AC Voltage Regulation By C^uk Switch Mode Power Supply

By

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DEDICATION

To my parents

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ABSTRACT

High frequency switching power supplies have become part of electronic equipments to provide regulated DC of desired voltages at a low cost and high efficiency. These power supplies have several advantages over their counterpart the linear power supplies. Main advantages are smaller compact size due to elimination of step down transformer and small filters due to high frequency operation. These power supplies have high efficiency because the regulating devices in them works as switches ensuring low device loss. Their output voltage can be controlled for a wide range of input voltage fluctuation by changing the duty cycle of the switching signals.

Four common types of switch mode converters are used in DC to DC conversion. They are BUCK, BOOST, BUCK-BOOST and C^UK converters. Researchers are trying to modify these DC regulator to regulate AC voltages.

Utility AC voltage fluctuation both momentary and prolonged, affect adversely the domestic, industrial and commercial customers. In this thesis an AC C^uk regulator made of ideal switches and practical IGBT switches have investigated. For generation of switching voltage a commercially available IC chip SG1524B is used, thus circuit is compact and more viable. The same chip is utilized to regulate the output voltage by varying the gate signal voltage of the IGBTs if any changes occur in output voltage. As a result the regulator is maintaining constant voltage across the load during any change in supply voltage as well as for variation of load. Freewheeling path and surge voltage across switches create problem in the proposed regulator. Snubbers are used for suppressing surge voltage across switches. Input current of this regulator is greatly reduced to a acceptable limit but still efficiency of this regulator is very poor and needs further research to increase the efficiency to make the regulator commercially viable. In this thesis input filter capacitor of proper size is used for improving the power factor and which decreases the input current.

LIST OF ABBREVIATION

EMI = Electromagnetic Interference

SMPS = Switctch Mode Power Supply.

BJT = Bipolar Junction Transistor.

MOSFEET = Metal Oxide Semiconductor.

IGBT = Insulated Gate Bipolar Transistor.

PWM = Pulse Width Modulation.

OPAMP = Operational Amplifier.

SCR = Silicon Control Rectifier.

GTO = Gate Turn Off SCR.

Rms = Root mean square.

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CHAPTER – 1

INTRODUCTION

1.1 INTRODUCTION

Voltage fluctuation is a very common problem prevailing in the power system. It is mainly due to the fault occurring in the transmission and distribution system. Short time voltage sags may also occur because of momentary a-periodic loads like welding and operation of building construction equipment. Switching of the loaded feeders or equipments also create momentary voltage sags. In Bangladesh continuous voltage sags are also prevalent due to poor condition of distribution system, inadequate supply and demand situation. Both momentary and continuous voltage sags are undesirable in complex process controls and household appliances as they use precision electronic and computerized control. Major problems associated with the unregulated long-term voltage sags include equipment failure, overheating and complete shutdown. Tap changing transformers with SCR switching are usually used as a solution to continuous voltage sags [1]. They require large transformer with many SCRs to control the voltage at the load that lacks the facility of adjusting to momentary changes. Some solutions based on electronic compensators have been suggested in the past to encounter problems of voltage sag [2,3,4]. But these proposals have not been realized practically to replace conventional tap changing transformers. Advances in power semiconductor devices are making it possible for utilities to use a variety of power control equipment to raise power quality levels to meet the requirements. Manual and auto ac voltage regulators are also used for low, medium and high power applications in domestic, commercial and industrial use. Compact and fully electronic voltage regulators are still unavailable practically. This work is a continuation of previous research to develop a switch mode regulator to maintain load voltage constant in case of any fluctuation of input supply voltage and also in the case of variation of load.

1.2 REVIEW OF SWITCH MODE DC- DC CONVERTER [5]

A switch mode DC-DC power supply (SMPS) is switched at very high frequency. Conversion of both step down and step up dc with insignificant filter size having facility of feed back regulation by On/Off high frequency switching is possible in an SMPS. The regulation is normally achieved by pulse width modulation at a fixed frequency and the switching device is normally a power BJT, MOSFEET or IGBT. The element of switching mode regulations is shown in fig-1 (a). We can notice from fig.1 (b) that the output of DC regulator with resistive load is discontinuous and contains harmonics, the ripple contents is normally reduced by an LC filter.

Main components of a dc-dc Converters are:

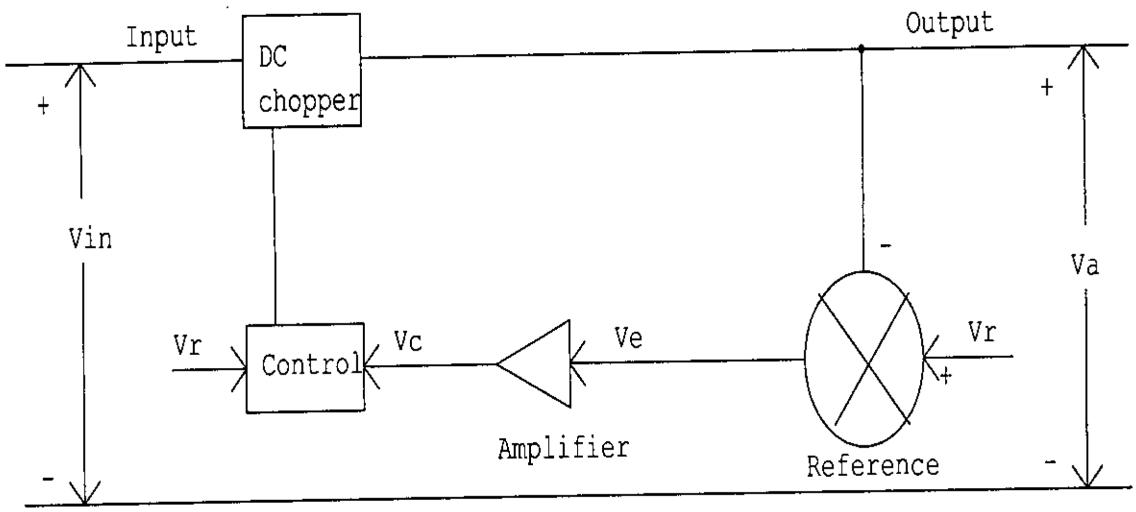
1. power circuit
2. Control circuit
3. Magnetic circuit.

The control circuit of an SMPS basically generates high frequency gating pulses for the switching device to control the dc. Switching is performed in multiple pulse width modulation (PWM) fashion according to feedback error signal from the load to serve two purposes.

a) Produce high frequency switching signal
b) Control On/Off period of switching signal to maintain a constant voltage across the load.

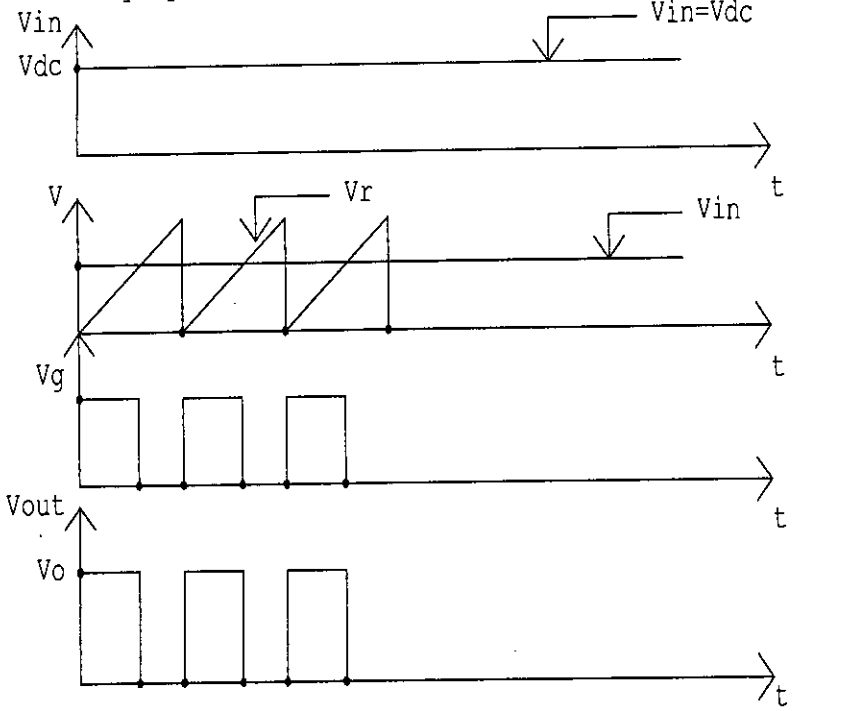
High frequency switching reduces filter requirements at the Input/Output of the converter. Simplest PWM control uses multiple pulse modulations generated by comparing a dc with a high frequency carrier triangular wave.

Switching deregulators are commercially available as integrated circuits. The designer can select the switching frequency by choosing the value of RC to set oscillator frequency. As a rule of thumb to maximize the efficiency, the oscillator period should be about 100 times longer than the transistor switching time; for example, if a transistor has a switching time of 0.5us, the oscillator period would be 50 us, which gives the maximum oscillator frequency of 20KHz. The limitation is due to switching loss in the transistor. The transistor switching loss increases with the switching frequency and as a result the efficiency decreases. In addition, the core loss of inductors limits the high frequency operation. Control voltage v_c is obtained by comparing the output voltage with its desired value. v_c can be compared with a saw tooth voltage v_r to generate the PWM control signal for the regulator. This is shown in fig 1(b).



(a) Block diagram

Ve=(Vr-Va)
K=Duty cycle=On time/Time period



(b) Control signals & input/output voltages

Figure-1. Elements of switching mode regulators

1.2.1 PRINCIPLE OF OPERATION [6]

Fig.-2 illustrates the circuit of a classical linear power conversion. Here power is controlled by a series linear element, a variable resister is used in the linear mode. The total load current passes through the series linear element. In this circuit greater the difference between the input and the output voltage, more is the power loss in the controlling device. Linear power conversion is dissipative and hence is inefficient. The efficiency range is typically 30 to 60% for linear regulators.

The circuit of Fig.-3 illustrates basic principle of a dc-dc switch mode power conversion. The controlling device is a switch. By controlling the ratio of the time intervals spent in on and off positions (defined as duty cycle), the power flow to the load can be controlled in a very efficient way. Ideally this method is 100% efficient. In practice, the efficiency is reduced as the switch is non-ideal and losses occur in power circuits.

The semiconductor devices can be used as a switch in an efficient way. The dc load to the voltage can be controlled by controlling the duty cycle of the rectangular waveform supplied to the base or gate of the switching device. When the switch is fully On, it has only a small saturation voltage drop across it. In the Off condition the current through the device is zero.

The output of the switch mode power conversion control (Fig.-3) is not pure dc. This type of output is applicable in some cases such as oven

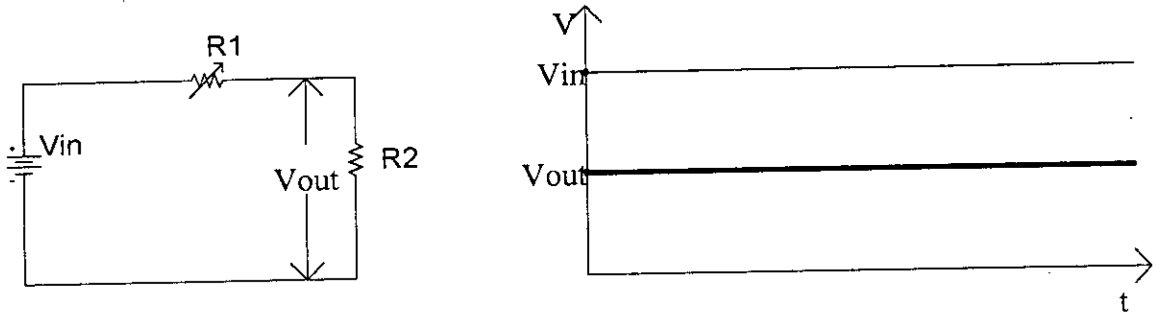


Figure 2. Linear (dissipative) power conversion circuit

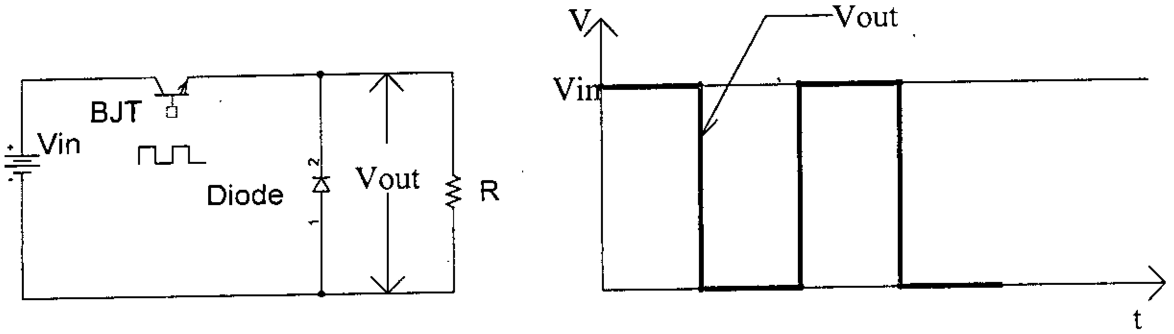


Figure3.Switchmode(nondissipative)power conversion circuit

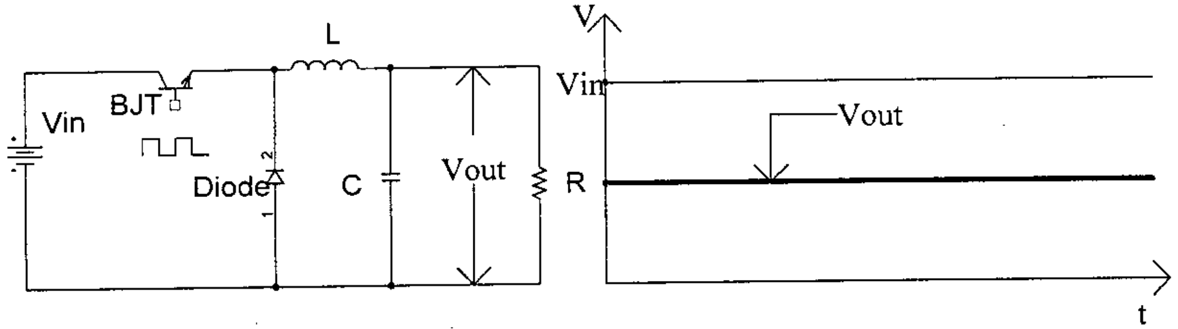


Figure 4.Typical switchmode power conversion circuit

heating without proper filtration. If constant dc is required, then output of SMPS has to be smoothed out by the addition of a low-pass LC filter. Switches are required as basic components for efficient electric power conversion and control. Ideally lossless storage components, inductors and capacitors are required to generate dc output voltage. Inductors and capacitors are used to smooth the pulsating dc originating from the switching action.

Although the conversion would be 100% efficient in the ideal case of lossless components (Fig.-4), in practice all components are lossy. Thus, efficiency is reduced. Hence, one of the prime objectives in switch mode power conversion is to realize conversion with the least number of components having better efficiency and reliability.

1.2.2 TYPES OF DC-DC CONVERTERS [6,7]

There are four basic topologies of switching regulators:

1. Buck regulator,
2. Boost regulator,
3. Buck Boost regulator and
4. C^uk regulator.

1.2.2.1 BUCK REGULATOR

In Buck regulators, output voltage is regulated and is less than the input voltage, Hence the name "buck". The circuit diagram is shown in fig-5, the circuit operation can be divided in two modes. Mode 1, begins when Transistor is switched on at t=0, input current rises and flows through inductor L, capacitor C and load resistor R. Mode 2 begins when transistor Q_1 is switched off at $t=t_1$. The freewheeling diode D_m conducts due to energy stored in the inductor and the inductor current continuous to flow through L, C, load, and diode D_m. The inductor current falls until transistor is switched on again in the next cycle.

The voltage across the inductor L, is in general,

$$e_L = L \frac{di}{dt} \tag{1.1}$$

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$V_s - V_a = L \frac{I_2 - I_1}{t_1} = L \frac{\Delta I}{t_1} \tag{1.2}$$

or

$$t_1 = \frac{L \Delta I}{V_s - V_a} \tag{1.3}$$

And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$- Va = L \frac{\Delta I}{t_2} \tag{1.4}$$

or

$$t_2 = \frac{\Delta I L}{V_a} \tag{1.5}$$

Where, $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L. Equating the value of ΔI in eqs-(1.2) and (1.4) gives

$$\Delta I = \frac{(V_s - V_a)\, t_1}{L} = \frac{V_a\, t_2}{L} \tag{1.6}$$

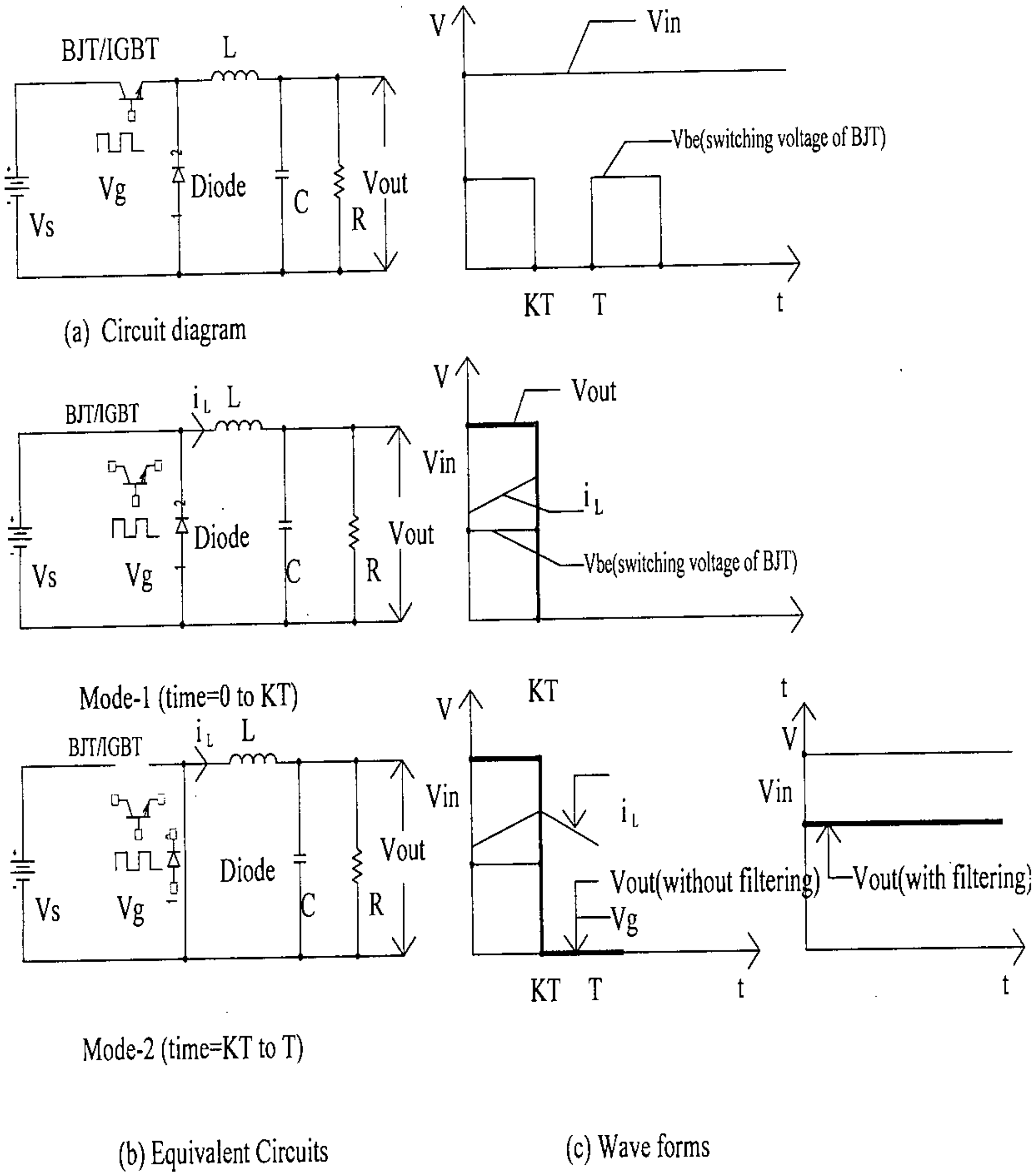


Figure-5. Buck regulator with continuous i_L

Substituting $t_1 = KT$ and $t_2 = (1-k)T$ yields the average output voltage as.

$$V_a = V_s \frac{t_1}{T} = KV_s \qquad (1.7)$$

1.2.2.2 BOOST REGULATOR

In a Boost Regulators, the output voltage is greater than the input voltage, hence the name "boost"(fig.6). The circuit operation is divided in two modes. Mode 1 begins when the transistor Q_1 is switched on at time t=0. The input current, which rises, flows through inductor L and transistor Q_1. Mode 2 begins when transistor Q_1 is switched off at $t = t_1$. The current which was flowing through the transistor would now flow through L, C, load and diode D_m. The inductor current falls until transistor Q_1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the load.

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$Vs = L \frac{I_2 - I_1}{t_1} = L \frac{\Delta I}{t_1} \qquad (1.8)$$

or

$$t_1 = \frac{\Delta I L}{V_s} \qquad (1.9)$$

And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$V_s - V_a = -L \frac{\Delta I}{t_2} \qquad (1.10)$$

or

$$t_2 = \frac{\Delta I L}{V_a - V_s} \qquad (1.11)$$

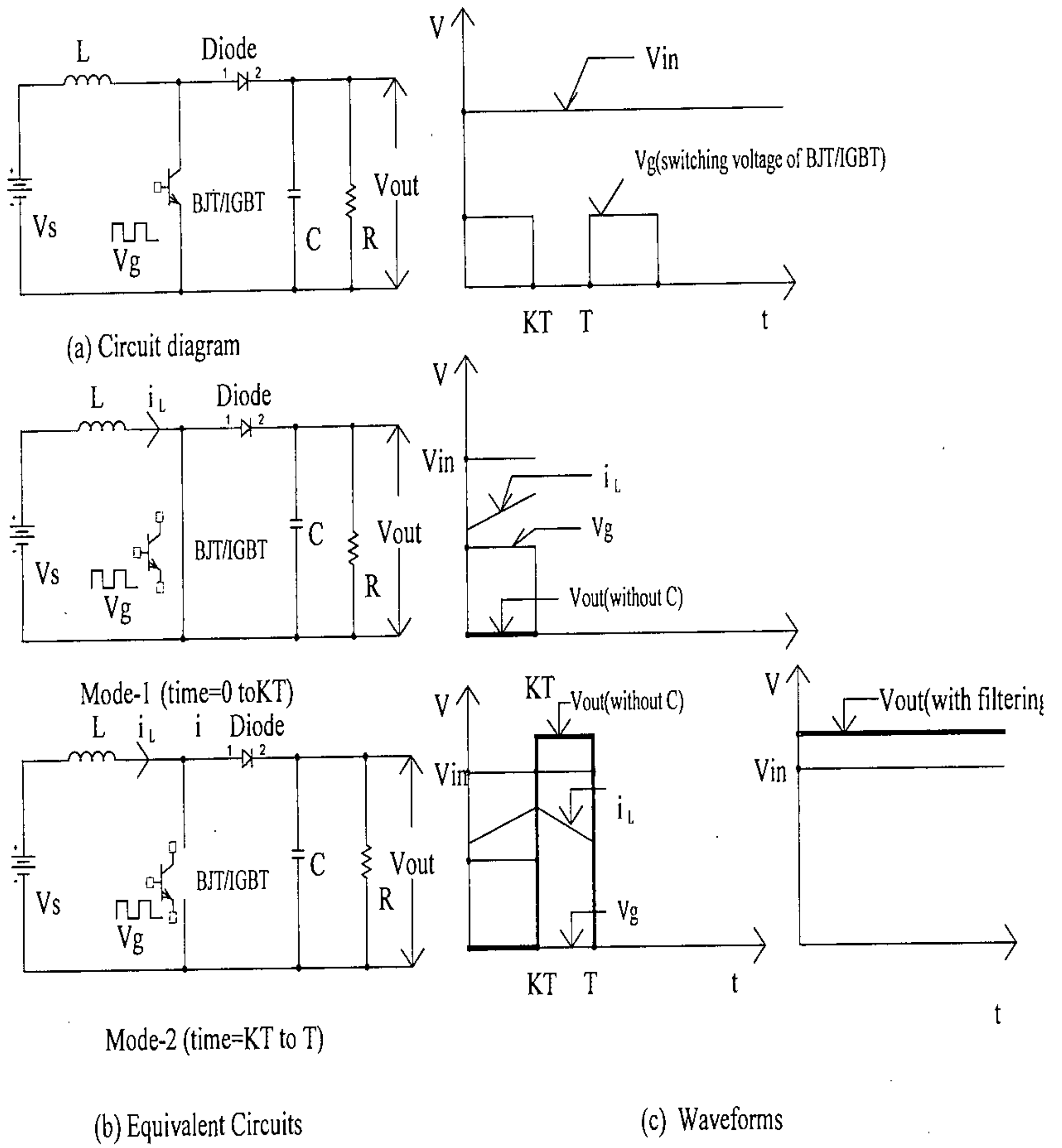


Figure-6. Boost regulator with continuous i_L

Where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L. From eqs- (1.8) and (1.10) ,

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s) t_2}{L} \qquad (1.12)$$

Substituting $t_1 = KT$ and $t_2 = (1-K)T$ yields the average output voltage,

$$V_a = V_s \frac{T}{t_2} = \frac{Vs}{1-K} \qquad (1.13)$$

1.2.2.3 BUCK-BOOST REGULATOR

In a Buck-Boost regulator the output voltage is regulated in buck and boost both ways. The output voltage polarity is opposite to input voltage and as a result the regulator is known as an inverting regulator. Operation of the regulator can be explained with the help of fig-7. During mode 1, transistor Q_1 is turned on and diode D_m is reversed biased. The input current, which rises, flows through inductor L and transistor Q_1. During mode 2, transistor Q_1 is switched off and the current, which was flowing through inductor L, would flow through L, C, D_m, and the load. The energy stored in inductor L would be transferred to the load and the inductor current would fall until transistor Q_1 is switched on again in the next cycle.

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$Vs = L \frac{I_2 - I_1}{t_1} = L \frac{\Delta I}{t_1} \qquad (1.14)$$

or

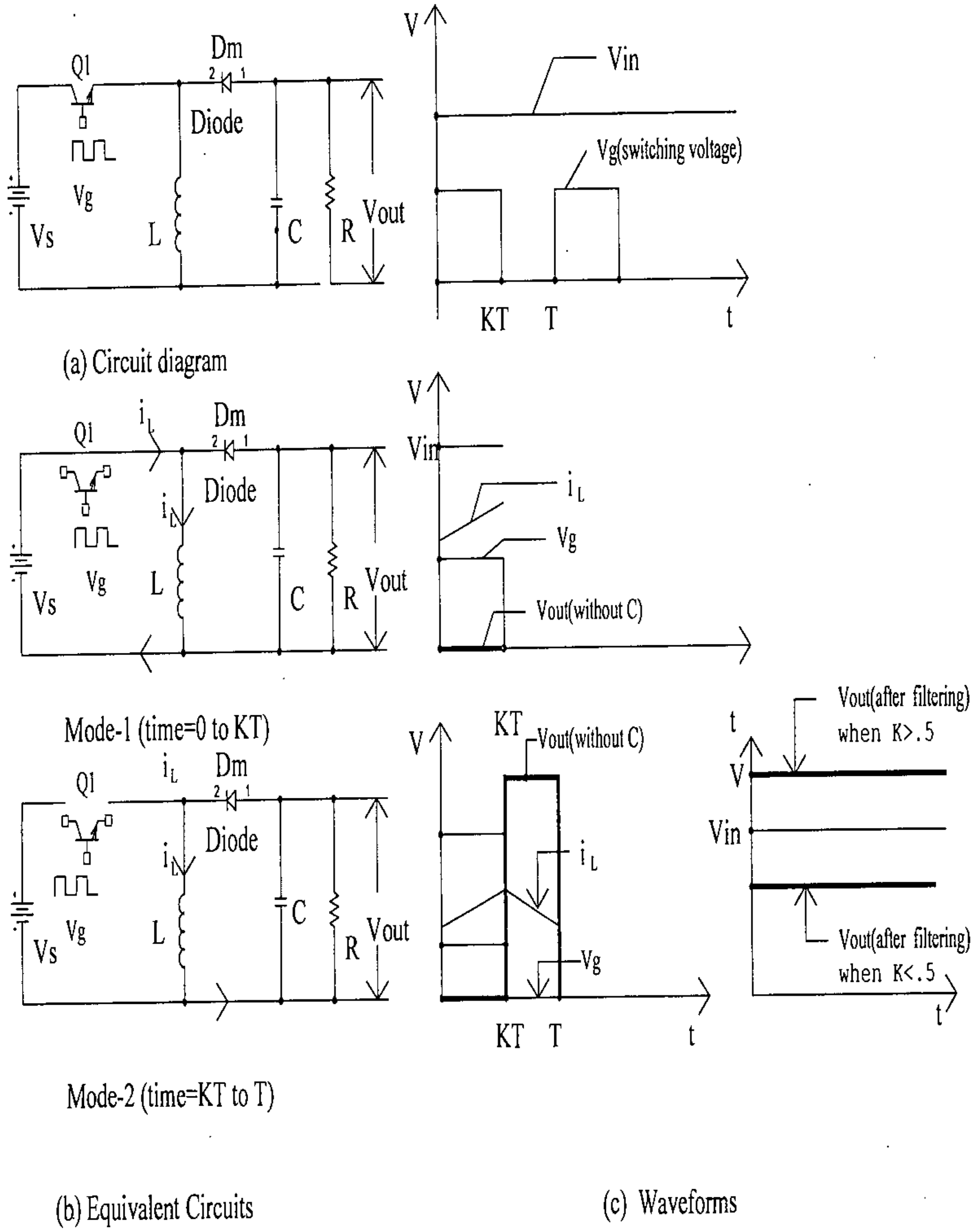


Figure-7. Buck-boost regulator wih continuous i_L.

$$t_1 = \frac{\Delta I\, L}{V_s} \tag{1.15}$$

And the inductor current falls linearly from I_2 to I_1 in time t_2,

$$V_a = - L \frac{\Delta I}{t_2} \tag{1.16}$$

or

$$t_2 = \frac{- \Delta I\, L}{V_a} \tag{1.17}$$

where $\Delta I = I_2 - I_1$ is the peak to peak ripple current of the inductor L.

Equating the value of ΔI in eqs-(1.14) and (1.16) gives

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s)\, t_2}{L} \tag{1.18}$$

Substituting $t_1 = KT$ and $t_2 = (1\text{-}K)T$ yields the average output voltage is.

$$V_a = \frac{V_s T}{K} = \frac{V_s}{1-K} \tag{1.19}$$

1.2.2.4 C^UK REGULATOR

It is the modified form of Buck-Boost regulator having the capability to regulate input voltage in both buck and boost way. The operation can be explained with the help of fig-8. Mode 1 begins when transistor Q_1 is turned on at t=0. The current through inductor L_1 rises. At the same time, the voltage of the capacitor C_1 reverse biases diode D_m and turns it off. The capacitor discharges its energy to the circuit formed by C_1, C_2, the load and L_2. Mode 2 begins when transistor Q_1 is turned off at $t = t_1$. The capacitor C_1 is charged from input supply and the energy stored in

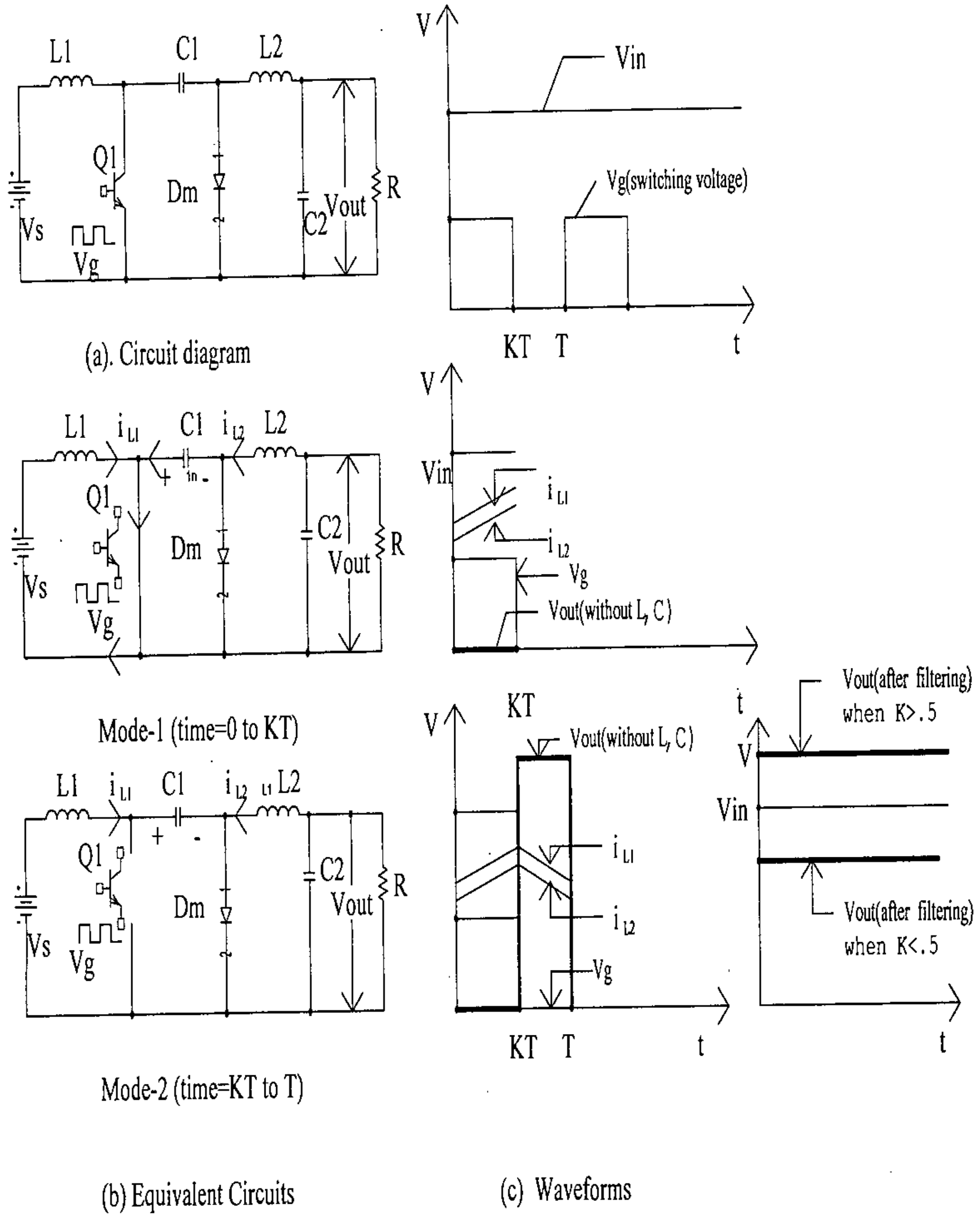


Figure 8. C^uk regulator with continuous i_L.

the inductor L_2 is transferred to the load. The diode D_m and transistor Q_1 provide a synchronous switching action. The capacitor C_1 is the medium for transferring energy from the source to the load.

Assuming that the current of inductor L_1 rises linearly from I_{L11} to I_{L12} in time t_1,

$$Vs = L_1 \frac{I_{L12} - I_{L11}}{t_1} = L_1 \frac{\Delta I_1}{t_1} \tag{1.20}$$

or

$$t_1 = \frac{\Delta I_1 L_1}{Vs} \tag{1.21}$$

And due to the charged capacitor C_1, the inductor L_1 current falls linearly from I_{L12} to I_{L11} in time t_2,

$$V_s - V_{c1} = \frac{-\Delta I_1 L_1}{t_2} \tag{1.22}$$

or

$$t_2 = \frac{-\Delta I_1 L_1}{V_s - V_{c1}} \tag{1.23}$$

where V_{c1} is the average voltage of capacitor C_1 and $\Delta I_1 = I_{L12} - I_{L11}$. From eqs. (1.20) and (1.22),

$$\Delta I_1 = \frac{V_s t_1}{L_1} = \frac{-(V_s - V_{c1}) t_2}{L_1} \tag{1.24}$$

Substituting $t_1 = KT$ and $t_2 = (1-K)T$ the average voltage of capacitor C_1 is V_{c1}.

$$V_{c1} = \frac{V_s}{1 - K} \tag{1.25}$$

Assuming that the current of filter inductor L_2 rises linearly from I_{L21} to I_{L22} in time t_1,

$$V_{c1}+V_a = L_2 \frac{I_{L22} - I_{L21}}{t_1} = \frac{\Delta I_2}{t_1} \tag{1.26}$$

or

$$t_1 = \frac{\Delta I_2 L_2}{V_{c1} + V_a} \tag{1.27}$$

And the current of inductor L_2 falls linearly from I_{L22} to I_{L21} in time t_2,

$$Va = -L_2 \frac{\Delta I_2}{t_2} \tag{1.28}$$

or

$$t_2 = -L_2 \frac{\Delta I_2}{V_a} \tag{1.29}$$

Where $\Delta I_2 = I_{L22} - I_{L21}$. From eqs.(1.26) and (1.28),

$$\Delta I_2 = \frac{(V_{c1} + V_a)\, t_1}{L_2} = \frac{- V_a t_2}{L_2} \tag{1.30}$$

Substituting $t_1 = KT$ and $t_2 = (1\text{-}k)T$ the average voltage of capacitor C_1 is V_{c1}.

$$V_{c1} = \frac{- V_a}{K} \tag{1.31}$$

Equating Eqs.(1.25) and (1.31) we can find the average output voltage as

$$V_a = \frac{-KV_s}{1 - K} \tag{1.32}$$

Assuming a loss less circuit, $V_s I_s = - V_a I_a = V_s I_a K / (1 - K)$ and the average input current,

$$I_s = \frac{K I_a}{1 - K} \quad (1.33)$$

1.2.3 ADVANTAGES OF AN SMPS [6,7]

Switch mode power supplies have following advantageous features:

* Isolation between the source and the load
* High power density resulting reduction of size and weight
* Controlled direction of power flow
* High conversion efficiency
* Input and output waveforms with low total harmonic distortion for small filters
* Controlled power factor if the source is an ac voltage

1.3 AC VOLTAGE REGULATORS

1.3.1 REVIEW OF AC VOLTAGE REGULATORS [8,9]

The AC voltage regulator is a device by which the voltage can be set to a desired value and can be maintained constant all the time. This subject is vast and the field of application extends from very large power systems to small electronic apparatus. Naturally, the types of regulators are also numerous. The design of the regulator system depends mainly on the power requirements and degree of stability. The voltage regulator may be:

a) Manually controlled or

(b) Automatically controlled.

