POWER FACTOR CORRECTION OF A DIODE RECTIFIER USING DUAL SLOPE DELTA MODULATION TECHNIQUE

by

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APPROVAL

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TABLE OF CONTENTS

LIST OF FIGURES

Chapter 3: Study of Power Factor Correction of a Single Phase Diode Rectifier

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ABSTRACT

Now a days power converters with high power factor are becoming part of the electronic equipment. These power converters generally use high frequency switching and have three distinct advantages over their counterpart, the linear power supplies. The advantages are smaller compact size due to elimination of step down transformer and small filters due to high frequency operation. They are more efficient because the regulating switches work in switching (ON/ OF) mode ensuring minimum device loss. The other advantages are their output voltages are isolated and can be controlled for a wide range of input voltage fluctuation by ON/OFF ratio (duty cycle) control.

At present power converters with high power factor commonly use high frequency multiple pulse or sine triangular modulation to generate controlling signals of switching devices. Delta modulation technique has been adopted in many power converters for easy implementation and versatile control. In this Thesis possible use of dual slope delta modulation (one form of delta modulation) technique for an efficient power factor correction of a diode rectifier has been investigated. The implementation of this method requires the use of a single switch boost chopper. The switch is activated by dual slope delta modulation technique. The effect of the switch at the output and input side of the diode rectifier is analysed. The converter draws sinusoidal ac currents from the ac source with nearly unity power factor while operating at a fixed switching frequency. The theoretical analysis has been verified by the practical hardware implementation. From theoretical and practical analysis it is clear that power factor correction of a diode rectifier using dual slope delta modulation is possible, advantageous and easy to implement.

CHAPTER 1

BASICS OF POWER FACTOR CORRECTION OF A SINGLE PHASE DIODE RECTIFIER

1.1 Introduction

The non ideal character of the input current drawn by the diode rectifiers creates a number of problems for the power distribution network and for other electrical system in the vicinity of the rectifiers. These are:

a. Phase displacement between the current and the voltage (fundamentals) increases reactive power causing need for excess volt-ampere rating of power equipment,

b. Low input power factor,

c. Lower rectifier efficiency and

d. Input ac mains voltage distortion because of the associated higher peak currents.

International agencies have set standards which are to be strictly followed for all electrical equipment. To conform to the standards set by the international agencies, system designers are now increasingly incorporating active input power factor correction methods. A number of control methods have been presented by many authors to improve the input power factor of ac to dc rectifier [1]-[12]. In all cases it is found that the power factor correction circuit or switches are used on the output side of the rectifier. The modulation techniques used for switching the power device are various hysteresis current [1]-[2], [7], [10] and other PWM techniques [3]-[6]. The hysteresis current control technique is complex and difficult to implement because it requires a input synchronization logic. Other reported PWM methods used are easier than hysteresis current control technique but their practical implementation is difficult. Delta modulation scheme, particularly the dual slope delta modulation which provides voltage control mechanism will be investigated for rectifier control due to its easy implementation and versatility in this Thesis.

1.2 Rectifiers

A rectifier is a circuit that converts an ac signal into a unidirectional signal. Diodes are used extensively in rectifiers.

1.3 Single Phase Full Wave Diode Rectifiers

The circuit diagram of a single phase full wave diode rectifier is shown in Fig-1.1. During the positive half cycle of the input voltage, the power is supplied to the load through diodes D1 and D2. During the negative cycle diodes D3 and D4 conducts. The various waveforms are shown in Fig-1.2.

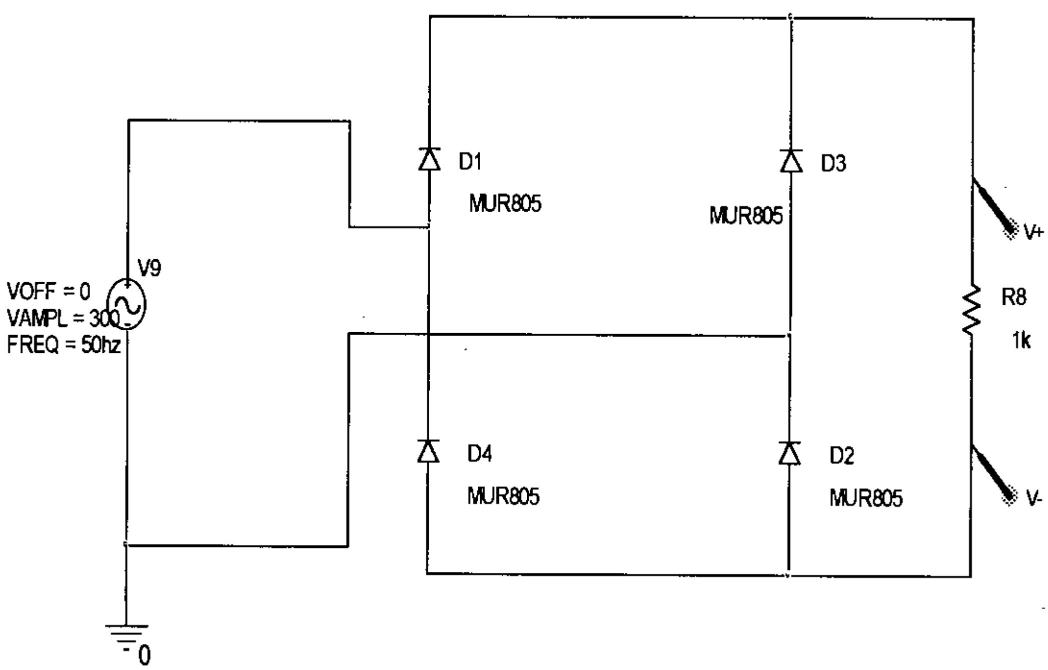


Fig-1.1: Single Phase Basic Diode Rectifier Circuit

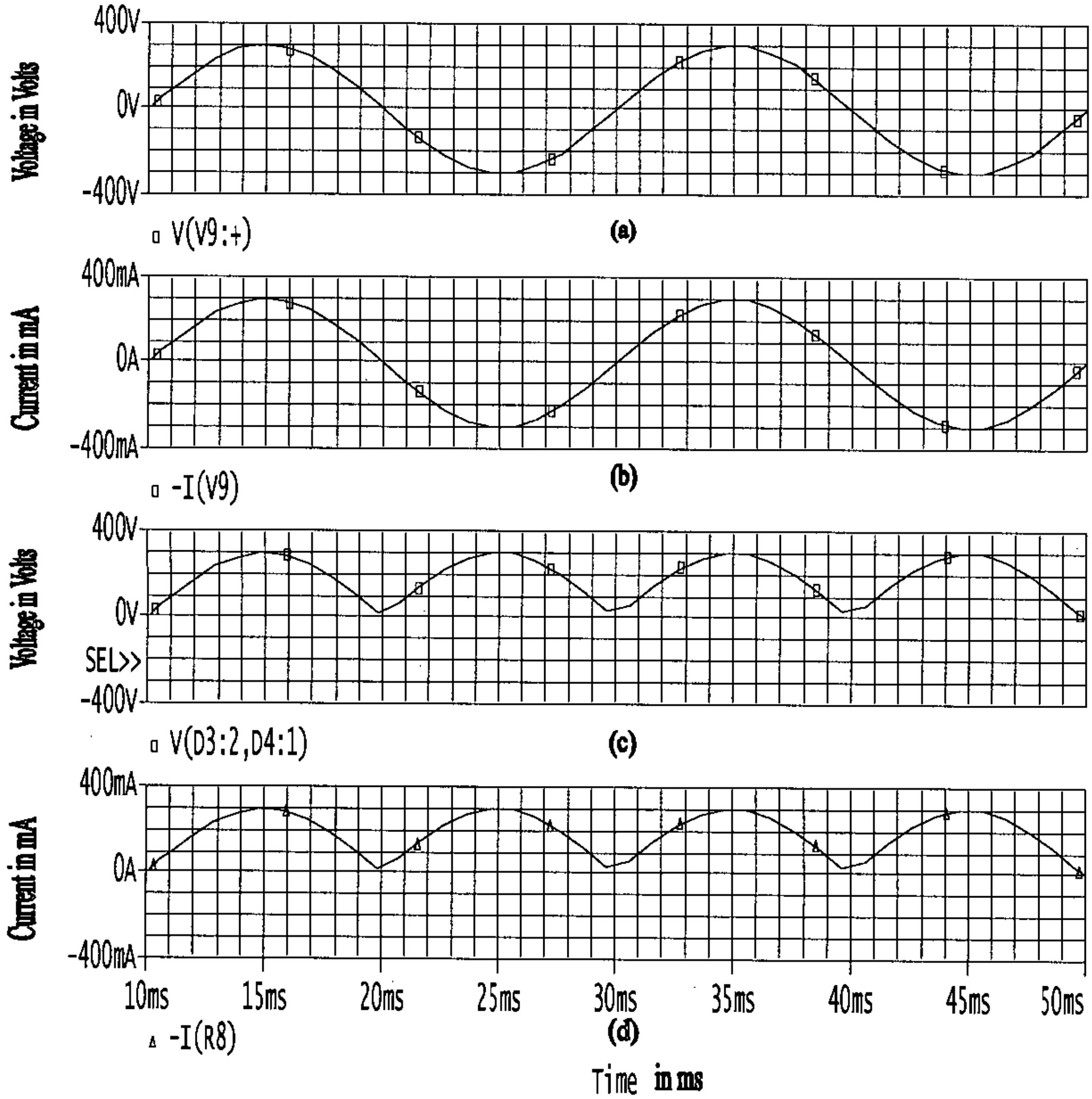


Fig-1.2: Various Waveforms of a Basic Diode Rectifier

(a) Input Voltage,

(b) Input Current,

(c) Output Voltage and

(d) Output Current.

If we analyse the input voltage, output voltage and input current, we find all waveforms are sinusoidal. From the circuit of (Fig-1.2) the output we get is a pulsating dc. To get the pure dc voltage the output is passed through a capacitor C_1 which is shown in Fig-1.3.

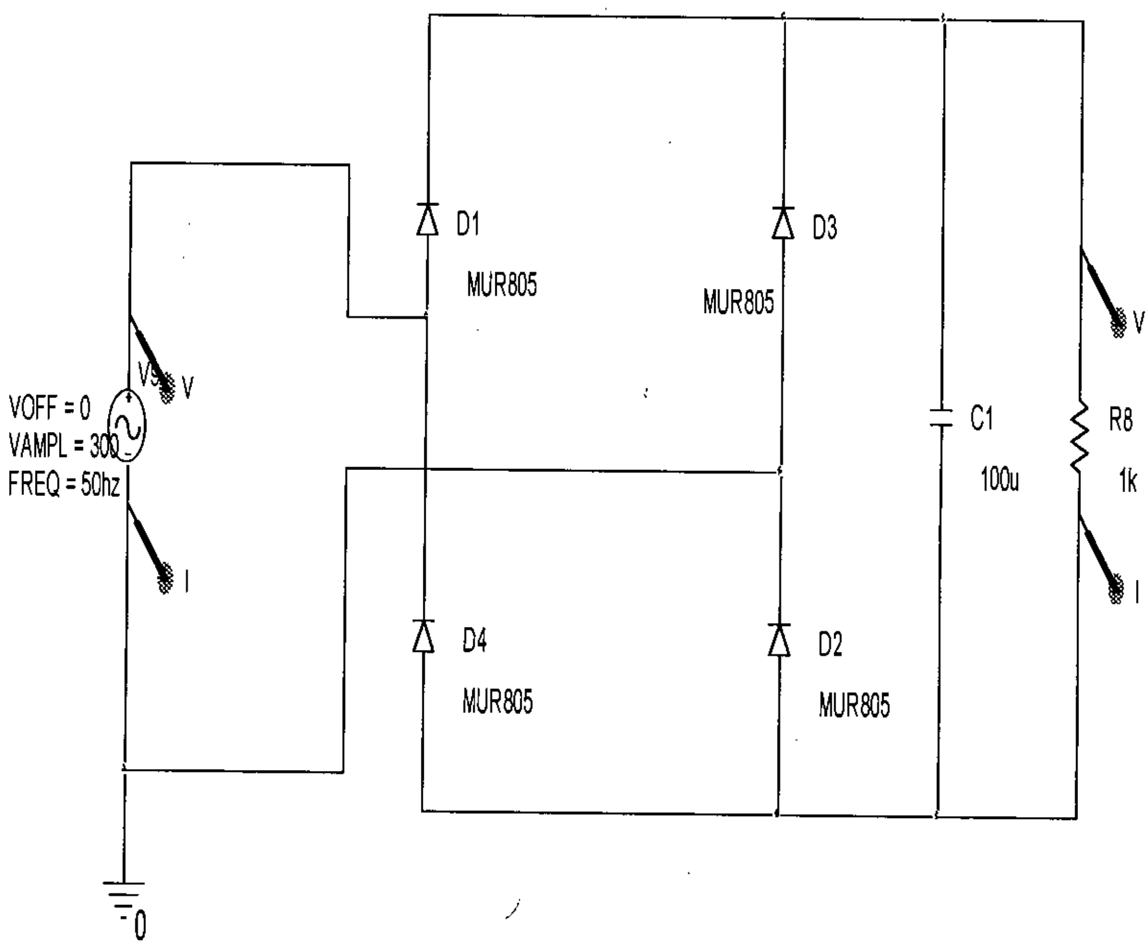


Fig-1.3: Single Phase Basic Diode Rectifier Circuit with a Capacitor at the Output.

From this circuit we find that when the input voltage is sinusoidal, input current is non sinusoidal, output voltage and output current is dc with ripple. The waveforms are shown in Fig-1.4.

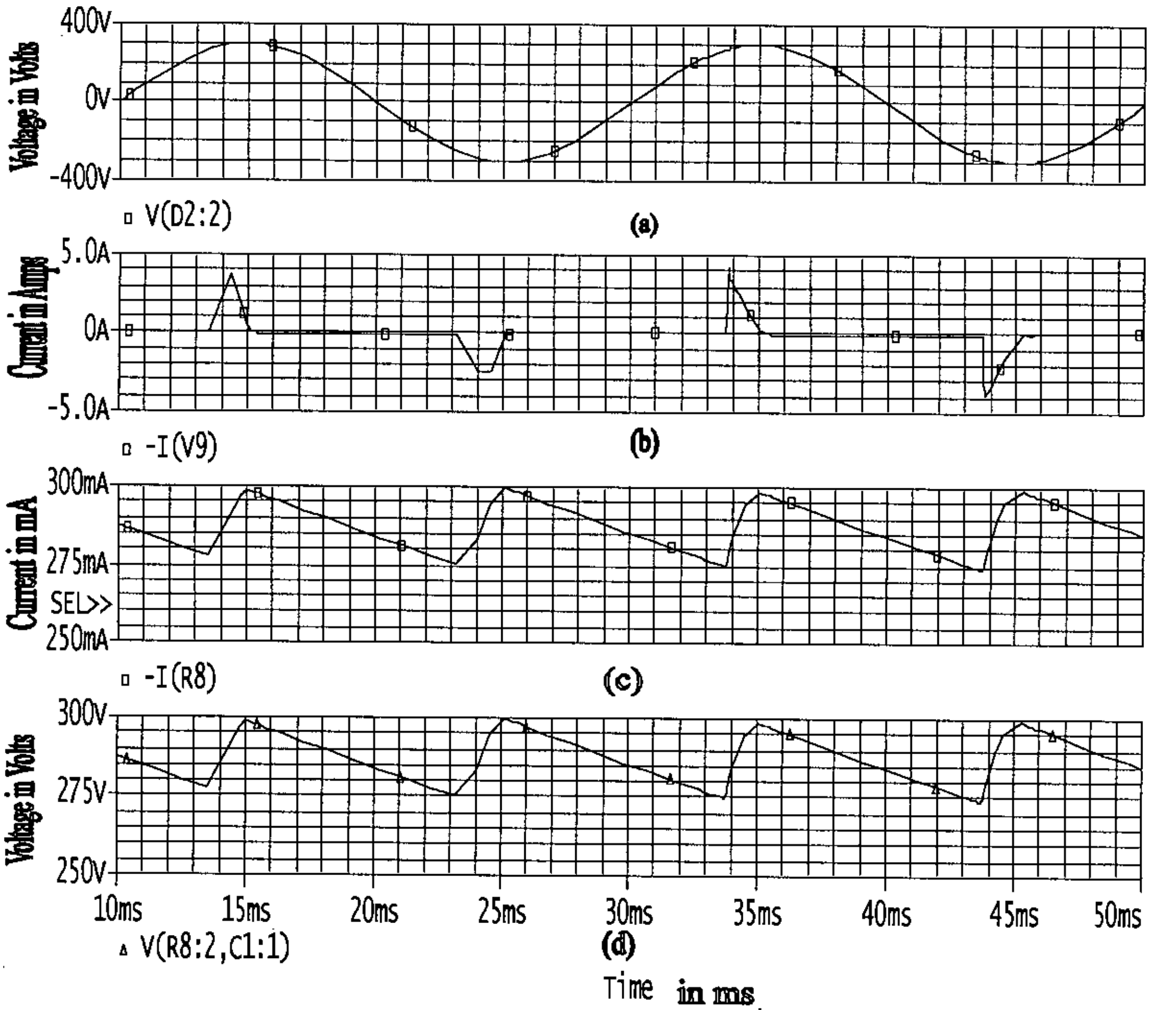


Fig-1.4: Various Waveforms of Single Phase Basic Diode Rectifier with a Capacitor at the Output

(a) Input Voltage,

(b) Input Current,

(c) Output Current and

(d) Output Voltage.

Now if we take the Fourier transforms of this input current we get the harmonics of multiple of 50 Hz. This is shown in Fig-1.5.

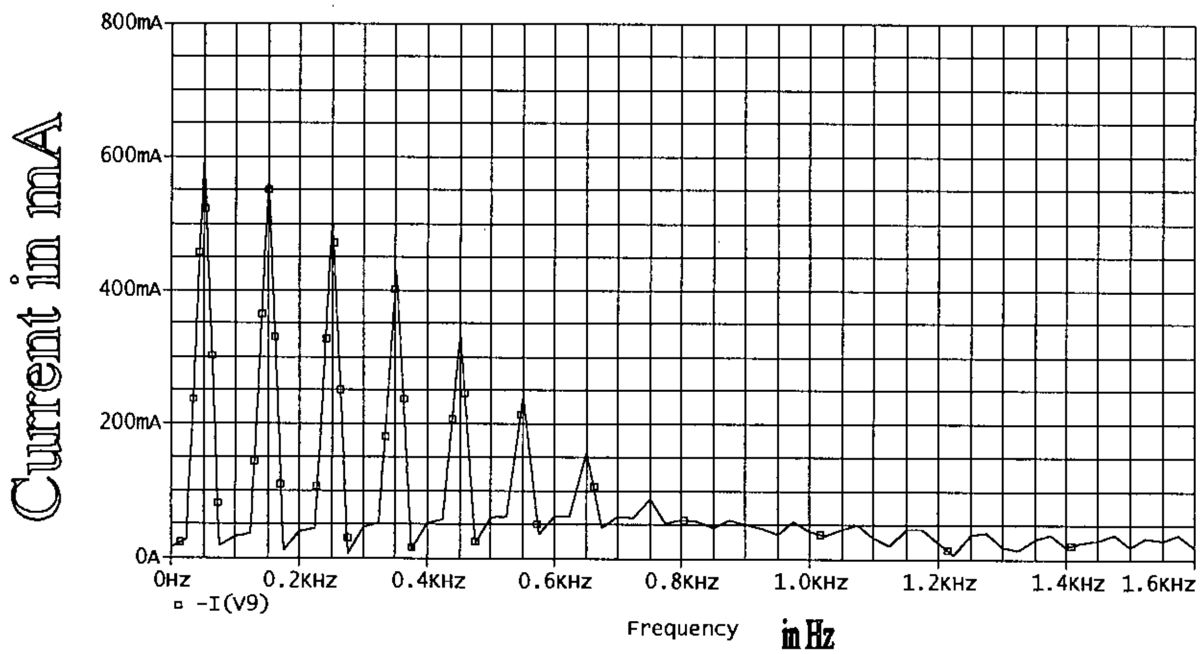


Fig-1.5: Fourier Transform of Input Current of Single Phase Diode Rectifier Circuit with a Capacitor at the Output

Usually to make the input current sinusoidal we need to incorporate LC filter (L_1 and C_2 in Fig-1.6) at the input side of the rectifier. The value of inductor generally varies between 10 mH to 150 mH and capacitor value is 100 uF. Circuit is shown in Fig-1.6 and result is shown in Fig-1.7.

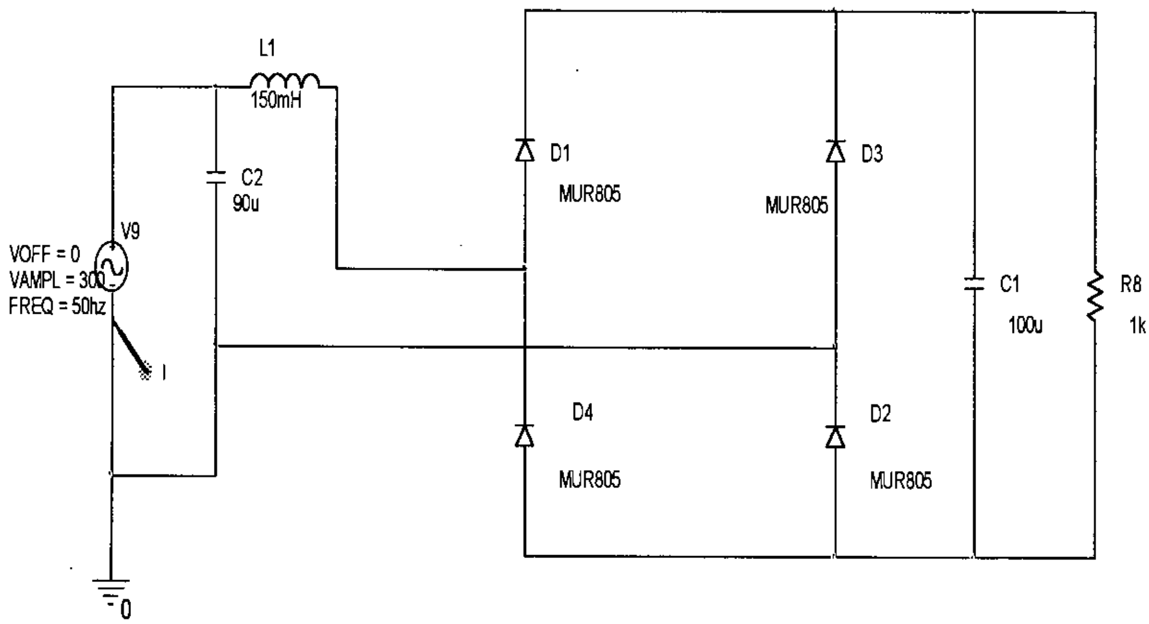


Fig-1.6: Single Phase Basic Diode Rectifier Circuit with a Capacitor at the Output and a LC Filter at the Input

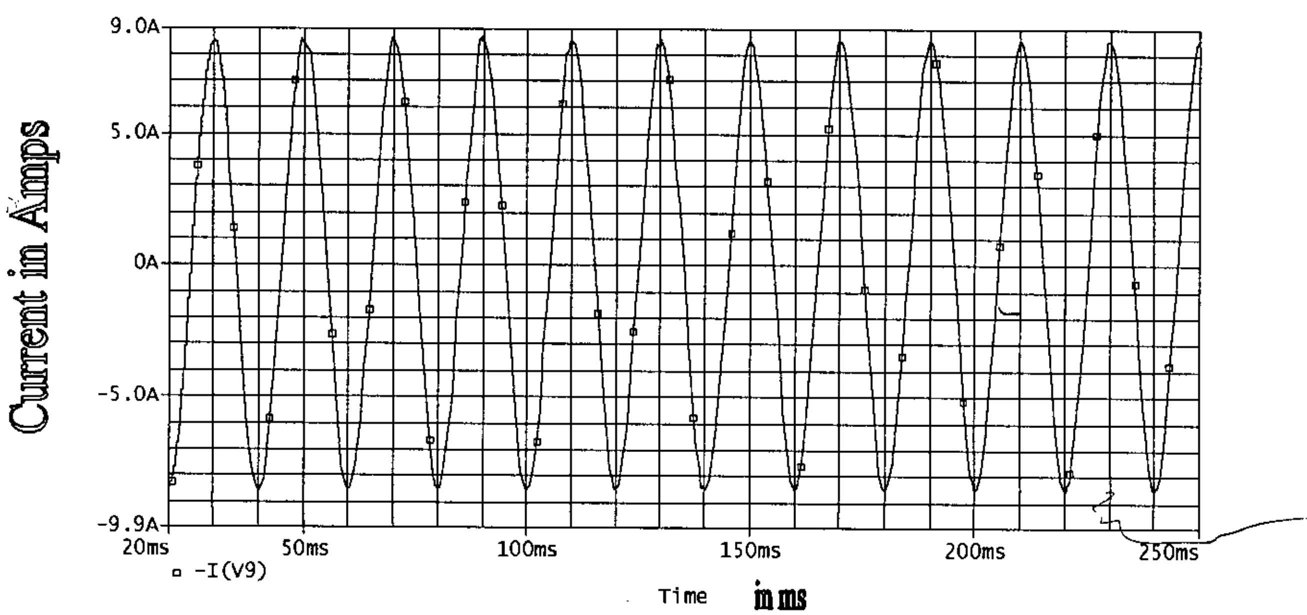


Fig-1.7: Input Current of a Single Phase Basic Diode rectifier circuit with a Capacitor at the Output and a LC Filter at the Input

Now if we analyse the values of inductor and capacitor of a input filter, we find the values are quite large for which the cost and size will be more.

1.4 Single Phase Controlled Rectifiers

The circuit diagram of a single phase controlled rectifier is shown in Fig-1.8. Generally thyristors are used in controlled rectifier,but for the purpose of simulation four ideal switches are used in this single phase controlled rectifier instead of thyristors. During the positive half cycle, switch S1 and S2 conducts and the load is connected to the input supply through S1 and S2. During the negative half cycle of the input voltage, switch S3 and S4 conducts and the switch S1 and S2 will be turned off and the load current will be transferred from S1 and S2 to S3 and S4. The various waveforms are shown in Fig-1.9 for resistive load and $\alpha = 90^0$. It is evident that in a controlled rectifier the input current is nonsinusoidal for any value of α other than 0^0. Hence in controlled rectifiers input filters are necessary to make input current sinusoidal even if output filter is not used to make the pulsating wave to pure dc output.

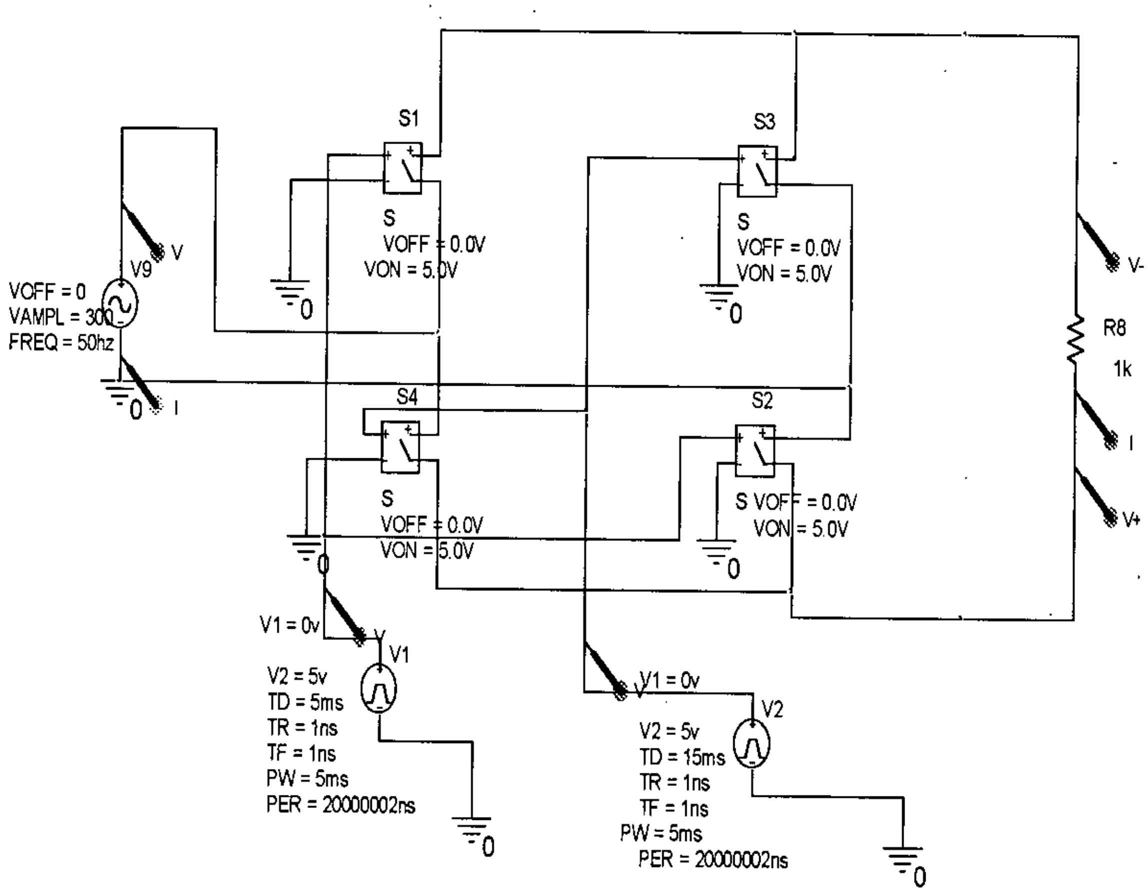


Fig-1.8: Single Phase Controlled Rectifier

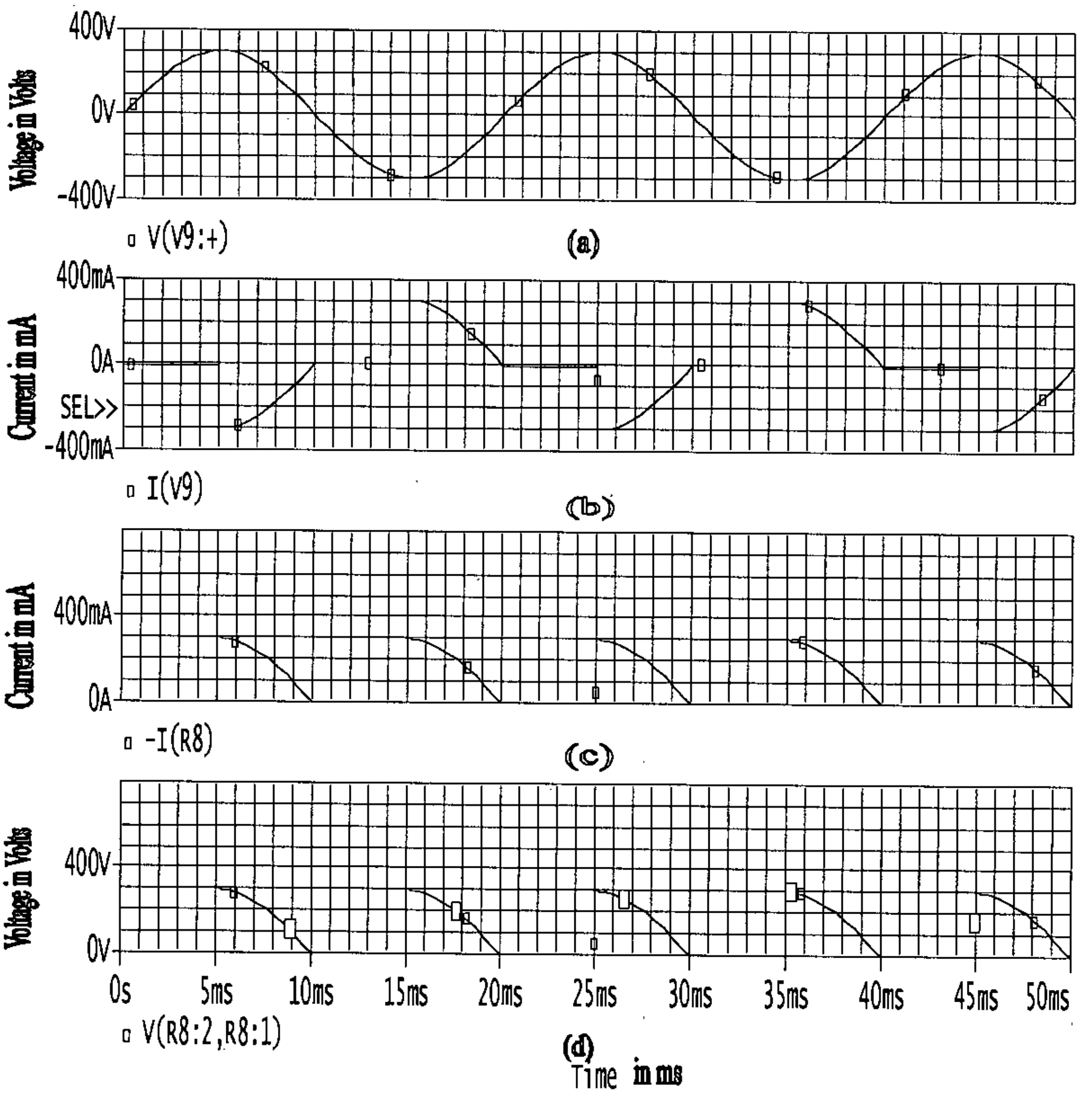


Fig-1.9: Various Waveforms of a Single Phase Controlled Rectifier with resistive load (α=90^0)

(a) Input Voltage,

(b) Input current,

(c) Output Current and

(d) Output Voltage.

From Fig-1.9 we can see the output voltage is a pulsating dc. Now to make the output of this rectifier pure dc, a filter capacitor C_1 is used. Circuit diagram is shown in Fig-1.10 and results are shown in Fig-1.11.

