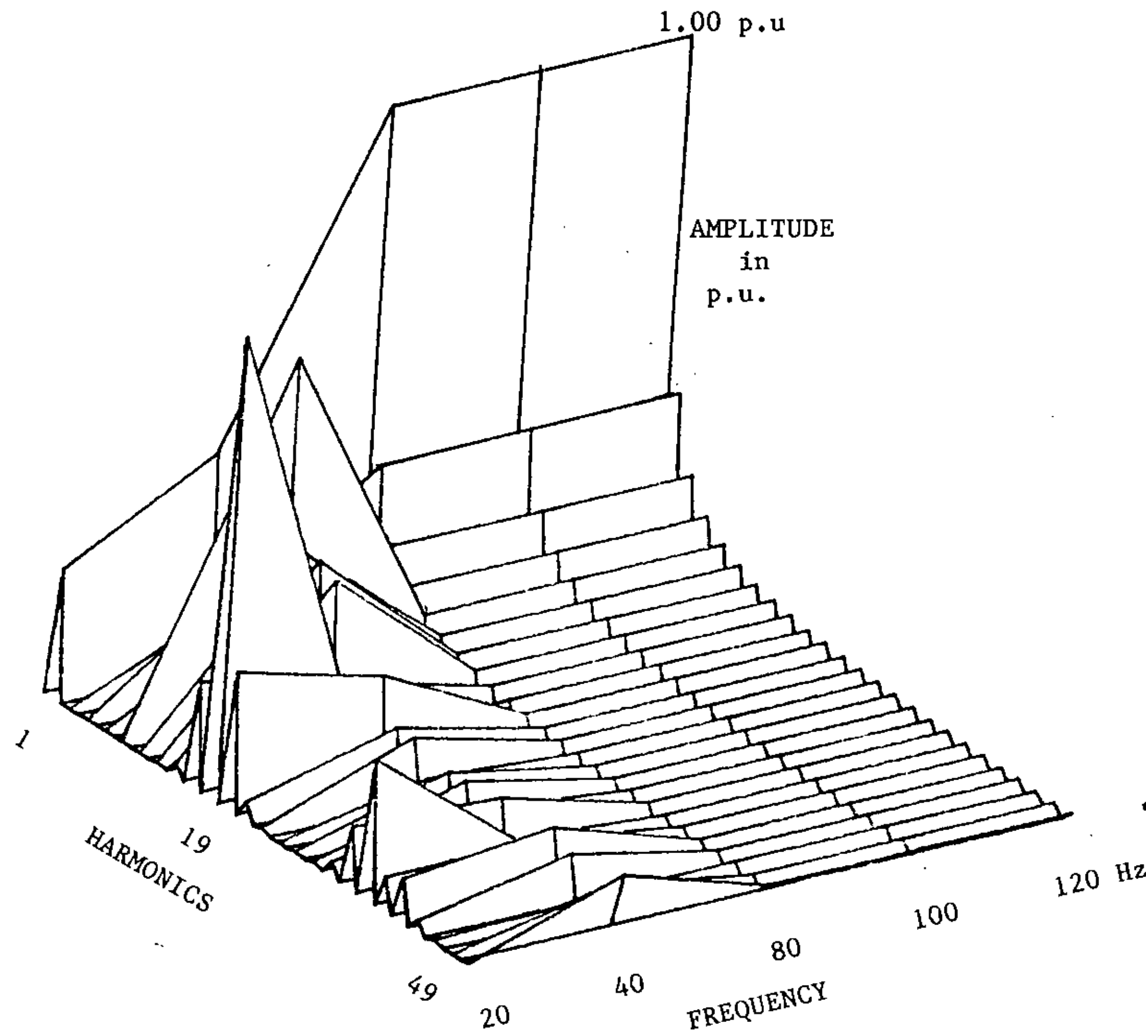


Fig. 3.11 Spectra of rwdm waves for frequency of operation from 20-120 Hz and window width = 1.25V and Slope = 2000V/S.

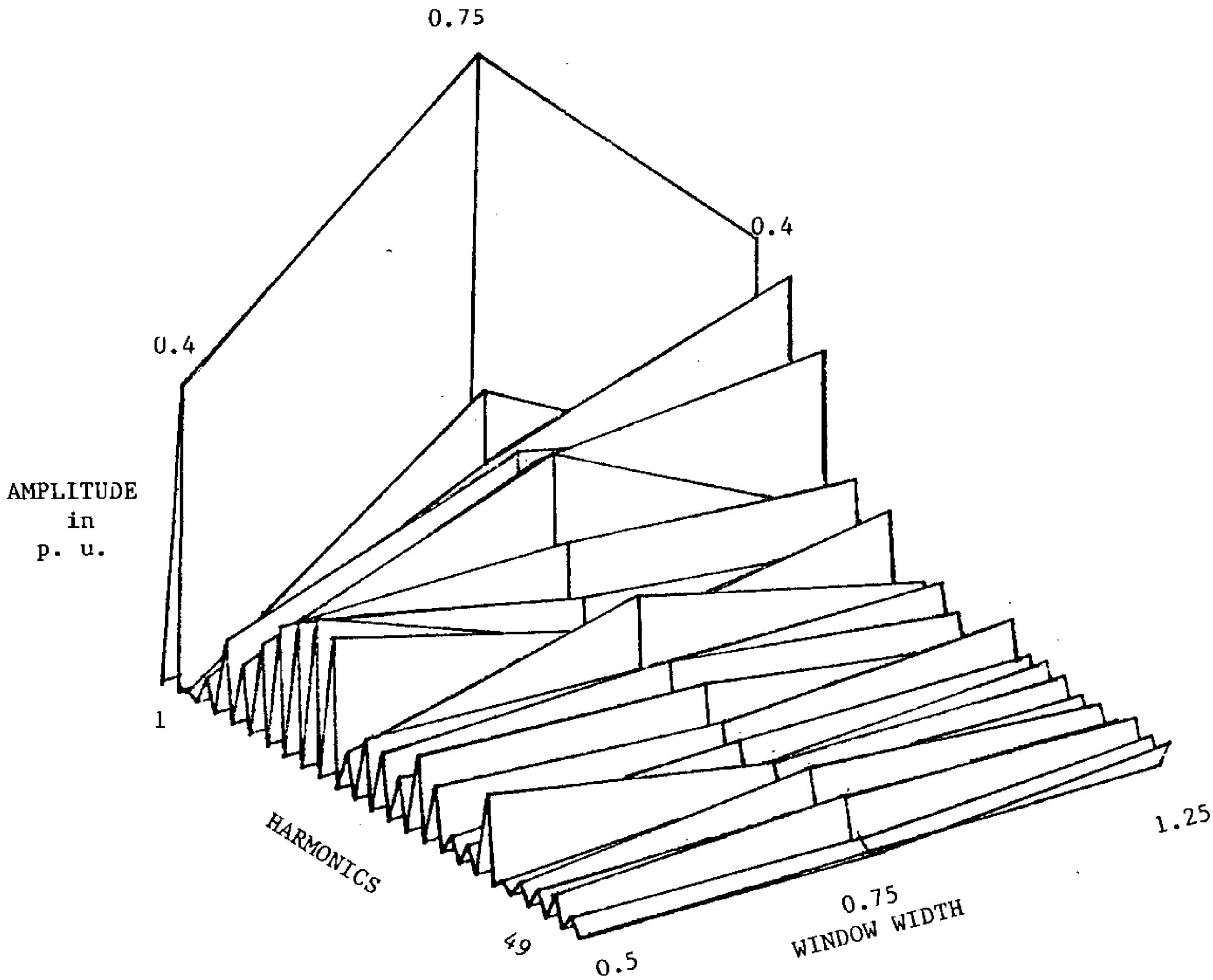


Fig. 3.12 Spectra of variable step rwdm for window width =0.5-1.25V at 100 Hz operation and Slope = 3500 V/S.

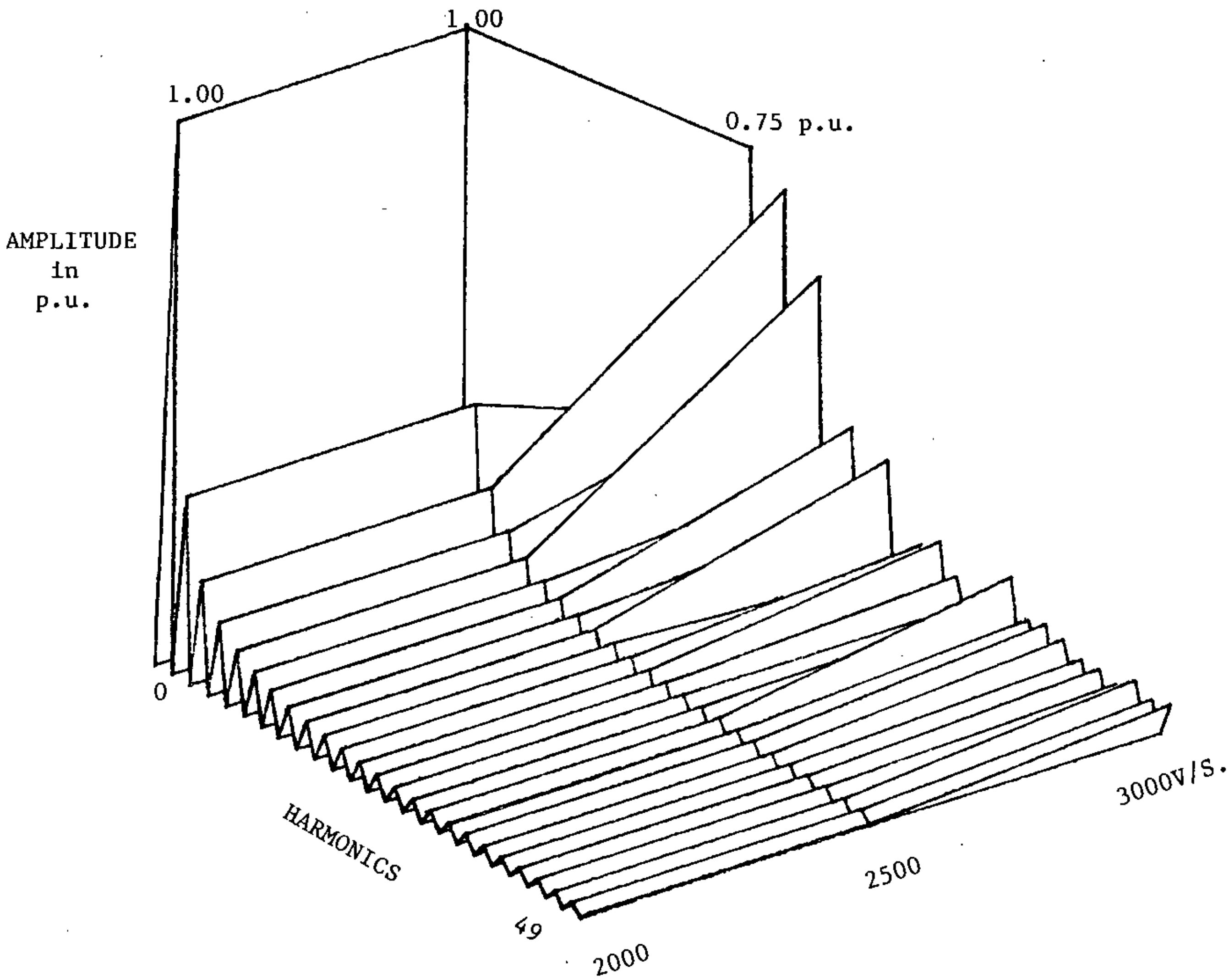


Fig. 3.13 Spectra of tuned rwdm waves for slope = 2000-3000 V/S.
at 100 Hz operation and window width = 1.25V

RWDM technique. If the waveform would be unsymmetrical Discrete Fourier transform should be carried out instead of the ordinary Fourier transform. But in our case the practical circuit is such that the wave from is forced to be symmetrical so given analysis is valid.