When the stability is not very stringent, manual control is generally preferred from economic considerations. The voltage can be regulated either in steps (discontinuous), or continuously. In the automatic regulator, there is a sensing element, a signal-processing unit, and finally the power-control unit. The output voltage is compared with a fixed reference voltage, and the error thus generated is amplified, integrated or differentiated whenever necessary. The processed error voltage is fed to the main controlling unit to have required corrective action. Thus the output voltage is maintained constant.

All regulators take a finite time to effect a change in the supply voltage or load. This time is referred to as the time constant of the regulator, but in most case it is termed as response time. In some cases, the response time is dependent on the magnitude of the change of output voltage, but the rate of change remains constant. The maximum allowable response time depends upon the type of application. It is always desirable to make the response time as small as possible to reduce the transients in the output voltage.

1.3.1.1 MANUALLY CONTROLLED VOLTAGE REGULATOR [10]

The voltage can be regulated manually by:

a) Tap-changing switches,

b) A variable auto-transformer (variac) or

c) An induction regulator.

In some cases, variable resistance and variable inductances are also used.

1.3.1.1.1 TAP-CHANGING SWITCHES

The voltage regulations by tap-changing switches are used in many industrial applications, where, the maintenance of output voltage at a constant value is not very important. In smaller installations, Off-load tap-changing switches are used, but for large installations, incorporation of On-load tap-changing switches are necessary. The arrangement of Off-load tap-charging switch is shown in fig-9.

The switches are generally incorporated at the secondary of the transformer as shown. When the required number of control steps is large than the number of positions available at the switch, more than one switch is used, but the taps are so arranged that equal voltage steps are available at the output points. In the figure three four-position switches are shown such that the minimum of X volts per step are available at the output. The transformer taps are such that the fine-control coil has four taps having X volts each, whereas, the medium section of the coils should have four taps each having 4 X V, and the coarse control section should have four taps of 16X volts each.

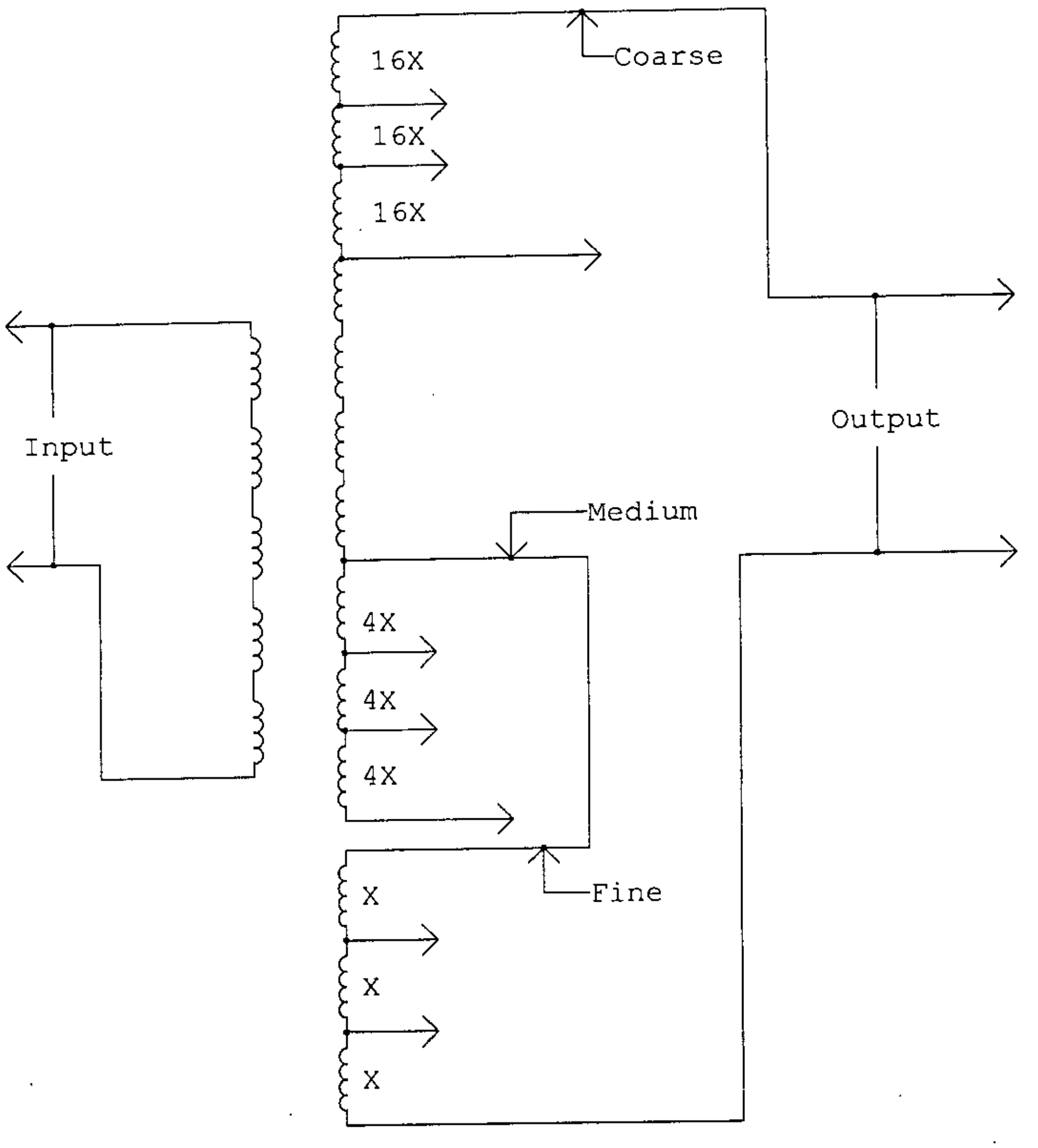


Figure-9 Off load tap changing switch arrangement.

1.3.1.1.2 STEPLESS CONTROL BY VARIAC [8,11]

Tap-charging switches in steps correct the voltage. In many applications, this may be objectionable. Where stepless control is required, variable autotransfromers or variacs are used. The normal variac consists of a toroidal coil wound on a laminated iron ring. The insulation of the wire is removed from one of the end faces and the wire is ground to ensure a smooth path for the carbon brush. Carbon brush is used to limit the circulating current, which flows between the short-circuited turns. An almost stepless control of voltage may be obtained due to gradual change of contact area as the brush moves from one turn to the next. For three-phase operation, three variacs are ganged together. The toroidal structure of variacs is limited to smaller current ratings. For large currents, rectangular cores are used. Stepped core with round coils are used for high power variacs. These variacs are available as single-and three-phase units. The construction is similar to that of ordinary transformers except that coils are wound on a single layer to facilitate 100% variation. The carbon brush slides on the bare surface of the coils. The electrical circuit representation is shown in Fig.-10.The input is connected to a tap on the total winding so as to obtain a greater output than the input. The volts per turn of the variac is made much smaller than that of a transformer of similar rating because its choice is guided by the circulating current due to the interturn voltage through the sliding brush. Generally, 1 V per turn is allowed to limit the circulating current and special high-resistance brush is used for this purpose.

When 100% variation is not required, a Buck-Boost transformer is often used as shown in Fig.-11. The maximum voltage impressed at the primary of the Buck-Boost transformer is ± $E_l/2$ and that the secondary is ($E_l/2$) (N_s / N_p). The output voltage can therefore be varied steplessly. For three-phase units, a three-phase variac and three Buck-Boost transformers are required.

1.3.1.2 AUTOMATIC VOLTAGE REGULATORS [8,12]

In manual control, the output voltage is sensed with a voltmeter connected at the output; the decision and correcting operation is made by a human judgment. The manual control may not be feasible always due to various factors. In automatic voltage regulators, all functions are performed by instruction, and give much better performance, so far as stability, speed of correction, consistency, fatigue, etc. are concerned. Moreover, the highly unpredictable personal factor is totally absent.

There are two types of automatic control – discontinuous control and continuous control. It has been already said that the automatic-control system consists of a sensing or measuring unit and a power control or regulating unit. The measuring unit compares the output voltage or the controlled variable with a steady reference and gives an output proportional to their difference. The regulating unit is driven by the error signal derived from the measuring unit and gives the correcting power.

In the discontinuous type of control, the measuring unit is such as to produce no signal so long as the voltage is within certain limits. This region where no signal is given is called the `dead zone'. When the voltage goes outside the dead zone, a signal is produced by the measuring unit until the voltage is again brought within this zone. An

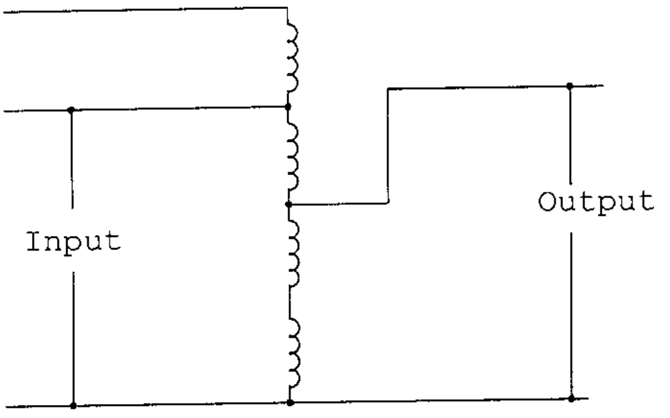


Figure-10 Normal arrangement of a Variac

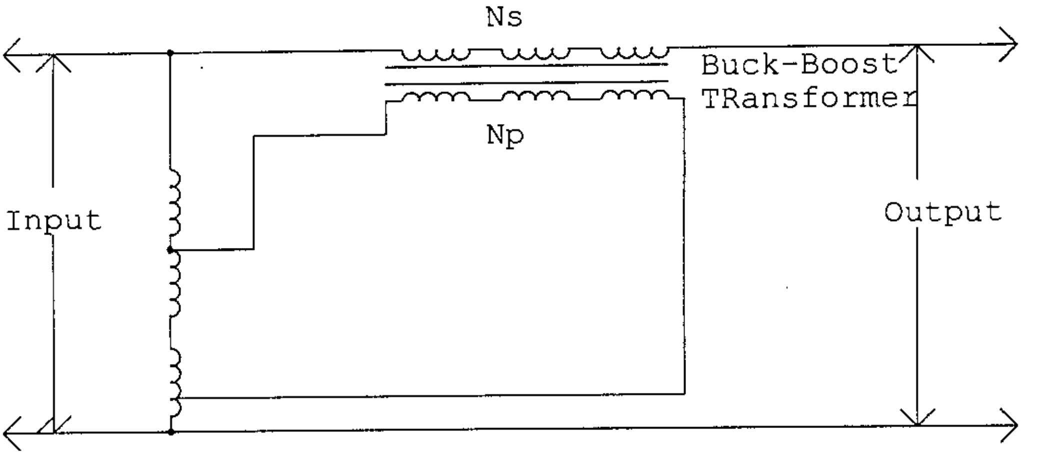


Figure-11 Voltage control by combination of a Buck-boost transformer and a variac example of this type of measuring unit is the voltage-sensitive relay with changeover contacts. In this type of measuring or sensing unit, the correcting voltage is independent of percentage of error.

In the discontinuous-control system, the regulating or the power-controlling unit also operates in a discontinuous manner. It is activated by a discontinuous measuring unit and selects a fixed and predetermined amount of correction voltage. When the voltage is brought back to the dead zone, the signal from the measuring unit is zero and the regulating unit remains at its new position until another signal is received from the measuring unit.

In continuous control, the measuring unit produces a signal with amplitude proportional to the difference between the fixed reference and the controlled voltage. The output of the measuring unit is zero when the controlled voltage or a fraction of it is equal to the reference voltage. An example of this type of measuring unit is a voltage-sensitive bridge or a comparator. The regulating or the controlling unit, which is associated with the continuous measuring unit, gives a correcting voltage proportional to the output of the measuring unit. This is nothing but a voltage-and-power amplifier. This may be associated with a phase-sensitive detector and a driving mechanism. The discontinuous control system is simpler than the continuous-control system, but its response time is longer and less accurate. Therefore, it is used, where, the required output stability or the accuracy of control is not more than ± 1%. This is due to the presence of a finite width of dead zone in the measuring unit. The continuous-control type has faster response due to feedback action, and the output can be achieved more than ± 1%, but it is costly.

1.4 OBJECTIVE OF THE THESIS

In manual control, the output voltage is sensed with a voltmeter connected at the output; the decision and correcting operation is made by a human judgment. The manual control may not be feasible always due to various factors. In automatic voltage regulators, all functions are performed by instruction, and give much better performance, so far as stability, speed of correction, consistency, fatigue, etc. are concerned. Moreover, the highly unpredictable personal factor is totally absent there. Objective of these thesis is to regulate the output AC voltage in an automatic way by using the AC to AC C^uk regulator. C^uk regulator is actually a Buck-Boost type voltage regulator. The principle will be utilized here to regulate Ac-to-Ac voltage. For this a signal generating control circuit is to be associated with the power circuit for getting pulses of the switches. In the control circuit the output is compared with a reference voltage and the error signal is amplified to provide the desired control signal. The control signal is compared with a saw tooth voltage to generate the PWM signal. For the variation of output voltage, duty cycle of the gate signal would be changed for necessary correction of the output voltage. In the long run commercially available IC for dc switching regulator will be investigated for regulation of an ac voltage controller of switching type. For filtering the output voltage a filter circuit with proper value of L,C is to be associated with the power circuit. In this arrangement output voltage will remain constant for either increase or decrease of the input voltage and also for any change in load. The output voltage of the converter will be compared with a reference voltage and proper PWM signal will be generated (by adjusting pulse width) to compensate the voltage difference. The proposed voltage regulator is expected to provide a practical way of compensation for both short term and long term voltage changes at the load for either input voltage variation or the load variation within specified limit.

Proposed C^uK converter consist mainly of the loss less components like inductor and capacitor together with semiconductor devices as diode, IGBT and Integrated chip. Ideally this method is 100 % efficient. In practice, the efficiency is reduced as the switch is non-ideal and losses occur in power circuits due to lossy components.

1.5 OUTLINE OF THE THESIS

This thesis consists of three chapters. Chapter-1 deals with introduction to SMPS, review of voltage regulators and PWM techniques. It incorporates various advantages and requirements of an SMPS. Objective of the thesis and discussion on expected results are also included in chapter-1.

Chapter-2 includes the detailed study of AC C^uk regulator. AC C^uk regulator with ideal and practical IGBT switch implementation has been proposed and studied. Input /output ideal and non-ideal relationship for C^uk SMPS are presented in this chapter. Uncontrolled AC C^uk regulator by ideal switch, gate signal generating circuit and results of the operation of an AC C^uk regulator is included in chapter-2. This chapter also includes proposed controlled AC C^uk regulator implemented by practical IGBT switches. Automatic control circuit and results of AC C^uk regulator is presented in this chapter. Problems faced like freewheeling path, surge voltage across switches and possible remedy of freewheeling path and surge voltage are included in this chapter.. Input /output filter requirement is also described in brief in chapter-2.

Chapter-3 concludes the thesis with summary, achievements and suggestion on future works.

CHAPTER-2

AC C^UK VOLTAGE REGULATOR

INTRODUCTION

AC C^uk voltage regulator is a Buck-Boost regulator with some modification in the circuitry to work with ac voltage. This regulator would provide an output voltage which may be less than or greater than the input voltage. The output voltage polarity is opposite to that of the input voltage and the regulator is therefore known as an inverting regulator. A C^uk converter can be obtained by the cascade connection of the two basic converters: the step down (Buck) converter and the step up (Boost) converter. In steady state, the output to input voltage conversion ratio is the product of the conversion ratios of the two converters in cascade.

C^UK REGULATOR TOPOLOGY

C^uk voltage regulator provide an output voltage which may be less or greater than the input voltage. In chapter 1, it has been explained how an input DC voltage is regulated. Same principle is utilized here to regulate AC voltage in the output. AC voltage is segregating to a number of DC pulses then each of the pulse is to be regulated as per requirement by changing the duty-cycle of the gate pulse signals. AC C^uk regulator with ideal switch implementation circuit is shown in fig-12. This is associated with manual control gate signal generating circuit and filtering circuits, the circuit operation can be explained in positive and negative cycle separately. During positive half cycle of input voltage switch-1 is turns On and switch-2 turns Off at time t=0, the current through inductor L_1 rises and previously charged capacitor C_1 discharges its energy to the circuit formed by SW-1, C_2, the load and L_2 then at time $t=t_1$, Switch-1 is Off and switch-2 is on then the capacitor C_1 is charged from the input supply and the energy stored in the inductor L_2 is transferred to the load. The capacitor C_1 is the medium of transferring energy from the source to the load. During negative half cycle of input voltage the same operation takes place but direction of energy stored in inductor is opposite.

2.1 MANUAL CONTROLLED AC C^UK REGULATOR (Ideal Switch Implementation)

When the stability is not very stringent, manual control is generally preferred from economic considerations. When any change in output voltage occurs due to change in input voltage or change in load the voltage may be regulated by changing the DC of the gate signal generating circuit manually as shown in fig-13. In the proposed thesis we have shown that voltage regulation by C^uk regulator is possible to a constant 300V AC if the supply voltage goes down to 200V and goes up to 400V and also as load varies from 30 ohm to 200 ohm. So it is a suitable instrument for voltage regulation manually.

2.1.1 CONTROL CIRCUIT (Gate signal generating circuit)

The gate signal generating circuit for manual controlled AC C^uk regulator is shown in fig-13. The control circuit shows an OPAMP whose inputs are a fixed saw-tooth wave, V_2 and a variable DC voltage V_3. OPAMP acts as comparator, output of the OPAMP depends on the difference of two inputs, viz: $(V_+ - V_-)$. In this circuit positive input (saw-tooth wave) is kept fixed and negative input (DC voltage) is varied. So, output pulse width depends on DC input voltage of OPAMP. Fig-14 shows the input voltage waveforms (V_3=3.1 volt) of the OPAMP and output is the 'Duty cycle' of the Ac c^uk regulator and fig-15 shows the corresponding gate signals of switch-1 and switch-2. This signal will be utilized to regulate output voltage at 300 volts when input voltage is down at 250 volt, the waveforms are shown in fig-16. Fig-18 shows the input voltage waveforms and output gate signal of an OPAMP when input DC voltage is 2.5 volt and fig-19 shows the corresponding gate signals of switch-1 and switch-2. This signal will be utilized to regulate output voltage at 300 volts when input voltage is down at 200 volts, shown in fig-17. Fig-21 shows the input voltage waveforms and output gate signal of an OPAMP when DC voltage of the OPAMP is 4.2V and fig-22 shows the corresponding gate signals of switch-1 and switch-2. This signal will be utilized to regulate output voltage at 300 volts when input voltage is up at 400 volts, shown in fig-20. Comparing fig-18 and 21 it is clear that the output pulse widths of OPAMP are wider when the input DC is less. Variation of pulse width controls the duty cycle. Output signal of OPAMP is passed through two limiters. One directly to the input of the limit-1. The function of limit1 is to limits the magnitude of signal from 0V-5V without change of the shape or pulse width of signal. The output of limit-1 is the gate signal for switch-2 and output of limit-2 is the gate signal for switch-1. When switch-1 is On then switch -2 is Off. So the gate signal generating circuit is arranged in such a way that when gate signal for Switch-1 is On then gate signal for switch Switch-2 is Off and vise versa. For this reason output of OPAMP is multiplied by (-1) by using a gain unit Gain-1. Output of the gain-1 passes through the limit-2. The output voltage of limit-2 of magnitude 0-5 V those are the gate signal for switch-1. The gate pulses of switch-1 and switch-2 for input voltage 250V, 200V and 400V to keep output voltage 300V are shown in fig-15, 19 and 22 respectively.

2.1.2 RESULTS OF MANUAL CONTROLLED AC C^UK REGULATOR (Ideal Switch Implementation)

By applying AC C^uk regulator with ideal switch implementation output voltage is regulated at 300 volt when input voltage is 250V and load is 60 ohm, shown in fig.16. Keeping load 60 ohm constant input voltage is varied from 200V to 400V but output voltage is regulated and kept at 300 volt as shown in fig-17 and 20. Here DC voltage, V_3 of the OPAMP is varied from

2.5 volt when input is 200 volt to 4.2 volt when input is 400 volt, as shown in fig-18 and 21. This voltage regulation is done by changing the duty-cycle of the gate signal, and duty-cycle is changed by changing the DC of the gate signal generating circuit manually. Now it is shown in fig-23 and fig-25 that output voltage is regulated at 300V when input voltage is 200V but load is at 100 ohm and 200 ohm respectively. It is also shown in fig-27 and fig-29 that output voltage is regulated at 300V when input voltage is 400V but load is at 100 ohm and 200 ohm respectively. Similarly by changing the load to 30 ohm and keeping the input voltage at 250V and 350V the output voltage is maintained at 300V as shown in fig 31 and 32. We have seen that applying this regulator it is able to regulate output voltage at 300 volt if input voltage is varied from 200 volt to 400 volt and load is varied from 30 ohm to 200 ohm. From the results it is seen that due to input voltage change or load change output voltage across the load could be maintained constant by changing the pulse width of gate signals of switch-1 and switch-2.

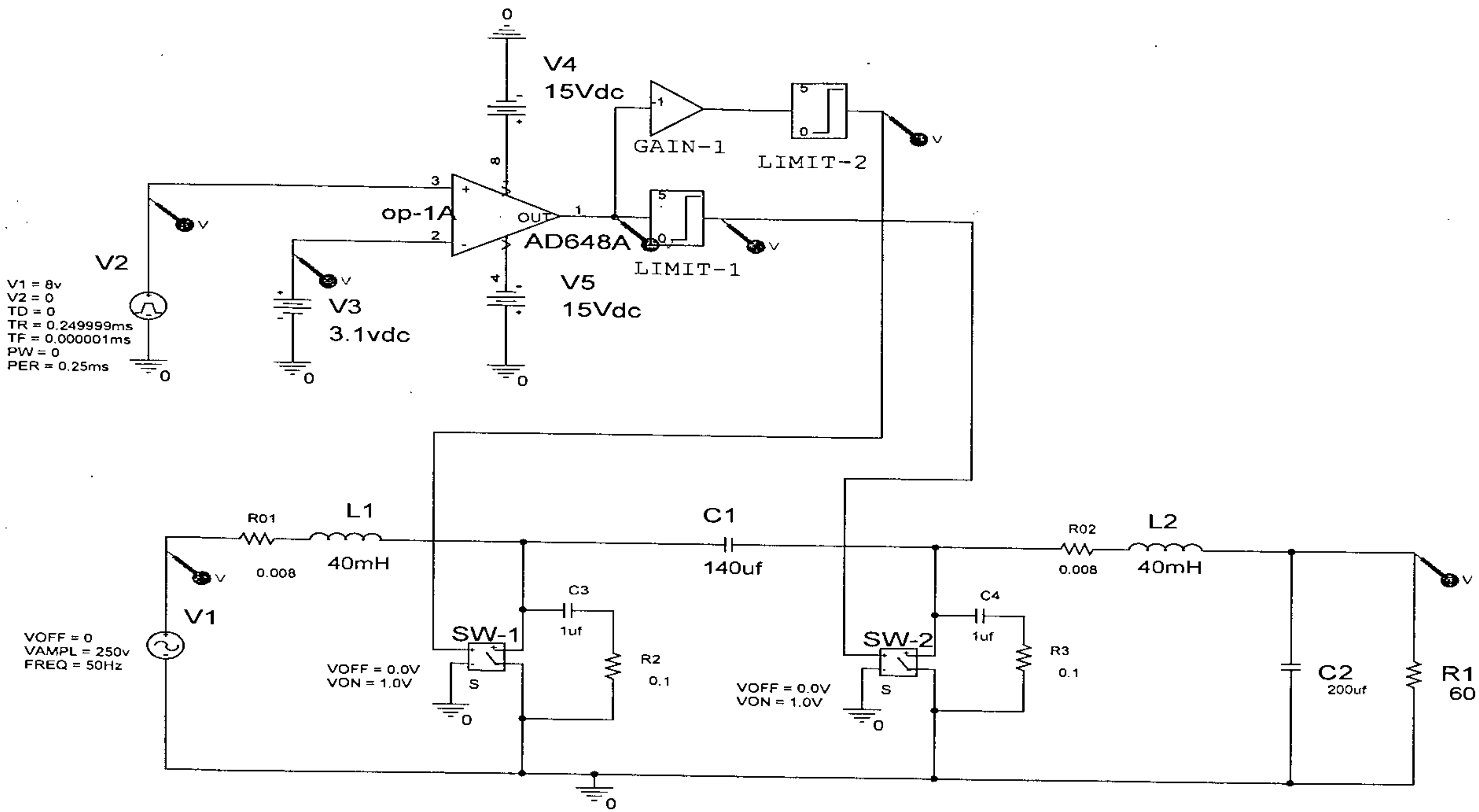


Figure-12. AC C^uk Regulator circuit with ideal switch and manual control.

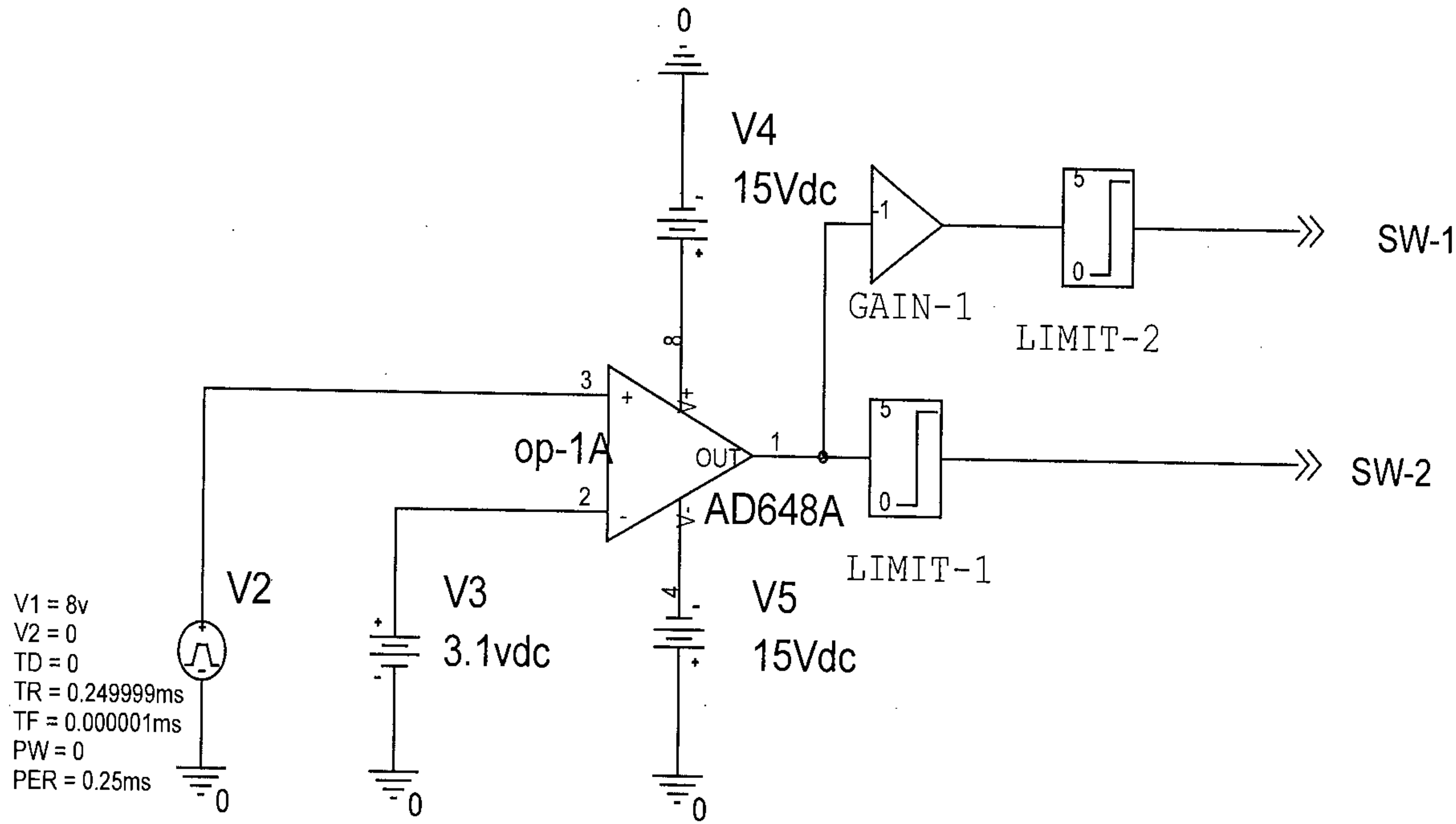


Figure-13. Gate signal generation circuit of AC C^uk regulator.

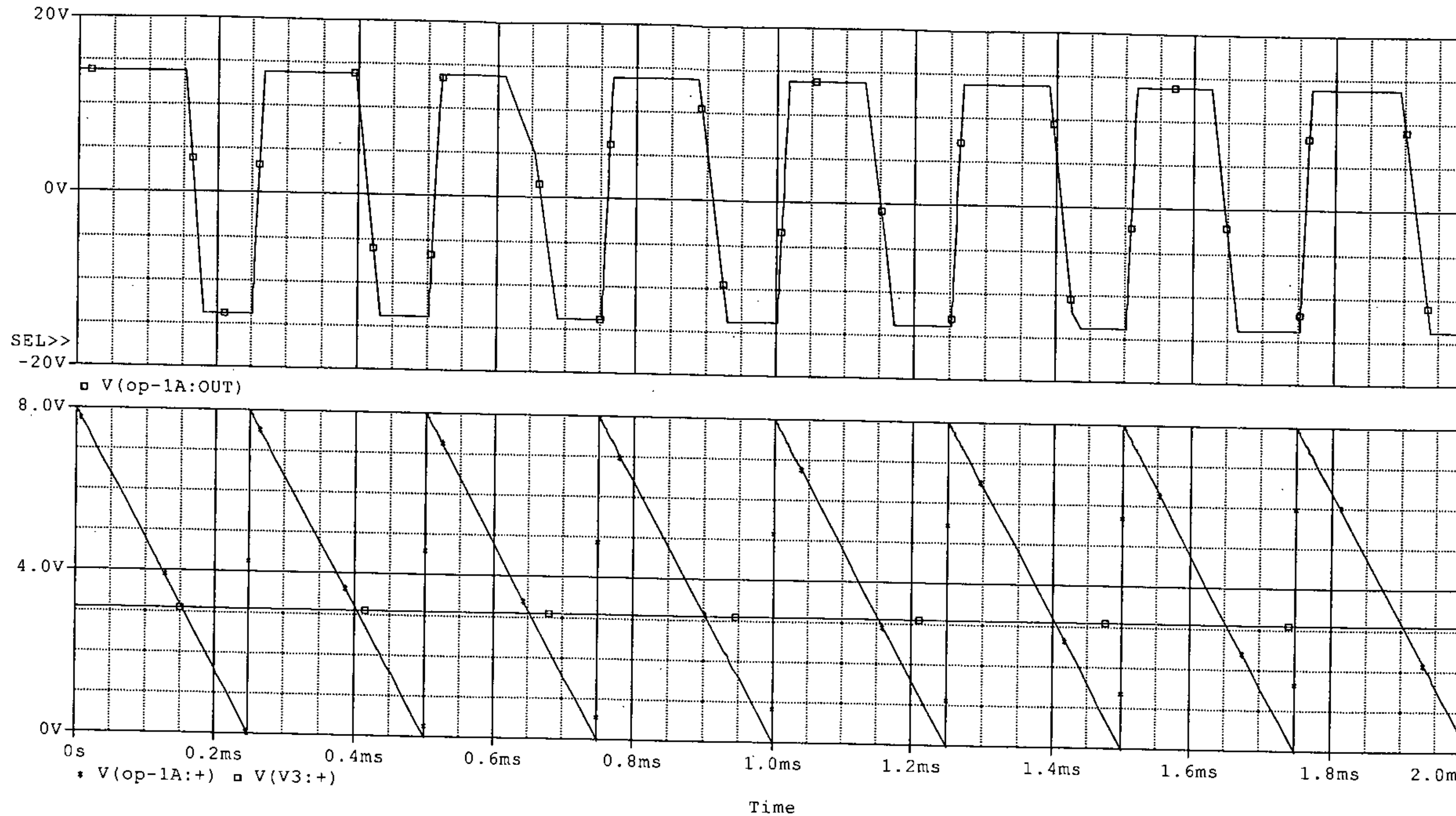


Figure-14. Generation of gate signal voltage (duty-cycle), when input voltage 250V, load 60 ohm.
V(op-1A:+)-- Fixed triangular wave.
V(V3:+)-- DC voltage 3.1volt.
V(op-1A:out)--Generation of gate voltage.

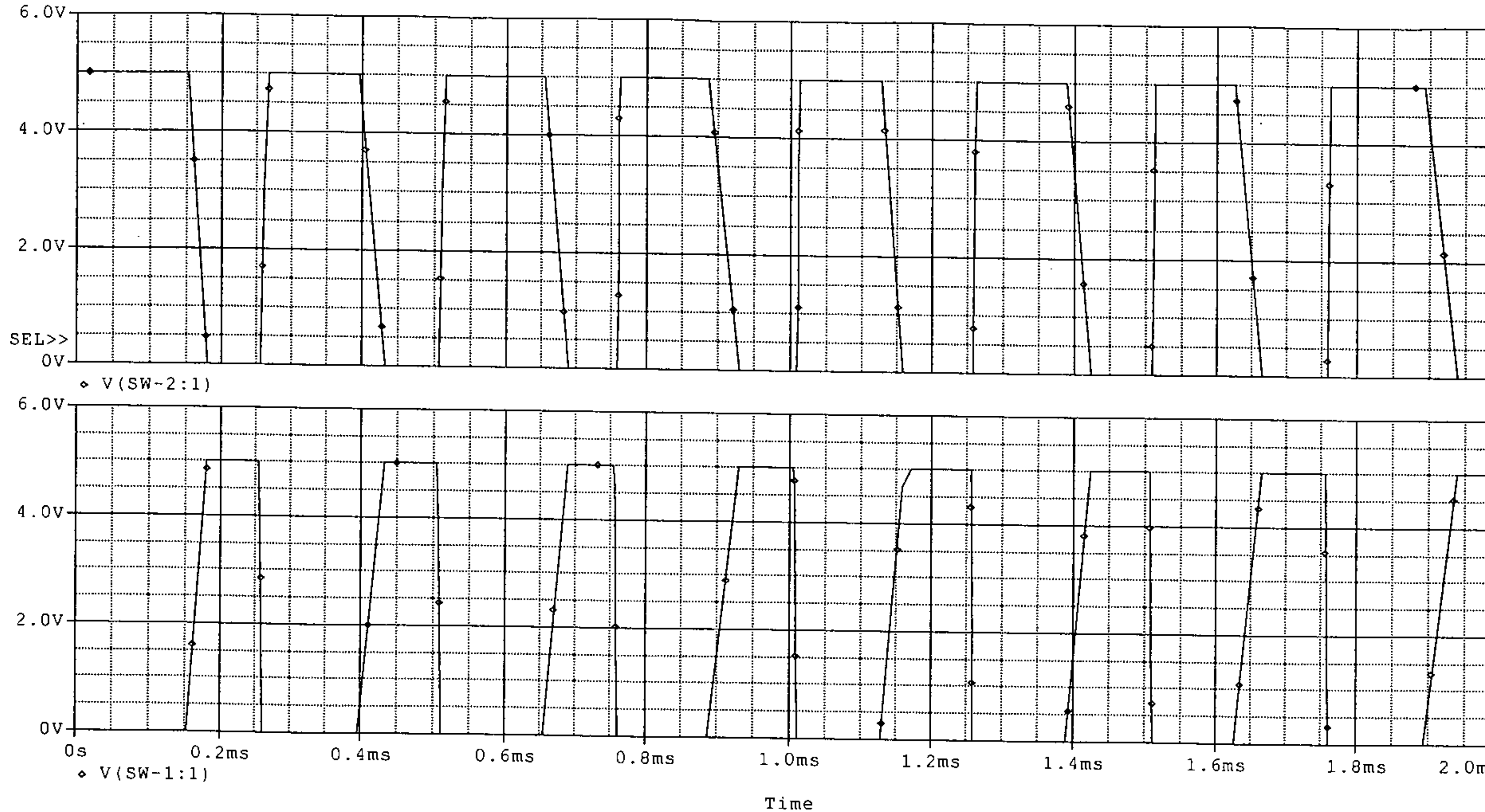


Figure-15. Switching pulses, when input voltage 250V,load 60 ohm (V_3=3.1volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

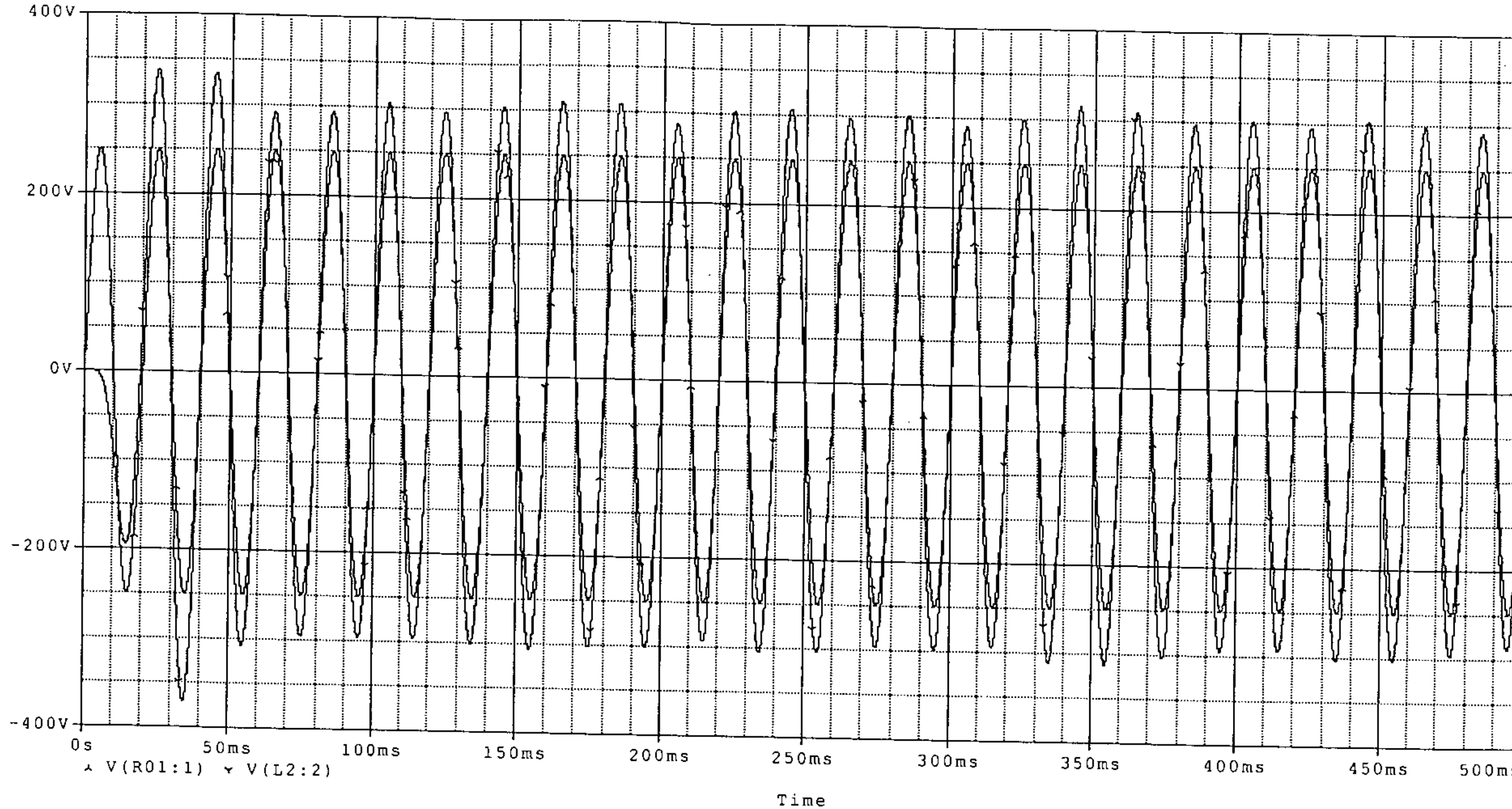


Figure-16. Input output voltage waveform when input voltage 250V, load 60 ohm (V_3=3.1volt).
V(R01:1)--Input voltage=250V.
V(L2:2)--Output voltage=300V.