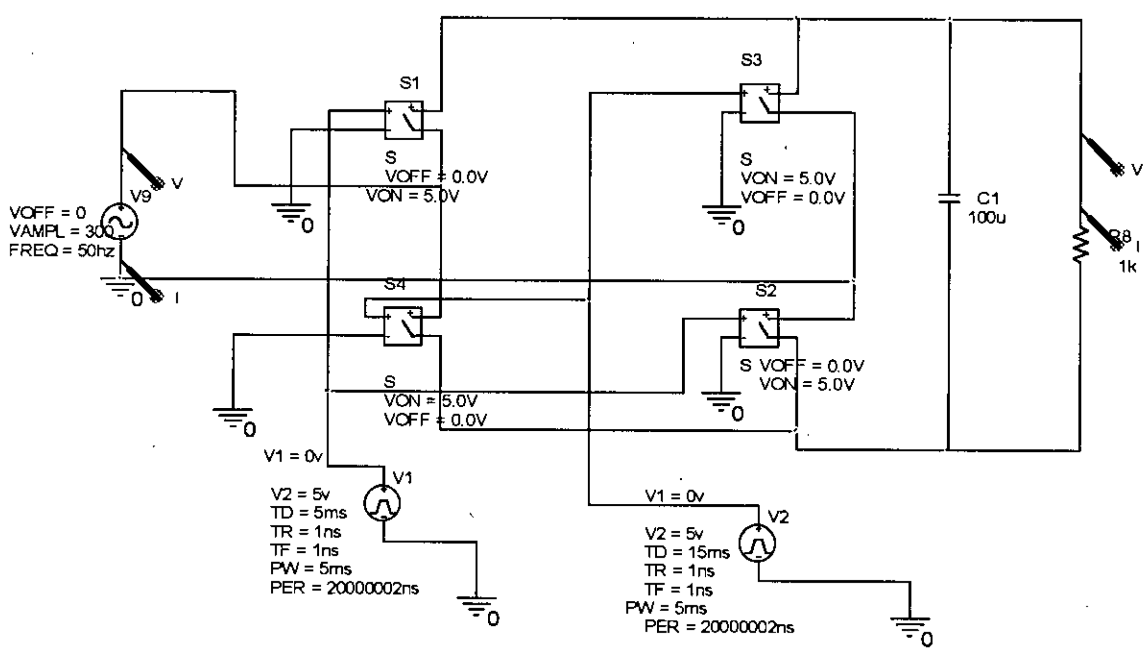


Fig-1.10: Single Phase Controlled Rectifier with a capacitor at the output

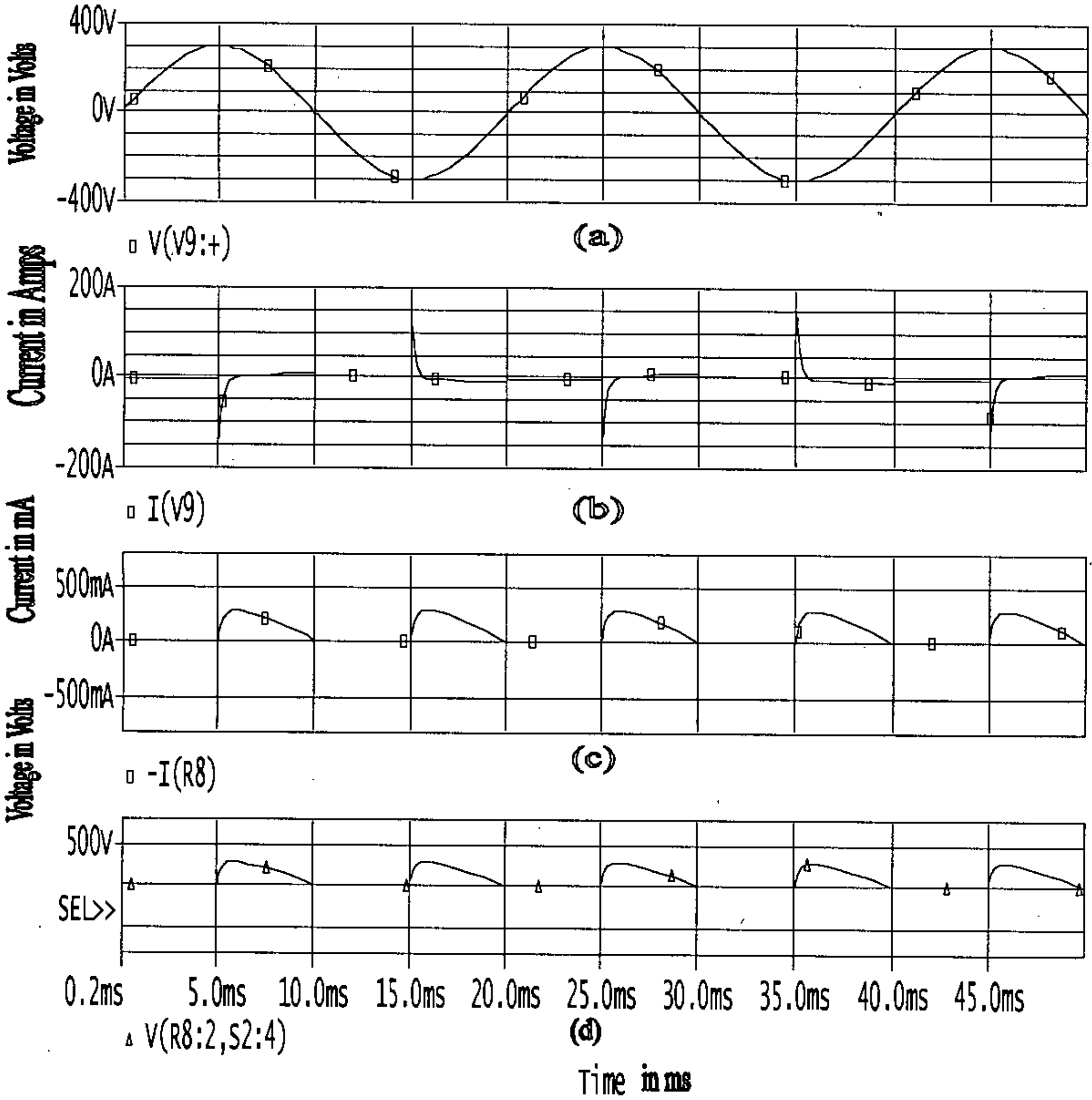


Fig-1.11: Various Waveforms of a Single Phase Controlled Rectifier with a Capacitor at the Output

(a) Input Voltage,

(b) Input Current,

(c) Output Current and

(d) Output Voltage.

Fourier transforms of the input current contains harmonics of multiple of 50 Hz. This is shown in Fig-1.12

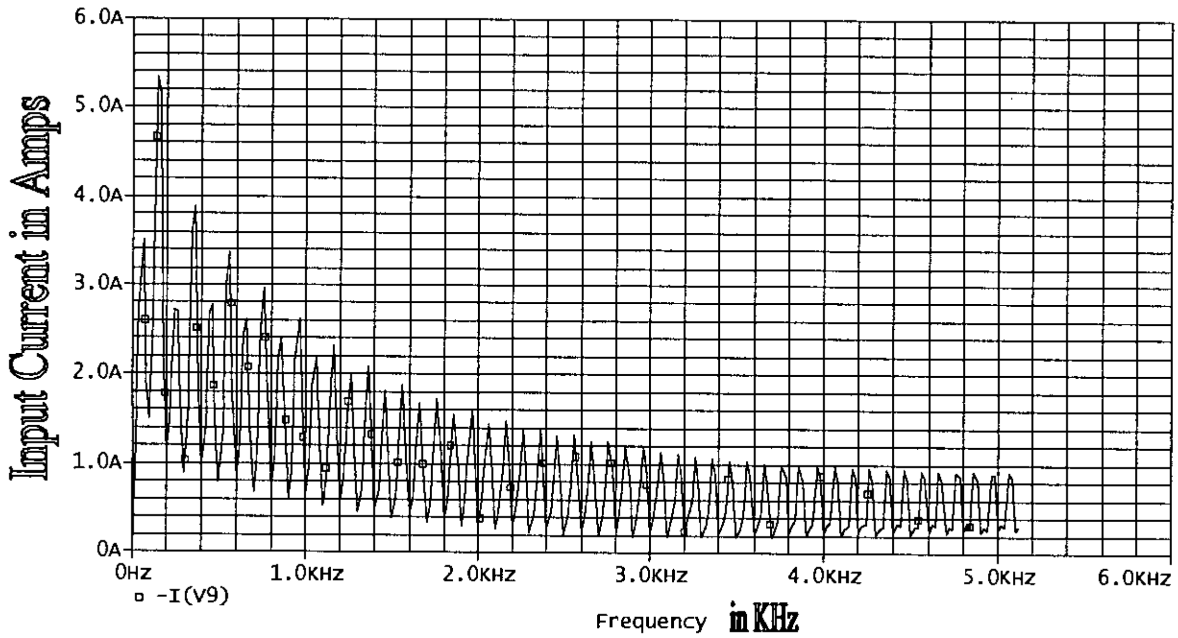


Fig-1.12: Fourier Transform of Input Current of the Single Phase Controlled Rectifier Circuit with a Capacitor at the Output.

Though we are getting dc output, the input current is not sinusoidal. To make the input current sinusoidal we have to pass the input through a LC filter (L_1 and C_3 in Fig-1.13),where, the values of L varies from 10 mH to 150 mH and value of capacitor is approximately 100 uF. These values are comparatively very high. The arrangement is shown in Fig-1.13 and the result is shown in Fig-1.14.

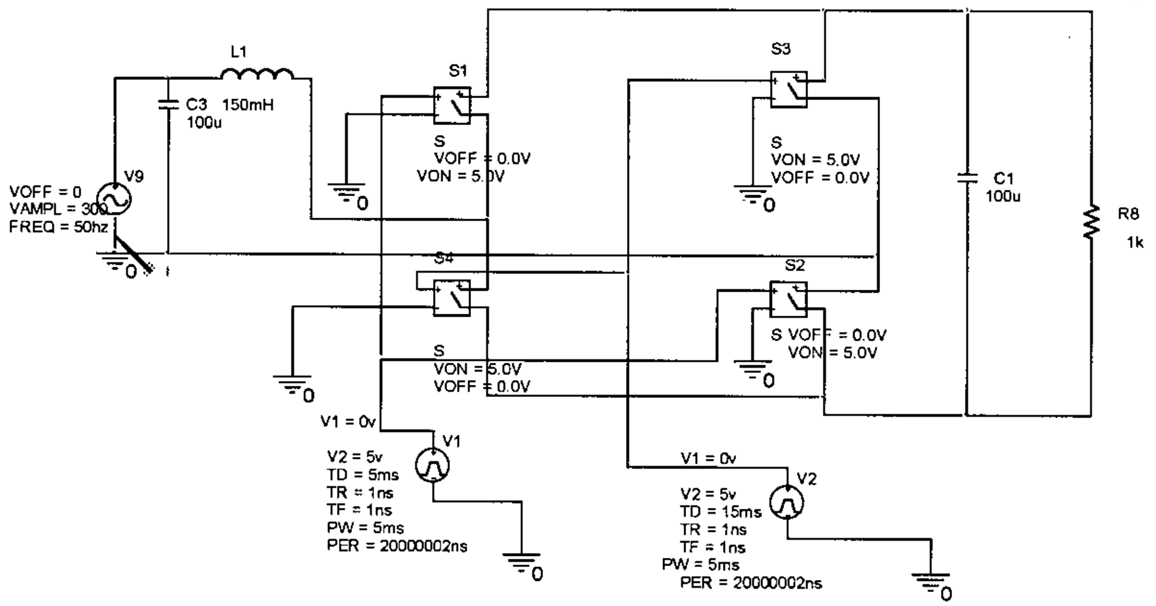


Fig-1.13: Single Phase Controlled Rectifier with a Capacitor at the Output and a LC Filter at the Input.

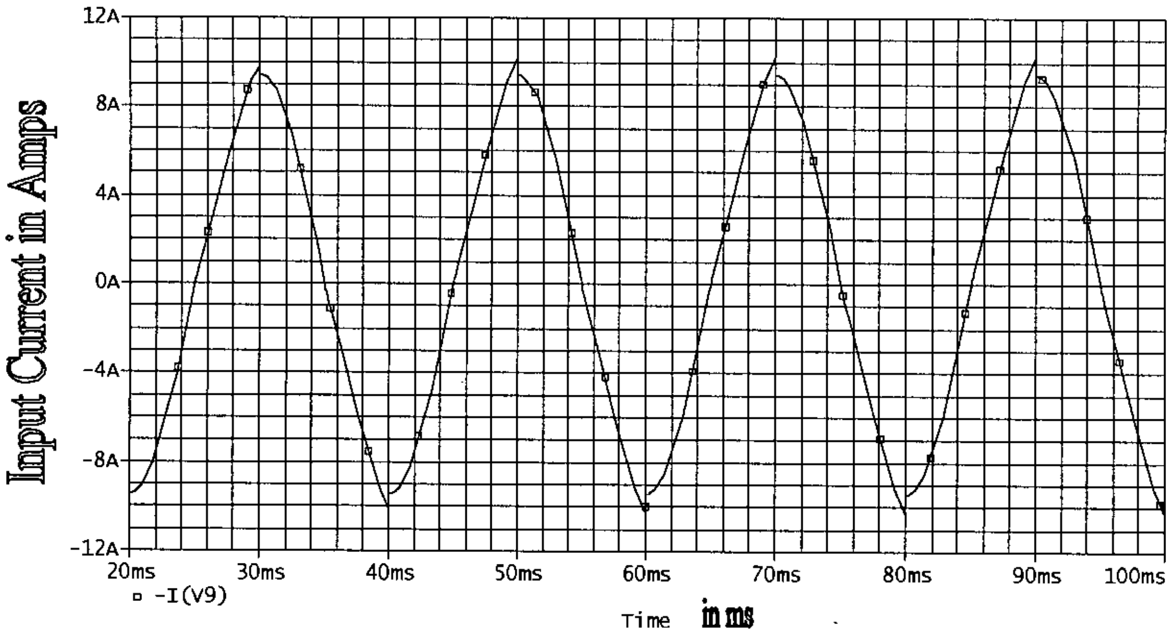


Fig-1.14: Input Current of a Single Phase Controlled rectifier Circuit with a Capacitor at the Output and a LC Filter at the Input.

1.5 Limitations of Diodes Rectifiers [13]

Power supply systems using the diode rectifier are often exposed to large ac source-voltage variations. Moreover, these converters typically use a front-end single-phase diode rectifier feeding the respective dc bus capacitors through a very low inductive path. This approach has many disadvantages like,

a. higher input current harmonic components,

b. Lower rectifier efficiency because of large rms values of the input current,

c. Input ac mains voltage distortion because of the associated higher peak current and

d. Maximum input power factor of approximately 0.50 while a large filter inductor is required for a higher input power factor.

1.6 Requirements of Power Factor Correction

To combat the limitations of diode rectifiers used in power supply systems, manufacturers are now increasingly incorporating input power factor correction components into their power supplies. For power supplies connected to the single-phase ac mains, power factor correction implies the use of input current waveshaping techniques that can be broadly divided as active and passive.

1.7 Types of Power Factor Correction Techniques

A power factor correction technique is mainly classified in two broad categories. These are passive and active.

a. Passive Power Factor Correction Technique [13]

Passive waveshaping or power factor correction techniques have the advantage of being easy to understand, easy to implement and more reliable than their active counterparts. However, they also have several disadvantages, which include:

(1) Large size,

(2) a narrow range of operating points for which the input power factor can be optimized,

(3) the relatively high costs of the series capacitor in resonant input filter technique and the ferro resonant transformer technique and

(4) the relatively large input inductor results in a significant dc bus voltage regulation that will have a negative impact on the associated voltage control strategy.

b. Active Power Factor Correction Technique [13]

The disadvantages discussed above for the passive power factor correction technique can be eliminated through the use of active input waveshaping or power factor correction technique. There are various types of active power factor correction techniques. These are:

(1) Bang-bang hysteresis control method,

(2) Constant-off-time control method,

(3) Constant-on-time control method,

(4) Constant-frequency with turn-on at clock time control method and

(5) Constant-frequency with turn-off at clock time control method.

1.8 Switching Requirement [14]

Diode rectifiers used in power converters draw the input currents from the supply systems with low frequency components and its harmonics. To eliminate low frequency current components, high values of capacitance and inductance are required for the input filter. But if the input current is fed through the high frequency switch the harmonics generation will be of the high frequency. Elimination of high frequency components, the values of capacitor and inductor will be less causing reduction of size and cost of the rectifier system and it will also improve the power factor of the diode rectifier. This is the most important aspect for which the electronic switch is used in diode rectifier. Electronic switch used in power converters can be of various types. Some of these are:

a. Bipolar junction transistors (BJTs),
b. Silicon controlled rectifier (SCR),
c. Metal oxide semiconductor field effect transistors (MOSFETs),
d. Gate turn off thyristors (GTO),
e. Insulated gate bipolar transistors (IGBTs) and
f. Static induction transistors (SITs).

1.9 Control Circuits [15]

In many industrial applications, it is often required to control the output voltage of the converter. In the proposed system the output of the diode rectifier is controlled by incorporating a control circuit. The most efficient method of controlling the gain and the output voltage is to incorporate the pulse-width-modulation (PWM) control. The commonly used techniques are:

a. Single-pulse-width-modulation,
b. Multiple-pulse-width-modulation,
c. Sinusoidal-pulse-width-modulation,
d. Optimized-pulse-width-modulation,
e. Delta-pulse-width-modulation or dual slope delta modulation,
f. Trapezoidal-pulse-width-modulation and
g. Hysteresis pulse width modulation techniques.

1.9.1 Sinusoidal-Pulse-Width-Modulation [16]

In sinusoidal-pulse-width-modulation the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the pulse. The distortion factor and the lower-order harmonics are reduced significantly. The gating signal as shown in Fig-1.15 are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency f_c. The frequency of reference signal, f_r, determines the converter output frequency, f_0, and its peak amplitude, A_r, controls the modulation index, M, and in turn controls the rms output voltage, V_0.

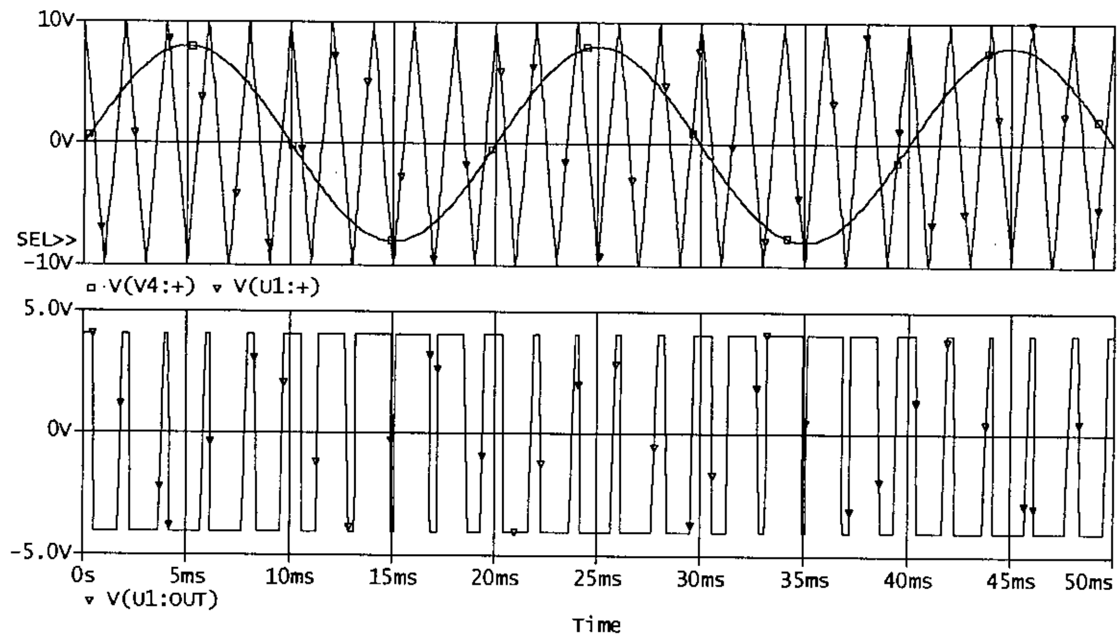


Fig-1.15: Sinusoidal-Pulse-Width-Modulation

1.9.2 Delta-Pulse-Width-Modulation and Dual Slope Delta Modulation [17]

In delta modulation, a triangular wave is allowed to oscillate within a defined window ▲V above and below the reference sine wave V_r. The converter switching function, which is identical to the output voltage V_0 is generated from the vertices of the triangular wave as shown in Fig-1.16. It is also known as hysteresis modulation. If the frequency of the modulating wave is changed keeping the slope of the triangular wave constant, the number of pulse and the pulse widths of the modulated wave would change. Similarly if the slope of the triangular wave is changed keeping the frequency of the modulating wave constant the number of pulse and pulse widths of the modulated wave would change. In this configuration when two different slopes are used for modulation is known as dual slope delta modulation. The fundamental output voltage can be upto 1.27 V_s and is dependent on the peak amplitude a_r and frequency f_r of the reference voltage.

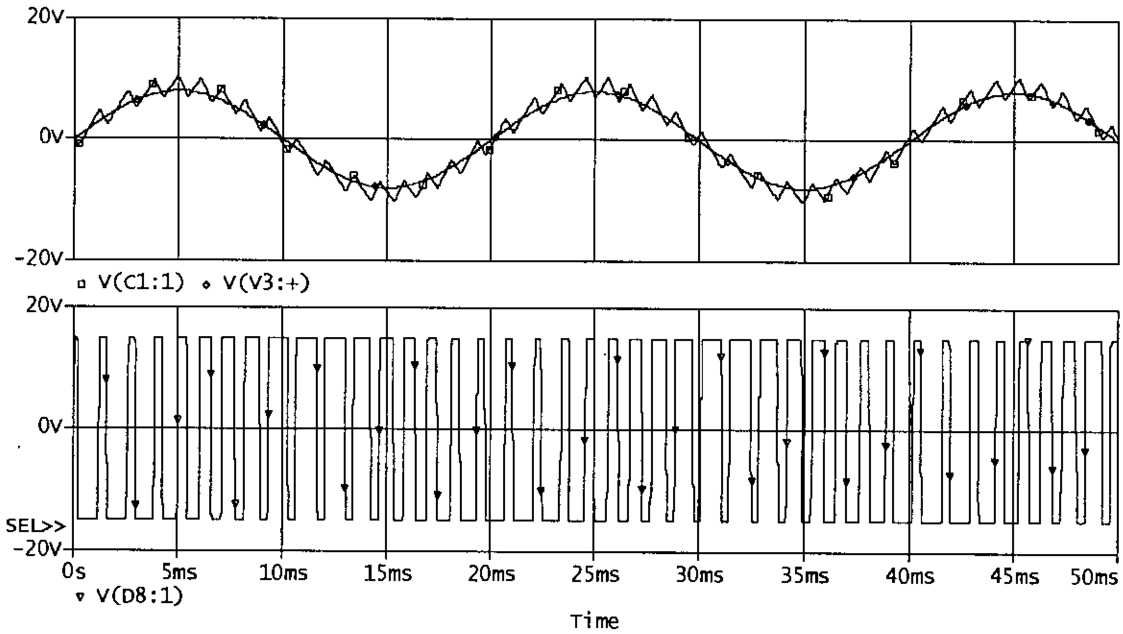


Fig-1.16: Delta-Pulse-Width or Dual-Slope-delta-Modulation

1.10 Delta Modulation and its Advantages

Linear delta modulation was first reported in 1946 and early description emerged in 1950s [18, 19]. In linear delta modulation, an encoder, is accommodated at the transmitter and receives a band limited analog signal and produces a binary output signal. The output pulse are also locally decoded back into an analog waveform by an integrator in feedback loop and is subtracted from the input signal to form an error which is quantized to one of the two possible levels depending on its polarity. The closed loop arrangement of the delta modulator ensures that the polarity of the pulses is adjusted by the sign of the error signal which causes the locally decoded waveform to track the input signal. Stated another way, the delta modulator produces binary pulses at the output which represents the sign difference between the input and feedback signal. The modulation is known as linear, because the decoder is a linear network. Despite the attractive simplicity of the delta modulation coders, their drawbacks had prevented their wide use initially [20]. Delta modulation remained simply an interesting field for theoretical studies in communication systems for decades. This situation began to change when refinements were suggested [21] and today the development of delta modulation is in full progress. Many communication research laboratories are engaged in exploring in depth the theory and the application of delta modulation [22-24]. The simplicity of delta modulation (DM) has inspired numerous refinements and variations since its basic invention in 1946 by Deloraine and Derjavictch. Most of these DM systems have been motivated by application to digitization of audio and video signals. The initial DM coder consisted of signal integrator (analog) or a first order predictor (digital implementation) in its feedback path. Subsequently, DM with double integrator and multiple integrators or its counterpart, the predictors was used in the feedback path for more precision in digitization [25]. Some investigators replaced the integrator of the feedback loop by RC network [26] giving rise to exponential delta modulation encoders. Both signal integration or the double integration delta modulation were found suitable for coding signals of correlated waveforms. To suit the DM technique for uncorrelated signal, sigma delta modulation was introduced in 1962 [27, 28]. Sigma delta modulation uses an integrator to integrate the input prior to DM coding. This pre-emphasizes the low frequencies in the input and increases the adjacent sample correction. For using variable step size quantization to compete with pulse width modulation (PWM), adaptive delta modulation (ADM) was suggested by many authors [28, 29]. In adaptive DM, the value of the signal at each sample time is predicted to be non-linear function of the past values of the quantized signal. The other two kinds of delta modulation scheme encountered in literatures are companded delta modulation scheme and the asynchronous delta modulation [30, 31]. Companded DM technique uses compression of large levels as compared to the smaller ones prior to encoding, using compressor circuit. The asynchronous delta modulation systems have digital output quantized in amplitude but not in time. The rectangular wave delta modulation (RWM) is one type of asynchronous DM technique. In RWM DM, the memory less quantizer of delta modulation scheme is replaced by nonlinear element whose characteristics are that of a hysteresis loop and the sampler is permanently closed. This form of delta modulation was first reported by Sharma and Das [32, 33].

In single stage delta modulation scheme, the encoder generates information which is dependent on the polarity of the error signal, where the error signal is the difference between input signal and the reconstructed version of the input signal. The basic problem with any form of single stage DM is that the encoder generates information which is only dependent on the polarity of the error and once the input signal is modulated to pulse waveforms, the error information is lost and no minimization of signal distortion is possible. Multistage delta modulation was introduced in communication networks to overcome this problem by successive approximation of input signals with the help of several coders [34-36].

1.11 Proposed Research and Objectives

Delta modulation is the simplest technique requiring minimum hardware components. Recently its application in power electronics has been reported in switching power converters. In this thesis possible use of dual slope delta modulation in switching a diode rectifier has been investigated. Theoretical study has been made to find out suitable parameter variation of a dual slope delta modulator to determine an effective method of voltage regulation of a diode rectifier by dual slope delta modulation. Practical implementation of a dual slope delta modulated diode rectifier has been carried out to verify the theoretical results.

1.12 Outline of the Thesis

This thesis work is presented in four chapters. Chapter 1 contains the basics of power factor correction of a single phase diode rectifier. This includes the basics of a single phase full wave diode and controlled rectifier with their limitations. Types of power factor correction technique and switching requirements are also discussed. Control scheme with various methods with special emphasis on dual slope delta modulation is included. Finally this chapter contains the proposed research and objectives. Chapter 2 contains the incorporation of dual slope delta modulation in the control scheme. This also contains the theoretical analysis and hardware implementation of the circuit with various waveforms taken from storage oscilloscope. Chapter 3 is the main part of this thesis work. This contains the study of power factor correction of a single phase diode rectifier circuit keeping switch at the output and input of a diode rectifier. Practical circuit analysis of the same is also done and various waveforms from storage oscilloscope is included. Finally chapter 4 contains the conclusion and proposed future work. At the end the references are included.

CHAPTER 2

DUAL SLOPE DELTA MODULATION IN THE CONTROL SCHEME FOR POWER FACTOR CORRECTION

2.1 The Dual Slope Delta Modulation

The delta modulation technique requires simple circuitry to generate switching waveforms for switching the device (transistor, MOSFET, IGBT etc) of Power Converter Circuits. Fig-2.1 is an analog circuit which is capable of producing the waveforms shown in Fig-2.2.

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; wherever the output voltage of A_2 exceeds the upper or lower window boundary (preset by R_4 / R_3 ratio), the comparator A_1 reverses the polarity of V_1 at the input of A_2. It forces carrier wave V_f to oscillate around the reference waveform V_r at ripple frequency f_r. The switching waveform is obtained at the output A_1.

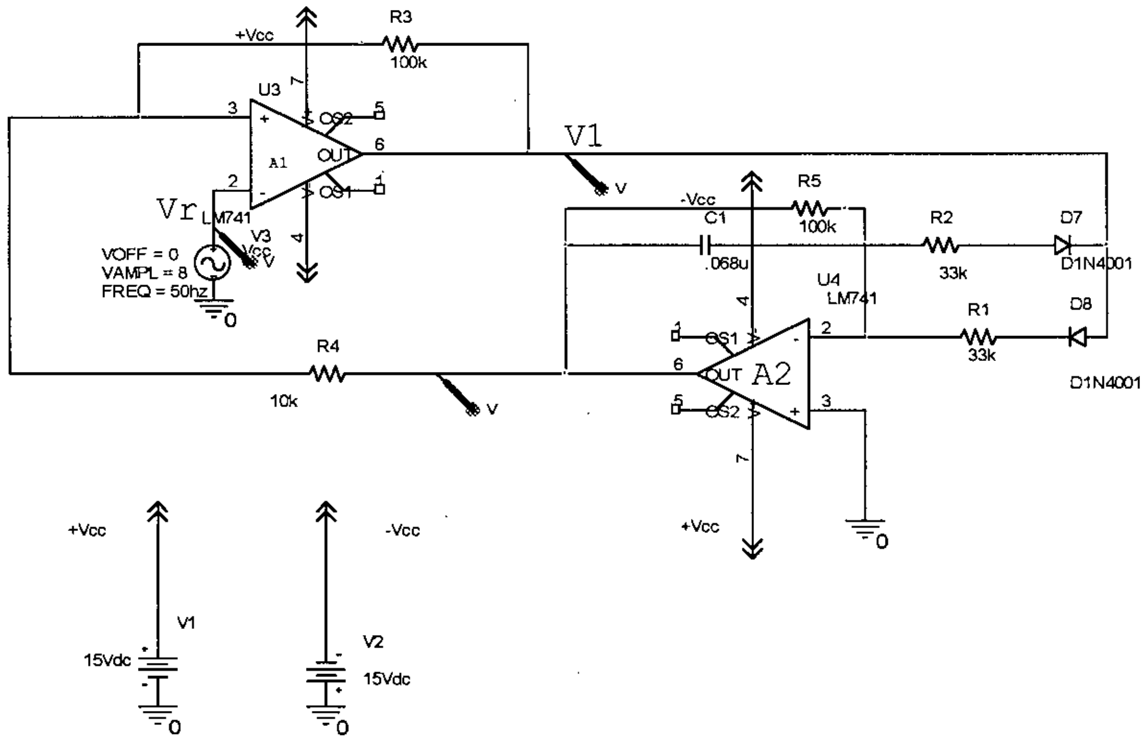


Fig-2.1: Basic Delta Modulation Circuit

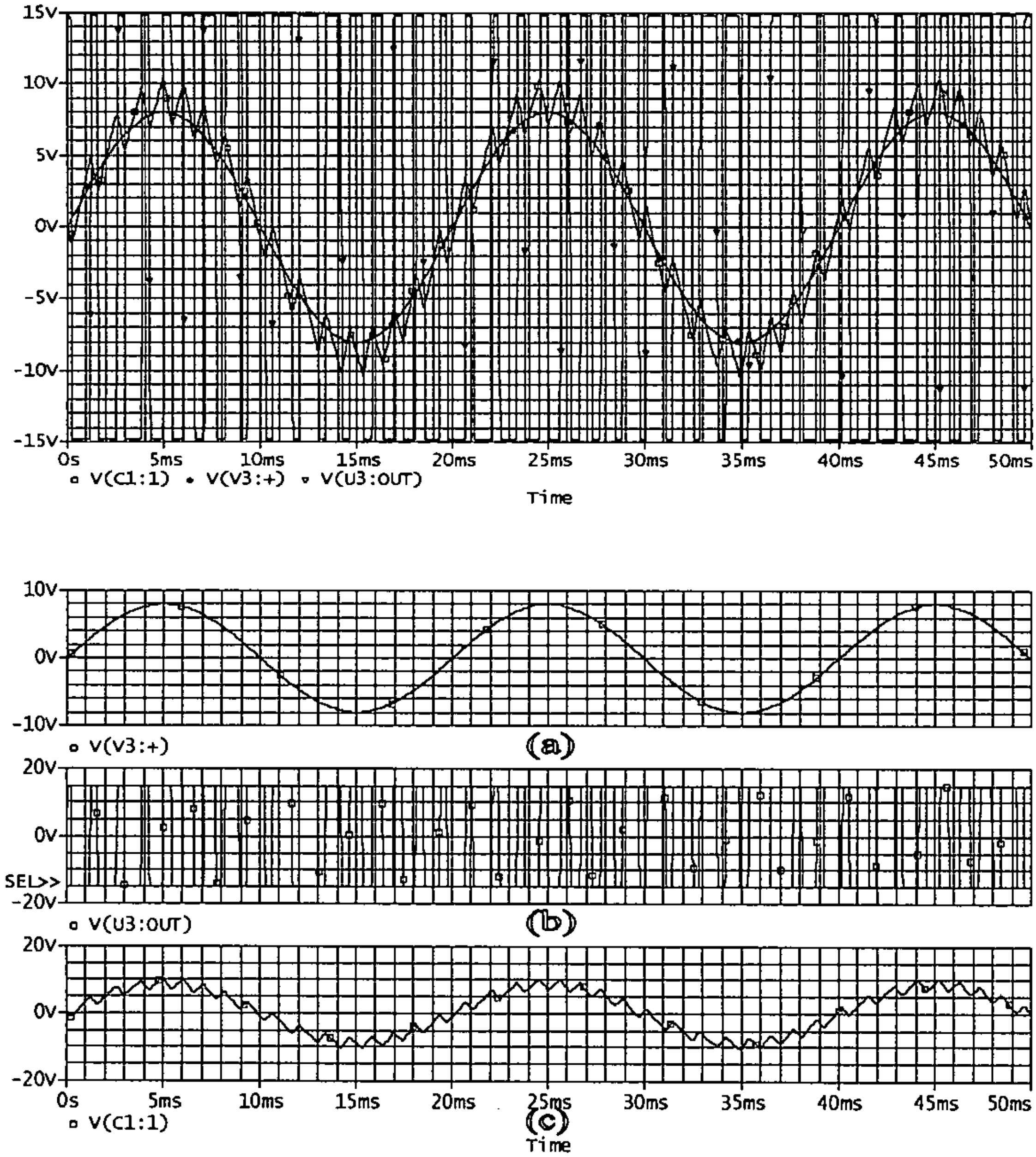


Fig-2.2: Various Waveforms of Delta Modulation Circuit

(a) Sine Reference voltage V_r,

(b) Switching Waveform Obtained at the Output of A_1 and

(c) Carrier Wave at the Output of A_2.

