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AN ANALYSIS OF DELTA MODULATED INVERTER FOR UNINTERRUPTABLE POWER SUPPLIES

BY

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ABSTRACT

Uninterruptible Power Supply (UPS) is a device for supplying electrical energy to the appliances connected to it during the failure of utility electric supply. The main component of an UPS is the inverter. Inverters are devices used for conversion of dc to ac electrical energy. The simplest inverters take dc in their inputs and produce square wave at their outputs of arbitrary phase and frequency . 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) schemes are being used in inverter control. One of the commonly used PWM technique in inverter control is the sine PWM. Inverters have many uses in drives, uninterruptible power supplies (UPS), dc link for high voltage dc (HVDC) transmission, and induction heating etc. One of the main disadvantage of inverters is the presence of harmonics at the output. It has been a constant effort of researchers to reduce the harmonics to desired level and hence minimize the filter requirements at the output.

Recent studies showed that delta modulation (DM) 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. The delta modulation switching strategy provides low harmonics and easy control of output volts. For UPS system rectangular wave delta modulator can successfully be used for harmonics reduction at the output to reduce the filter size. In this thesis an attempt has been under-taken to analyze the performance of this newly proposed modulator with respect to inverter operation for an UPS. It has been shown both analytically and experimentally that the proposed modulator has significant improvement in the performance interms of harmonic minimization then those reported earlier.

CONTENTS

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LIST OF SYMBOLS

A_n = Fourier coefficients

B_n = Fourier coefficients

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 the 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 = nw 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
RWDM	Rectangular wave delta modulation
SCR	Silicon controlled rectifier
SPWM	Sine pulse width modulation
UPS	Uninterruptible power supply
VLSI	Very large scale integration
sgn	signum function

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CHAPTER - 1

1.1 Introduction:

Growing automation in industries, offices and commercial organizations has put great emphasis on power supply reliability. Uninterruptible power supplies (UPS) for computers, telephone switching systems and other critical types of equipments are typically fed from rectifier - inverters. In such a system, the inverter is the most sensitive component. The output of the inverter being non-sinusoidal, it is desired that unwanted harmonics be kept at minimum level. Various PWM techniques are in use both in UPS and in inverters for other applications so as to obtain near sinusoidal output voltage at the inverter output [1 2 3 4 5]. Delta Modulated (DM) PWM technique has recently been used for inverter switching [6]. The technique is tested in a UPS system for gating the inverter switches. Figure 1.1 shows a block diagram for an UPS system. The figure shows that an UPS system consist mainly of the following components

1) Step down transformer
2) Rectifier
3) Filter + storage device and charge controller.
4) Inverter
5) Filter
6) Step up transformer

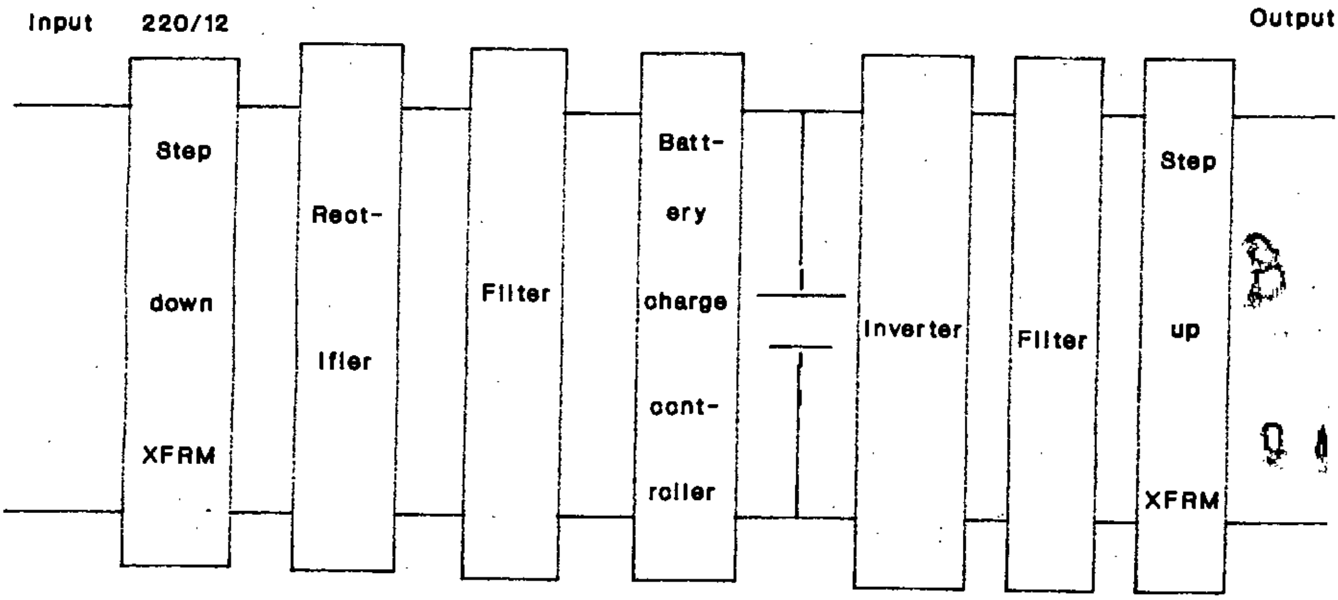


Figure 1.1 Basic block diagram of an UPS.

The function of the transformers are to step down and step up voltage levels. The rectifier at the front end converts ac input to dc and the inverter converts dc to ac to supply the load. In between, the battery provides the storage for the electrical energy which supply the load in case of sudden power interruption of the main ac line. Input side filter is used for coverting rippled dc to pure dc and the output side filter is used for obtaining pure sinusoidal output at the load.

It is apparent that the main objectives of an UPS system are achieved largely through storage device(battery), the inverter and the filter. It has been a constant effort of researchers to reduce the size of the main components of an UPS by reducing the sizes of inverter and filter. For this various modulation schemes have so far been used. In this work DM swithing strategy is proposed for an UPS inverter operation. The advantages of using DM technique for switching UPS are minimization of undesired low frequency harmonics from inverter output[7]. A limitation of low frequency harmonics reduces the size of the filter at the inverter output. The proposed delta modulation technique [6] is relatively quite easy to implement. Delta modulation(DM) technique leads to inherent voltage /frequency control and attenuation of low order harmonics at the output of the inverter[8]. These inherent characteristics are obtained as a result of the modulation process without any complex circuitry as required for other pulse width modulated inverters[8]. Besides inverter side of the UPS, the filter selection and its minimization due the PWM technique has been studied in brief in this thesis. A comparison has been carried out to see how much reduction of filter can be achieved by the use of DM techniqe than its counter part square wave inverter linked UPS system. Also simple design and implementation steps have been carried out for a battery charger with overvoltage protection and low-battery voltage isolator. All the results are substantiated by practical results as far as possible with the available equipments at the laboratory.

1.2 Objective of the thesis:

The objective of this study is the application of the delta modulated inverter for UPS system. Delta modulation is the simplest known method for converting analog signals to digital ones with minimum hardwares components. Sinusoidal pulse width modulation(SPWM) is one of the most commonly used modulation techniques in static inverters. The implementation of the SPWM switching strategies for inverters varies according to the needs of control, optimization, harmonic reduction and implementational involvements. The primary objective of most switching strategy is to provide low harmonics, low number of commutations and easy control of the inverter output voltage. The delta modulated (DM) switching strategy provides most of these features without much implementational complexities as required in those of SPWM swithing strategies. For UPS the switching of inverter switches are to be kept very low which can be attained by the DM switching technique. The number of commutation can be controlled in the DM switching strategy without any component change in the logic network. This can be done by variation of modulating sine wave signal level. In this study the operational characteristics of different delta modulators were studied to faciliate the choice of the type of modulator. The study of the selection criteria was concentrated mainly on the three simplest delta modulators and rectangular wave delta modulation technique was selected for inverter switching. The characteristics of the rectangular wave delta modulated waveforms were analyzed to find the performances of the modulator and the inverter. The harmonic contents of the modulated waveform can be controlled through variation of several parameters in rectangular wave delta modulator during on-line operation. Some of these are 1) magnitude of the input wave II) the window width and III) the slope of the carrier wave.

This thesis adopts a noble technique of optimization of the output waveform of the inverters during operation by controlling the window width i,e the width of the hystersis band and also the slope of the carrier wave of the rectangular wave delta modulator. But these parameters were individually controlled in previously reported works.Practically it has been proved that the size of the filter required in delta modulation technique is much less than as required in that of ordinary square wave inverters as used in the commonly used UPS system in Bangladesh.

1.3 Outline of the thesis:

The choice of modulator for the UPS is made on the basis of requirements. The operational characteristics of different delta modulators were studied to facilitate the choice of the type of modulator.The study of selection criteria was concentrated mainly on the three simplest delta modulators and the results of the study are presented in chapter 2. The rectangular wave delta modulation technique was selected for inverter switching. In chapter 3 characteristics of the rectangular wave delta modulated waveforms were analyzed to find the performances of the modulator and inverter. For the waveform analysis the discrete Fourier Transforms were used. Chapter 4 is concerned with studying a practical uninterruptible power supply. In this chapter the circuit diagrams of a UPS and also inverter circuits are studied. Also the circuit diagram of over-voltage breaker and low-voltage cut off unit are presented in this chapter. A hypothetical analysis on filter sizes for delta modulated inverter and square wave inverter are also carried out. Finally conclusion of this thesis are summarized in chapter 5 together with recommendations for future works.

CHAPTER - 2

DELTA MODULATION TECHNIQUE

2.1 Introduction:

The objectives of this chapter are to describe several delta modulation systems, their important characteristics as well as their limitations with regard to inverter operation. At present, there are different 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 adopted are restricted to the simpler ones. A brief review of delta modulation technique is presented in this chapter. Selection criteria of the modulator for inverter switching are discussed. Characteristics of three modulators are studied. These are the linear, the sigma and the rectangular wave delta modulator. Based on this study, the rectangular wave delta modulator (RWDM) has been chosen for the inverter switching for uninterruptible power supplies.

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

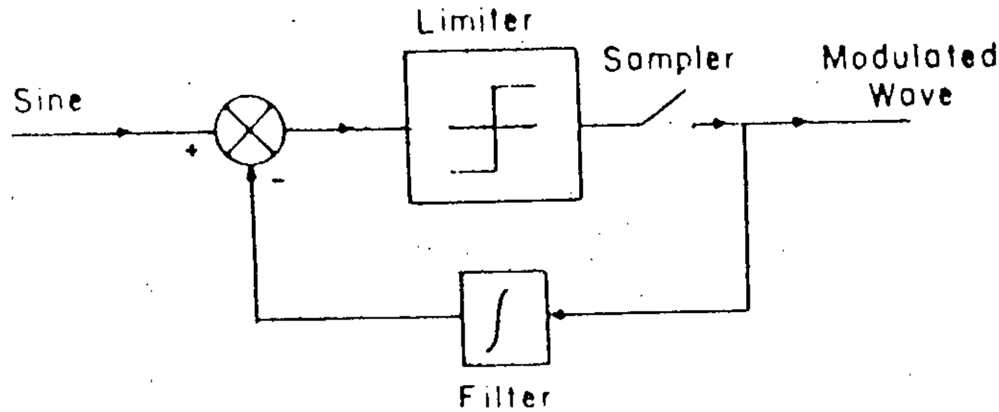


Figure 2.1 The block diagram of a simple delta modulator.

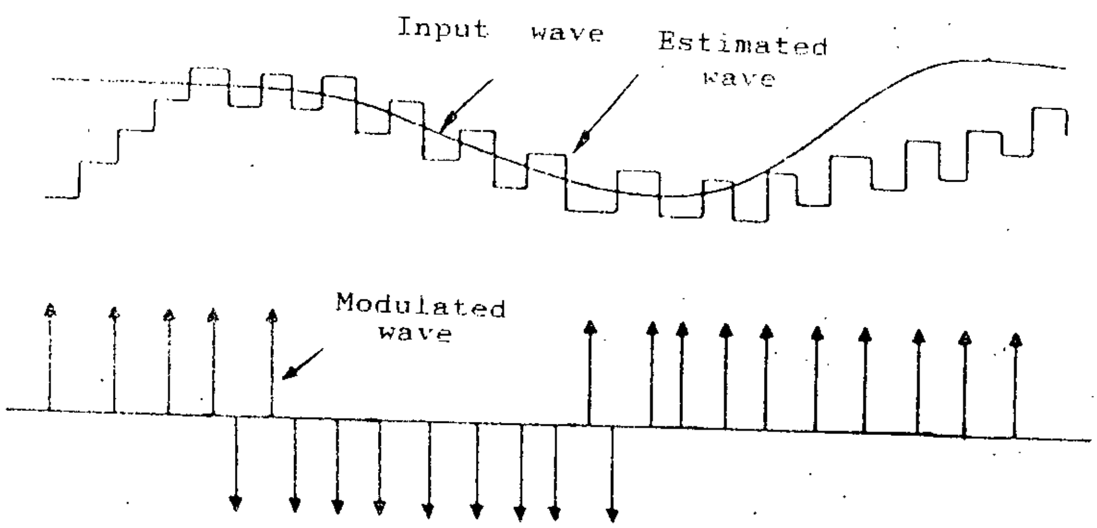


Figure 2.2 Waveforms of the simple delta modulator.

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

For modulator with sampler:

$$e(KTs) = x(KTs) - \bar{x}(KTs) \qquad (2.4)$$

$$m(t) = V_D \text{ Sgn } [x(KTs) - \bar{x}(KTs)]\ \delta\ (t-KTs) \qquad (2.5)$$

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

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 feedback and integrated that impluse produces a step wise change in e(t). As the signal x(t) remains constant, $\bar{x}(t)$ follows it in step 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 ΔV is too small to track a rapidly changing signal. Slope overload occurs due to the modulator's inability to track large chages 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 quantizer instead of two level quantization. Functionally, DPCM signal is a pulse code modulated (PCM) representation of the difference signal $[x(t) - \bar{x}(t)]$. Signal $\bar{x}(t)$ follows signal $x(t)$ 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 communication.

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 [10,11]. The linear delta modulation 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 qunatized 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 modulation is known as a linear modulation 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[12]. Delta modulation remained an interesting field for theoretical studies in communication systems for decades. This situation began to change when more refinements were suggested [13] 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 [14,15,16]. The simplicity of delta modulation has inspired numerous refinements and variations since its basic invention in 1946 by De loraine and Derjavgotch [12]. 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 integrator (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 [17]. Some investigators replaced the integrator or the feedback loop with RC network to introduce the concept of exponential delta modulators [18]. In order to suit the technique for uncorrelated signals, sigma delta was introduced in 1962 [19,20]. In the initial sigma delta modulation, 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 reseracherssuggested an adaptive delta modulation(ADM) scheme [20,21]. In adative delta modultation 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 DM and asychronous DM technique [22,23]. 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 modualtion system has digital output quantized in amplitude but not in time. The rectangular wave delta modualtion (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 controller. Also, samplers of ordinary modulators are permanently closed. This form of delta modulation was first reported by Sharma [24,25].

In addition to the modulators already mentioned there are various other delta modulators which have been sporadically suggested by different researchers[12]. Nonetheless, their operations are basically similar to the modulators already discussed.

2.4 Delta Modulation Scheme for Inverter Fed UPS System:

Inverters are functionally power amplifiers used for the frequency and voltage control of the supply to the device. Inverters are used typically in drive systems to provide power for adjustable frequency a.c. motors, to regenerate energy back to a.c. line from deccelerating d.c. motors and to pump rotor power back to the a.c. line from wound rotor induction motors. In non-drive systems, these are used to supply uninterruptable a.c. power to computers and to convert energy from a.c. to d.c. at the terminal of high frequency links between utilities and in high frequency induction heating. Application of DM-PWM technique for switching of the control rectifier and the inverter in an UPS system has several advantages interms of performance of total system. The technique improves the rectifier input current waveshape, input power factor, displacement factor, harmonic factor and attenuates the low order harmonics as a results of multiple pulse width modulation process. All these are achieved through easy implementation process than the other PWM techniques.

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 generating such switching logic utilizes a sine reference waveform and astepped 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 width of the switching pulses. The key waveforms associated with this technique are shown in Figs2.3(a) and 2.3(b). The switching waveform oscillates between $\pm V_S$ and can be expressed as

$$V_I(t) = V_S \ \mathrm{sgn}[x(kT_S) - \overline{x}(kT_S)] \qquad (2.7)$$

and bounded by ΔV.

where,

ΔV = quantization level

V_S = level of switching pulses

$x(kT_S)$ = sine(kT_S) = modulating signal in this case at kT_S

$\overline{x}(kT_S)$ = Predicted signal at kT_S

T_S = sampling time

In implementing the DM technique to produce the necessary

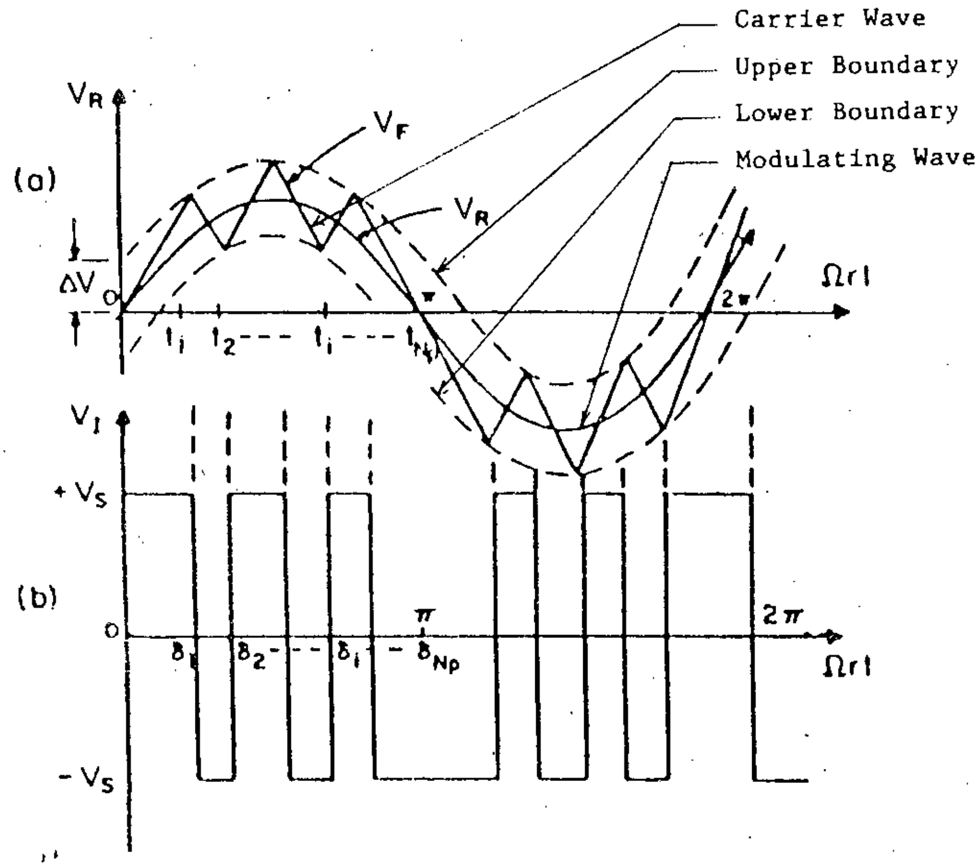


Figure 2.3 Graphical illustration of DM technique for inverters.

switching function for inverters, the switching pulses are generated by the interaction of reference sine wave and stepped triangular carrier 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 wave or by changing the window widths(quantization level) ΔV. Thus it is important to set these values such that sufficent 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 Figs2.3(b) and 2.4 illustrated the basic single phase full bridge inverter circuit.

2.5 Characteristics of Three Simple Delta Modulators:

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

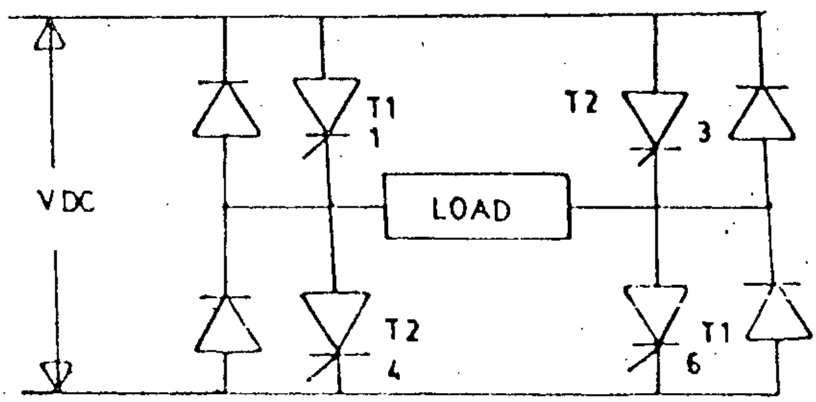
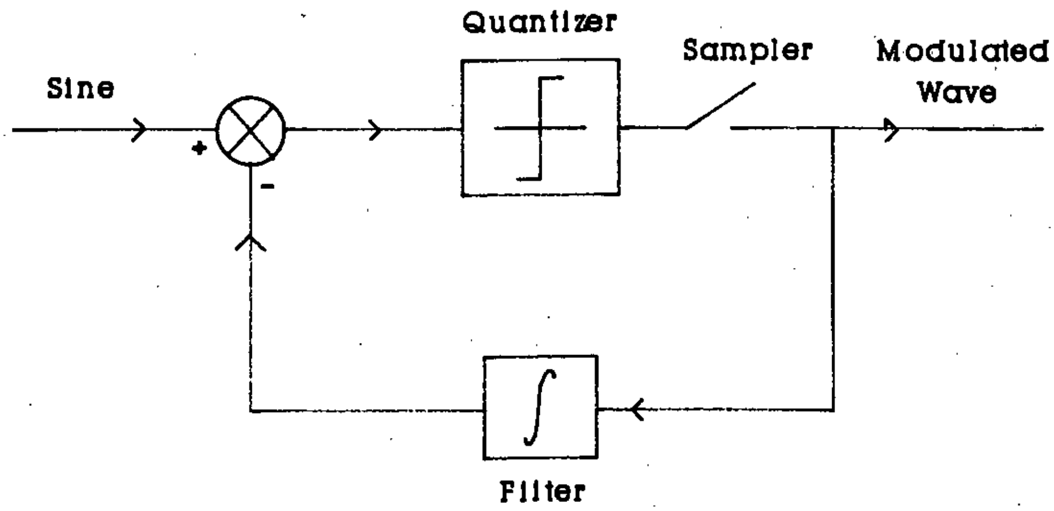
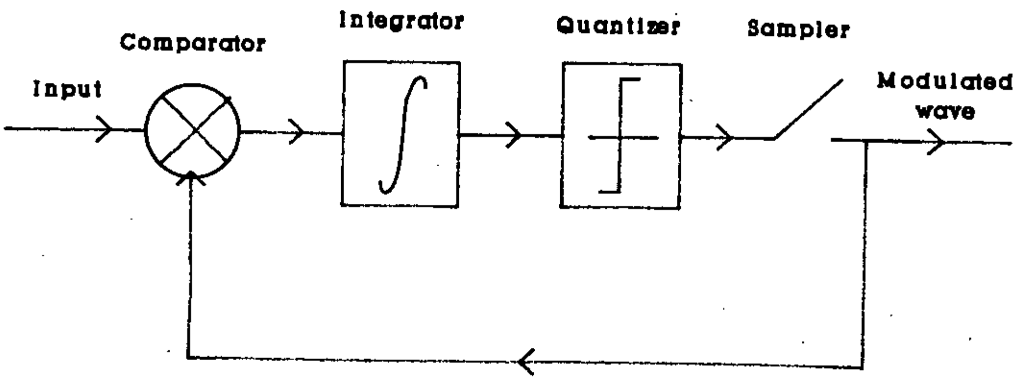


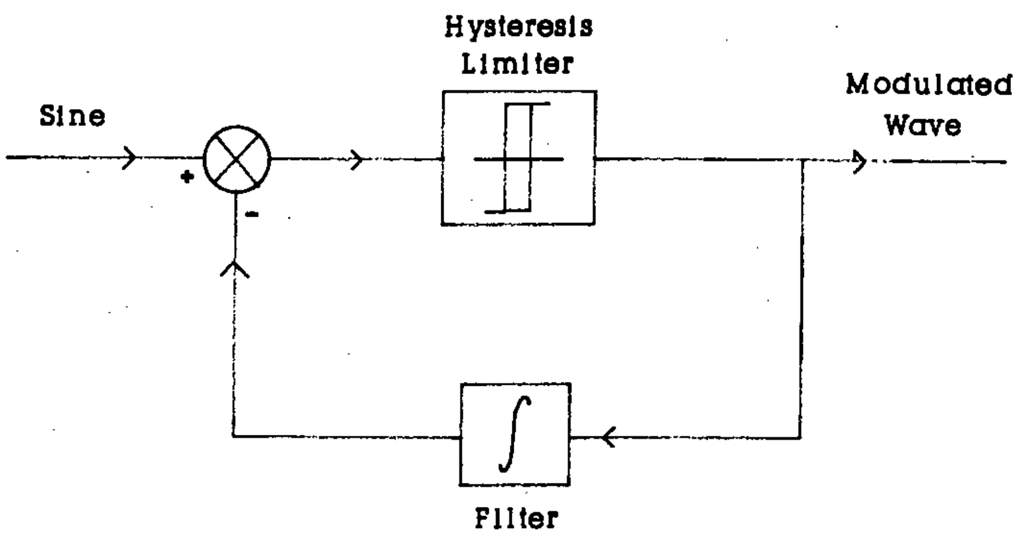
Figure 2.4 Basic single phase bridge inverter circuit.