CHAPTER 4

Practical Results

4.1 Introduction.

The delta modulation technique requires relatively simple circuitry to obtain the switching waveform for thyristor switching.This chapter shows how the proposed method of the thesis is implemented practically. Theoritical results obtained in the previous chapter is examined practically. The output waveforms of the practical circuit is viewed in the oscilloscope and their photographs are presented here. Finally a brief description is given about how these output waveforms of the control circuit of the inverter will be processed to be used as final switching signal.

4.2 Implementation of Variable Step RWDM Circuit for PWM Inverters.

Fig.4.1 is an analog circuit that is capable of producing the waveforms shown in Fig.3.2. The operation of the circuit can be described as follows: Sine reference or modulating wave V_R is supplied to the input of the comparator A_1 and the 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 R_2/R_3) the comparator A_1 reverses the polarity of V_I at the input of A_2. This reverses the slope of V_F at the output of A_2. It forces carrier wave V_F to oscillate around the reference waveform, V_R at ripple frequence ω_r. So in this circuit we can vary the window width ΔV by changing the resistors of R_2 or R_3 as the ratio of R_2 and R_3 determines the value of ΔV. Also the slope of the carrier wave can be changed by changing the integrator parameter R_1. Once the switching waveform is obtained the signals for the main and commutation thyristors can be obtained through the logic circuit implementation for such inverters. The basic signals for such inverter (fig.2.4) thyristor operation

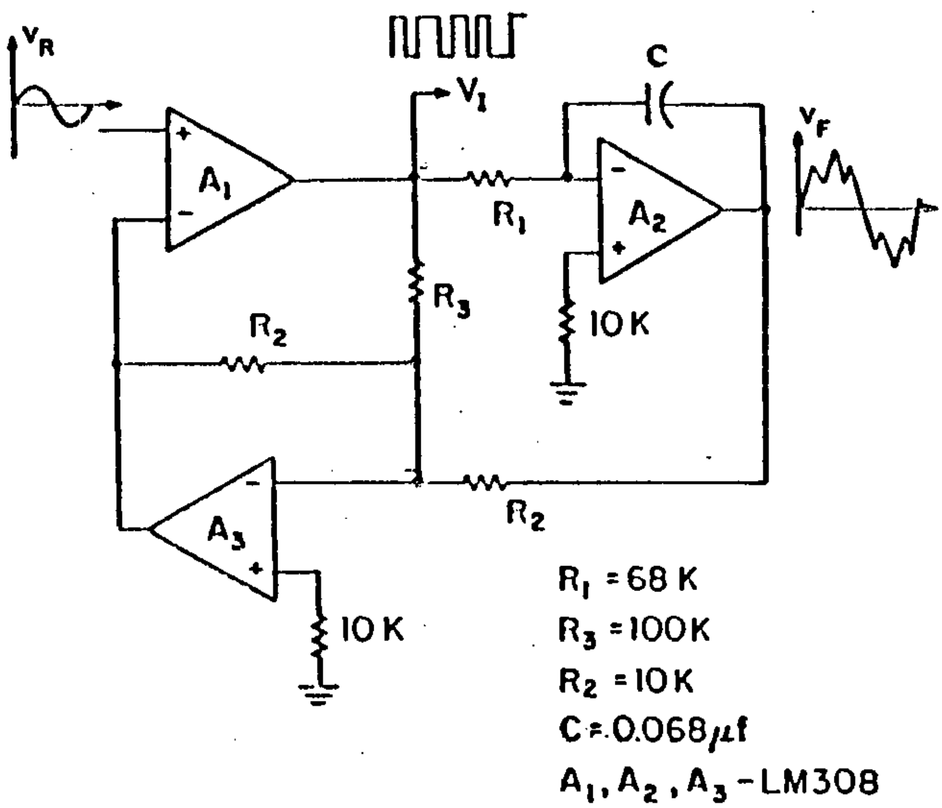


Fig. 4.1 A practical circuit for producing switching waveform of delta modulated inverters

are shown in Fig. 4.2.

4.3 Ripple Frequency of Carrier Wave and Number of Commutation in DM.

Number of commutation in any inverter is an important feature of the inverter. The increase in commutations results in increased commutation losses of the inverters. Some applications such as the uninterruptible power supply system, requires the commutation in the inverters to be limited for the lowest commutation losses as well as for perfect commutation porcess. In delta modulation the commutation number depends on the ripple frequency of the carrier wave. Because each ripple cycle corresponds to two transition points in the modulated waveform V_I, each of the these transition points corresponds to a commutation in the inverter. In the delta modulation, if the window width ΔV is kept constant, the ripple frequency ω_r varies as the amplitude of the modulating wave varies. The decrease in V_R increases the ripple frequency, while the increase in V_R decreases the ripple frequency. In the delta modulation implementation circuit of Fig. 4.1, the window width ΔV is determined by the circuit constants and the logic supply votage as

$$\frac{\Delta V}{V_s} = \frac{R_2}{R_3} \tag{4.1}$$

For particular V_R, the maxium number of commutation is given by [23]

$$N_{CM} = \frac{1}{2R_1C} \cdot \frac{R_3}{R_2} \tag{4.2}$$

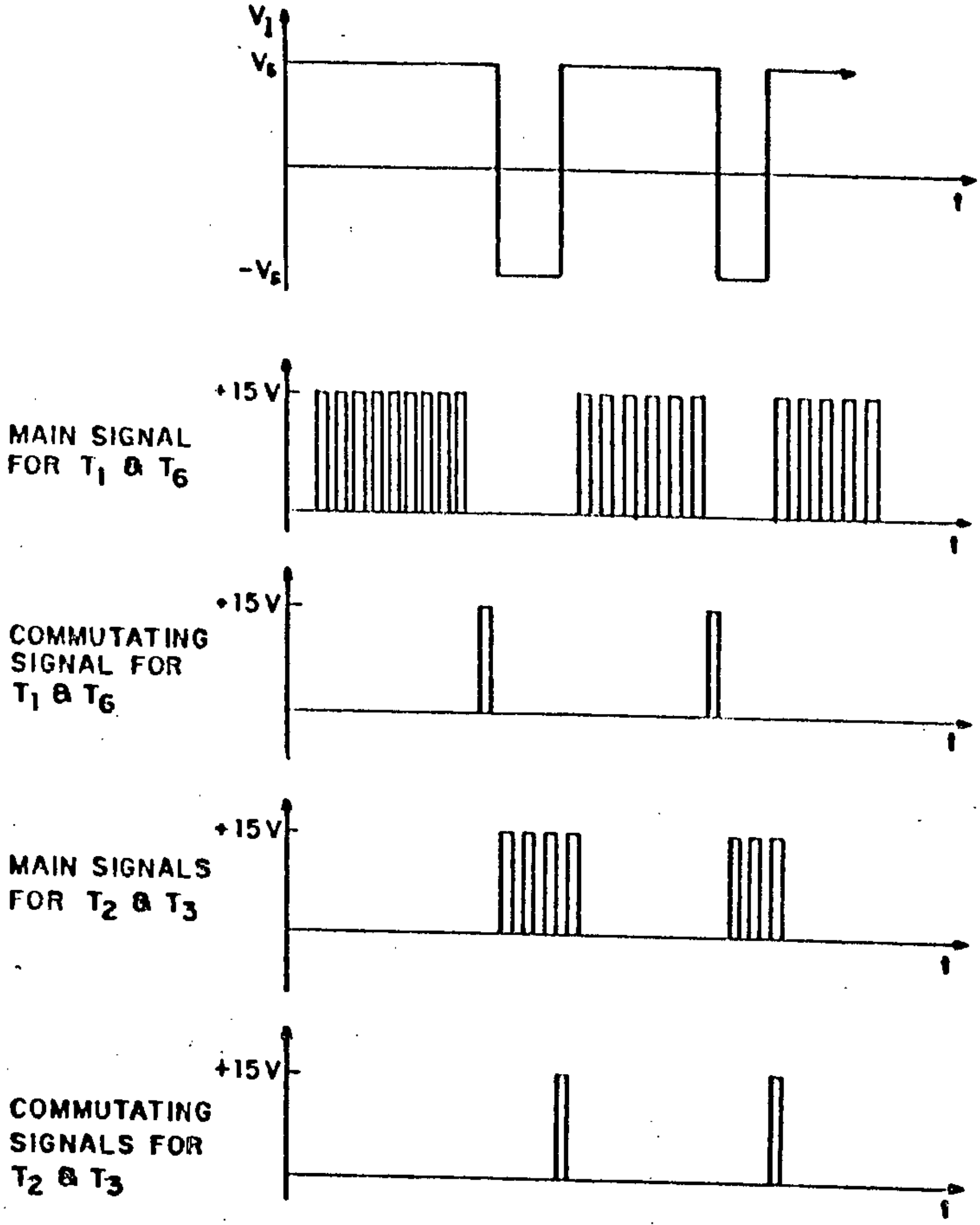


Fig. 4.2 Basic switching signals for the main and commutation thyristors of a single phase full bridge inverter

The design of logic circuit for delta modulation can be done for a certain maximum allowable number of commutation per second by choosing the appropriate capacitors and resistance in the circuit. The number of commutation at any operating frequency can be changed by changing V_R.

Since number of commutation is related to the number of modulated pulses per cycle, another easy way of finding the number of commutation is to determine the number of pulses/cycle.

The pulse termination position is given by

$$\delta_i = \omega_R t_i \tag{4.3}$$

where t_i is given by equation 3.26. Solution of the equation (4.3) for δ_i at $\delta_i = \pi$, gives the number of pulses/half cycle of the modulating wave V_R.

$$i = N_P \ \ [for\ \delta_i = \pi] \tag{4.4}$$

where, N_P = number of pulses for half cycle The number of commutation per second is given by

$$N_C = 2N_P f_R \tag{4.5}$$

where, f_R = frequency of modulating wave

The ripple frequency of the carrier wave is given by

$$f_r = \frac{N_c}{2} \, cycles/second \tag{4.6}$$

Equations (4.3) and (4.6) are solved for varying frequency.

4.4 Experimental Verification for Delta Modulation Technique.

This section deals with the verification of the analysis of delta modulation carried out so far. The implementation of the logic circuits and verification of the main features of delta modulation are described in the following subsections in details.

4.4.1 Experimental Results.

Figs. 4.3 are the photgraphs of the carrier and modulated waves generated by the practical circuit of fig. 4.1. The oscillographs show that as the input frequency of V_R is increased, the number of switching points are decreased and there is gradual transition from PWM mode to pure square wave mode which is expected.

Figs. 4.4 show the oscillographs of carrier and modulted waves of the circuit of fig. 4.1 for different values of slope of the carrier waves. It is observed that as the slope is increased by changing R_1, the number of switching points are increased. Figs 4.5 are the frequency spectrums of the modulated waves of figs. 4.4. As expected by theory it is observed that as the slope is increased, the dominating harmonics shift to the right.