2.2 Implementation of Dual Slope Delta Modulation in the Control Scheme

The basic circuit used for the delta modulation is shown in Fig-2.1. Different outputs of the modulator are obtained by changing

a. Frequency, f of the input signal to the DM.

b. Window width, ▲V of the hysteresis band of the DM and

c. Slope S, of the carrier wave of the DM.

By keeping frequency and window width fixed and using two different slopes 'S' of carrier wave of delta modulator we can implement the dual slope delta modulation.

2.2.1 Effect of Change of Slope (Volt / Sec) of the Carrier Wave:

The slope of the carrier wave effects the output of the DM window width. .As slope increases, the pulse width of the output of the DM decreases and vice versa. This is illustrated in Fig-2.3(for R_1 = 33k ohms and R_2 = 33k ohms), Fig-2.4 (for R_1 = 33k ohms and R_2 = 66k ohms), Fig-2.5 (for R_1 = 66k ohms and R_2 = 33k ohms) and Fig-2.6 (for R_1 = 3.3k ohms and R_2 = 33k ohms).

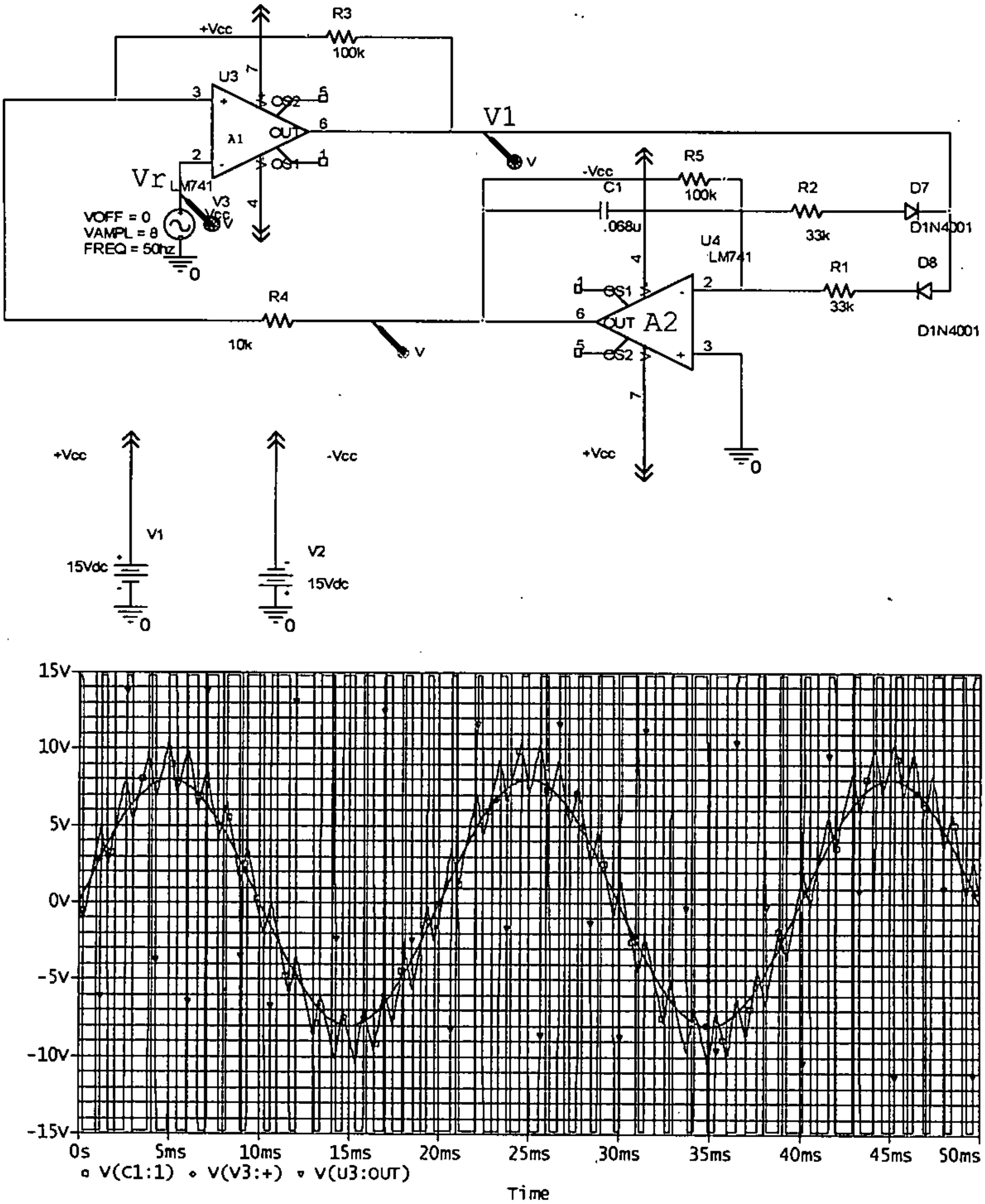


Fig-2.3: Delta modulation circuit and waveforms with same slope (R_1 = 33k, R_2 = 33k)

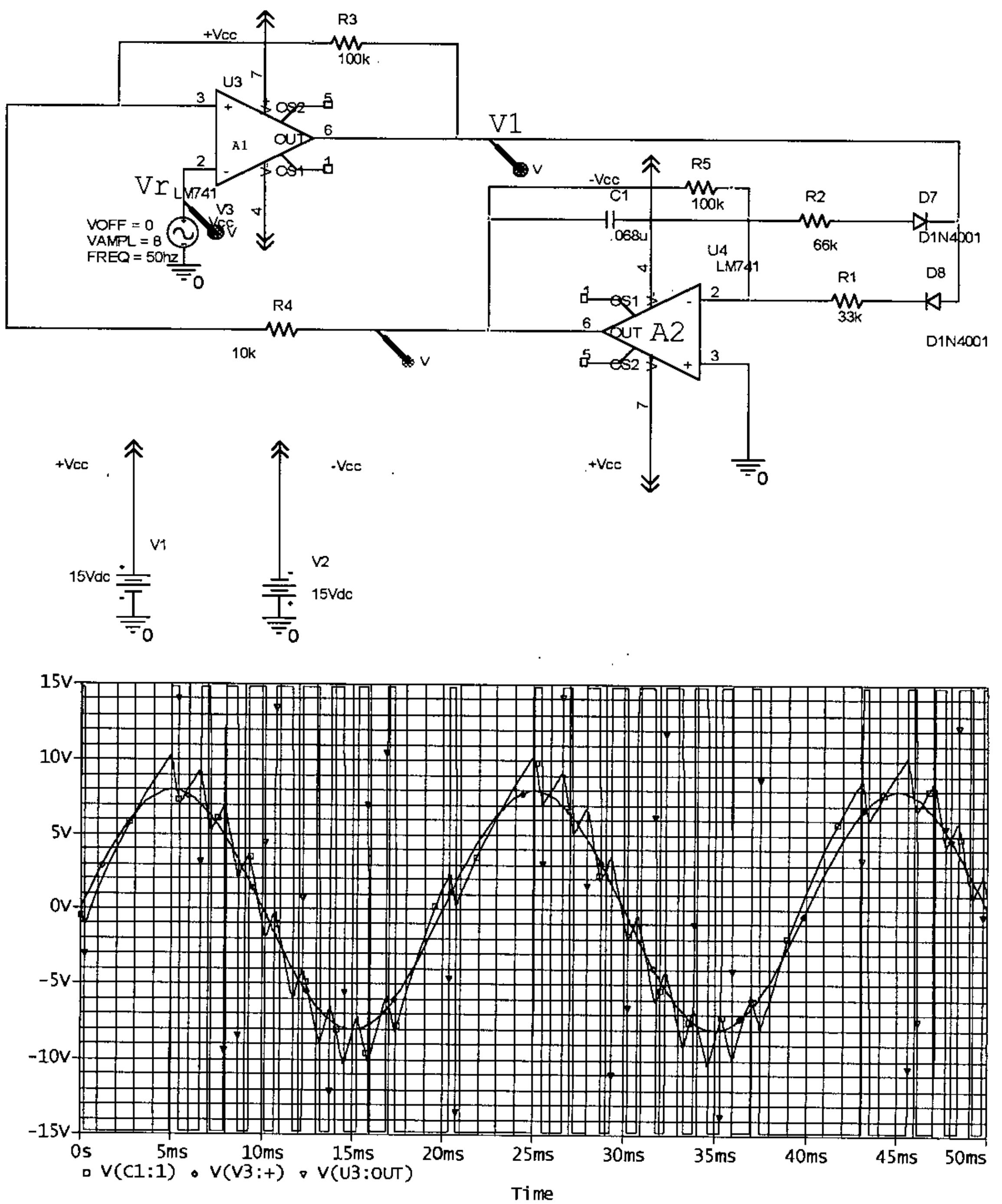


Fig-2.4: Dual slope delta modulation circuit and waveforms ($R_1 = 33k$, $R_2 = 66k$)

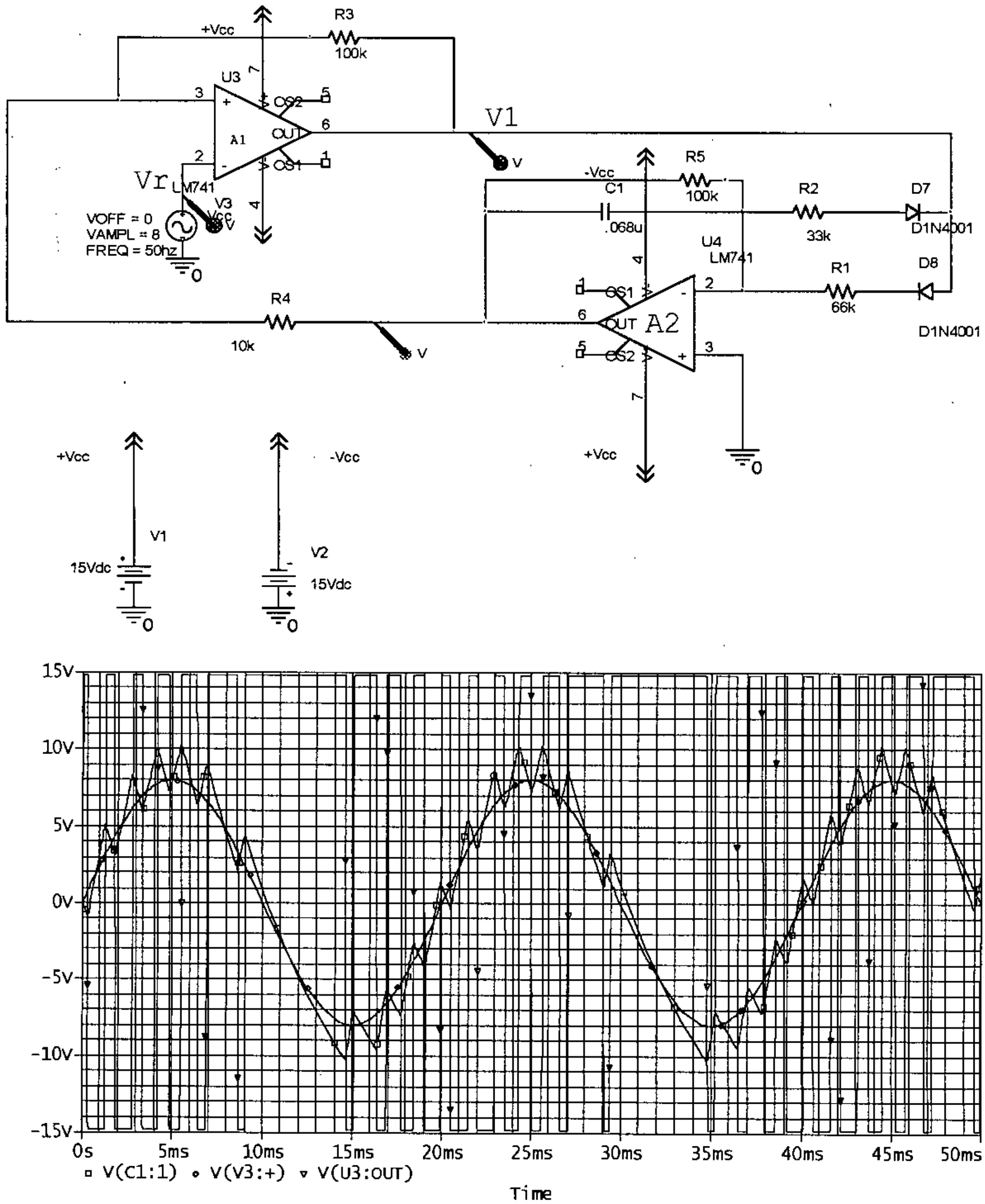


Fig-2.5: Dual slope delta modulation circuit and waveforms ($R_1 = 66k$, $R_2 = 33k$)

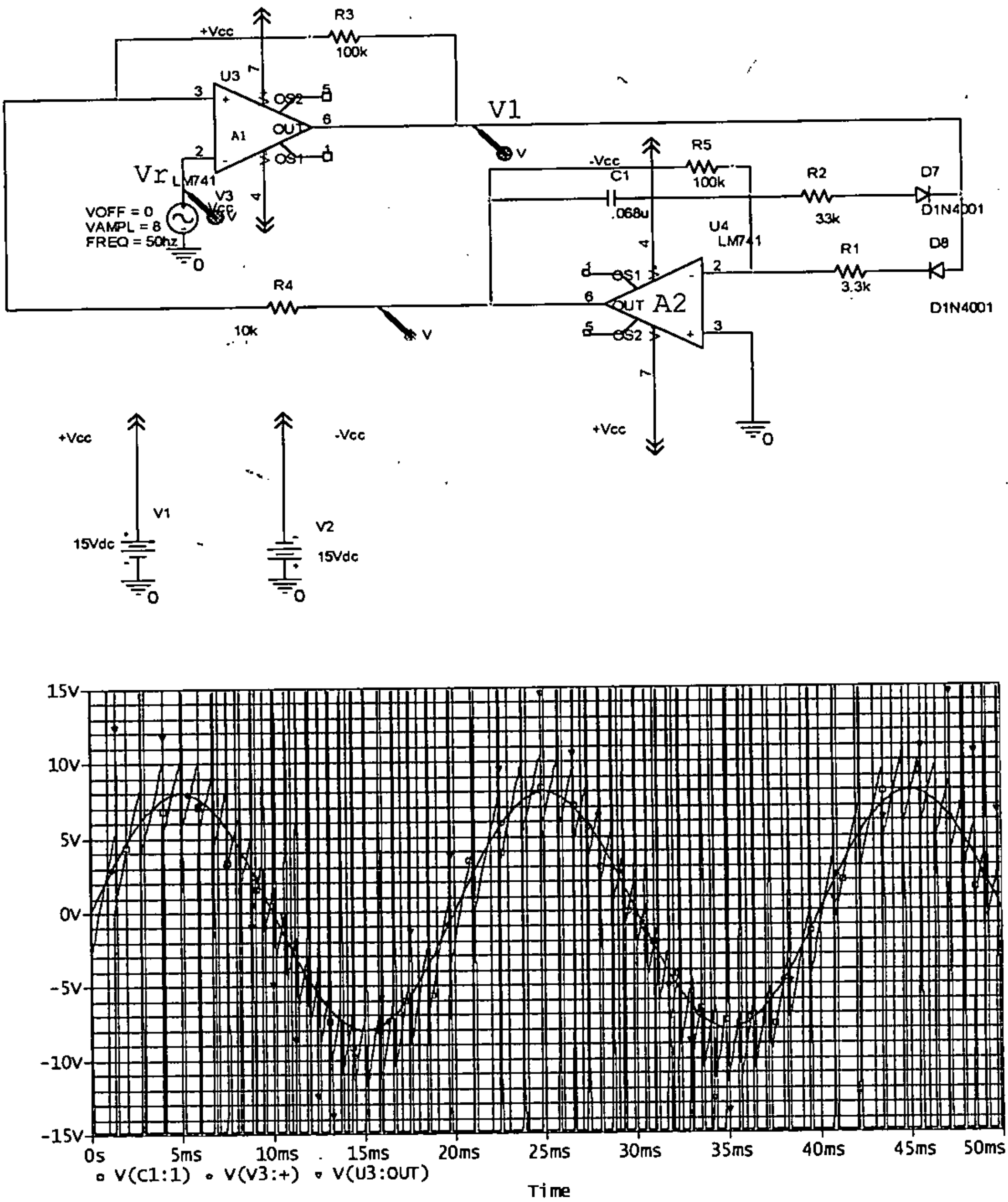


Fig-2.6: Dual slope delta modulation circuit and waveforms (R_1 = 3.3k, R_2 = 33k)

2.2.2 Discussion

It is clear that by changing any of the parameter (f, ▲V, Slope) of the DM, the output pulse width can be increased or decreased. But in this proposed circuit only the slope parameter is varied to achieve dual slope delta modulation keeping the frequency and the window width parameter fixed. The output from this dual slope delta modulator (varied pulse width pulse) are given to the MOSFET or IGBT which acts as the switch of a diode rectifier. As the pulse width can be increased or decreased, the OFF / ON time of the switch can be increased or decreased controlling the switching time of the diode rectifier. Window width or slope can be chosen as the control parameter of the modulator to control the output voltage of a diode rectifier. In this work the method of changing the slope of the modulating wave is investigated for reduction of harmonics and to improve the input power factor. In the case of rectifier operation input and output waveforms are fixed hence variation of frequency is not required. Window width variation changes the switching frequency only, hence it cannot be varied for output voltage controllability of a rectifier. However, it can be optimized for getting particular switching frequency of the overall scheme to minimize component size. Switching frequency increase has a limit according to the switching power device used and power handling capability of the rectifier circuit. In the case of power rectifiers and inverters, switching is maintained between 2-5 KHz. Hence in this work window width is maintained constant with allowable switching frequency.

2.3 Hardware Implementation of Dual Slope Delta Modulation

The hardware implementation of a dual slope delta modulation is done by a circuit diagram shown in Fig-2.7 and Fig-2.8 (same as discussed in theoretical analysis paragraph 2.2). Various waveforms taken from storage oscilloscope are shown in Fig-2.9 to Fig-2.11 (where $R_1 = R_2 = 33$k ohms)

Fig-2.9 : Sine reference voltage V_r

Fig-2.10 : Switching waveform obtained at the output of A_1

Fig- 2.11 : Carrier wave V_f at the output of A_2

For various combinations of R_1 and R_2 the various waveforms taken from storage oscilloscope are shown in Fig-2.12 to Fig-2.17

For R_1 = 33k ohms and R_2 = 66k Ohms

Fig-2.12 : Sine reference voltage V_r

Fig-2.13 : Switching waveform obtained at the output of A_1

Fig- 2.14 : Carrier wave V_f at the output of A_2

For R_1 = 33k ohms and R_2 = 3.3k Ohms

Fig-2.15 : Sine reference voltage V_r

Fig-2.16 : Switching waveform obtained at the output of A_1

Fig- 2.17 : Carrier wave V_f at the output of A_2

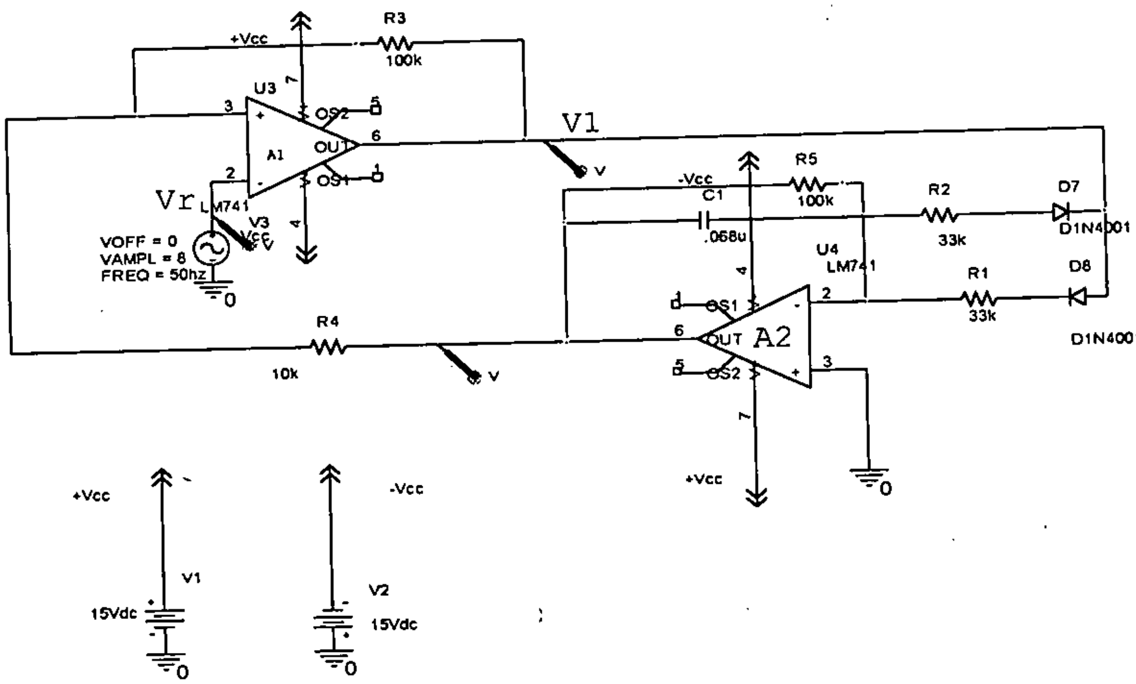


Fig-2.7: Practical Dual Slope Delta Modulation Circuit

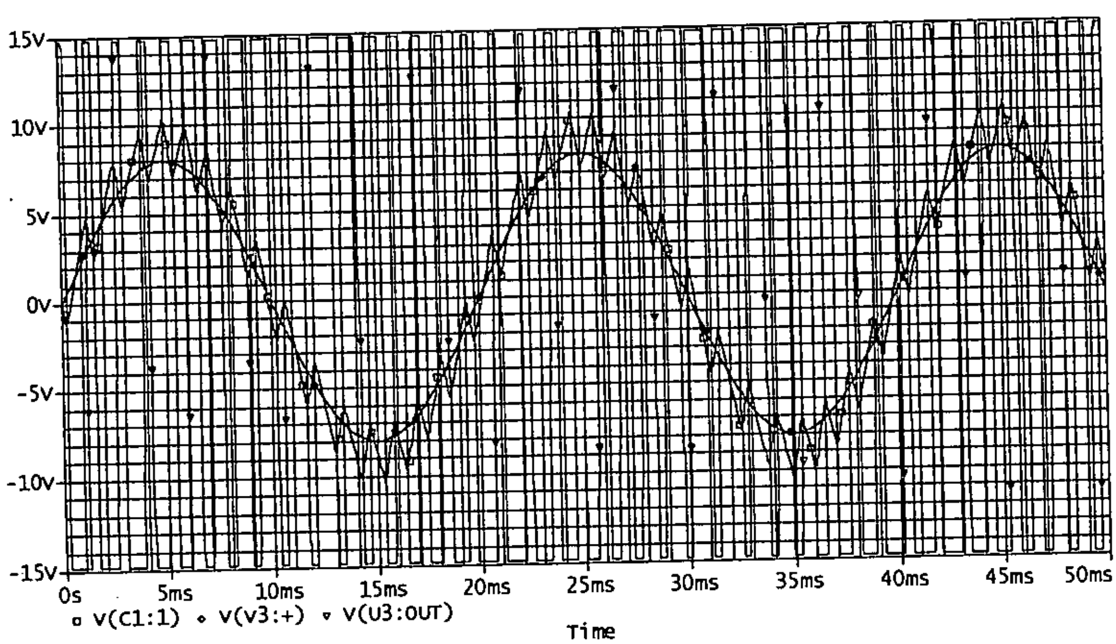


Fig-2.8: Various Waveforms of Practical Dual slope Delta Modulation Circuit

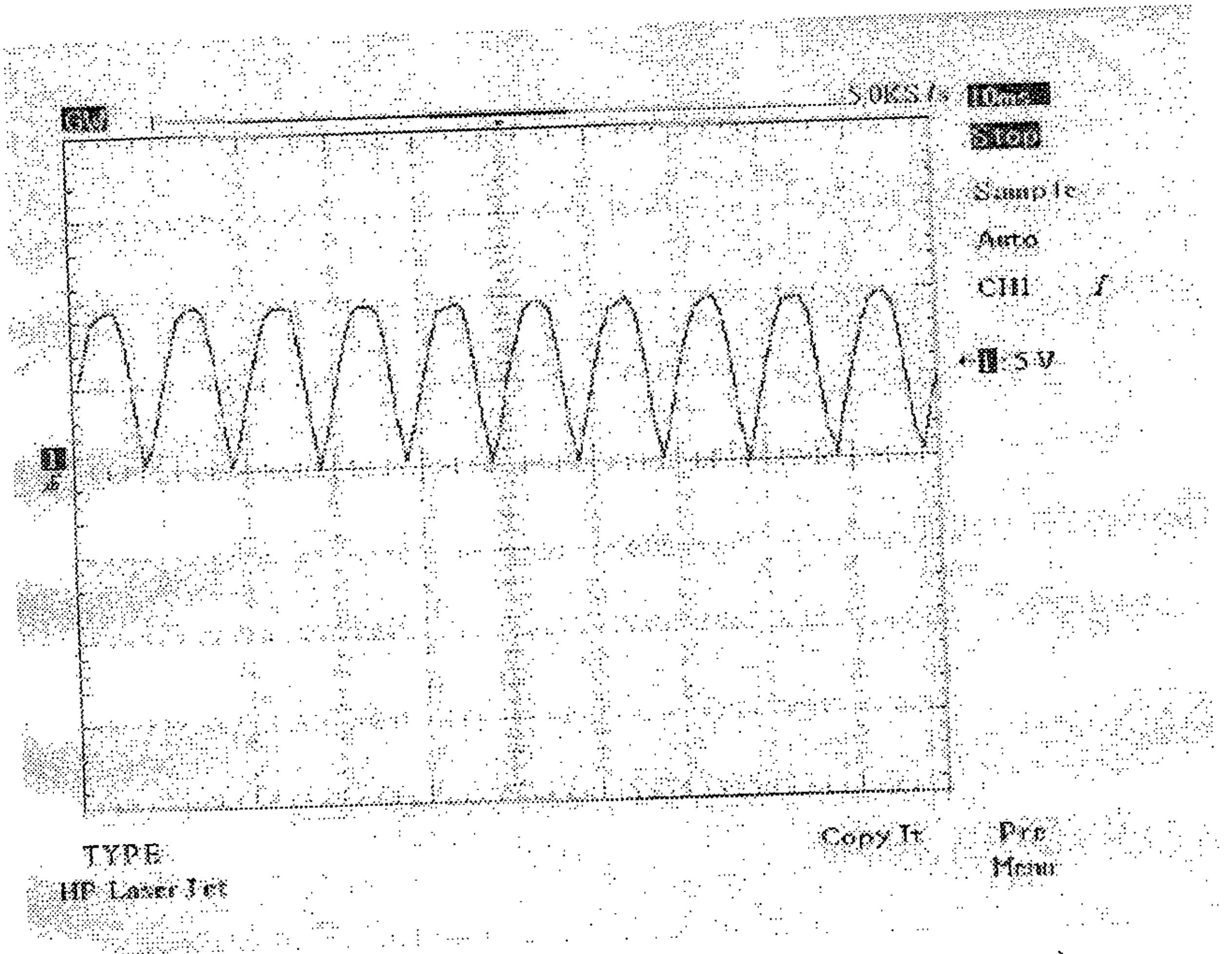


Fig-2.9: Sine reference voltage V_r(where $R_1 = R_2 = 33$k ohms) (rectified sine wave)

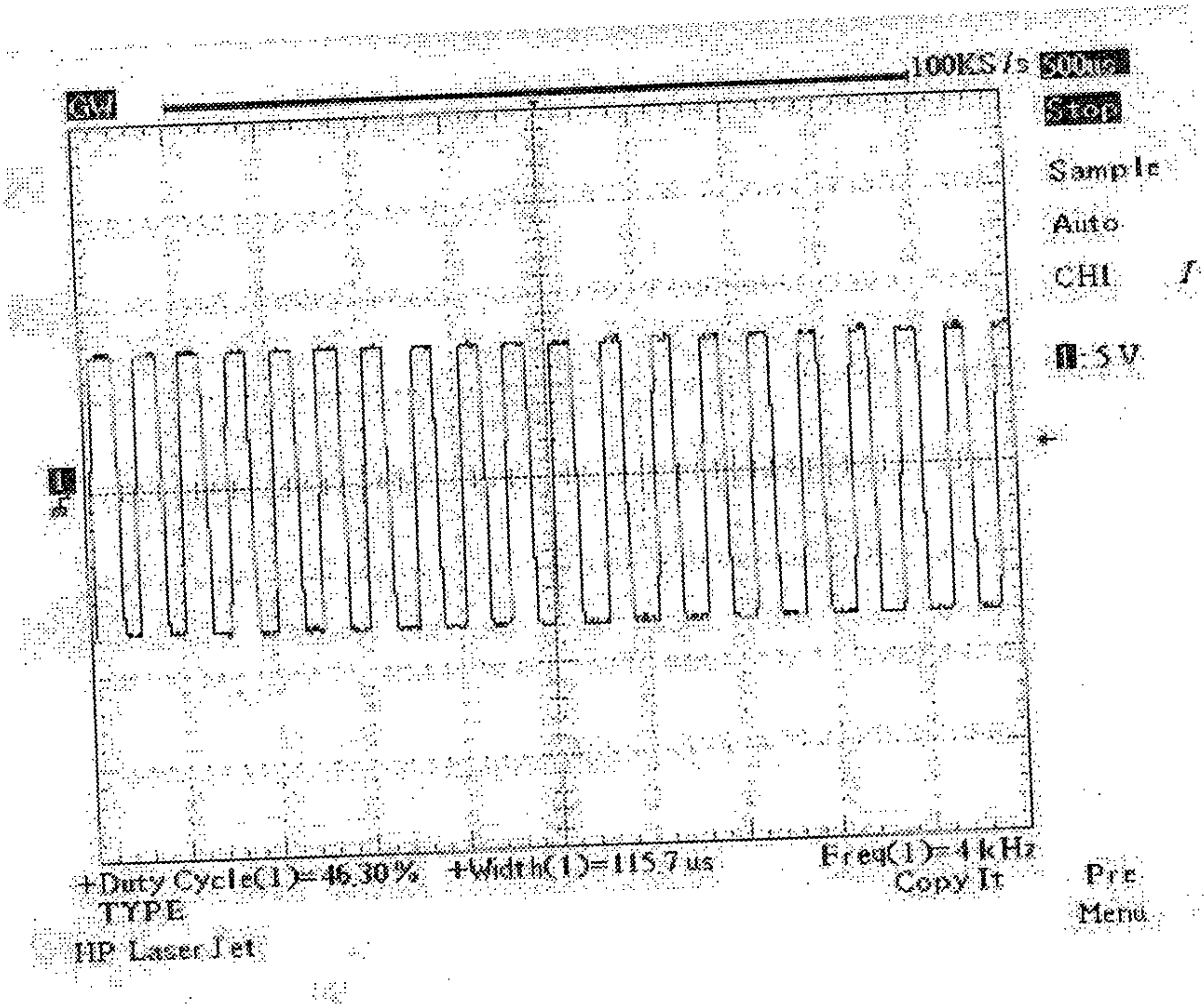


Fig-2.10: Switching waveform obtained at the output of A_1(where $R_1 = R_2 = 33k$ ohms)