(a)



(b)



(C)

Figure 2.5 Block diagrams of three basic delta modulators

a)the linear delta modulator

b)the sigma delta modulator

c)the rectangular wave delta modulator.

has a hysteresis qunatizer. The sampler in the rectangular wave modulator is permanently closed. The output of the linear and the sigma 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 rectangular wave delta modualtors 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 modulator performance depends on many factors. The basic characteristics on which the performance of modulators depend 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, and the
6. Current tracking capability in the open loop control of drives.

Table 2.1 contains both the summary and the 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 advantages features already mentioned, the rectangular wave delta modulator was considered to be that best among the simple delta modulators because of its lowest signal to noise ratio, and low quantization error [30].

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 qunatizer.

Table 2.1 [34]

Comparison of LDM, SDM and RWDM

	LDM	SDM	RWDM
Idling output	Square wave output of high frequency.	Square wave output of high frequency.	Square wave of output 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 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.

2.6 Conclusion:

The delta modulation technique is proposed for the switching of inverters in UPS application. The criteria for the modulator and the requirements for UPS system have been established. On the basis of requirements for UPS applications, the characteristics of three simple delta modulators have been discussed to select the best suitable delta modulation 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 the operation of UPS system.

CHAPTER - 3

ANALYSIS OF DELTA MODULATED WAVE

3.1 Introduction:

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.

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.

3.2.1 The Simple Rectangular Wave Delta Modulator:

The following are the intrinsic features of rectangular wave delta modulators.

1. Upto the base freqeuency 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 commutation 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.

A basic rectangular wave delta modulator is shown in figure 3.1. With a sinusoidal input to this block, the output waveform is a modulated waveform as shown in 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. The 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 hystersis comparator quantized the error signal to give the modulated signal. Due to the presence of the hysteresis

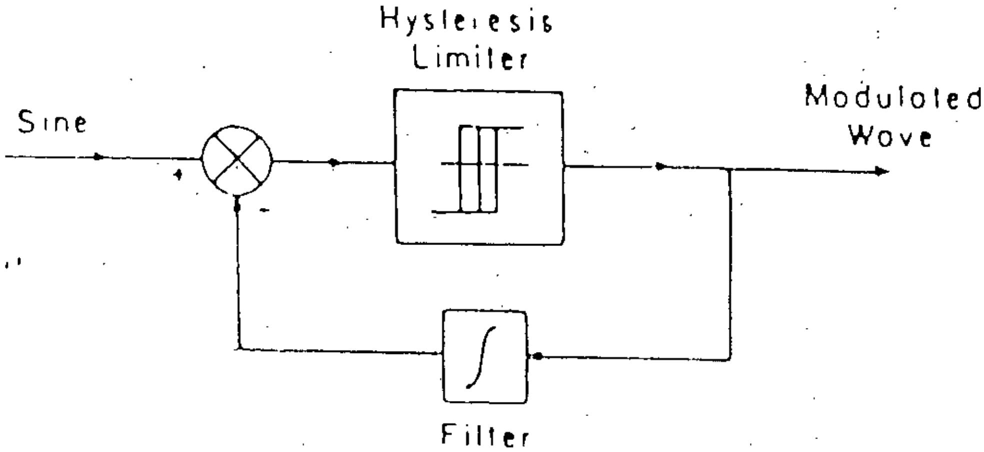


Figure 3.1 The block diagram of a rectangular wave delta modulator.

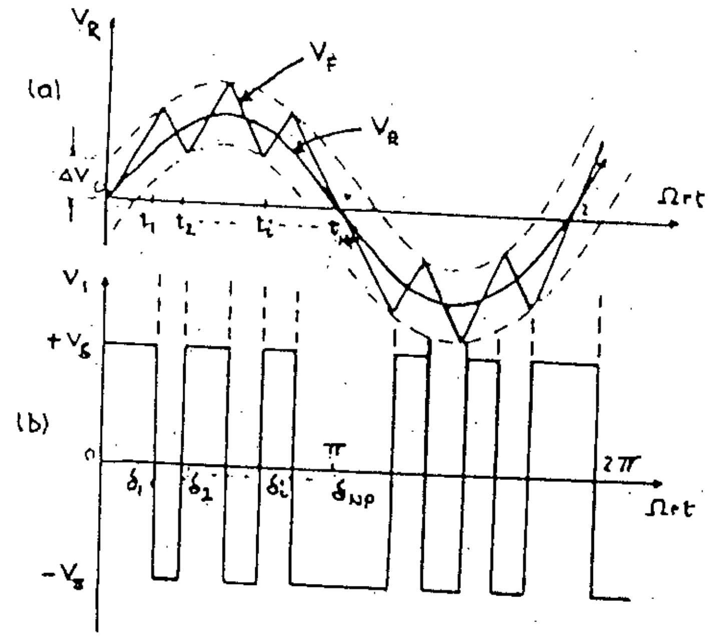


Figure 3.2 Expected waveforms of a rectangular wave delta modulator

a) the input sine wave and the estimated trangular wave

b) the modulated wave.

comparator, the error signal is bounded between ± 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 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 ± V. The various waveforms of the rectangular wave delta modulator are shown in figure 3.2.

3.2.2 Analysis of the Rectangular Wave Delta Modulator:

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

Termination of the first pulse position is governed by the relationship [32].

$$(\Delta V/S) + (V_R/S)\sin\omega_R t_1 = \omega_R t_1 \qquad (3.1)$$

where,

ΔV = half the window width as shown in figure 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)[32].

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

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

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

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

$$g(t,v,w) = u(t-v) - u(t-w) \qquad (3.4)$$

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

$$u(t-v) = 1 \quad \text{for } t > v$$
$$= 0 \quad \text{for } t \le v \qquad (3.5)$$
$$u(t-w) = 1 \quad \text{for } t > w$$
$$= 0 \quad \text{for } t \le w \qquad (3.6)$$

The waveforms of the rectangular wave delta modulation were defined using the switching points obtined 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 co-efficients of modulated waveforms in terms of switching points can be written as

$$A_n = \frac{2V_{dc}}{n\pi} \sum_{i=1,2,3,..}^{N_p} (-1)^{i+1}(\sin n\delta_i - \sin n\delta_{i-1}) \quad (3.7)$$

$$B_n = \frac{2V_{dc}}{n\pi} \sum_{i=1,2,3,...}^{N_p} (-1)^{i+1}(\cos n\delta_{i-1} - \cos n\delta_i) \quad (3.8)$$

where, $\delta_i = w_R t_i$ is the i-th pulse position in radians.

V_{dc} is the dc supply voltage.

n is the order of harmonics.

A_n and B_n are the n-th order Fourier co-efficients.

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

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

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

Fundamental voltage is given as

$$V_1=\sqrt{(A^2{}_1 + B^2{}_1)} \tag{3.11}$$

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

$$\left|\frac{y_n}{m_n}\right| = \left|\frac{1}{\tau w_n}\right| \tag{3.12}$$

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

$$\left|\frac{Y_1}{M_1}\right| = \left|\frac{1}{\tau w_1}\right| = \left|\frac{1}{\tau w}\right| \tag{3.13}$$

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

$$\left|\frac{V_R}{m_1}\right| = \left|\frac{1}{\tau w}\right| \tag{3.14}$$

$$\left|\frac{m_1}{V_R}\right| = |\tau w| \qquad (3.15)$$

Since V_R remains cosntant, 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:

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

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

Equation (3.16) can be simplified to

$$f_R = \frac{\tau}{4\Delta_R} \qquad (3.17)$$

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

$$V_n = \frac{4V}{n\pi} \qquad (3.18)$$

The fundamental voltage variation is given as

$$V_1 = \frac{4V_s}{\pi} \qquad (3.19)$$

A typical fundamental voltage relationship of rectangular wave delta modulated waveform with variation of operating frequency is shown in figure 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 theoritical harmonic analysis is carried out using the expressions obtain in this section and the result are shown in figure 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 harmonics 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.

3.3 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 points decreases i,e number of pulses per cycle

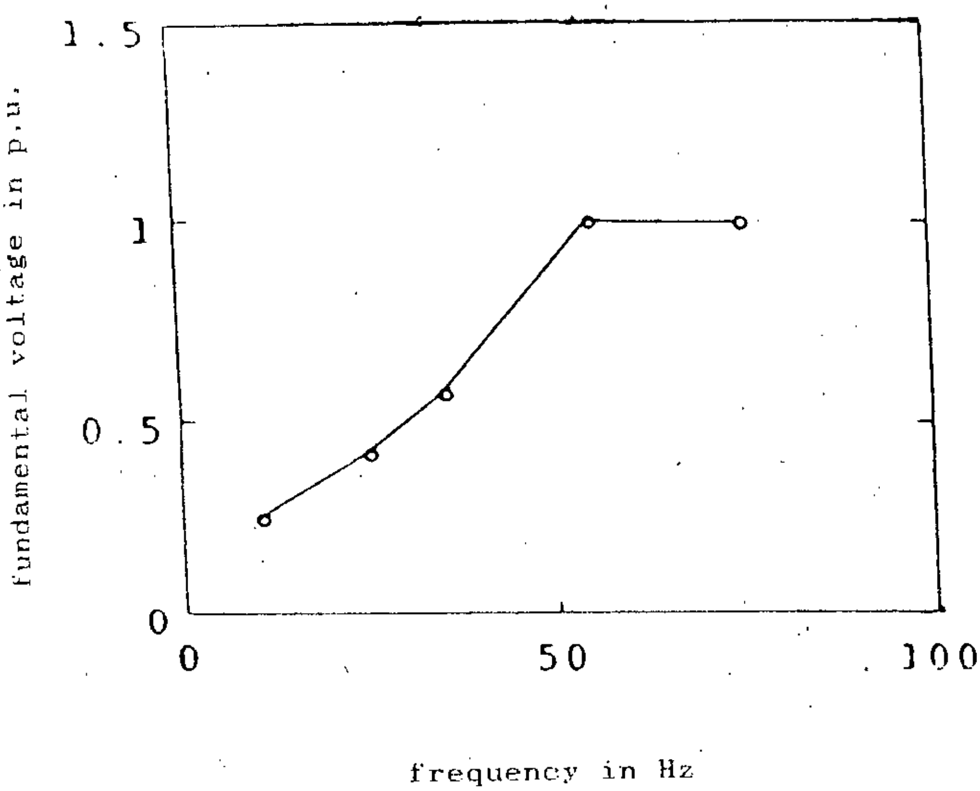


Figure 3.3 Fundamental voltage variation of rectangular wave delta modulated waves with change in operating frequency. (p.u. value of the output voltage is the ratio of output voltage to the fundamental voltage of a square wave of the same frequency.)

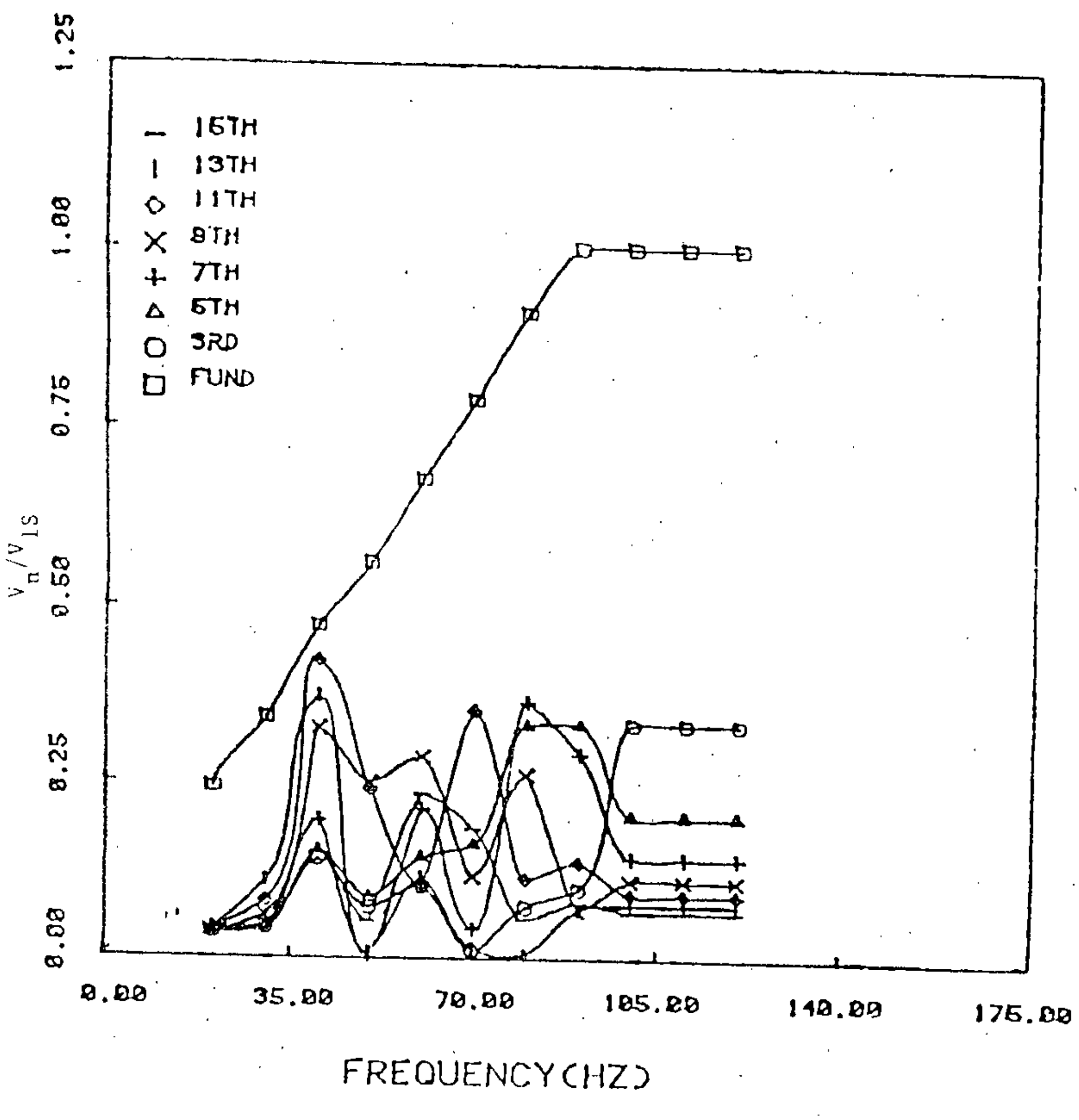


Figure 3.4 Harmonics of DM inverter output at various operating frequencies

V_n = Magnitude of nth harmonic.

V_{1s} = Magnitude of fundamental of square wave having same voltage level.

decrease. This results domination of lower harmonics. But in our case the operating frequency is fixed and it is 50 Hz. And our variable factors are window width and slope. For different window width Δv typical estimated waveforms of tuned RWDM is shown in figs. 3.5(a) to 3.5(c). For different window width with constant slope and also for different slope with constant window width the switching points are calculated which are shown in figs. 3.6(a) to 3.6(h) again the spectra analysis of the output, for those parameters (for which switching points have been calculated) of the inverters have been calculated and shown are in figs. 3.7(a) to 3.7(h). The spectra of the output of the inverter show that for different parameters harmonics content is different. From these we have chosen the operating parameters for the inverter so that lower harmonics are low at the output.

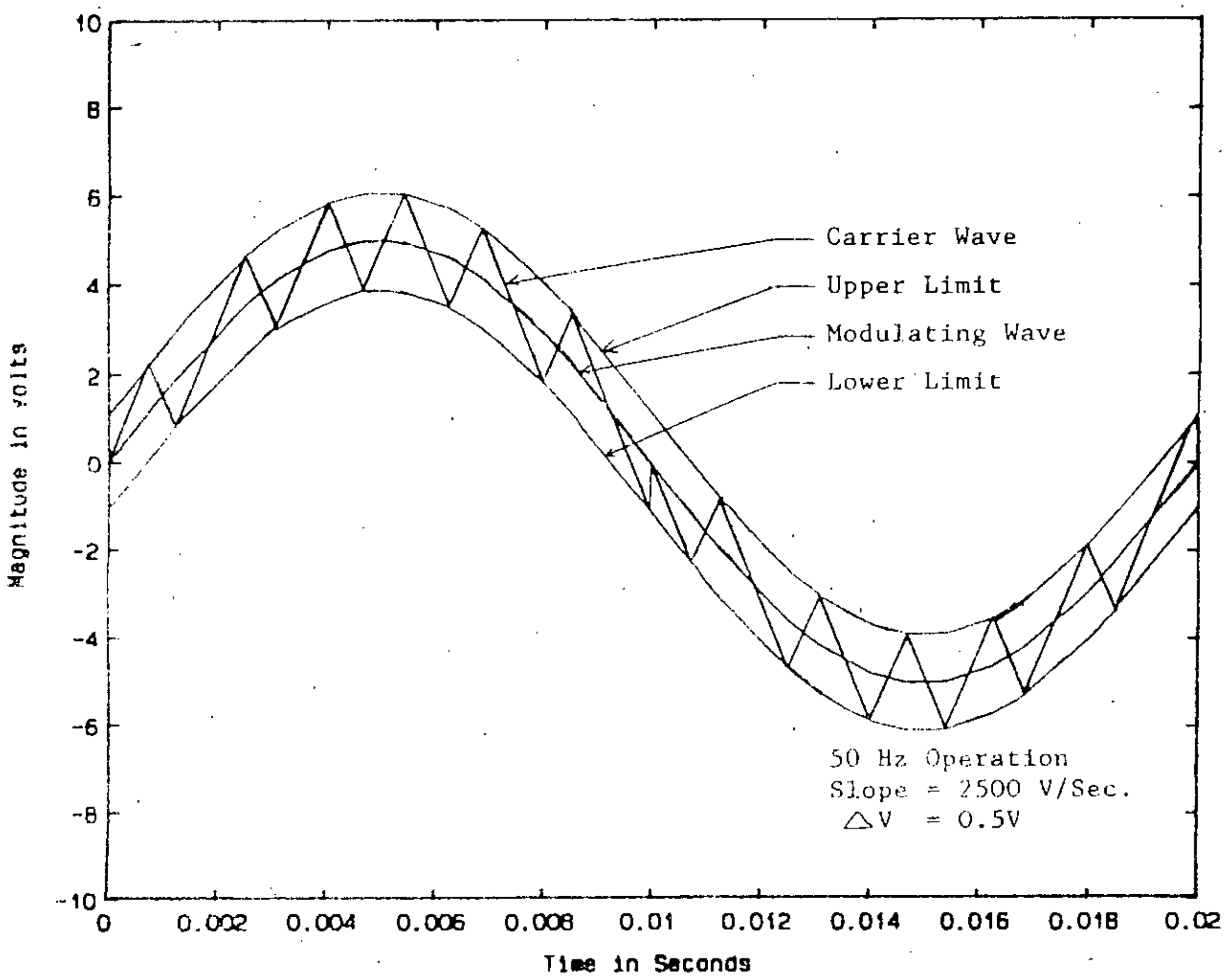


Figure 3.5(b) Typical estimated waveforms of variable step rwdm at f=50 Hz, slope=2500 V/S, ΔV=0.5 V.

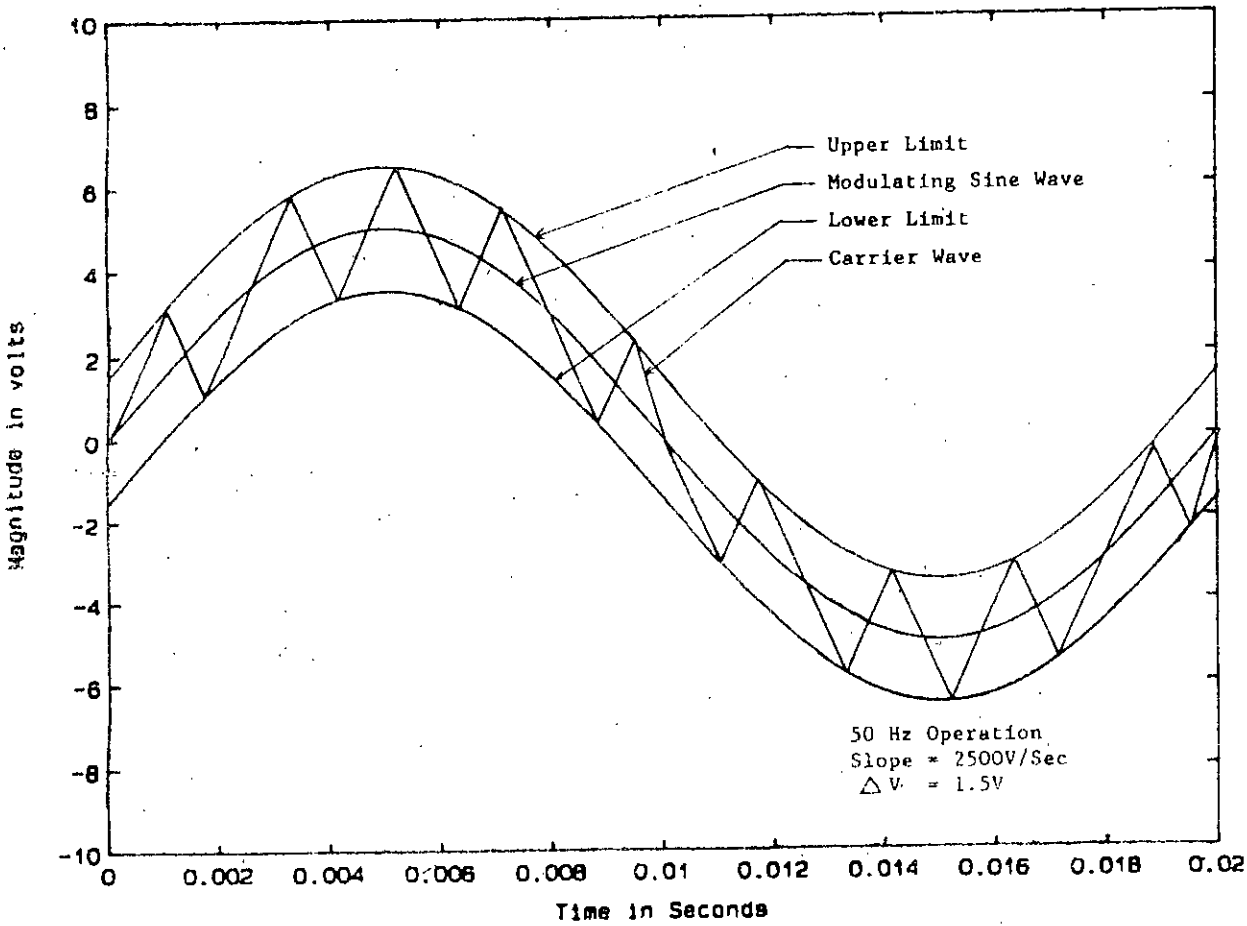


Figure 3.5(a) Typical estimated waveforms of variable step rwdm at f=50 Hz, slope=2500 V/S, ΔV=1.5 V.