Figs. 4.6 are the oscillographs of the waveforms generated by the practical circuit of fig. 4.1 for different values of window width ΔV. And figs. 4.7 show the frequency

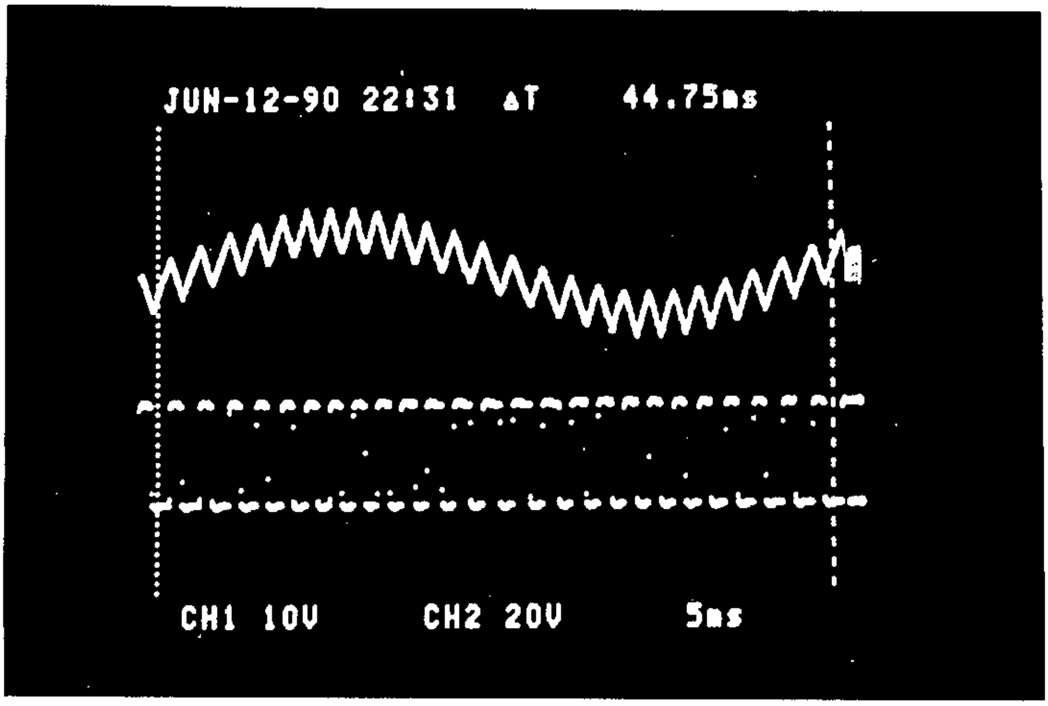


Fig. 4.3 (a)

20 Hz
VR=10V
ΔV=3V

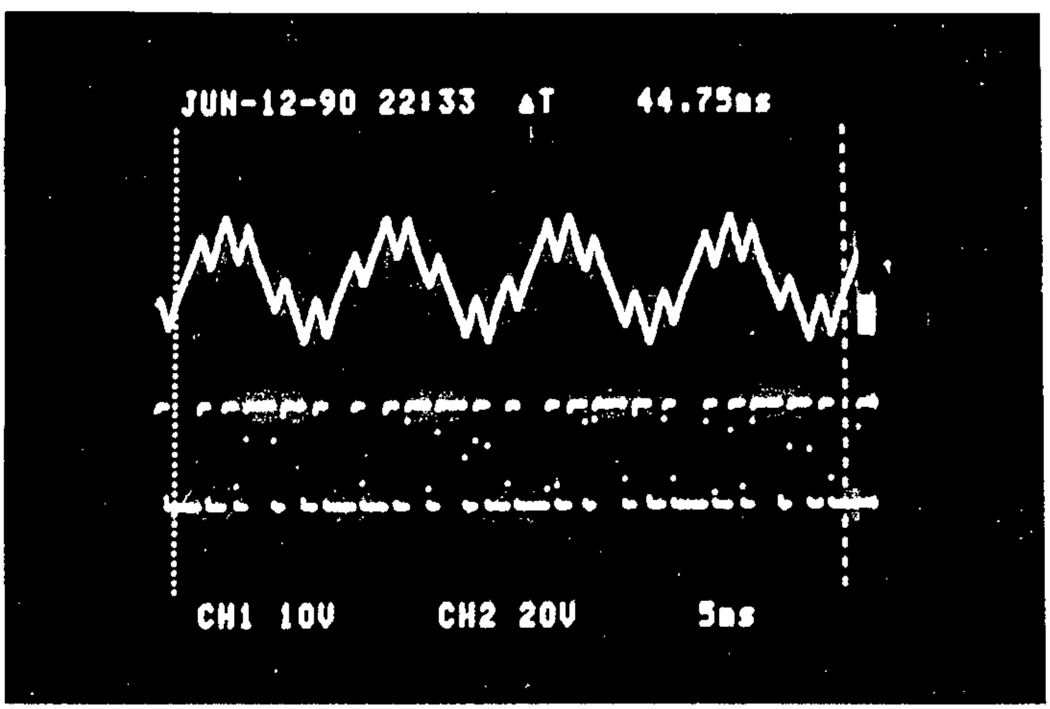


Fig. 4.3 (b)

70 Hz
VR=10V
ΔV=3V

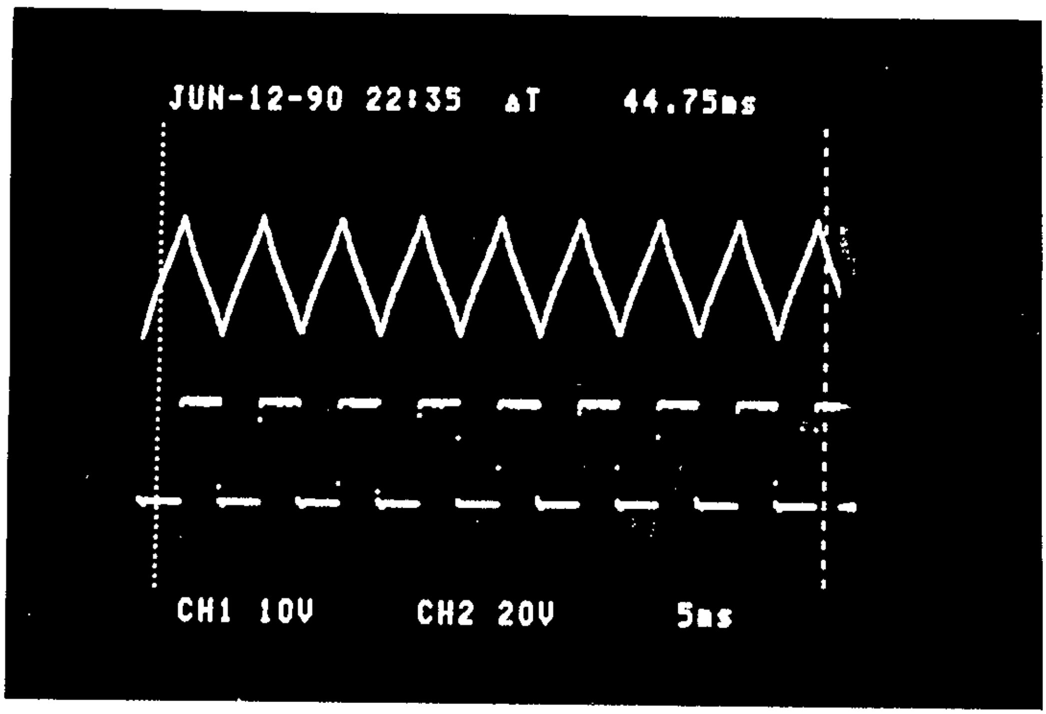


Fig. 4.3 (c)

180 Hz
VR= 10V
ΔV= 3V

Fig. 4.3 Waveforms of variable step rwdm as the frequency of the modulating wave is increased.

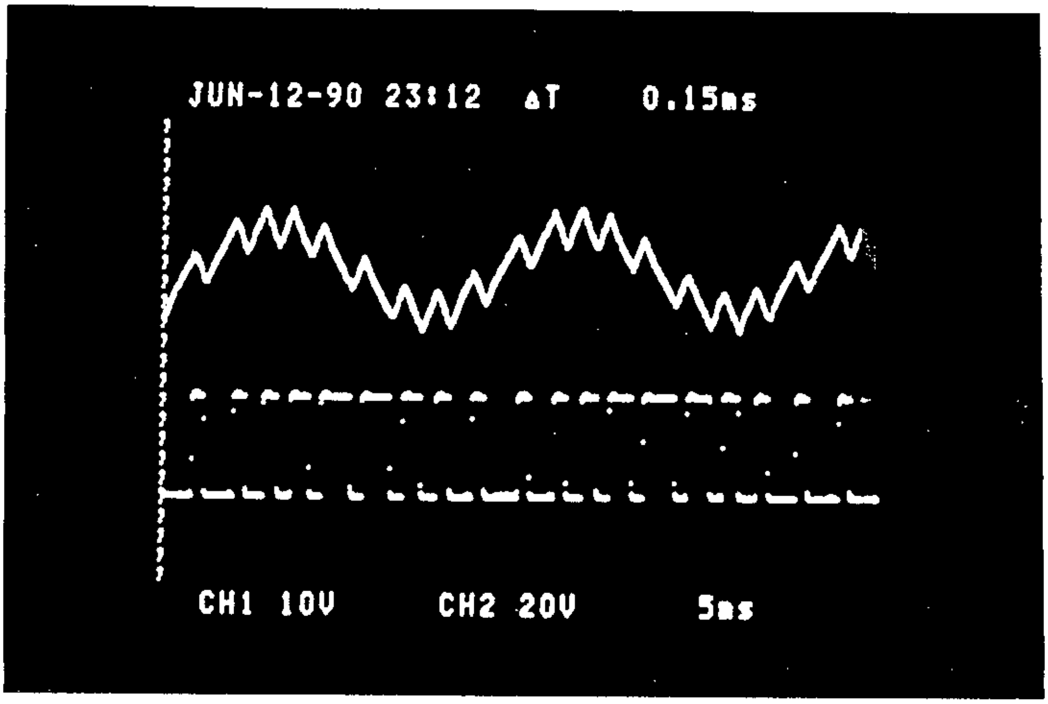


Fig. 4.4 (a)