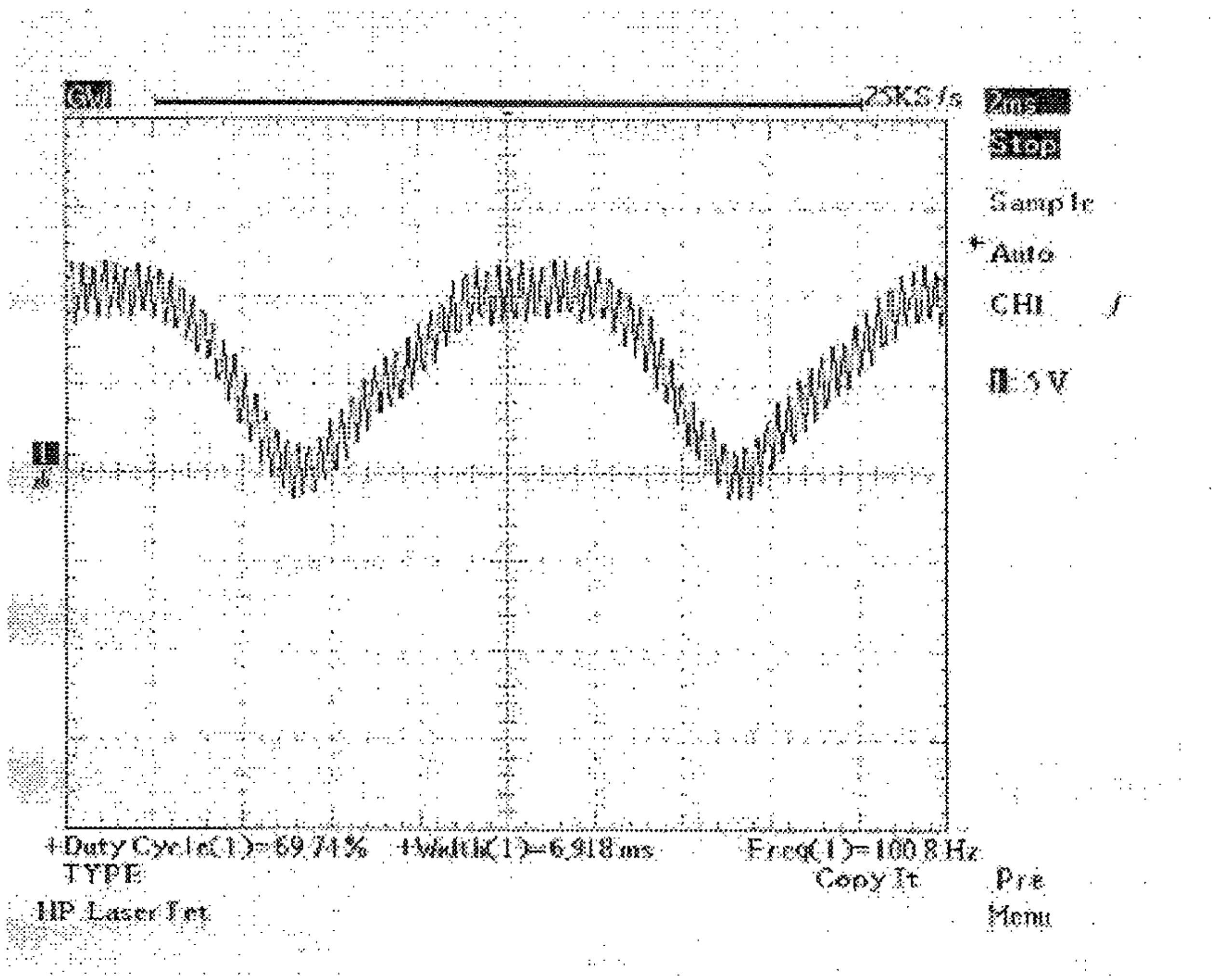


Fig- 2.11: Carrier wave V_f at the output of A_2 (where $R_1 = R_2 = 33k$ ohms)

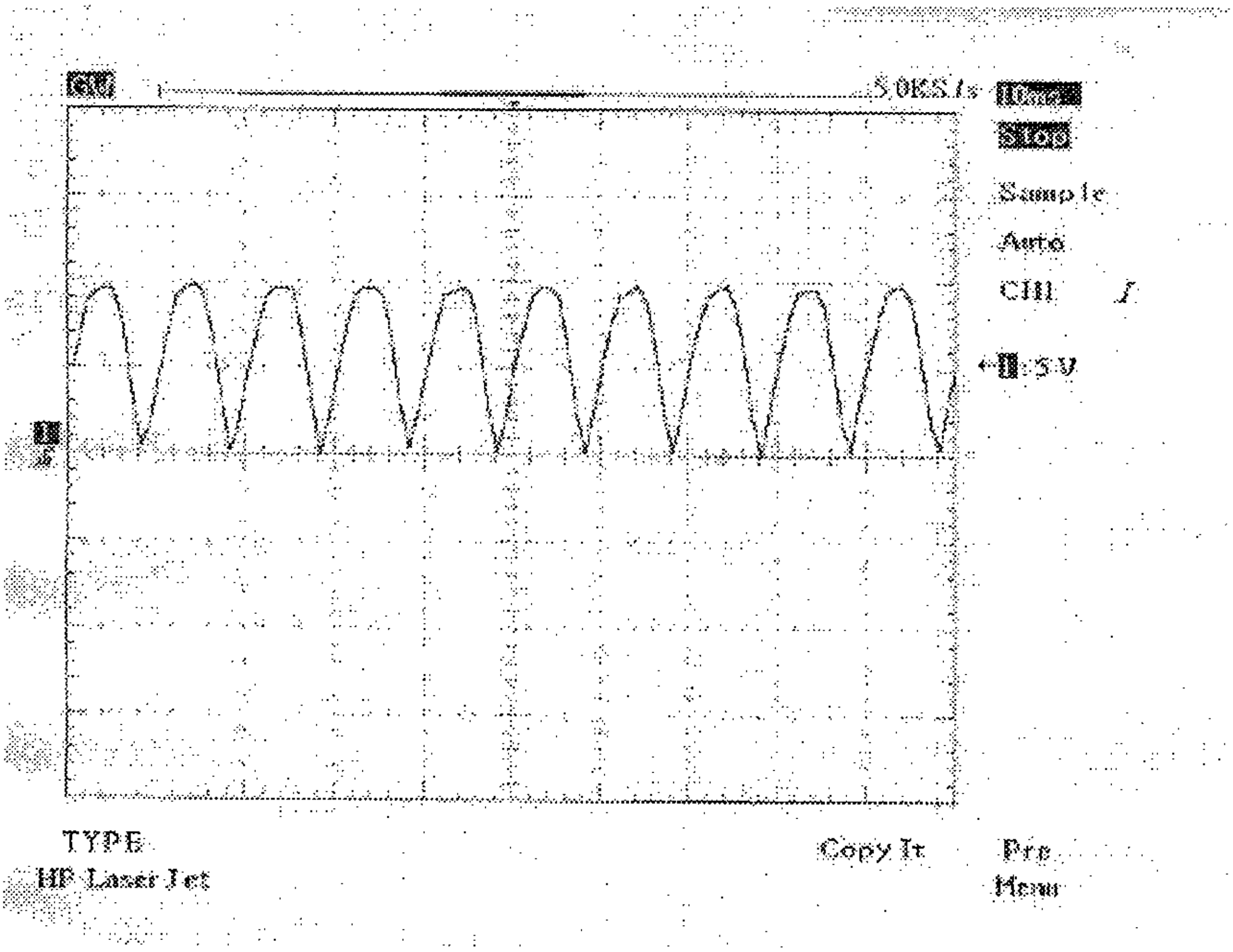


Fig-2.12: Sine reference voltage V_r(where R_1 = 33k ohms and R_2 = 66k Ohms) (rectified sine wave)

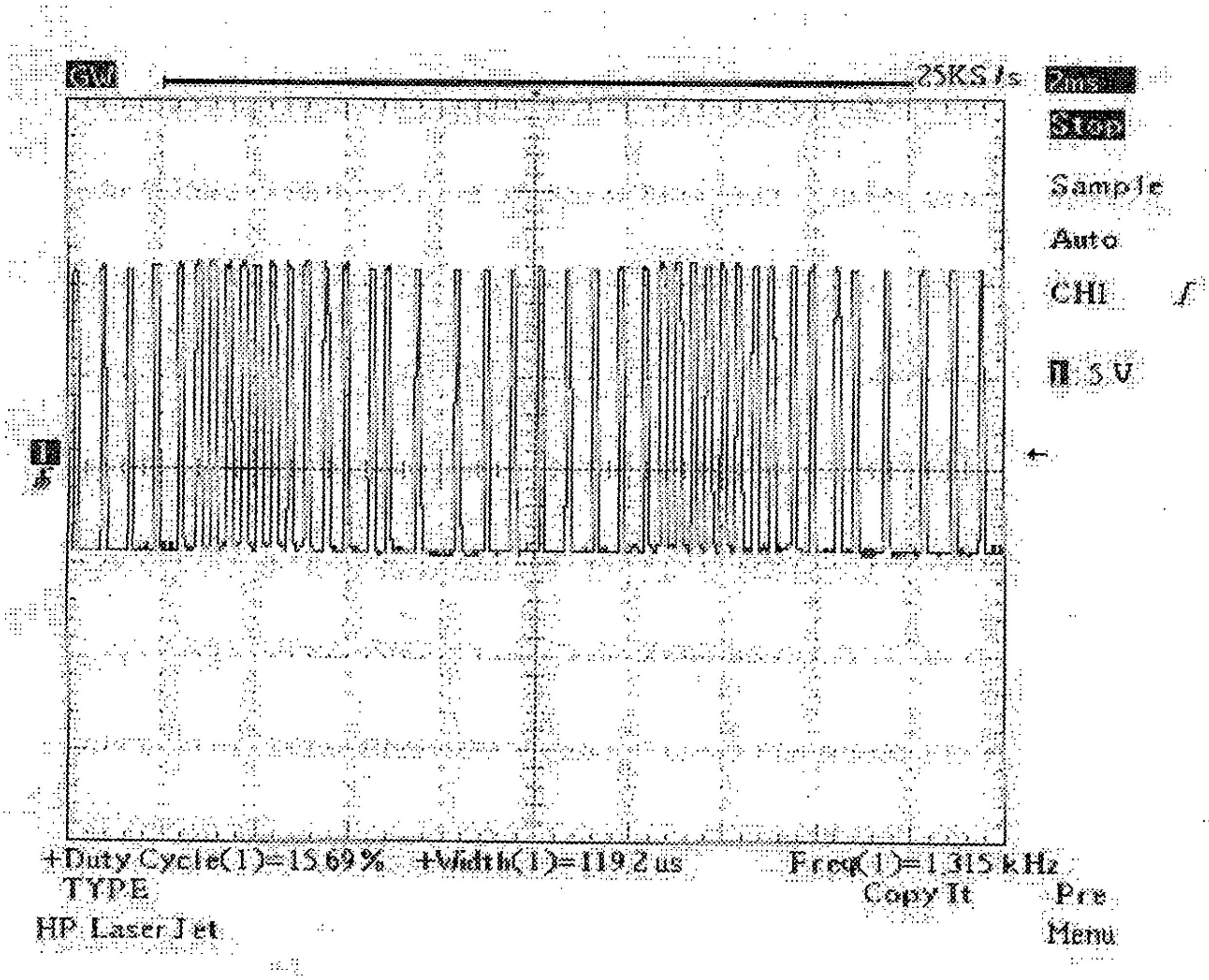


Fig-2.13 : Switching waveform obtained at the output of A_1(where R_1 = 33k ohms and R_2 = 66k Ohms)

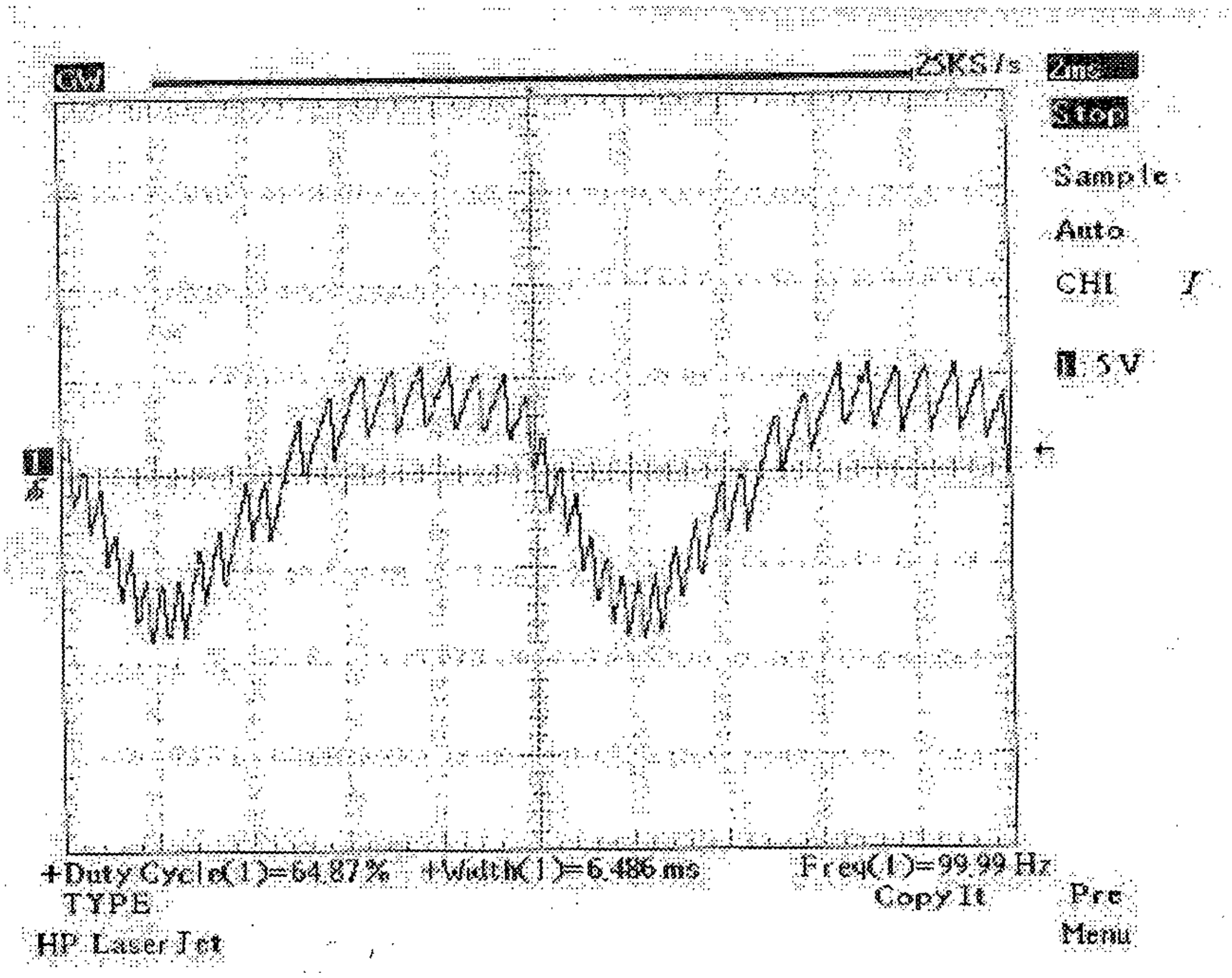


Fig- 2.14 : Carrier wave V_f at the output of A_2 (where R_1 = 33k ohms and R_2 = 66k Ohms)

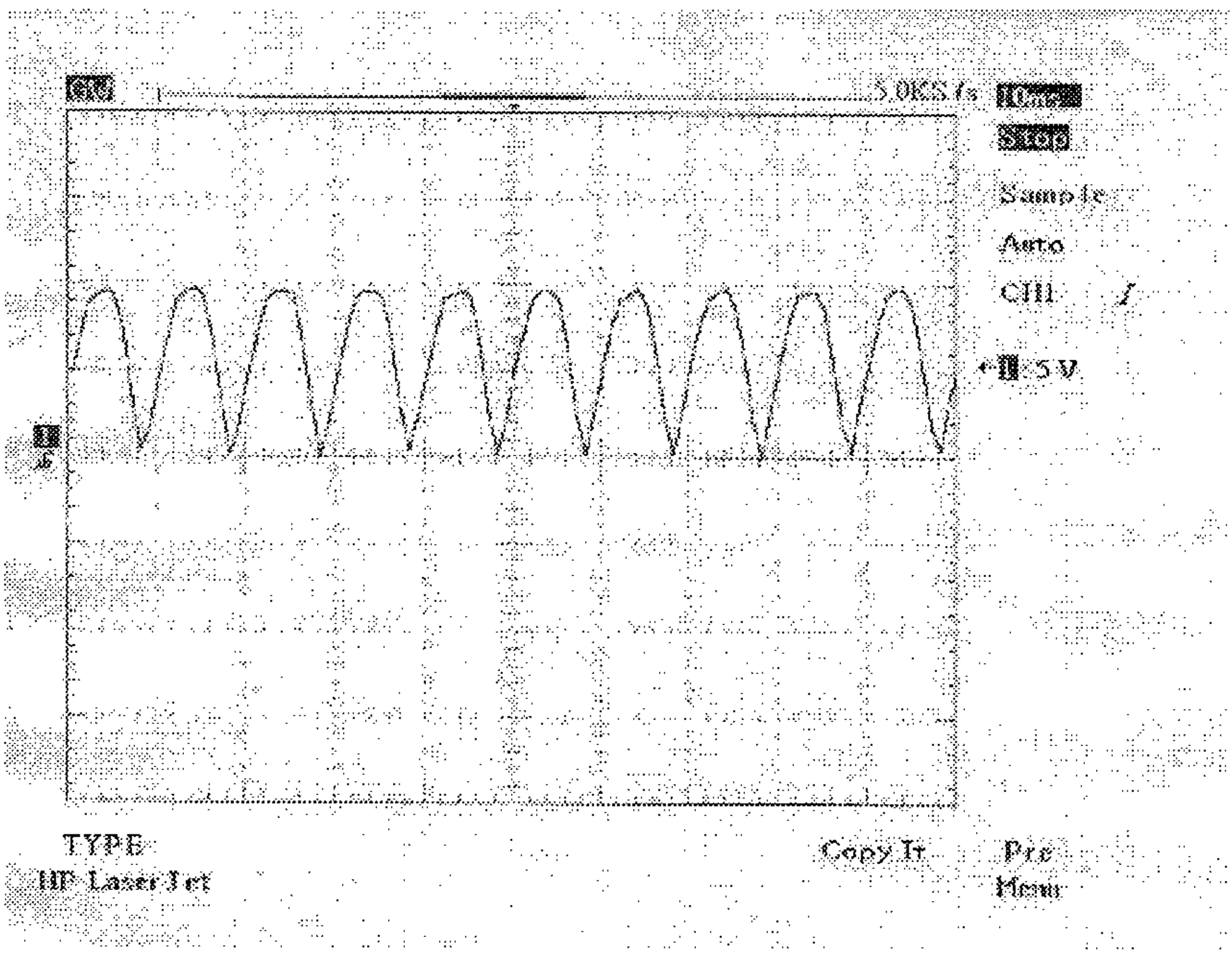


Fig-2.15: Sine reference voltage V_r (where R_1 = 33k ohms and R_2 = 3.3k Ohms) (rectified sine wave)

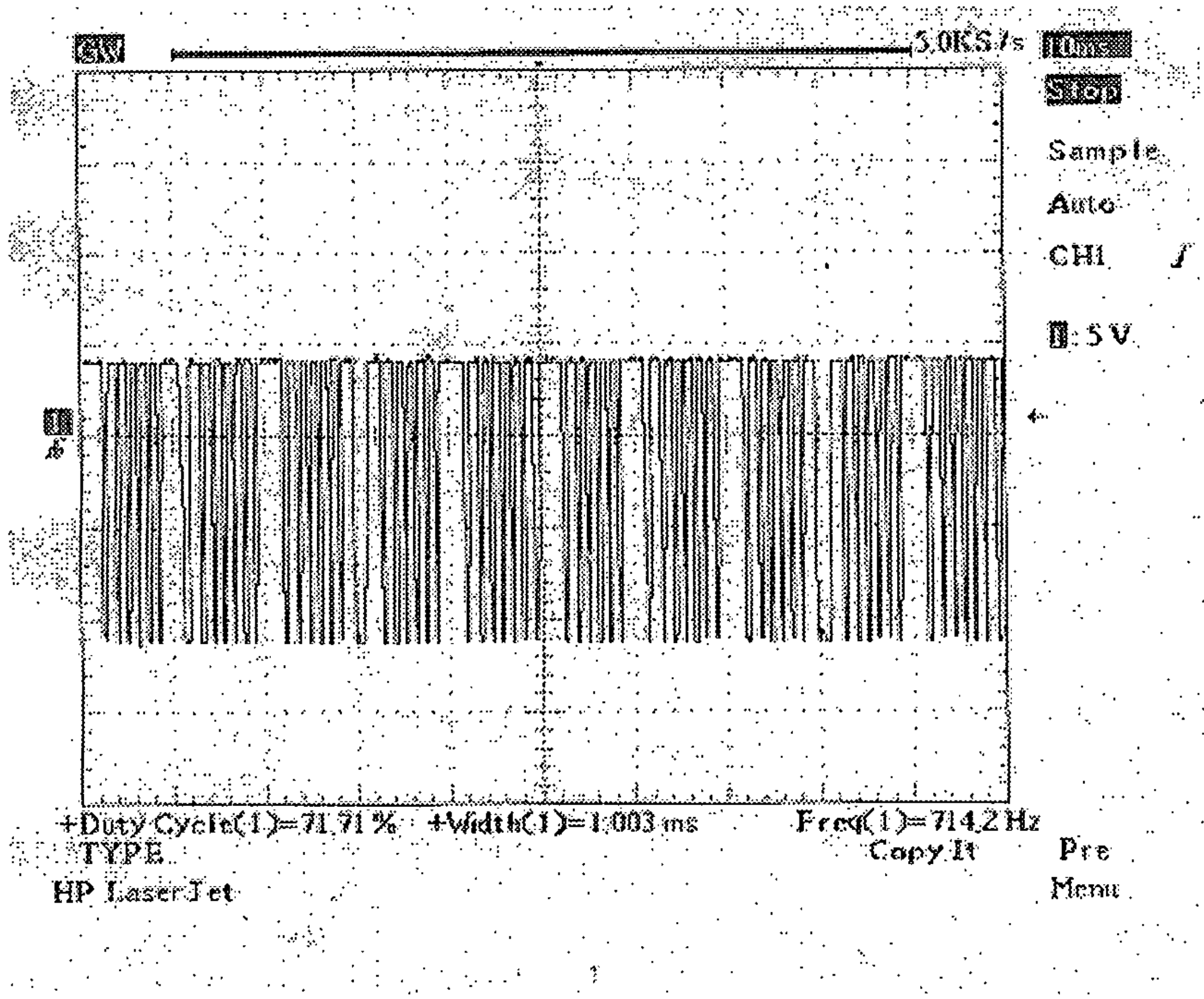


Fig-2.16 : Switching waveform obtained at the output of A_1 (where R_1 = 33k ohms and R_2 = 3.3k Ohms)

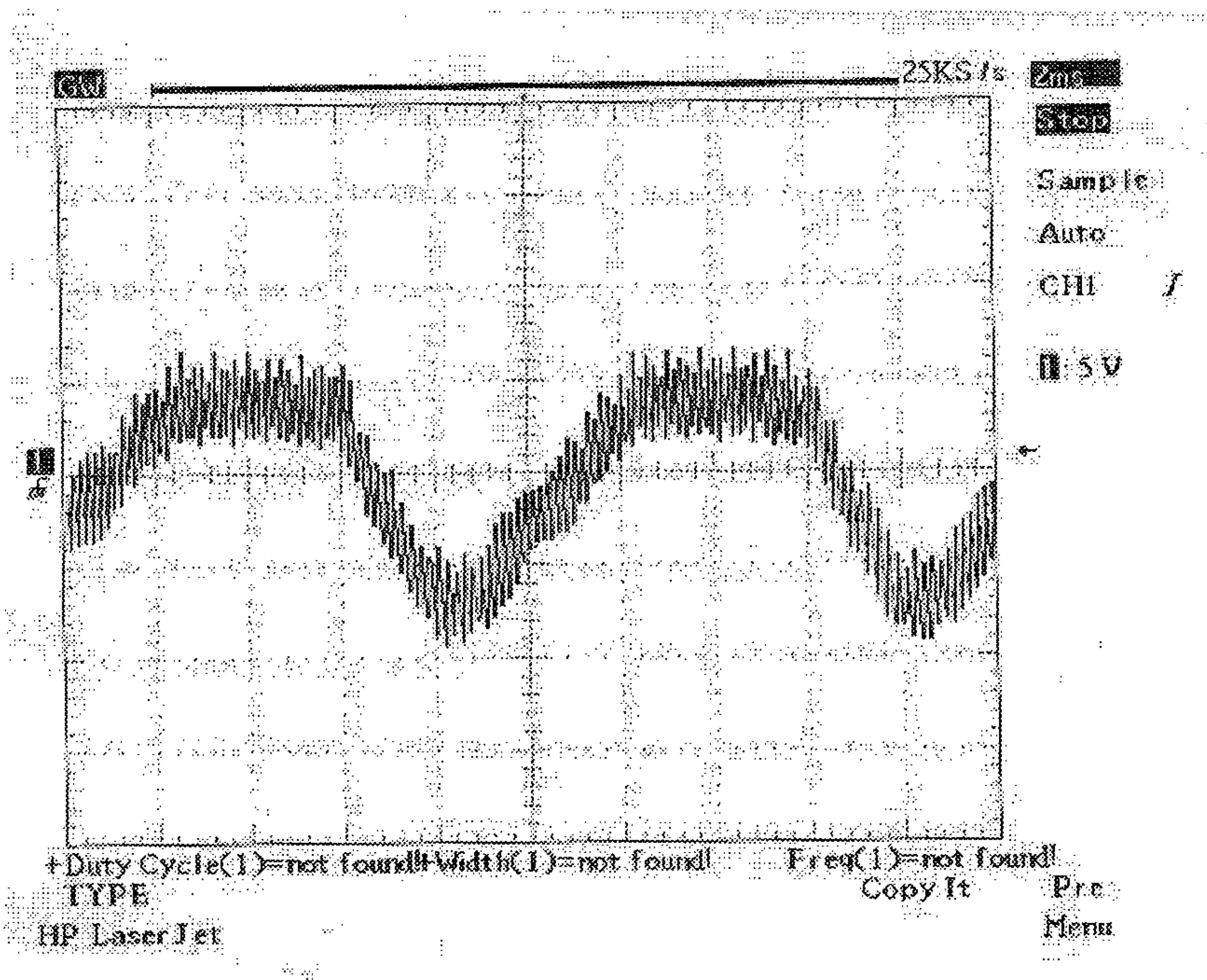


Fig- 2.17 : Carrier wave V_f at the output of A_2 (where R_1 = 33k ohms and R_2 = 3.3k Ohms)

2.3.1 **Discussions**

By analysing the various waveforms shown under paragraph 2.2 and 2.3 it is evident that the hardware implementation of dual slope delta modulation is very easy. As such the input power factor of a diode rectifier can be improved very easily by using this technology.

CHAPTER 3

STUDY OF POWER FACTOR CORRECTION OF A SINGLE PHASE DIODE RECTIFIER

3.1 A Single Phase Diode Rectifier Circuit Switched at the Output Side (Theoretical Analysis) [3]

The power factor correction of a diode rectifier using dual slope delta modulation technique consists of two main power conversion stages. The first stage is a single phase ac to dc uncontrolled rectifier consisting of an input filter, a boost inductor, a single phase diode rectifier, an active power factor correction technique and a dc link filter capacitor. The second stage can be modelled as any type of load requiring a regulated or unregulated dc bus such as general purpose single phase inverters or dc to dc converters etc. The active waveshaping of the input current waveform is obtained through the use of the boost chopper component L_7, Z_1 and D_6 as shown in Fig-3.1. The boost switch Z_1 is turned on at constant frequency. The duty cycle of Z_1 is varied for load variation only and it is such that the input current is always discontinuous. During the ON period of the boost switch the ac signal become shorted through inductor L_7, the four diodes and the boost switch Z_1. Consequently the input current begins to increase at a rate proportional to the instantaneous input voltage. Moreover the specific peak current values during each ON interval are proportional to the average values of their input voltage. Since each of these voltage average values varies sinusoidally the input current peaks also vary sinusoidally ((Fig-3.2(b)). As the current pulses always begin at zero, their average values also vary sinusoidally. The input ac current consists of the fundamental (50 Hz) component and a band of high frequency unwanted components centered around the switching frequency (f_z) of the boost switch. Since this frequency (f_z) can be in the order of KHz, filtering the unwanted input current harmonics becomes relatively easy. From Fig-3.1 and Fig-3.2 it is also seen that power control (or output voltage regulation) can be achieved through dual slope delta modulation of the boost switch ON interval at constant frequency (f_z). Incidentally f_z can be easily locked to the mains 50 Hz frequency to avoid beat frequency effects in the input currents.

Under the operating conditions described, the displacement input power factor ($\cos\Phi_i$) before filtering is made unity. As a result, the overall input power factor (before filtering) becomes equal to the harmonic input power factor and it is given by

$$\text{power factor} = \left[\frac{\frac{I_{ia,1}}{\sqrt{2}}}{\sqrt{\sum_{n=1}^{\infty} \left(\frac{I_{ia,n}}{\sqrt{2}} \right)^2}} \right]$$

Where,

$I_{ia,n}$ is the Fourier component of the nth harmonic component of current I_a (Input Current) and $\cos\Phi_i$ is the displacement factor.

It is noted that the current harmonics associated with this power factor can be suppressed by a relatively small input capacitor (C_{10}) and inductor (L_1) because of their high frequencies. Therefore the overall input power factor after filtering (ie, at the ac source) is very close to unity. Various waveforms are shown in Fig-3.2

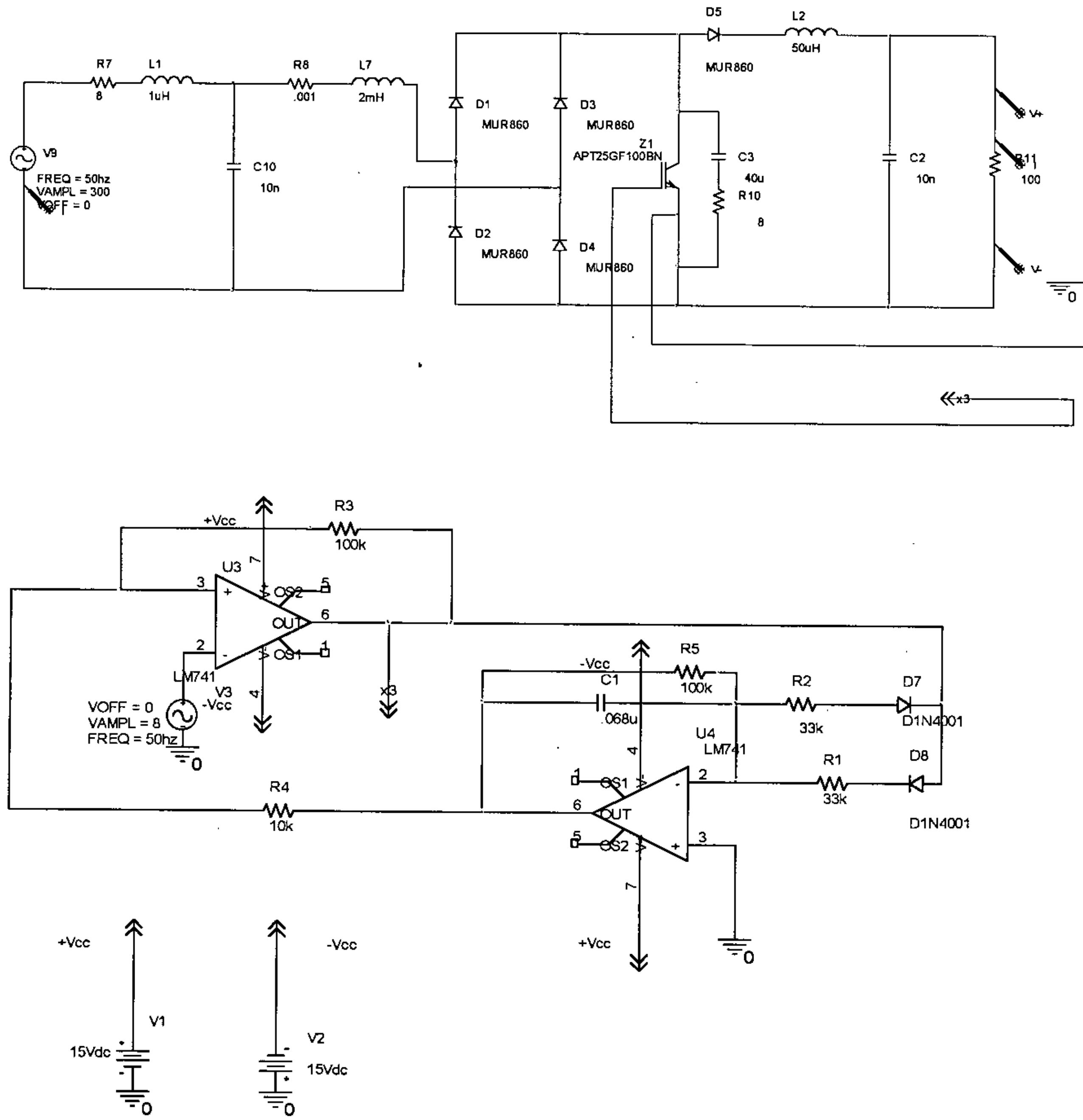


Fig-3.1: Single Phase Diode rectifier Circuit Switched at the Output side.