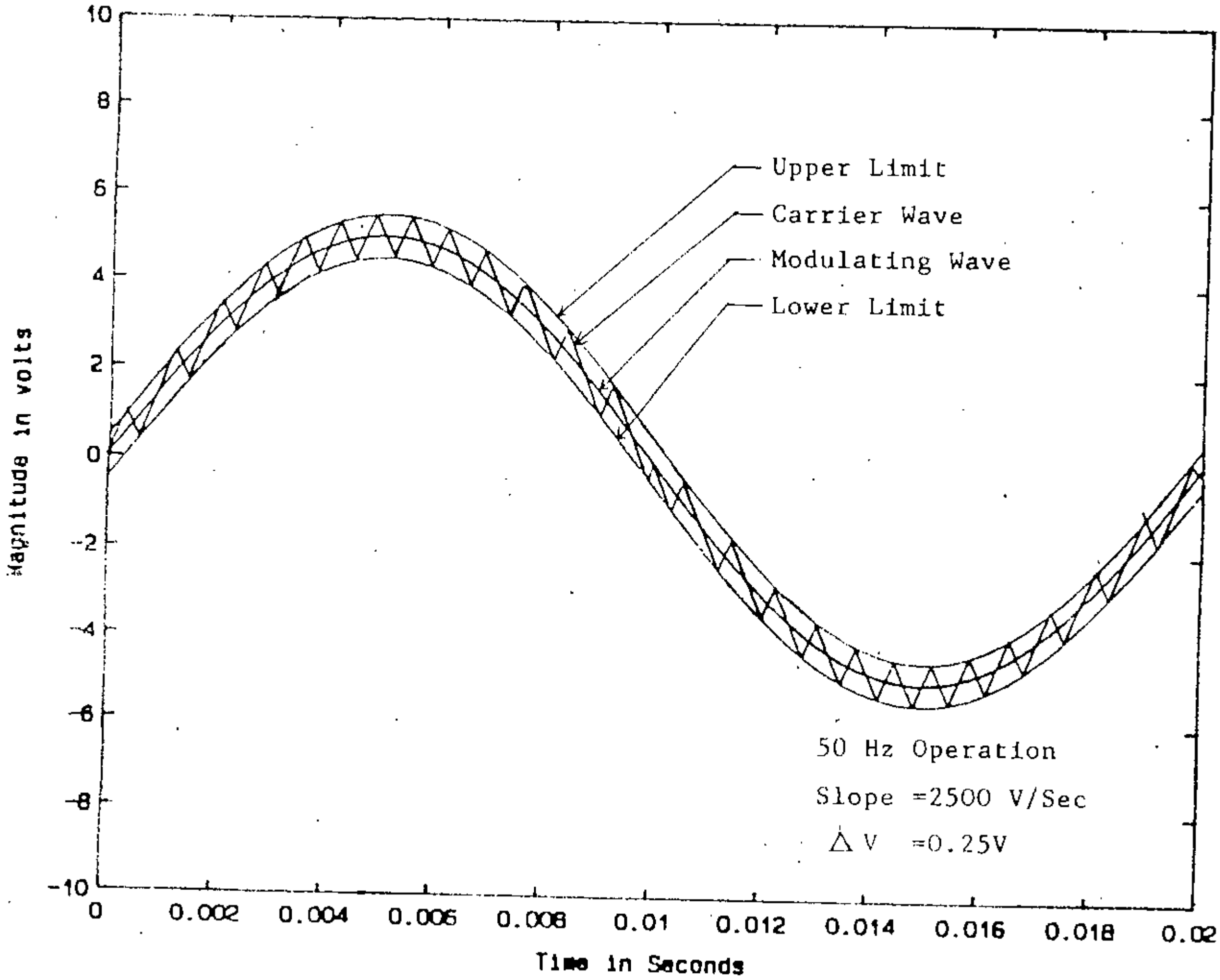


Figure 3.5(c) Typical estimated waveforms of variable step rwdm at f=50 Hz, slope=2500 V/S, ΔV=0.25 V.

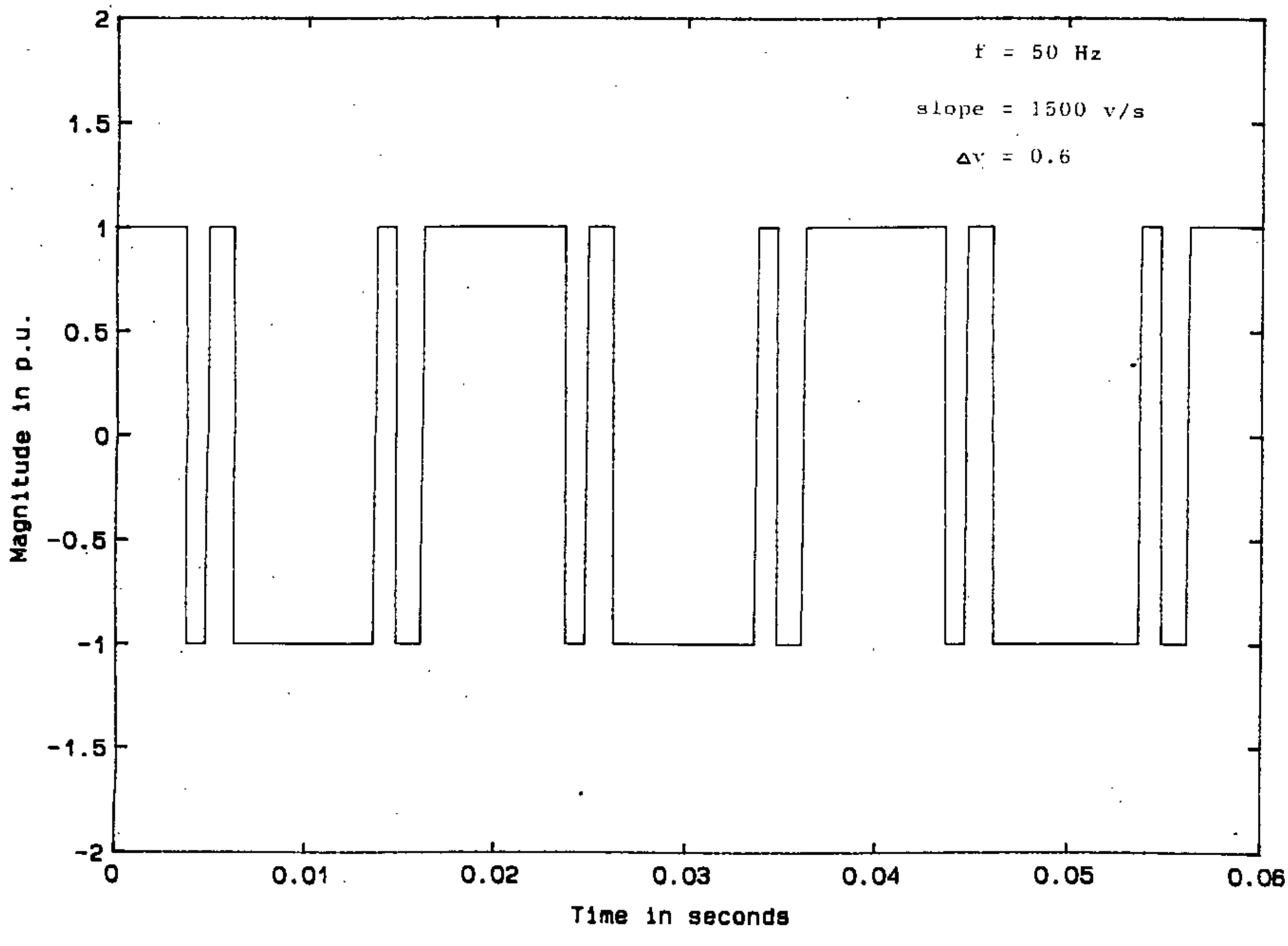


Figure 3.6(a) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=1500 V/S, ΔV=0.6 V.

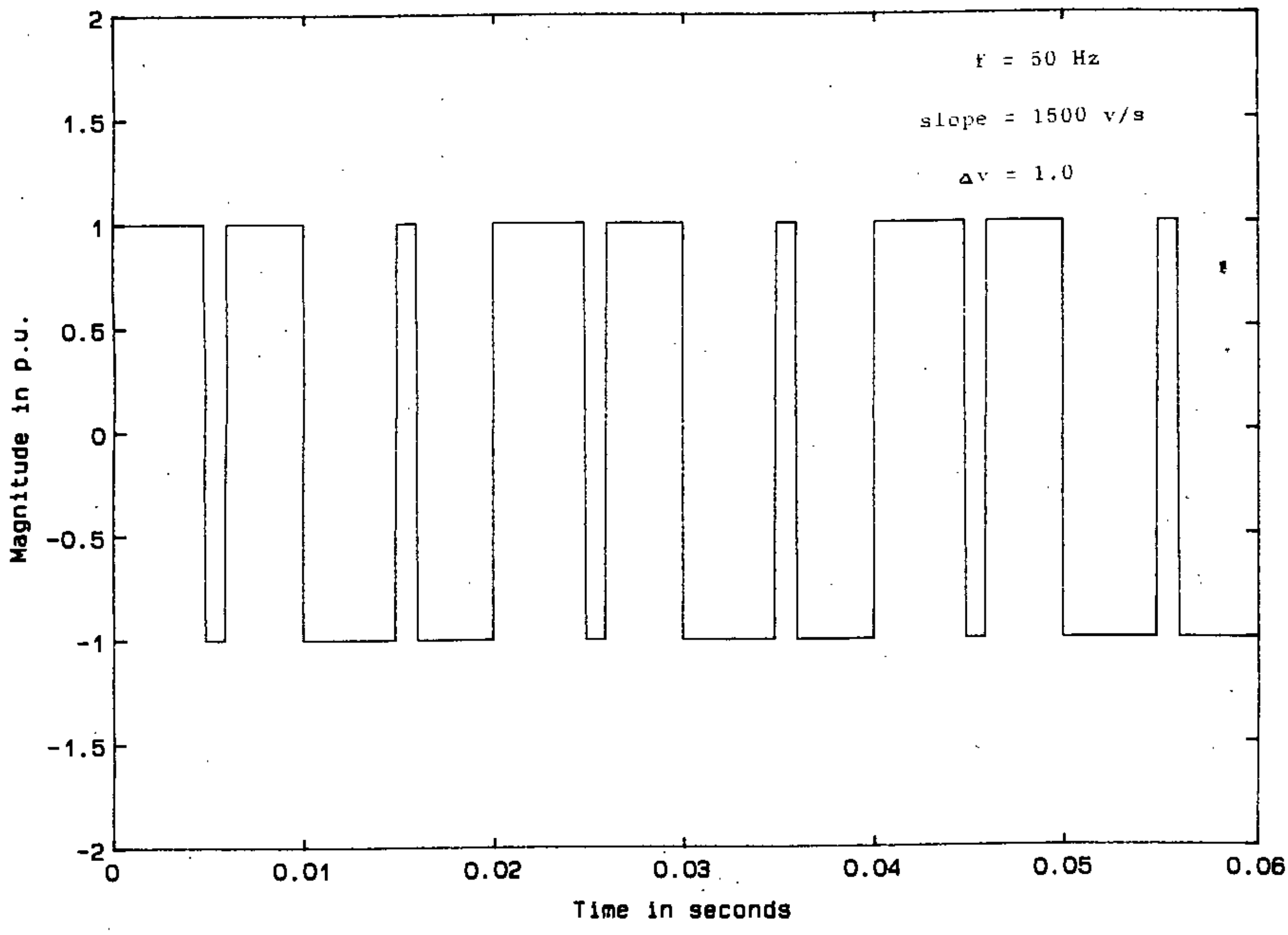


Figure 3.6(b) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=1500 V/S, ΔV=1.0 V.

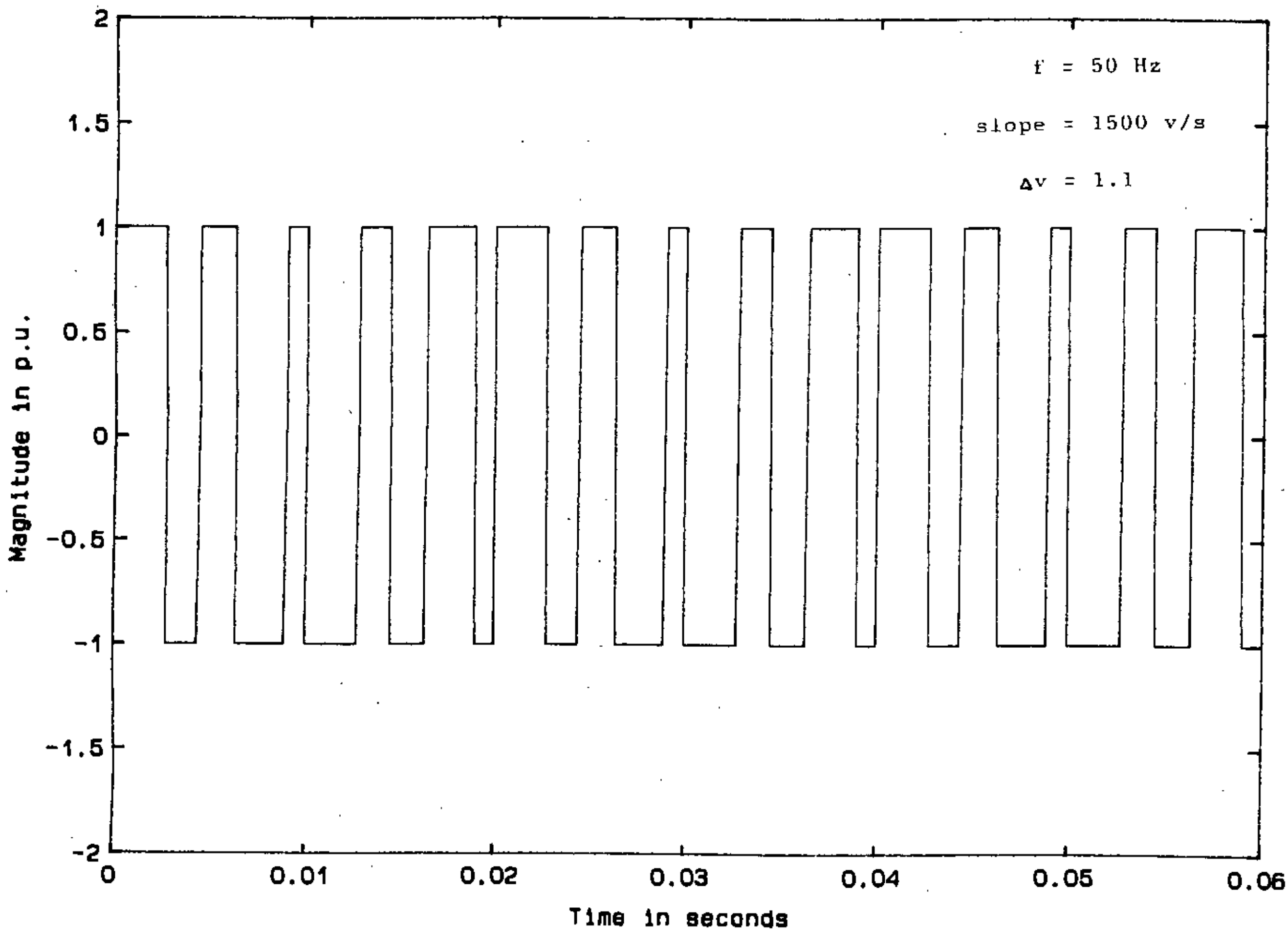


Figure 3.6(c) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope =1500 V/S, ΔV=1.1 V.

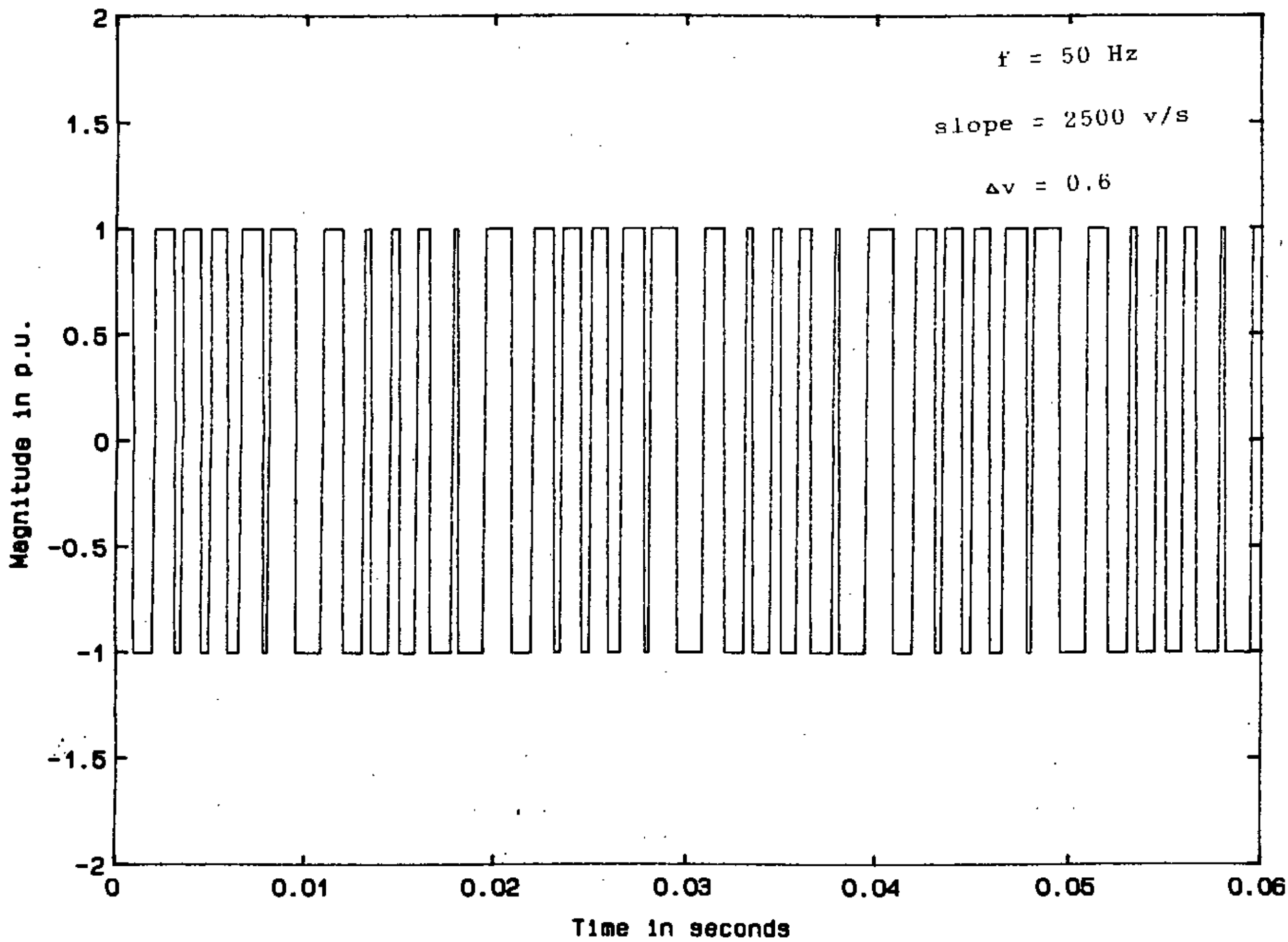


Figure 3.6(d) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=2500 V/S, ΔV=0.6 V.

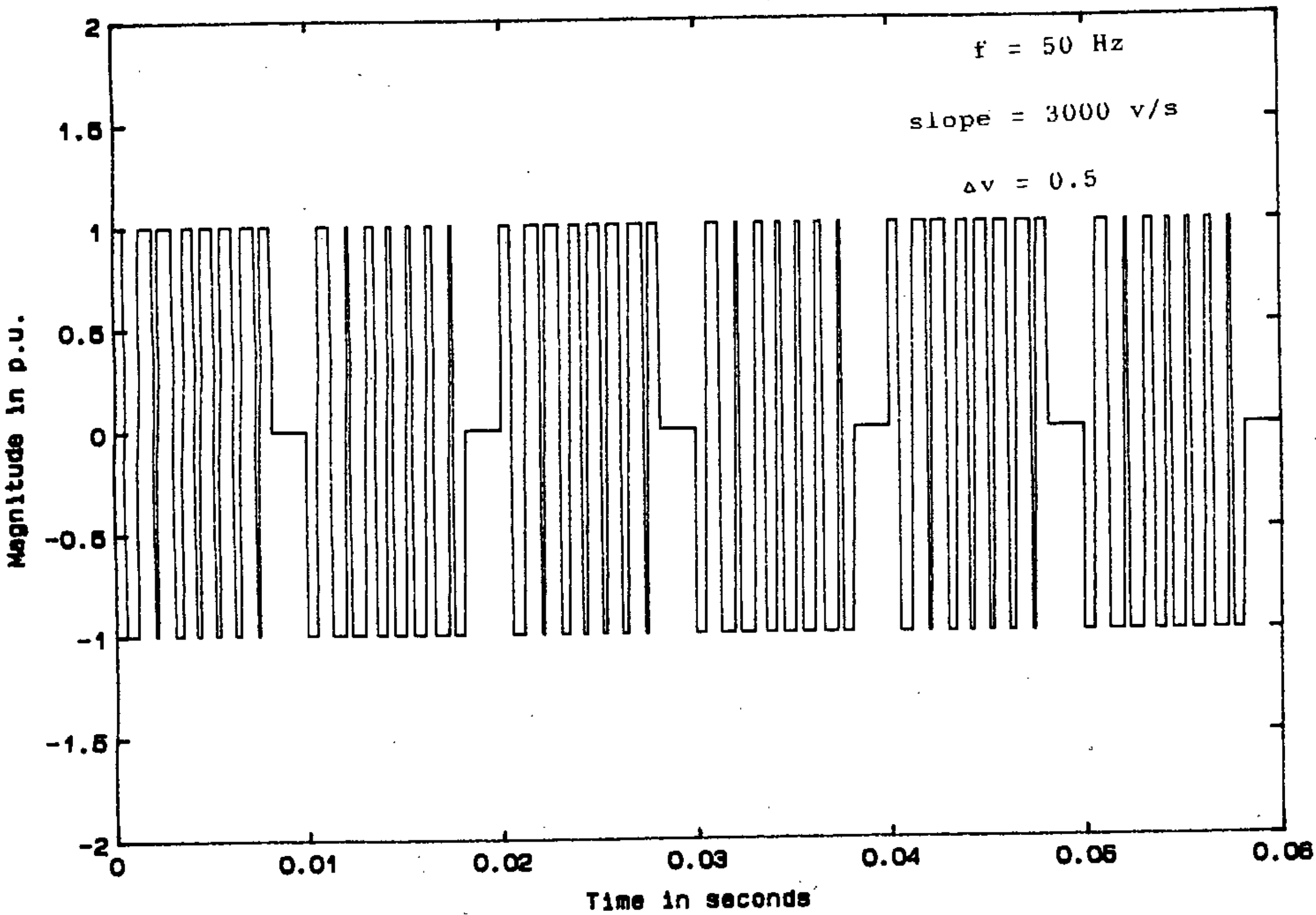


Figure 3.6(e) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=3000 V/S, ΔV=0.5 V.