40 Hz
S =2000 V/Sec
ΔV=3V

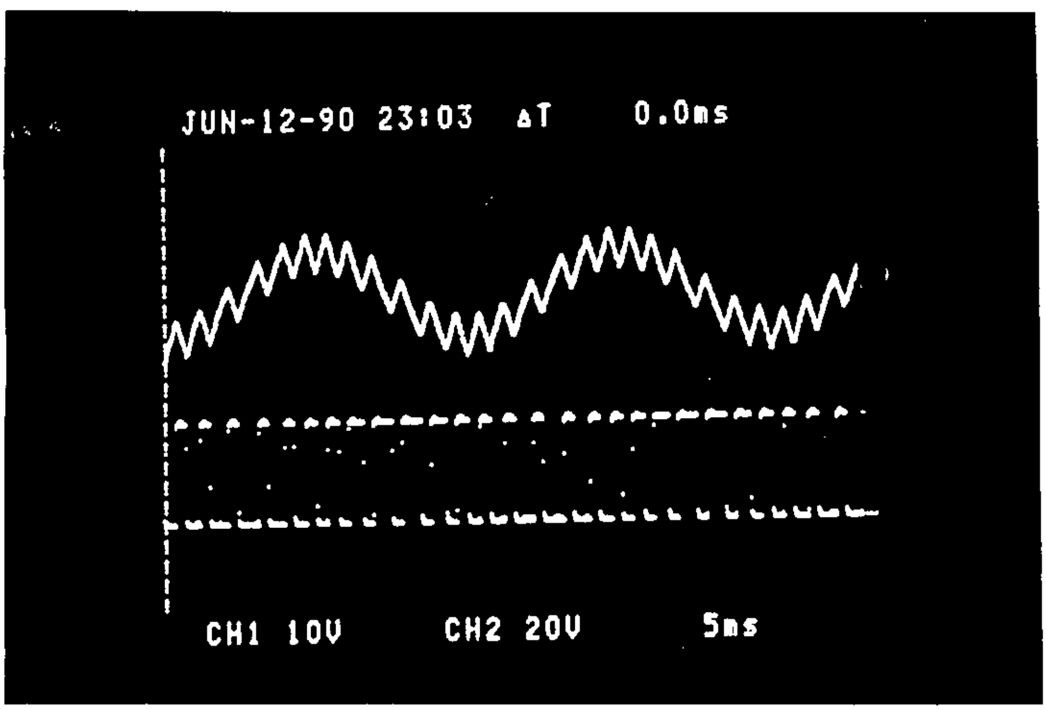


Fig. 4.4 (b)

40 Hz
S =4500V/Sec
ΔV=3V

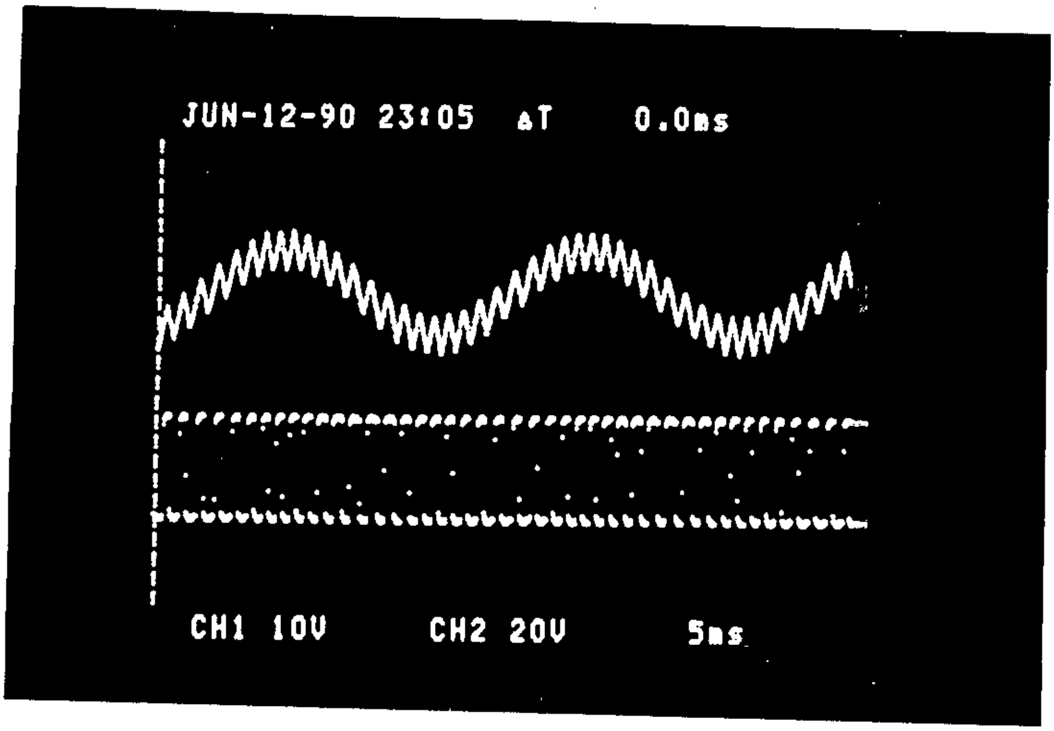


Fig. 4.4 (c)

40 Hz
S =6500 V/Sec
ΔV=3V

Fig. 4.4 Waveforms of tuned rwdm as the slope of the carrier wave is increased.

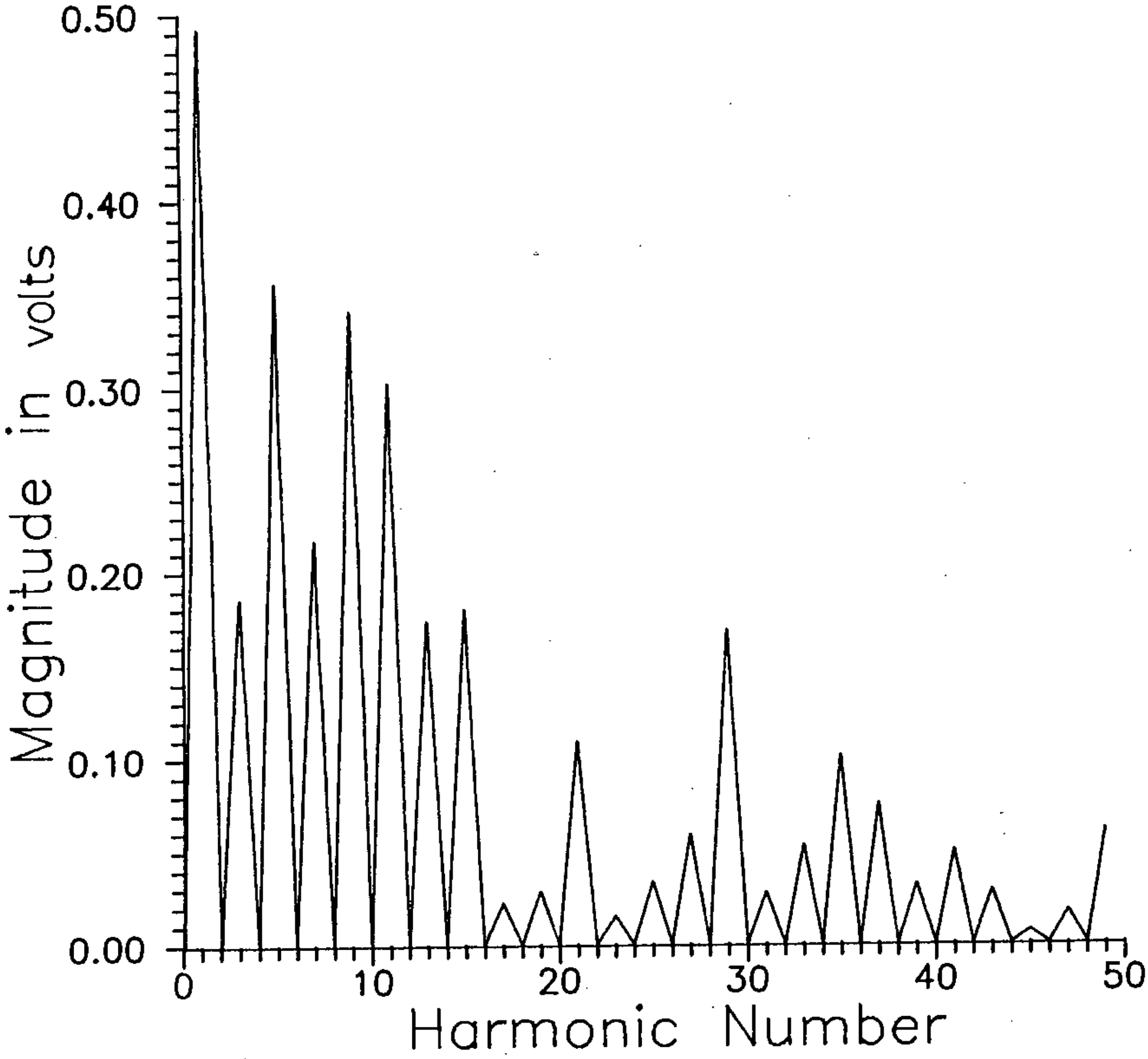


Fig. 4.5(a) Spectra of tuned rwdm waves of Fig. 4.4(b).
(Not normalized with respect to square wave fundamental, also magnitude of the modulated wave i s assumed to be ±1V).

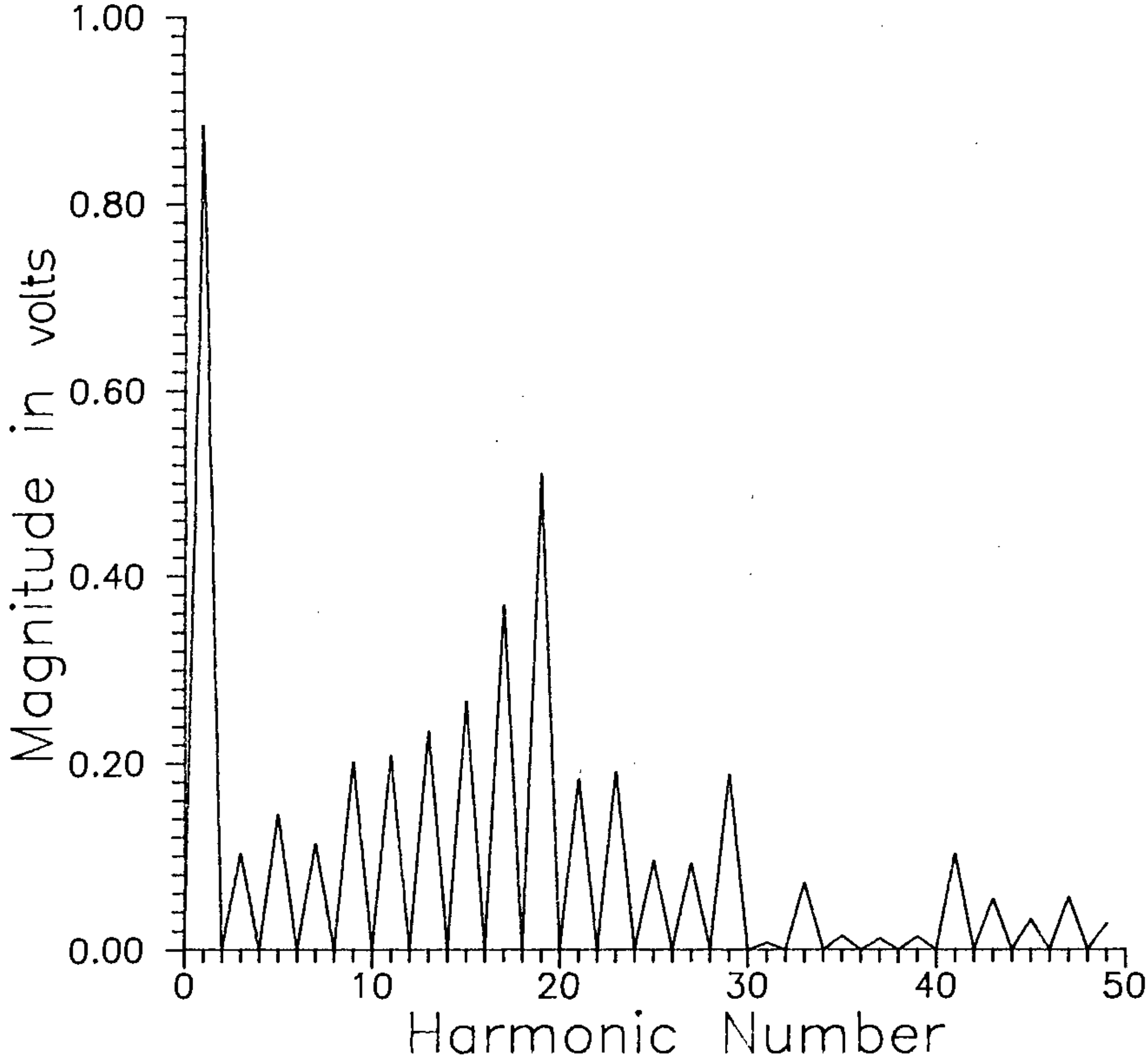


Fig. 4.5(b) Spectra of tuned rwdm waves of Fig. 4.4(c)

(Not normalized with respect to square wave fundamental, also magnitude of the modulated wave is assumed to be ±1V).