Figure-17. Input output voltage waveform when input voltage 200V,load 60 ohm(V_3=2.5volt).
V(R01:1)--Input voltage=200V.
V(L2:2)--Output voltage=300V.

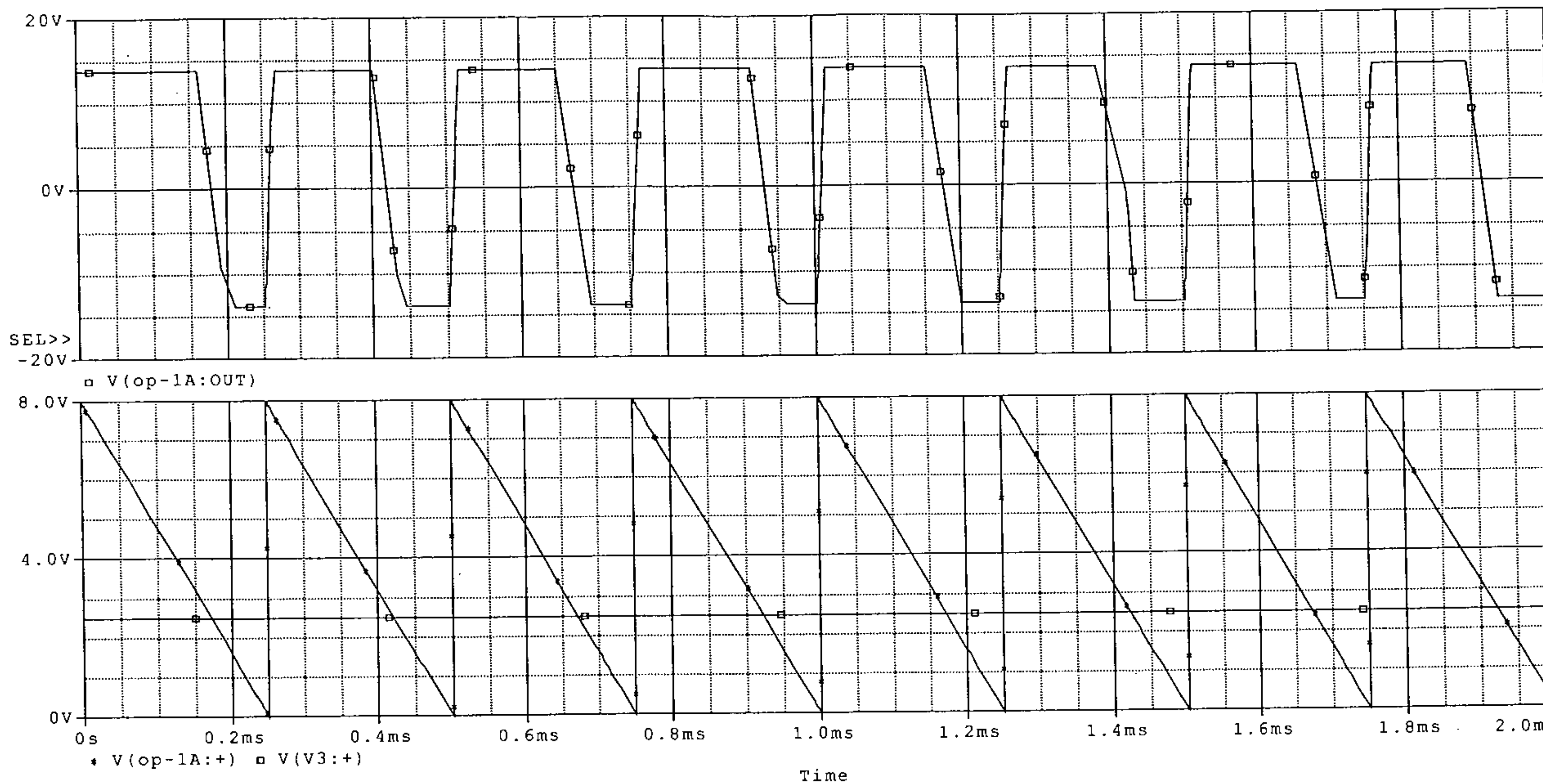


Figure-18. Generation of gate signal voltage, when input voltage 200V.
V(op-1A:+)- Fixed triangular wave.
V(V3:+)----- Dc voltage 2.5V.
V(op-1A:out)--Generation of gate voltage.

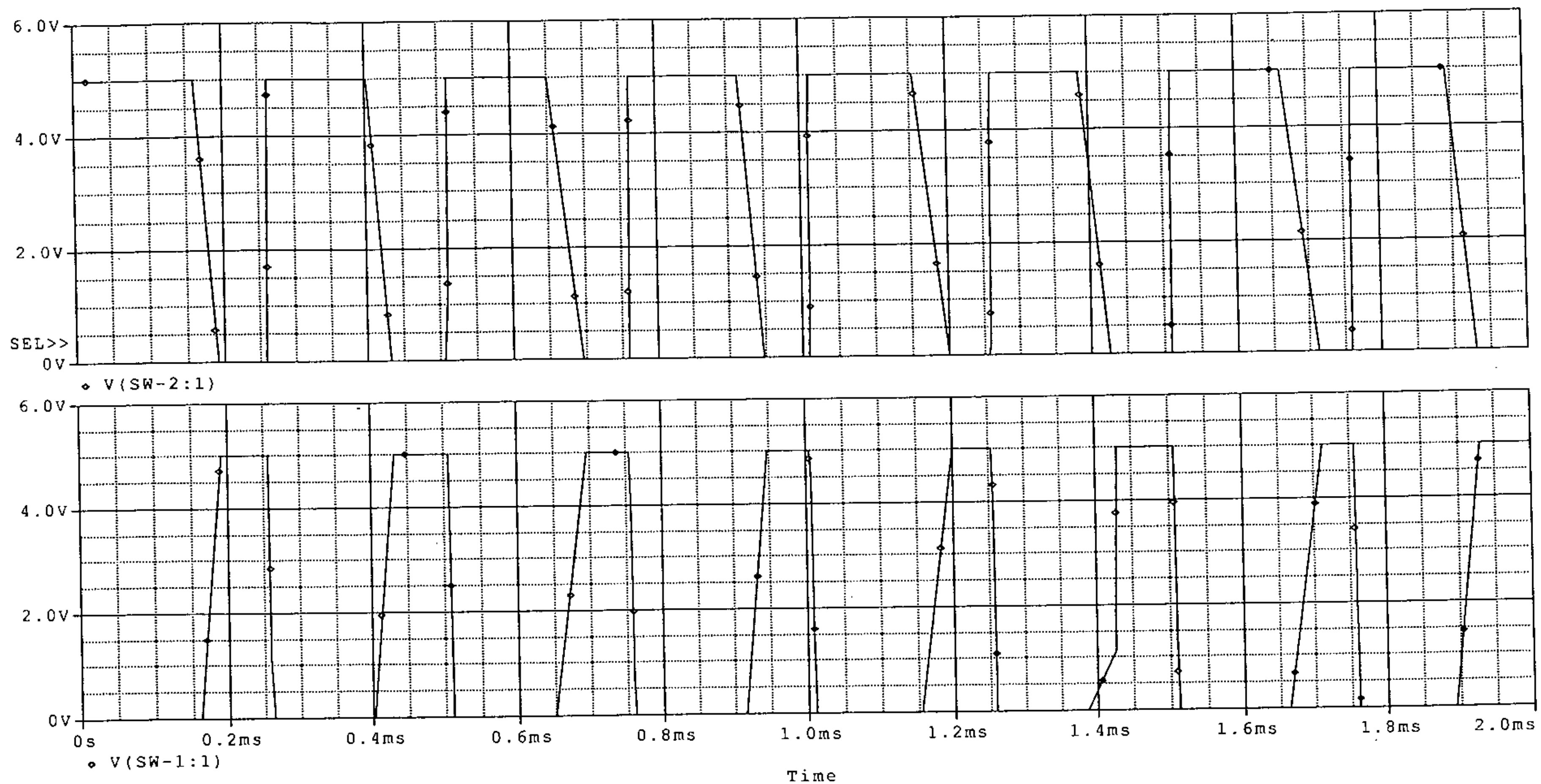


Figure-19. Switching pulses, when input voltage 200V (V_3=2.5volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

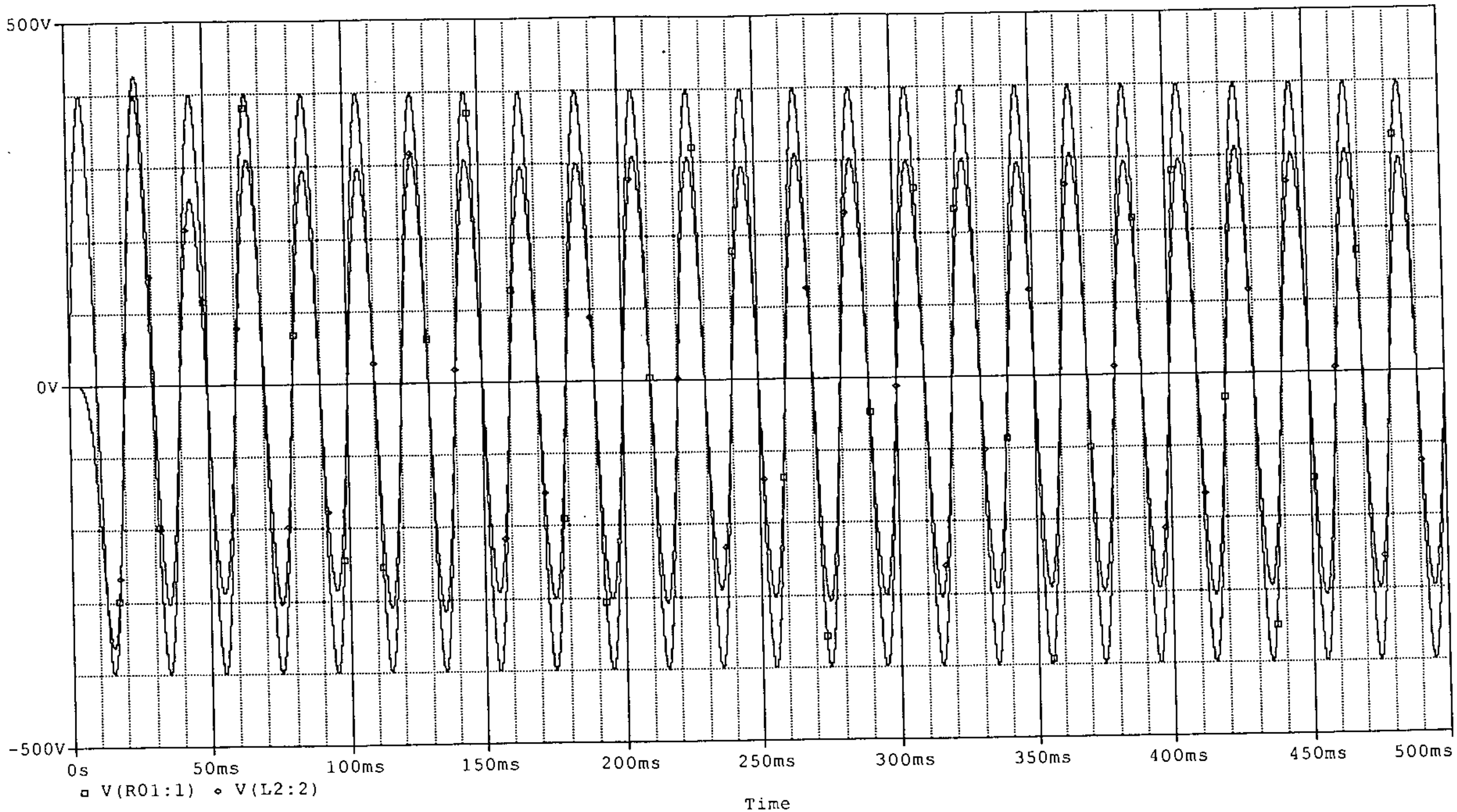


Figure-20. Input output voltage waveform when input voltage 400V, load 60ohm (V_3=4.2volt).
V(R01:1)--Input voltage=400V.
V(L2:2)--Output voltage=300V.

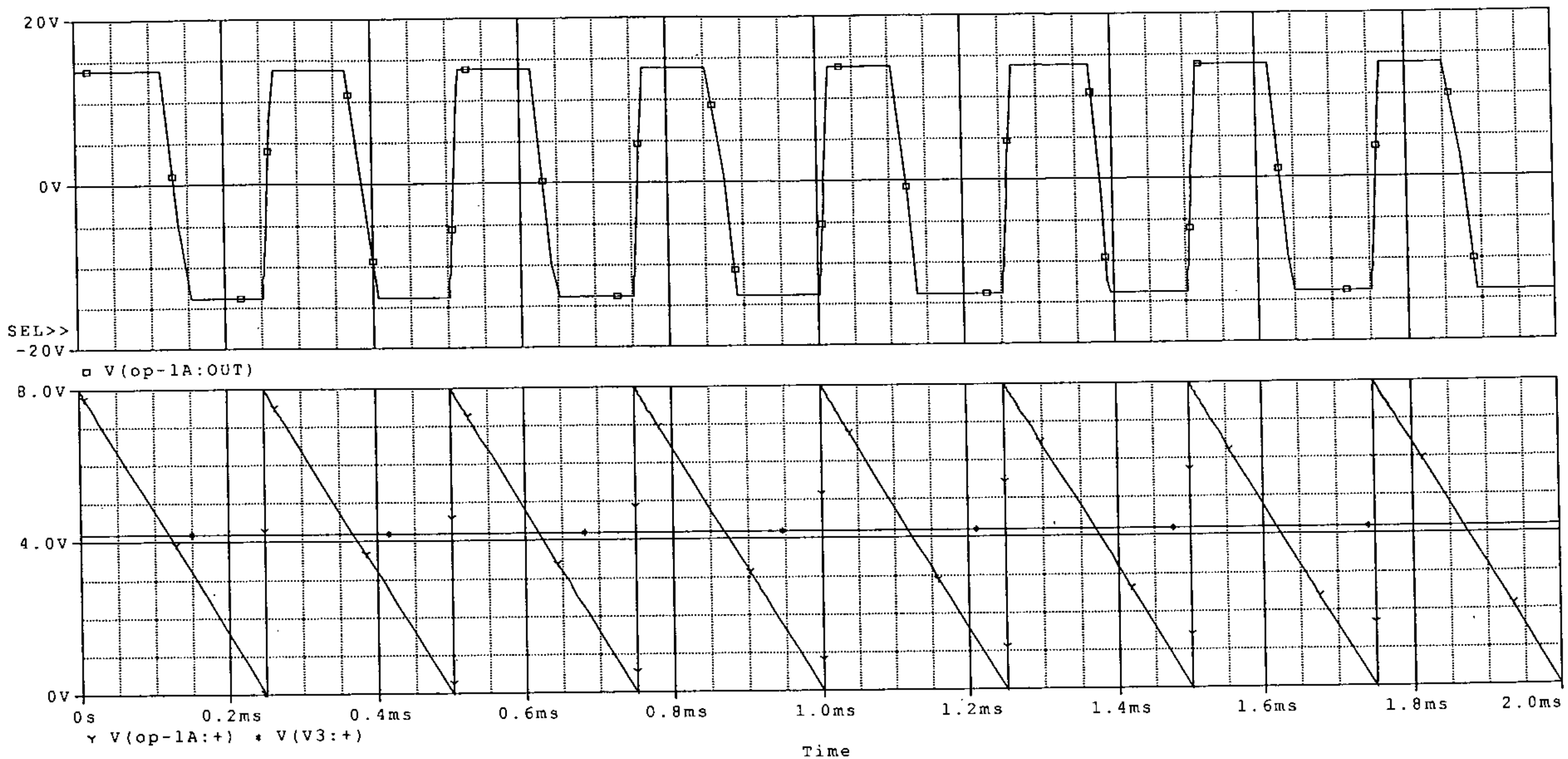


Figure-21. Generation of gate signal voltage, when input voltage 400V,load=60 ohm.
V(op-1A:+)- Fixed triangular wave.
V(V3:+)----- Dc voltage 4.2volt.
V(op-1A:out)--Generation of gate voltage.

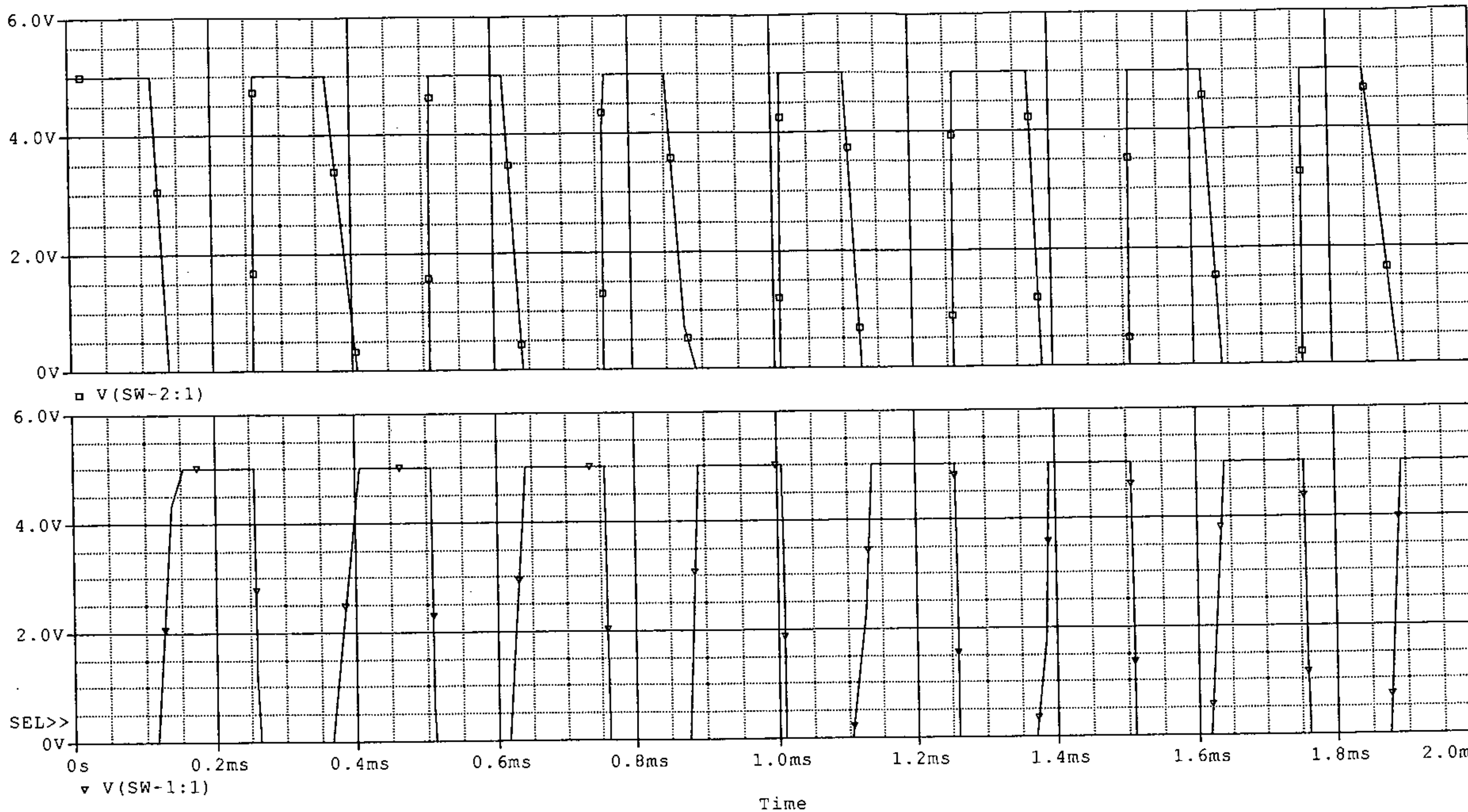


Figure-22. Switching pulses, when input voltage 400V(Vdc=4.2volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

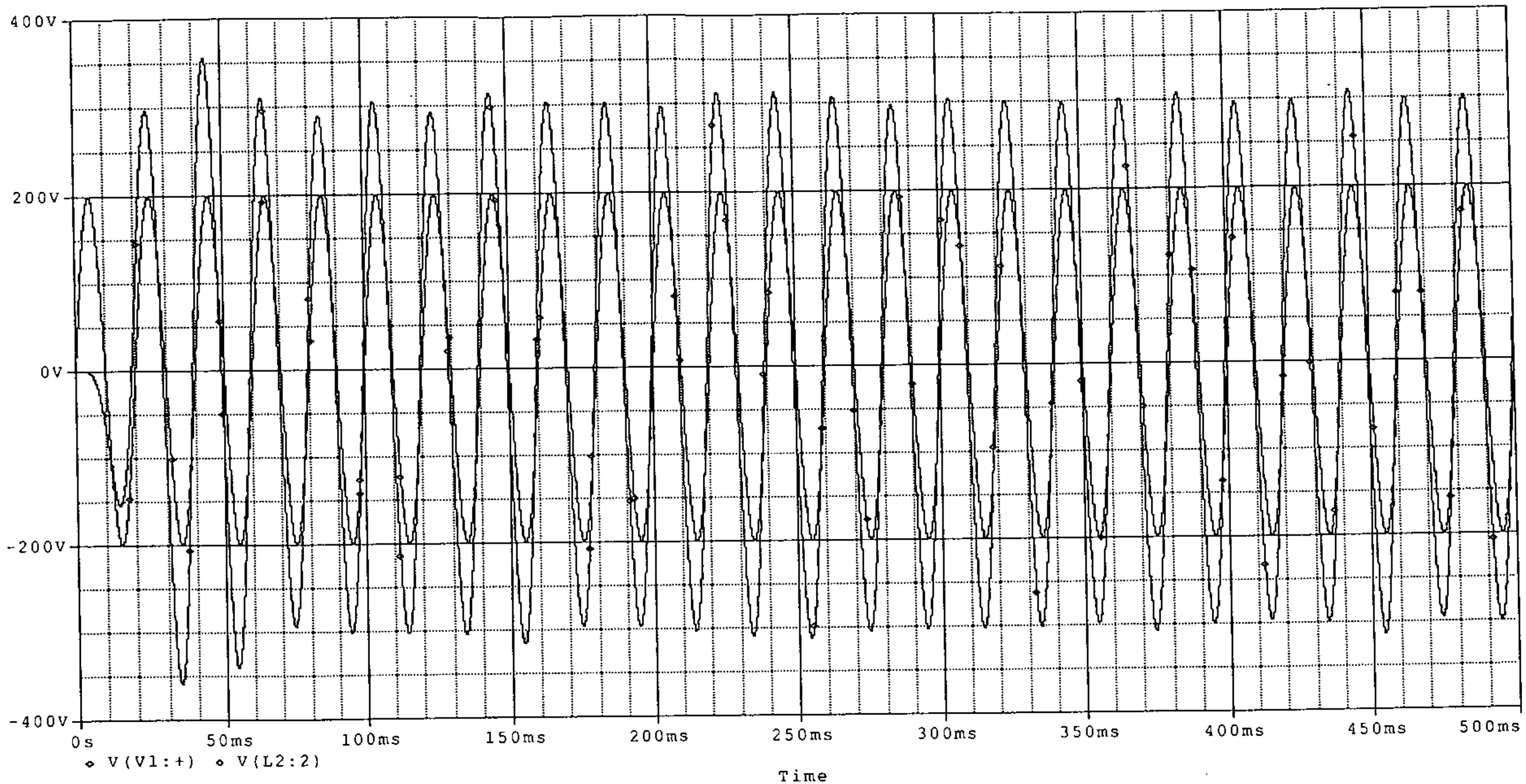


Figure-23. Input output voltage waveform when input voltage 200V,load=100ohm.

V(R01:+)--Input voltage=200V.

V(L2:2)--Output voltage=300V.

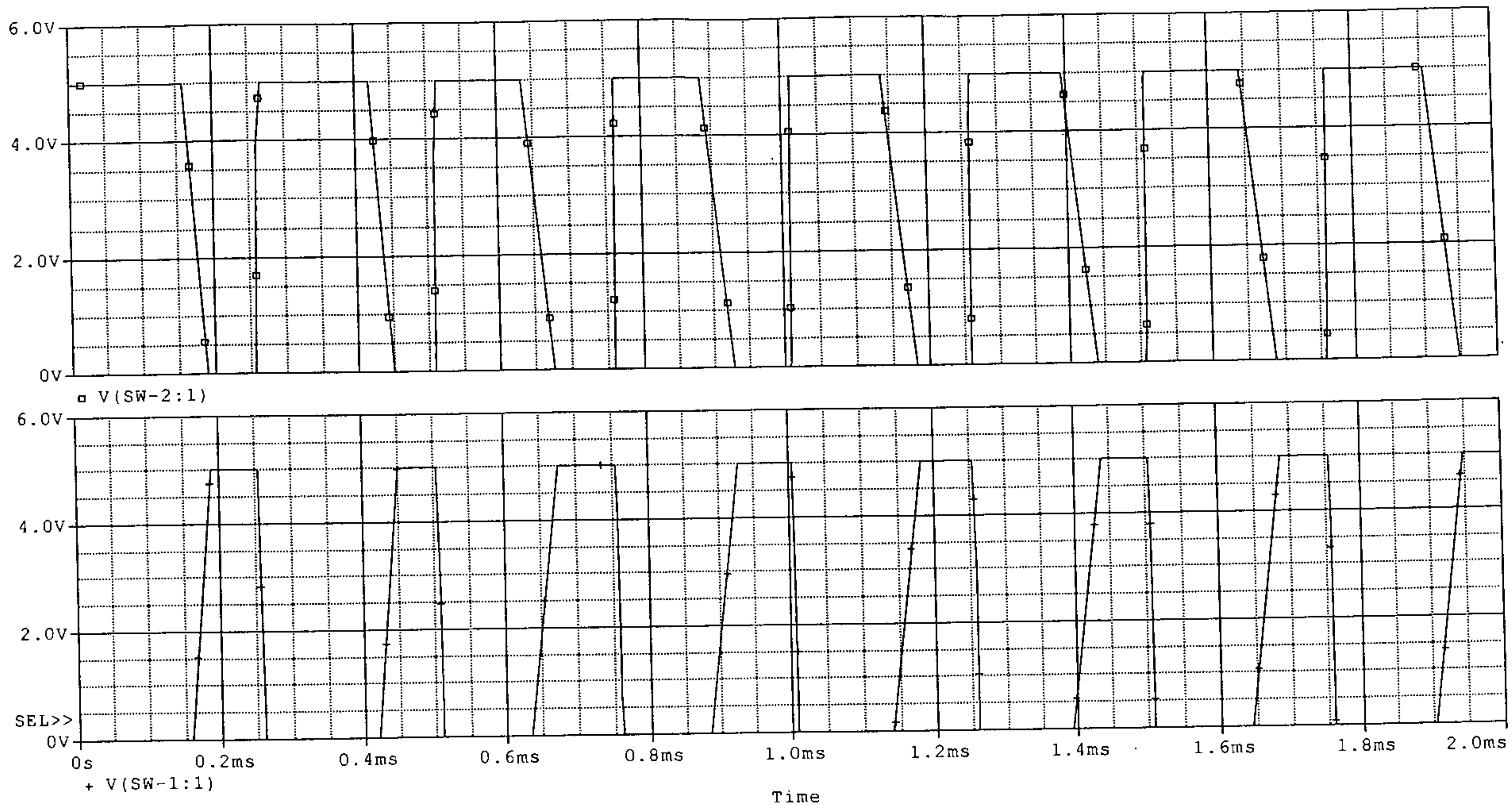


Figure-24. Switching pulses, when input voltage 200V, load=100ohm (V_3=2.6volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

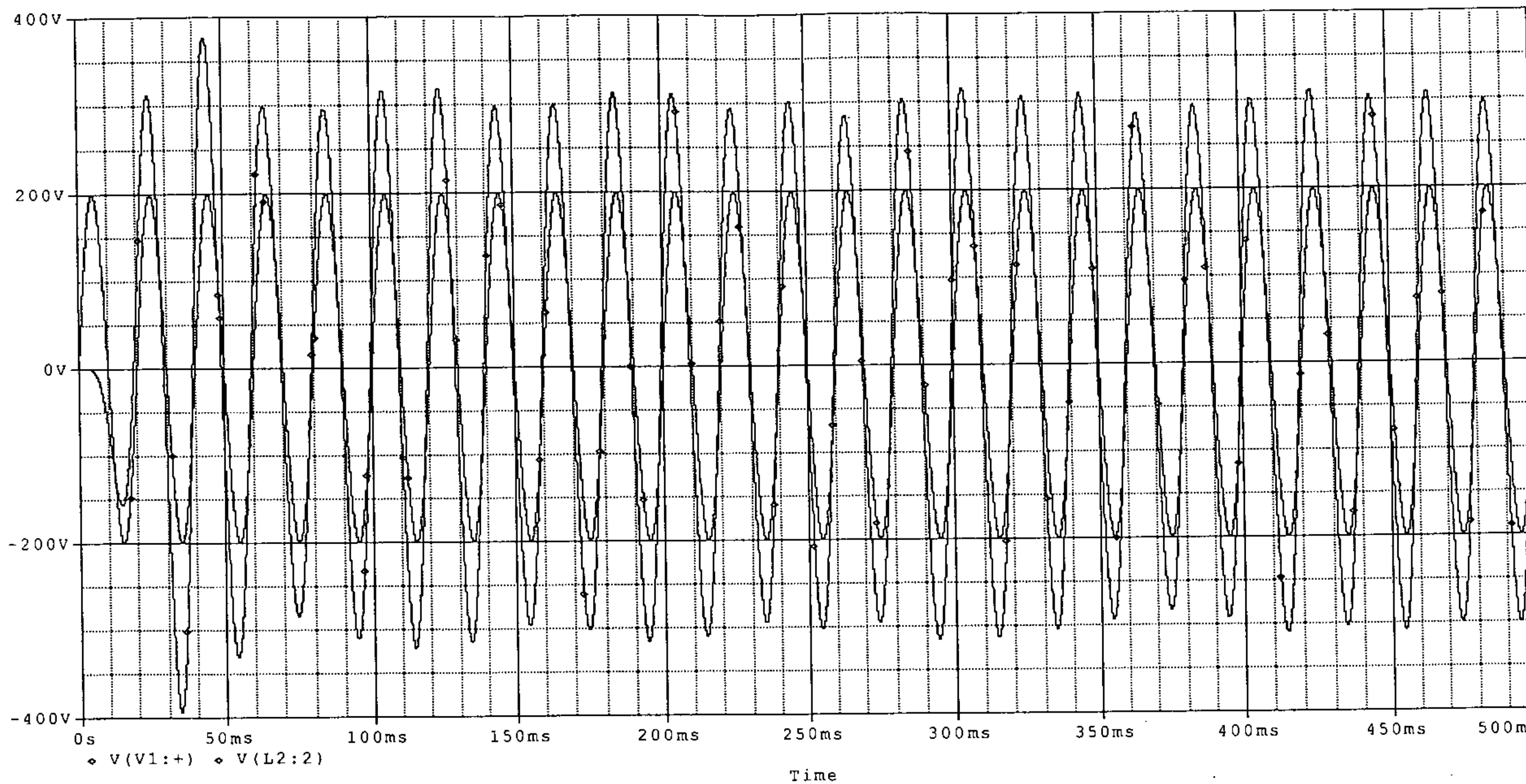


Figure-25. Input output voltage waveform when input voltage 200V,load=200ohm (V_3=2.7volt).
V(V1:+)--Input voltage=200V.
V(L2:2)--Output voltage=300V.