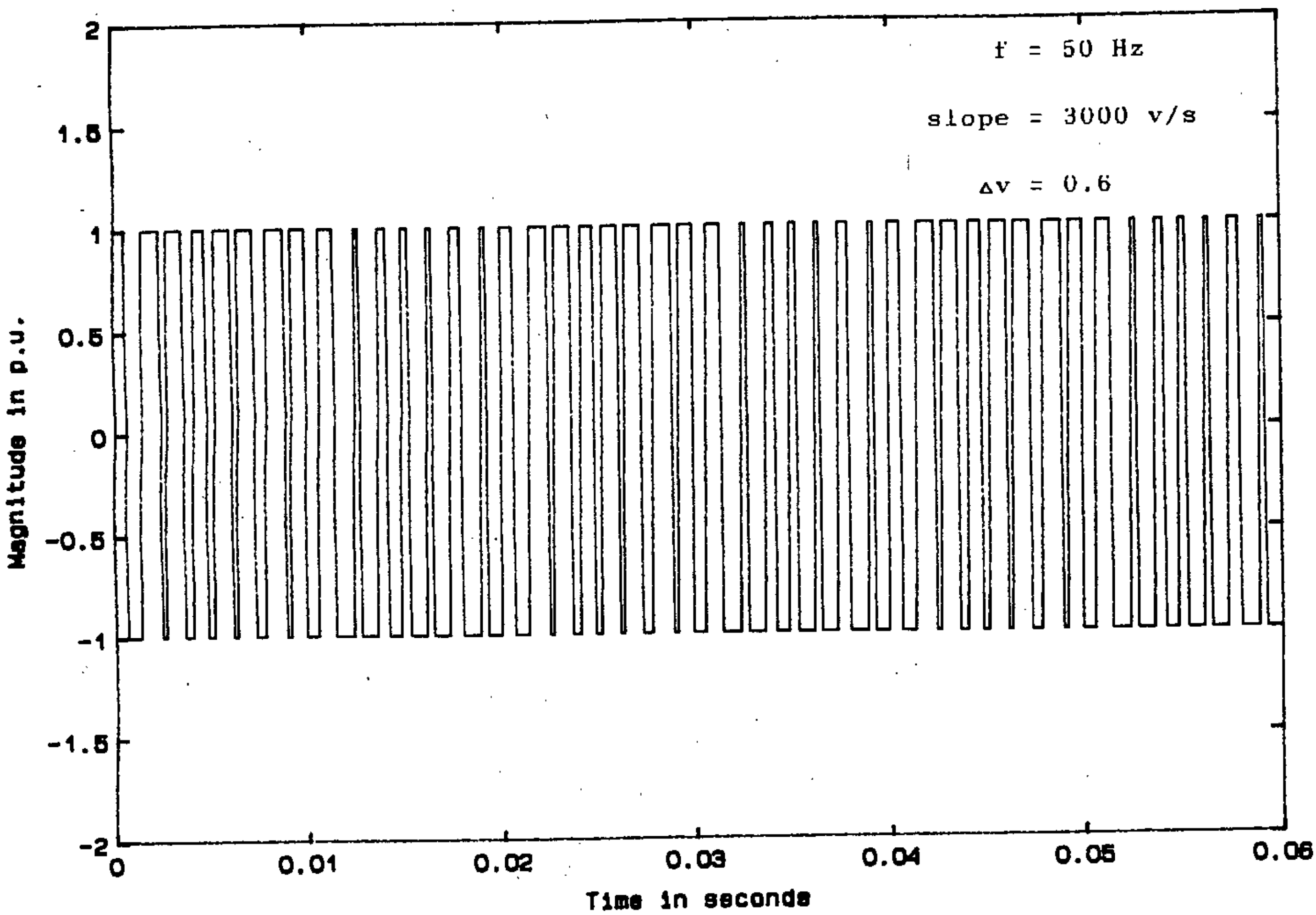


Figure 3.6(f) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=3000 V/S, ΔV=0.6 V.

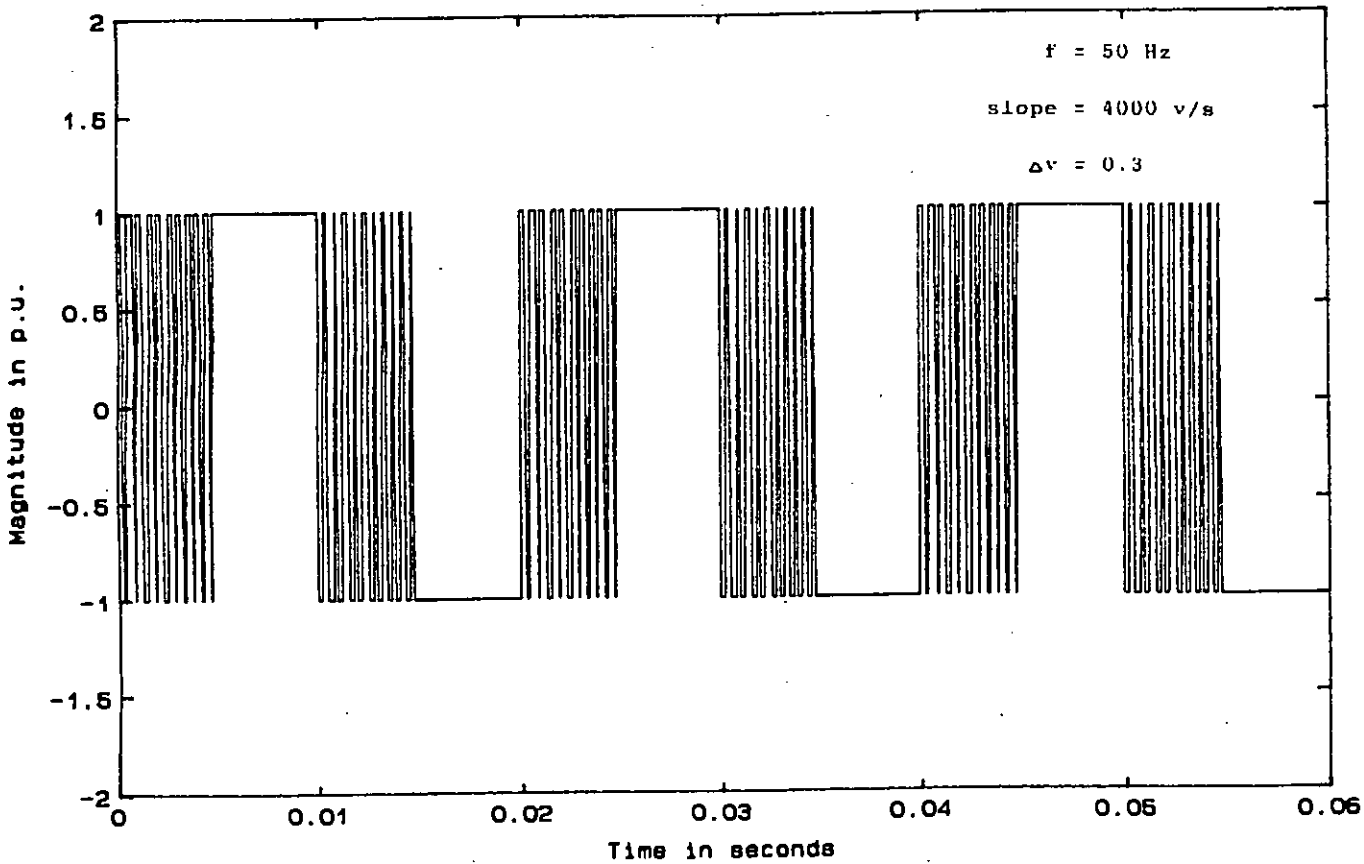


Figure 3.6(g) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=4000 V/S, ΔV=0.3 V.

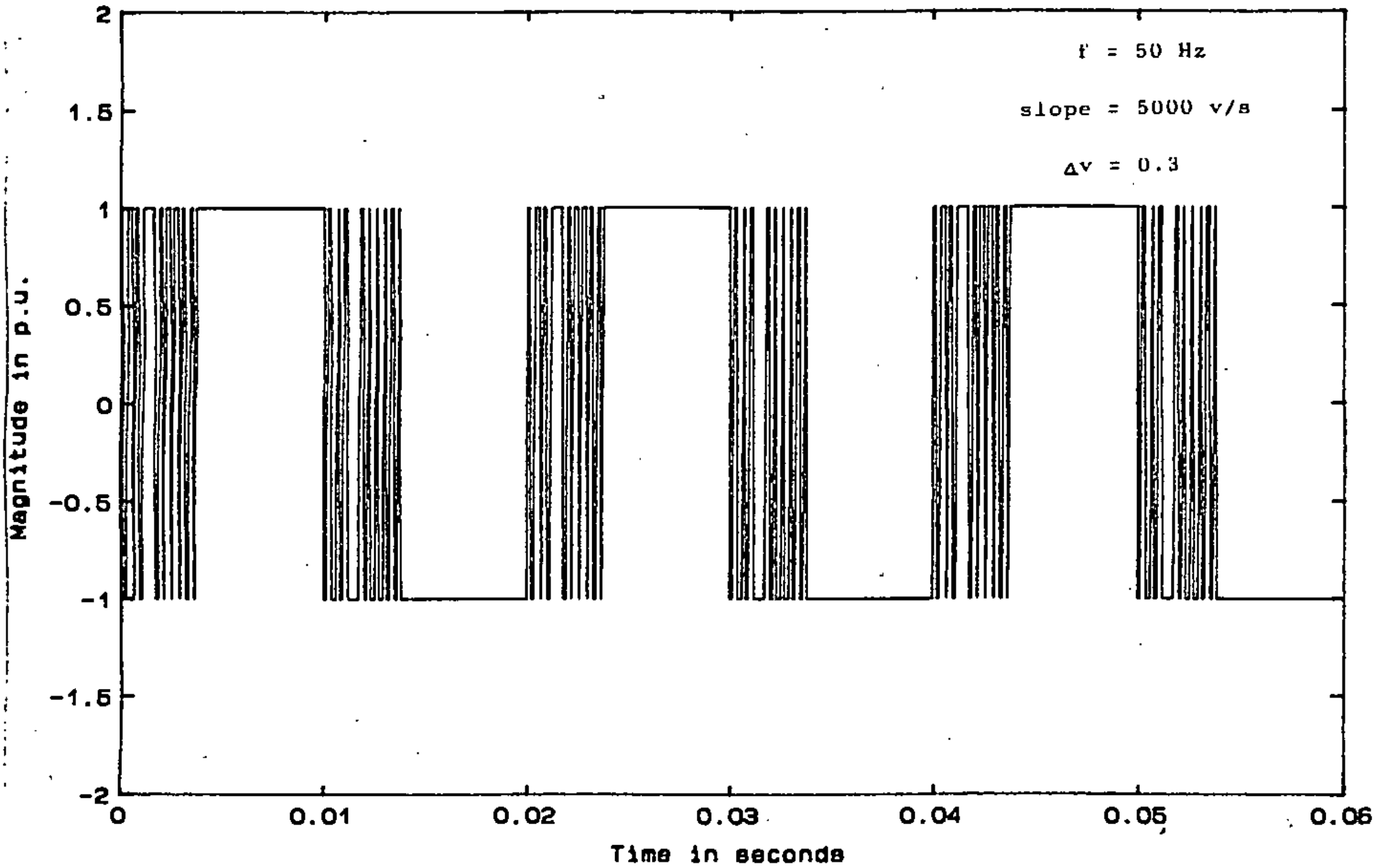


Figure 3.6(h) Typical modulated waveforms of variable step rwdm at f=50 Hz, slope=5000 V/S, ΔV=0.3 V.

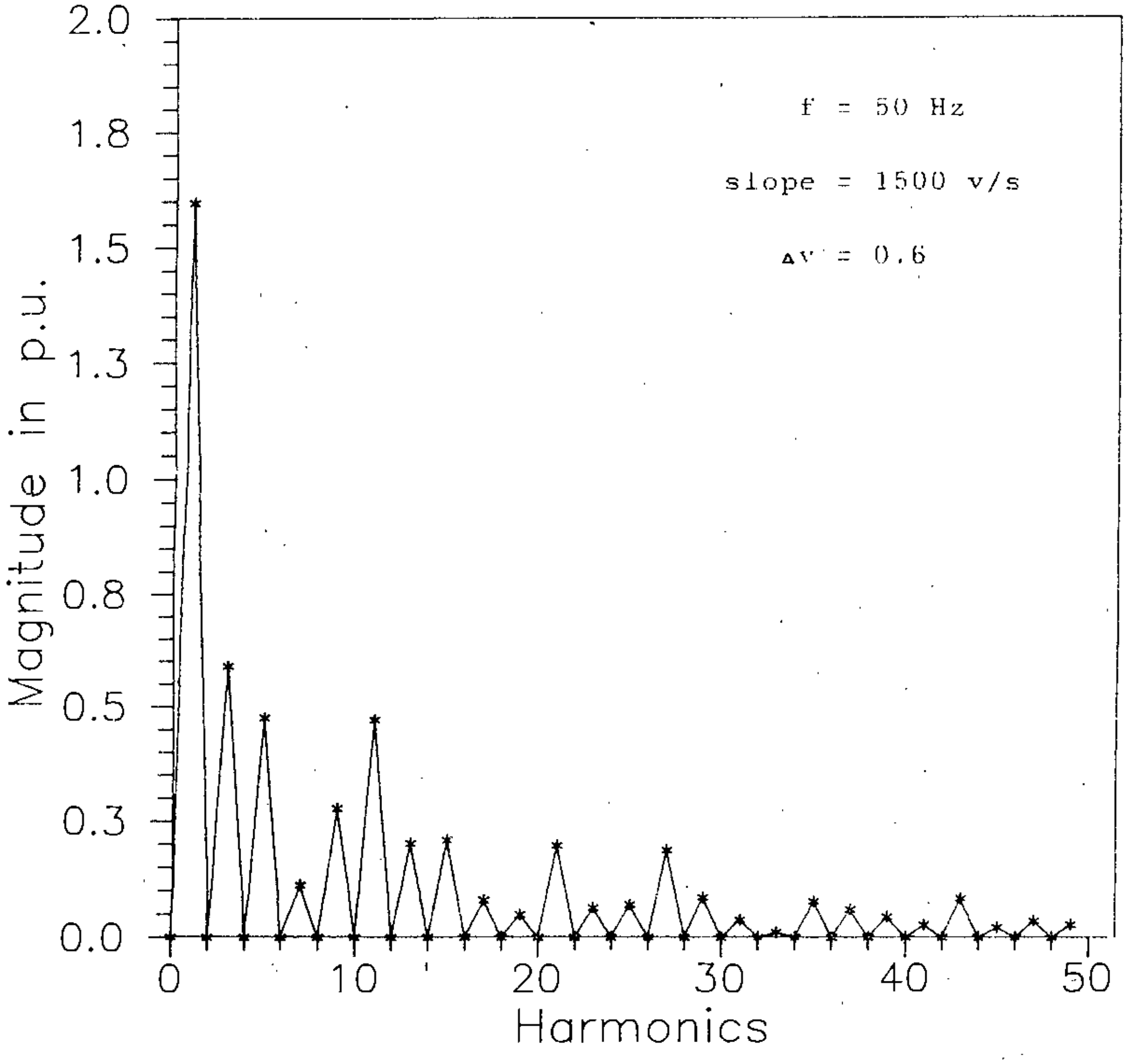


Figure 3.7(a) spectra of tuned rwdm wave with
f=50 hz, slope=1500 V/S, ΔV=0.6 V.

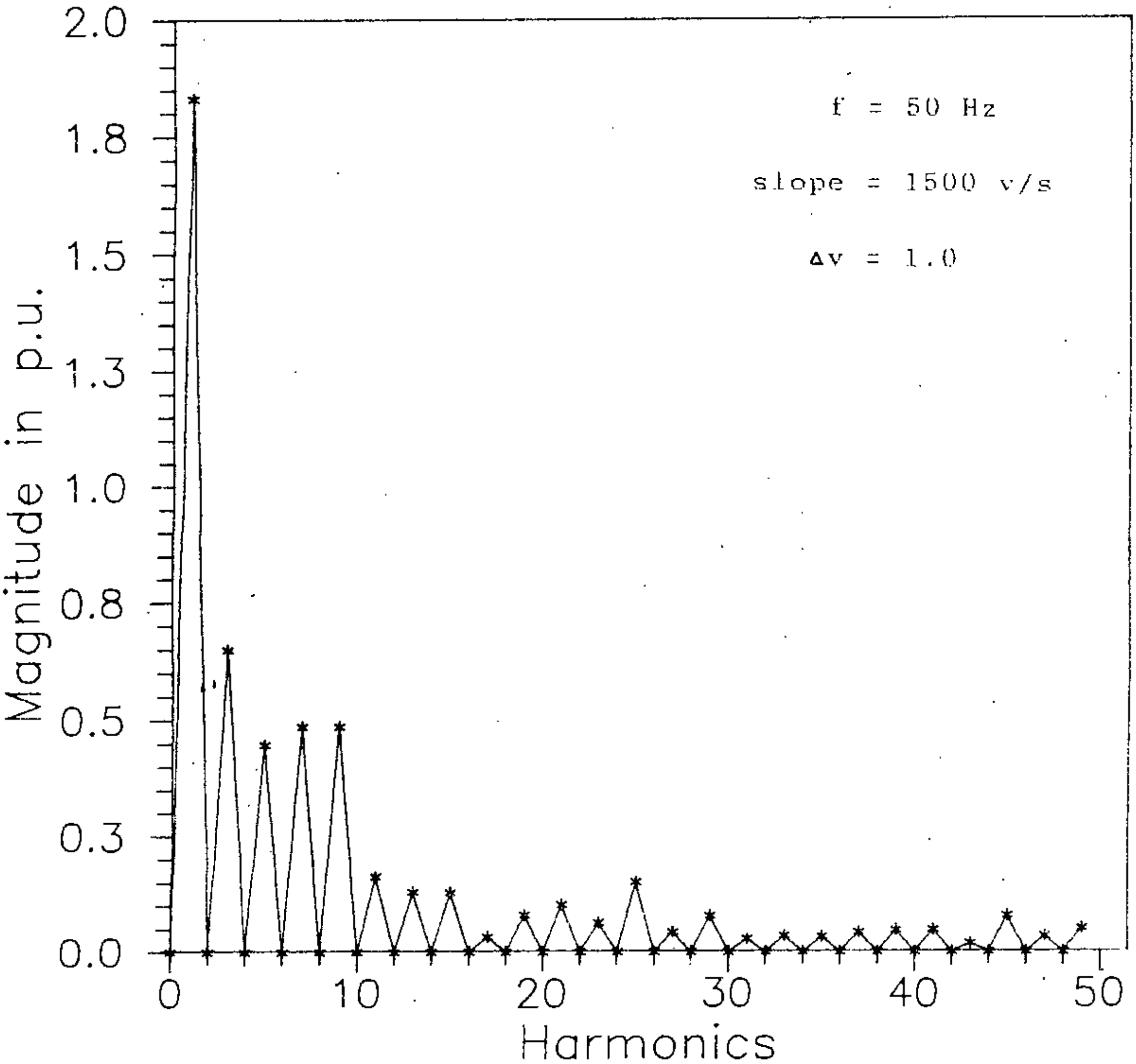


Figure 3.7(b) Spectra of tuned rwdm wave with f=50 Hz, slope=1500 V/S, ΔV=1.0 V.

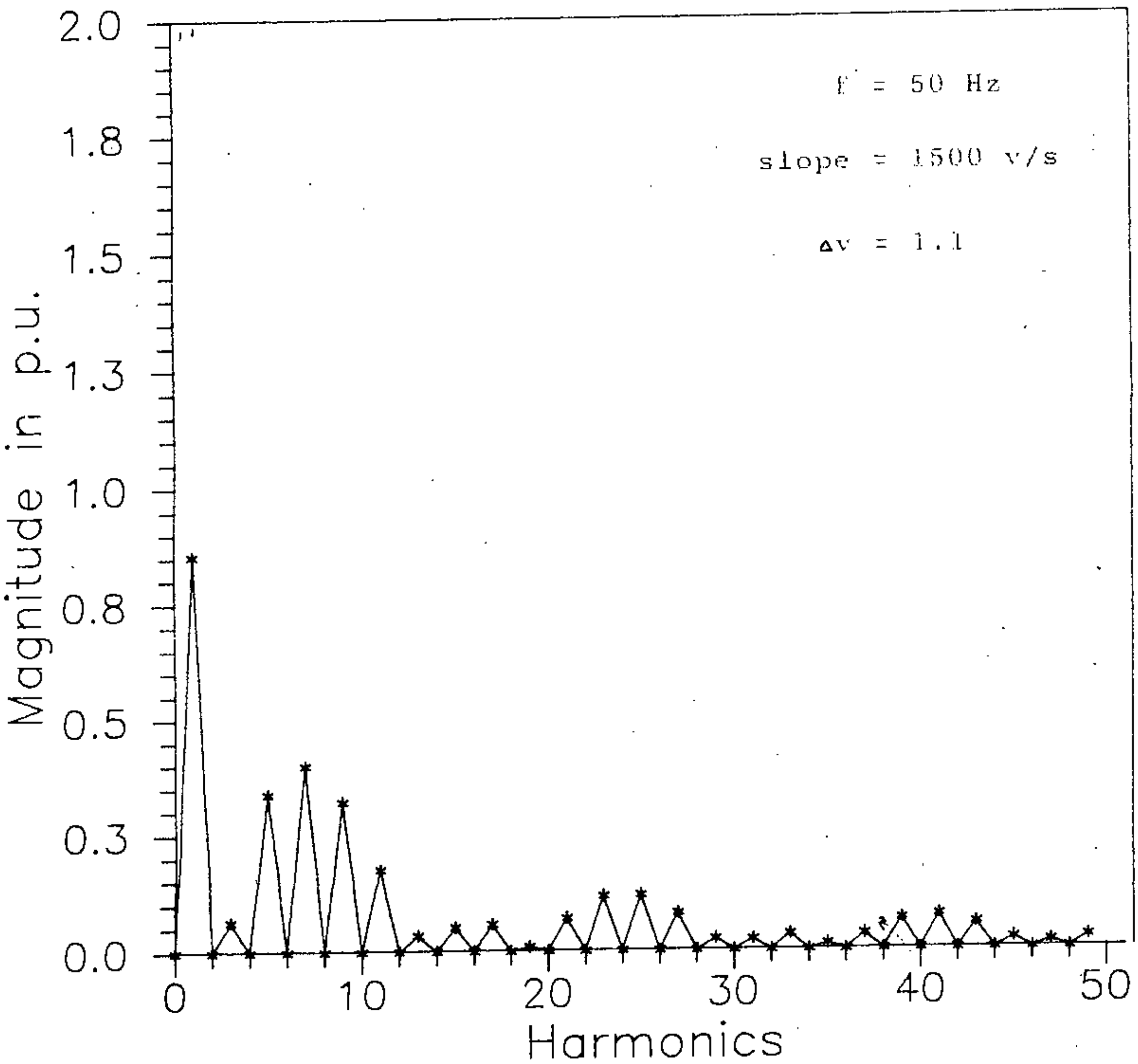


Figure 3.7(c) Spectra of tuned rwdm wave with f=50 hz, slope=1500 V/s, ΔV=1.1 V.