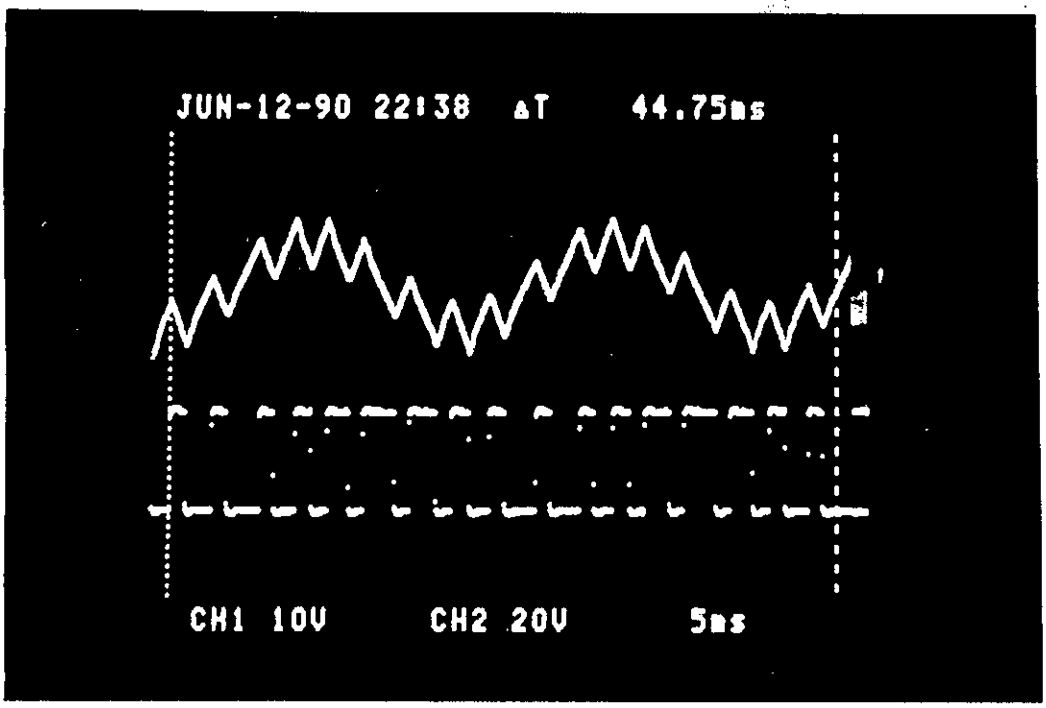


Fig. 4.6 (a)

40 Hz
ΔV=3V
S =2500V/Sec

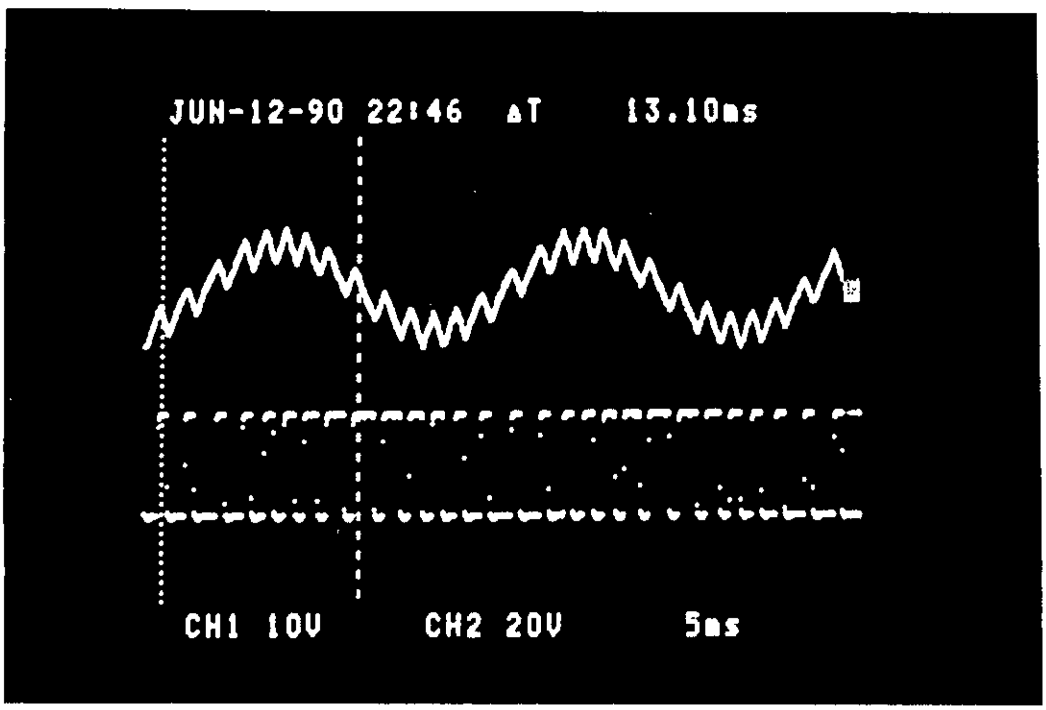
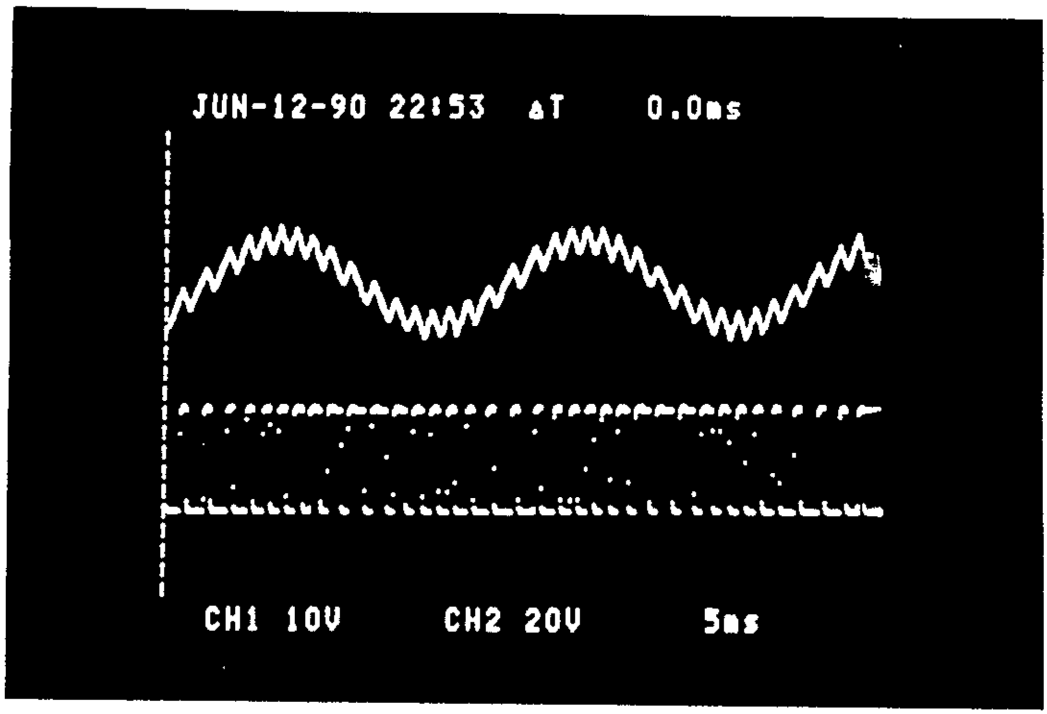


Fig. 4.6 (b)

40 Hz
ΔV=1.5V
S =2500 V/Sec.



40 Hz
$\triangle V=.75$
S =2500V/Sec

Fig. 4.6 (c)

Fig. 4.6 Waveforms of variable step rwdm as the window width is decreased.

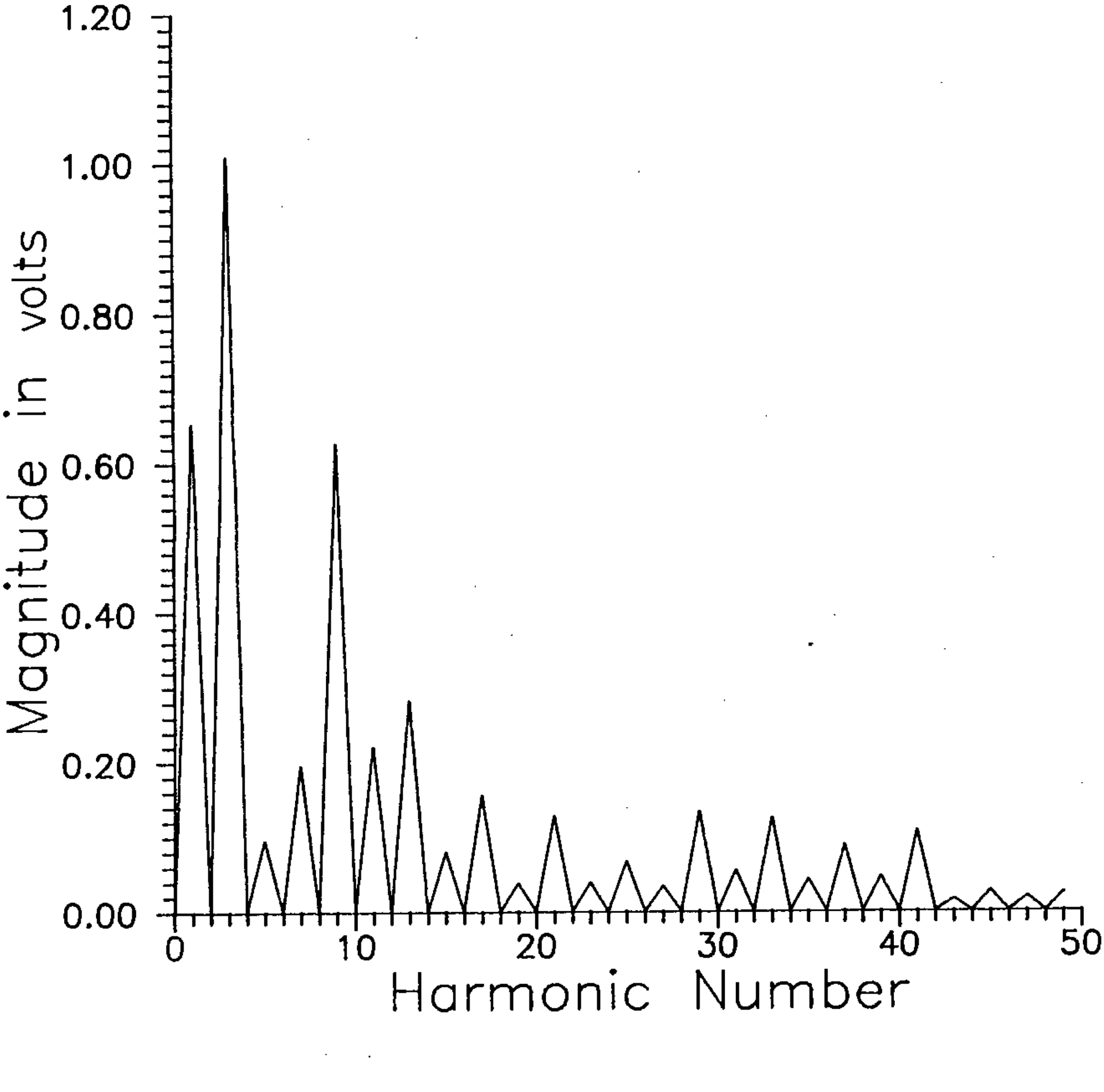


Fig. 4.7(a) Spectra of variable step rwdm waves of fig. 4.6(a)

(Not normalized with respect to square wave fundamental, also magnitude of the modulated wave is assumed to be ±1V).