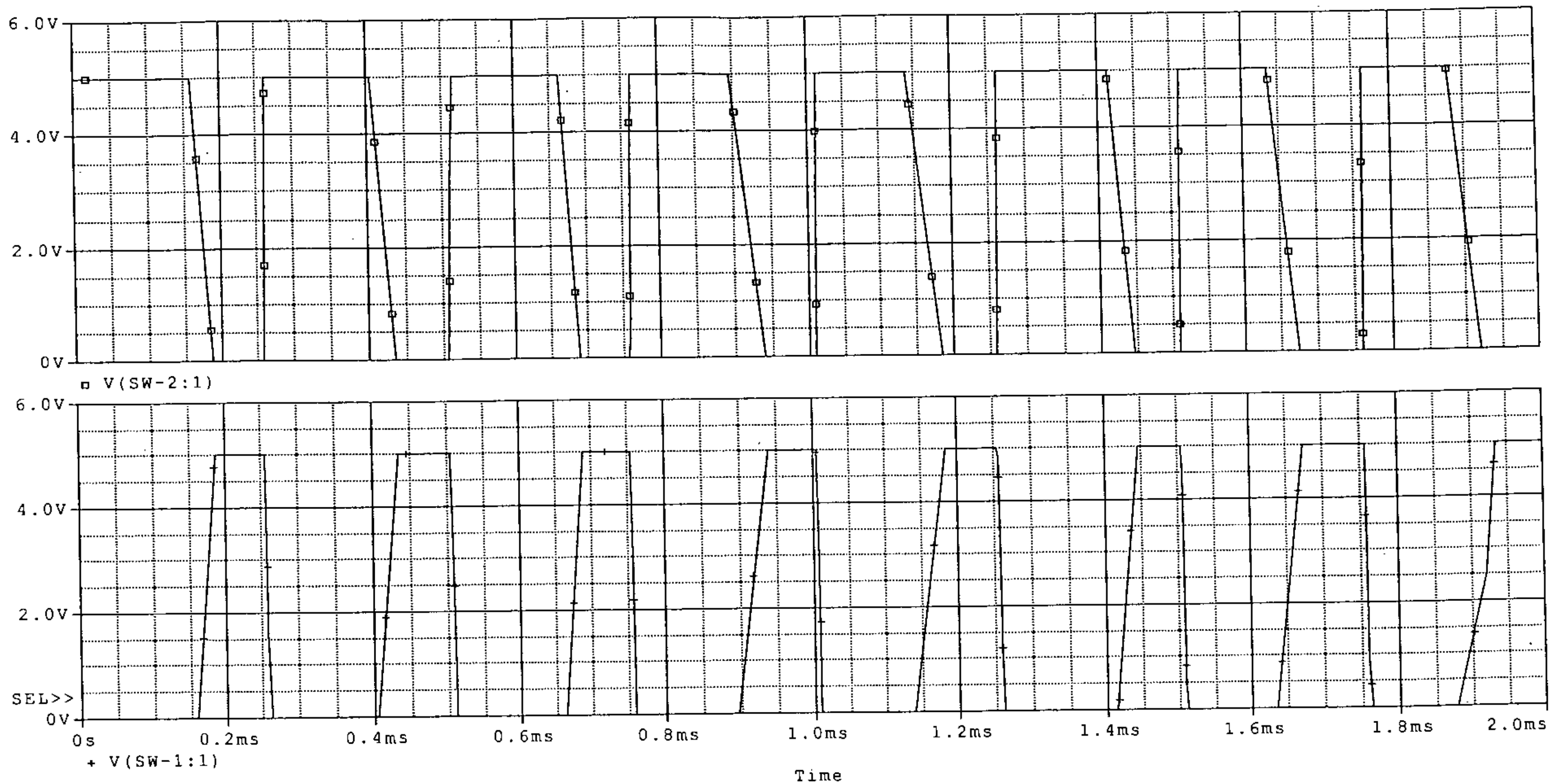


Figure-26. Switching pulses, when input voltage 200V,load=200ohm (V_3=2.7volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

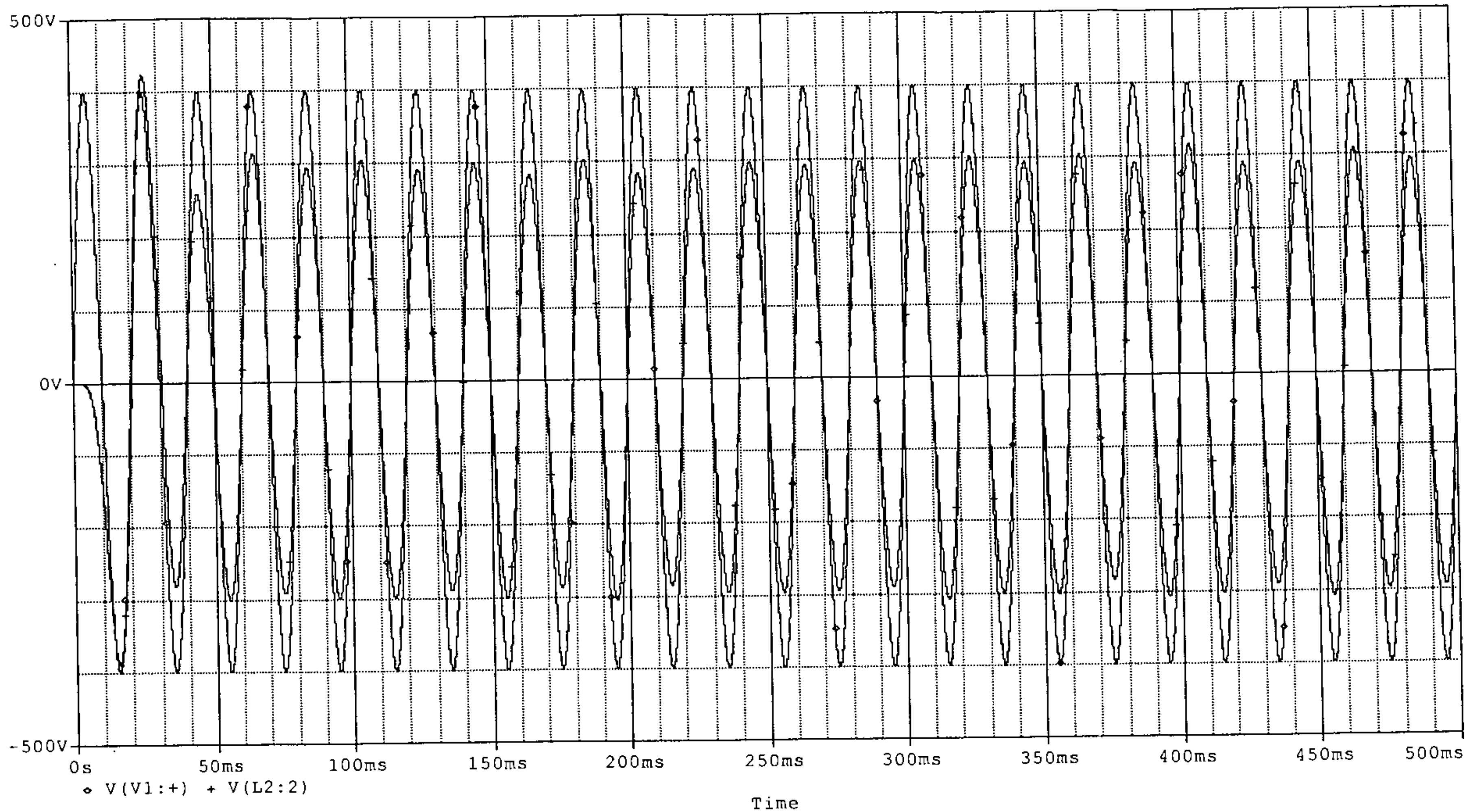


Figure-27. Input output voltage waveform when input voltage 400V,Load=100ohm (V_3=4.3volt).
V(R01:1)--Input voltage=400V.
V(L2:2)--Output voltage=300V.

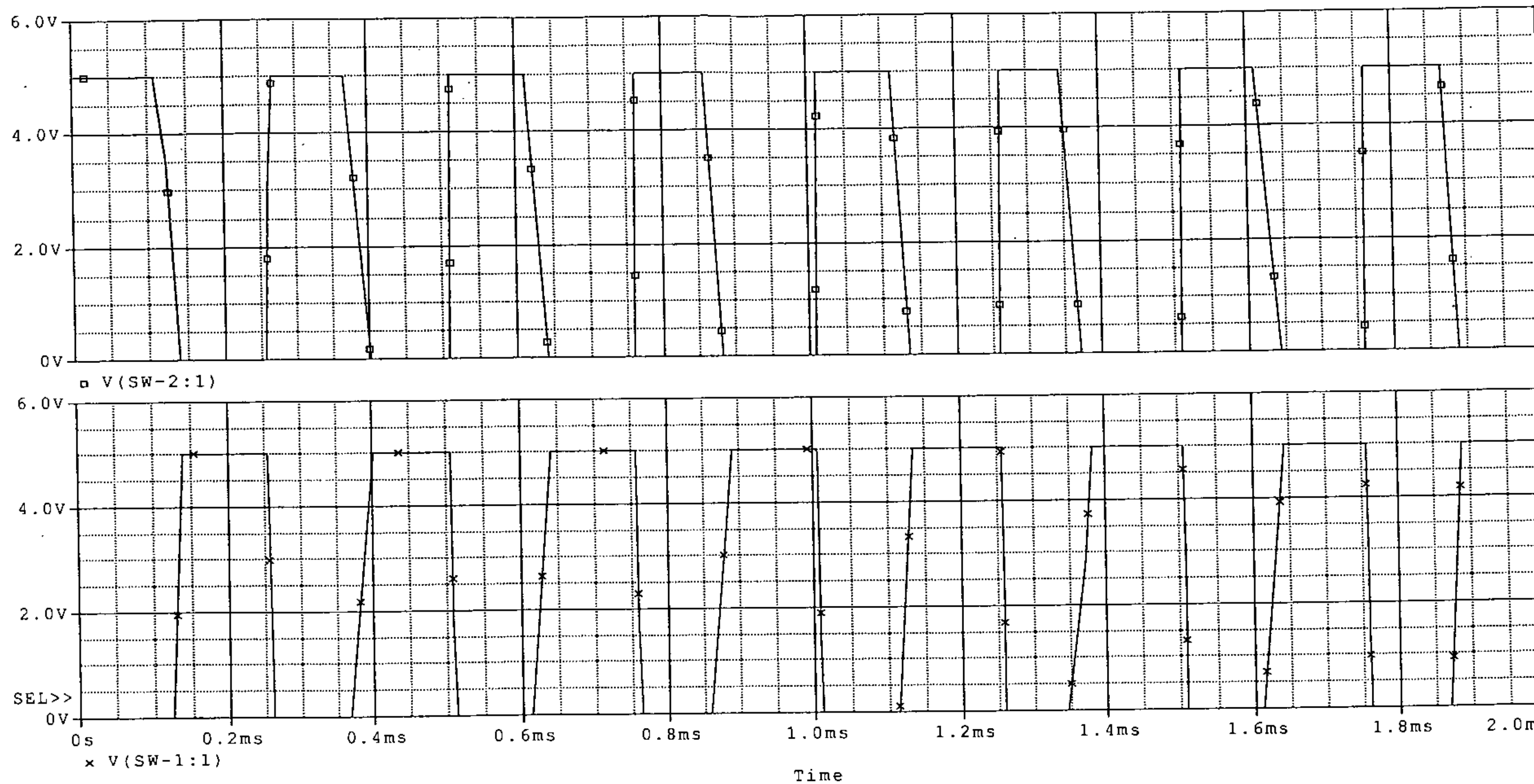


Figure-28. Switching pulses, when input voltage 400V,load=100ohm (V_3=4.3volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

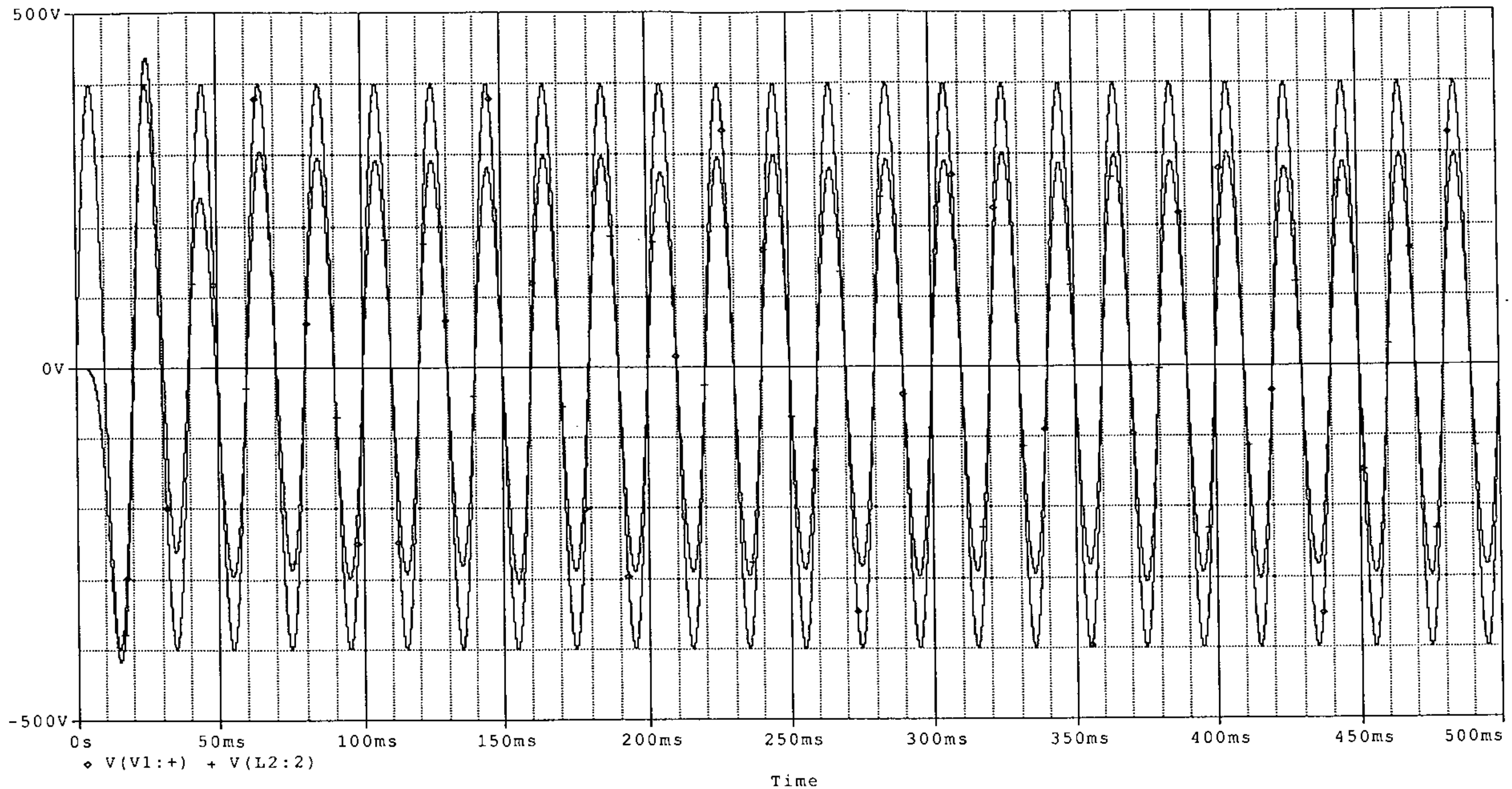


Figure-29. Input output voltage waveform when input voltage 400V,load=200ohm (V_3=4.4volt).
V(V1:+)--Input voltage=400V.
V(L2:2)--Output voltage=300V.

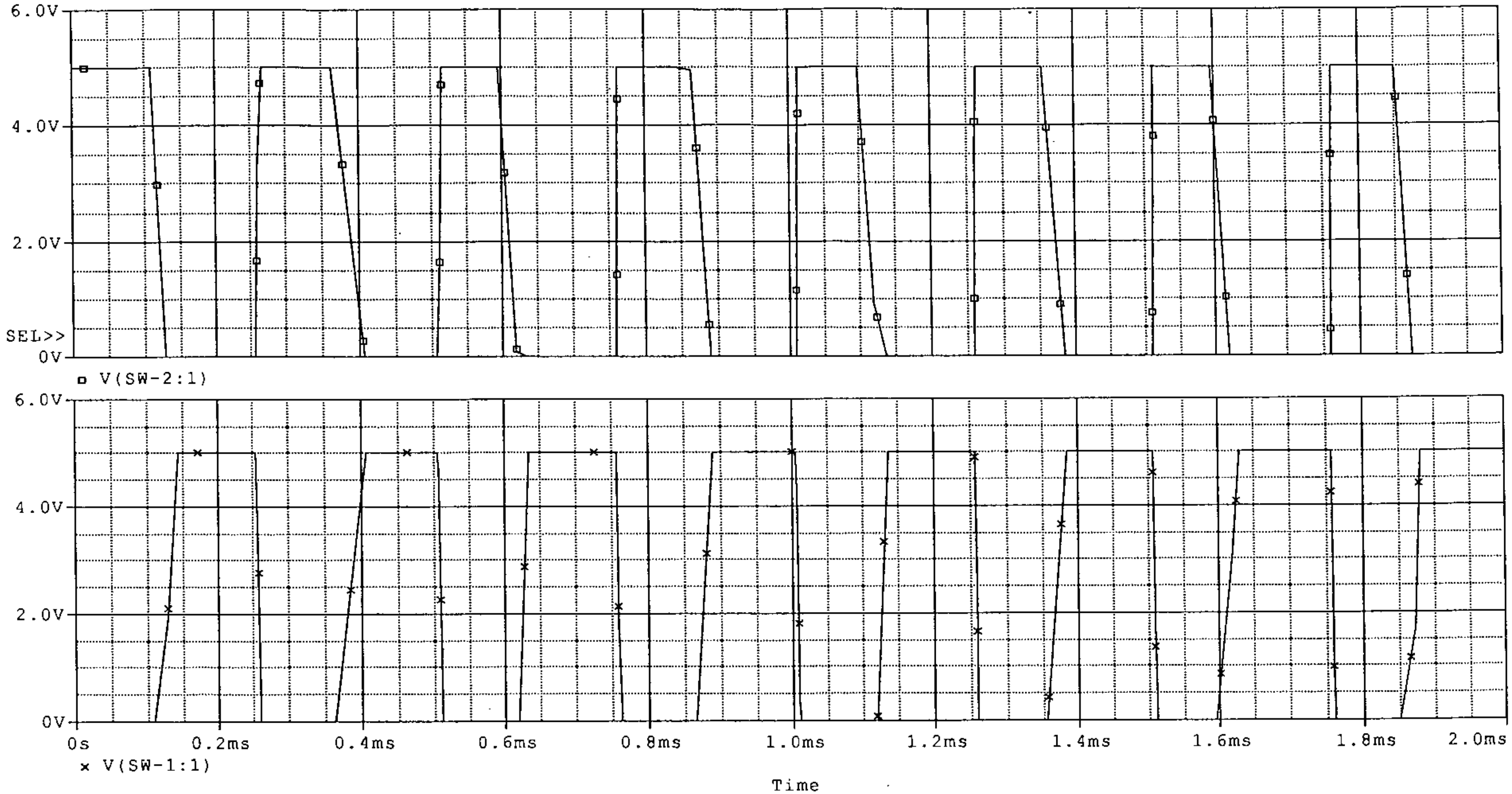


Figure-30. Switching pulses, when input voltage 400V,load=200ohm (V_3=4.4volt).
V(sw-1:1)--Switching voltage of switch-1.
V(sw-2:1)--Switching voltage of switch-2.

Figure-31. Input output voltage waveform when input voltage 250V, load=30ohm (V_3=2.8volt).
V(R01:1)--Input voltage=250V.
V(L2:2)--Output voltage=300V.

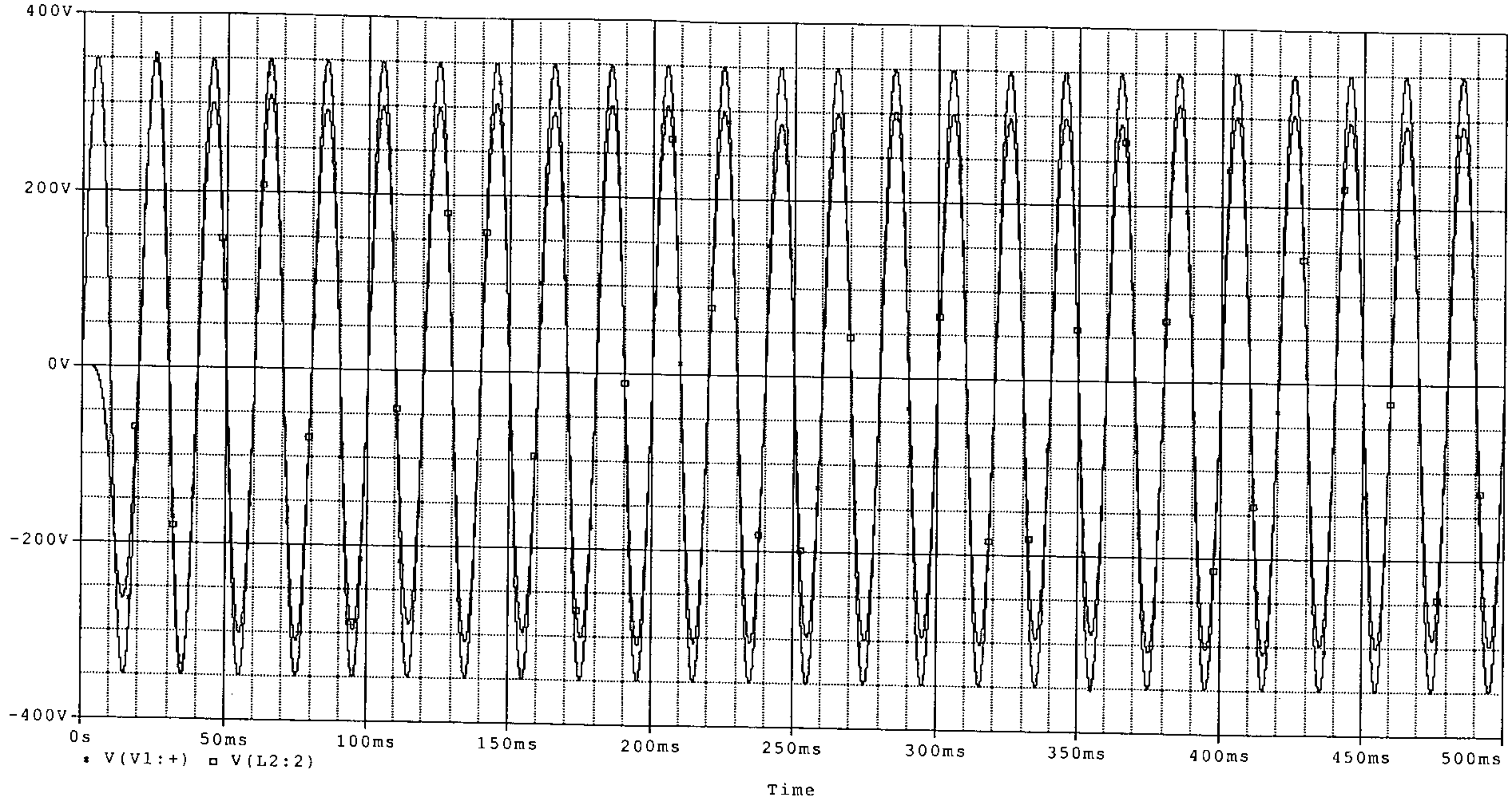


Figure-32. Input output voltage waveform when input voltage 350V,load=30ohm (V_3=3.7volt).
V(V1:+)--Input voltage=350V.
V(L2:2)--Output voltage=300V.

2.1.3 AUXILLIARY COMPONENTS

In addition to the basic C^uk regulator circuit with switching elements much needed topologies and circuits of 'Free wheeling path' and 'Output filter circuits' for smooth functioning of the regulator, are given below.

2.1.3.1 FREE WHEELING PATH AND SURGE VOLTAGES ACROSS SWITCHING DEVICE

Current does not change in an inductance circuit instantaneously. When inductive circuits are switched On and Off, abrupt change of current causes high $\frac{di}{dt}$ resulting high voltages. These voltages appear across the switches as surge. Usually providing freewheeling path made of diodes in power circuits restricts such occurrence.

Surge Voltage:

In the proposed circuit the two switches serve as the freewheeling path for each other. However, for very short period when one switch is turned Off and other is turned On, an interval elapses due to delay in the switching time. As a result, freewheeling during this interval is disrupted in the proposed circuit. If the current in any circuit is abruptly disrupted, a high $L\frac{di}{dt}$ across the switch appears due to absence of freewheeling path. High spiky surge voltage appears across the switches during these short intervals as shown in fig-34 for switch-1 and switch-2 of C^uk AC regulator. These spiky voltages across the switches may be excessively high, about thousand of kilovolt and which may destroy the switches during operation of the circuit. Remedial measures should be taken to prevent this phenomenon to make the circuit commercially viable. In this thesis, as shown in fig-12, R-C snubbers are used for suppressing surge voltages across the switches. Typical waveforms across switches with snubber circuits are shown in fig-35 and fig-36. However, in practical circuit with IGBT switches this problem does not exist which may not be so always. Use of snubber reduces the spike voltage across the switches to a tolerable limit for practical application of the C^uk regulator. A C^uk regulator circuit without any surge suppressor device is shown in fig- 33 and the voltage across the switches are shown in fig-34.

2.1.3.2 OUTPUT FILTER REQUIRMENT

For getting smooth output voltage, a capacitor C2 with proper size is to be introduced in parallel with the output load, without capacitor C2 the shape of the output voltage is shown in fig-37.

DESIGN OF OUTPUT FILTER CIRCUITS

From chapter-1, fig-8 (DC to DC C^uk regulator circuits) and eqs-(1.21) and (1.23), we get,

$$t_1 + t_2 = \frac{\Delta I_1 L_1}{V_s} - \frac{\Delta I_1 L_1}{V_s - V_{c1}} = \frac{-\Delta I_1 L_1 V_{c1}}{V_s(V_s - V_{c1})} \qquad (2.1)$$

or

$$t_1 + t_2 = T = \frac{1}{f} = \frac{-\Delta I_1 L_1 V_{c1}}{V_s(V_s - V_{c1})} \qquad (2.2)$$

$$\Delta I_1 = \frac{-V_s(V_s - V_{c1})}{f L_1 V_{c1}} \tag{2.3}$$

putting the value of V_{c1} from eqs-(1.25 as) $V_{c1} = V_s/1\text{-}K$

$$\Delta I_1 = \frac{V_s K}{f L_1} \tag{2.4}$$

The switching period can also be found from eqs-(1.27) and (1.29)

$$T = \frac{1}{f} = t_1 + t_2 = \frac{\Delta I_2 L_2}{V_{c1} + V_a} - \frac{\Delta I_2 L_2}{V_a} = \frac{\Delta I_2 L_2 V_{c1}}{V_a(V_{c1} + V_a)} \tag{2.5}$$

And this gives the peak to peak ripple current of inductor L_2 as

$$\Delta I_2 = \frac{-V_a(V_{c1} + V_a)}{f L_2} \tag{2.6}$$

By applying eqs-(1.31) as $V_{c1} = V_a/K$ and eqs-(1.32) as $V_a = -KV_s/(1\text{-}K)$

$$\Delta I_2 = \frac{KV_s}{f L_2} \tag{2.7}$$

When transistor Q2 is Off , the energy transfer capacitor C1 is charged by the input current for time $t = t_2$. The average charging current for C1 is $I_{c1} = I_s$ and the peak to peak ripple voltage of the capacitor is

$$\Delta V_{C1} = \frac{1}{C1}\int_0^{t_2} I_{C1}\,dt = \frac{1}{C1}\int_0^{t_2} I_s\,dt$$

$$= \frac{I_s t_2}{C_1} \tag{2.8}$$

We know $t_2 = (1-K)T$ and from eqs-(1.32) as $V_a = -KV_s/(1-K)$ we can proved that $t_2 = V_s/(V_s-V_a)f$ so,

$$\Delta V_{c1} = \frac{I_s V_s}{(V_s - V_a) f C_1} \tag{2.9}$$

putting the value of $V_a = -KV_s/(1-K)$ we get,

$$\Delta V_{c1} = \frac{I_s(1-K)}{f C_1} \tag{2.10}$$

If we assume that the load current ripple $\Delta i_0 = \Delta i_{c2}$. The average charging current of C2, which flows for time T/2 is $I_{c2} = \Delta I_2/4$ and the peak to peak ripple voltage of capacitor C2 is ,

$$\Delta V_{c2} = \frac{1}{C_2}\int_0^{T/2} I_{c2}\, dt = \frac{1}{C_2}\int_0^{T/2} \Delta I_2/4\, dt$$

$$= \frac{\Delta I_2}{8fC_2} \tag{2.11}$$

putting the value of ΔI_2 from eqs-(2.7) we get,

$$\Delta V_{c2} = \frac{KV_s}{8C_2L_2f^2} \tag{2.12}$$

$$C_2 = \frac{KV_s}{8\Delta V_{c2}L_2f^2} \tag{2.13}$$

Let us consider duty cycle K=.25, $V_s = 200V$, $L_2 = 40mH$, f=4 KHz, ripple voltage of the capacitor C_2, $\Delta V_{c2} = 0.05$ volt then from eqs-(2.13) we find

$C_2 = 200\mu F$(approx.)

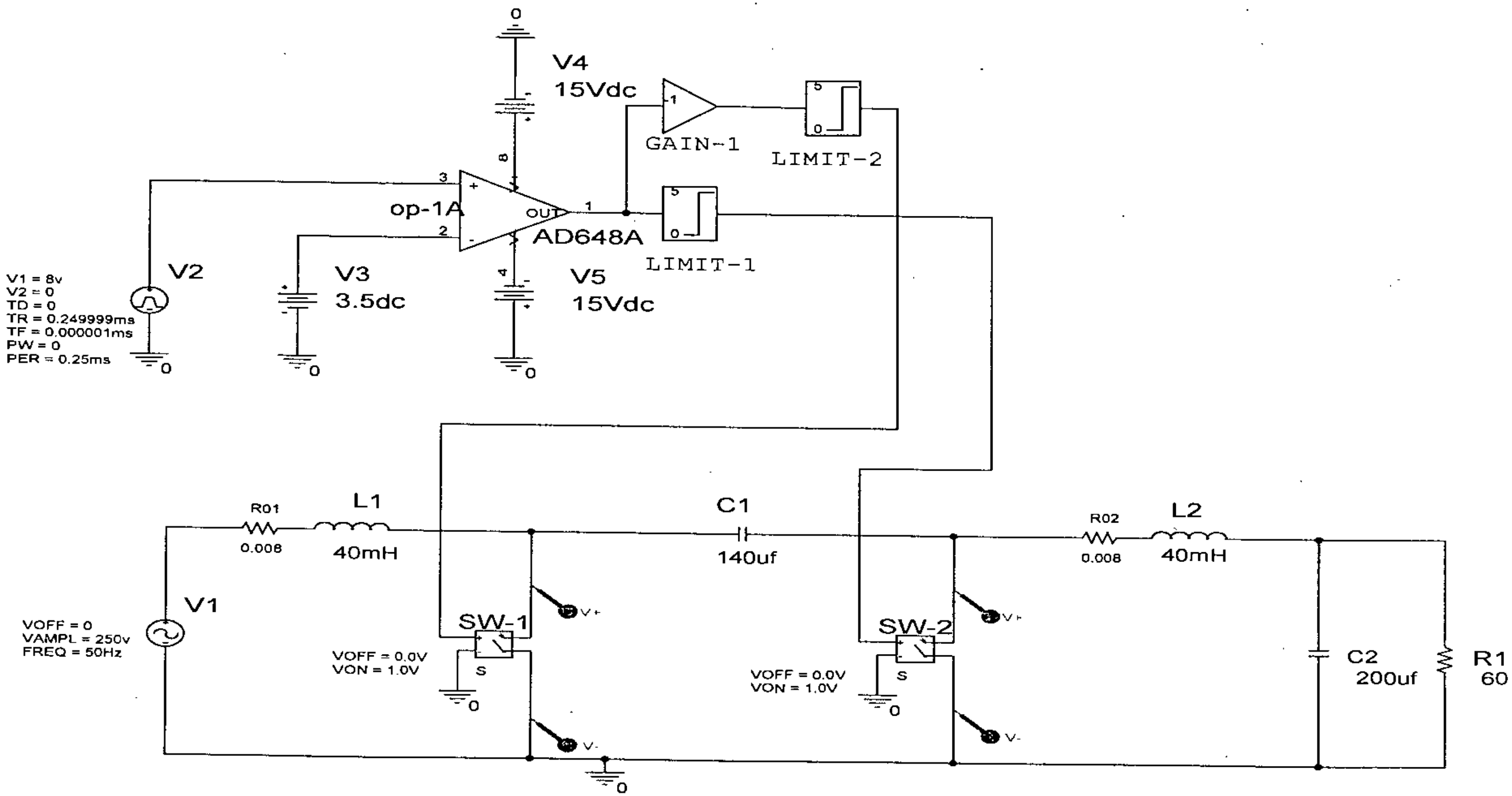


Figure-33. AC C^uk regulator circuit without snubber circuit (free wheeling path) across switches.

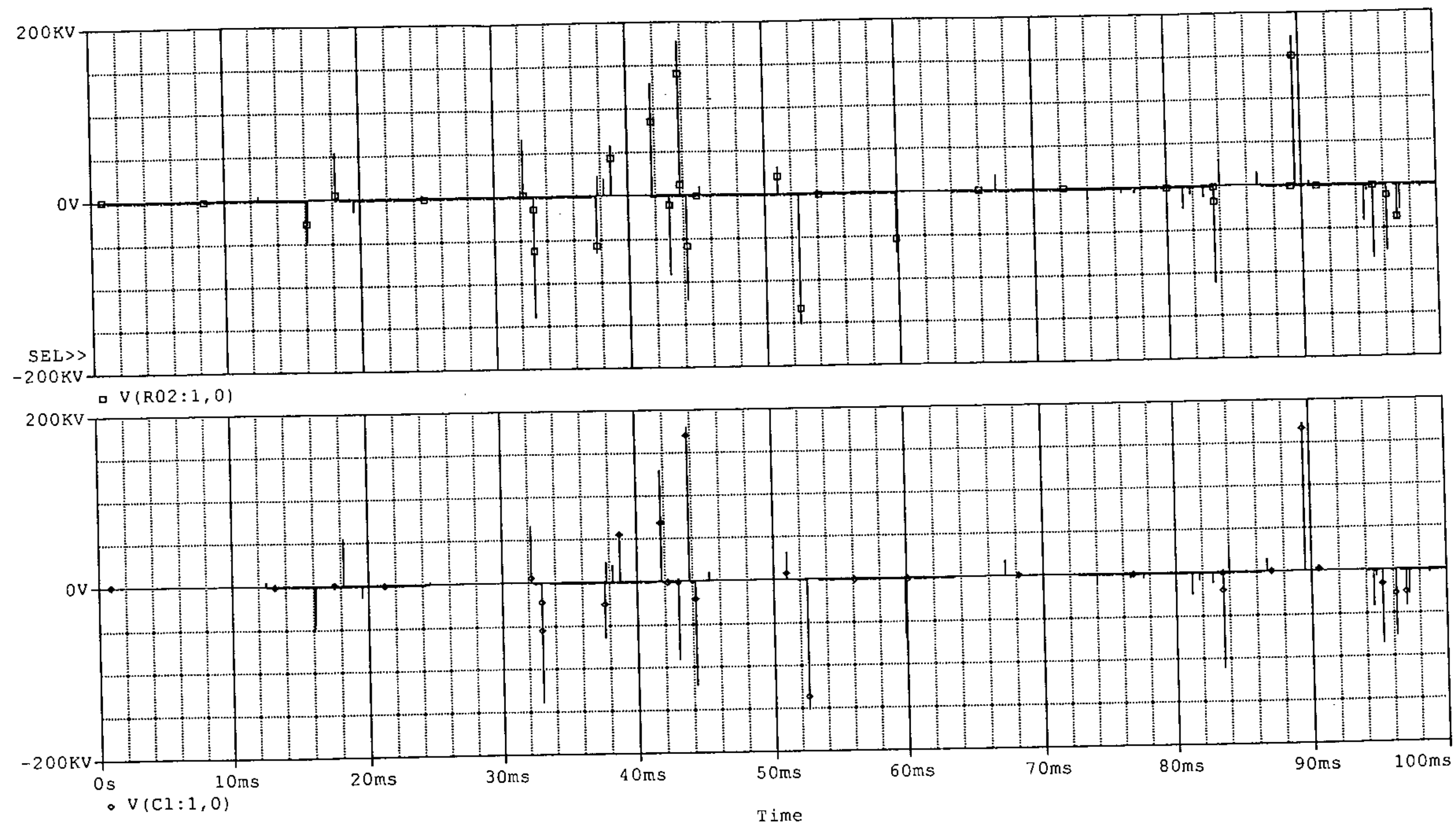


Figure-34. Voltage waveform across switches without snubber circuit.
V(C1:1,0)--voltage across switch-1.
V(R02:1,0)--voltage across switch-2.

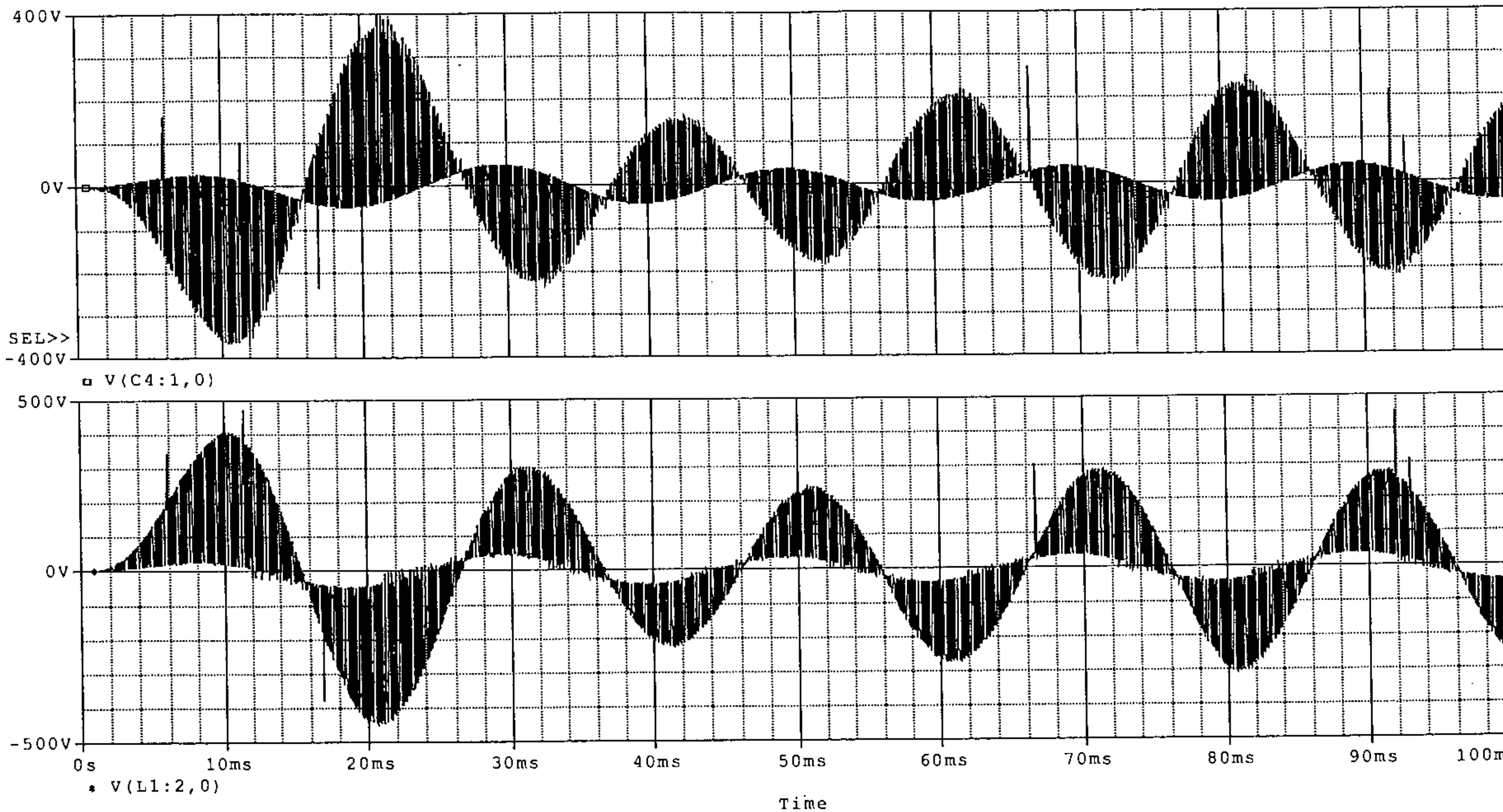


Figure-35. Voltage waveform across switches with snubber circuit.
V(L1:2,0)--voltage across switch-1.
V(C4:1,0)--voltage across switch-2.