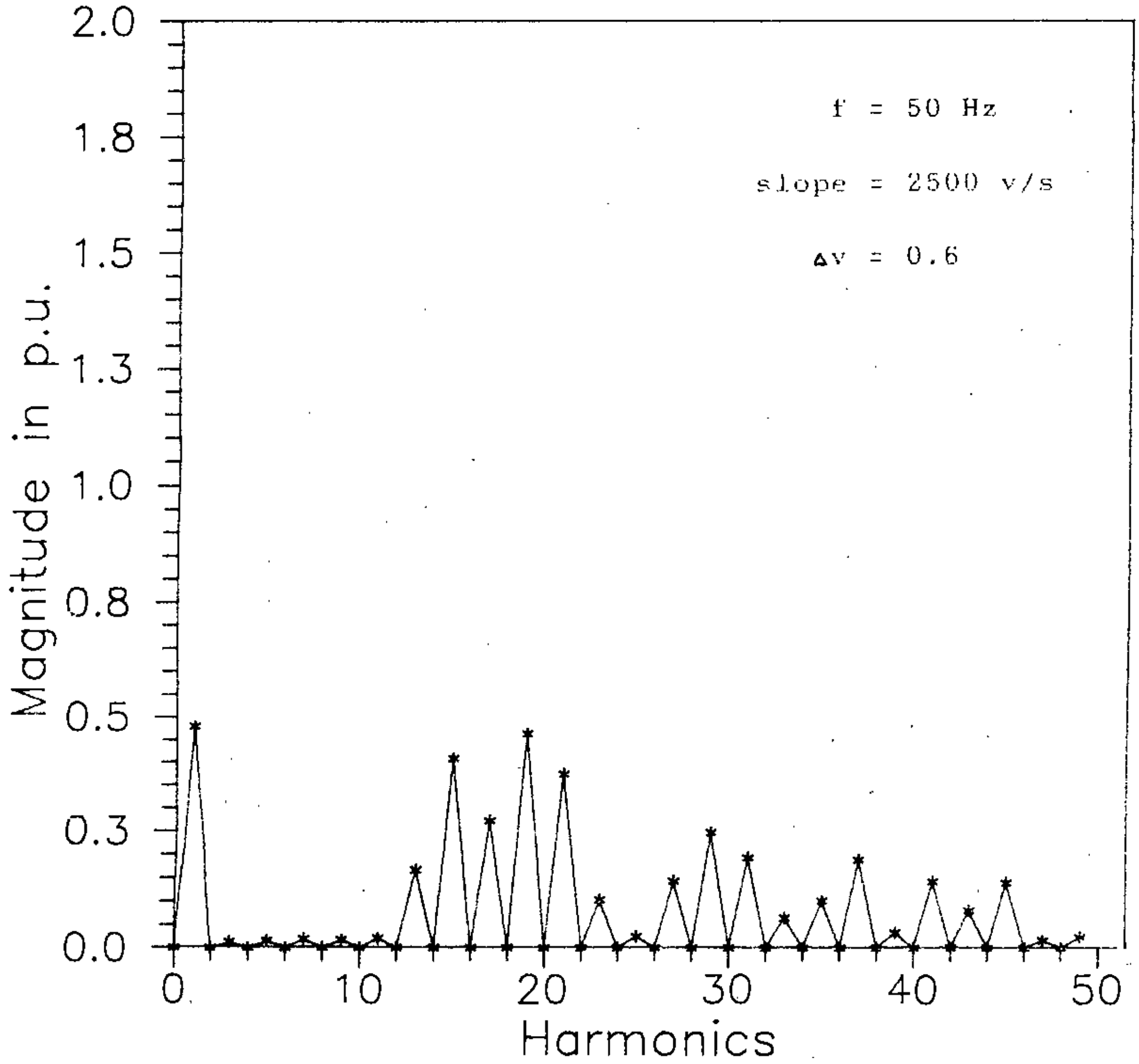


Figure 3.7(d) Spectra of tuned rwdm wave with f=50 Hz, slope=2500 V/S, ΔV=0.6 V.

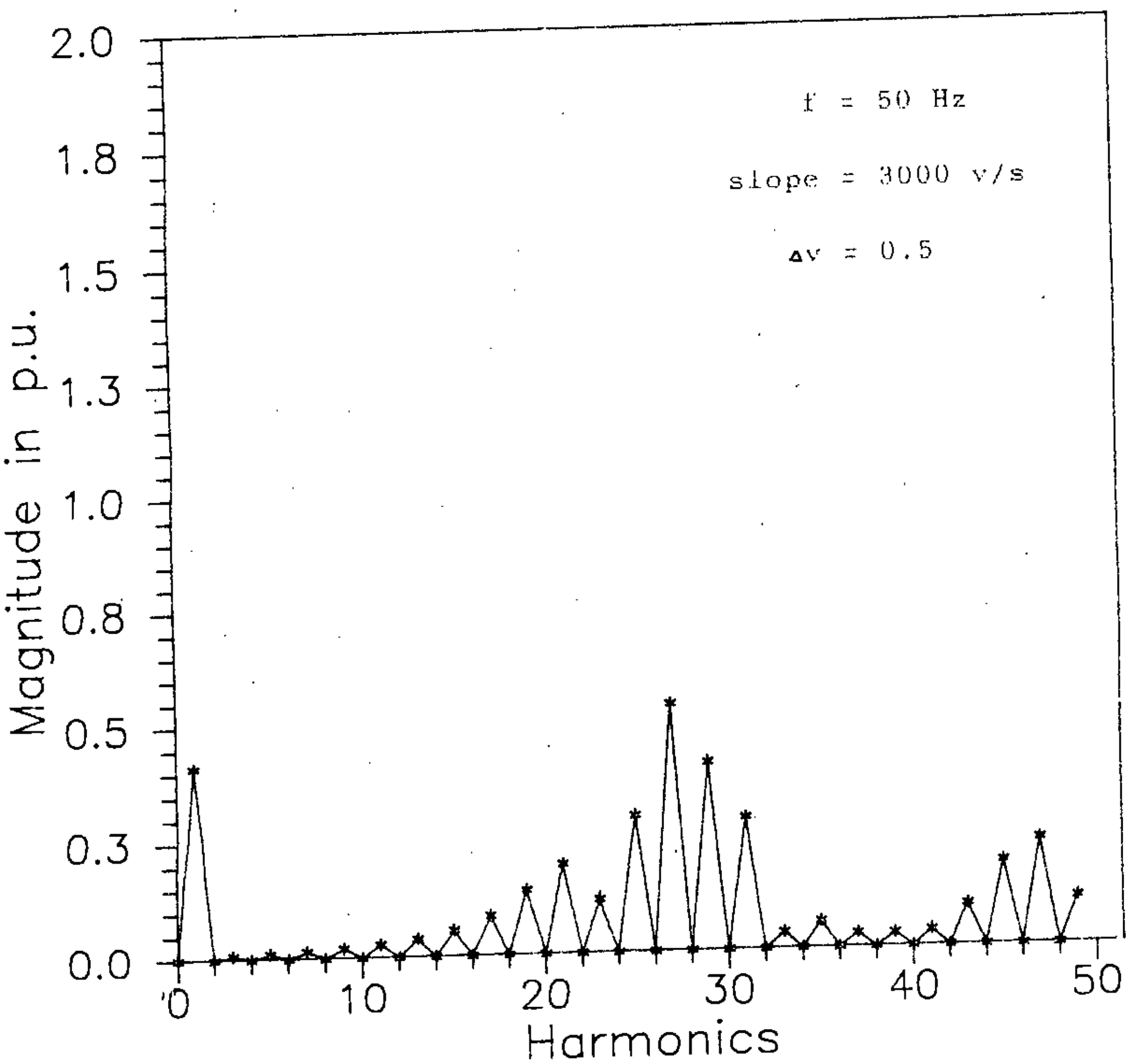


Figure 3.7(e) Spectra of tuned rwdm wave with f=50 Hz, slope=3000 V/S, ΔV=0.5 V.

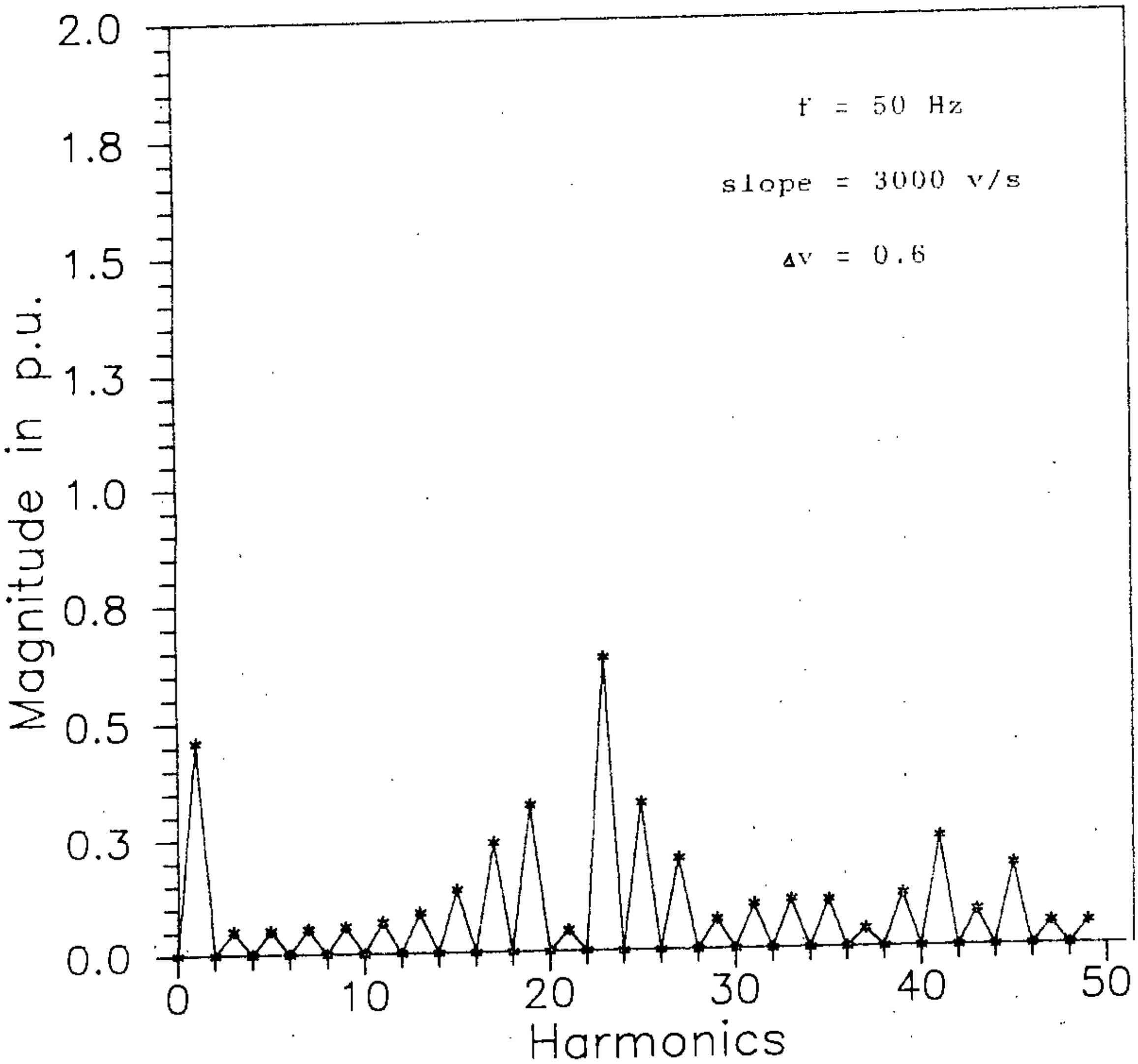


Figure 3.7(f) Spectra of tuned rwdm wave with f=50 Hz, slope=3000 V/S, ΔV=0.6 V.

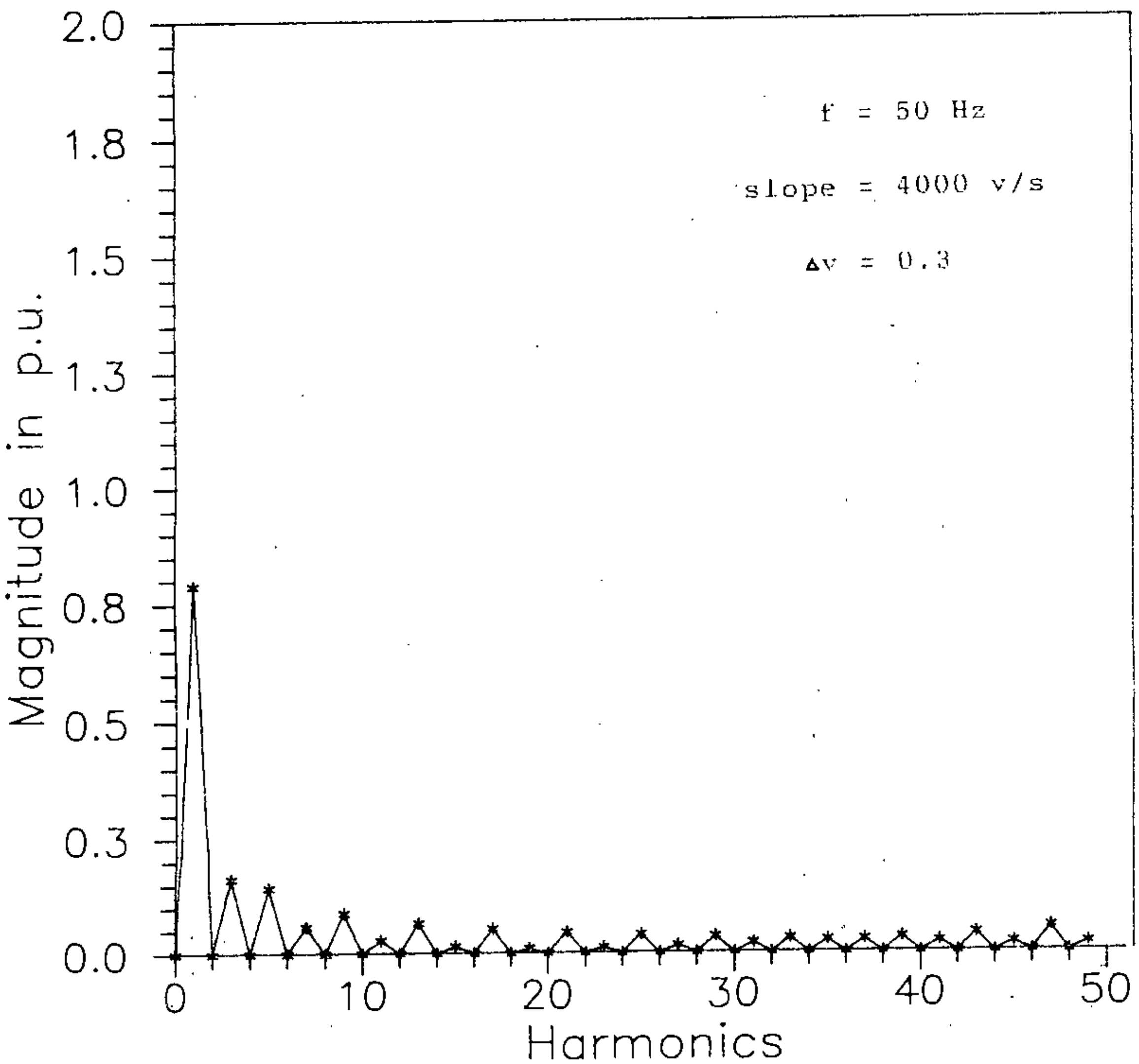


Figure 3.7(g) Spectra of tuned rwdm wave with f=50 Hz, slope=4000 V/S, ΔV=0.3 V.

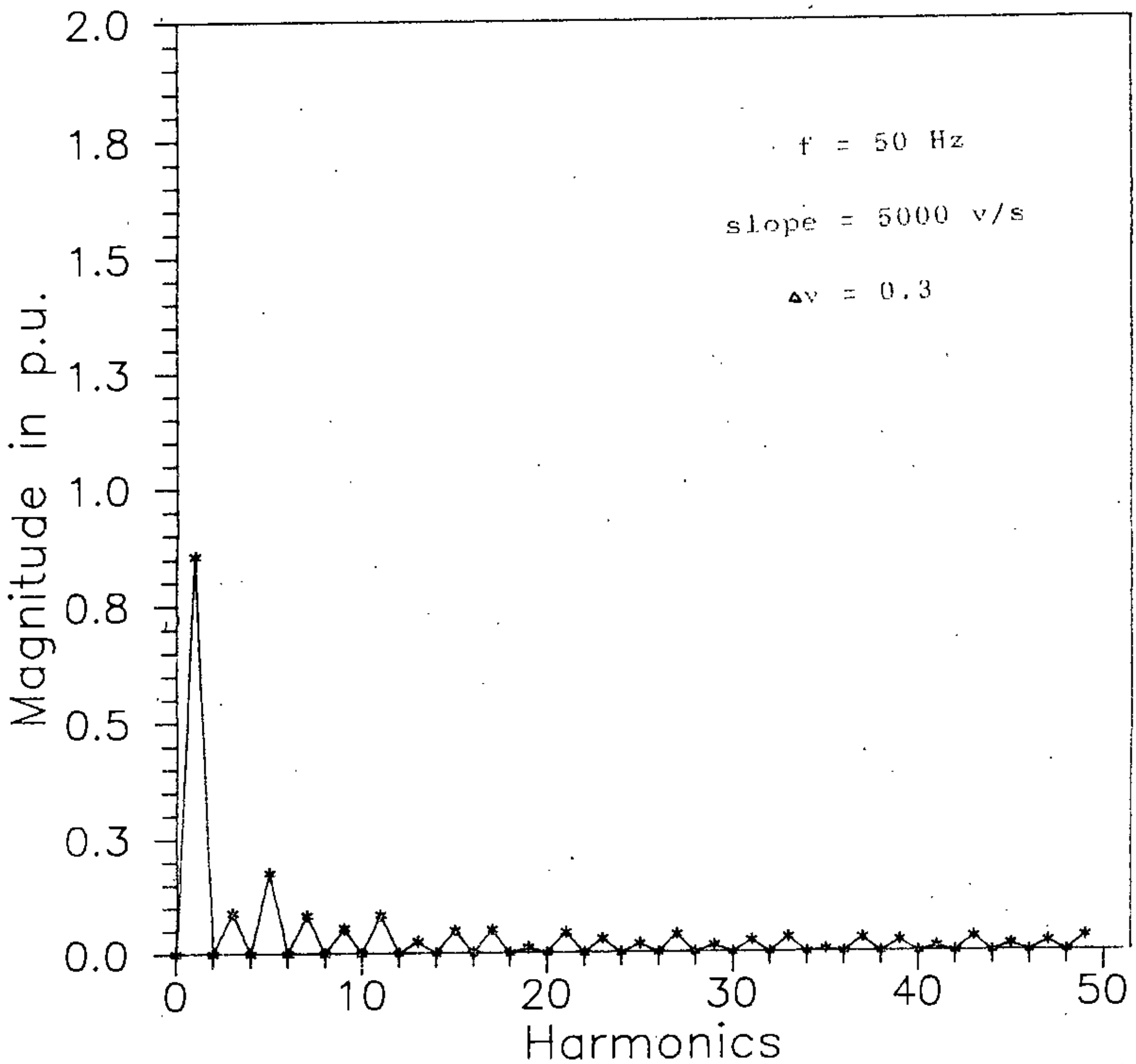


Figure 3.7(h) Spectra of tuned rwdm wave with f=50 Hz, slope=5000 V/S, ΔV=0.3 V.

CHAPTER 4

A PRACTICAL UNINTERRUPTIBLE POWER SUPPLY

4.1 Introduction

UPS supplies energy to electrical appliances during electrical failure. The basic block diagram of a normal UPS system is shown in figure 4.1(a). The building blocks of an UPS are the step down transformer, the ac-dc conversion unit(rectifier), the filter, the battery charge controller, the energy storage device(batteries), filter and step-up transformer. A possible circuit diagram is shown in figure 4.1(b) and the inverter circuit is seperately shown in figure 4.1(c). The inverter circuit in our experiment has been implemented with SCR but if the circuit is implemented with transistors (figure 4.1 d) then the circuit will be less costly and easy to implement. But as one of the objectives of the thesis is to verify the results of a DM inverter based UPS, analyze its performance and compare the size and cost of the filter to that of commercially avaliable square wave inverter based UPS, tests were conducted with SCR inverter available in the laboratory.