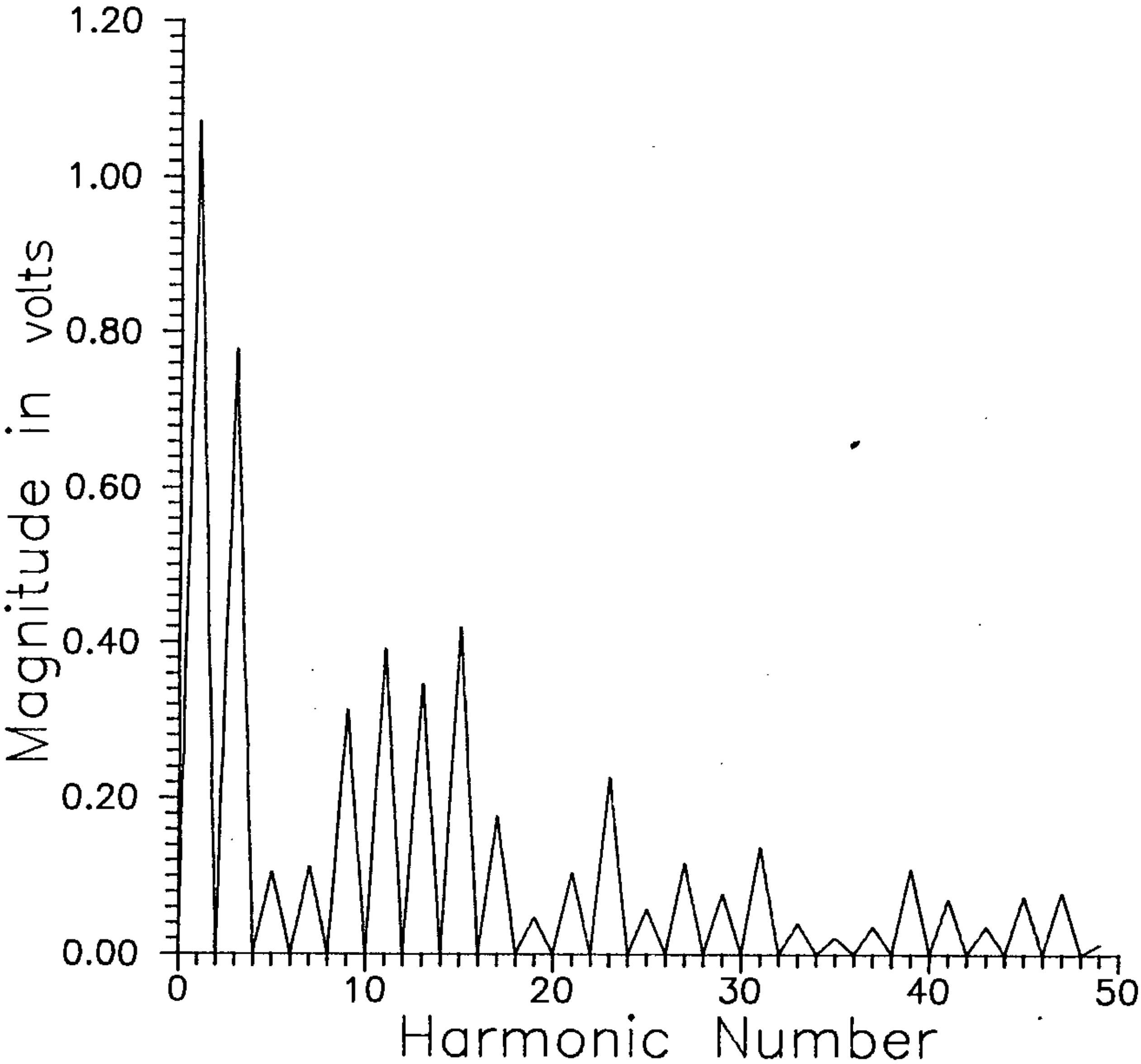


Fig. 4.7(b) Spectra of variable step rwdm waves of Fig. 4.6(b)
(not normalizdd with respect to square wave fundamental, also magnitude of the modulated wave is assumed to be ±1V).

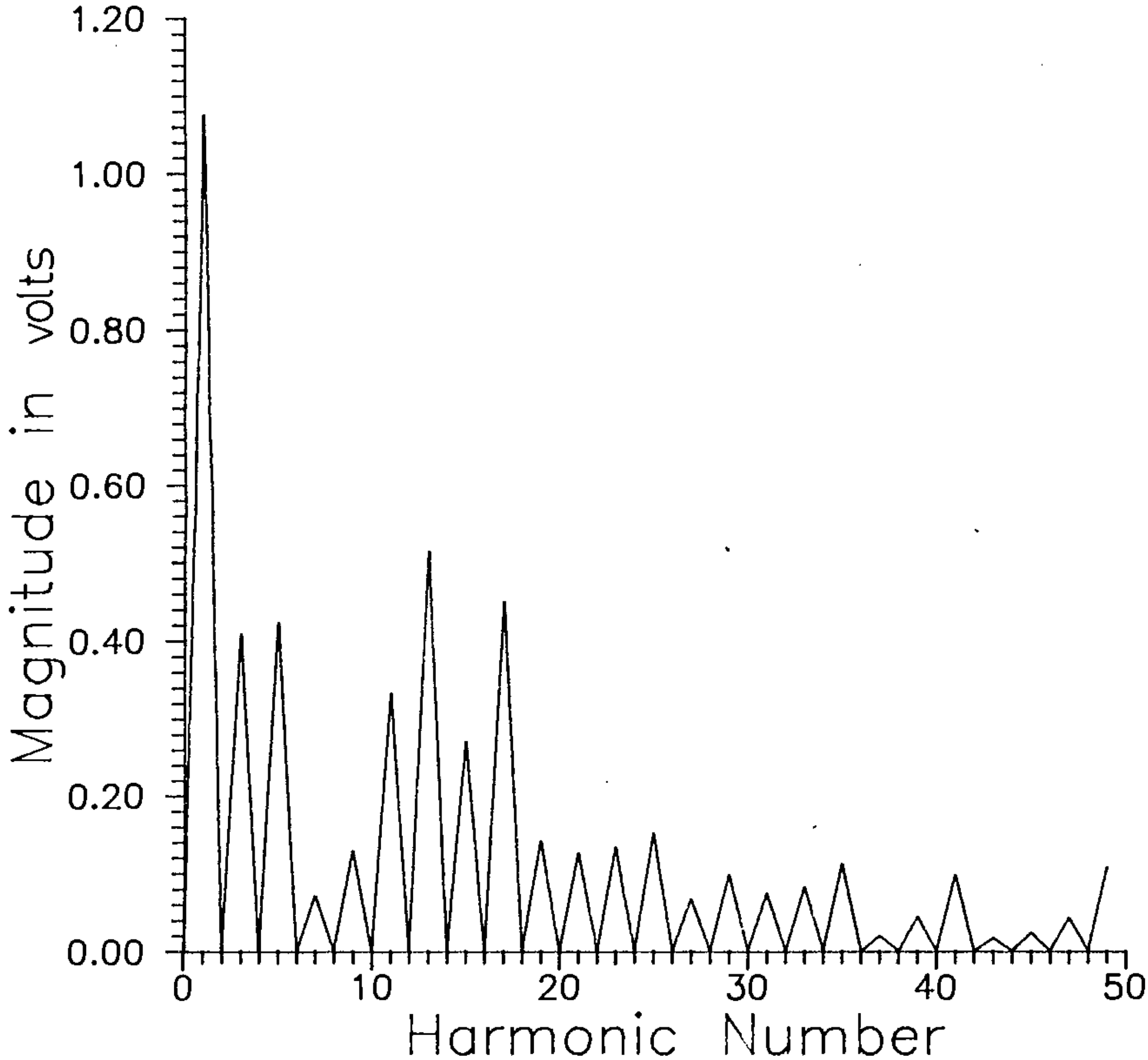


Fig. 4.7(c) Spectra of variable step rwdm waves of Fig. 4.6(c).

(Not normalized with respect to square wave fundamental, also magnitude of the modulated wave is assumed to be ±1V).

spectrums of the modulated waves of figs. 4.6. Here the experimental results follow the theoretical results. It is evident that as the window width ΔV is increased the number of switching points are increased and simultaneously the dominating harmonics are gradually shifted to higher frequency values i.e. to the the right.

4.4.2 Implementation of the Logic Circuits.

The basic control circuit used for delta modulation is shown in fig. 4.1. Before the output of the modulator circuit can be used for the inverter SCR operation, the signals are to be processed through the logic circuits to produce appropriate gating signals for the main and commutation thyristors. The timing diagram of the signals and logic diagram are shown in fig. 4.8 and 4.9 respectively. Details of the logic implementaion is shown in fig. 4.10.

4.5 Conclusions.

It is observed that the proposed method of variable step rwdm for optimizing the output waveform of the PWM inverter is practically simple and feasible to implement. Its different advatageous features and the theoretical results are varified practically.