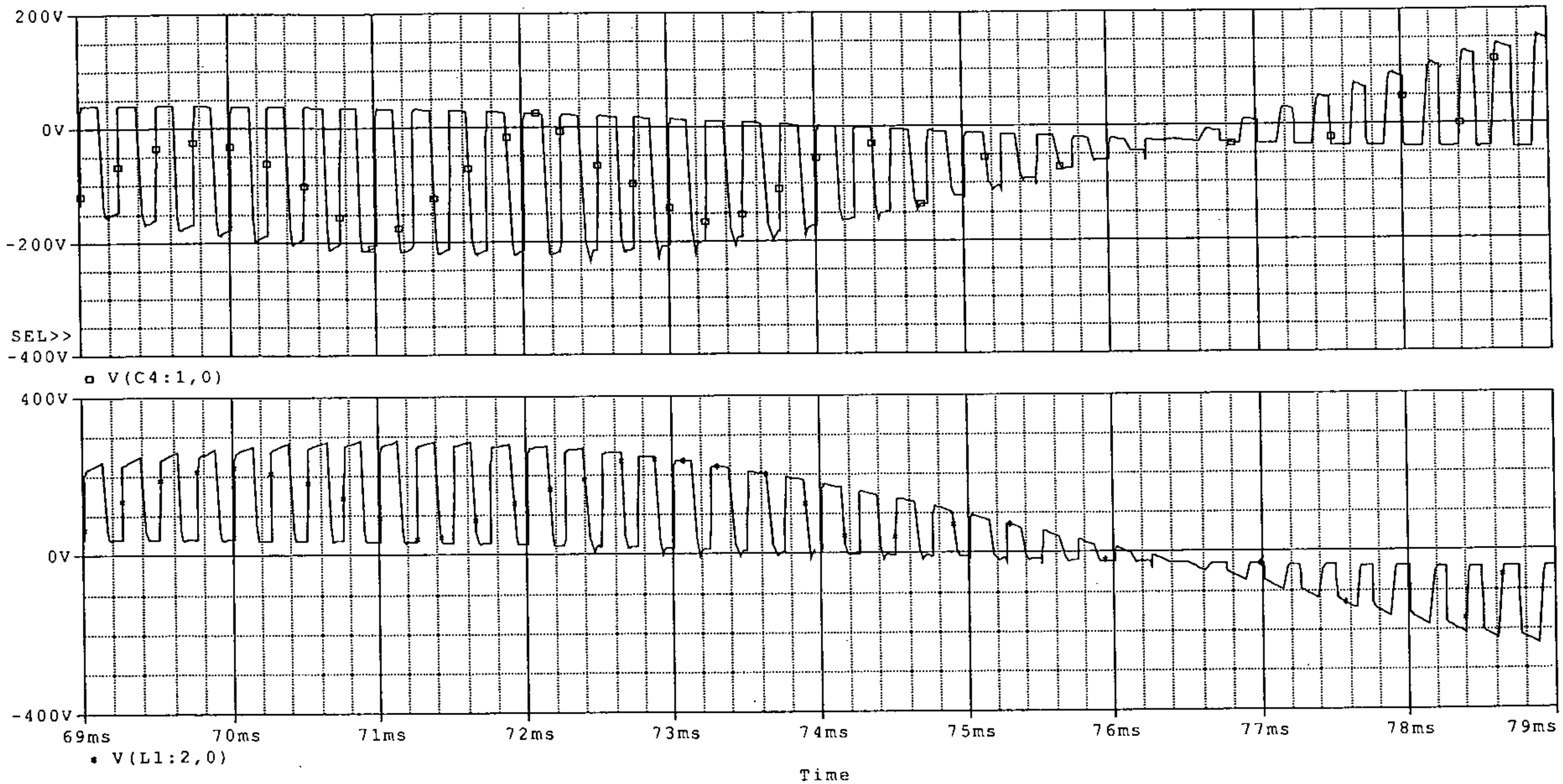


Figure-36. Voltage waveform across switches with snubber circuit.
V(L1:2,0)--voltage across switch-1.
V(C4:1,0)--voltage across switch-2.

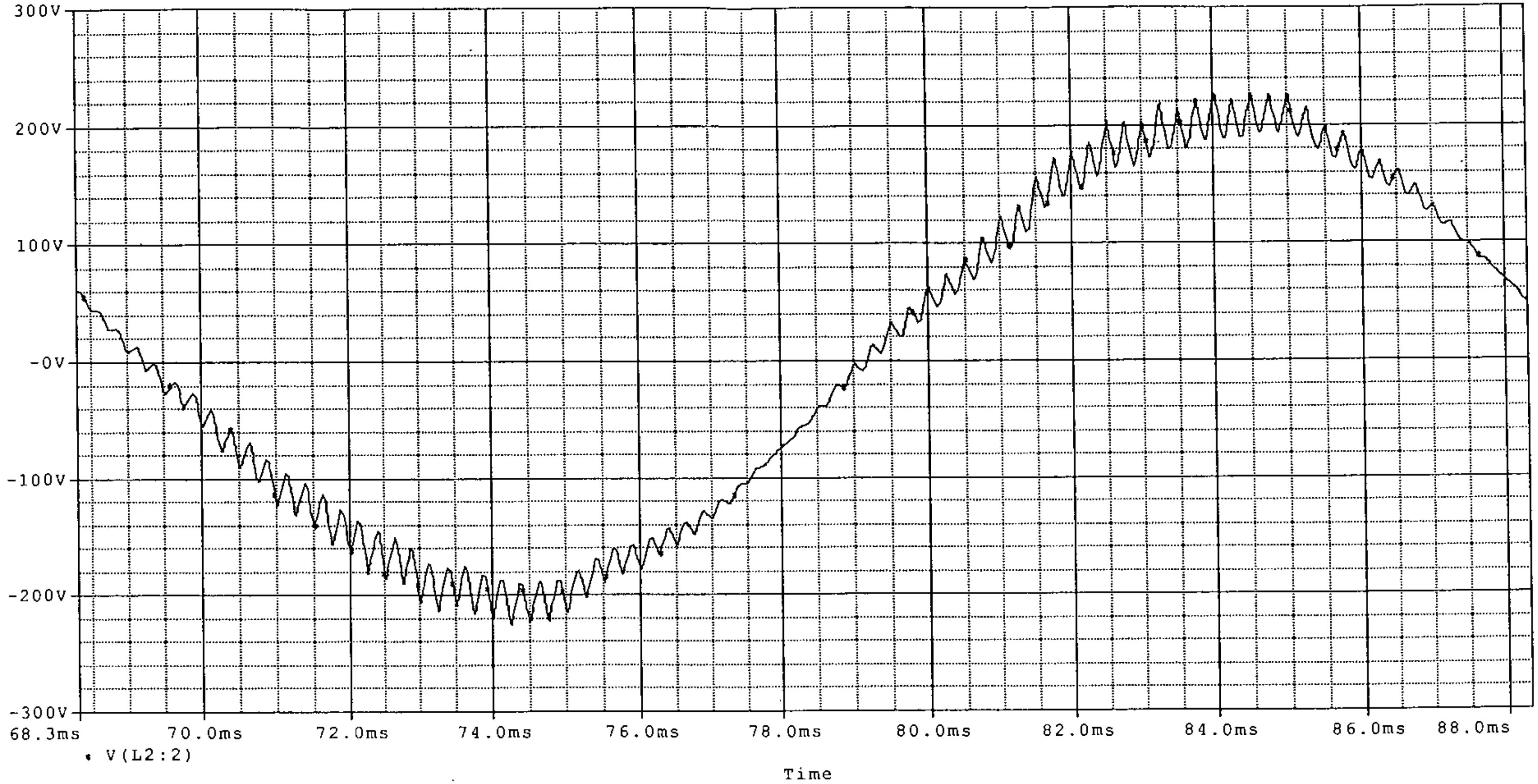


Figure-37. Output voltage waveform without filter circuit.

2.2 AUTOMATIC CONTROLLED AC C^UK REGULATOR (Ideal Switch Implementation)

In precision electronic equipments, computer controlled processing plants, chemical industries voltage regulator with automatic control is preferred. In automatic regulation process voltage can be regulated either in steps (discontinuous), or continuously. In this regulator, there is a sensing element, a signal-processing unit and a power control unit. The output voltage is compared with a fixed reference voltage and the error thus generated is a mplified, integrated or differentiated whenever necessary. The processed error voltage is feed to the main control unit to have required corrective action. Thus the output voltage is maintained constant. Controlled AC C^uk regulator with ideal switch implementation is shown in fig-38. Instead of using different OPAMP circuitry [5], in this thesis one Integrated chip, commercially available in the market (SG1524B) is used to control the duty-cycle and thus regulate the output voltage.

2.2.1 CHIP SG1524B FOR GENERATION OF DUTY-CYCLE

The circuit diagram of the chip SG1524B with necessary circuitry to control output voltage is shown in fig-39. It is a device by which we can generate duty cycle for gate pulse generation of the converter by varying the error voltage of the error amplifier of the chip. Fig-40 shows On and Off time of the 50 percent duty cycle ($K=.5$) as voltage difference of the error amplifier is 0 volt. Fig-41 shows pulse is wider ($K>.5$) than before as voltage difference of the error amplifier is positive 50 micro volt. Fig-42 shows pulse is narrower($K<.5$) than fig-41 as voltage difference of the error amplifier is negative 50 micro volt. In this way range of the error amplifier voltage is maximum up to +100μV to minimum upto -100μV, allows to generate all the range of the duty-cycle. Thus it is a very suitable device for using in the regulator circuits.

2.2.2 GATE SIGNAL GENERATING CIRCUIT

Fig-38(b) shows the automatic control and gate signal generating circuit for AC C^uk voltage regulator by the SG1524B. Output AC voltage of circuit fig-38(a) is converted to pulsating DC by using capacitive voltage transformer and a rectifier circuit. Output of the diode circuit is passed through a buffer amplifier to a voltage divider circuit consisting of two resistor 150k and 1 ohm. Voltage from 1 ohm is taken to the negative of the error amplifier of the chip. Reference 5 volts (which is generated inside the chip, terminal no-16) of chip is also passed through a voltage divider 60k and 1 ohm and voltage is taken from 1 ohm resistor to the positive of the error amplifier of the chip. If positive (terminal-1) and negative (terminal-2) terminal of the error amplifier applied voltage is same then difference of the error amplifier voltage is zero and the On and Off period of the duty-cycle is same (duty-cycle=. 5) then no regulation, output voltage is same to the required voltage (the reference voltage). If the output voltage is less than the reference voltage then difference of the error amplifier is positive then pulse of the duty-cycle will be wider (K>.5). This is shown in fig-44 and fig-45, here input voltage 250V to be regulated to 300V. Similarly when input voltage is 350V corresponding sample voltage will be more than the reference voltage then positive pulse of the duty-cycle will be narrower (K<. 5) then voltage would be regulated downwards, this is shown in fig-50 and fig-51.

2.2.3 RESULTS OF AUTOMATIC CONTROLLED AC C^UK REGULATOR (Ideal switch implementation)

By applying of C^uk regulator with ideal switch implementation, output voltage is regulated to 300V for a wide variation of input voltage down to 250V and up to 350V and also for variation of load. Fig-43 shows output voltage is regulated to 300V when input voltage is 250V and load is 50 ohms. Keeping the input voltage at 250V constant, load is varied to 60 ohm and 70 ohm while output voltage is maintained at 300V as shown in fig-46 and fig-49 respectively. Similarly keeping the input voltage 300 constant while load is varied to 50 ohm, 60 ohm and 90 ohm the output voltage is still maintained at 300V as shown in fig-52, fig-53 and fig-54 respectively. Also keeping the input voltage 350 constant while load is varied to 50 ohm, 60 ohm and 90 ohm the output voltage is still maintained at 300V as shown in fig-55, fig-56 and fig-57 respectively. Thus this regulator is suitable for both way of regulation, either step-up or step-down.

From fig-44, fig-47 and fig-50, we see 'sample voltage' is less than the 'reference voltage' and this is a pre-requisite for this regulator to make duty cycle greater than 0.5 and corresponding duty cycle are shown in fig-45, fig-48 and fig-51 respectively.

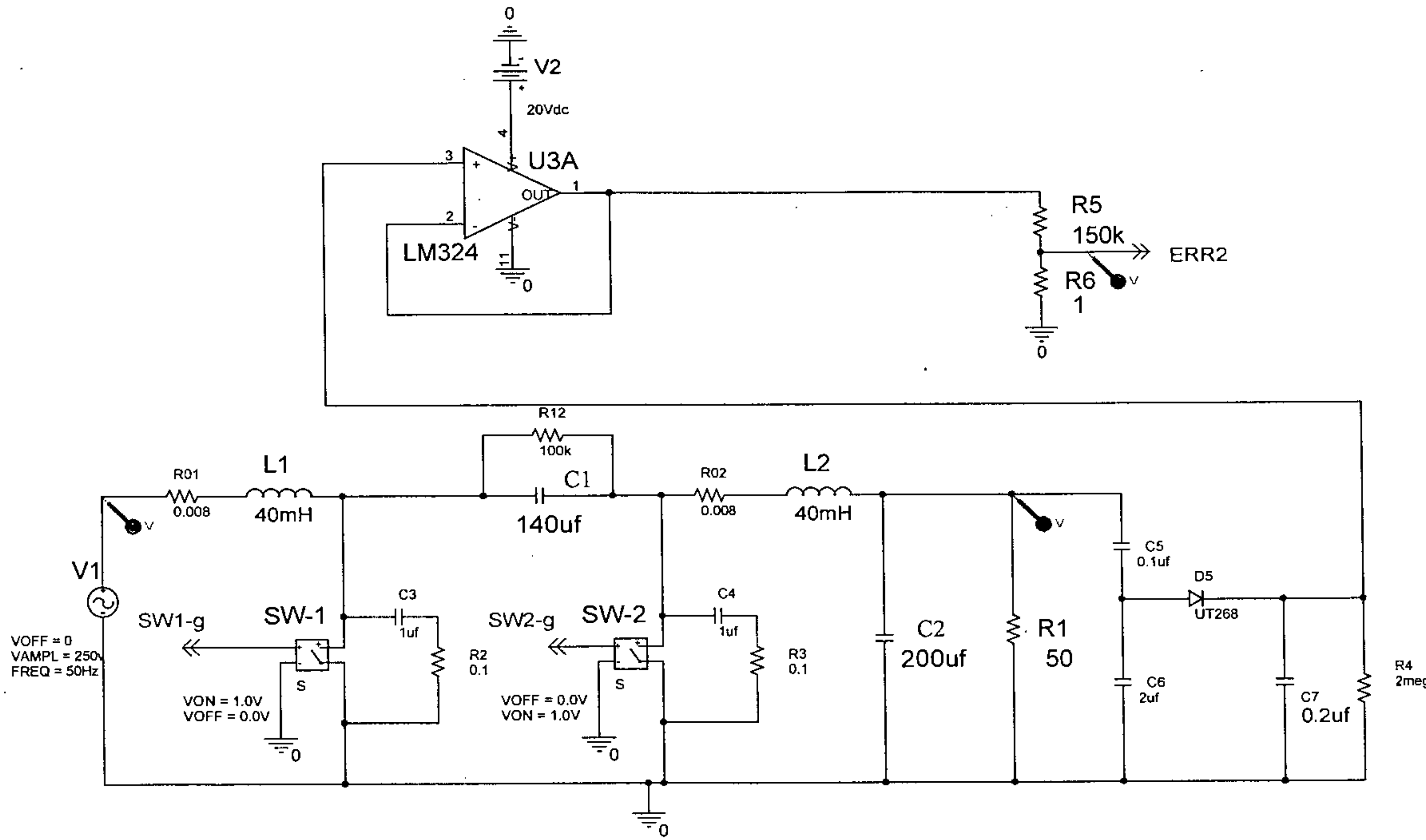


Figure-38(a). Automatic control AC C^uk regulator circuit, ideal switch implementation (page-1).

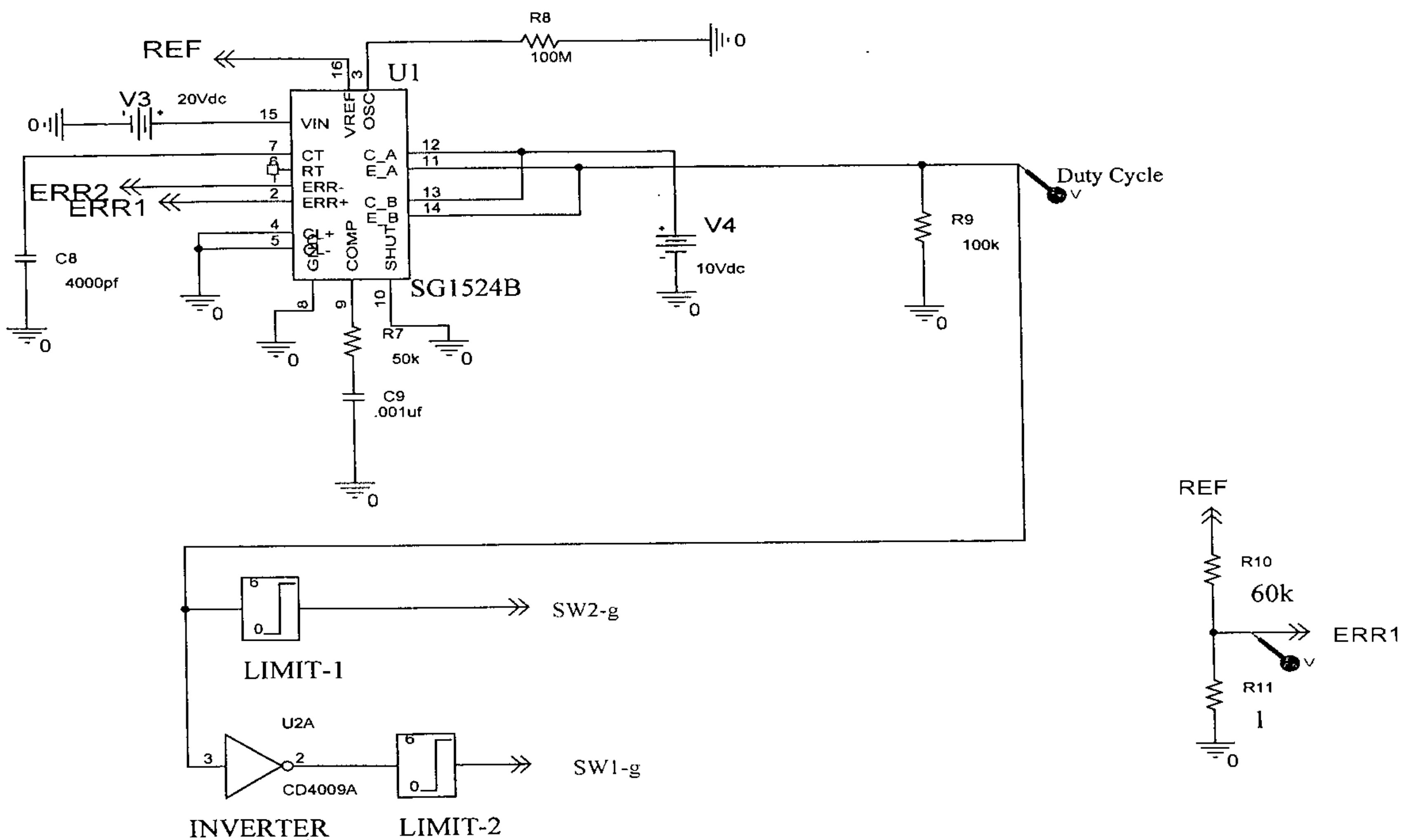


Figure-38(b). Automatic control AC C^uk regulator circuit, ideal switch implementation (page-2).

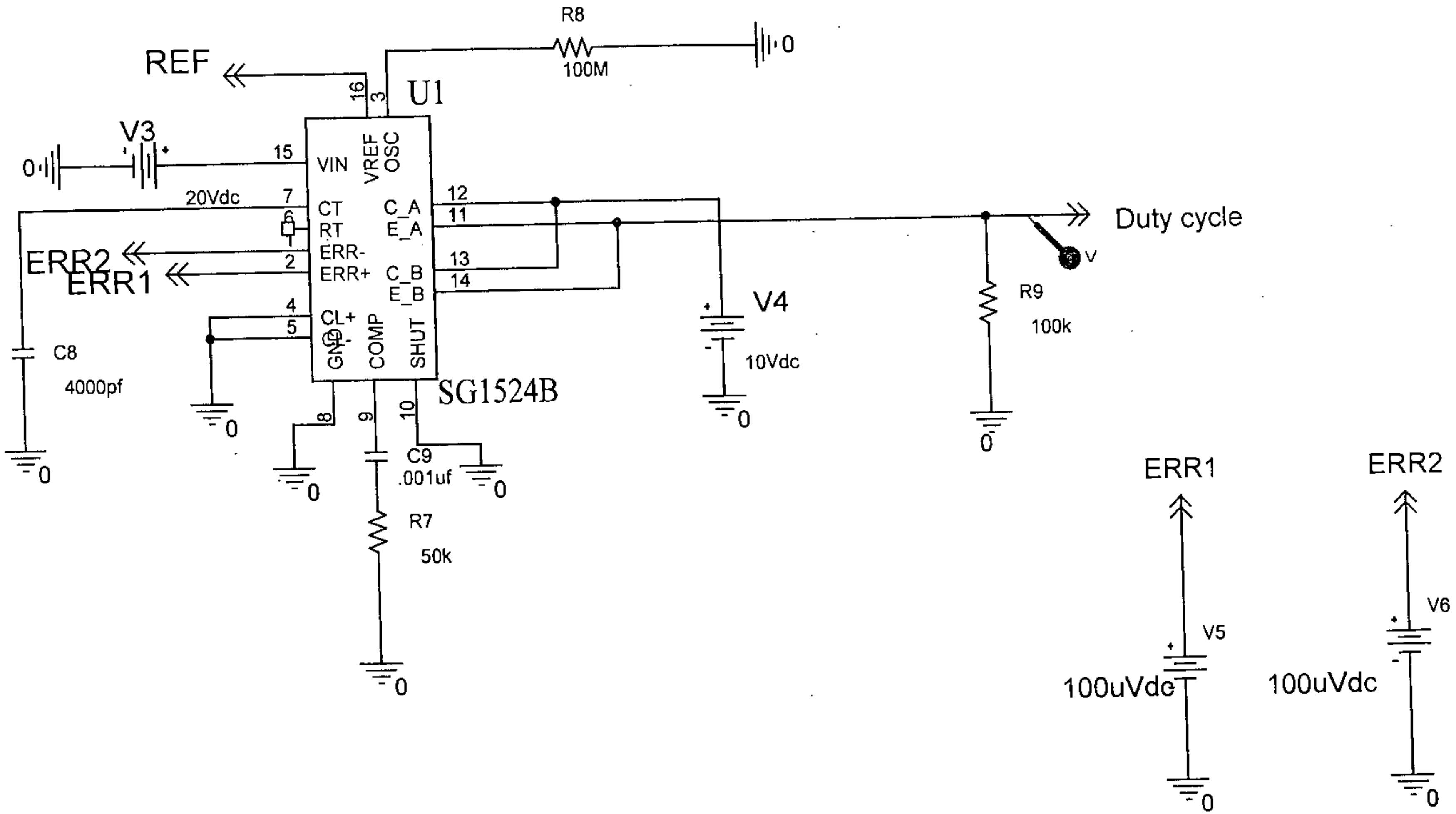


Figure-39. Ic Chip no-SG1524B with circuitry for generation of Duty cycle.

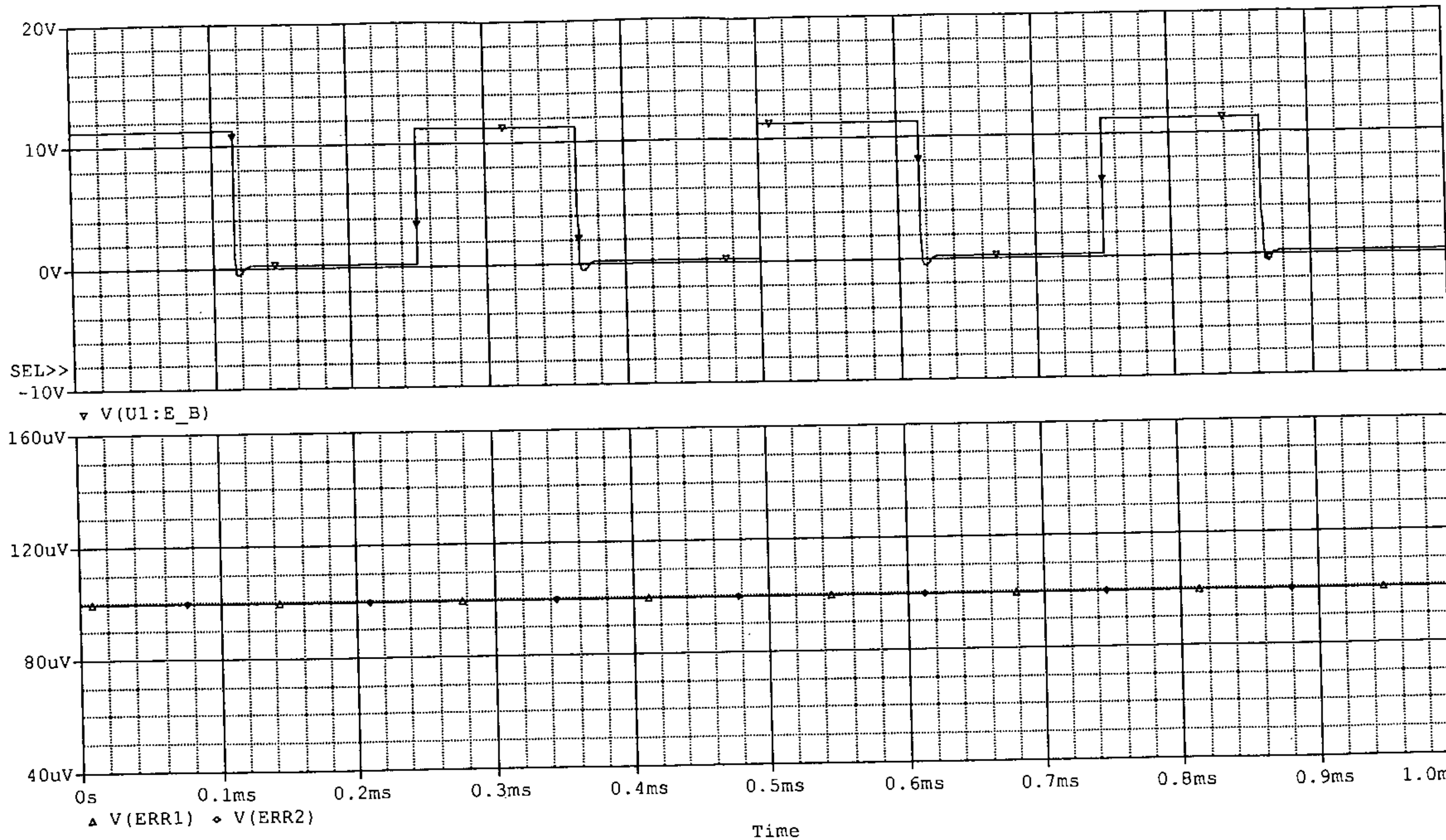


Figure-40. Generation of Duty cycle when difference of error amplifier voltage is 0 volt.
V(ERR1)--Input of the positive terminal of error amplifier of the chip = 100μV.
V(ERR2)--Input of the negative terminal of error amplifier of the chip = 100μV.
V(U1:E.B)--Duty cycle, K = 0.5.

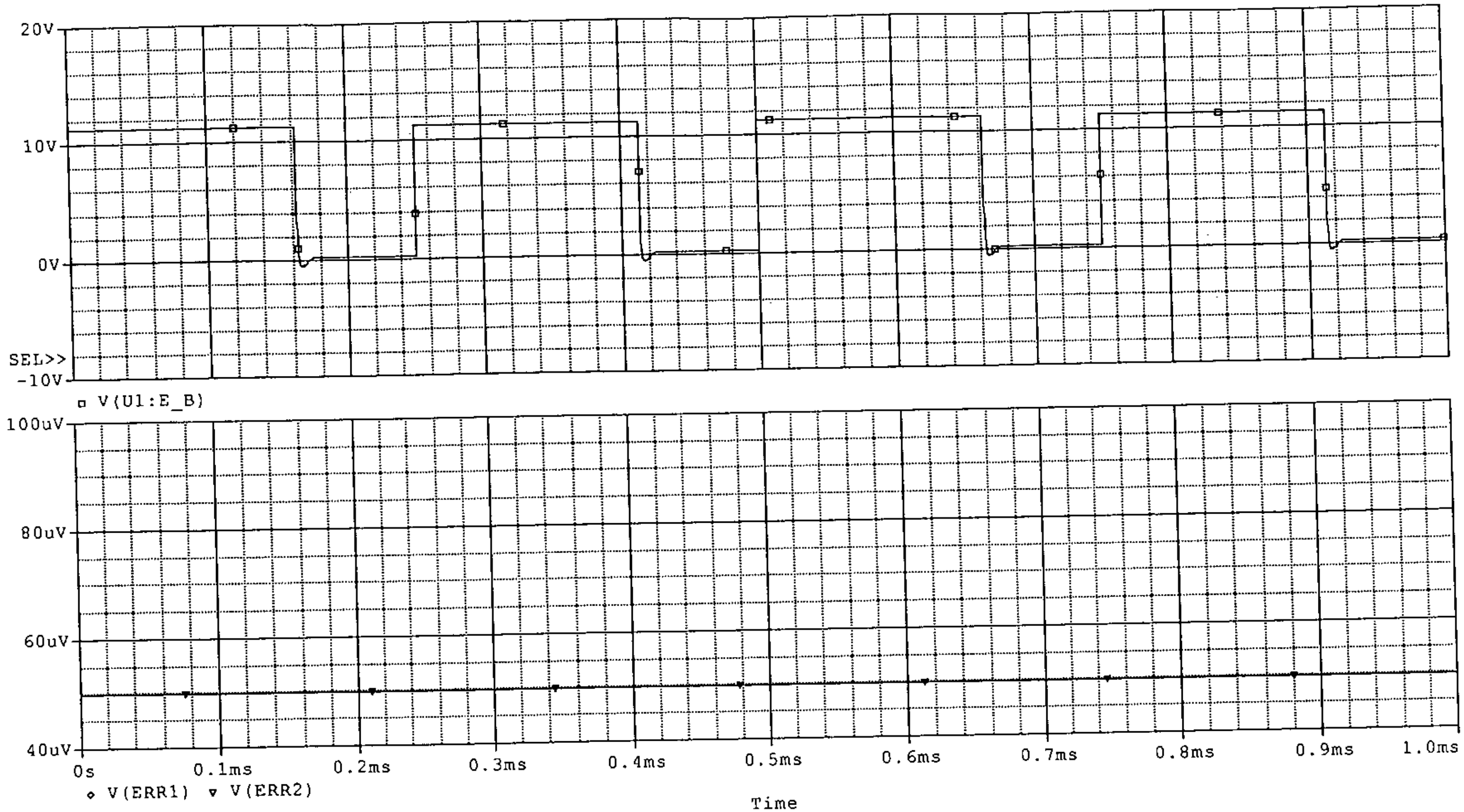


Figure-41. Generation of Duty cycle when difference of error amplifier voltage is +50 micro volt.
V(ERR1)--Input of the positive terminal of error amplifier of the chip = 100μV.
V(ERR2)--Input of the negative terminal of error amplifier of the chip = 50μV.
V(U1:E.B)--Duty cycle, K>0.5.

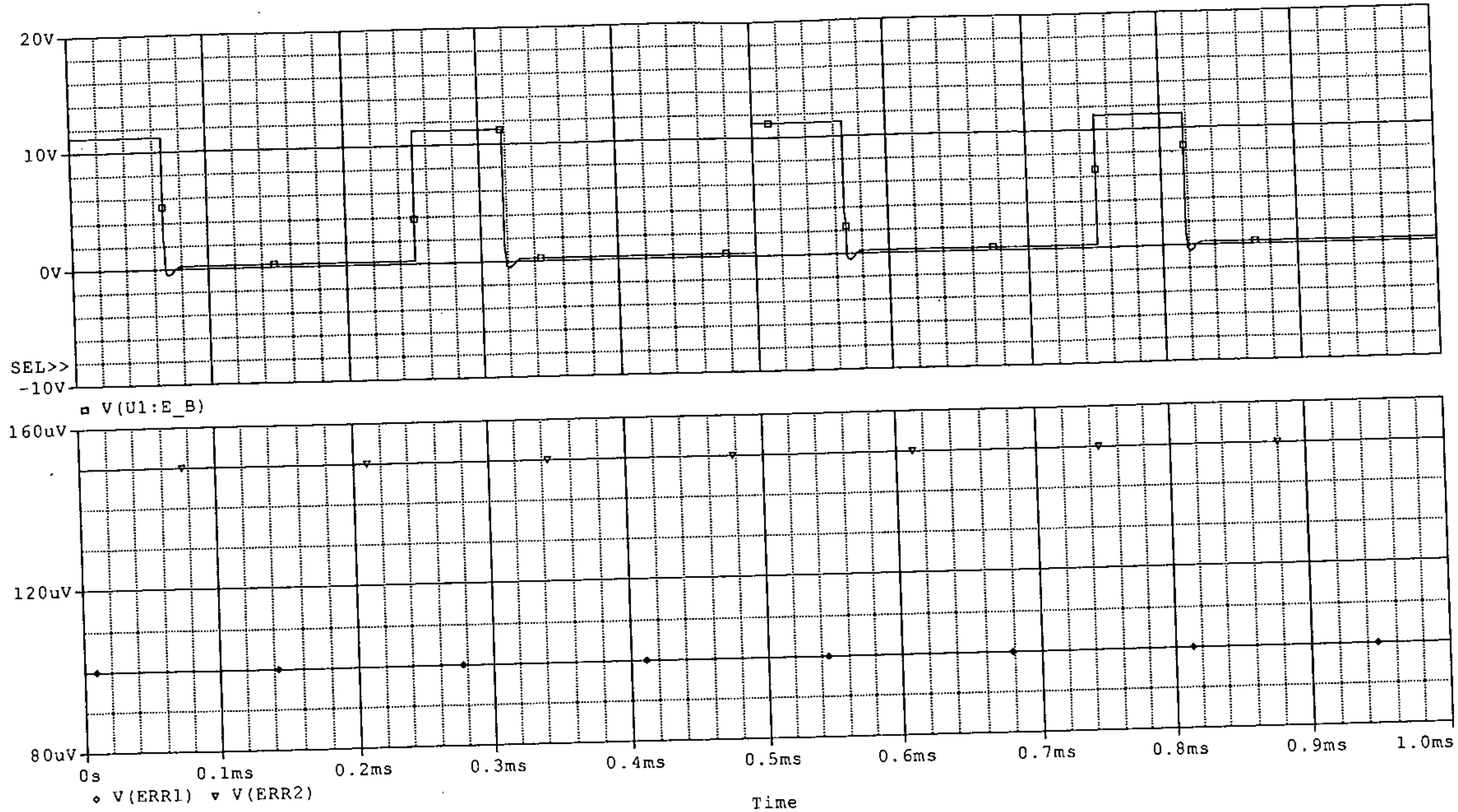


Figure-42. Generation of Duty cycle when difference of error amplifier voltage is –50 micro volt.
V(ERR1)--Input of the positive terminal of error amplifier of the chip=100 µV.
V(ERR2)--Input of the negative terminal of error amplifier of the chip=150 µV.
V(U1:E.B)--Duty cycle, K<0.5.

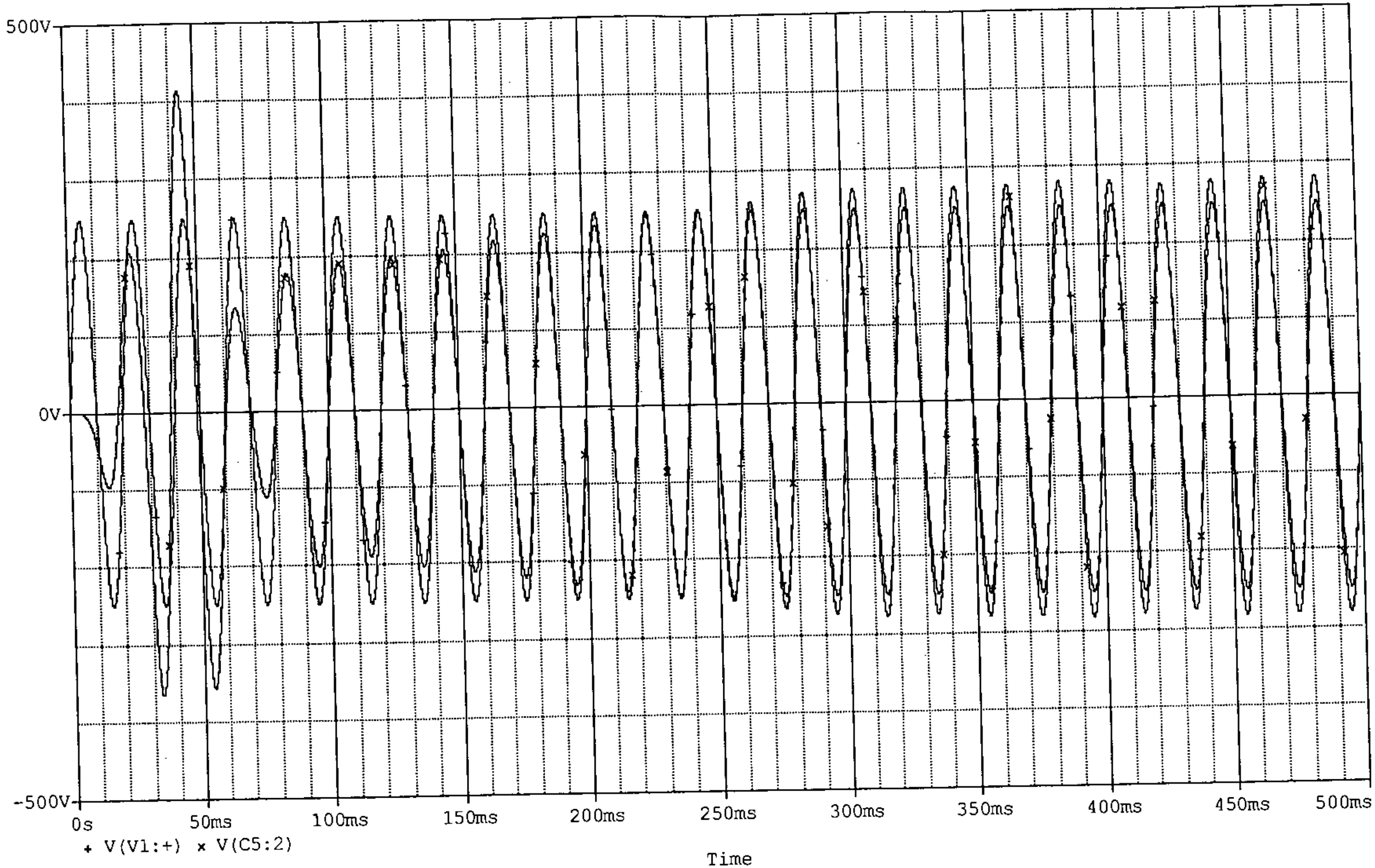


Figure-43. Input/output voltage waveforms when input voltage 250V and load 50 ohm.
V(V1:+)-- Input voltage = 250V.
V(C5:2)--Output voltage = 300V.