4.2 Implementation of UPS system:

The main component of an UPS are

1) Step down transformer
2) ac to dc converter

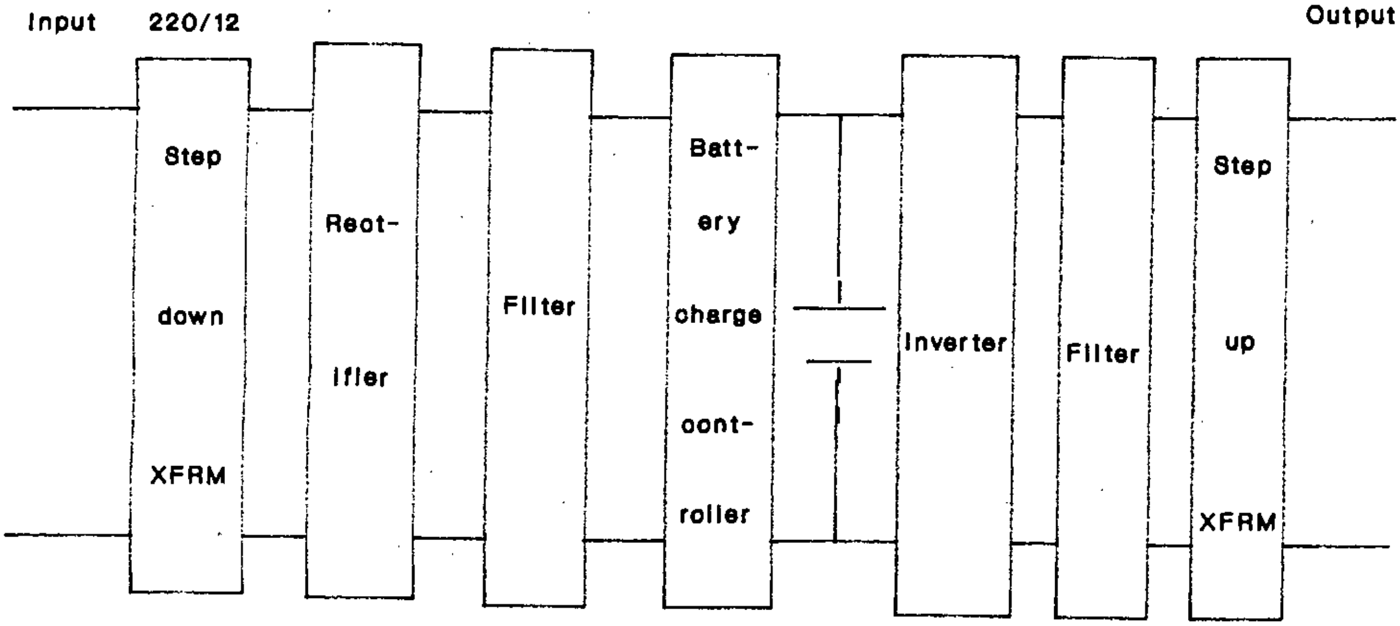


Figure 4.1(a) Basic block diagram of an UPS.

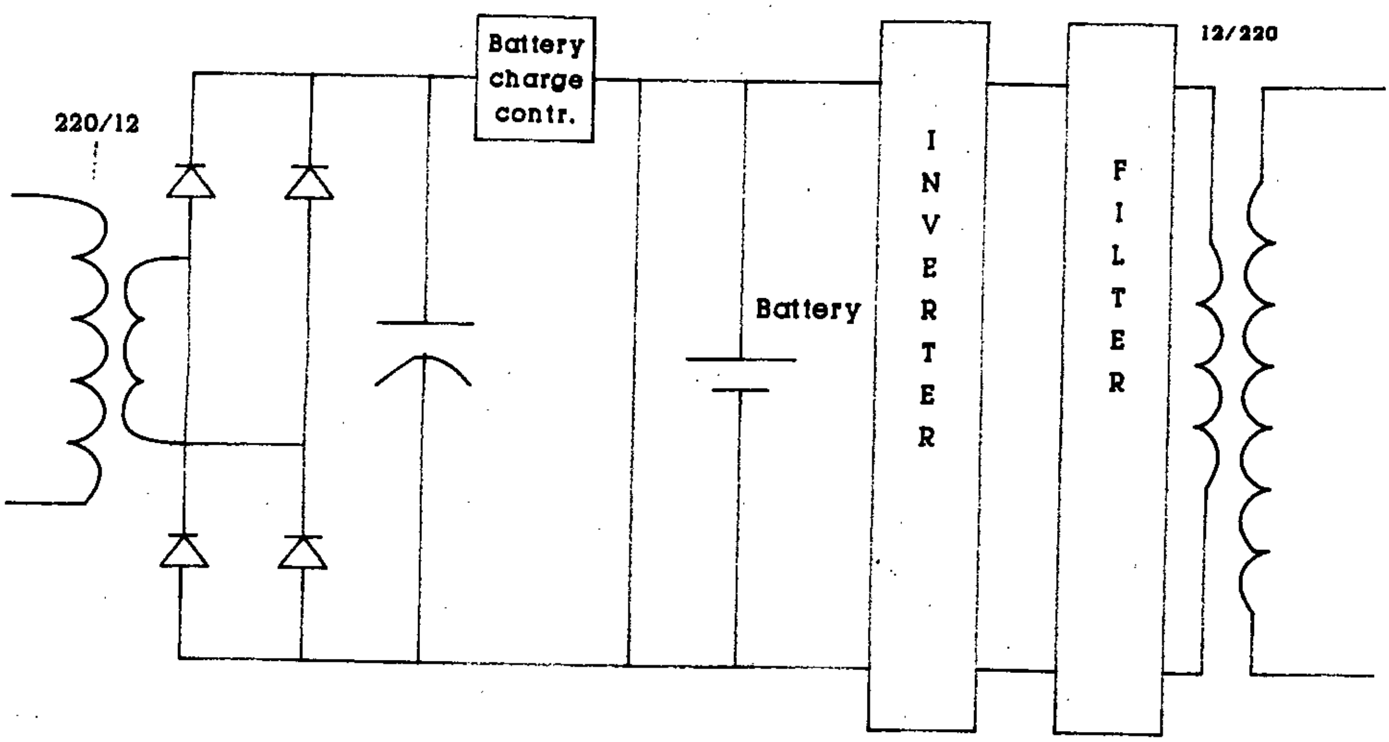


Figure 4.1(b) Possible circuit diagram of an UPS.

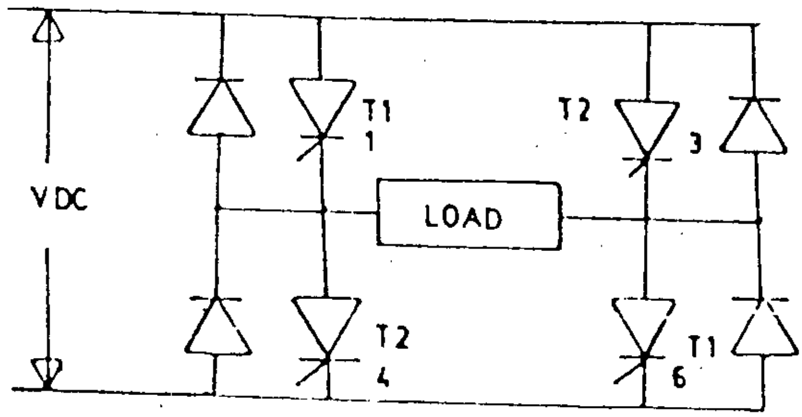


Figure 4.1(c) Inverter circuit of an UPS with SCR.

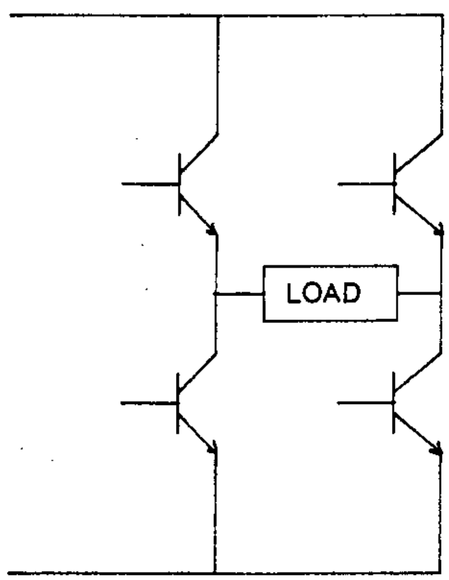


Figure 4.1(d) Inverter circuit of an UPS with Transistors.

3) battery charge controller

4) Inverter

5) Filter

6) Step up transformer

The remaining section describes the other three different parts. The purpose of the step down and step up transformer at the front and tail end of UPS are to match the system voltage with battery voltage and converted to the system voltage respectively. The front end rectifier converters stepped down ac to dc for charging the battery/battery banks and this rectifier may be single phase or 3 phase with or without phase control. For better harmonic performance more complicated pulse width modulated rectifier has also been suggested in the recent past for use in UPS. 7

4.2.1 Single phase inverter operation with Delta Modulation Switching:

In our experimental verification two laboratory SCR chopper have been used for the purpose of inverter with modulation applied for switching.

The delta modulation technique requires relatively simple circuitry to obtain the switching waveform for switching inverter switches. The operation of single phaseinverter as was made from two quadvart choppers is described as below.

The sequence of operation for the entire circuit (as shown in fig. 4.2) is

1. The inverter is connected to the source by closing the switch SW and all capacitors C_1, C_1', C_2, C_2' are charged up to $V_C = V$ volts via R_C resistors.

2. At $t = 0$, when the capacitor C_1 and C_1' are fully charged, SCRs Q_1 and Q_1' are turned ON and load current increases exponentially from zero to I_{max}.

3. At $t = t_{ON}$, SCRs Q_{11} and Q_{11}' turned ON initiating the commutation cycle and two oscillatory currents flow in the two ringing circuits C_1, L_1, Q_{11} and C_1', L_1', Q_{11}'. i_{C1} and i_{C1}' are initially negative. It is assumed that i_o remains sensibly constant at the value I_{max} throughout the commutation interval. It is also assumed that R_{C1} and R_{C1}' are sufficiently large to permit i_{RC1} and i_{RC1}' to be neglected in the analysis of the commutation circuit but is yet small enough to permit V_C to decay to the value V before the next commutation cycle is initiated.

4. After some time i_{C1} and i_{C1}' reverse in direction and Q_{11} and Q_{11}' turn OFF. Capacitor currents now flow

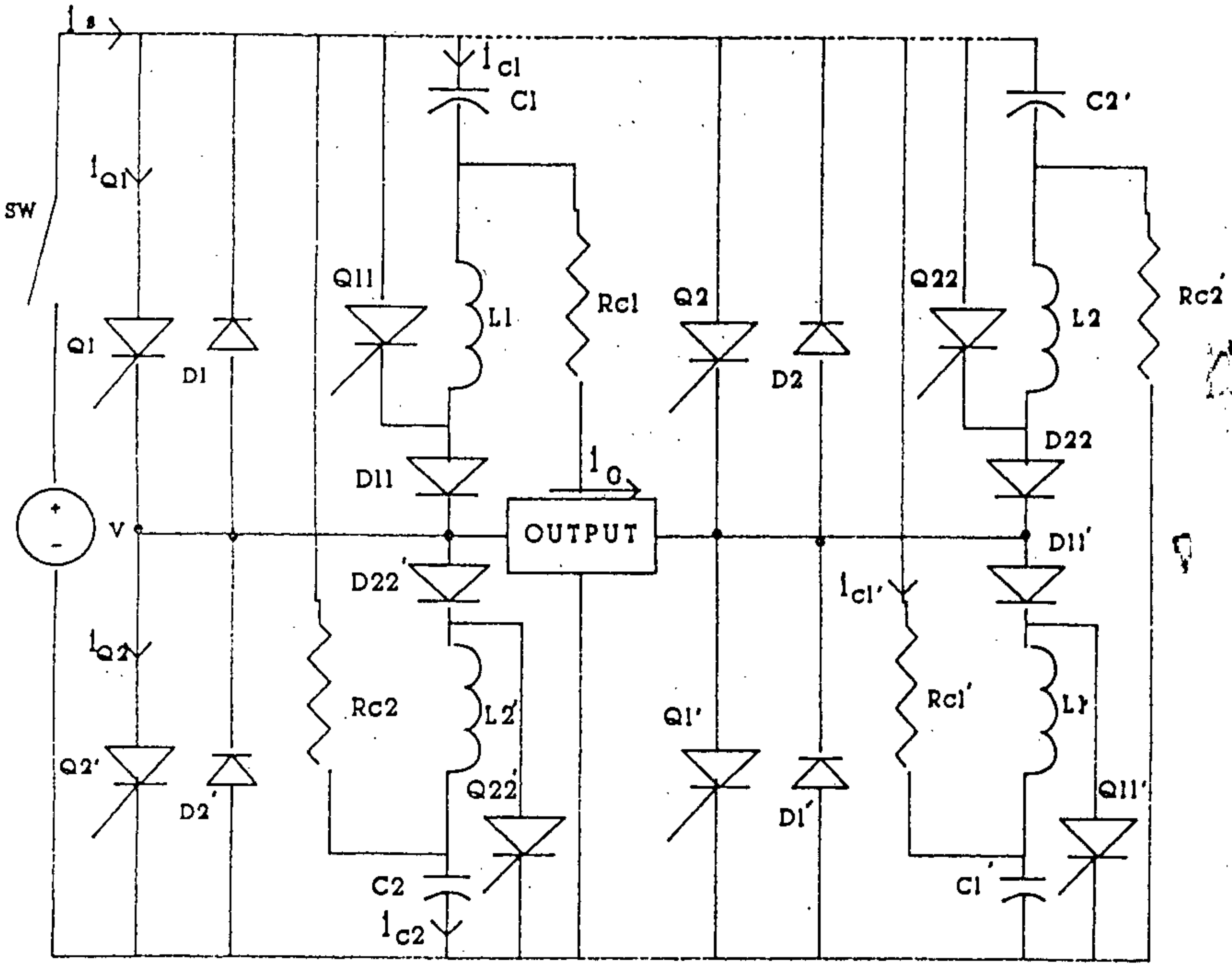


Figure 4.2 A single phase Inverter circuit.

through diodes D_{11} and D_{11}' and since the voltage across the SCRs Q_1 and Q_1' are zero, the oscillatory elements continue to be short circuited. For this part i_{C1} and i_{C1}' may be considered to flow in a negative direction through Q_1 and we get $i_{Q1} = i_o - i_{C1}$, and $i_{Q1}' = i_o - i_{C1}'$. Since i_o is assumed constant, i_{C1} and i_{C1}' reduces i_{Q1} and i_{Q1}' respectively.

5. When i_{Q1} and i_{Q1}' are reduced to zero by the increasing value of i_{C1} and i_{C1}' diodes D_1 and D_1' begins to conduct and the forward voltage drop across this diode commutates SCR Q_1 and Q_1'.

6. i_o decays exponentially and simultaneously V_c decays through R_c to $V_c = V$.

7. At $t = T/2$, when $i_o = I_{min}$, Q_2 and Q_2' are turned ON and the above sequence of operation are repeated.

4.3 Electrical Circuits of Battery Charge Controller :

The battery charge controller unit consists of two parts:
(i) Over voltage breaker ii) Low voltage cut off unit.

i) Over voltage breaker:

When electric supply from PDB is available the battery will be fully charged by that supplied energy. But if the battery is overcharged then the battery plates will be damaged. The function of the over voltage breaker is to safeguard the battery from being overcharged. If the voltage of the battery goes beyond a certain limit (12 volts) then the over voltage breaker will disconnect the supply from the battery thereby stopping the charging. There are two indicating lights; green during charging and red when breaker will disconnect battery from being overcharged. Figure 4.3 shows the circuit diagram of over voltage breaker.

Principles of Operation:

In the circuit the function of D_2 is to block any power flow from battery to line during failure of electricity. Any input at inverting terminal(2) of operational amplifier will appear as negative at output(6) but any input at non-inverting terminal(3) will appear as positive at output (6). The normally close contact of the relay is connected to the battery. The reference voltage at 2 will be less than or equal to 2.3 volt since zener diode is of 2.3 volt rating. The reference voltage will be compared with sample voltage derived from the variable resistance R. Resistance R is so adjusted that for panel voltage below 12 volt the sample voltage will be less than or equal to reference voltage. As a result, a negative voltage will appear at the base of the NPN transistor and the relay will not operate and

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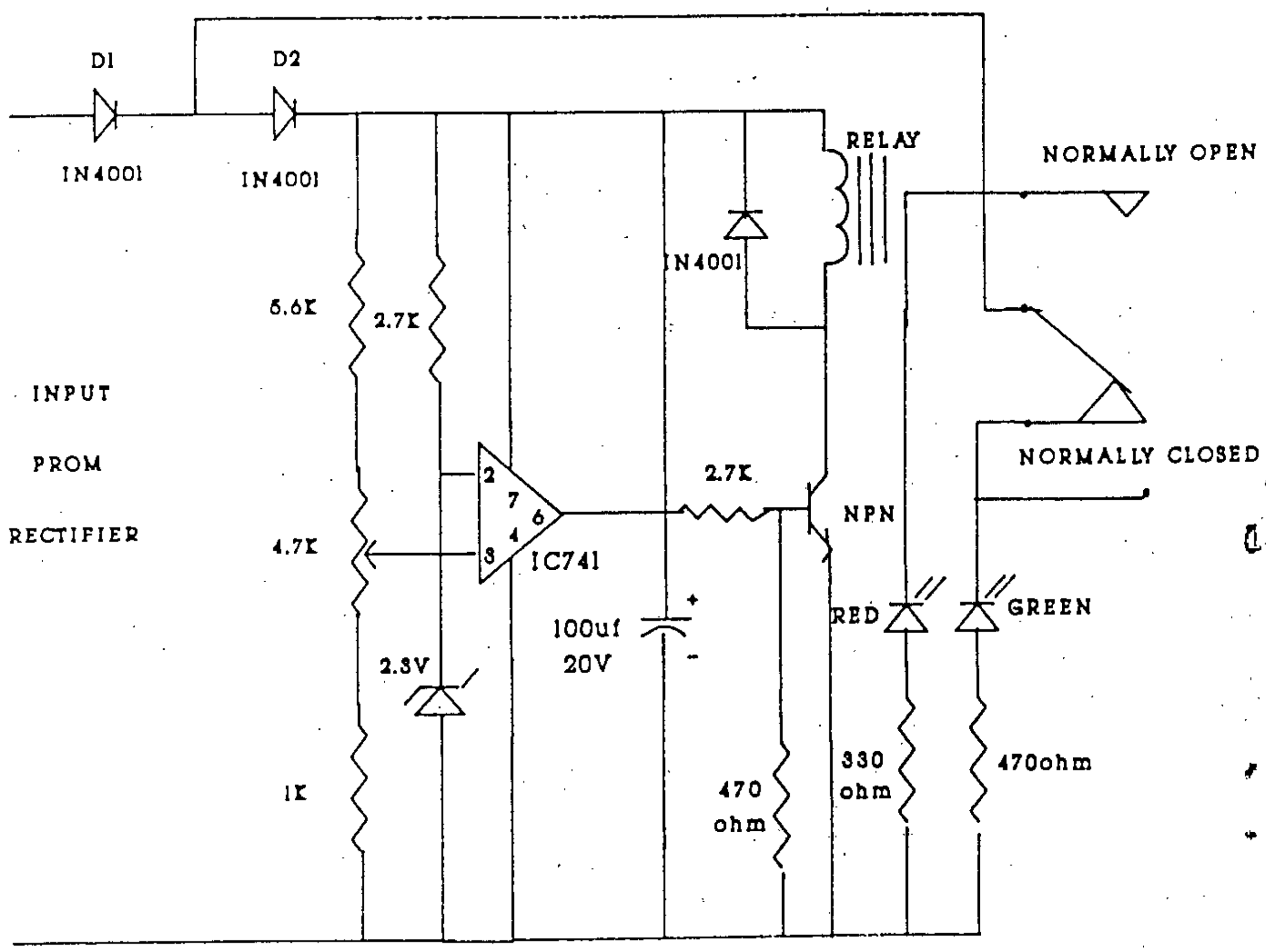


Figure 4.3. A circuit diagram of over-voltage breaker.

green LED (Light Emitting Diode) will glow. But if the panel voltage is more than 12 volts then the sample voltage will exceed reference voltage and a positive voltage will appear at the base of the transistor. So the relay will operate thereby disconnecting the battery from the supply and red LED (Light Emitting Diode) will glow.

ii) **Low voltage cut-off unit:**

If the voltage of the battery supplying energy to the load falls below 11.5 volts, then the control unit will disconnect the battery from load thereby saving the battery cells from damages by overdischarge. Figure 4.4 shows the circuit diagram of low voltage cut off unit.

Principle of Operation:

In this case, unlike over voltage breaker power will be supplied to load from battery when the relay operates. The variable resistance R is so adjusted that for voltage above 11.5 volts the sample voltage at 3 will be greater than reference voltage and positive voltage will appear at the base of the NPN transistor. So the relay will operate and green LED (Light Emitting Diode) will glow. But if the battery voltage is equal to or less than 11.5 volts then reference voltage will be greater than sample voltages and negative voltage will appear at the base of the NPN transistor. Hence the relay will not operate thereby

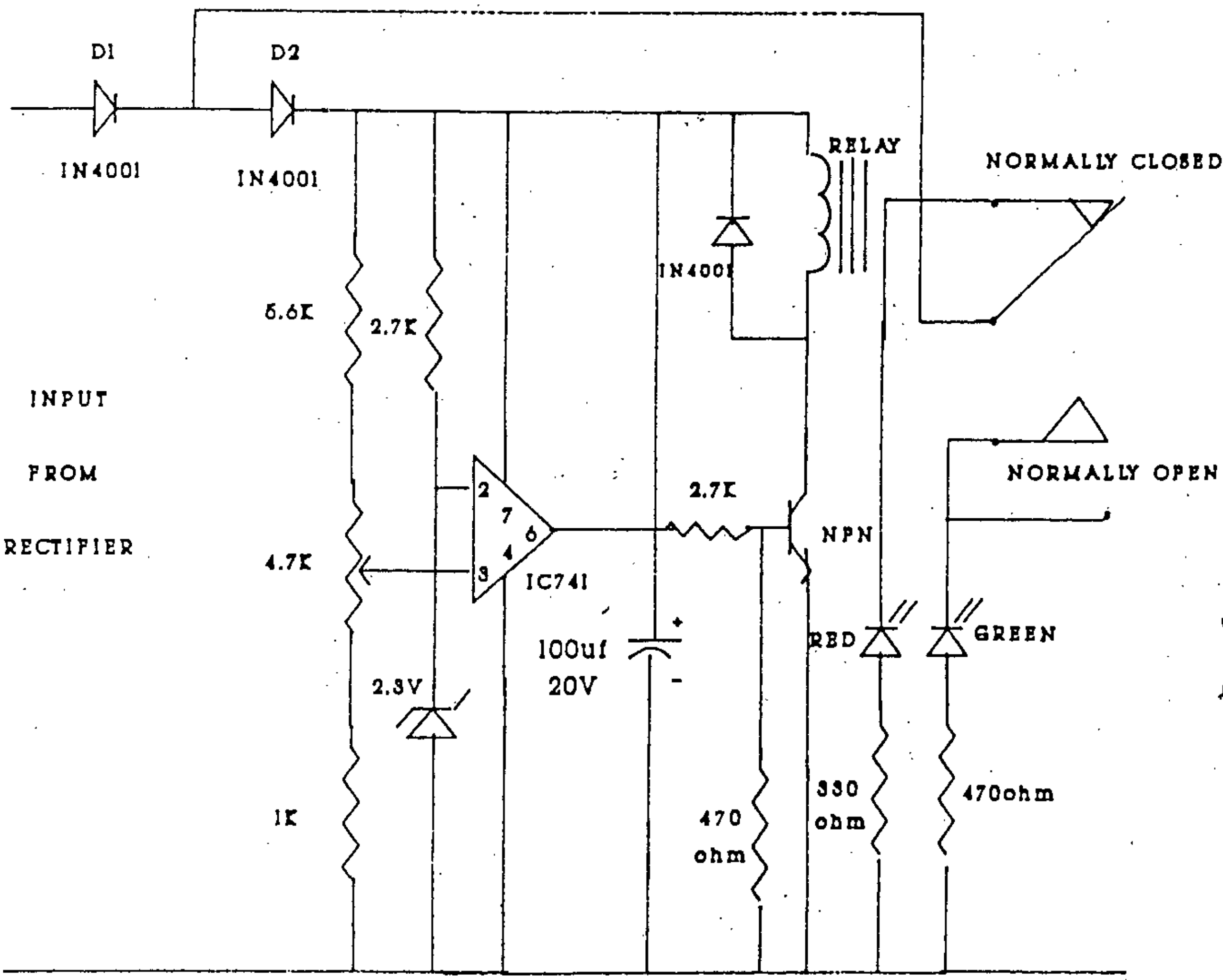


Figure 4.4. A circuit diagram of low voltage cut-off unit.

disconnecting the battery from the load and the red LED (Light Emitting Diode) will glow.