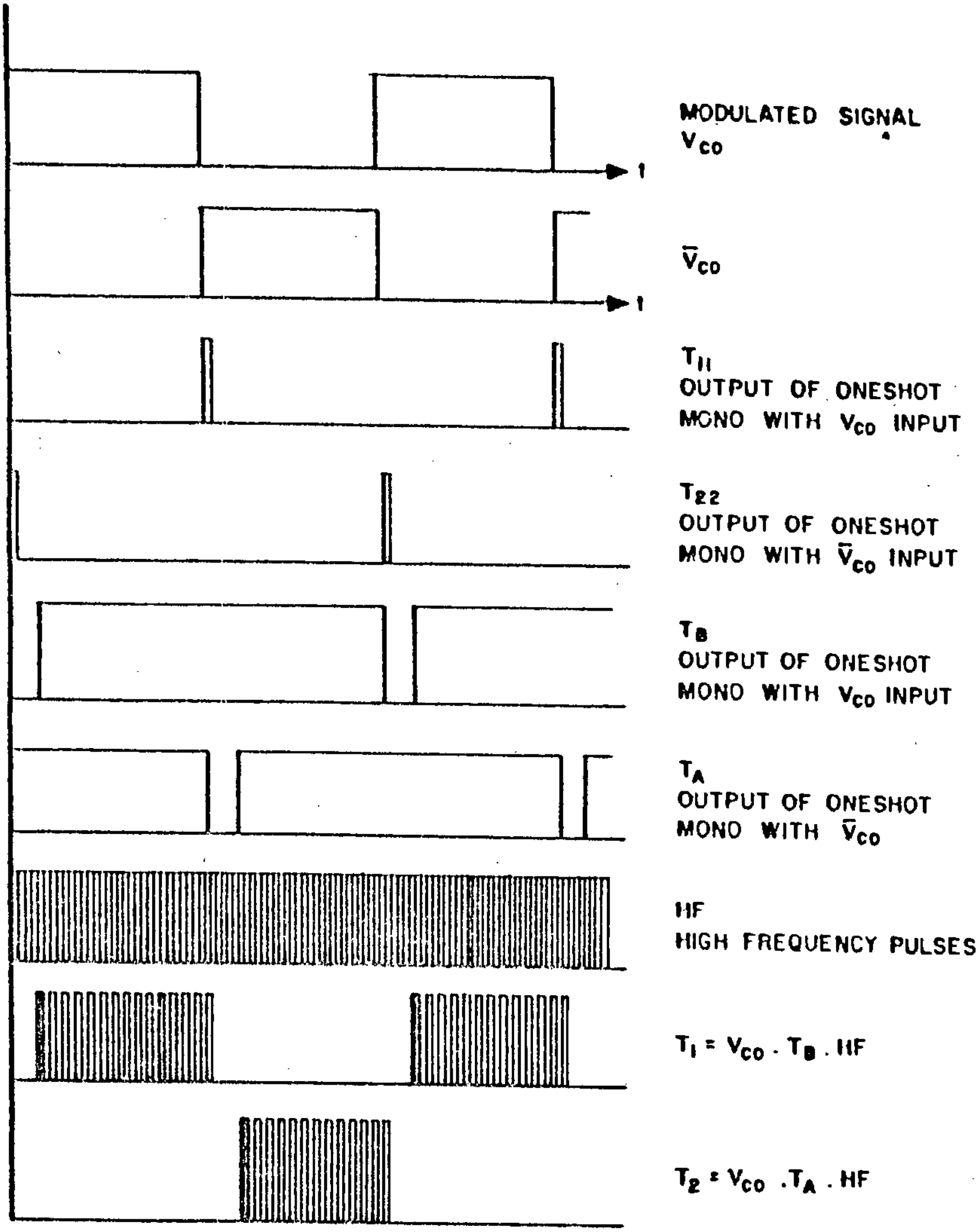


Fig. 4.8 Timing diagram of 1-phase delta modulated wave generation

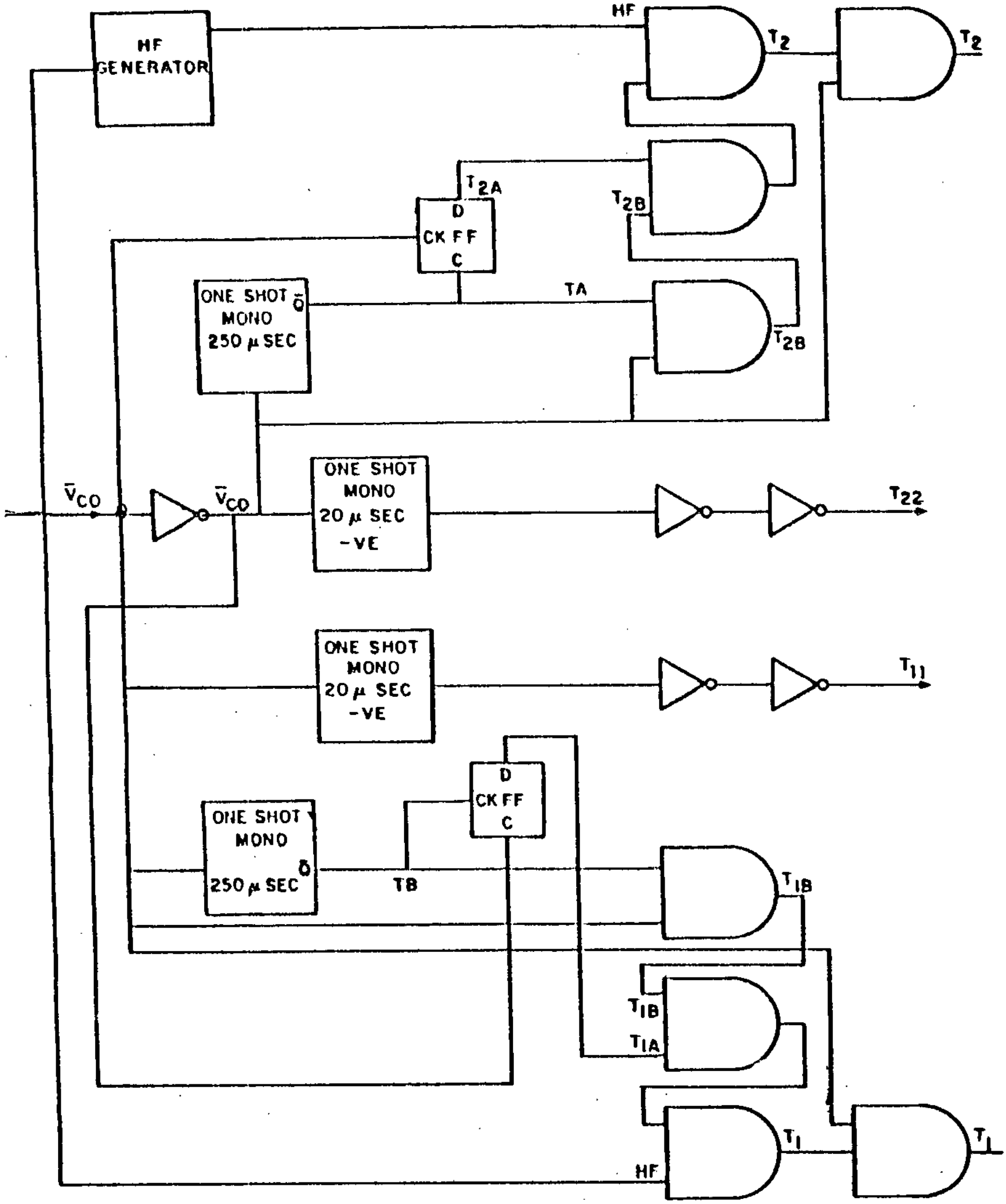


Fig. 4.9 Block diagram of logic circuit to produce the signals of the timing diagram for the switching signals of the single phase DM inverter

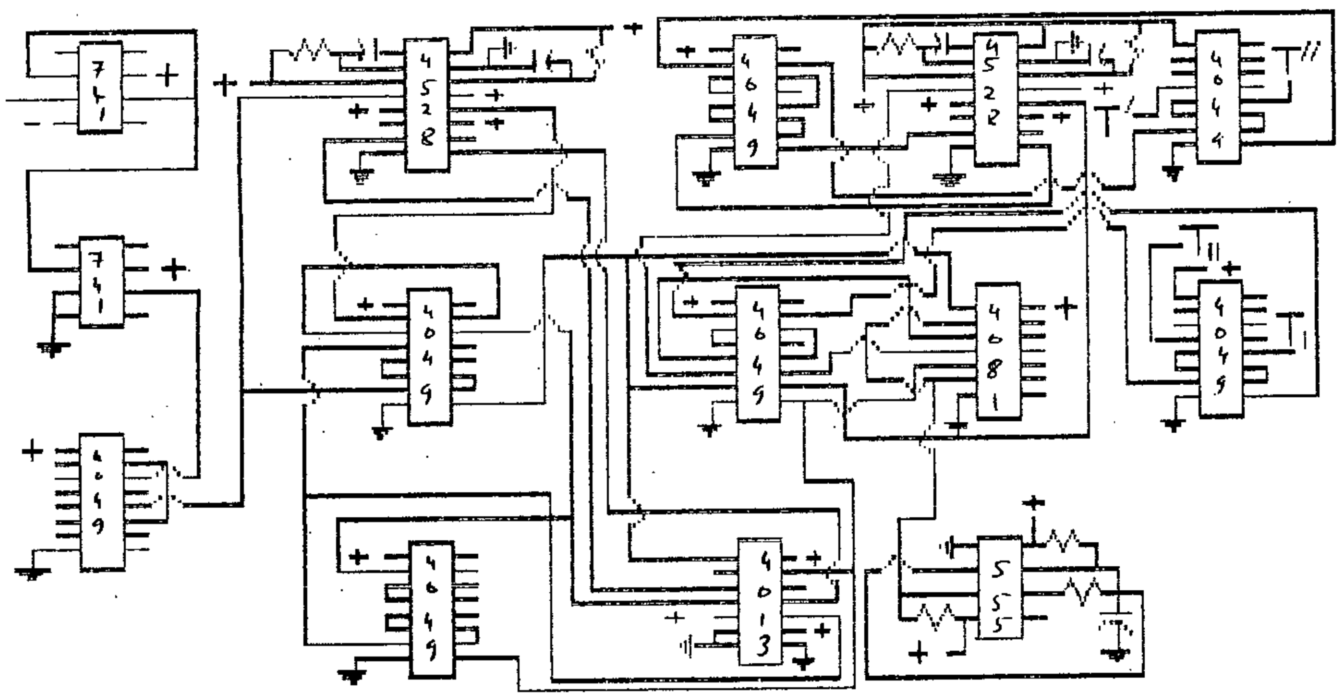


Fig. 4.10 Actual circuit connection for logic circuits producing gating signals of 1-phase bridge inverter.

741 - OP AMP

4049- HEX INVERTER

4013- DFF

4528- ONE SHOT MULTIVIBRATOR

4081- QUAD AND GATE

555 - TIMER

CHAPTER 5

Summary and Conclusion

The objectives established to investigate the use of the delta modulation technique for online optimization of inverter output waveforms were satisfactorily realized during this research. Different types of PWM techniques were examined and compared with the delta modulation technique. Delta modulation proved its supremacy for inverter waveform control over others. Further, the performances of three delta modulators were discussed and the rectangular wave delta modulator was selected for inverter switching. A novel method of on-line optimization of pulse width modulated waveforms using variable step rectangular wave delta modualtion has been proposed. Unlike conventional inverter waveform optimization techniques this method is suitable for easy online hardware implemention. Furthermore, variable step rwdm allowed the optimization criteria for inverter wave-forms to be changed easily.

The features of delta modulation, namely easy implementaion, lower harmonics at the output of the inverter, transition of v/f characteristics from multiple pulse mode to single pulse mode, easy harmonic and commutation control have been varified. A Fourier analysis was done for the delta modulated wave. It has been found in the study that the harmonic behavior of delta modulated inverters are such that at the inverter output, the harmonic voltages are high at low frequency operation and low at high frequency operation. However, at low frequency operation, the dominant harmonics are higher in orders and at high frequency operation, the dominant harmonics are low in order. As a consequence, when the DM inverters are used for R-L load or dynamic motor loads, higher harmonics in the load currents are attenuated. This is because the harmonic reactances for higher order harmonics at low frequency operation are high and for low order harmonics at high frequency operation are high. This high reactance value at different dominant harmonics limits the harmonic load current. The theoritical results of the harmonic behaviour of the rectangular wave delta modulated inverter output was verified experimentally.

Different features, performances and analysis of the rectangular wave delta modulator are studied in this thesis work. 'Tuned rectangular wave delta modulation' - the latest proposed scheme for on-line optimization of PWM inverter waveforms is examined. Its various features are compared theoretically and experimentally with that of proposed variable step rectangular wave delta modulation. It has been observed that during variable frequency operation when the slope of the carrier wave is changed to control the switching points and harmonics using tuned rwdm, fundamental voltage of the inverters reduce. With aim to overcome this effect, the new technique called the variable step rwdm is proposed. The method has the capability to maintain near constant fundamental voltage of output waveform of the inverters. This method controls the switching points and harmonics by changing the window width of modulated waveforms which is very easy for harmonic elimination during on-line operation.