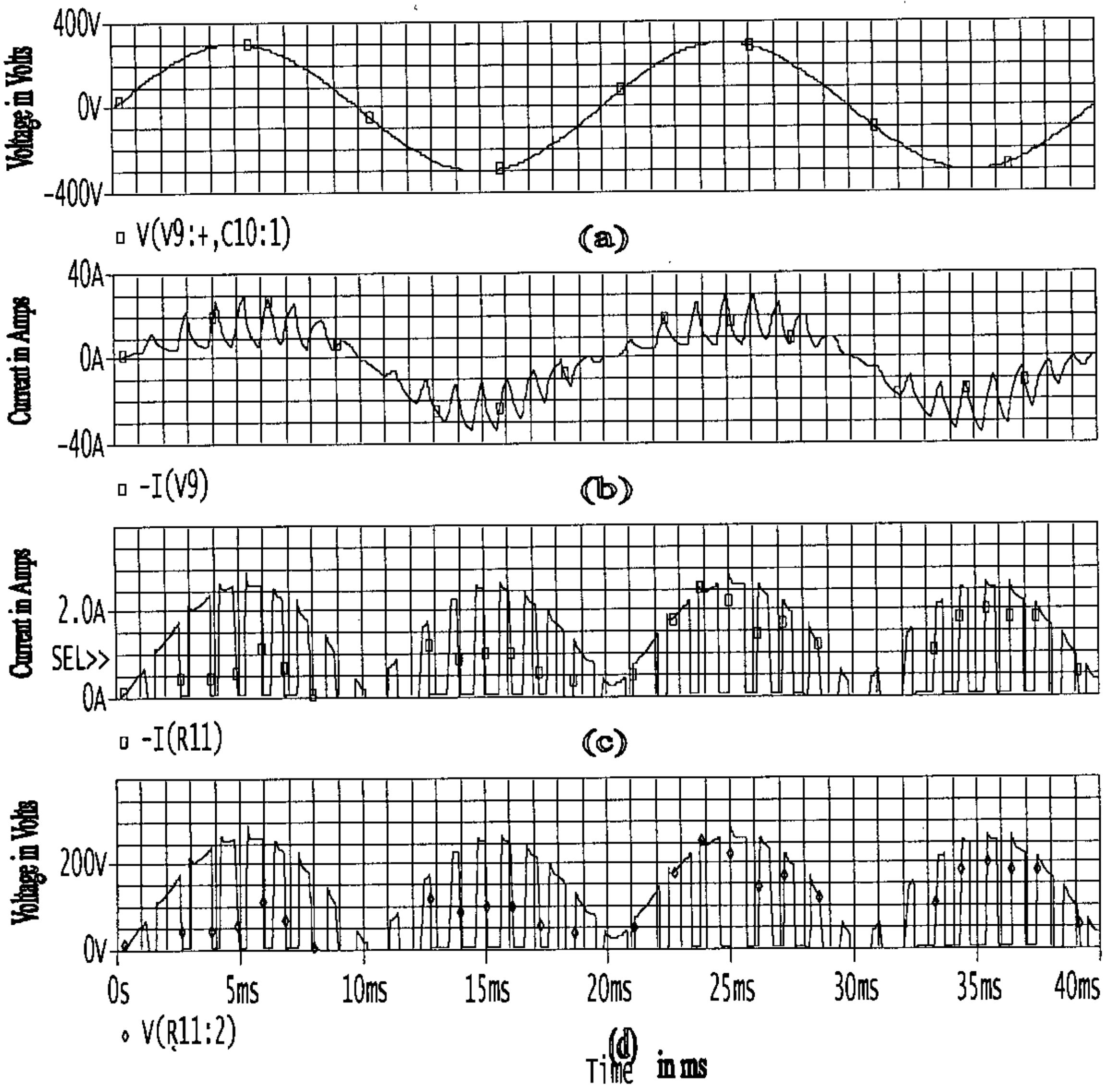


Fig-3.2: Various Waveforms of a Single Phase diode Rectifier Switched at the Output side

(a) Input Voltage,

(b) Input Current,

(c) Output Current and

(d) Output Voltage.

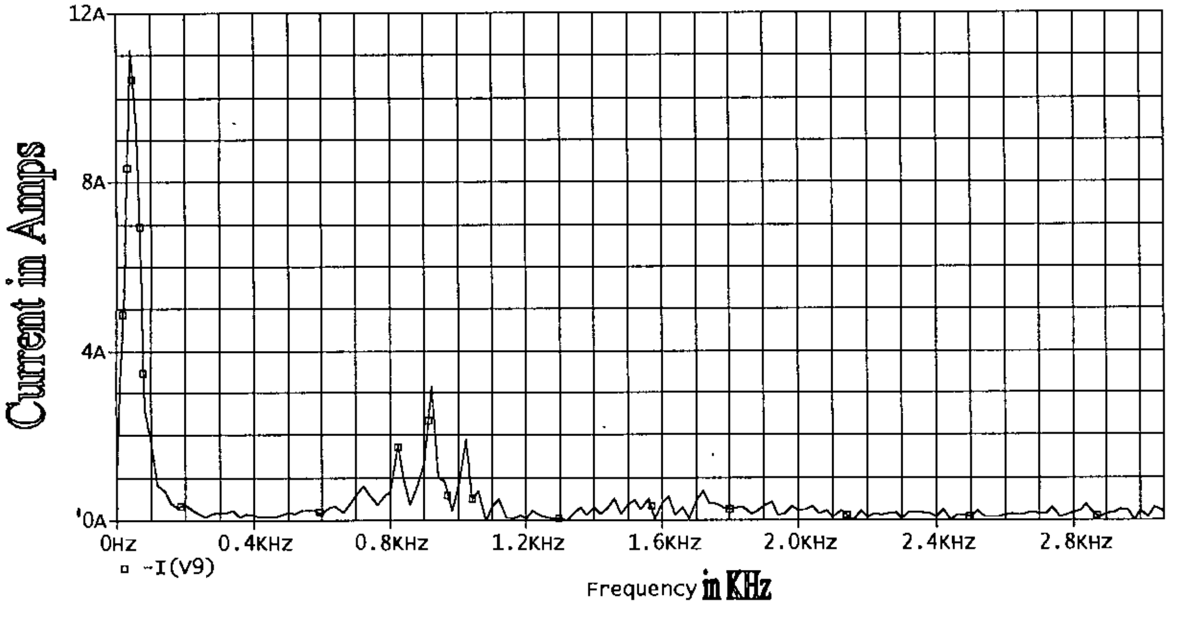


Fig-3.3: Fourier Transforms of Input Current of the Single Phase Diode Rectifier Circuit Switched at the Output Side (L_1=1uH, C_{10}=10nF and R_3=100k, R_4=10k)

3.1.1 **Making the Input Current Sinusoidal**

As the rectifier is connected with an IGBT switch Z_1, the input current follows the input voltage as discussed earlier (Input current peaks varies sinusoidally). But the whole input current is not sinusoidal because of switching action. This can be seen from the Fourier transforms of input current, where, the harmonic components are shown (Fig- 3.3). Now to make the input current sinusoidal, increase in the value of input filter is made. By putting the value of L_1 = 18mH and C_{10} = 150uF (when R_3=100k, R_4=10k) we get the sinusoidal input which is shown in Fig-3.4 and Fig-3.5. The Fourier transforms of this input current is shown in Fig-3.6, where, we can see there is less harmonic contents. Again by putting the value of L_1 = 5mH and C_{10} = 40 uF (when R_3=100k, R_4=1k) we get almost sinusoidal input current which is shown in Fig-3.7 and Fig-3.8. The Fourier transforms of this input current is shown in Fig-3.9, where, we can see there is less harmonic contents.

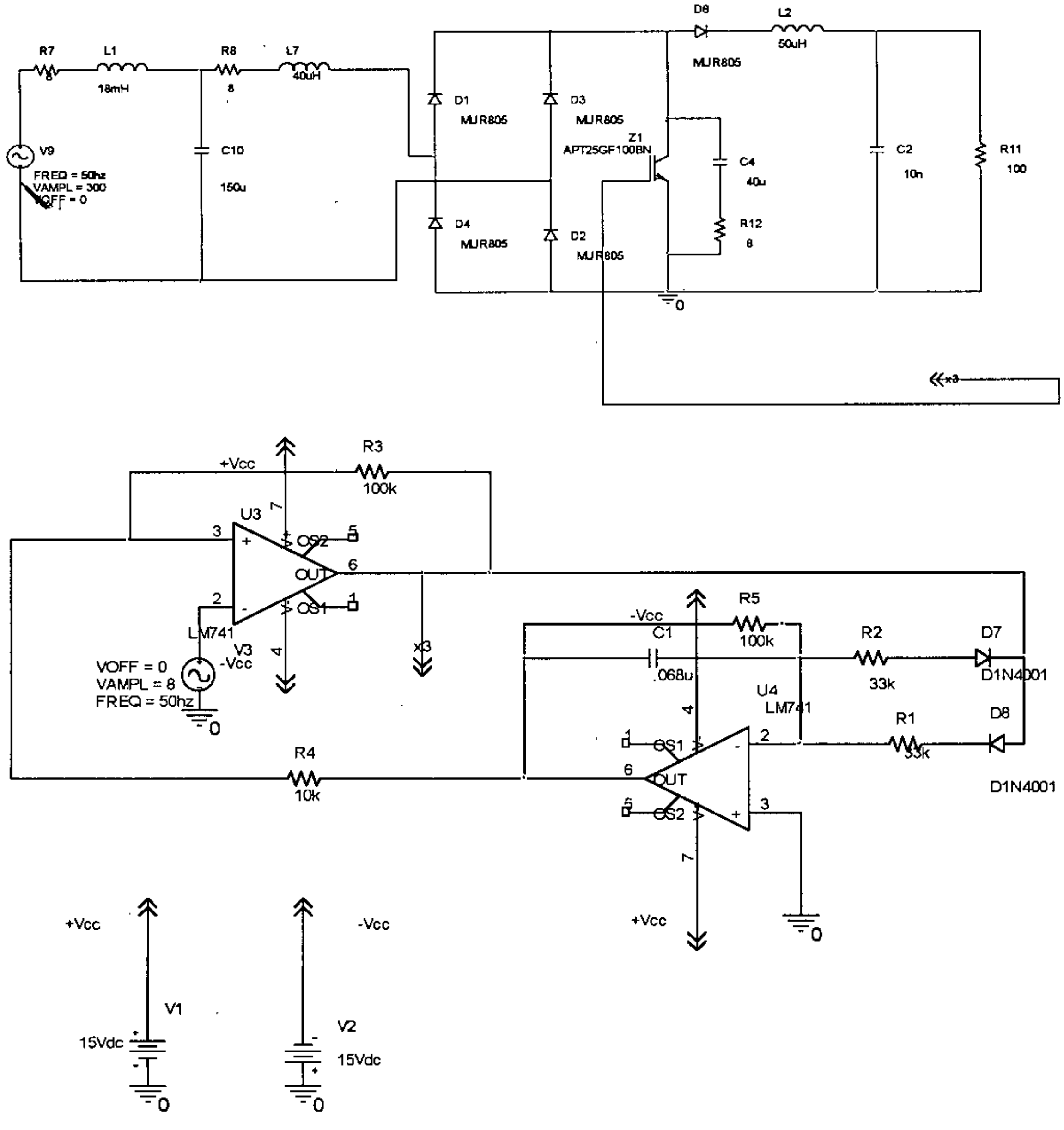


Fig-3.4: Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 18 mH, C_{10} = 150 uF and R_3 = 100k, R_4 = 10k).

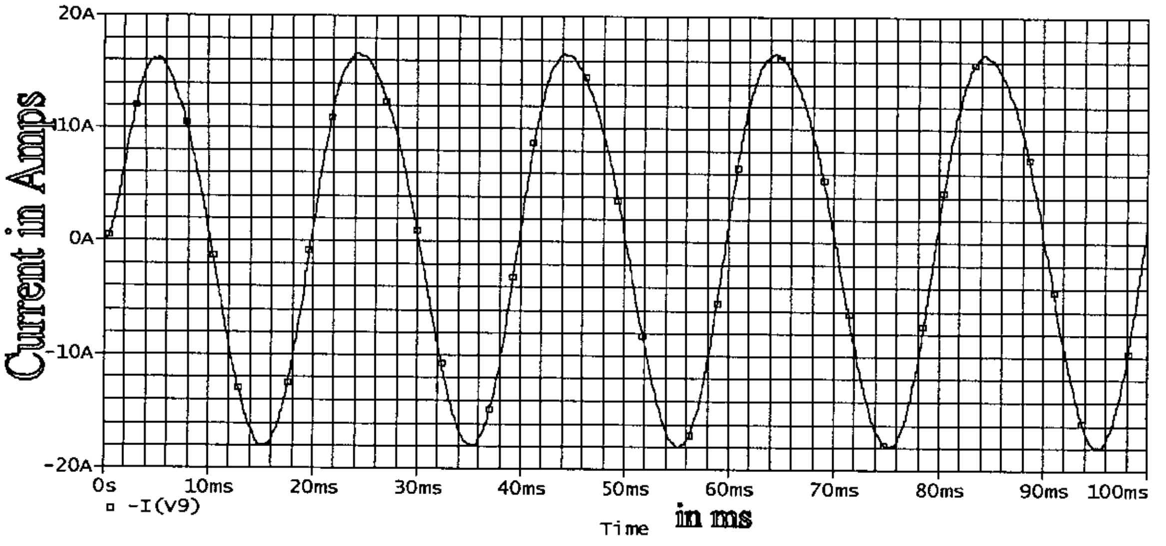


Fig-3.5: Input Current of a Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 18 mH, C_{10} = 150 uF and R_3 = 100k, R_4 = 10k)

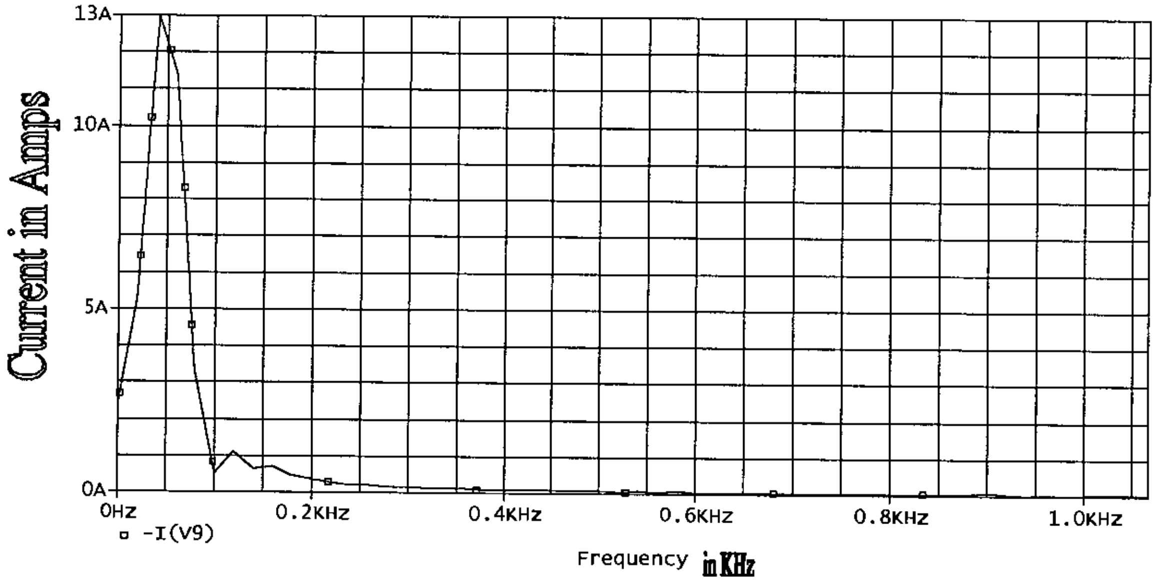


Fig-3.6: Fourier Transforms of Input Current of a Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 18 mH, C_{10} = 150 uF and R_3 = 100k, R_4 = 10k)

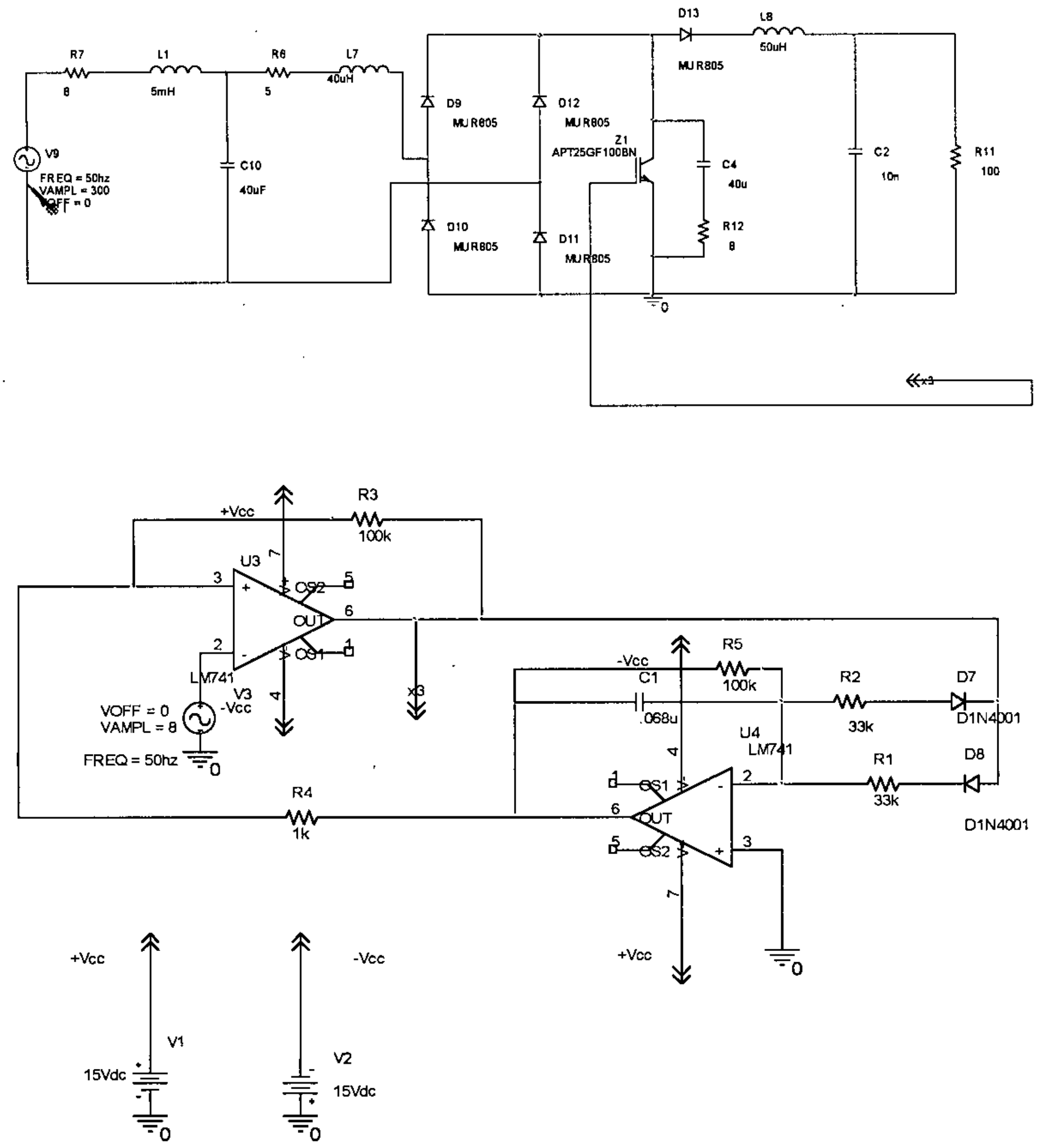


Fig-3.7: Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 5 mH, C_{10} = 40 uF and R_3 = 100k, R_4 = 1k)

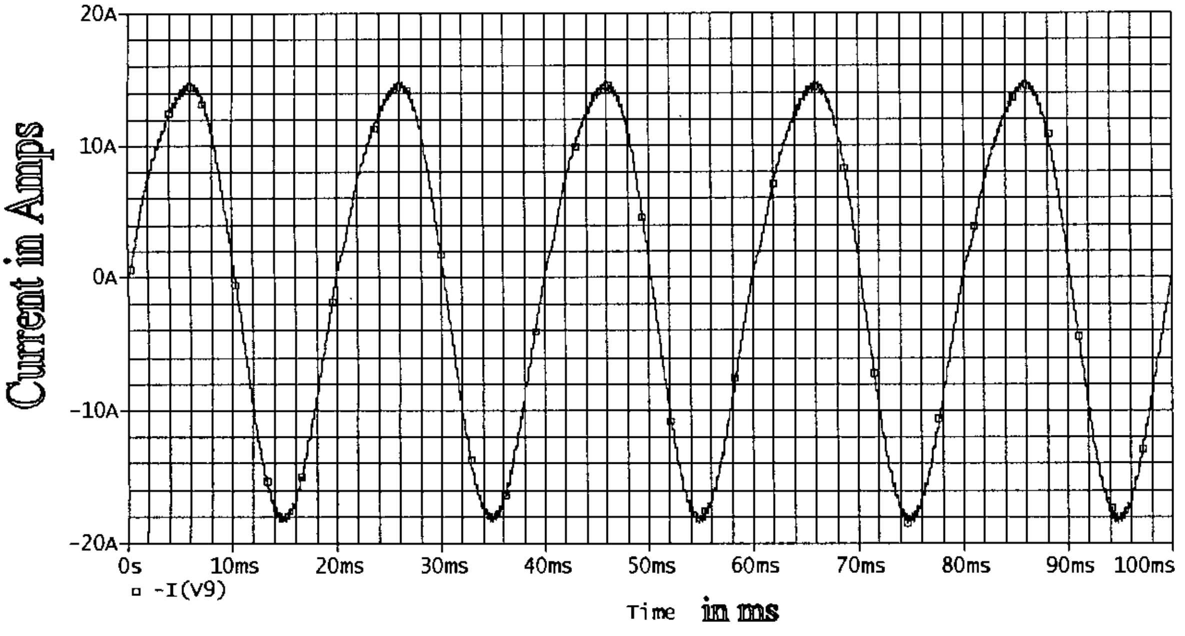


Fig-3.8: Input Current of a Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 5 mH, C_{10} = 40 uF and R_3 = 100k, R_4 = 1k)

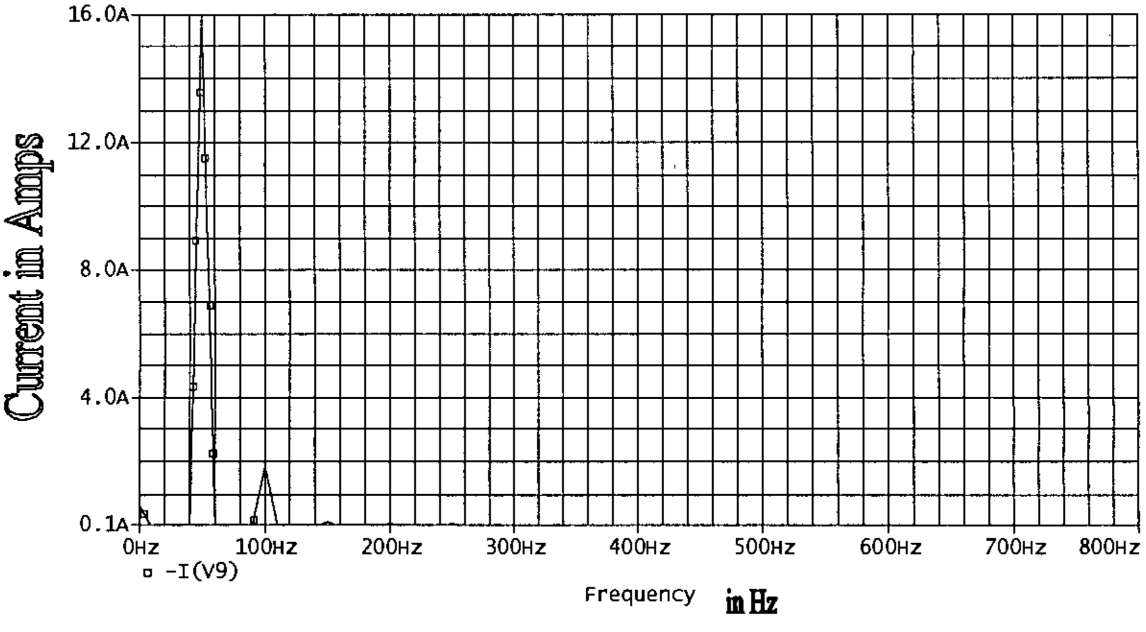


Fig-3.9: Fourier Transforms of Input Current of a Single Phase Diode rectifier Circuit Switched at the Output side (L_1 = 5 mH, C_{10} = 40 uF and R_3 = 100k, R_4 = 1k)

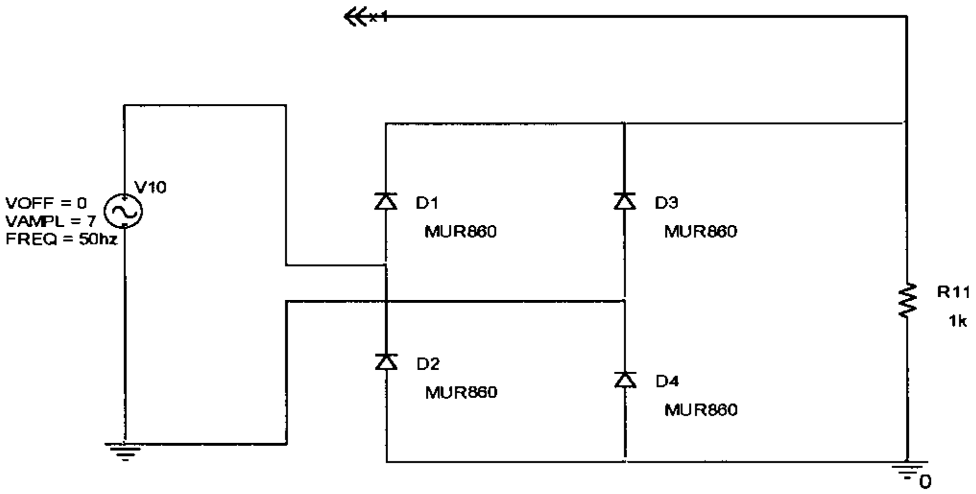
3.1.2 **Discussions**

By comparing the circuits shown in Fig-1.6 (L_1 =150 mH, C_2 = 90 uF) and Fig-1.13 (L_1 = 150 mH, C_3 = 100 uF) and Fig-3.4 (L_1 = 18 mH, C_{10} =150 uF for R_3 = 100k, R_4 = 10k) and Fig-3.7 (L_1 = 5 mH, C_{10} = 40 uF for R_3 = 100k, R_4 = 1k) we can say if the high frequency electronic switch is used in the diode rectifier the value of passive components (Input LC filter) is significantly reduced which in turn will reduce the size and cost of the equipment. Also as the switching is done in phase with the input voltage, the input power factor is unity.

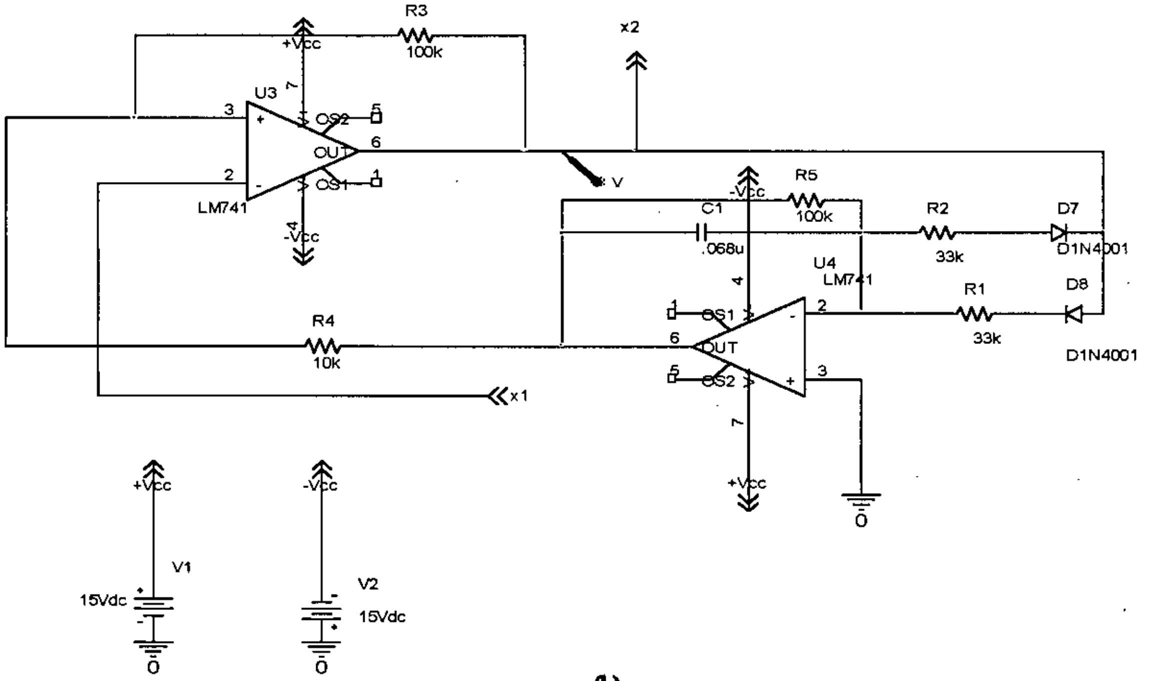
3.2 **A Single Phase Diode Rectifier Circuit Switched at the Output Side (Practical Circuit Analysis)**

A practical circuit with a switch at the output side of a diode rectifier is shown in Fig-3.10. In this scheme a dual slope delta modulation circuit ((Fig-3.10(b)) is used to provide gate pulses for switching the diode rectifier. A same source voltage is used as the input to the dual slope delta modulation but with full wave rectification and smaller magnitude. Before the gate pulse is applied to the MOSFET (M_4) the output of the dual slope delta modulator is taken through an optocoupler and buffers. The switch (MOSFET M_4) is connected at the output side of a single phase diode rectifier. The various waveforms of the circuit taken from storage oscilloscope and are shown in Figs-3.11 to Fig3.14.

Now after adding the LC filter in the input of a single phase diode rectifier various waveforms are taken from storage oscilloscope and are shown in Figs-3.15 to Fig-3.18

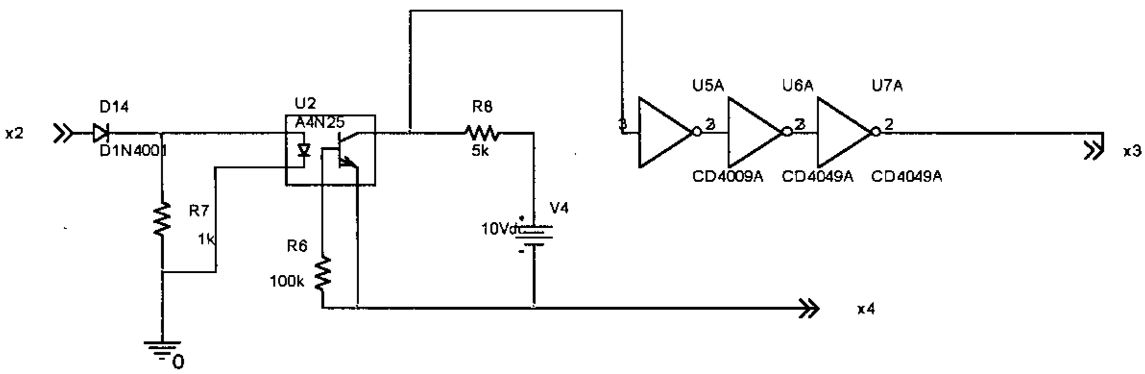


(a)

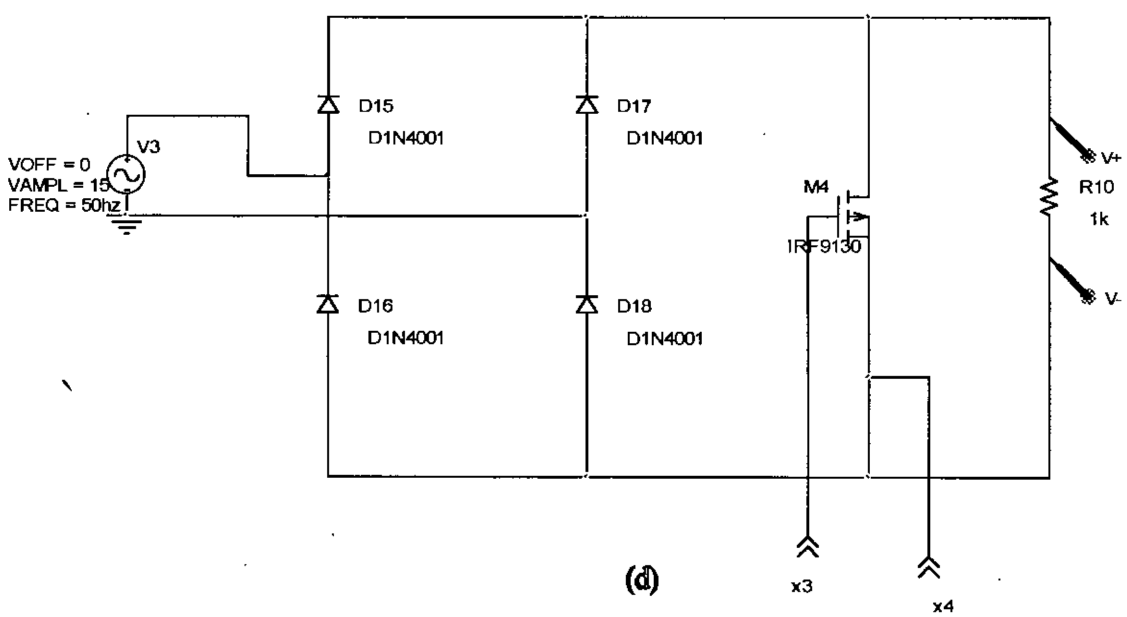


(b)

Fig-3.10: Practical Circuit of a Single Phase Diode Rectifier Switched at the Output side (Continued)



(c)



(d)

Fig-3.10: Practical Circuit of a Single Phase Diode Rectifier Switched at the Output side

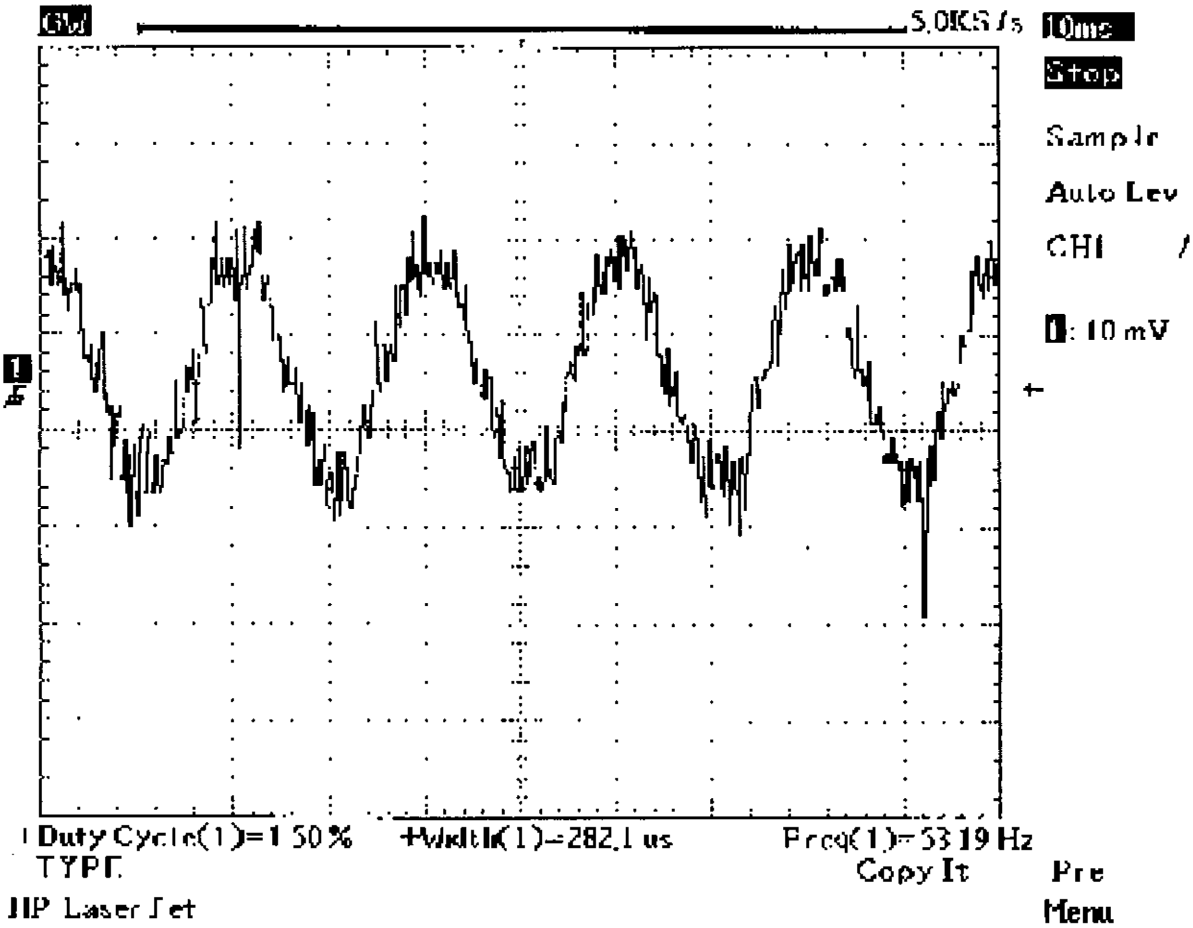


Fig-3.11: Input current of the diode rectifier circuit switched at the output side.