4.4 Choice of Battery :

Selection of battery is one of the important phenomenon of UPS system design. At fist we are to decide that for how long the UPS will have to supply energy to the load connected to it during the failur of PDB line? Let us suppose that our UPS is connected to a load with input voltage 220V, and current requirement is 5A. Considering unity power factor the input will be (220 x 5) watts i.e. 1000 watts. This load is connected to the secondary of the step up transformer and the primary of the transformer is at 12V, so current flowing through this primary windings is approx. 84 amps so for one hour operation of the UPS we have taken a battery of 100 Amps Hr.

4.5 Implementation of Variable Step RWDM Circuit for PWM inverters.

Fig.4.5) 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 reversed the polarity of V_1 at the input

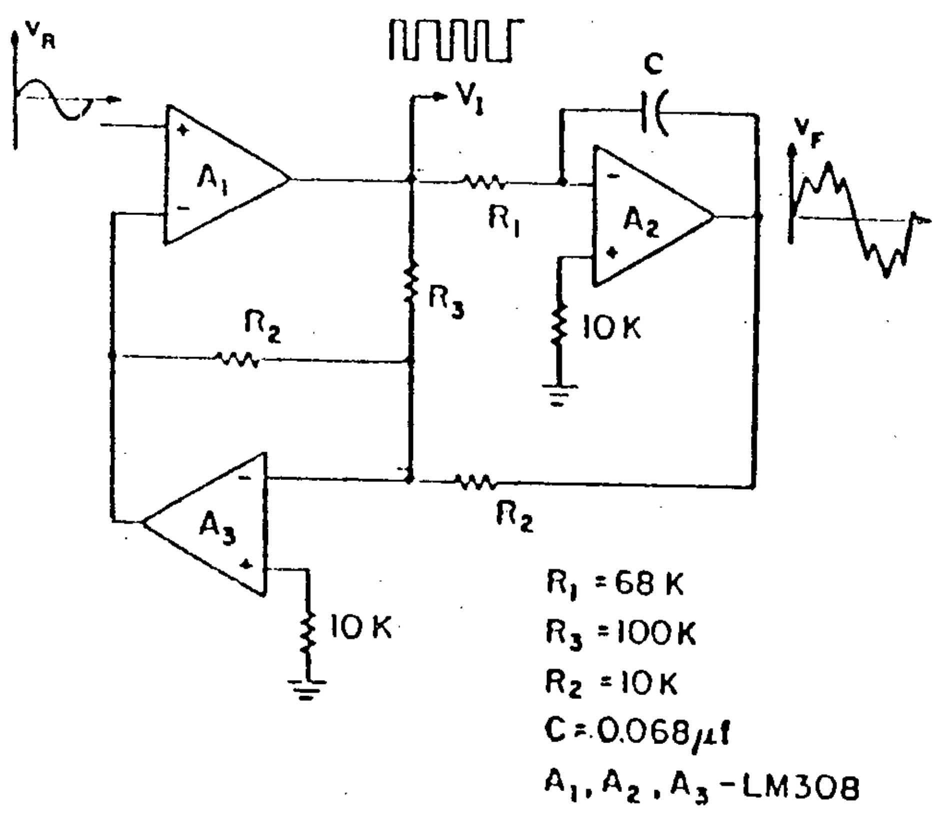


Figure 4.5 Practical circuit for producing switching waveform of delta modulated inverters.

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 w_r. So in this circuit we can vary the window width ΔV by chaging the resistors of R_2 or R_3 as the ratio of 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 are shown in Fig. 4.6.

4.6 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 correspons to two transition points in the modulated waveform V_1, each of the these transition points corresponds to a commutation in the inverter.

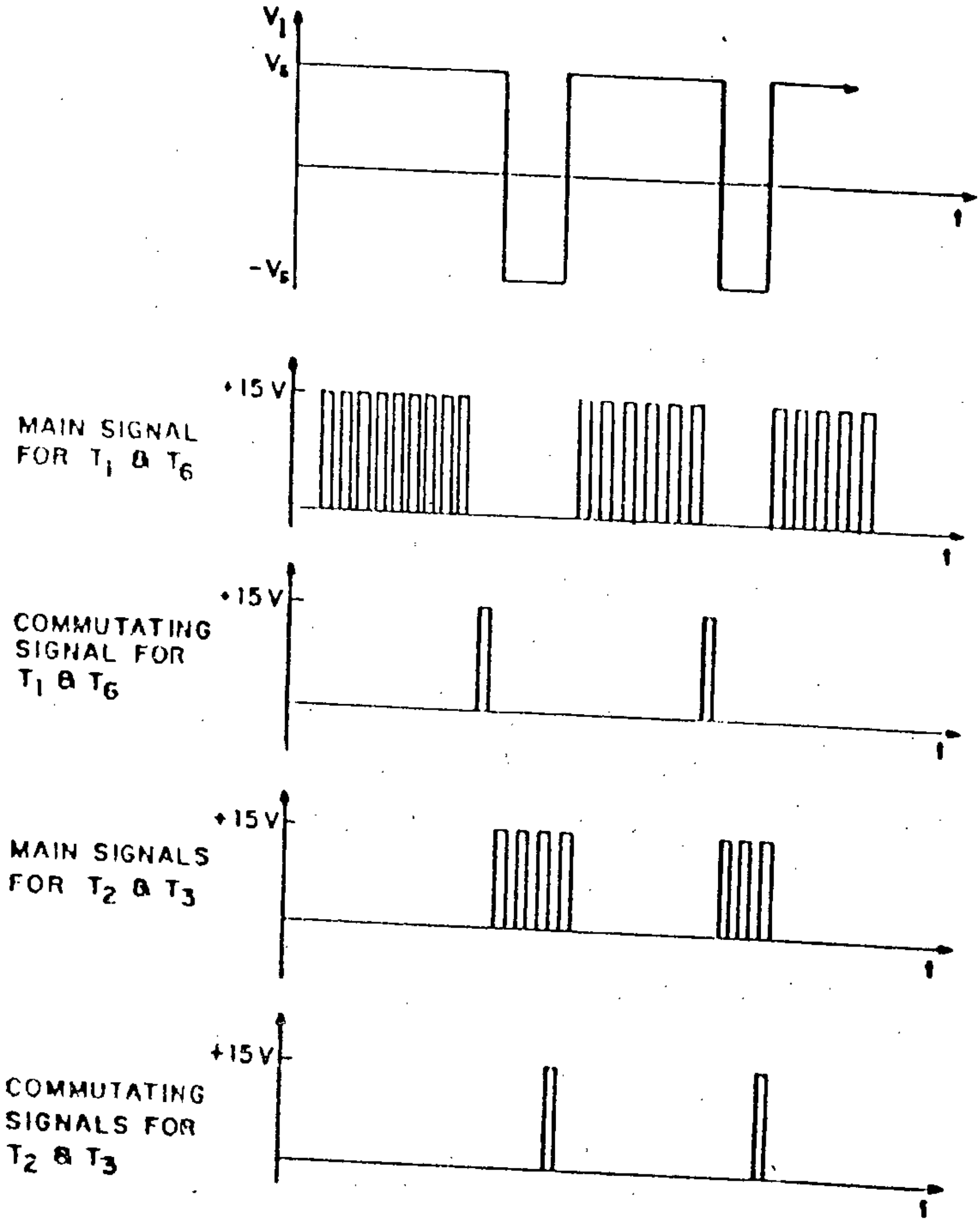


Figure 4.6 Basic switching signals for the main and commutation thyristors of a single phase full bridge inverter.

In the delta modulation, if the window width ΔV is kept constant, the ripple frequency w_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. 4.5, the window width ΔV is determined by the circuit constant and the logic supply voltage as

$$(\Delta V / V_S) = (R_2 / R_3) \quad (4.1)$$

For particular V_R, the maximum number of commutation is given by [27]

$$N_{CM} = (1/2R_1C)(R_3/R_2) \quad (4.2)$$

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 frequecny can be changed by changing ΔV or slope of the carrier wave. 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.

4.7 Experimental Verification for Delta Modulation Technique:

This section deals with the experimental verification of the results of delta modulation based UPS system. The verification of the main features of delta modulation is experimentally carried out and also compared it with conventional square wave. It should be mentioned here that due to the unavailability of spectrum analyzer in our laboratory the output wave at the transformer secondary can not be analyzed to have the harmonics content of the delta modulated wave and conventional square wave inverter UPS. But a trade off analysis has been made to find out the inductance required to make the output sinosuidal.

4.7.1 Experimental Results:

Figure 4.7 is the photograph of the carrier and modulated wave generated by the practical circuit of figure 4. .

Figure 4.8 is the photograph of firing signals of SCRs. Figure 4.9 is the main SCR and corresponding commutation signal.

Figures 4.10 and 4.11 show the voltage and corresponding current waveforms with resistive load at different frequencies.

Figure 4.12 is the photograph of one of the main pulses of the SCRs along with corresponding commutation pulses.

Figure 4.13 is the PWM pulses with corresponding commutation pulses for chopper mode of operation.

Figures 4.14 and 4.15 show the output of DM and square wave

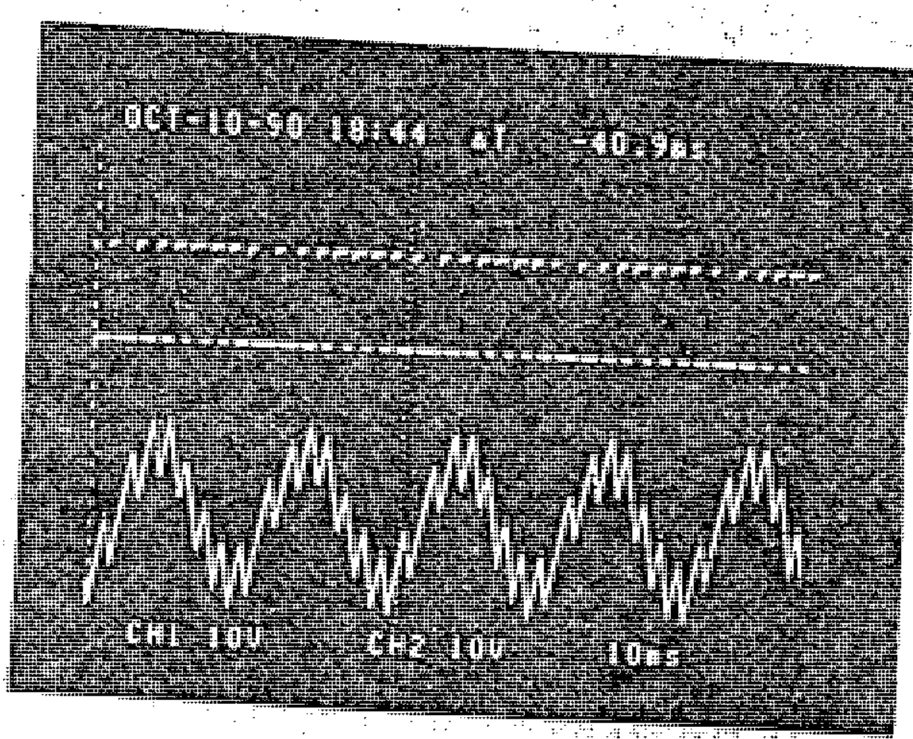


Figure 4.7. Waveforms of a rwdm modulator
a) estimated of carrier wave.
b) PWM wave.

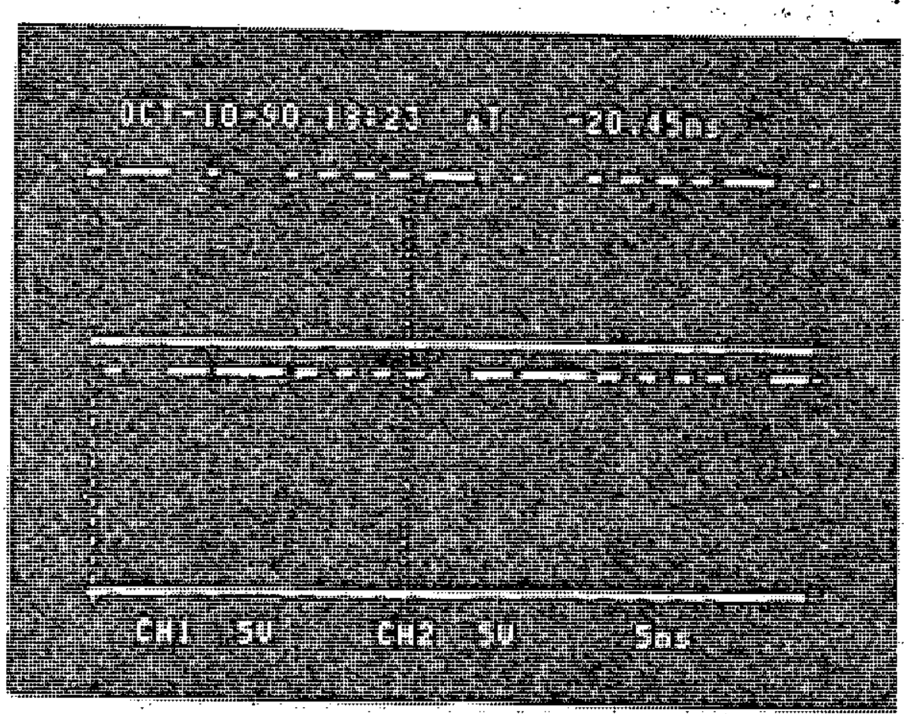


Figure 4.8 Main SCR firing signals of an inverter.

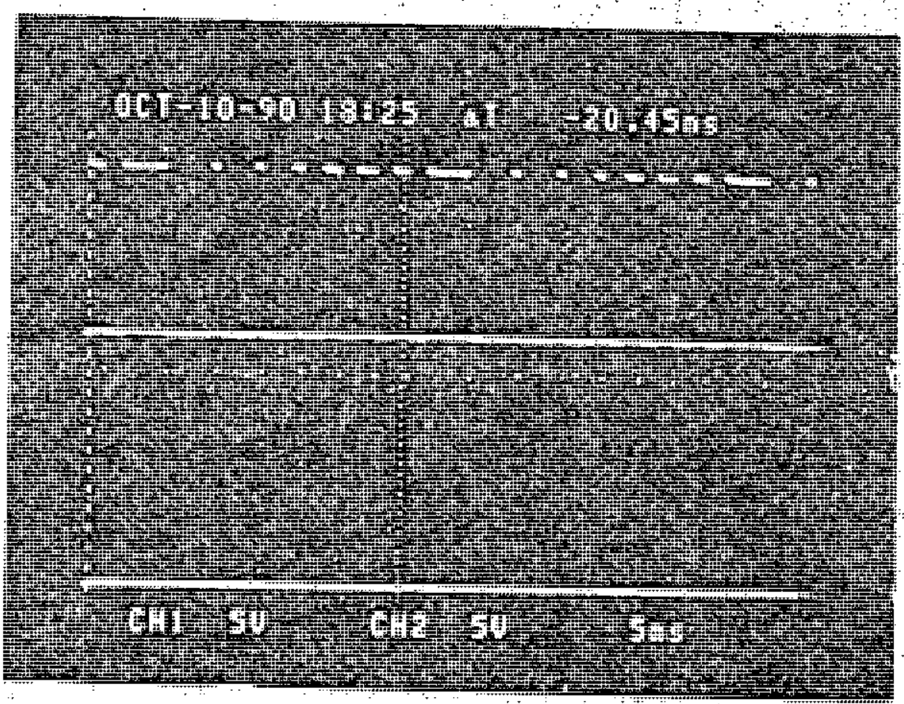
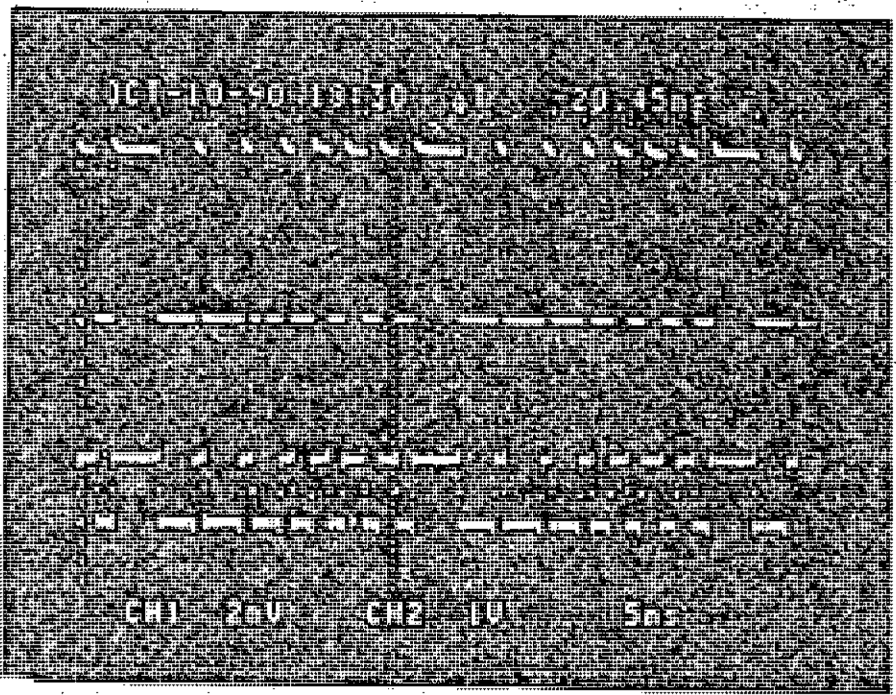


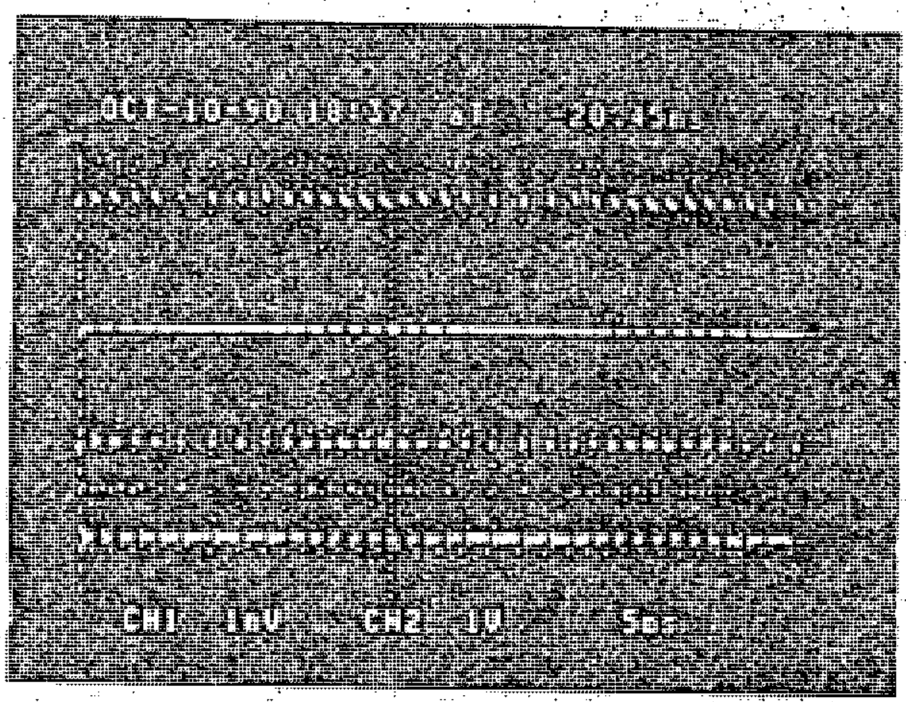
Figure 4.9 Main SCR and corresponding commutation signal of an inverter.



(a)

(b)

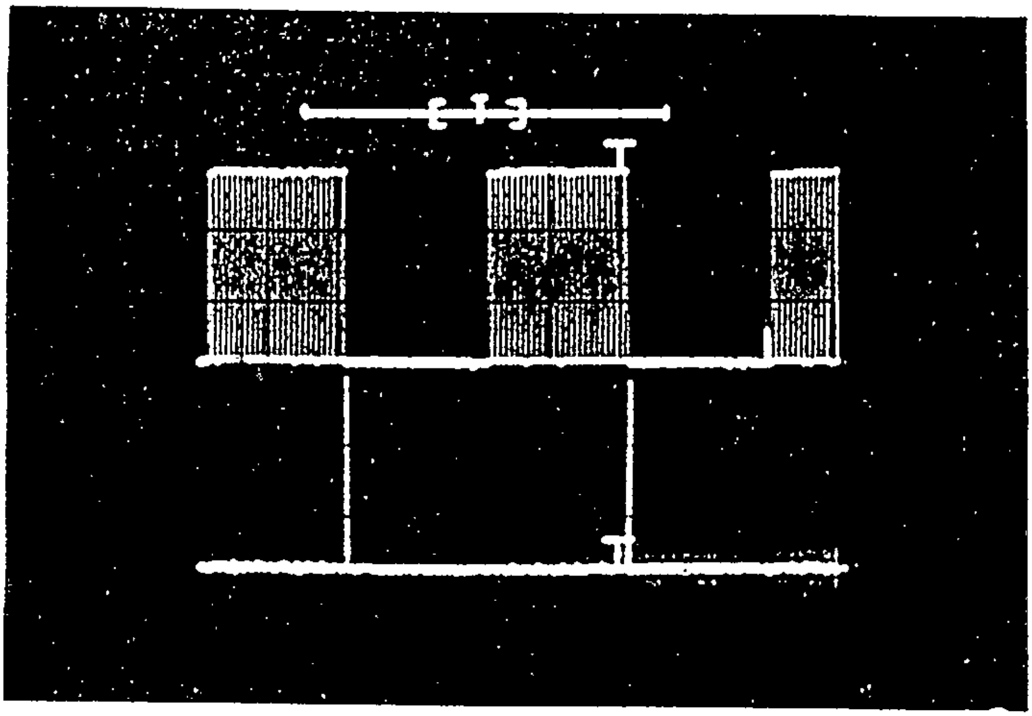
Figure 4.10 Photograph of
a) Voltage waveform of PWM inverter.
b) Corresponding current waveform with resistive load.