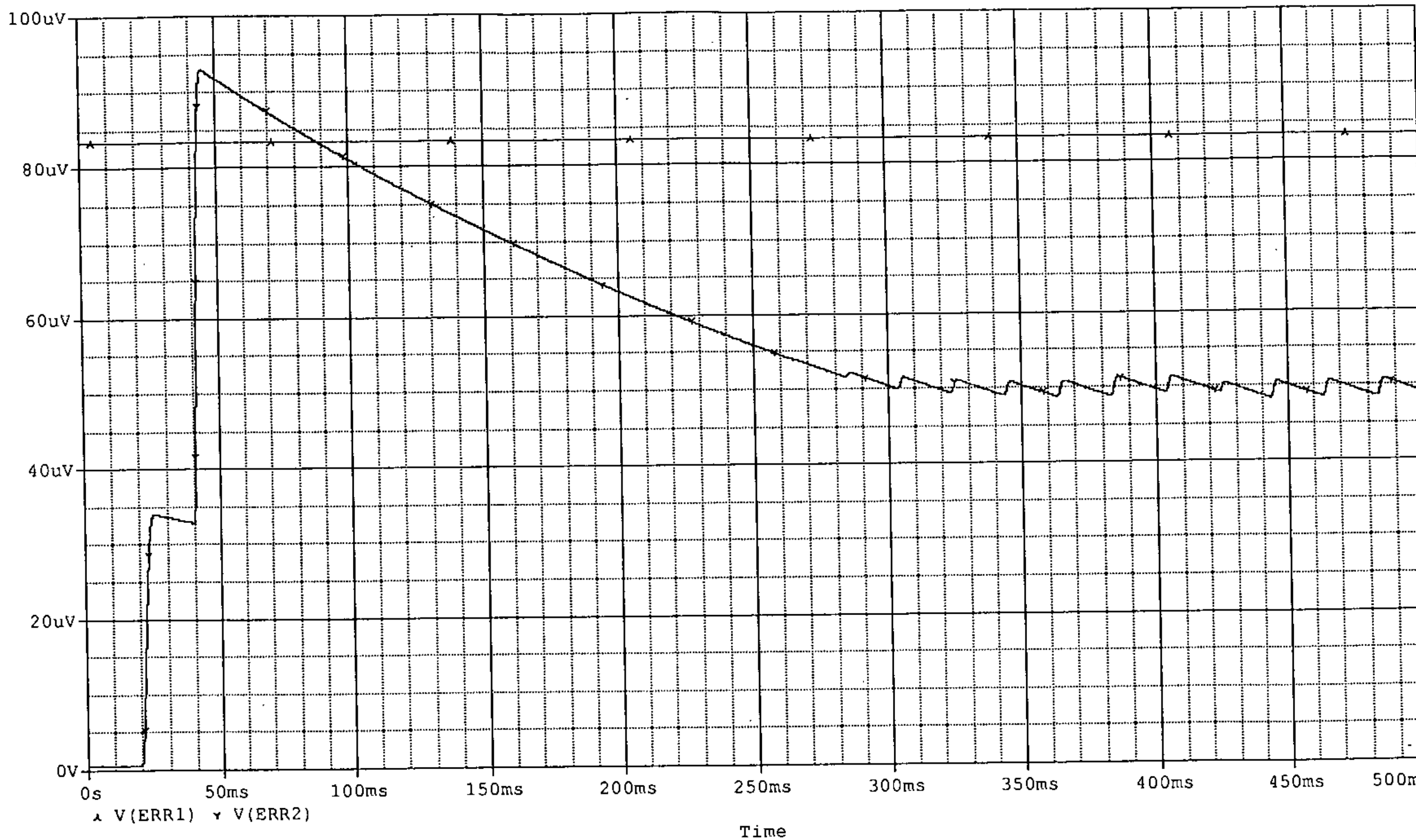


Figure-44. Comparison of sample voltage to the reference voltage, when input voltage 250V and load 50 ohm.
V(ERR1)--Sample of the reference voltage.
V(ERR2)--Sample of the output voltage.

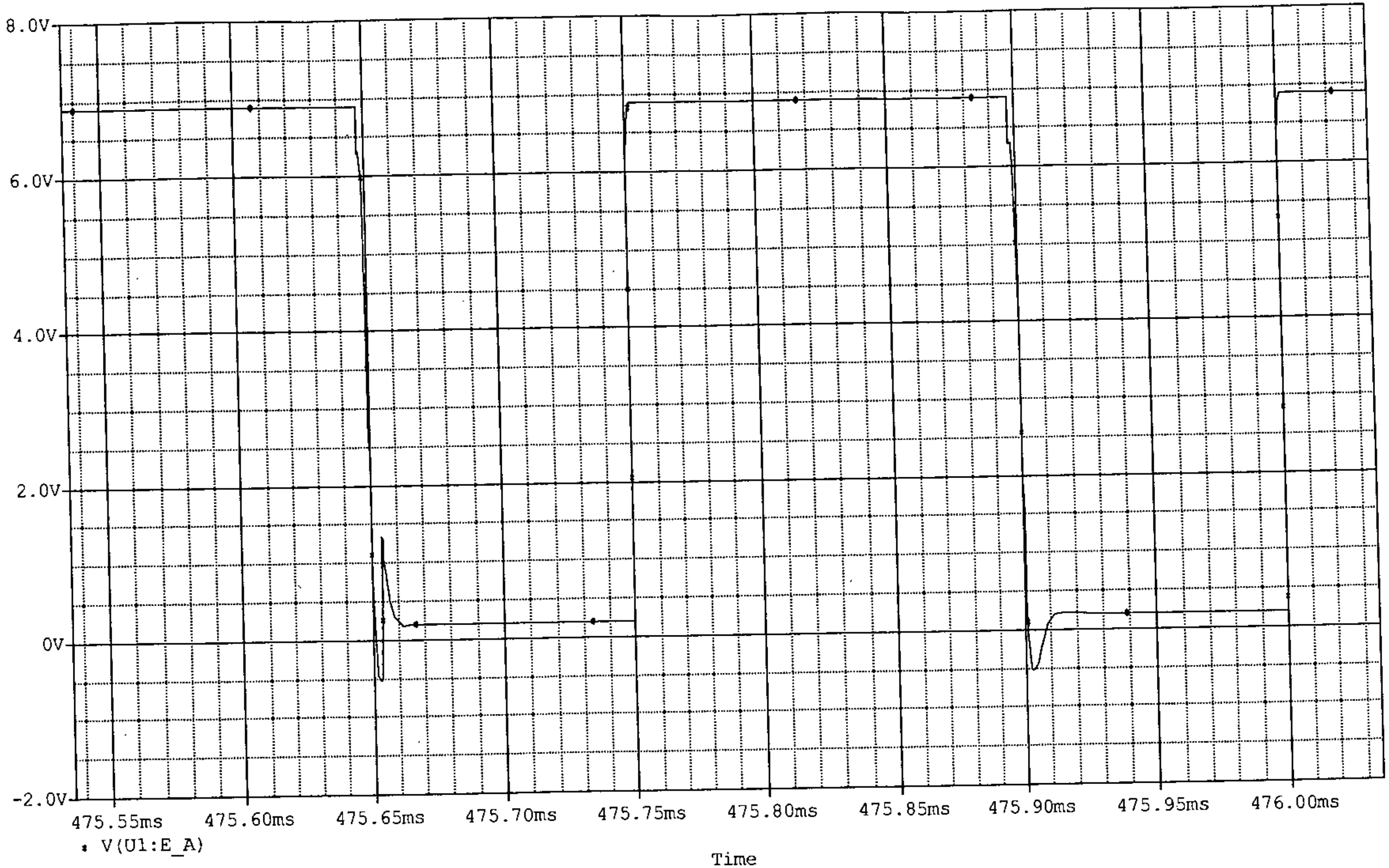


Figure-45. Duty cycle when input voltage 250V, (K>0.5), load = 50 ohm.

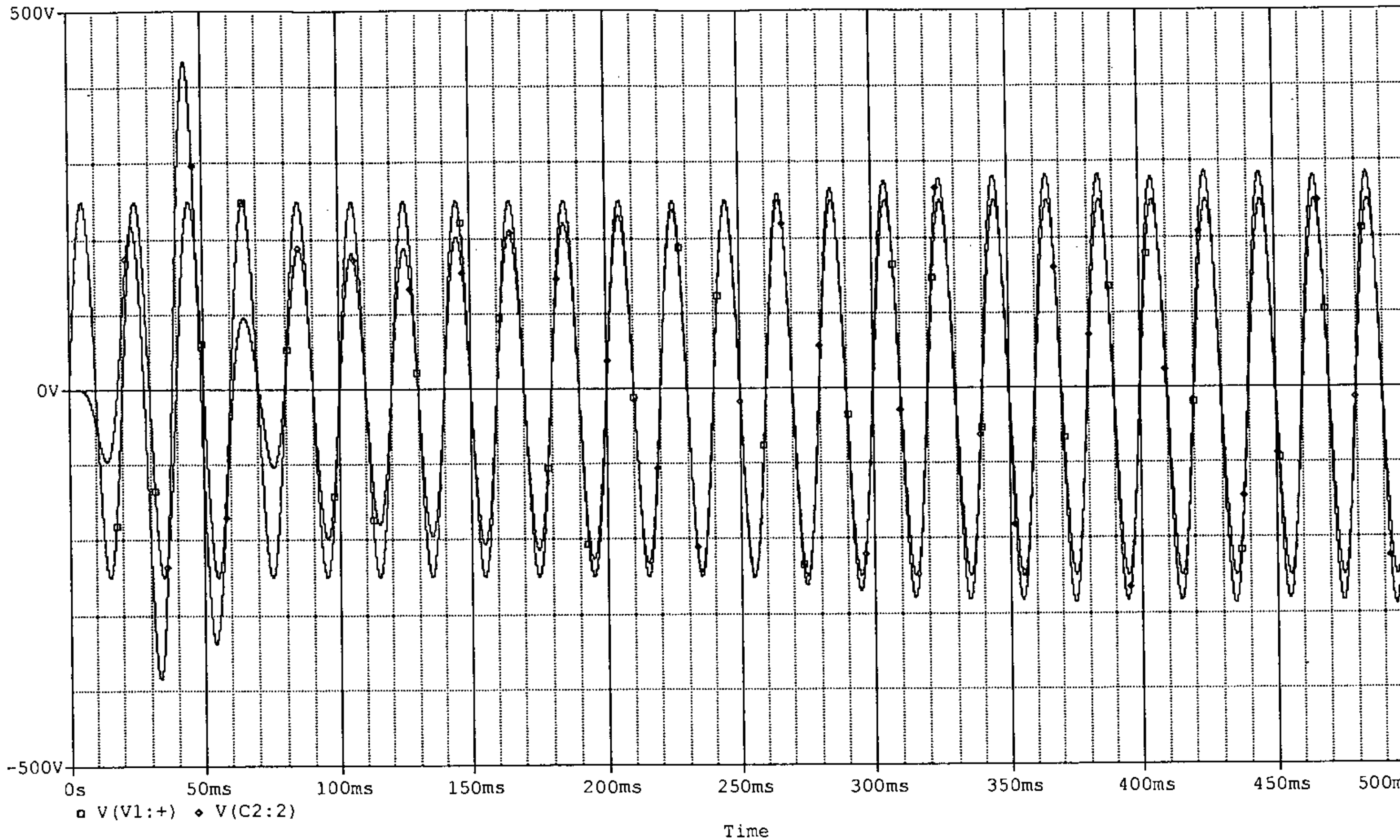


Figure-46. Input/output voltage waveforms when input voltage 250V and load 60 ohm.
V(V1:+)--Input voltage = 250V.
V(C2:2)--Output voltage = 300V.

Figure-47. Comparison of sample voltage to the reference voltage, when input voltage 250V and load 60 ohm.
V(ERR1)--Sample of the reference voltage.
V(ERR2)--Sample of the output voltage.

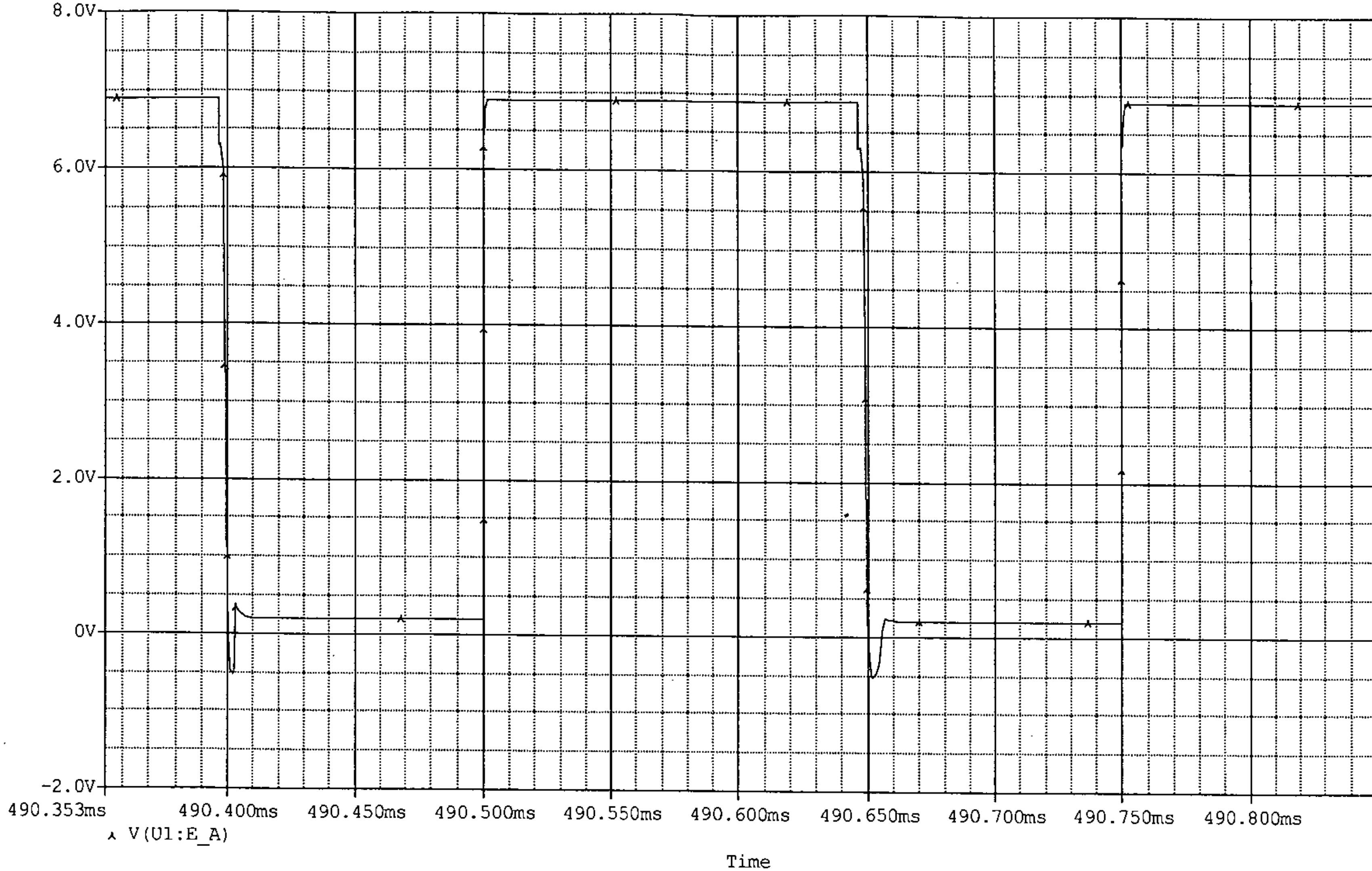


Figure-48. Duty cycle when input voltage 250V,(K>0.5), load = 60 ohm.

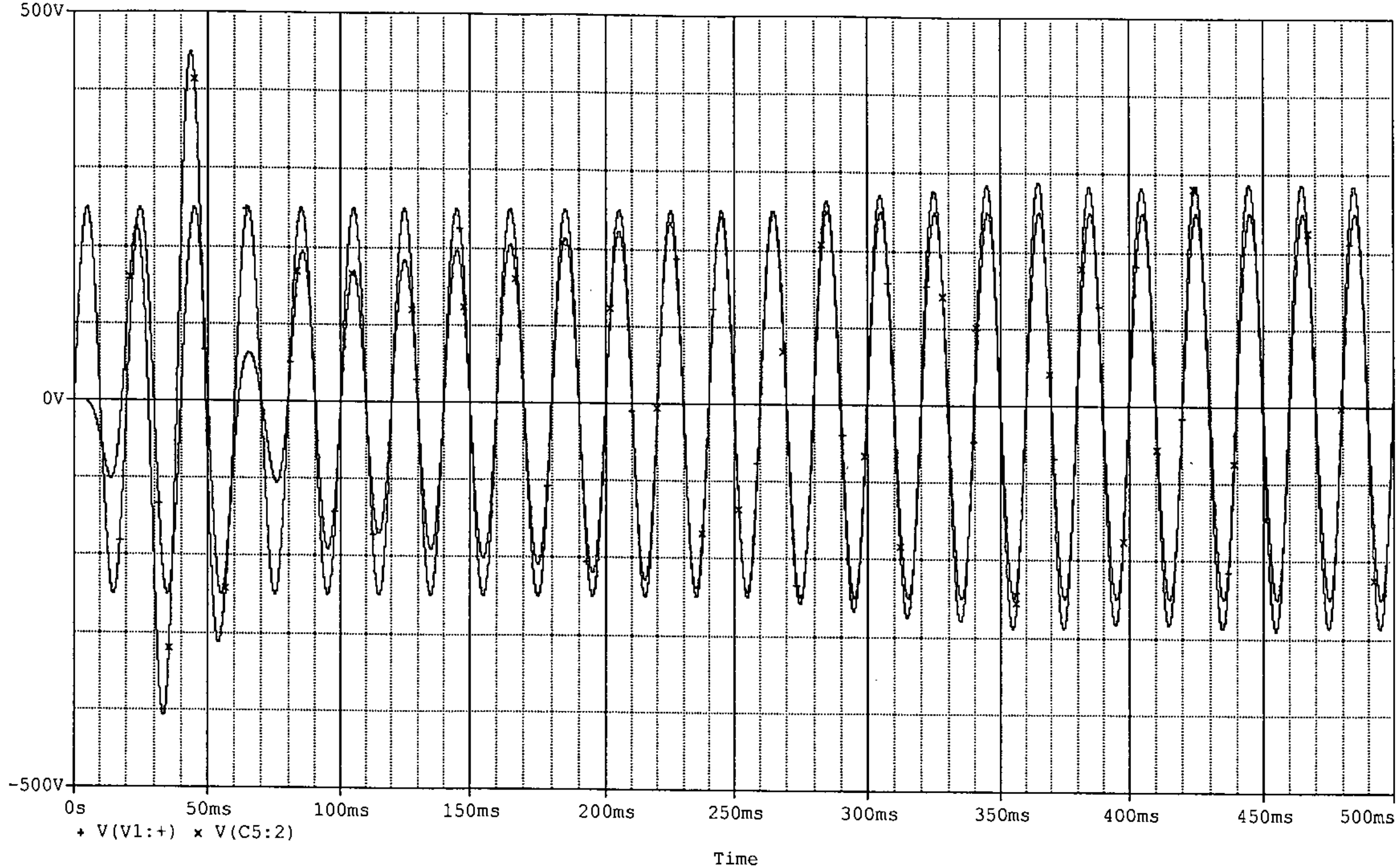


Figure-49. Input/output voltage waveforms when input voltage 250V and load 70 ohm.
V(V1:+)--Input voltage = 250V.
V(C5:2)--Output voltage = 300V.

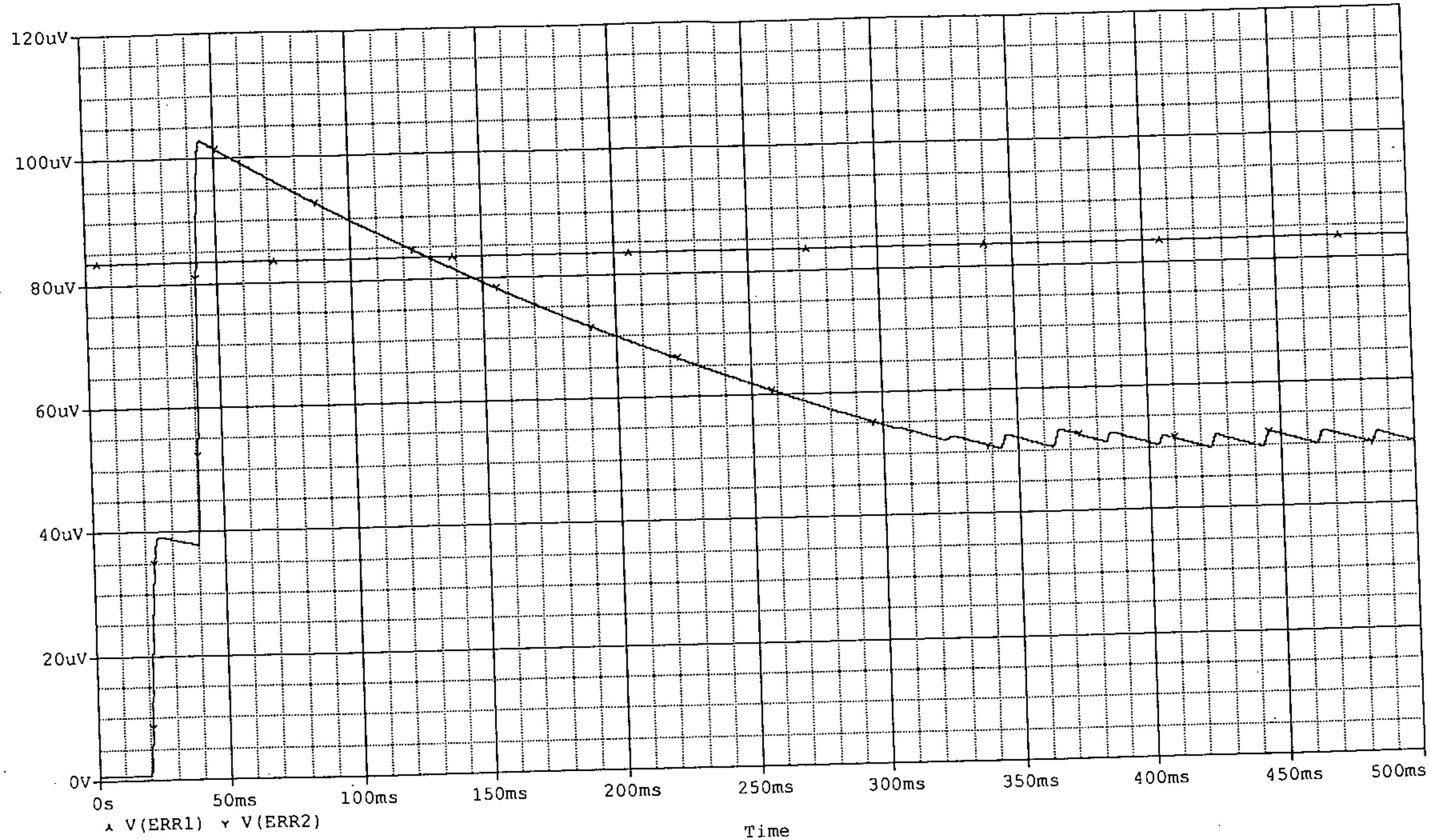


Figure-50. Comparison of sample voltage to the reference voltage, when input voltage 250V and load 70 ohm.
V(ERR1)--Sample of the reference voltage.
V(ERR2)--Sample of the output voltage.

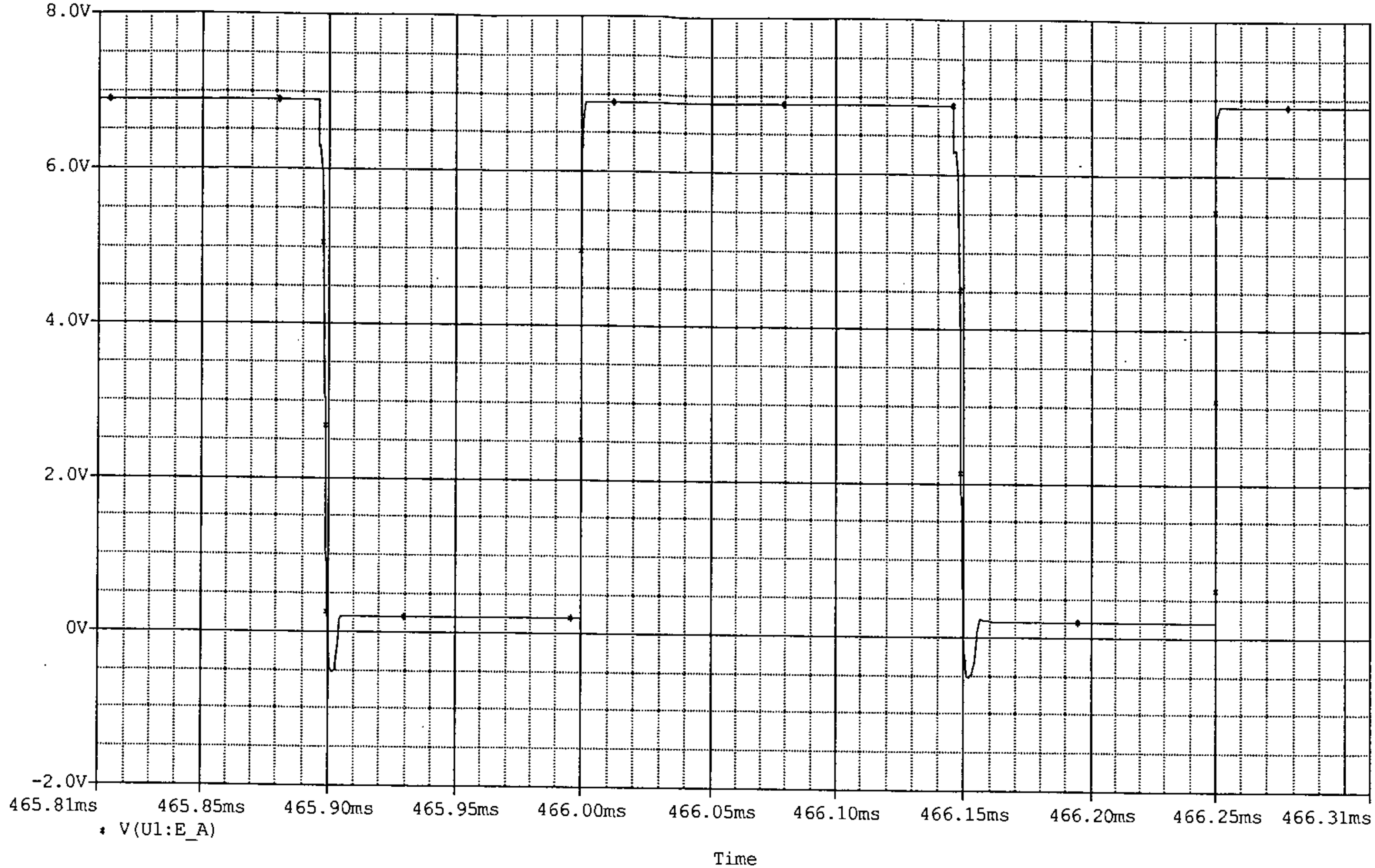


Figure-51. Duty cycle when input voltage 250V, (K>0.5), load = 70 ohm.

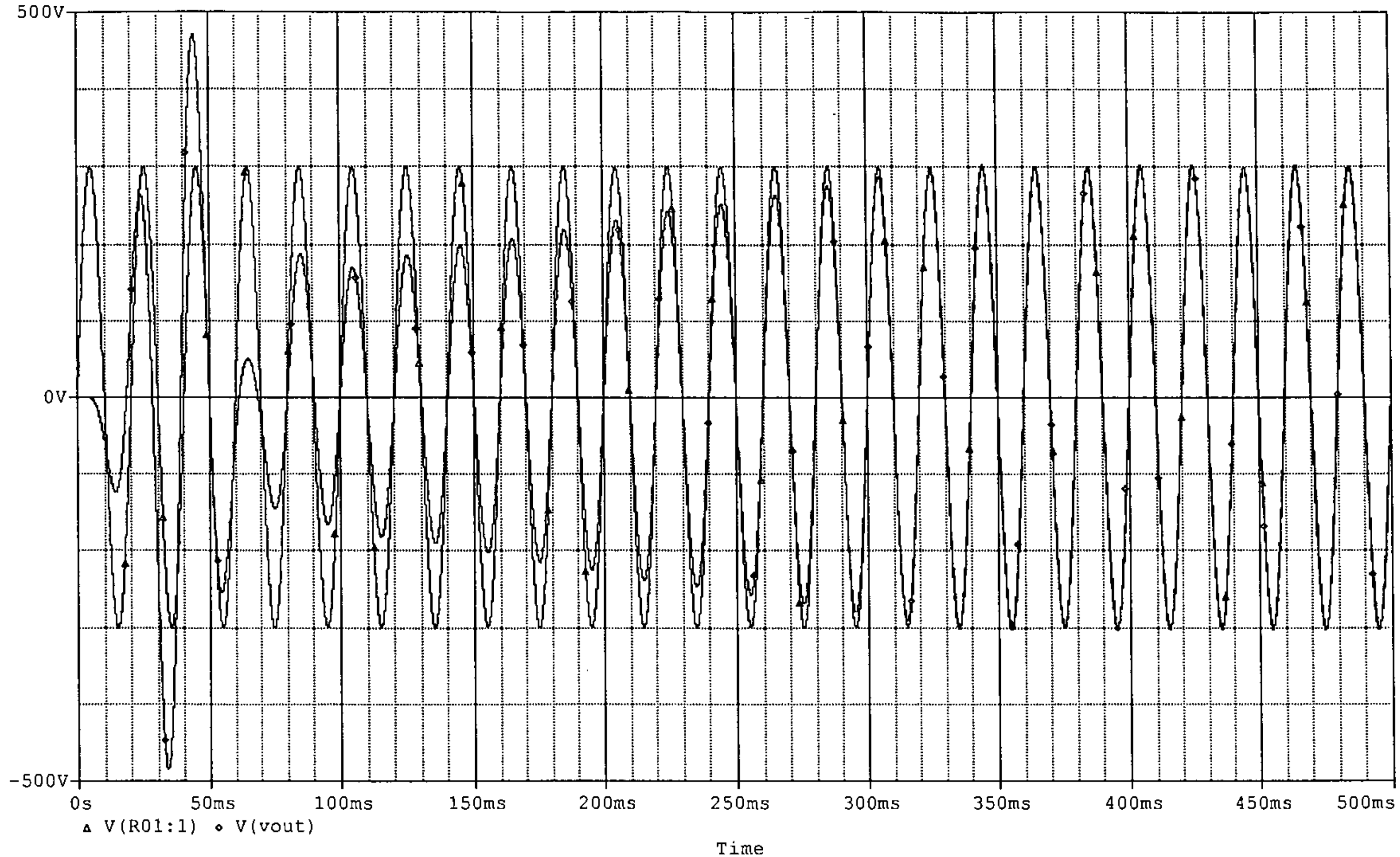


Figure-52. Input/output voltage waveforms when input voltage 300V and load 50 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

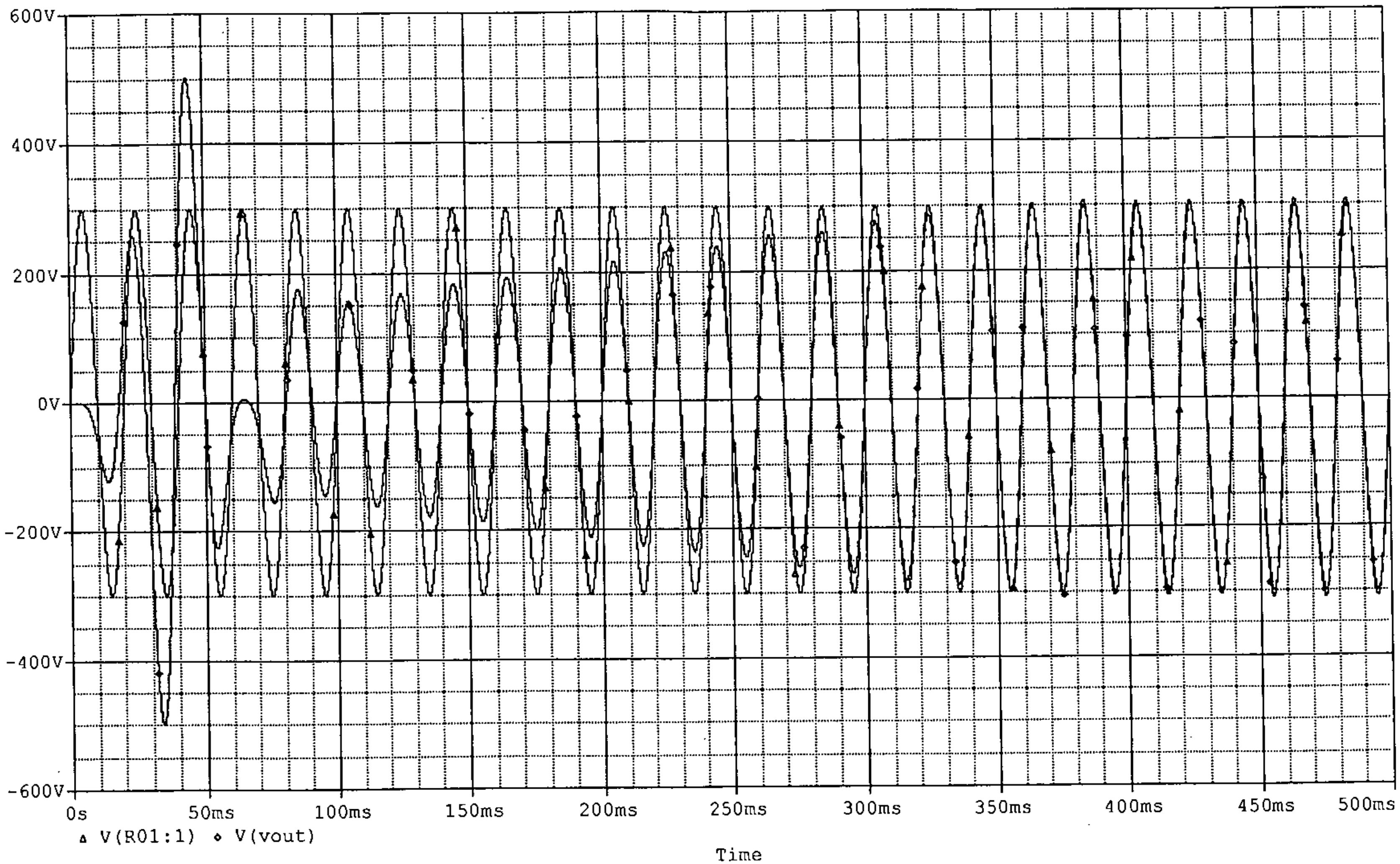


Figure-53. Input/output voltage waveforms when input voltage 300V and load 60 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

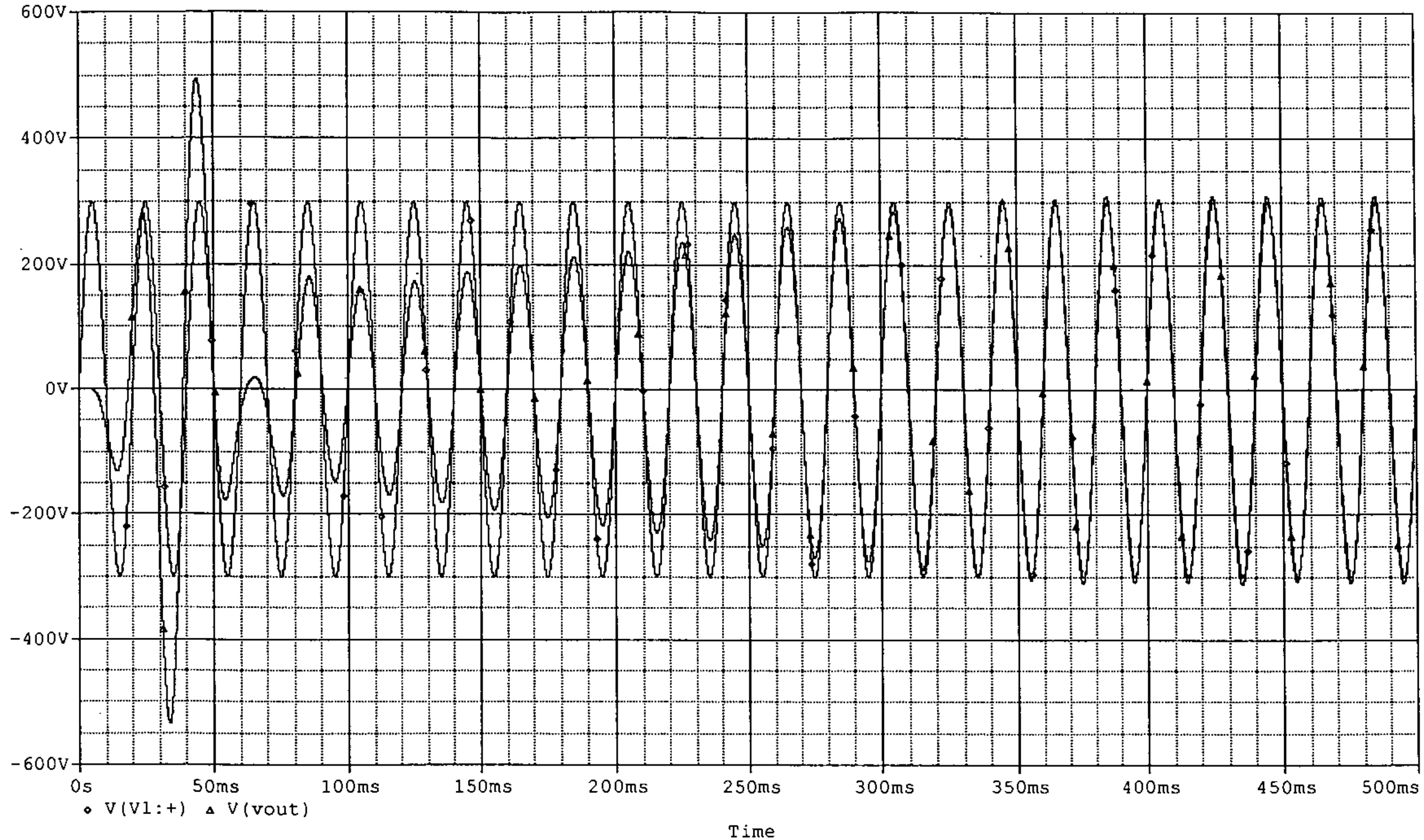


Figure-54. Input/output voltage waveforms when input voltage 300V and load 70 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