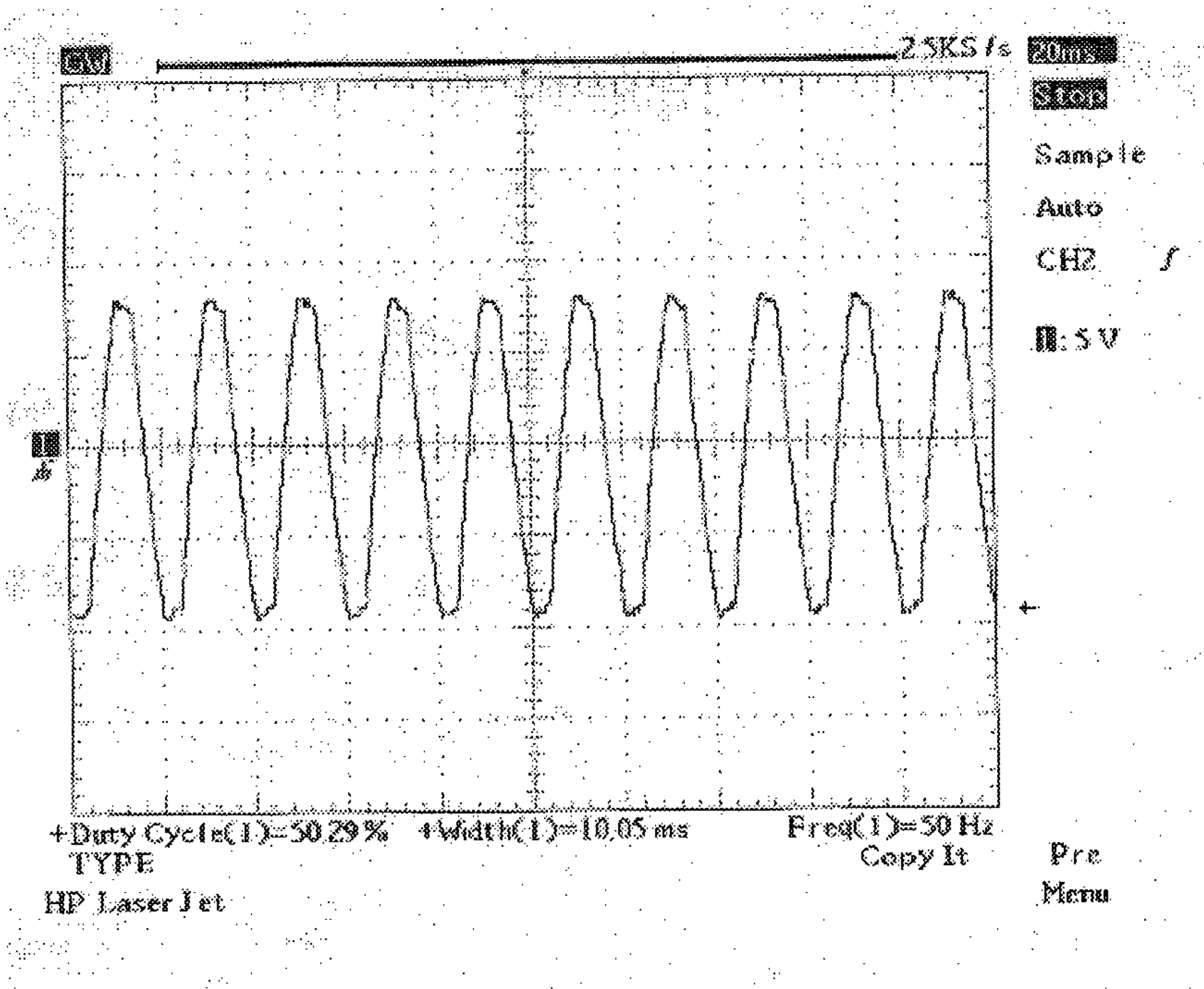


Fig-3.12: Input voltage of the diode rectifier circuit switched at the output side.

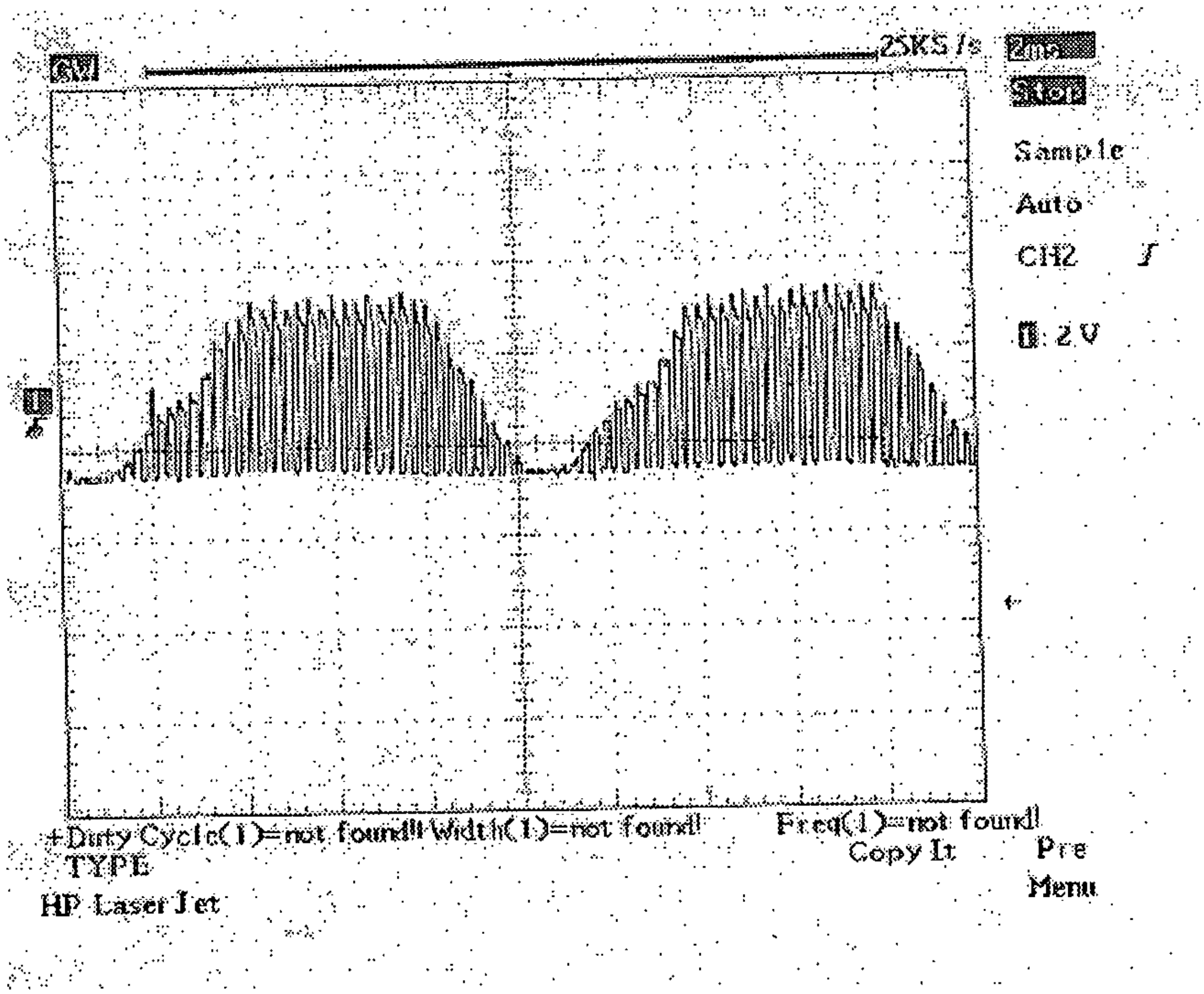


Fig-3.13: Output current of the diode rectifier circuit switched at the output side.

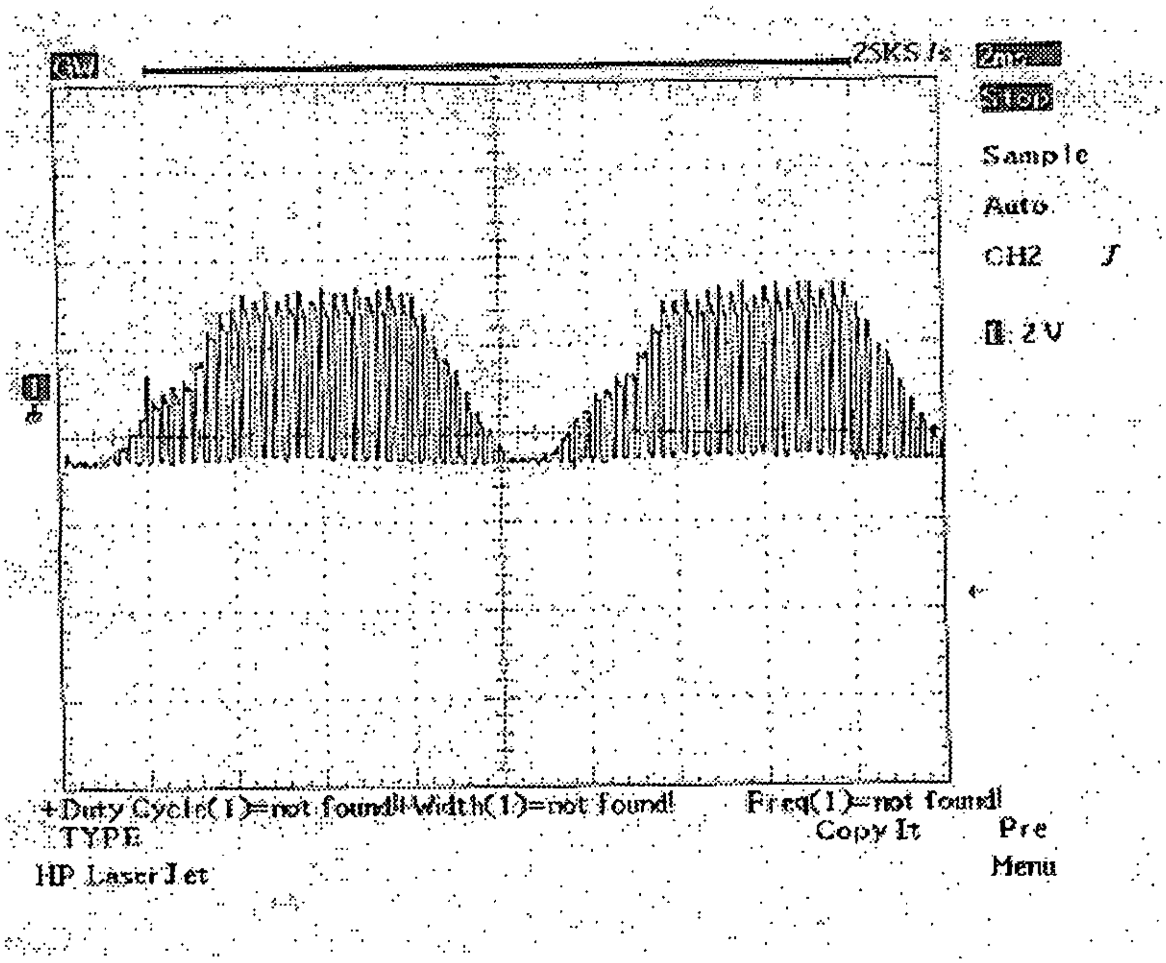


Fig-3.14: Output voltage of the diode rectifier circuit switched at the output side.

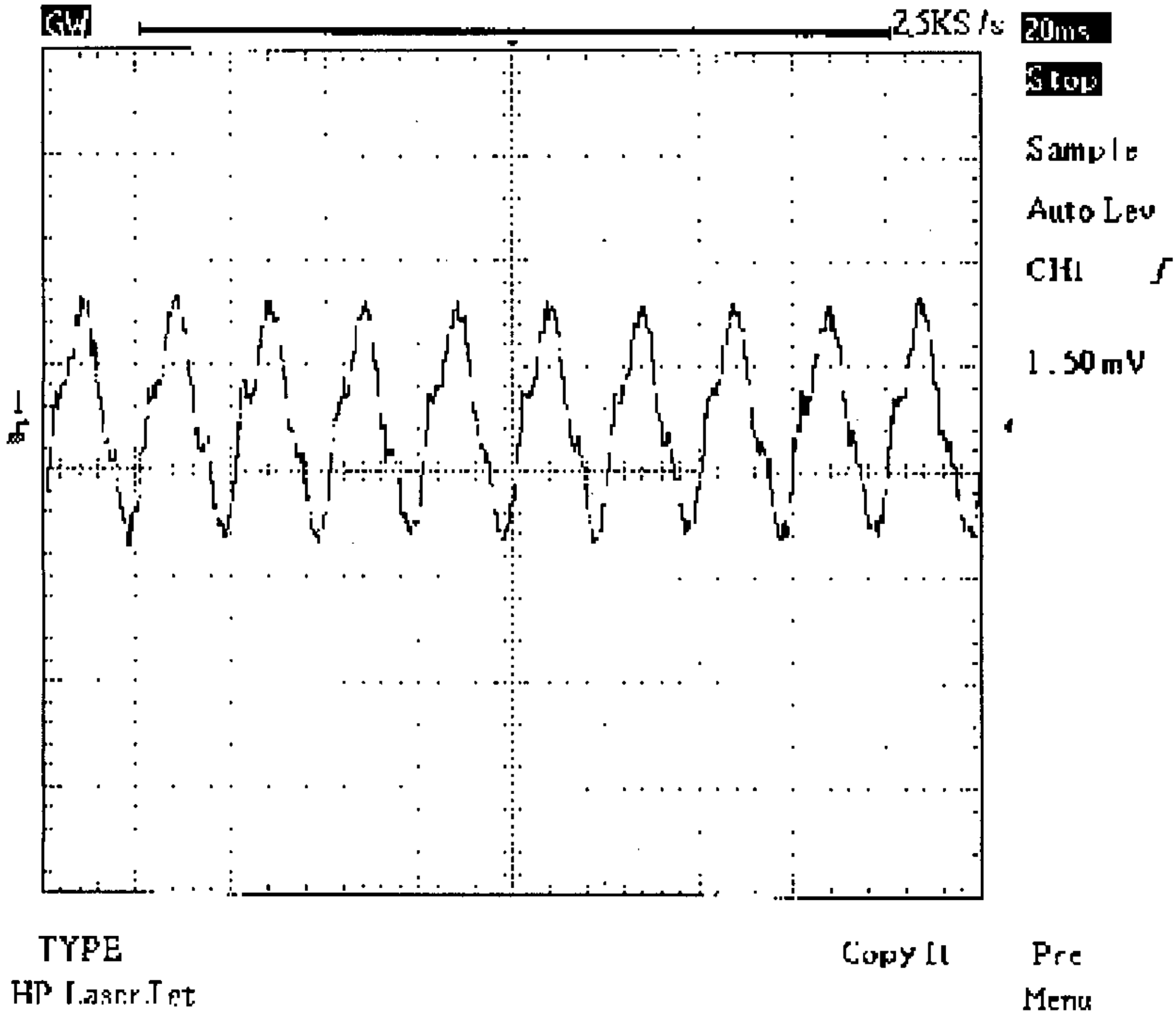


Fig-3.15: Input current of the diode rectifier circuit switched at the output side and a LC filter at the input (L = 5 mH, C = 40 uF).

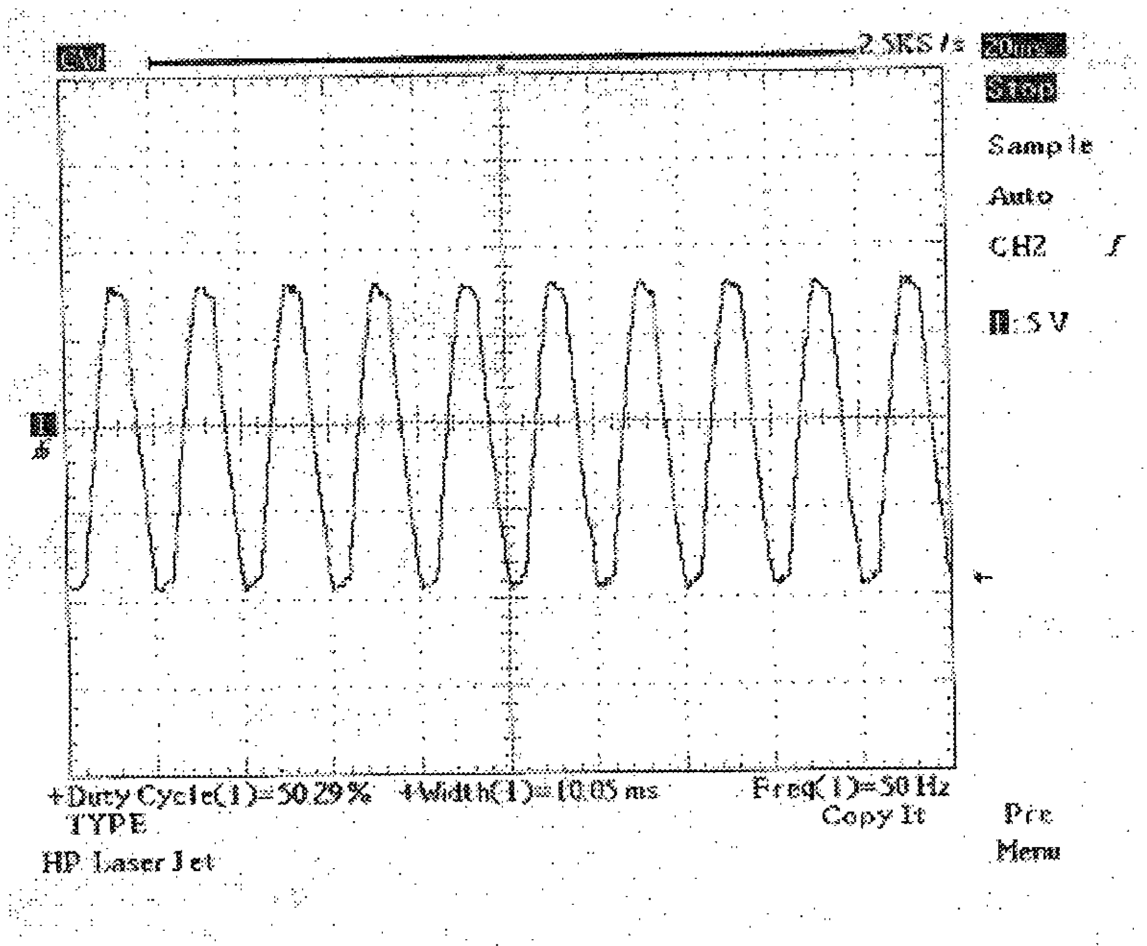


Fig-3.16: Input voltage of the diode rectifier circuit switched at the output side and a LC filter at the input.

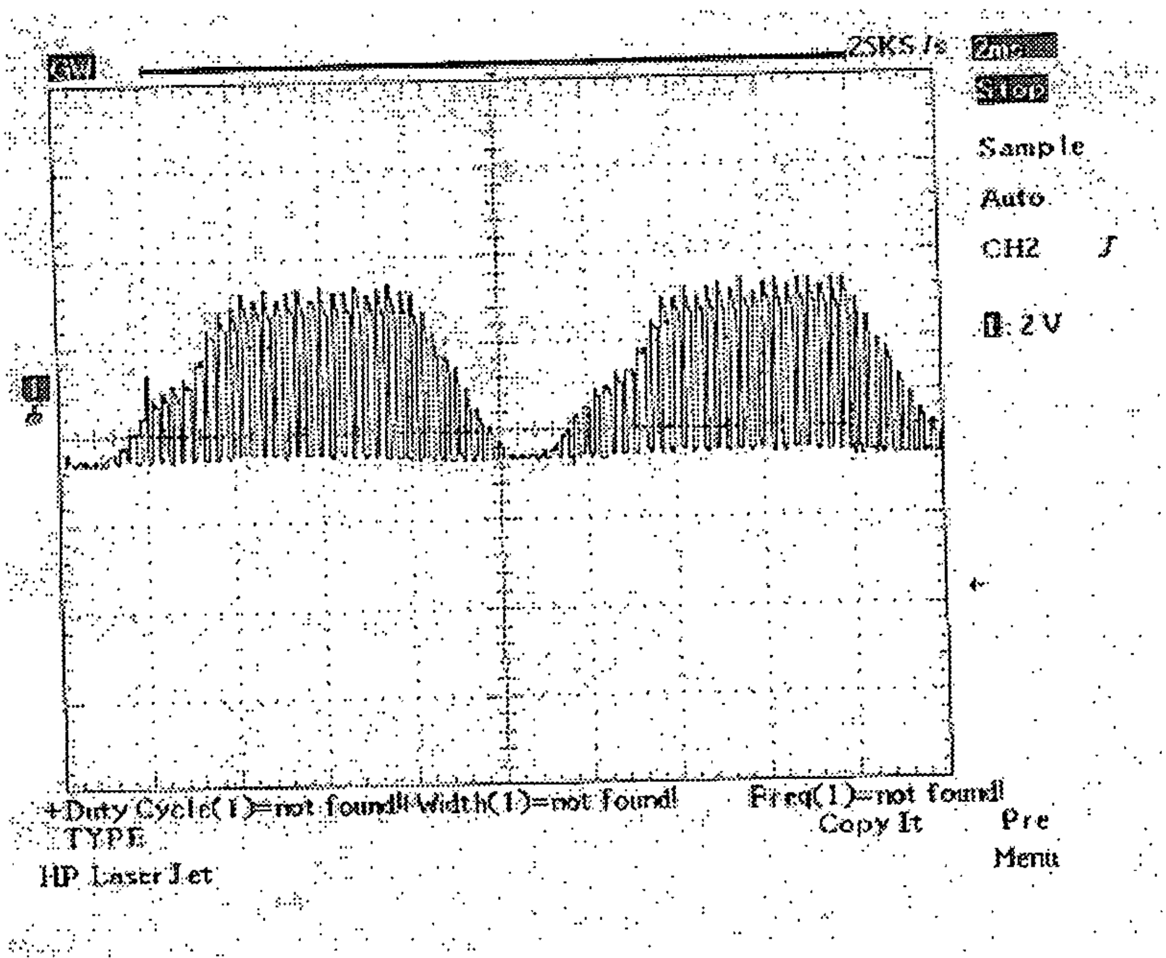


Fig-3.17: Output current of the diode rectifier circuit switched at the output side and a LC filter at the input.

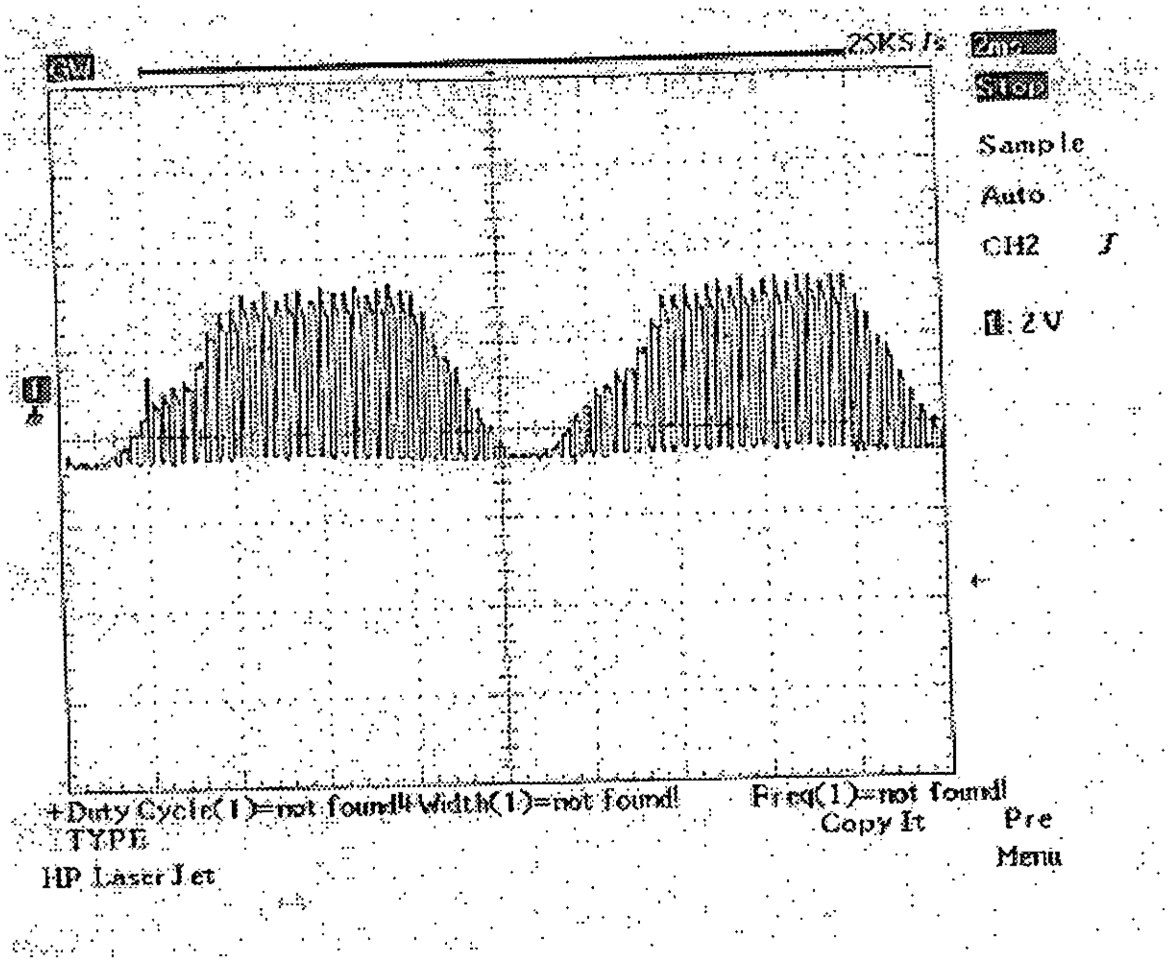


Fig-3.18: Output voltage of the diode rectifier circuit switched at the output side and a LC filter at the input.

3.2.1 Discussions

The theoretical analysis of a single phase diode rectifier circuit is verified by hardware implementation which has been discussed in paragraph 3.2. From various waveforms taken from storage oscilloscope it is clearly seen that these waveforms matches with the waveforms of the simulated waveforms produced by ORCAD programme. It is evident that by using electronic switch activated by dual slope delta modulation, the input current can be forced or shaped to follow the input voltage waveform. In other words the input power factor can be improved and that is near to unity.

3.3 A Single Phase Diode Rectifier Circuit Switched at the Input Side (Theoretical Analysis)

The power factor correction of a diode rectifier circuit keeping switch at the input side of a rectifier also consists of two main power conversion stages. The first stage is a single phase ac to dc rectifier consisting of an input filter, an active power factor correction technique, a boost inductor, a single phase diode rectifier and a dc link filter capacitor. The second stage can be modelled as any type of load requiring a regulated or unregulated dc such as general purpose single phase inverters or dc to dc converters etc. The active waveshaping of the input current waveform is obtained through the use of the boost chopper component L_7 and the bidirectional switch formed by diodes D_{10}, D_{11}, D_{12}, D_{13} and IGBT Z_1 as shown in Fig-3.19. The boost switch Z_1 is turned on at constant frequency. The duty cycle of Z_1 is varied for load variation only and it is such that the input current is always discontinuous. During the ON period of the boost switch the input current begins to increase at a rate proportional to the instantaneous input voltage. Specific peak current values during each ON interval are proportional to the average values of their input voltage during the same ON interval. Since each of these voltage average values varies sinusoidally the input current peaks also vary sinusoidally ((Fig-3.20(b)). The current pulses always begin at zero meaning that their average values also vary sinusoidally. Consequently the input ac current consists of the fundamental (50 Hz) component and a band of high frequency unwanted components centered around the switching frequency (f_z) of the boost switch. Since this frequency (f_z) can be in the order of several KHz, filtering out of the unwanted input current harmonics becomes a relatively easy task. From Fig-3.19 and Fig-3.20 it is also seen that power control (or output voltage regulation) can be achieved through dual slope delta modulation of the boost switch ON interval at constant frequency (f_z). Incidentally f_z can be easily locked to the mains 50 Hz frequency to avoid beat frequency effects in the input currents.

Under the operating conditions described, the displacement input power factor ($\cos\Phi_i$) before filtering is unity. Consequently, the overall input power factor (before filtering) becomes equal to the harmonic input power factor and it is given by

$$\text{power factor} = \left[\frac{\frac{I_{ia,1}}{\sqrt{2}}}{\sqrt{\sum_{n=1}^{\infty} \left(\frac{I_{ia,n}}{\sqrt{2}} \right)^2}} \right]$$

Where,

$I_{ia,n}$ is the Fourier component of the nth harmonic component of current I_a (Input Current), and $\cos\Phi_i$ is the displacement factor.

It is noted that the current harmonics associated with this power factor can be suppressed by a relatively small input capacitor (C_3) and inductor (L_1) in Fig-3.22 because of their high frequencies. Therefore, the overall input power factor after filtering (ie, at the ac source) is very close to unity. The various waveforms are shown in Fig-3.20

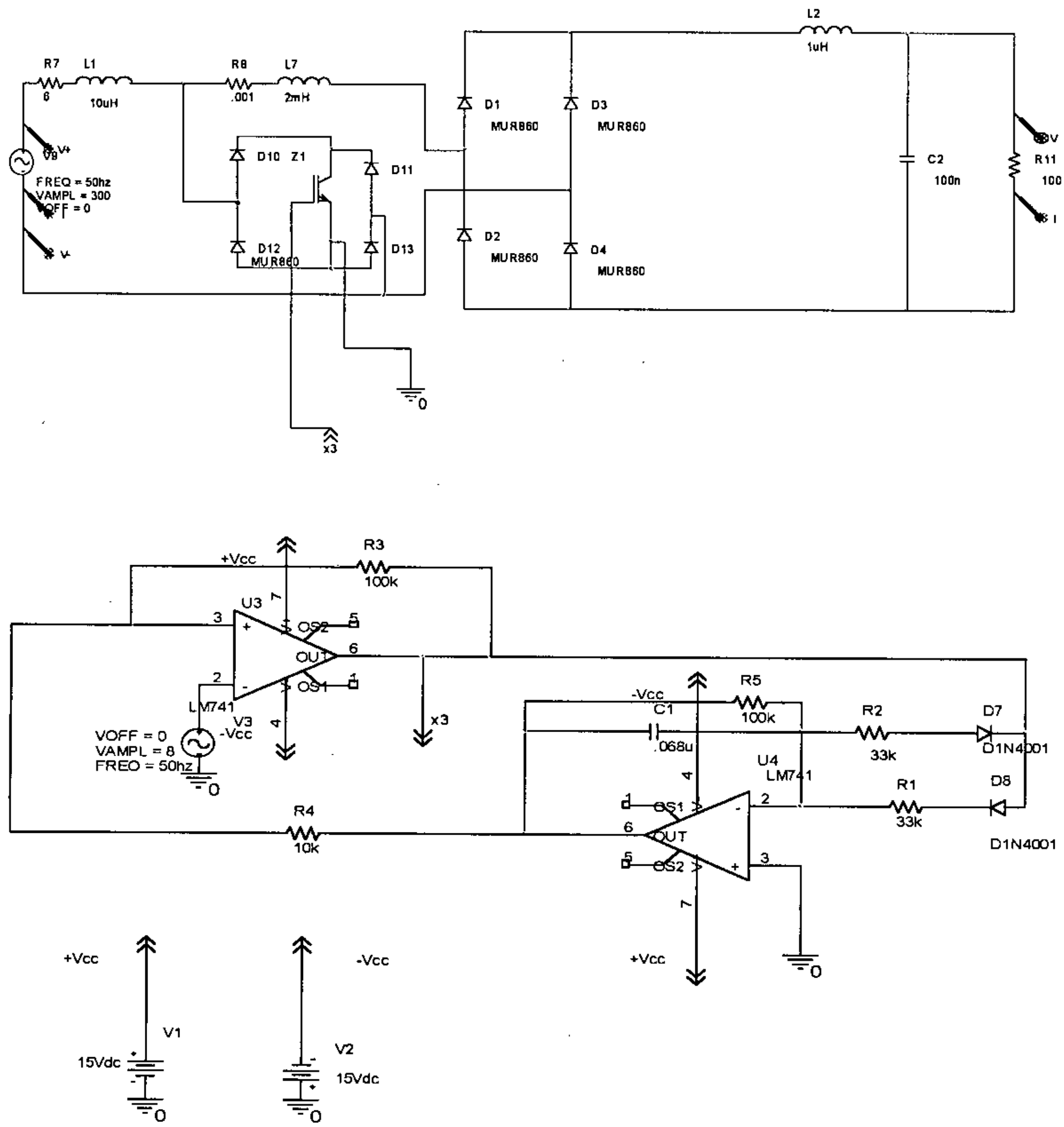


Fig-3.19: Single Phase diode Rectifier Circuit Switched at the Input side.