(a)

(b)

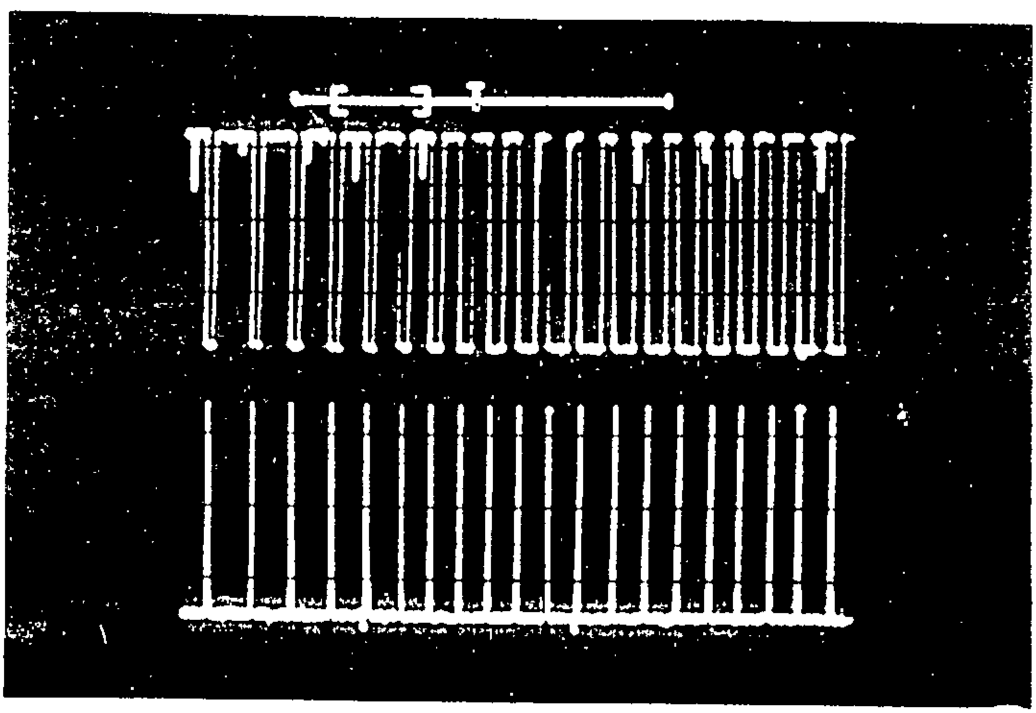
Figure 4.11. Photograph of
a) Voltage waveform of PWM inverter at different frequency.
b) Corresponding current waveform with resistive load.



(a)

(b)

Figure 4.12 Photograph of a
a) One of the main pulses.
b) Corresponding commutation pulses.



(a)

(b)

Figure 4.13 Photograph of
a) PWM pulses.
b) Corresponding commutation pulses for chopper mode of operation.

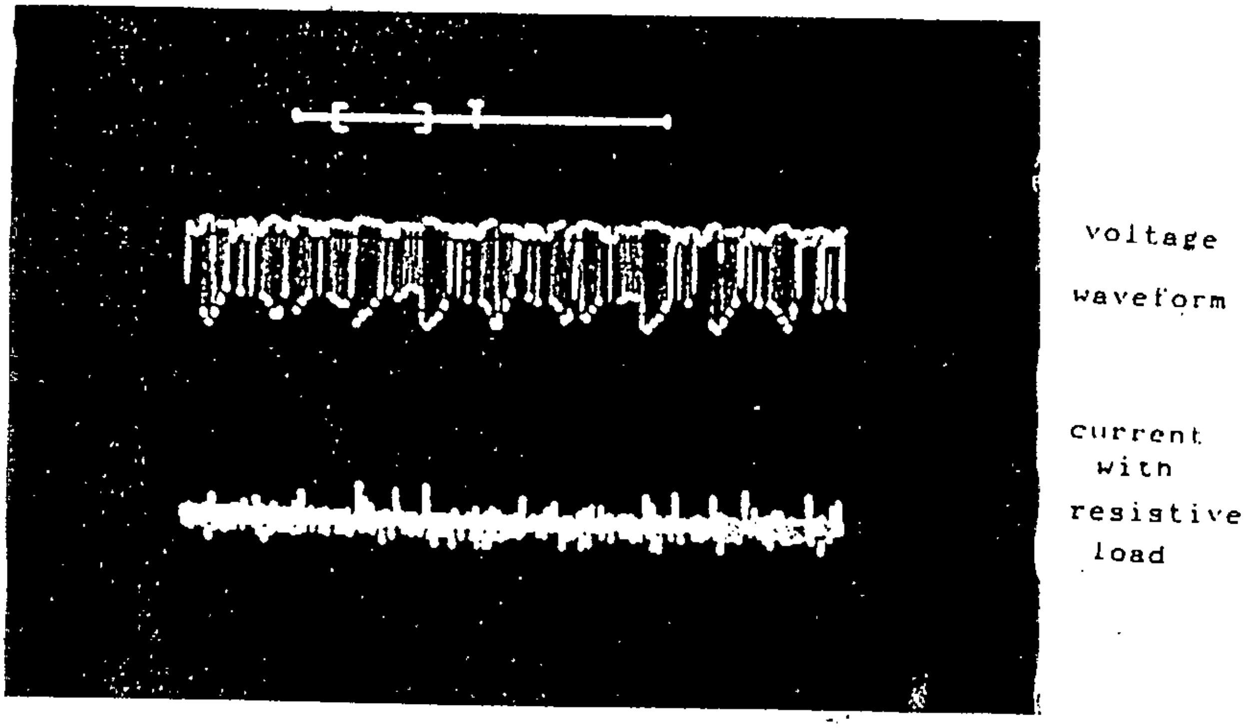


Figure 4.14 DM inverter output.

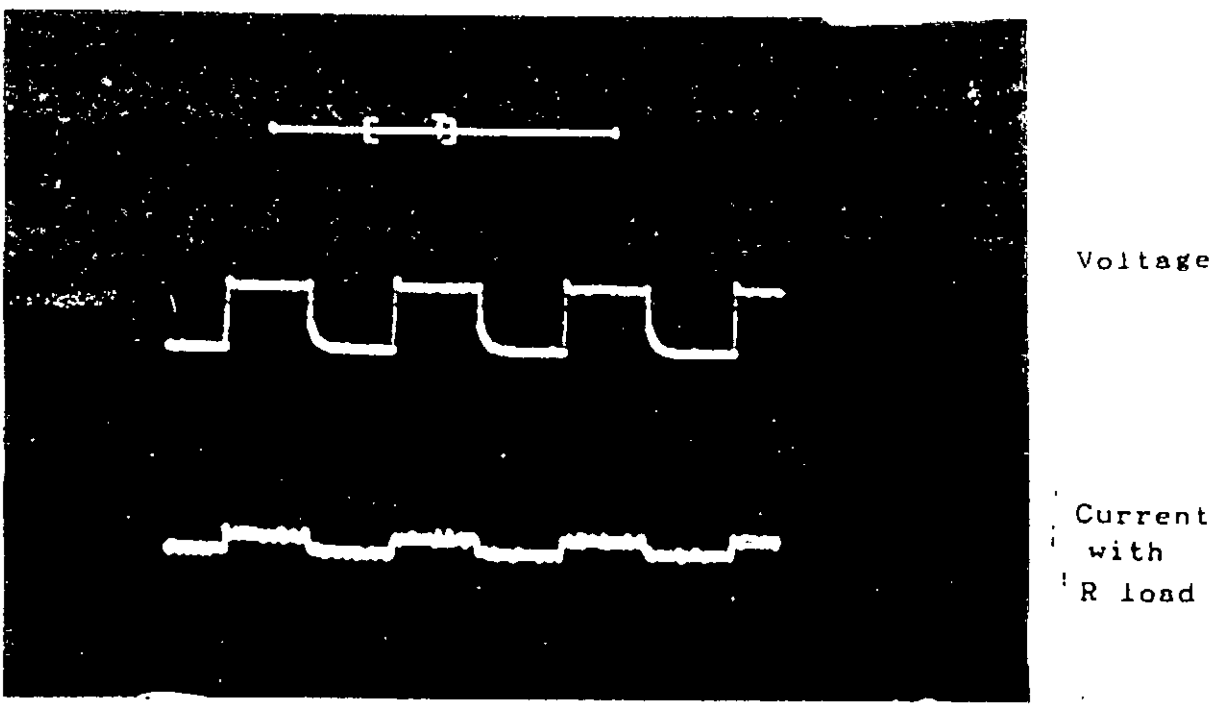


Figure 4.15 Square wave inverter output.

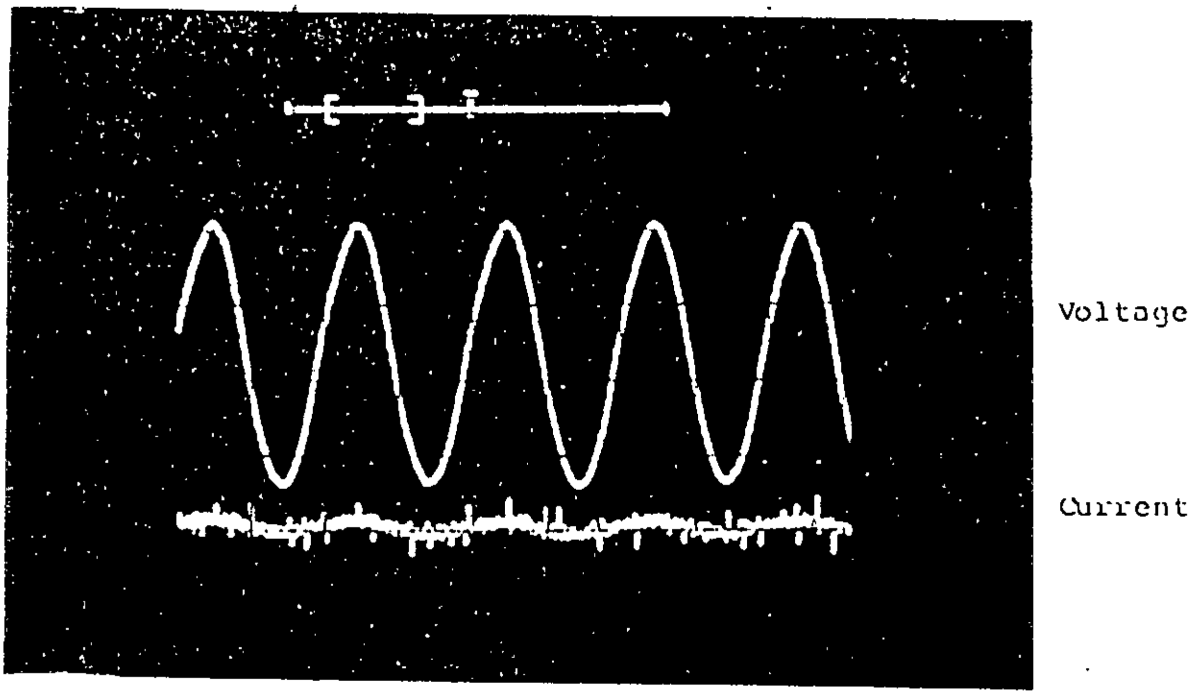


Figure 4.16 Output of UPS with PMW inverter.

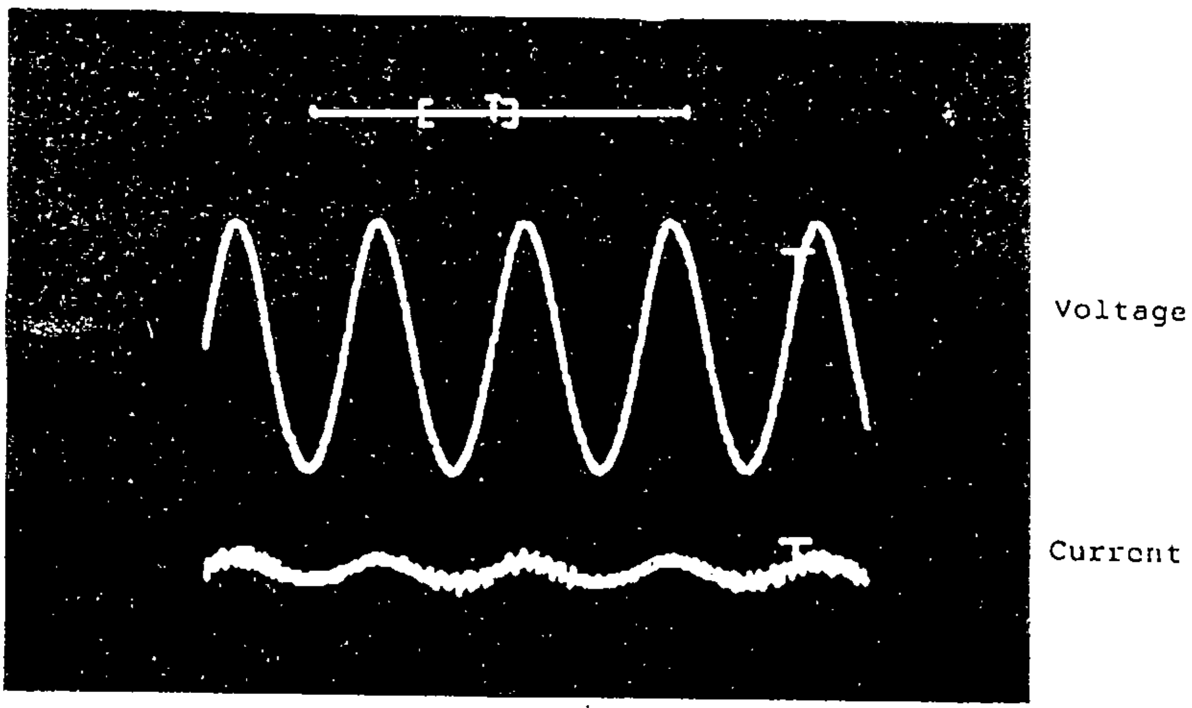


Figure 4.17 Output of UPS with square wave inverter.

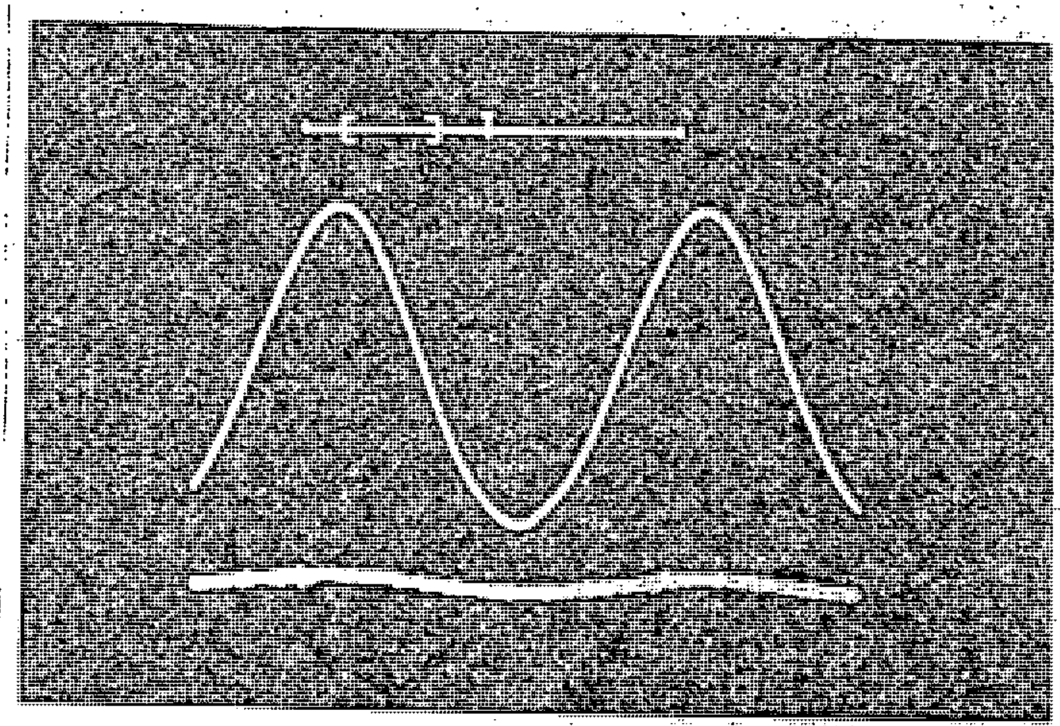


Figure 4.18 Expanded output of UPS with square wave inverter.

inverter respectively.

Figures 4.16 and 4.17 show the output of UPS with PWM inverter and square wave inverter respectively. From these two figures we can easily find that the output of the PWM inverter is sinusiodal but that of square wave inverter is not sinusiodal which can be more clearly explain with the expanded view given in figure 4.18.

4.8 Analysis of Filter Size :

The Fourier analysis of a square wave having maximum value 1 can be expressed as

$$e = (4/\pi)\sin(wt)+(4/3\pi)\sin(3wt)+(4/5\pi)\sin(5wt)+\ldots \quad (4.3)$$

It is clear from the equation that the third harmonic component is 33% of the fundamental. Our objective is to reduce the value of third harmonic component by a low pass filter. As the third harmonic will be reduced other harmonics will be reduced. Let us assume that we want to reduce the third harmonic current to 1% of the fundamental so that the output will be nearly sinusoidal. Assuming a inductance as a filter, the required value of inductance be L_{sq}. With this inductance fundamental value of current will be,

$$I_{1sq} = \frac{V_1}{2\pi f L_{sq}} \quad (4.4)$$

where, V_1 = fundamental value of voltage

Since third harmonic value of voltage is $0.33\ V_1$ the third harmonic value of current will be,

$$I_{3sq} = \frac{0.33V_1}{2\pi \times 3fL_{sq}} \tag{4.5}$$

Our target is to make $I_{3sq} = 0.01\ I_{1sq}$ (4.6)

now,

$$L_{sq} = \frac{0.33V_1}{2\pi \times 3f \times 0.01 \times I_{1sq}} \tag{4.7}$$

Let us consider the case of [illegible] [illegible] DM switching strategy. From fig 3.7 (e) we see that 19th harmonic component has a considerable value and it is nearly 38% of fundamental so to make 19th harmonic current to 1% of fundamental let us assume that required value of inductance is L_{dm} if the fundamental value of voltage is same as square wave i.e. V_1 then

$$I_{1dm} = \frac{V_1}{2\pi fL_{dm}} \tag{4.8}$$

And

$$I_{19dm} = \frac{0.38\ V_1}{2\pi \times f \times 19 \times L_{dm}} \tag{4.9}$$

and required condition is,

$$I_{19dm} = 0.01\ I_{1dm} \tag{4.10}$$

So,

$$L_{dm} = \frac{0.38 x V_1}{2\pi x f x 19 x 0.01 x I_{1dm}} \tag{4.11}$$

If $I_{1dm} \approx I_{1sq}$

then $L_{sq} = 5.5\ L_{dm}$

so, inductance required for square wave is 5.5 times of that required for PWM mode. So it can be inferred that cost of the filter will be considerably less in the case of PWM mode.

It is also revealed from the photographs of figs. 4.16, 4.17 and 4.18. In these figures we see that the output of dm inverter is sinusoidal but it is not perfectly sinusoidal in square wave inverter so more inductance is required to make it sinusoidal.

CHAPTER 5

5.1 Summary and Conclusions:

In this research an UPS has been successfully tested with the DM switching strategy to operate the inverter of the system. The performance of the inverter was analyzed and evaluated in terms of reduction of the size of filters and components of the UPS. A comparison has been carried out to quantify the reduction of size of filter as compared to that of UPS having a square wave inverter. Delta modulation proved its better performance fo inverter waveform control in terms of controllability and harmonic reduction. The rectangular wave delta modulator has been selected for inverter switching.

The features of delta modulation, namely easy implementation, lower harmonics at the output of the inverter, transition of from multiple pulse mode to single pulse mode, easy harmonic and commutation control have been verified. A Fourier analysis was done for the delta modulated waves for different window widths ΔV and also for different slopes, S of carrier wave. The study has been made to find out the inverter output voltage in which dominant harmonics are low. The theoretical results of the harmonic behavior of rectangular wave delta modulated inverter was substantiated by experimental studies.

Different features, performances and analysis of the rectangular wave delta modulator has been studied in this thesis work. Due to unavailability of the spectrum analyzer it was not possible to show that the low order harmonics have been eliminated from the output of the UPS. However, it has experimentally been shown that the output at the secondary side of the output transformer is sinusoidal in the case of DM inverter and also nearly sinusoidal in the case of square wave modulation. Analytically it is shown that inductance required in the case of square wave inverter based UPS is 5.5 times higher than that required for dm inverter based UPS. So the filter size will decrease and would reduce the manufacturing cost. Moreover DM switching provides easy control on output and the output can be varied by changing the input parameters such as,

i) frequency of modulated wave

ii) slope of the carried wave and also

iii) window width without any change in the circuit.

5.2 Recommendation for Future Work:

Delta Modulation is a variation of the pulse code modulation (PCM) used in communication networks. It is the simplest known method for converting analog signal to digital form. Delta modulation switching strategy in inverters provides low harmonics, low number of commutations and easy control of the inverter output voltage without implementational complexities as required in other switching strategies. In our present work we have examined delta modulation with slope, S and window width, ΔV as variable parameters. We have changed ΔV symmetrically but even better result can be achieved by changing ΔV asymmetrically, but it will make the circuit complex. We have left it for future study. Again the step down transformer can be replaced by only one transistor as shown in fig 5.1. The modulating pulse at the gate will chop the input signal and the capacitor will be charged at the dc value of the chopped pulse. So by varying the modulated pulse the dc value of the chopped pulse can be fixed at 12V. It is a innovative idea and requires further theoretical analysis.

To minimize the manufacturing cost, transistor type inverter can be used. For battery charger the over voltage and low voltage protection circuits may be further improved and modernized through use of solid state switches and printed circuit board (PCB) layout of the circuit.

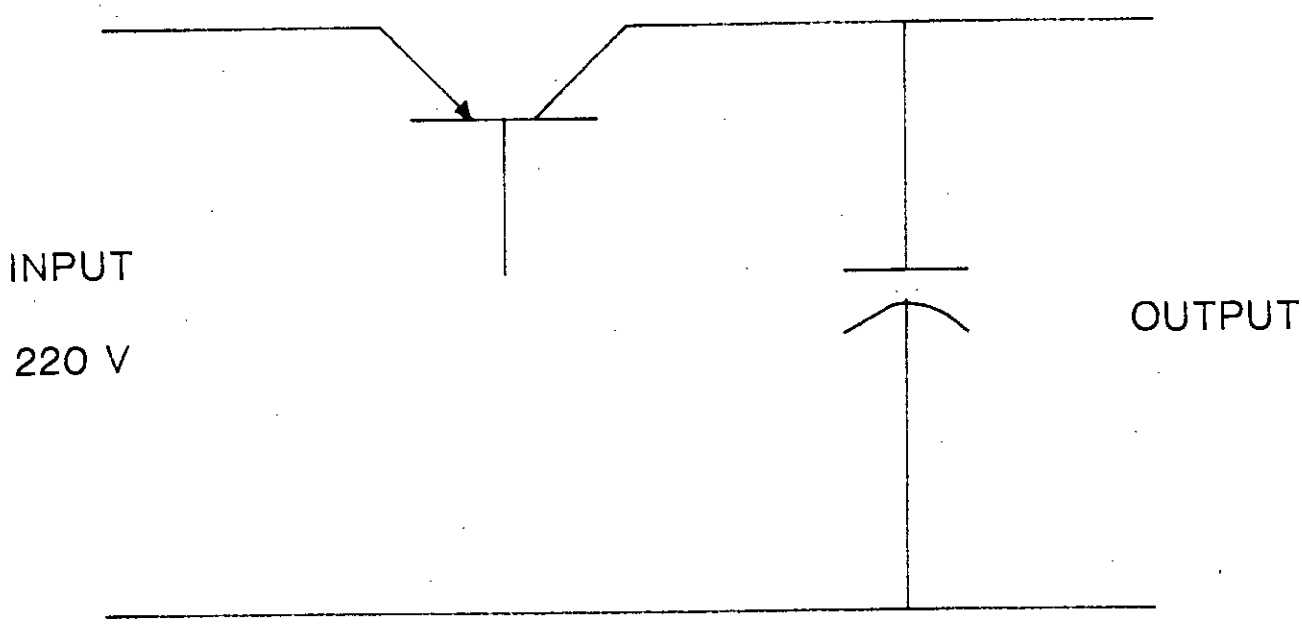


Figure 5.1 Chopper Circuit

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