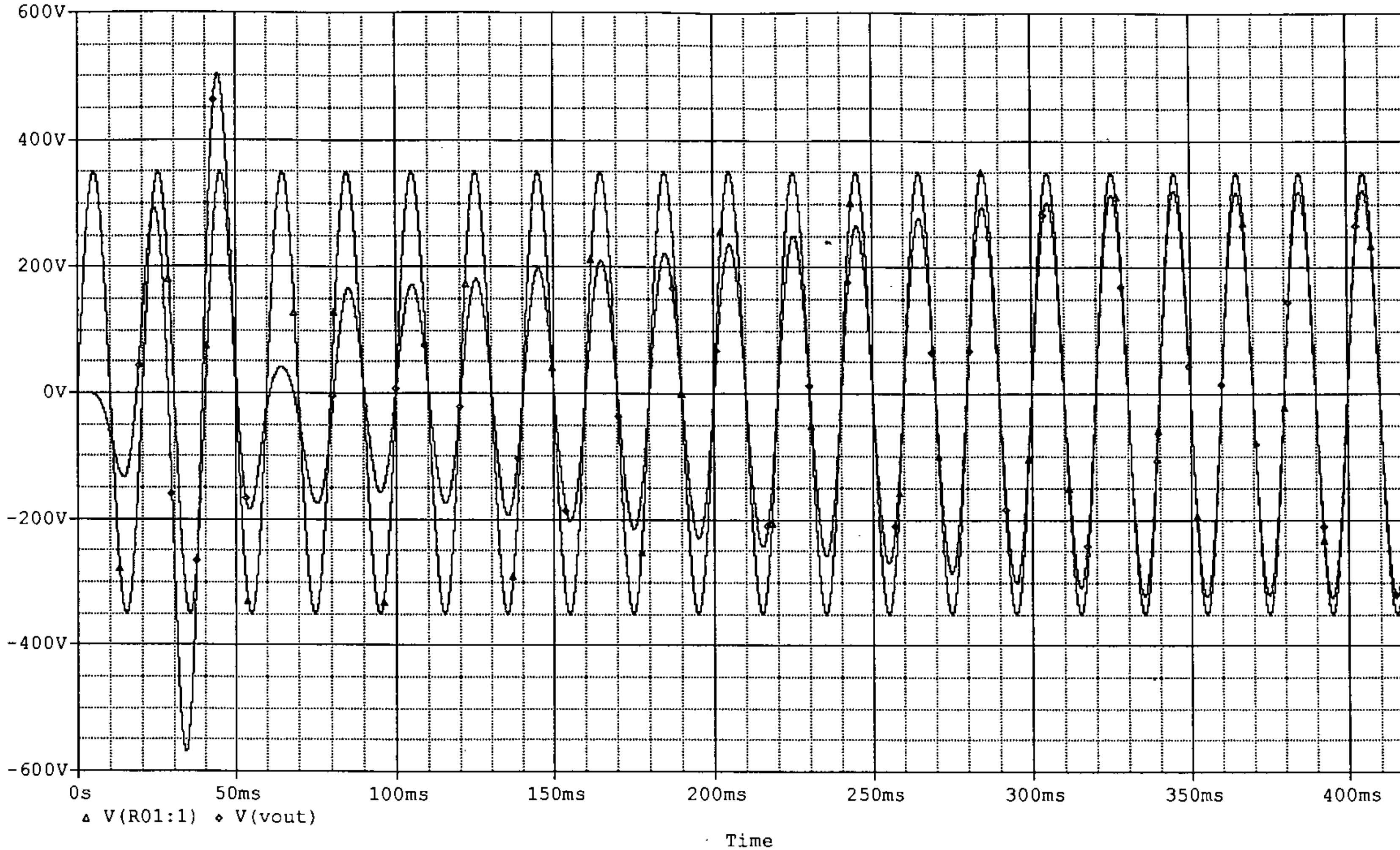


Figure-55. Input/output voltage waveforms when input voltage 350V and load 50 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

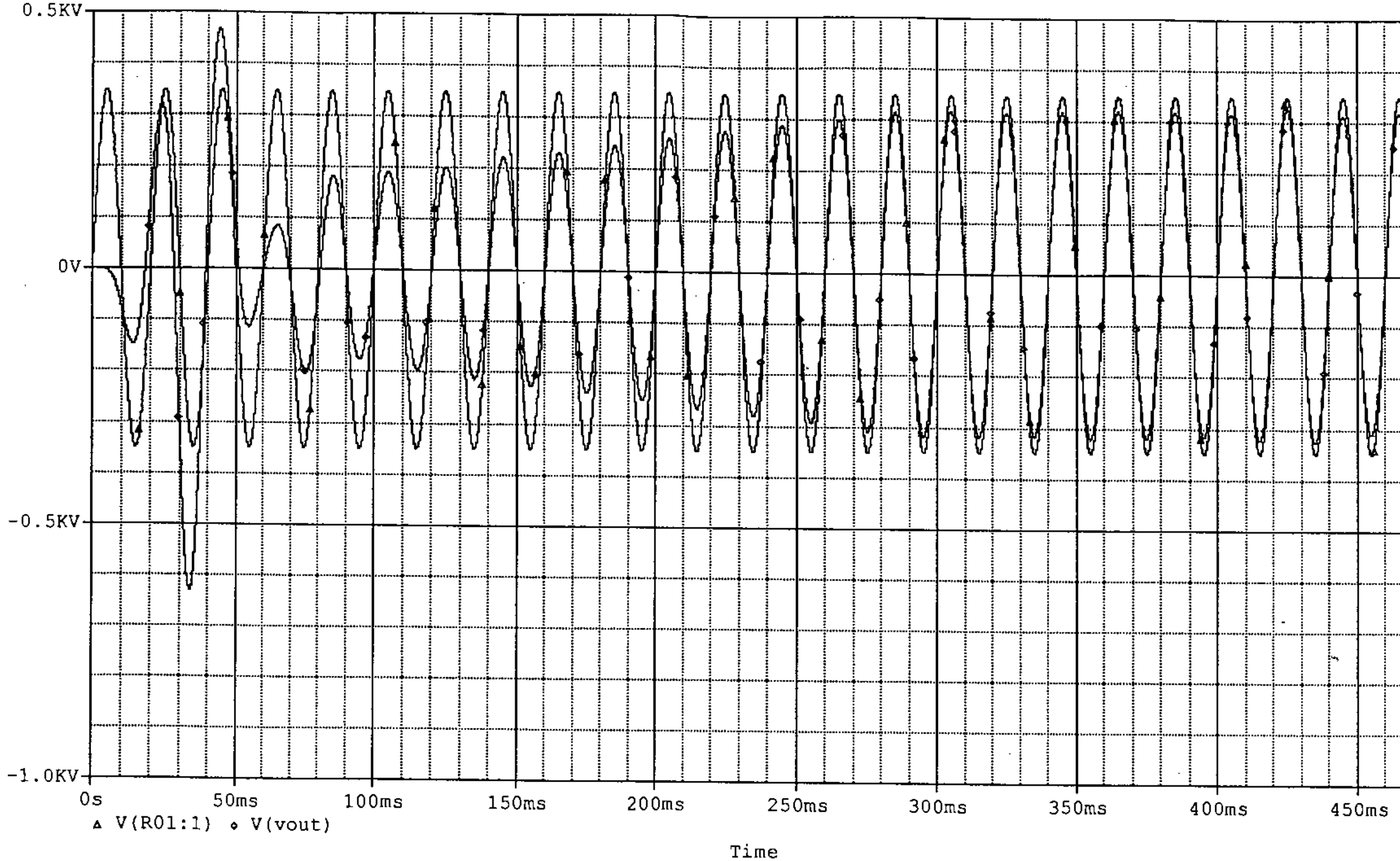


Figure-56. Input/output voltage waveforms when input voltage 350V and load 60 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

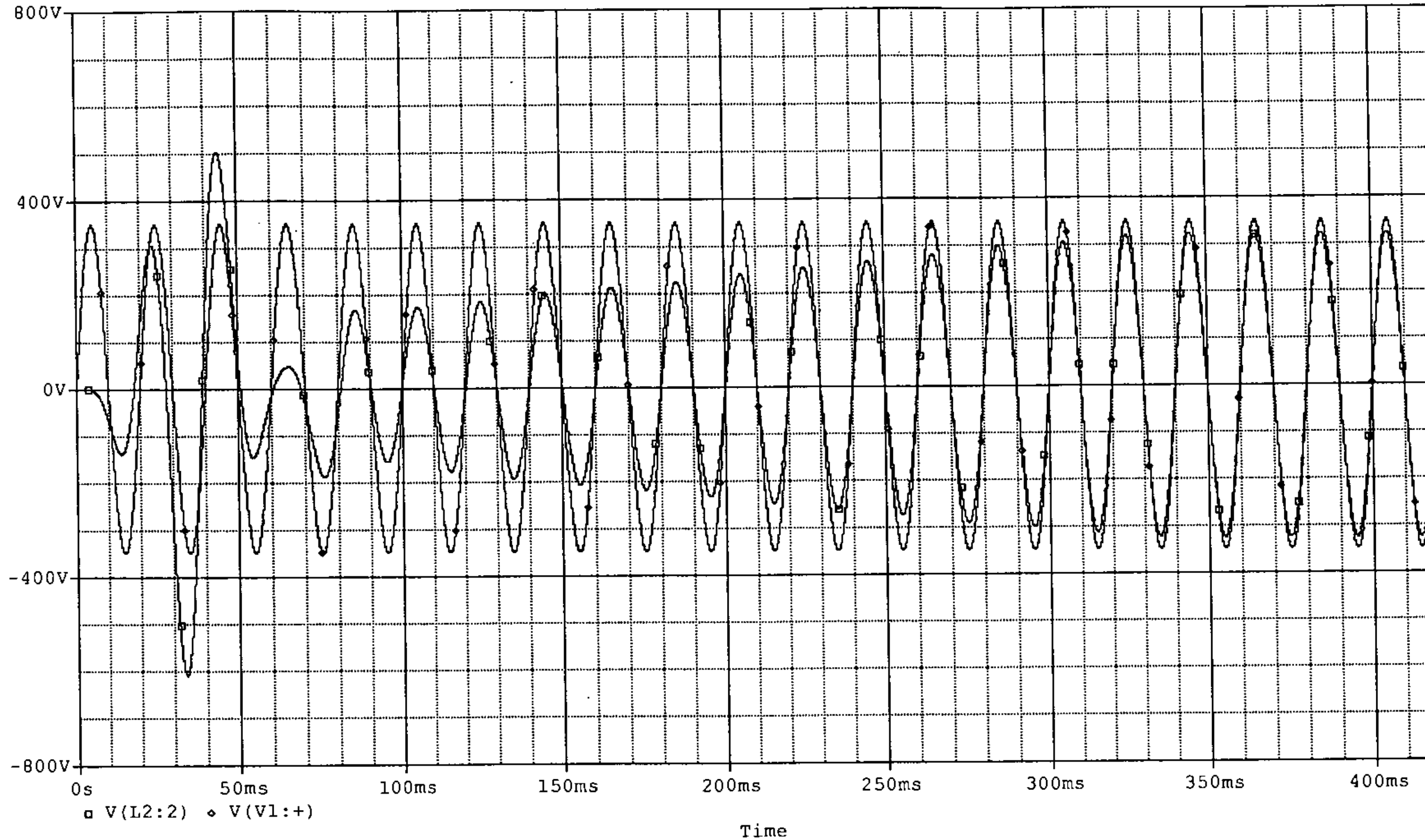


Figure-57. Input/output voltage waveforms when input voltage 350V and load 70 ohm.
V(R01:1)--Input voltage = 250V.
V(vout)--Output voltage = 300V.

2.3 PRACTICAL SWITCH IMPLEMENTATION OF AC C^UK REGULATOR

In our previous section we have used ideal S-break switches which have been operated by the pulses from the limiter. But for practical implementation, real switches are essential which are to be controlled by the pulses having ground isolation. The practical AC C^uk regulator of two-switch implementation is shown in Fig.58(a) and 58(b). The ideal S-break switch is replaced by four diode bridge and one IGBT. The pulses from optocoupler U2 and U3 control the IGBTs. Duty cycle from the chip is fed to the LIMIT-1 and INVERTER U3A. LIMIT-1 limits the duty cycle voltage from 0 to 6 volt then fed to the optocoupler U2 and output of the optocoupler fed to IGBT-1. U3A inverts the duty cycle voltage and fed to LIMIT-2, output of which is fed to optocoupler U3 and output of optocoupler is fed to gate of the IGBT-2. Optocoupler is used to generate signaling voltage with separate ground isolation and also for 180 degree phase shift. Thus phase position of the signaling voltage of IGBT-2 is same as the duty cycle voltage and for IGBT-1 having 180 phase shift.

In the circuit of this regulator IGBTs are provided having a snubber circuit across its terminal for smooth functioning of the regulator. Without snubber, very high surge voltages across the terminal may appear which may destroy the switches, more details are given on chapter 2.1.3.1.

During positive half cycle of input voltage when IGBT-1 is On (by gate signal), then current passes through inductor L1, diode D2, IGBT-1 and diode D3 and at the same time previously charged capacitor C1 transfers its energy through diode D2, IGBT-1 diode D3, load R1 and L2. When IGBT-1 is Off and IGBT-2 is On (by gate signal) the stored energy of the inductor L1 is transferred to the Capacitor C1 and energy stored in the inductor L2 transferred through diode D4, IGBT-2 diode D5 and to the load.

During the Negative half cycle of input voltage current passes through D6, IGBT-1, D7 and L1 and at the same time previously charged capacitor C1 transfers its energy through L2, load, D6, IGBT-1 and D7. When IGBT-1 is Off and IGBT-2 is On (by gate signal) the stored energy of the inductor L1 is transferred to the Capacitor C1 and energy stored in the inductor L2 transferred through load, diode D8, IGBT-2 diode D9.

2.3.1 RESULTS OF AUTOMATIC CONTROLLED AC C^UK REGULATOR (practical Switch Implementation)

Fig-59, fig-62 and fig-65 shows the output voltage is regulated to 300V when input voltage is 250V, load is 50 ohm, 60 ohm and 70 ohm respectively. Fig-68, fig-70 and fig-72 shows the output voltage is maintained 300V when input voltage is 300V and load is 50 ohm, 60 ohm and 70 ohm respectively. Fig-74, fig-76 and fig-78 shows the output voltage is regulated to 300V when input voltage is 350V, load is 50 ohm, 60 ohm and 70 ohm respectively.

Fig-60, fig-63 and fig-66 shows the Input and Output current of the regulator when input voltage is 250V, load is 50 ohm, 60 ohm and 70 ohm respectively. Fig-69, fig-71 and fig-73 shows the Input and Output current of the regulator when input voltage is 300V, load is 50 ohm, 60 ohm and 70 ohm respectively. Fig-75, fig-77 and fig-79 shows the Input and Output current of the regulator when input voltage is 350V, load is 50 ohm, 60 ohm and 70 ohm respectively. From the figures it is evident that input peak current is varied from 30 ampere to 38 ampere corresponding variation of load peak current from 5 ampere to 7 ampere.

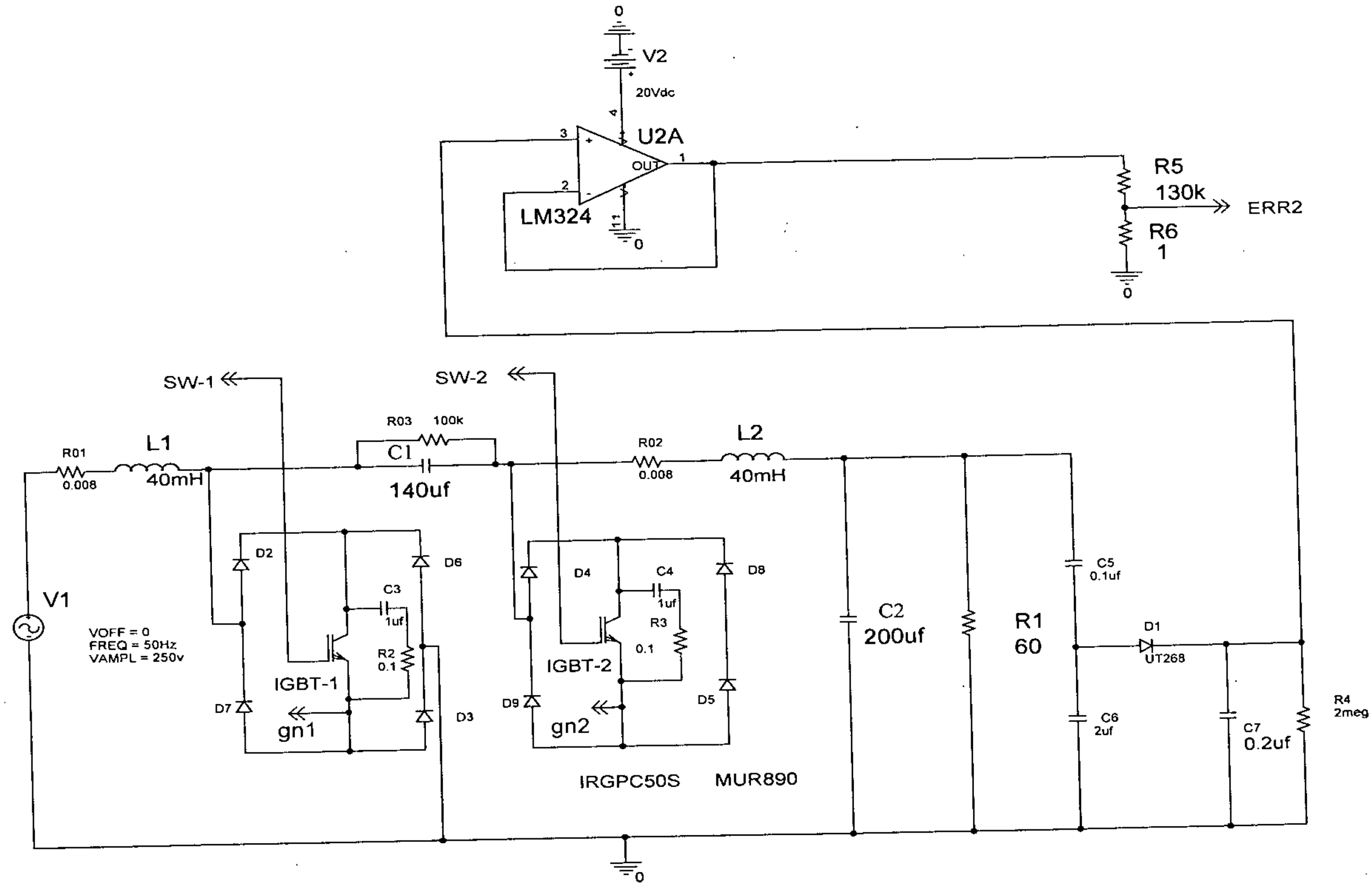


Figure-58(a). Automatic control AC C^uk regulator circuit,practical switch implementation (page-1).

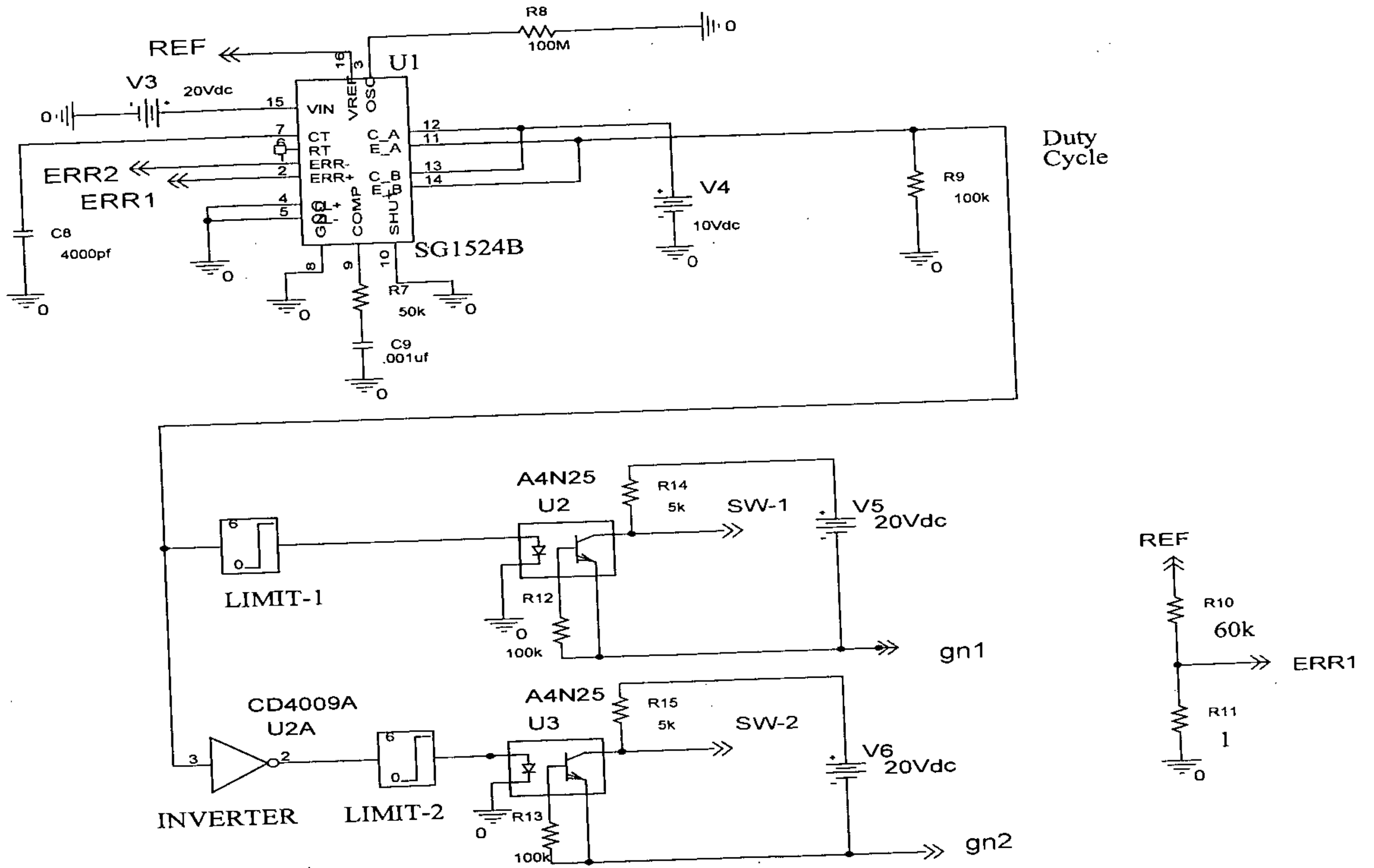


Figure-58(a). Automatic control AC C^uk regulator circuit,practical switch implementation (page-2).

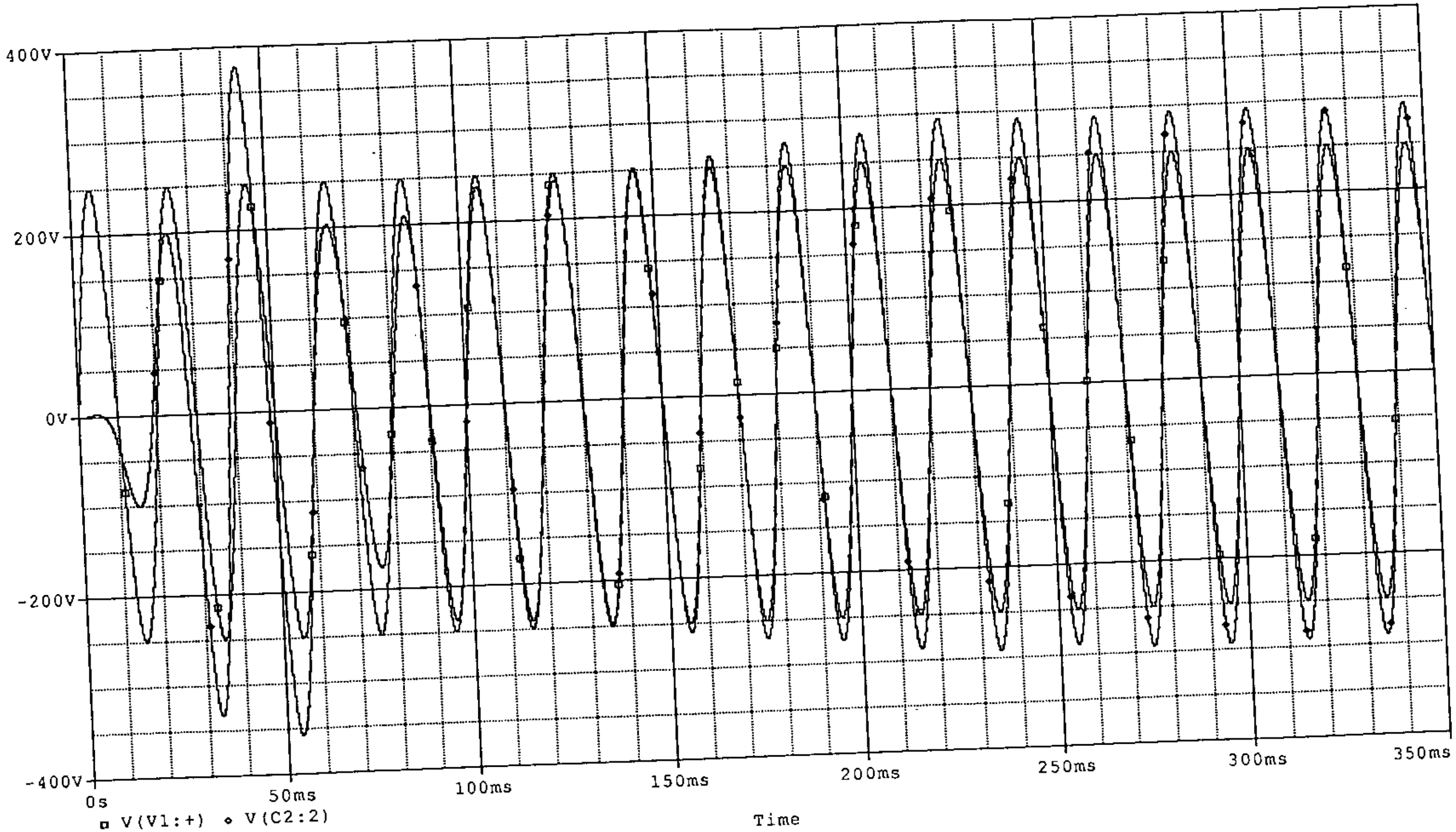


Figure-59. Input/output voltage waveforms when input voltage is 250V and load 50 ohm.

V(V1:+)—Input voltage = 250V.

V(C2:2)—Output voltage = 300V.

* Input power = 2775 watts. Output power = 950 watts. Power loss inside IGBT-1 = 1200 watts, IGBT-2 = 475 watts, snubber resistor R2 = 17 watts, R3 = 10 watts.

** Voltage regulation = 3.33%.

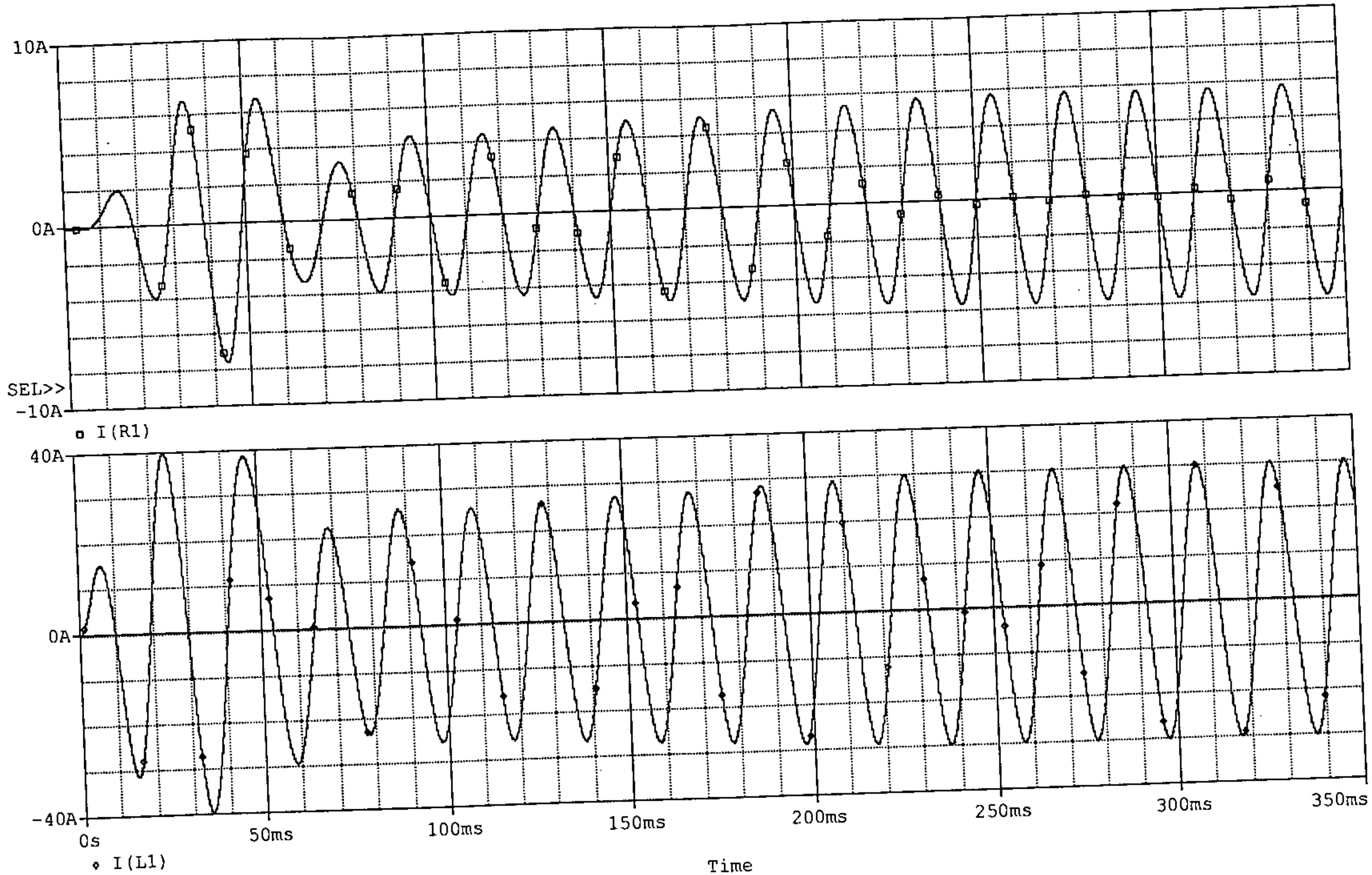


Figure-60. Input/output current waveforms when input voltage 250V and load 50 ohm.
I(L1)--Input current.
I(R1)--Output current.

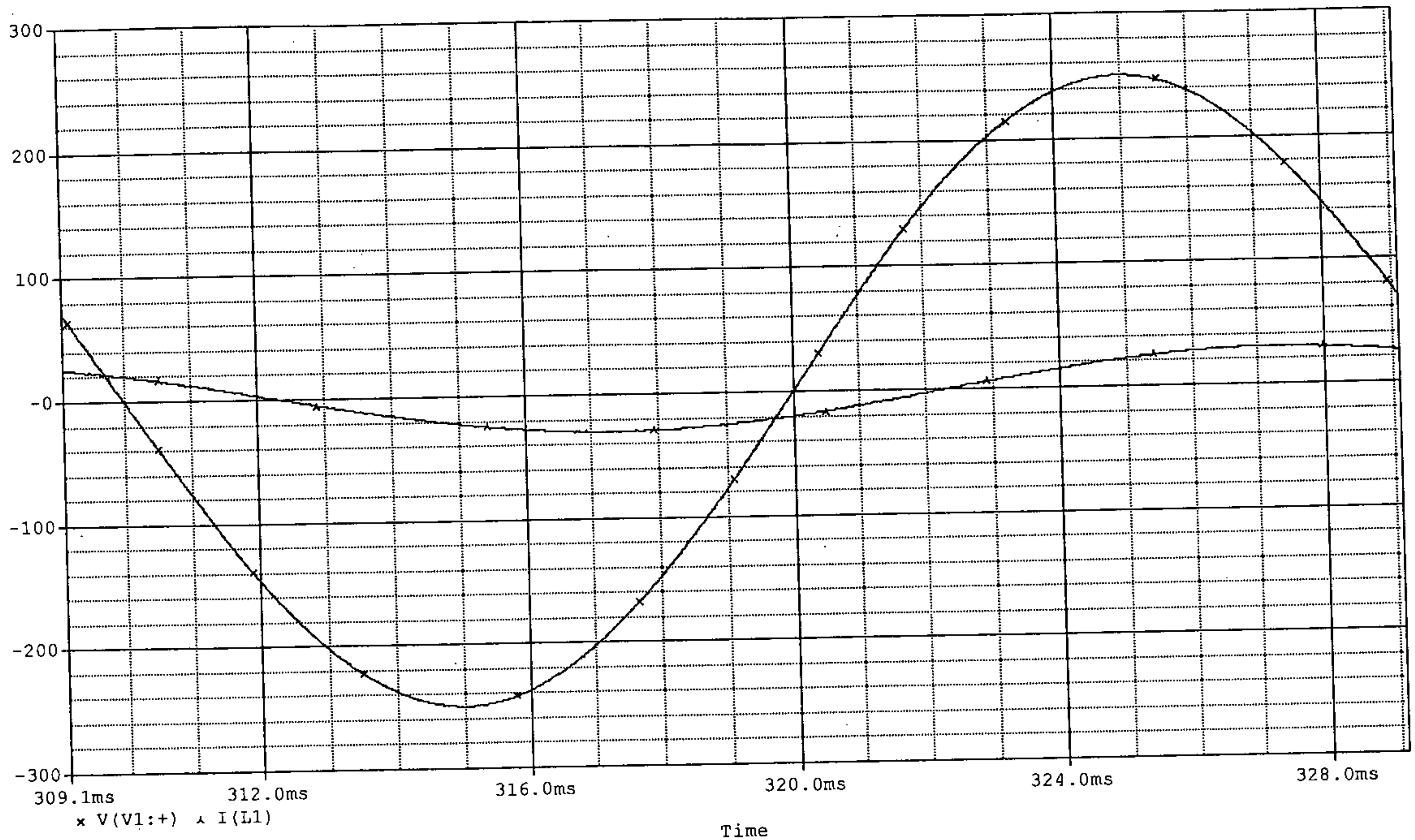


Figure-61. Input voltage and input current waveforms when input voltage 250V and load 50 ohm.
V(V1:+)--Input voltage.
I(L1)--Input current.

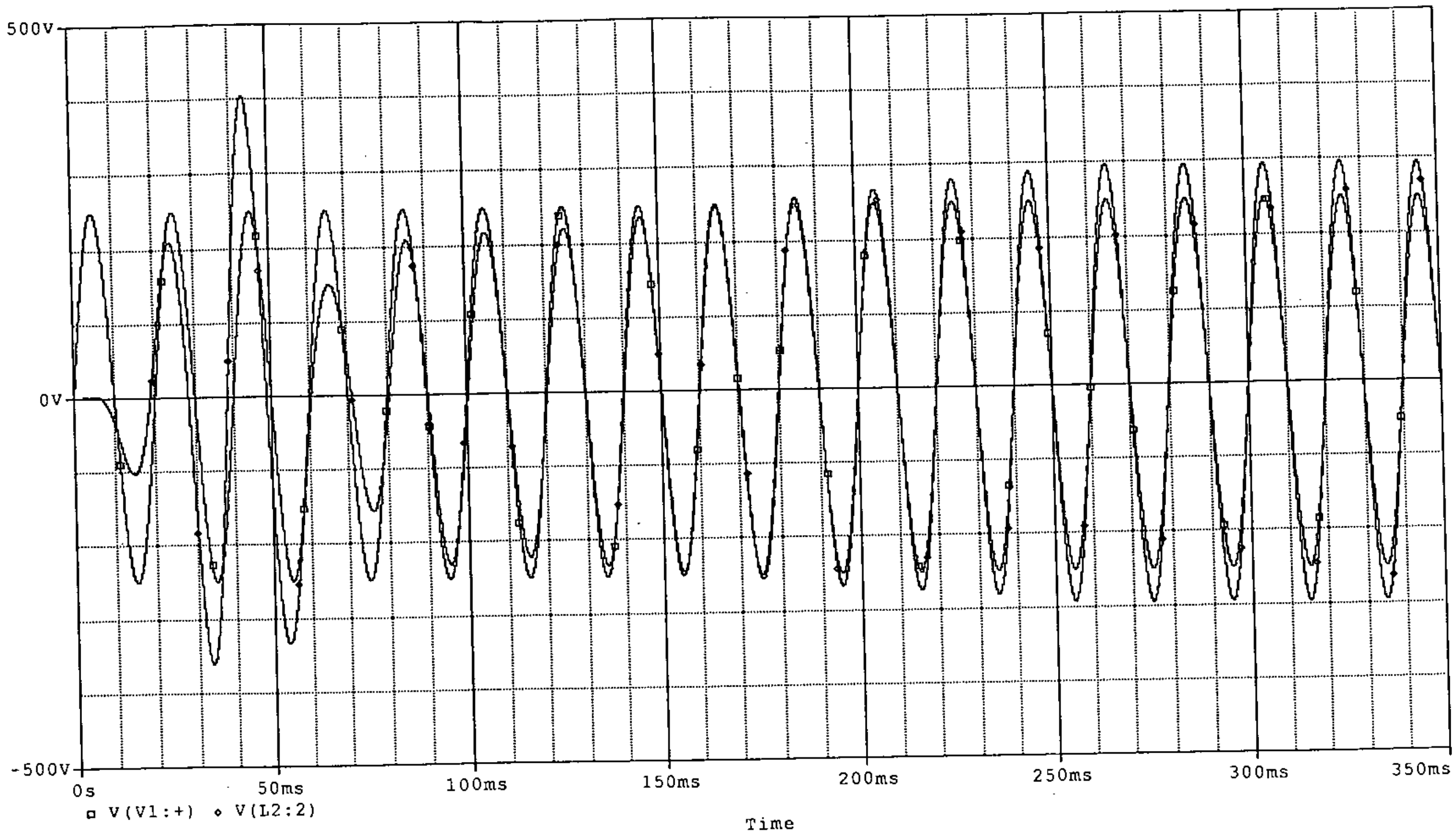


Figure-62. Input/output voltage waveforms when input voltage is 250V and load 60 ohm.
V(V1:+)--Input voltage = 250V.
V(L2:2)--Output voltage = 300V.