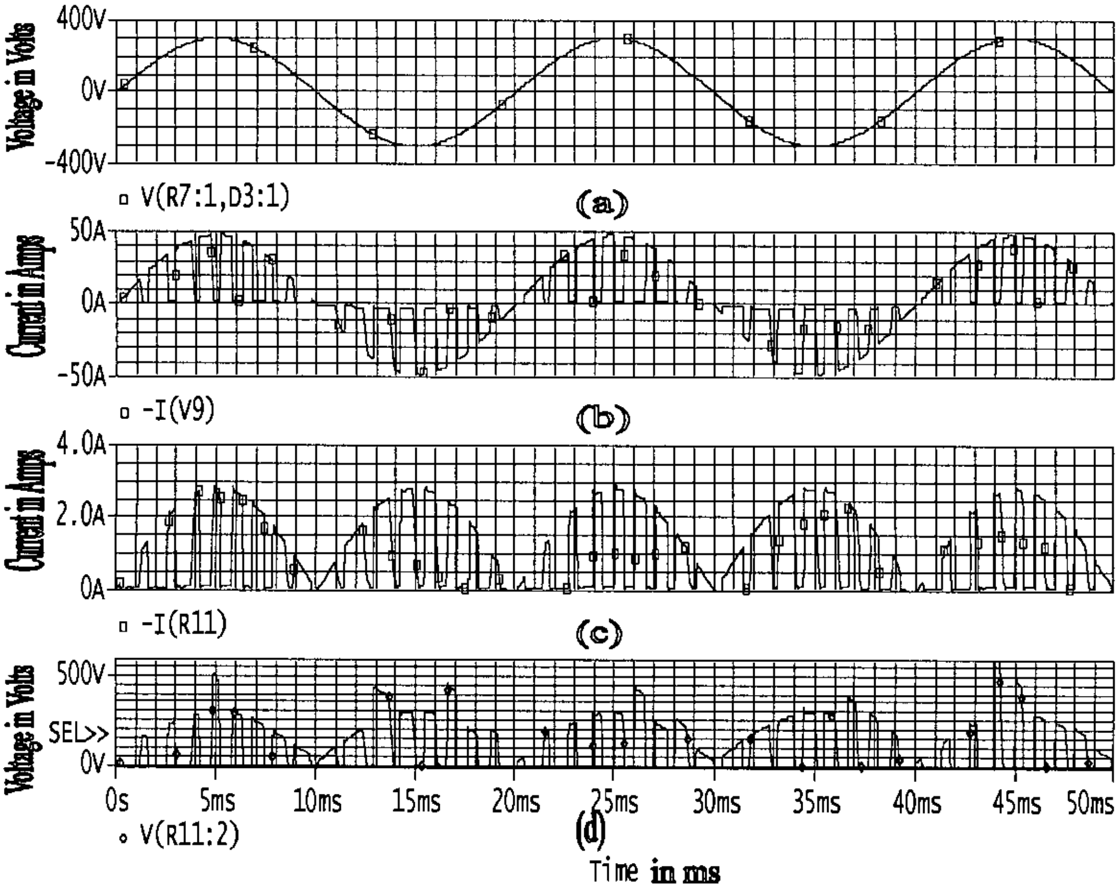


Fig-3.20: Various Waveforms of a Single Phase diode Rectifier Switched at the Input side

(a) Input Voltage,

(b) Input Current,

(c) Output Current and

(d) Output Voltage.

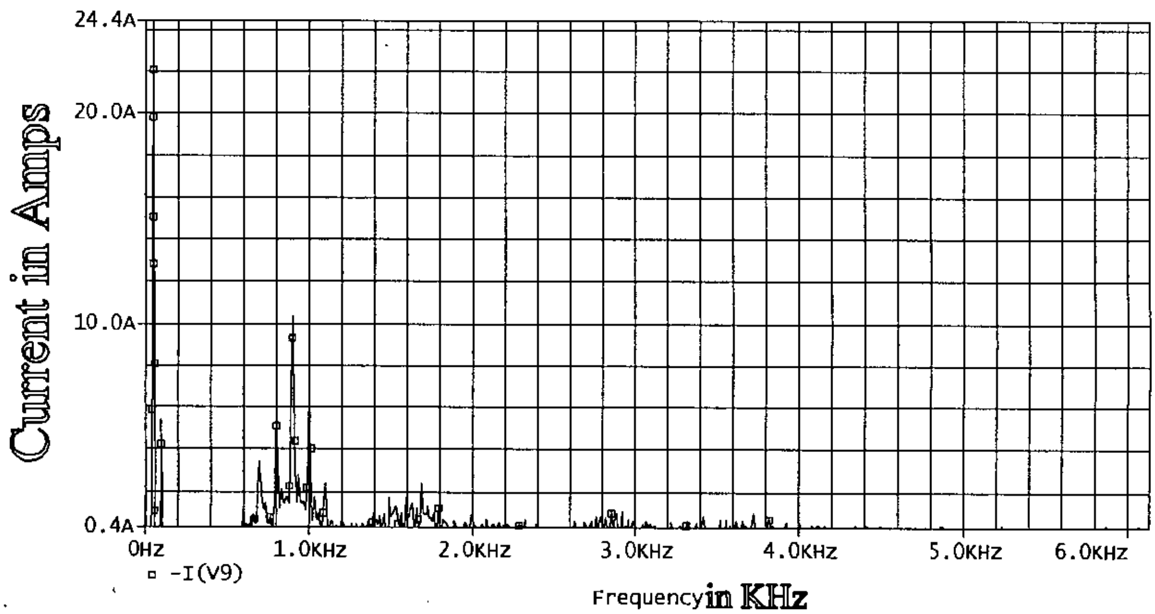


Fig-3.21: Fourier Transforms of Input Current of a Single Phase diode Rectifier Switched at the Input side

3.3.1 Making the Input Current Sinusoidal

As the rectifier is connected with an IGBT switch Z_1, the input current follows the input voltage as discussed earlier (Input current peaks varies sinusoidally). But the whole input current is not sinusoidal because of switching action. This can be seen from the Fourier transforms of input current where the harmonics components are shown (Fig-3.21). To make the input current sinusoidal, increase in the value of input filter is made. By putting the value of L_1 = 15mH and C_3 = 100uF when R_3 = 100k and R_4 = 10k we get the sinusoidal input which is shown in Fig-3.22 and Fig-3.23. The Fourier transforms of this input current is shown in Fig-3.24, where, we can see less harmonic contents meaning that the input power factor is near to unity. Again by putting the value of L_1 = 8mH and C_3 = 40uF when R_3 = 100k and R_4 = 1k we get the sinusoidal input which is shown in Fig-3.25 and Fig-3.26. The Fourier transforms of this input current is shown in Fig-3.27, where, we can see less harmonic contents meaning that the input power factor is near to unity.

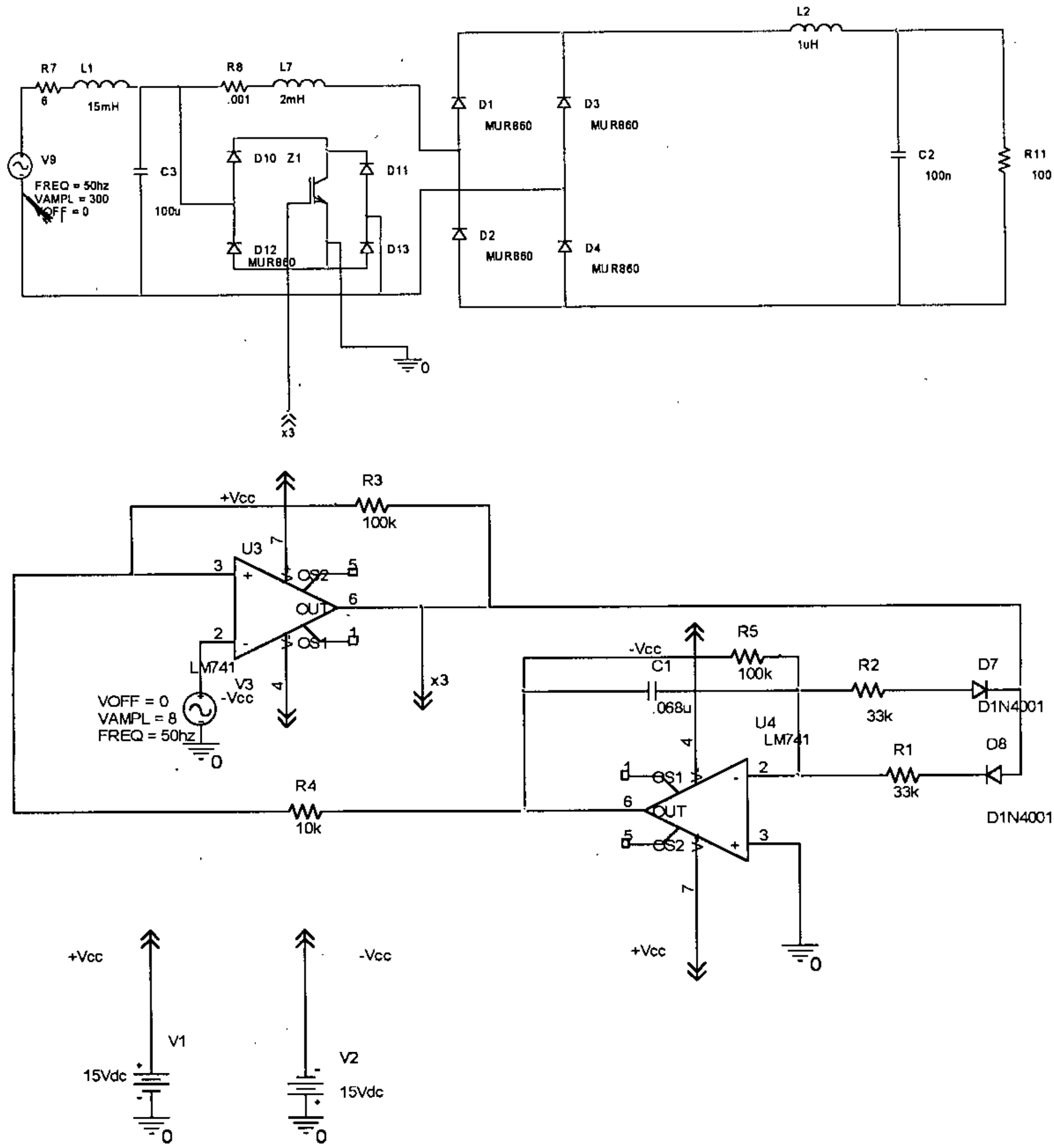


Fig-3.22: Single Phase Diode Rectifier Circuit Switched at the Input side (When L_1 = 15 mH, C_3 = 100 uF and R_3 = 100k, R_4 = 10k).

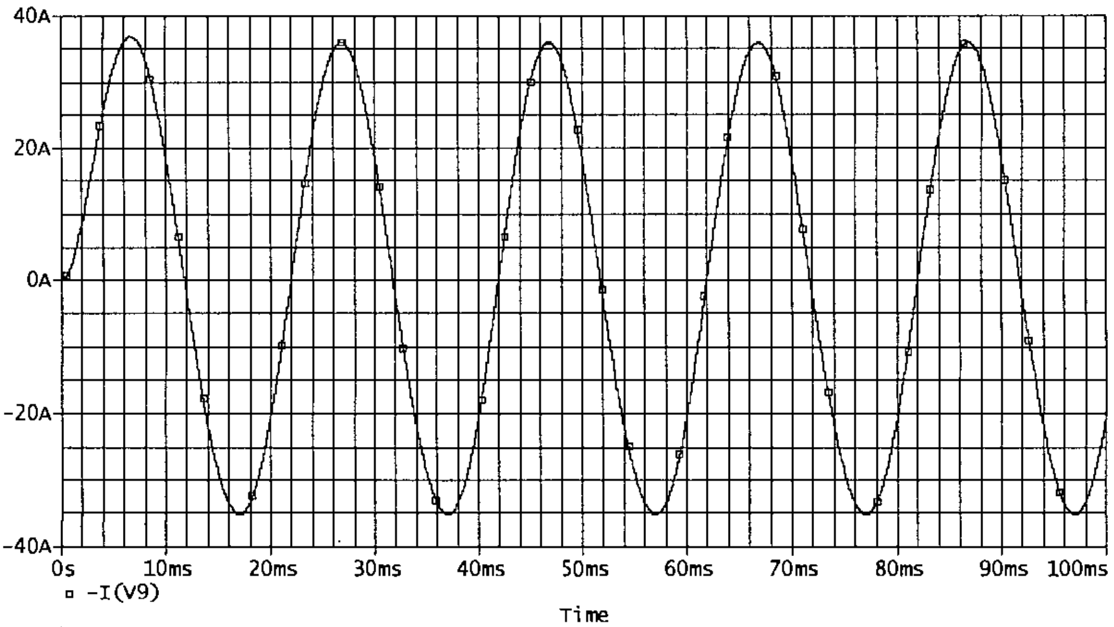


Fig-3.23: Input Current of a Single Phase Diode Rectifier Circuit Switched at the Input side. (When L_1 = 15 mH, C_3 = 100 uF and R_3 = 100k, R_4 = 10k)

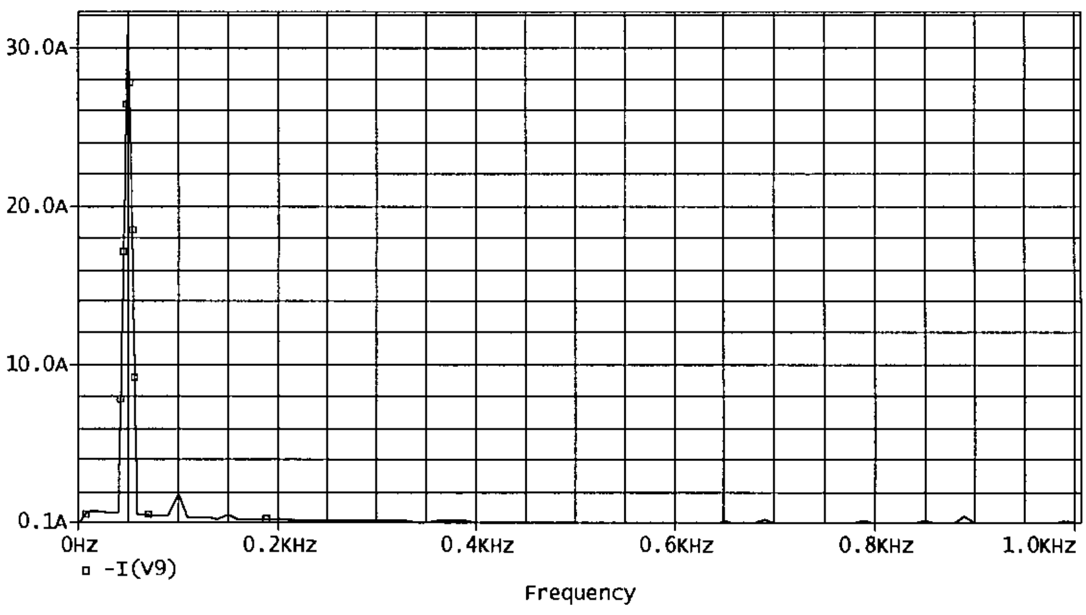


Fig-3.24: Fourier Transform of Input Current of a Single Phase Diode Rectifier Circuit Switched at the Input side. (When L_1 = 15 mH, C_3 = 100 uF and R_3 = 100k, R_4 = 10k)

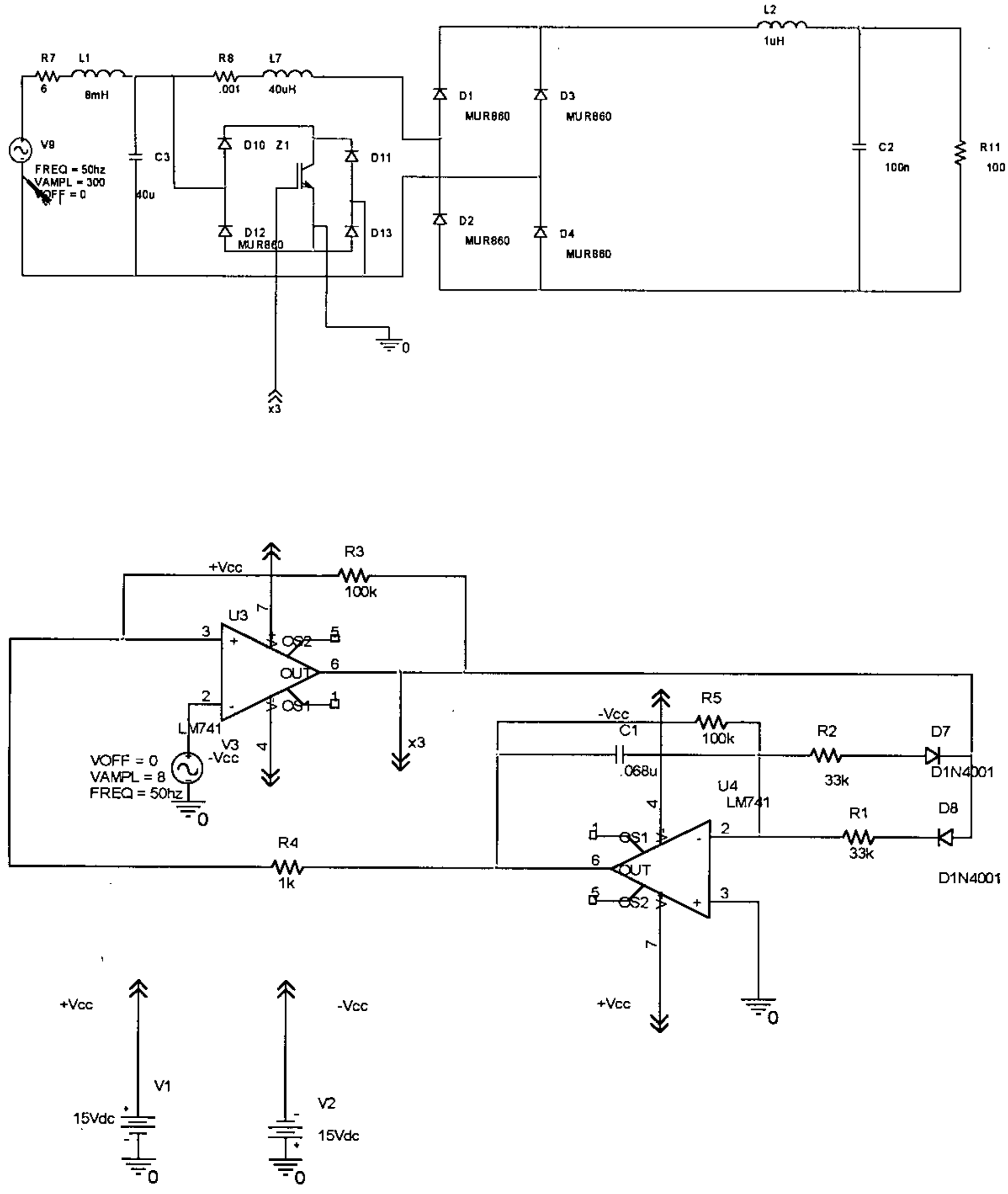


Fig-3.25: Single Phase Diode Rectifier Circuit Switched at the Input side. (When $L_1 = 8$ mH, $C_3 = 40$ uF and $R_3 = 100k$, $R_4 = 1k$)

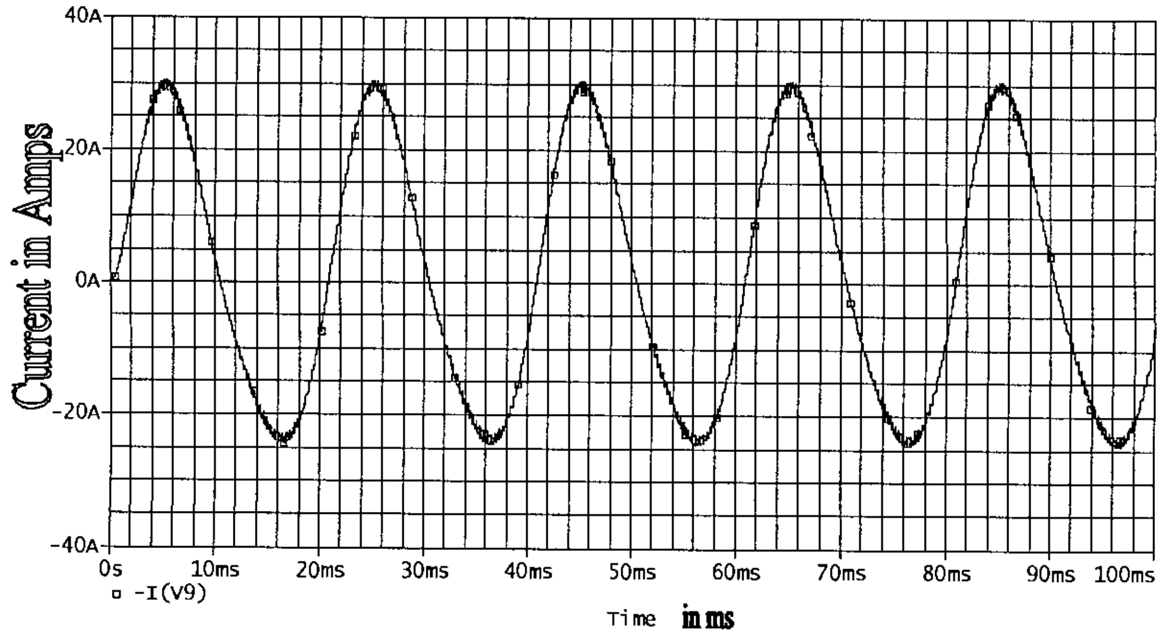


Fig-3.26: Input Current of a Single Phase Diode Rectifier Circuit Switched at the Input side. (When L_1 = 8 mH, C_3 = 40 uF and R_3 = 100k, R_4 = 1k)

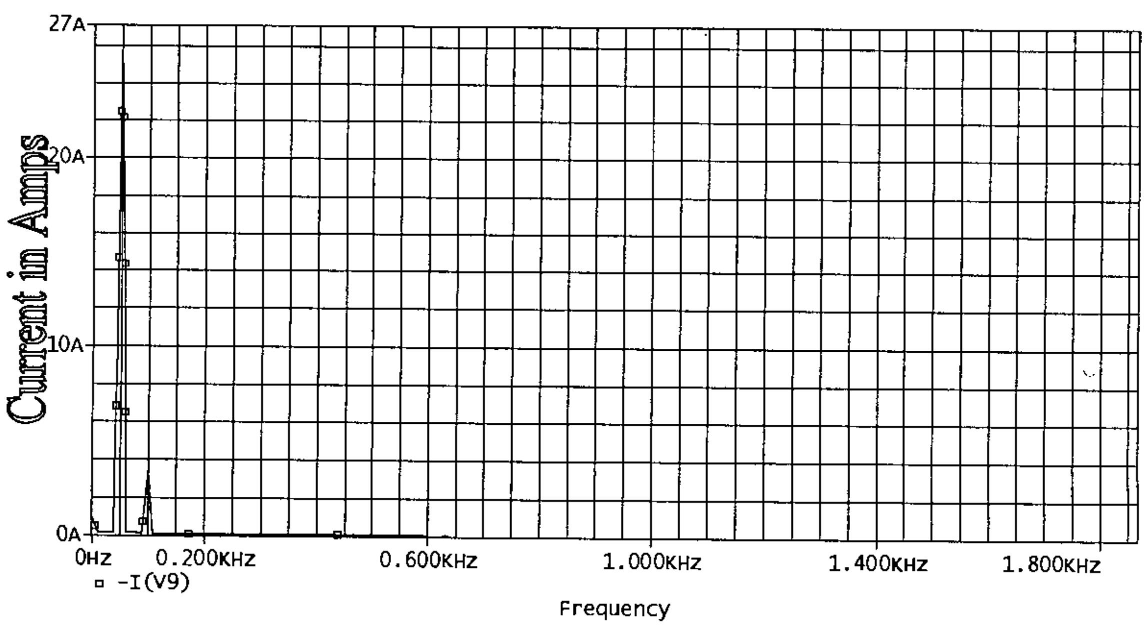


Fig-3.27: Fourier Transform of Input Current of a Single Phase Diode Rectifier Circuit Switched at the Input side. (When L_1 = 8 mH, C_3 = 40 uF and R_3 = 100k, R_4 = 1k)

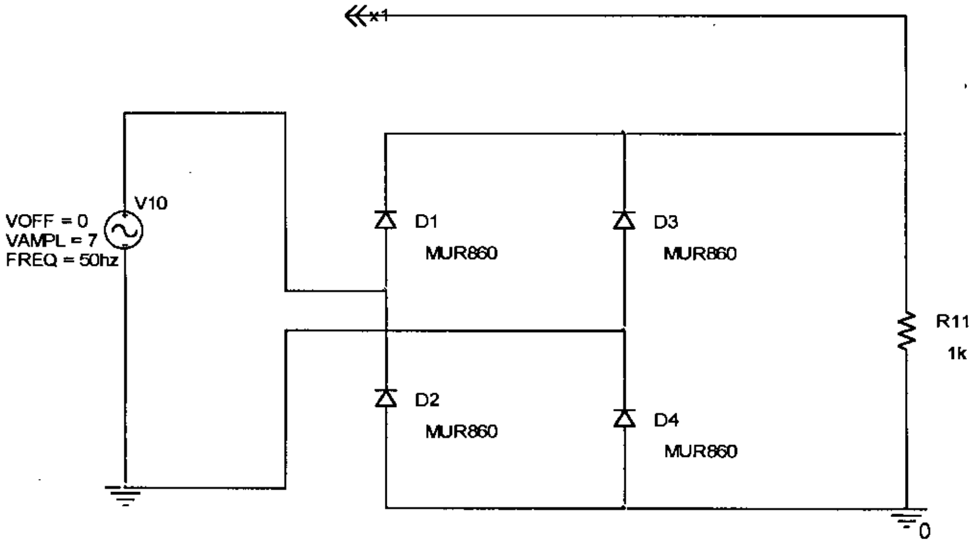
3.3.2 **Discussions**

By comparing the circuits shown in Fig-1.6 (L_1 =150 mH, C_2 = 90 uF) and Fig-1.13 (L_1 = 150 mH, C_3 = 100 uF) and Fig-3.22 (L_1 = 15 mH, C_3 =100 uF for R_3 = 100k, R_4 = 10k) and Fig-3.25 (L_1 = 8 mH, C_{10} = 40 uF for R_3 = 100k, R_4 = 1k) we can say if the high frequency electronic switch is used in the diode rectifier the value of passive components (Input LC filter) is significantly reduced which in turn will reduce the size and cost of the equipment. At the same time power factor is brought to almost unity as the switching is done inphase with the input voltage.

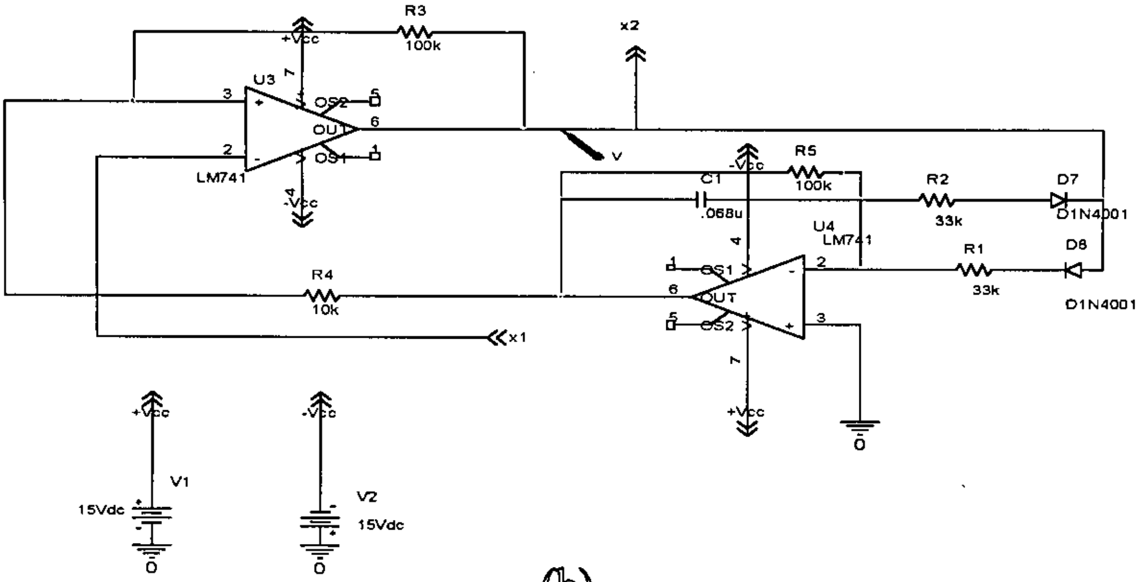
3.4 A Single Phase Diode Rectifier Circuit Switched at the Input Side (Practical Circuit Analysis)

A practical circuit with a switch at the input side of a diode rectifier is shown in Fig-3.28. In this scheme a dual slope delta modulation circuit ((Fig-3.28(b)) is used to provide gate pulses for switching the diode rectifier. A same source voltage is used as the input to the dual slope delta modulation but with full wave rectification and smaller magnitude. Before the gate pulse is applied to the MOSFET (M_4) the output of the dual slope delta modulator is taken through an optocoupler and buffers. The switch MOSFET M_4 is connected at the input side of a single phase diode rectifier with additional four diodes so that it can work as a bidirectional switch. The various waveforms of the circuit taken from storage oscilloscope are shown in Fig-3.29 to Fig3.32.

After addition of LC filter in the input of a single phase diode rectifier various waveforms are taken from storage oscilloscope and are shown in Fig-3.33 to Fig-3.36.

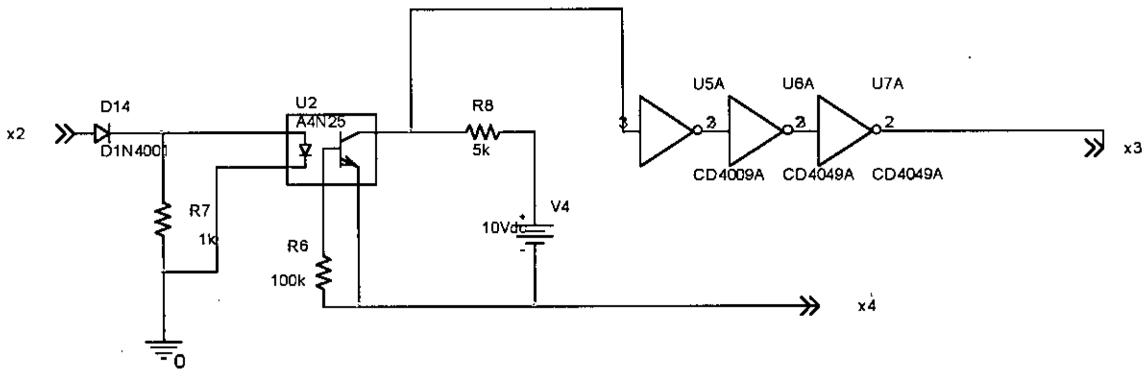


(a)

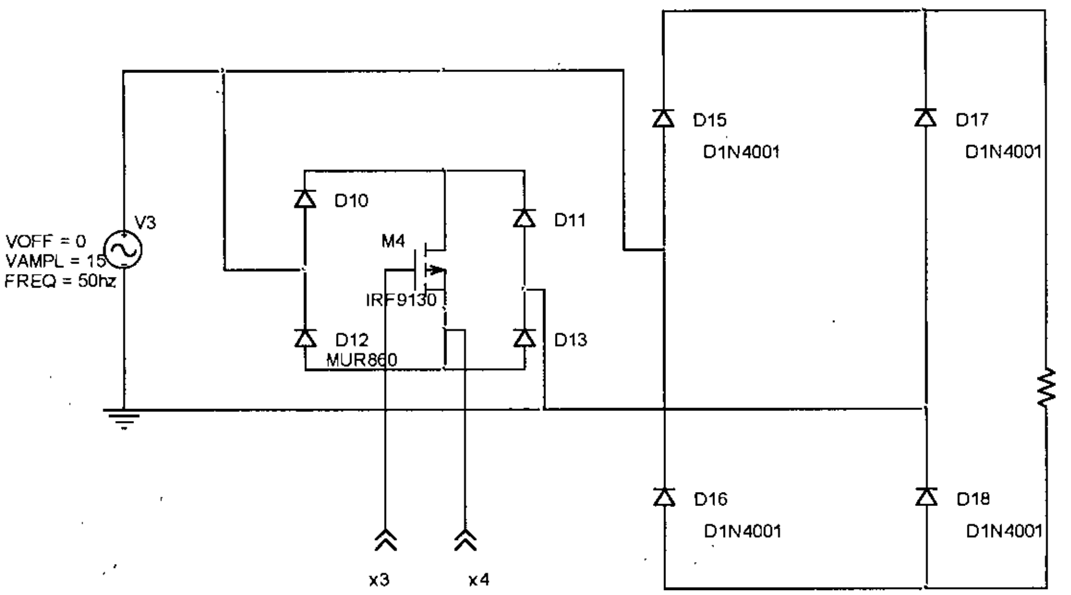


(b)

Fig-3.28: Practical Circuit of a Single Phase Diode Rectifier Switched at the Input side. (Continued)



(c)



(d)

Fig-3.28: Practical Circuit of a Single Phase Diode Rectifier Switched at the Input Side.