Future work:.

The delta modulation technique has been employed in various power converter applications such as inverter controlled rectifiers and voltage controllers. The use of this technique has been reported for drives and for uninterruptible power supplies as well. Efforts are under way to implement this technique for various converters with computer generated switching waveforms. Micro computer generation of three phase switching waveforms of various power converters can be undertaken in future works.

In waveform optimization, only window width variation is examined in the present work and variation of slope was proposed before. Optimization using simultaneous variation of the slope of the carrier wave and the window width can be examined and implemented. The block diagram of this type of modulator is shown in fig. 5.1. Also the possibility of using switched capacitors filter in the modulators can be explored in the future works.

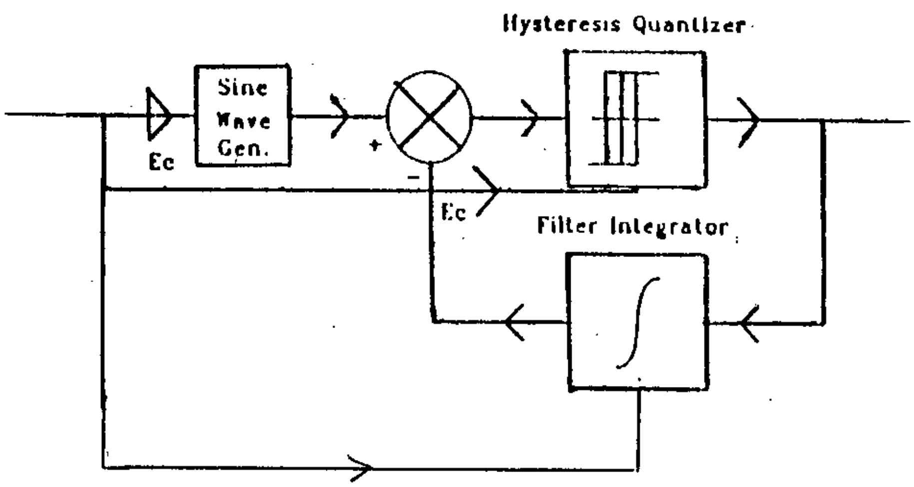


Fig. 5.1 Block diagram of the proposed tuned
+ variable step rwdm.

References

1. King, K.G., "Variable Frequency Thyristor Inverters for Induction Motor Speed Control", Direct Current, February 1965, pp. 125.

2. Kirnick, A., and Heinrich, "Static Inverter with Neutralization of Harmmonics", Trans. AIME, Vol. 81, May 1962, pp. 59-68.

3. Turnbull, F.G., "Selected Harmonic Reduction in Static DC-AC Inverters", Trans. AIEE, Vol. 83, July 1964, pp. 374-378.

4. Schonung, A., and Steimmler, H., "Static Frequency Changer with Subharmonic Control in Conjunction with Reversible Speed AC Drives", Brown Boveri Review, Aug/Sept. pp. 557-577.

5. Mokrytzki, B., "Pulse Width Modulated Inverters for AC Motor Drives", IEEE Trans. on IA, Vol. IGA - 3, Nov./Dec. 1967, pp. 493-503.

6. Adams, R.D. and Fox, R., "Several Modulation Technique for PWM Inverters", IEEE Trans. on IA Vol. 3, No. 5, Sept./Oct. 1972. pp. 636-643

7. Bowes, S.R., "New Sinusoidal Pulse Modulated Inverter". Proc. of IEE, Vol. 122, No.11, 1975, pp. 1279-1285.

8. Bowes, S.R. and Mount, M.J., "Micropocessor Control of PWM Inverters", IEE Proc. pt-B, Vol. 128, 1981, pp. 293-305.

9. Grant, D.A. and Seidner, R., "Ratio Changing in Pulse Width Modulated Inverters", IEE Proc., Vol. 128, 1981, pt. B, No. 5, Sept. 1981. pp. 243-248.

10. Bowes, S.R. and Clements, R.R., "Microporcessor Based PWM Inverters", IEE Proc., Vol. 129, pt. B, No. 1, Jan. 1982. pp. 1- 17.

11. Cook, B.J., Cantoni, A. an Evans, R.J., "A Microprocessor Based, 3-Phase Pulse Width Modulator, IEEE Ch. 1682-4/82/000- 0375, 1982, pp. 375-383.

12. Bowes, S.R. and Clarke, J.C., "PWM Inverter Drives", IEE Proc., Vol. 130, pt. B, No. 4, July 1983, pp. 229-240.

13. Zubeak, J. Abbondanti, A., Nordby, C.J., "Pulse Width Modulated Inverter Motor Drives with Improved Modulation", IEEE Trans. on IA, IA-11, No. 6, 1975, pp. 695-703.

14. Patel, H.S. and Hoft, R.G., "Generalized Technique of Harmonic Elimination on Voltage Control in Thyristor Inverter", Part-1, IEEE Trans. on IA, IA-10, 1974, pp. 310-317.

15. Patel, H.S. and Hoft, R.G., "Generalized Technique of Harmonic Elimination on Voltage Control in Thyristor Inverter", Part-II, IEEE Trans. on IA, IA-10, 1974, pp. 666-673.

16. Buja, G.S. and Indri, G.B., "Optimal Pulse Width Modulation for Feeding AC Motors", IEEE Trans. on IA, IA-13, 1977, pp. 38- 44.

17. Nonaka, S. and Okada, H., "Methods to control Pulse Width of Three Pulse Inverters", Journal of IEE Japan, Vol. 86, July 1972, pp.71-79.

18. Buja, G.S., "Optimum Output Waveforms in PWM Inverters", IEEE Trans. on IA, Vol. IA-16, No. 6, Nov./Dec. 1981, pp. 830-836.

19. Dewan, S.B. and Forsythe, S.B., "Harmonic Analysis of a Synchronized Pulse Width Modulated 3 Phase Inverter", IEEE Trans. on IA, Vol. IA-10, Jan./Feb. 1974, pp. 117-122.

20. Huang, I.B. and Lin, W.S., "Harmonic Reduction in Inverters by Use of Sinusoidal Pulse Width Modulation", IEE Trans. on Control Instrumentation, Vol. IECI-27, No.3, Aug/1982, pp. 201- 207.

21. Bowes, S.R. and Bird, B.M., "Novel Approach to Analysis of Modulation Processes in Power Converters", Proc. IEE, Vol. 122, No.5, May 1975.

22. Ziogas, P.D. and Photiadis, P.N.D.., "An Exact Input Current Analysis of Ideal Static PWM Inverters", IEEE Trans. on IA, Vol. IA-19, No.2, March/April 1983, p.281-295.

23. Ziogas, P.D., "The Delta Modulation Technique in Static PWM Inverters", IEEE Trans. on IA, March/April 1981, pp. 199-204.

24. Murphy, J.M.D., "Thyristor Control of AC Motors", Pergamon Press, 1973.

25. Steele, R., "Delta modulation systems', Halsted Press, John Wiley and Sons, 1975.

26. De Jager, F., 'Delta modulation - a new method of pcm transmission using the 1 unit code'., Philips research report, no.7, Dece., 1952, pp.442-446.

27. Vande weg, N., 'Quantization noise of a single integration delta modulation system with an N-digit code.', Philips research,Oct., 1953, pp. 367-385.

28. Schindler, H.R., 'Delta modulation.', IEEE Spectrum, Oct., 1970, pp. 69-78.

29. Greefkes, J.A. and De Jager, F., 'Continuous delta modulation', Philips research report, no.23, 1968, pp. 233-246.

30. Goodman, D.J., 'The application of delta modulation.', Philips research report, no. 23,1969, pp. 321-342.

31. Steele,R and Thomas, M.W.S., 'Two transistor delta modulator', Electronic Engineering, no. 40, 1968, pp. 513-516.

32. Steele, R., 'Pulse delta modulators-inferior performance but simpler circuitry.', Electronic Engineering, no.42,1970, pp. 55- 79.

33. Nielson, P.T., 'On the stability of double integrator delta modulation.',IEEE trans. on communication technology, June, 1971, pp. 364-366.

34. Johnson, F.B., 'Calculating delta modulator performance.', IEEE trans. on AU, vol.AU-16, 1968, pp. 122-129.

35. Slepain, D., 'On delta modulation.', Bell system technical journal, vol.51, Dec., 1971, no.10, pp. 2101-2137.

36. Jayant, N.S. and Noll, P., 'Digital coding of waveforms.',Prentice Hall, 1984, pp. 399-415.

37. Abat, J.E., 'Linear and adaptive delta modulation.', Proc.IEEE, vol.55, no.3,March, 1967, pp.298-307.

38. Cartmate,A.A. and Steele, R., 'Calculating the performance of syllabically companded delta-sigma modulators.', Proce.IEEE, 1970, pp. 1915-1921.

39. Sharma, P.D., 'Characteristics of asynchronous delta modulation and binary slope quantization pcm systems.', Electronic Engineering, Jan., 1968, pp. 33-37.

40. Sharma, P.D.,'Signal characteristics of rectangular wave modulation.', Electronic Engineering, vol.40,Feb.,1968, pp. 103- 107.

41. Das,J and Sharma, P.D., 'Some asynchronous pulse modulation systems.', Electronic Letters, vol.3,no.6,June,1967, pp. 75-79.

42. Steele,R and Stevens,P., 'An automatic digital trace encoder for polaroid photographs.' Electronic Engineering,September,1973, pp. 80-85.

43. Dempster,I.A. and Steele,R., 'Delta sigma wattmeter.',Electronics letters,7,no-18,September 9,1971, pp. 519- 520.

44. Kikkert, C.J., 'Digital techniques in delta modulation', IEEE trans. on com.Tech., vol-19,August,1971, pp. 570-573.

45. Lockhart,G.B., 'Digital encoding and filtering using delta modulation', Radio and Electronic Engineering,vol.42,no- 12,December, 1972, pp. 547-551.

46. Creighton,G.K. and Steele, R., 'Source frequency adjustement controls motor speed',Electronic Engineering,May,1973, pp. 70-71.

47. Choudhury,M.A., 'An analysis of delta PWM inverters ',- M.Engg thesis, Faculty of Engg. and Applied Science, Memorial University of Newfoundland, St.John's,Canada,1984.

48. M.A.Rahman, J.E. Quaicoe and M.A. Choudhury, 'An optimum delta modulation strategy for invertor operation', IEEE PESE conference record, Vancouver, B.C. 1986, pp. 410-416.

49. M.A. Rahman, J.E. 'Quaicoe and M.A. Choudhury', 'Harmonic minimization in delta modulated inverters using tuned filters.' IEEEPESC confernce record, Tokyo, Japan, 1988, pp. 462-464.

50. Yu J. Wong and W.E. OH.,'Function circuits.', McGraw Hill, 1976, pp. 264.

51. M.A. Rahman, J.E. Quaicoe and M.A. Chowdhury, 'Performance analysis of dm pwm inverters.', IEEE trans. on PE, vol. PE-2, no. 3, July 1987, pp. 227-233.

52. Muhammad Harunur Rashid, 'POWER ELECTRONICS, Circuits, Devices and Applications', Prentice Hall, pp. 226-279.