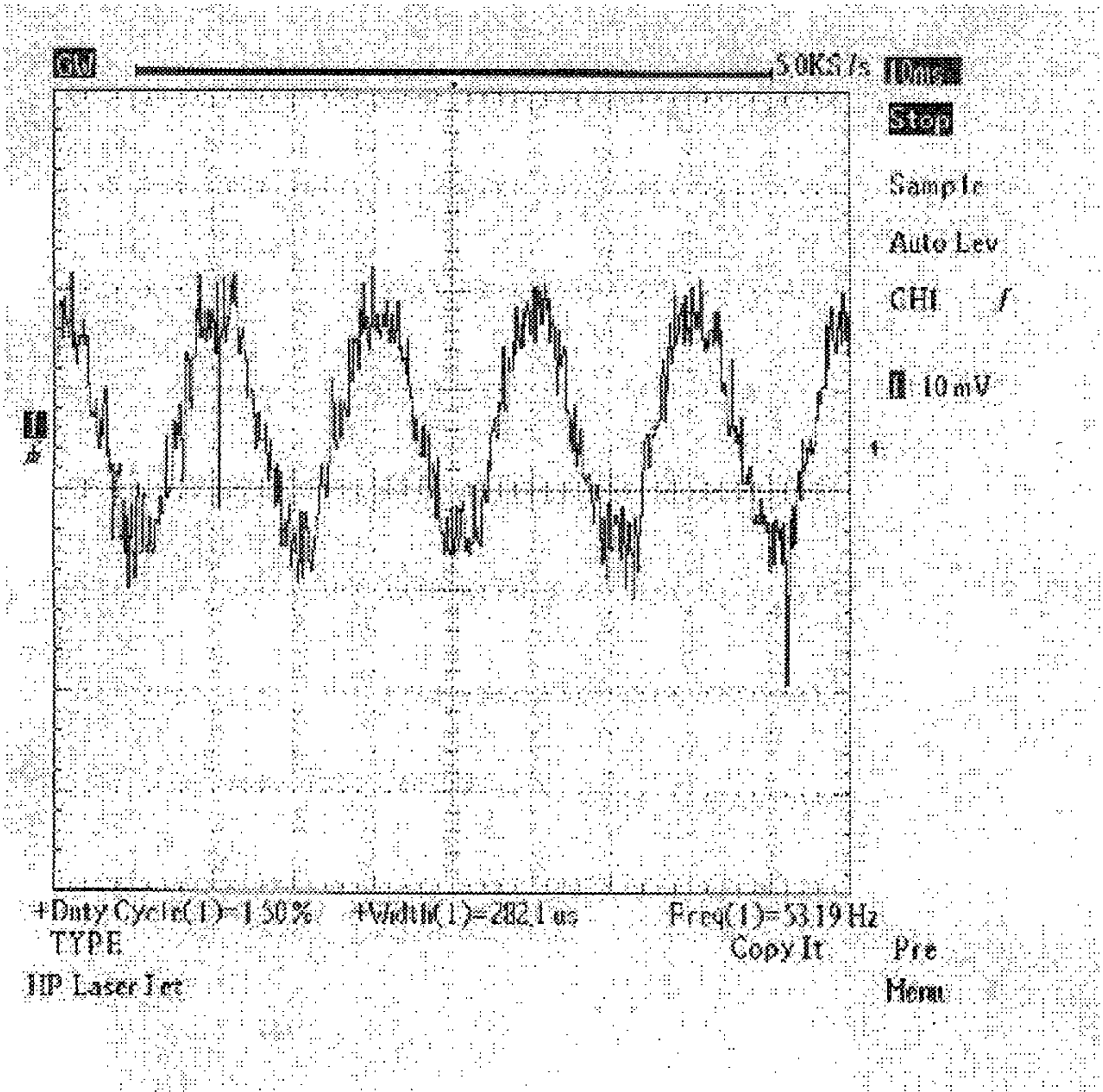


Fig-3.29: Input current of the diode rectifier circuit switched at the input side.

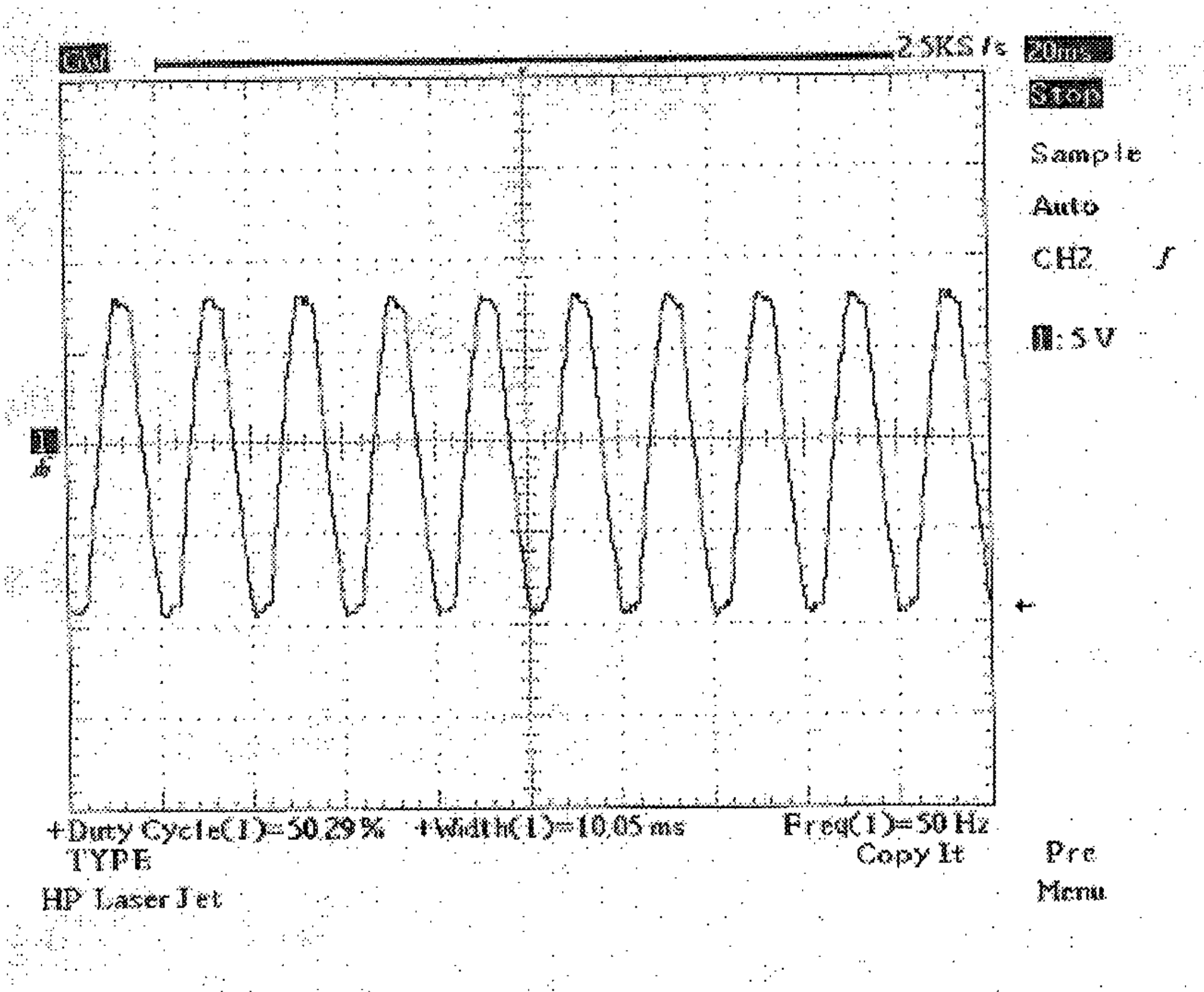


Fig-3.30: Input voltage of the diode rectifier circuit switched at the input side.

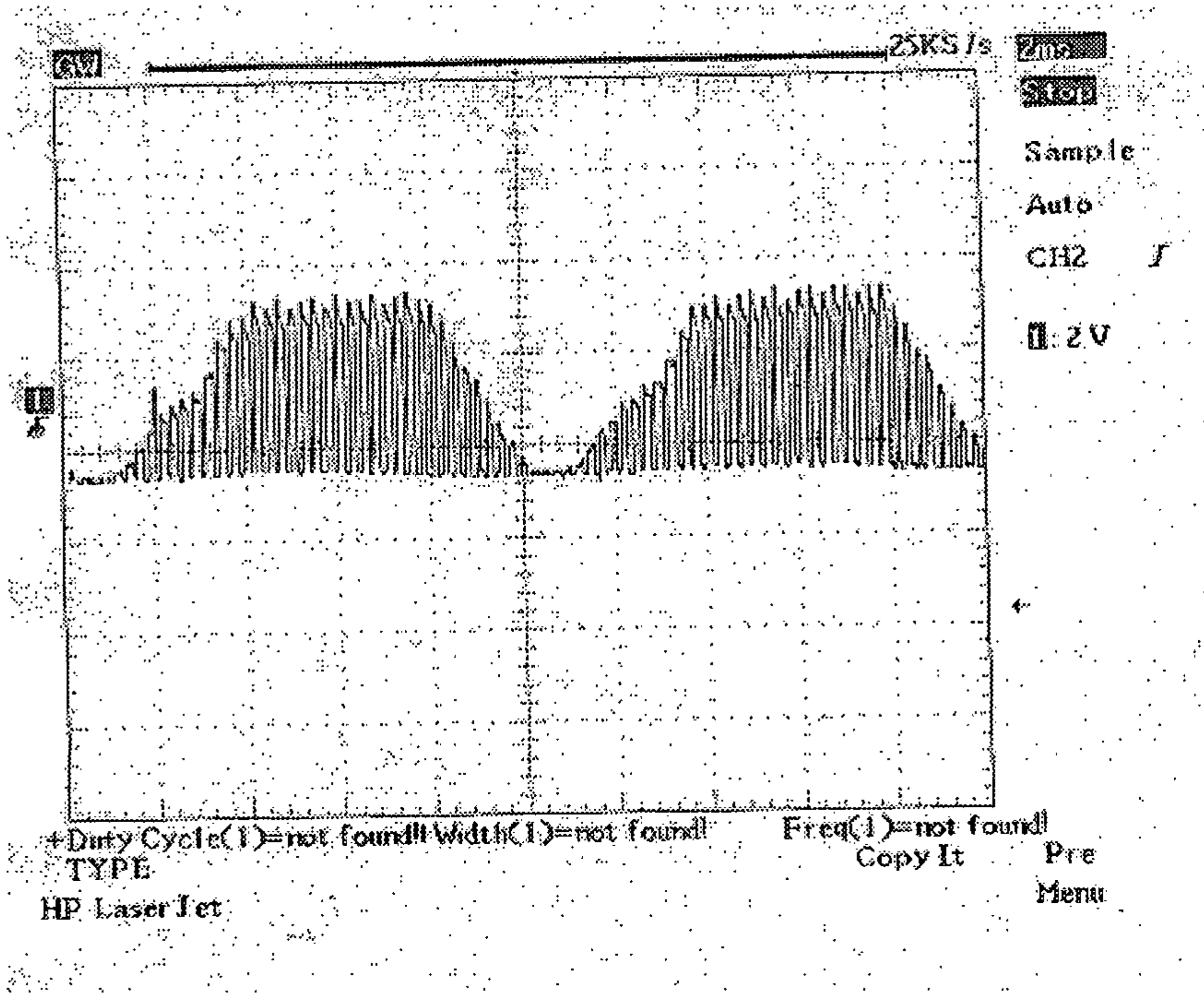


Fig-3.31: Output current of the diode rectifier circuit switched at the input side.

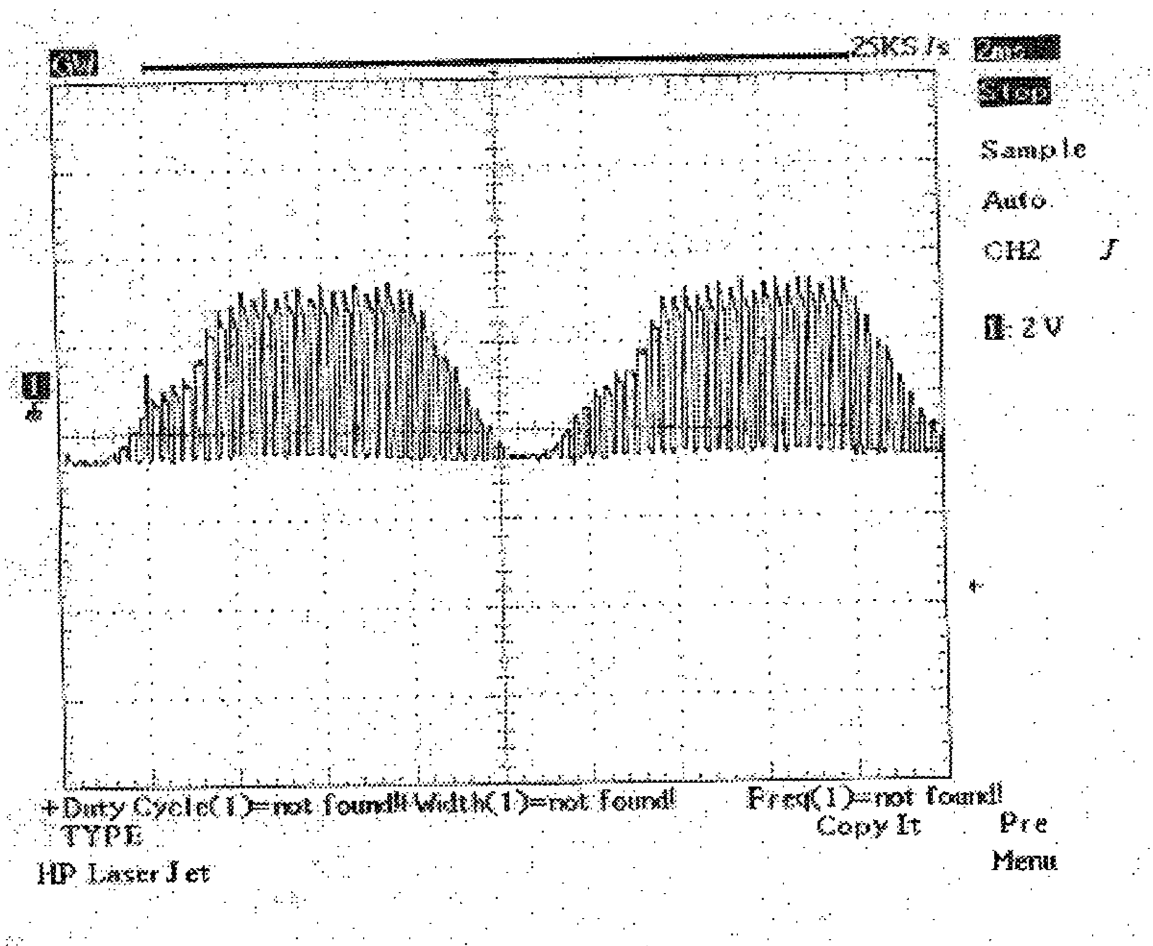


Fig-3.32: Output voltage of the diode rectifier circuit switched at the input side.

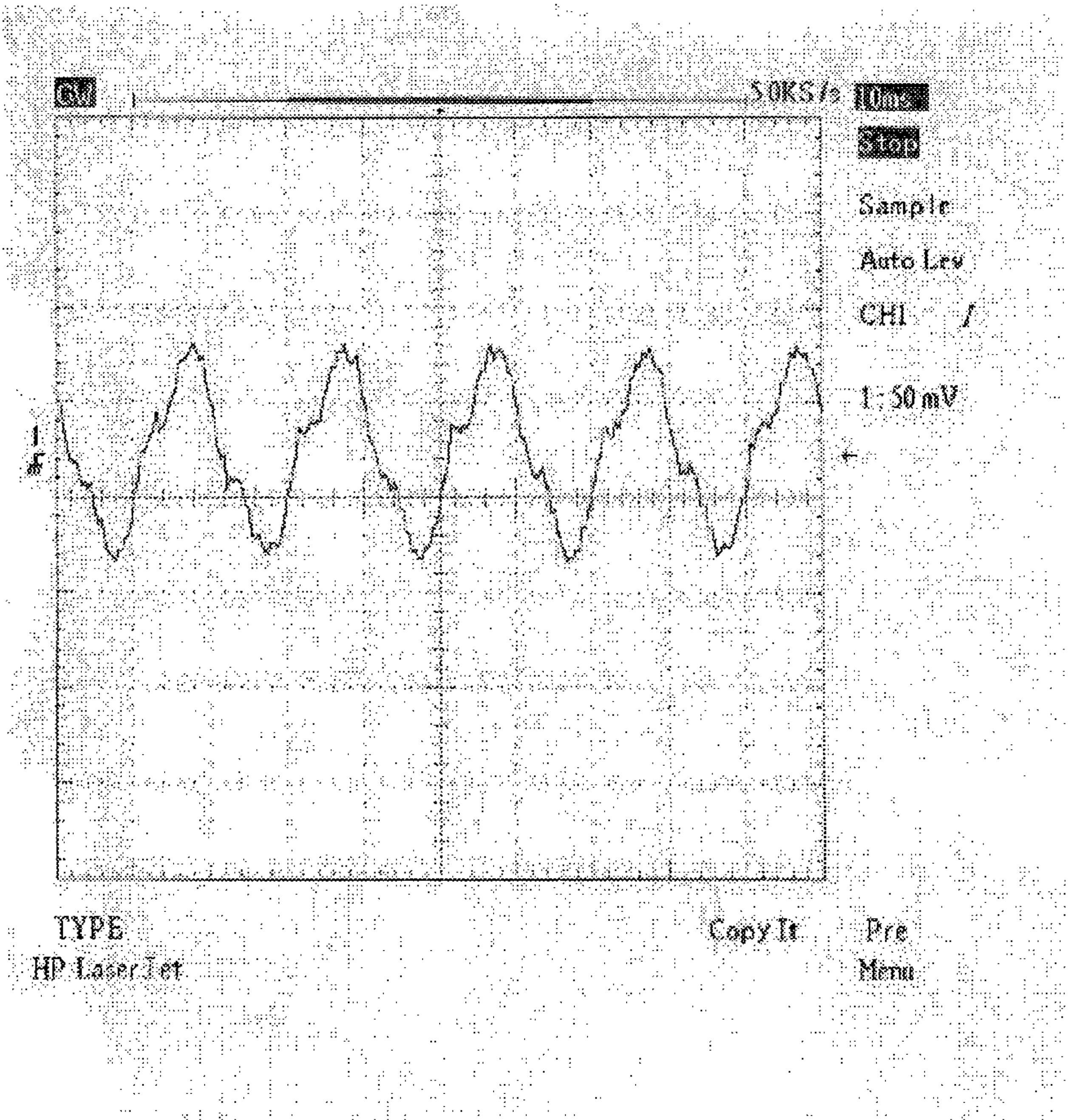


Fig-3.33: Input current of the diode rectifier circuit switched at the input side and a LC filter at the input (L = 8 mH, C = 40 uF).

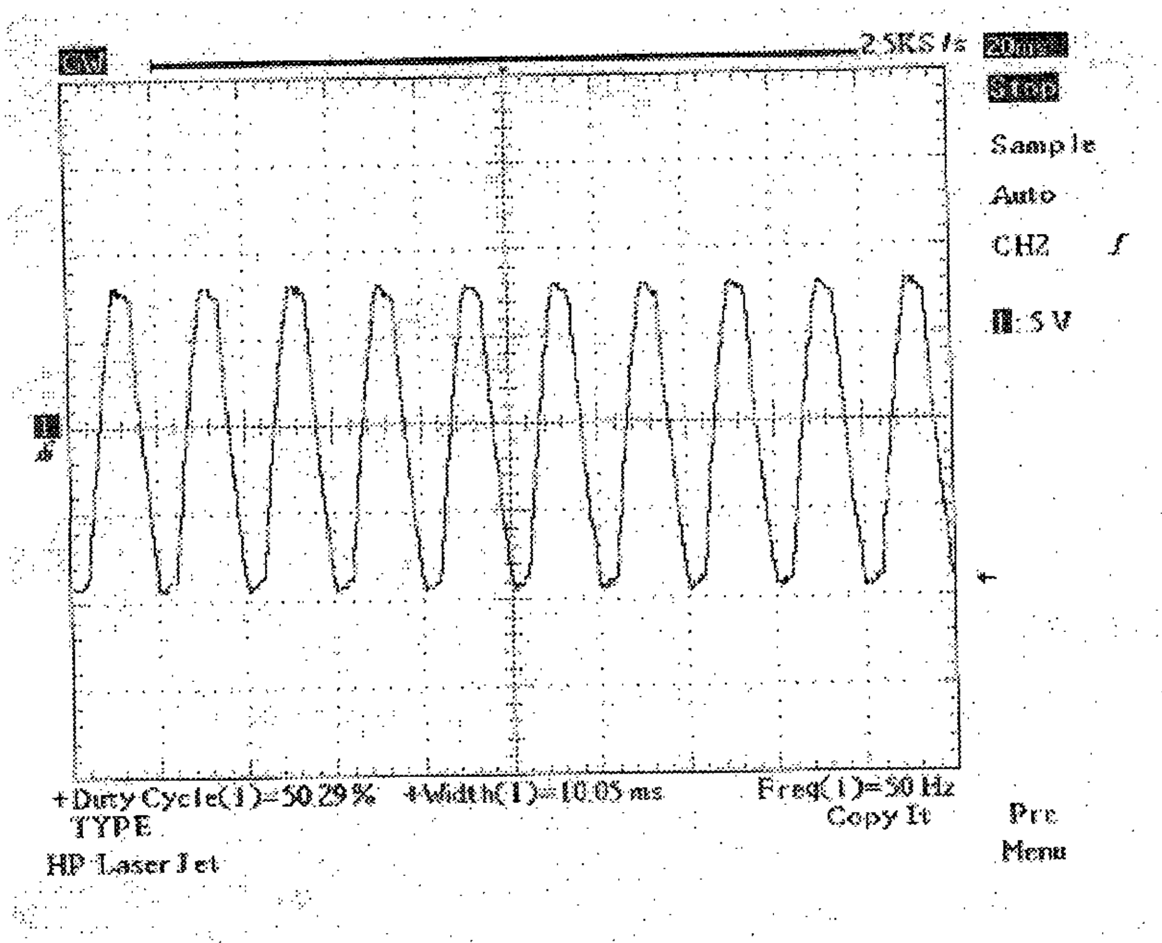


Fig-3.34: Input voltage of the diode rectifier circuit switched at the input side and a LC filter at the input.

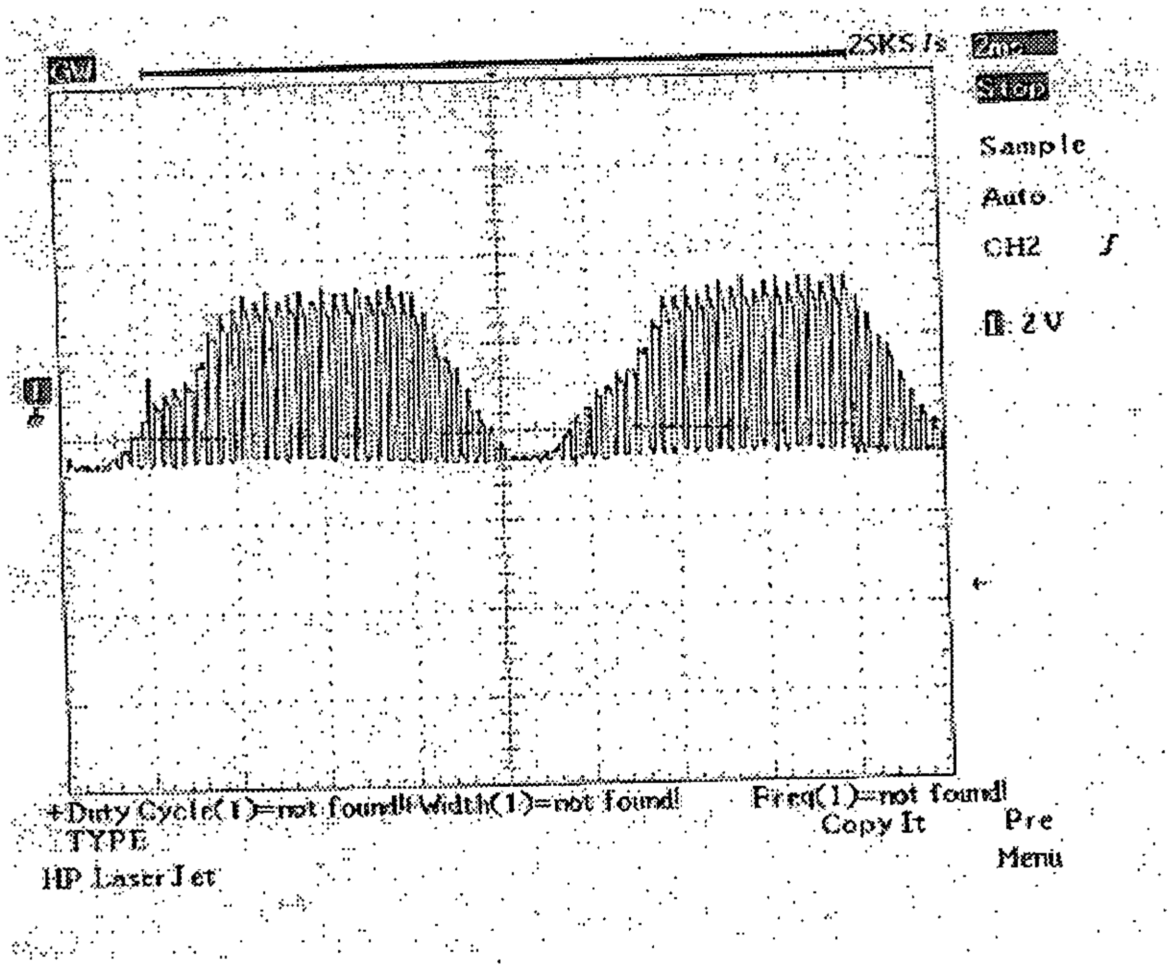


Fig-3.35: Output current of the diode rectifier circuit switched at the input side and a LC filter at the input.

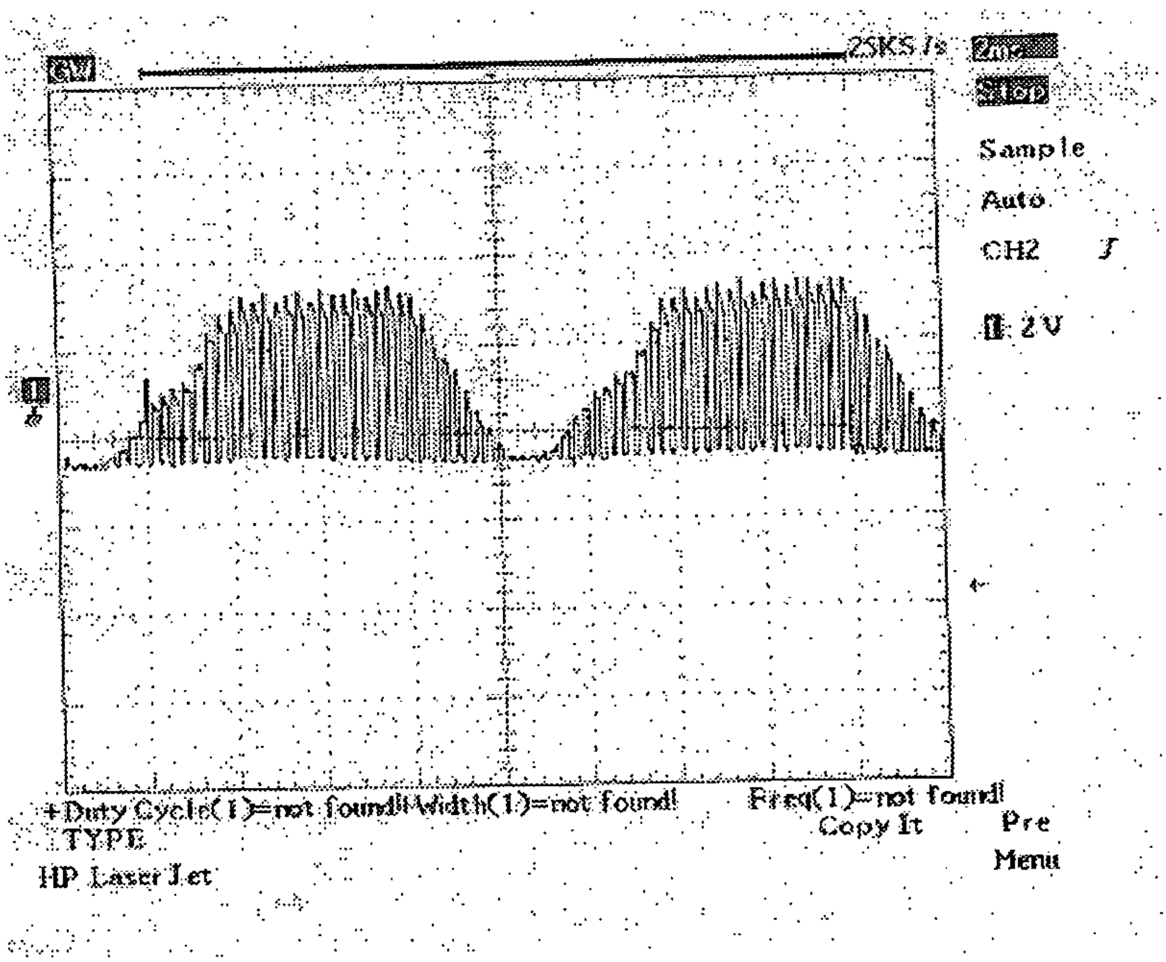


Fig-3.36: Output voltage of the diode rectifier circuit switched at the input side and a LC filter at the input.

3.4.1 **Results**

The theoretical analysis of a single phase diode rectifier circuit is verified by hardware implementation which was discussed in paragraph 3.4. From the discussion and from various waveforms it is clearly evident that by using electronic switch activated by dual slope delta modulation, the input current can be forced or shaped to follow the input voltage waveform. In other words the input power factor can be improved and that is near to unity.

If we compare the two circuits (single phase diode rectifier switched at the output and single phase diode rectifier switched at the input), it is seen that almost similar results can be achieved. But the circuit uses the switch at the input side of a rectifier will require a bidirectional switch, requires more number of components and additional circuitry. The comparison can be carried out to find the suitability of the switched rectifier for input current shaping. The proper choice will mainly depend on the prices set after detail study.

CHAPTER 4

CONCLUSIONS

4.1 Conclusions

4.1.1 In this paper an efficient power factor correction of a diode rectifier using dual slope delta modulation technique is proposed and analysed. Initially single phase full wave diode rectifiers and single phase controlled rectifiers are analysed in details. It is illustrated clearly in the analysis that power factor can be made near to unity in both cases with passive power factor correction technique. But the value of inductor and capacitor of input filter is comparatively high which will make the equipment heavy and costly. To overcome the limitations of diode and controlled rectifiers an active power factor correction technique is used, where the requirement of electronic switch come in. As the electronic switch needs to be provided with some control signal to achieve active power factor correction technique, a control circuit is provided. This control circuit can be implemented by many techniques like:

a. Single-pulse-width-modulation,
b. Multiple-pulse-width-modulation,
c. Sinusoidal-pulse-width-modulation,
d. Optimized-pulse-width-modulation,
e. Delta-pulse-width-modulation or dual slope delta modulation,
f. Trapezoidal-pulse-width-modulation and
g. Hysteresis pulse width modulation techniques.

In this thesis dual slope delta modulation technique is used in the control circuit to achieve near unity power factor.

4.1.2 The output of the delta modulator can be changed by changing

a. Frequency, f of the input signal to the DM.

d. Window width, ▲V of the hysteresis band of the DM and

c. Slope S, of the carrier wave of the DM.

By keeping frequency and window width fixed and using two different slopes 'S' of carrier wave of delta modulator the dual slope delta modulation is implemented. By using two different slopes the various output control signals are analysed. Hardware implementation of dual slope delta modulation is also shown.

4.1.3 An analysis of a diode rectifier circuit switched at the output side and input side is done in details. In the analysis it is shown that when the switch is used in the rectifier circuit the value of input filter components becomes less even when the input power factor is near to unity. This is because input current follows the input voltage. Fourier transforms of input currents are shown to show the less harmonic contents. Finally the comparison between the two circuits (a diode rectifier circuit switched at the output side and a diode rectifier circuit switched at the input side) is done. It is found that circuit used switch at the output side of a diode rectifier seems to be more suitable. However actual choice will mainly depend on the prices set after detail study.

4.1.4 This proposed method eliminates the complicated synchronization logic requirement, reduces the number of components and reduces the filter reactive components. This in turn reduces the cost and size of the rectifier system. The analyses of this method are verified by simulation and hardware implementation. However the proposed method has the disadvantage of increasing the switching stresses of the switching devices.

4.2 Recommendation on Future Work

In this thesis work the dual slope delta modulation technique is used to improve the input power factor (input current wave shaping). It is also shown that how this method can be incorporated in the control scheme. Auto control with feedback of the output voltage by this method is not implemented. This may be taken as further thesis work in future.

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