* Input power = 2600 watts. Output power = 750 watts. Power loss inside IGBT-1 = 1150 watts, IGBT-2 = 500 watts, snubber resistor R2 = 17 watts, R3 = 10 watts.

** Voltage regulation = 1.67%.

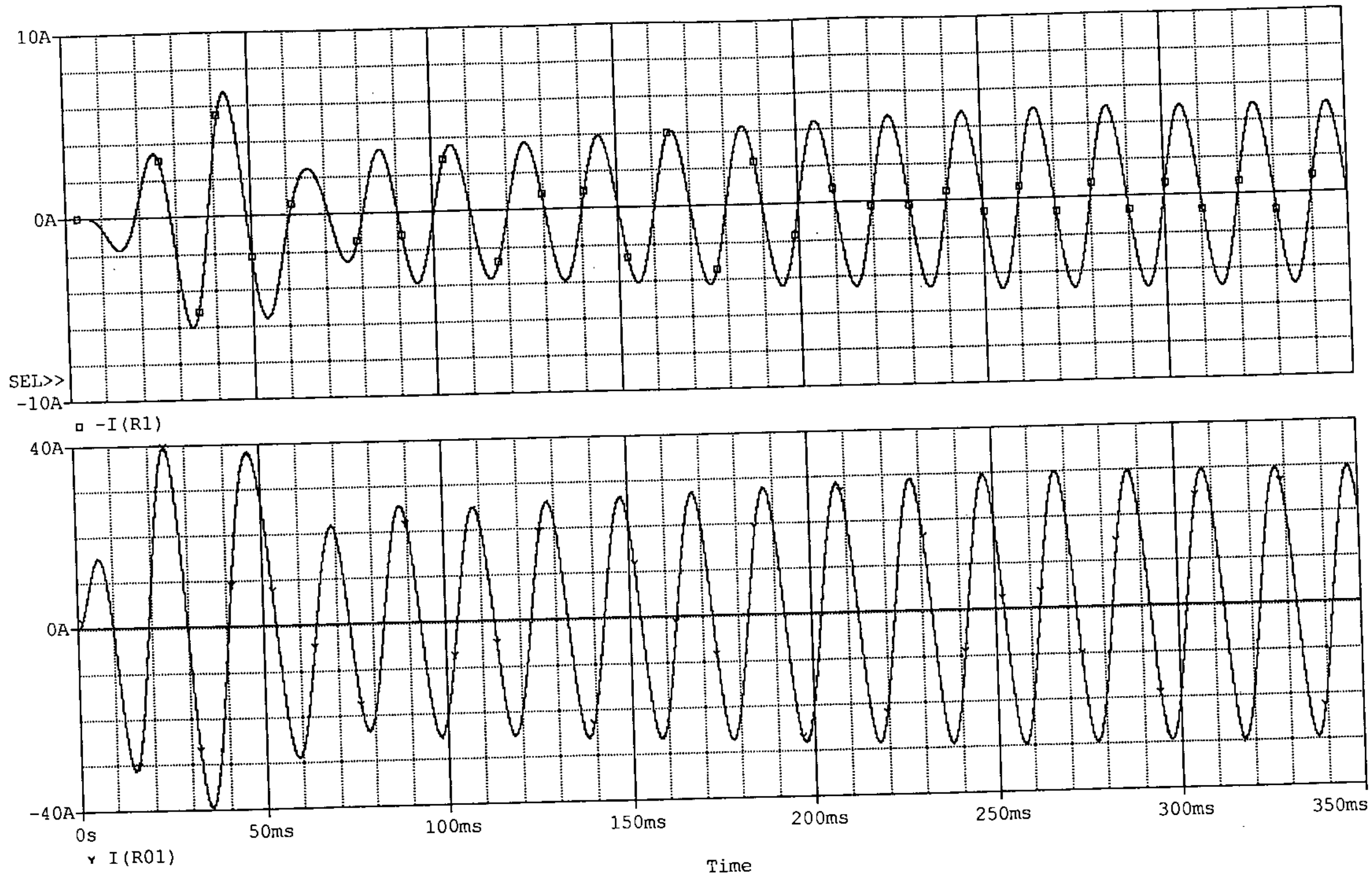


Figure-63. Input/output current waveforms when input voltage 250V and load 60 ohm.
I(R01)--Input current.
I(R1)--Output current.

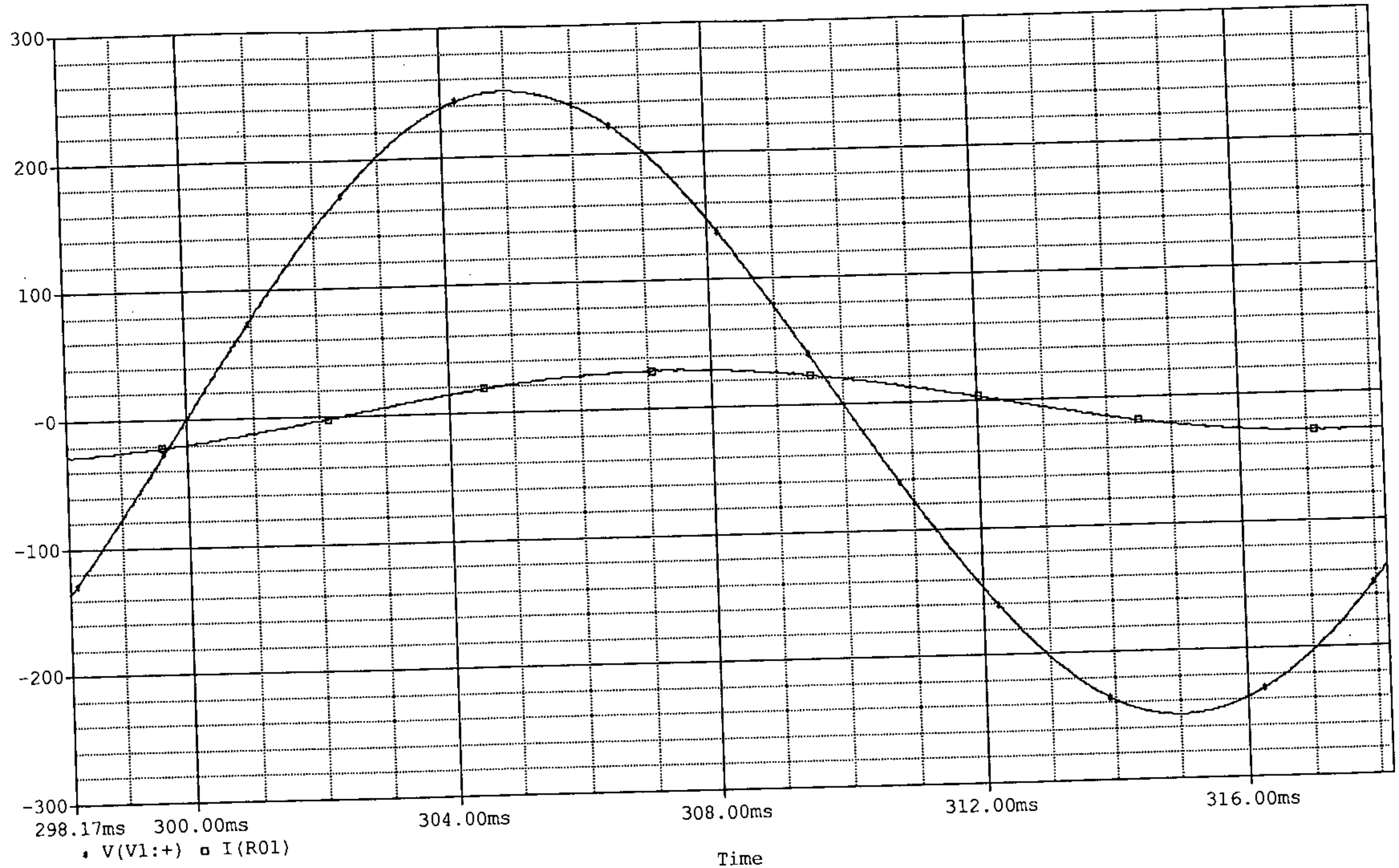


Figure-64. Input voltage and input current waveforms when input voltage 250V and load 60 ohm.
V(V1:+)--Input voltage.
I(R01)--Input current.

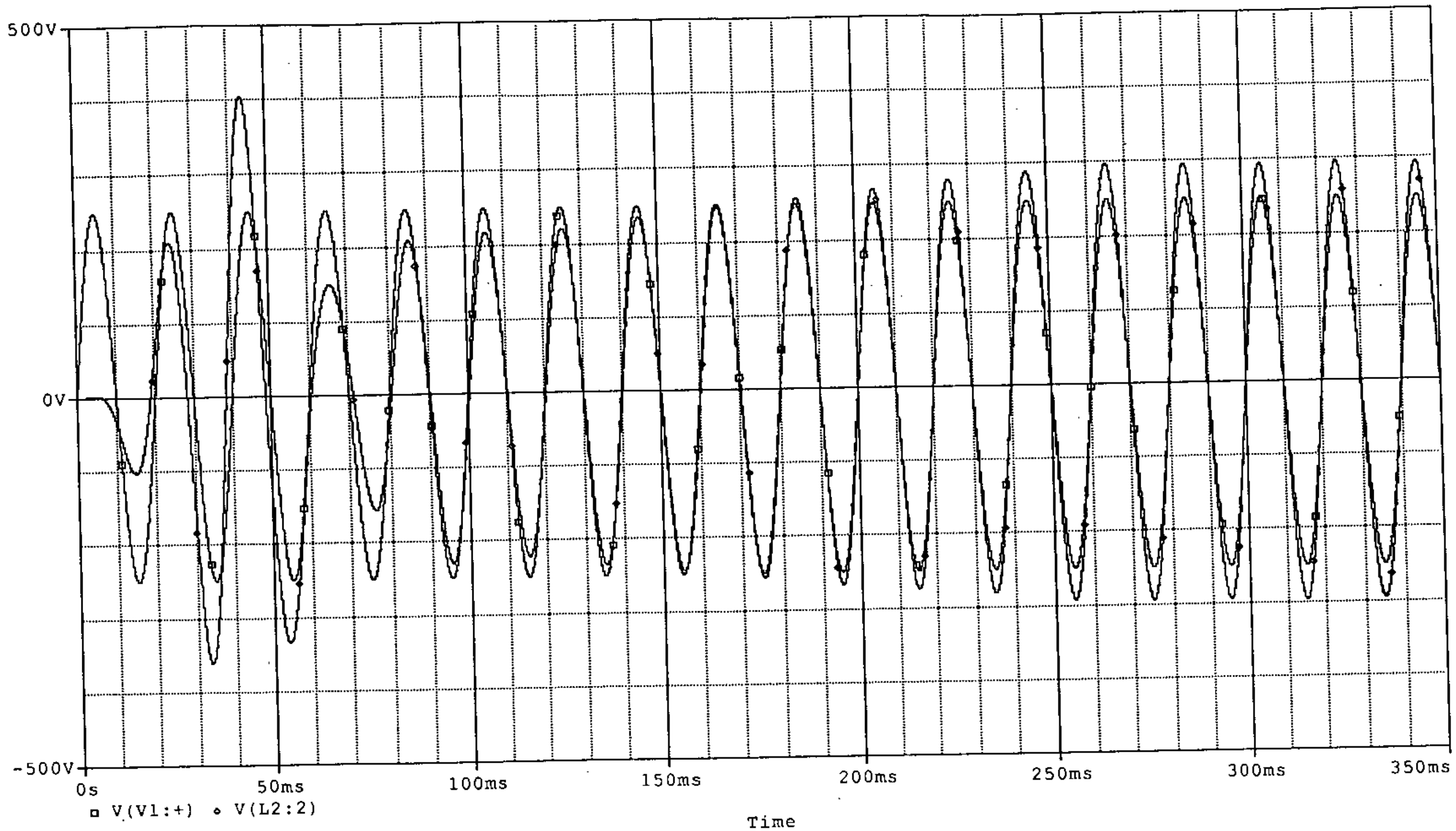


Figure-65 Input/output voltage waveforms when input voltage is 250V and load 70 ohm.

V(V1:+)--Input voltage = 250V.

V(L2:2)--Output voltage = 300V.

* Input power = 2450 watts. Output power = 650 watts. Power loss inside IGBT-1 = 1100 watts, IGBT-2 = 475 watts, snubber resistor R2 = 17 watts, R3 = 10 watts.

** Voltage regulation = 0%.

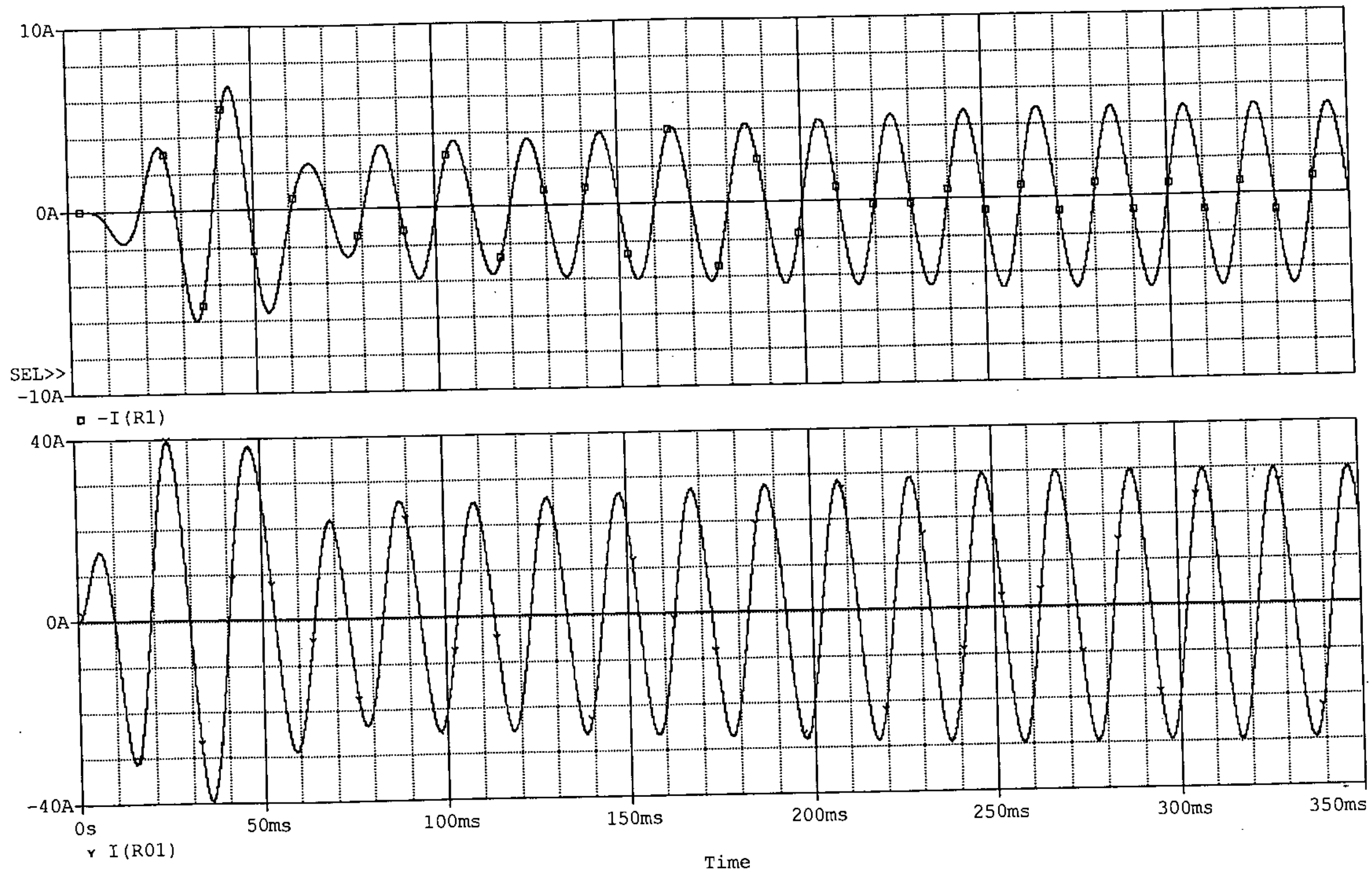


Figure-66 Input/output current waveforms when input voltage 250V and load 70 ohm.
I(R01)--Input current.
I(R1)--Output current.

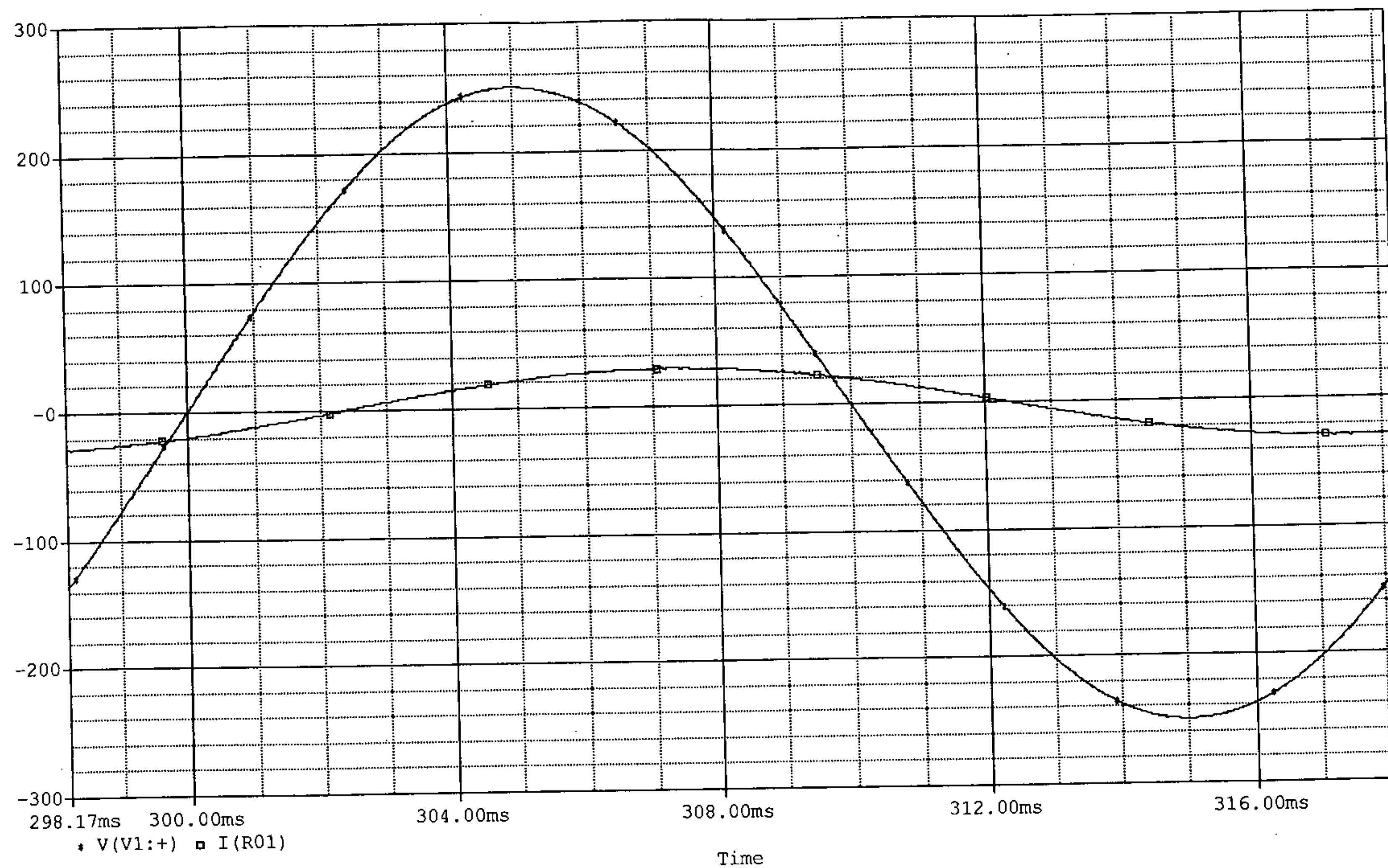


Figure-67 Input voltage and input current waveforms when input voltage 250V and load 70 ohm.
V(V1:+)--Input voltage.
I(R01)--Input current.

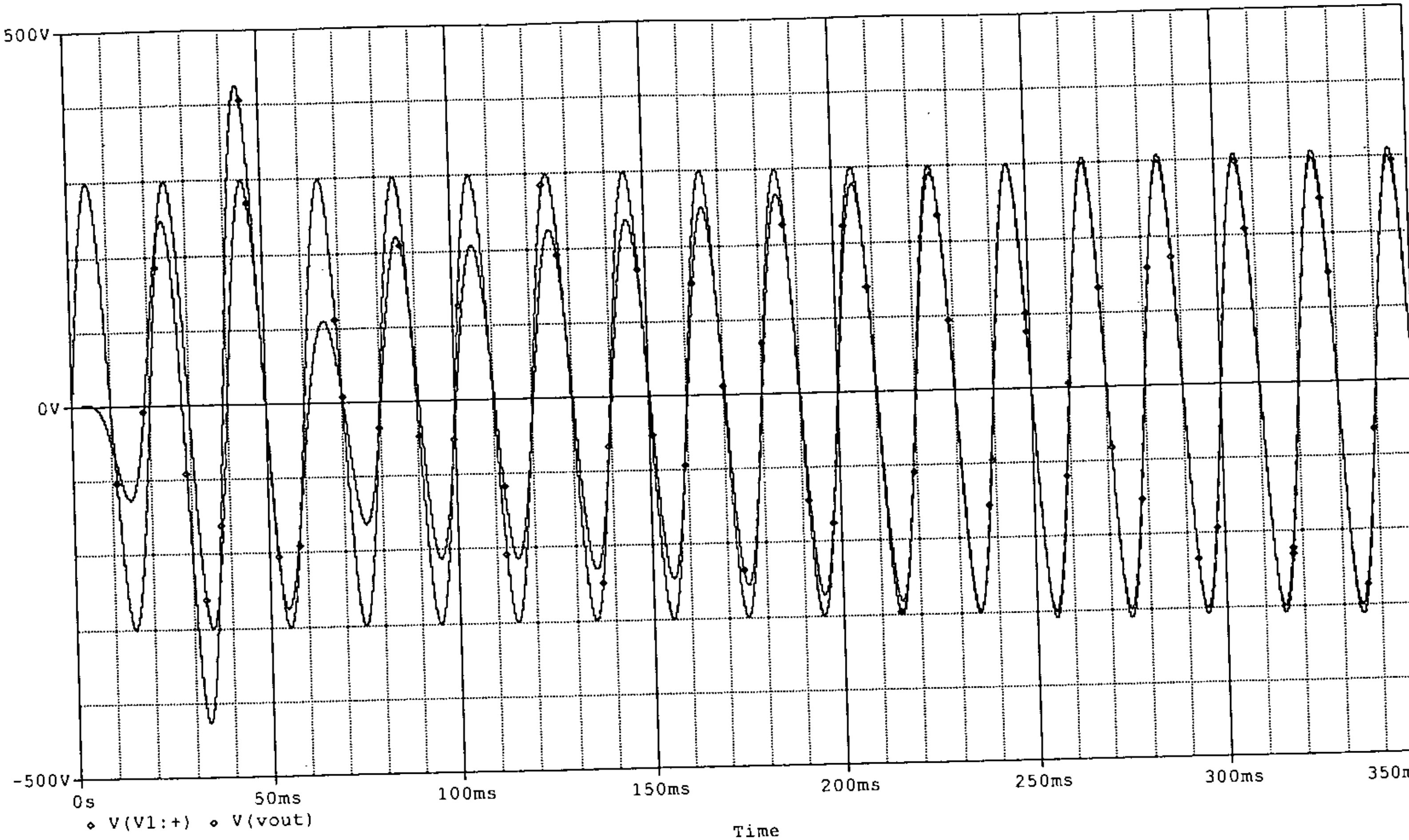


Figure-68 Input/output voltage waveforms when input voltage is 300V and load 50 ohm.
V(V1:+)--Input voltage = 300V.
V(L2:2)--Output voltage = 300V.

* Input power = 2850 watts. Output power = 950 watts. Power loss inside IGBT-1 = 1200 watts, IGBT-2 = 525 watts, snubber resistor R2 = 19 watts, R3 = 11 watts.

** Voltage regulation = -1.67%.

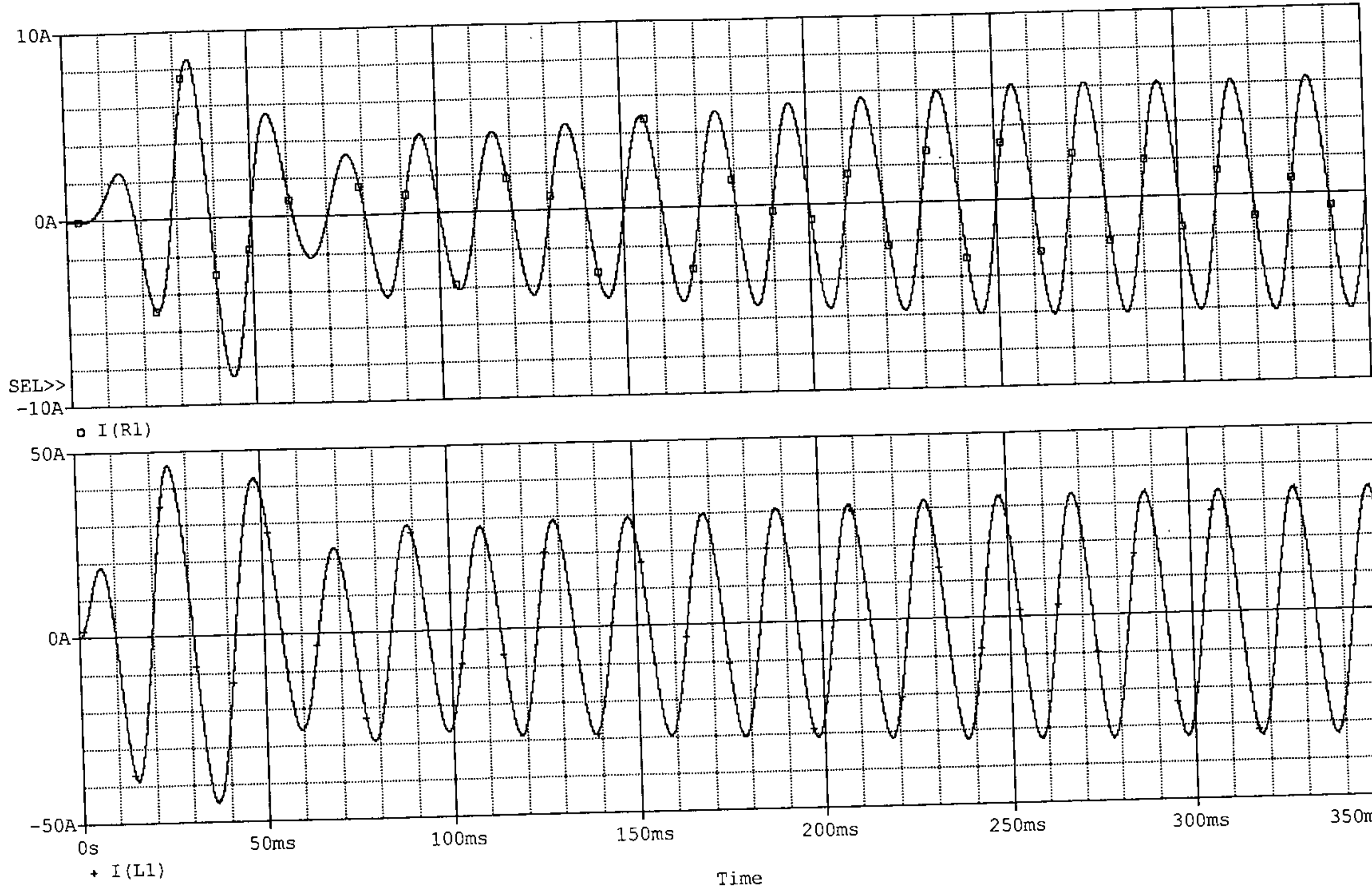


Figure-69. Input/output current waveforms when input voltage 300V and load 50 ohm.
I(L1)--Input current.
I(R1)--Output current.

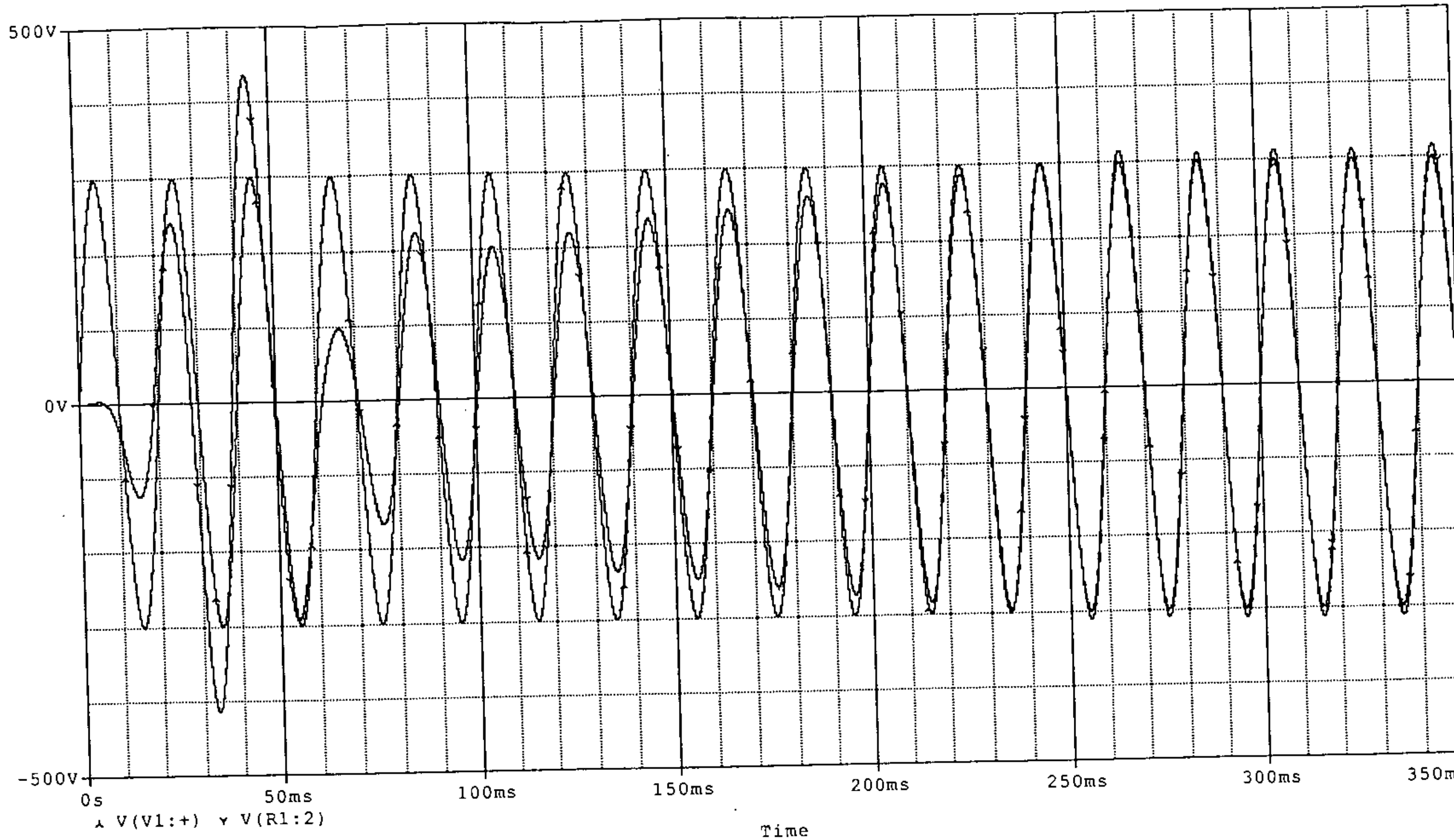


Figure-70 Input/output voltage waveforms when input voltage is 300V and load 60 ohm.

V(V1:+)--Input voltage = 300V.

V(L2:2)--Output voltage = 300V.

* Input power = 2700 watts. Output power = 750 watts. Power loss inside IGBT-1 = 1200 watts, IGBT-2 = 500 watts, snubber resistor R2 = 19 watts, R3 = 11 watts.

** Voltage regulation = -1.67%.

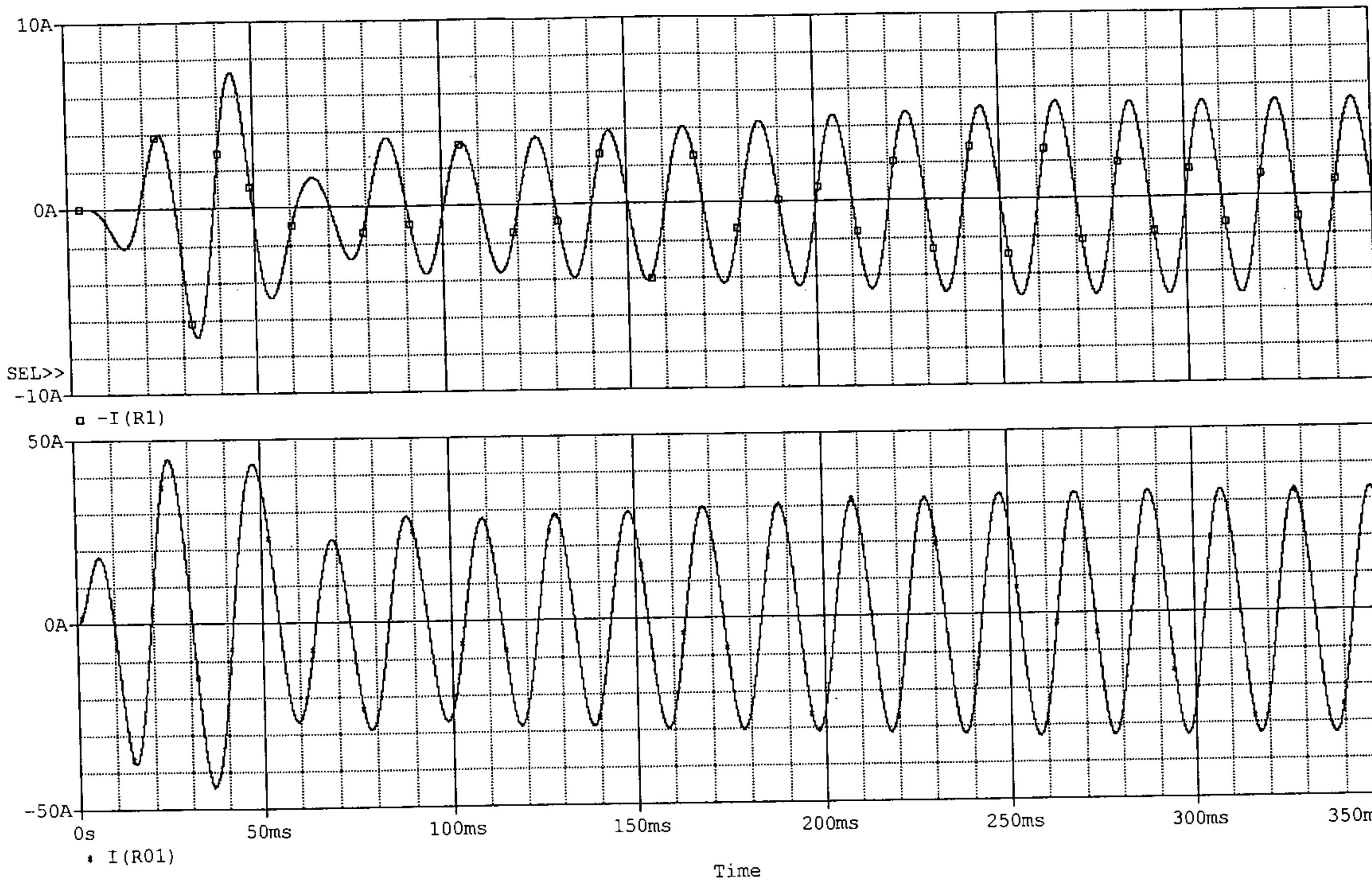


Figure-71. Input/output current waveforms when input voltage 300V and load 60 ohm.
I(R01)--Input current.
I(R1)--Output current

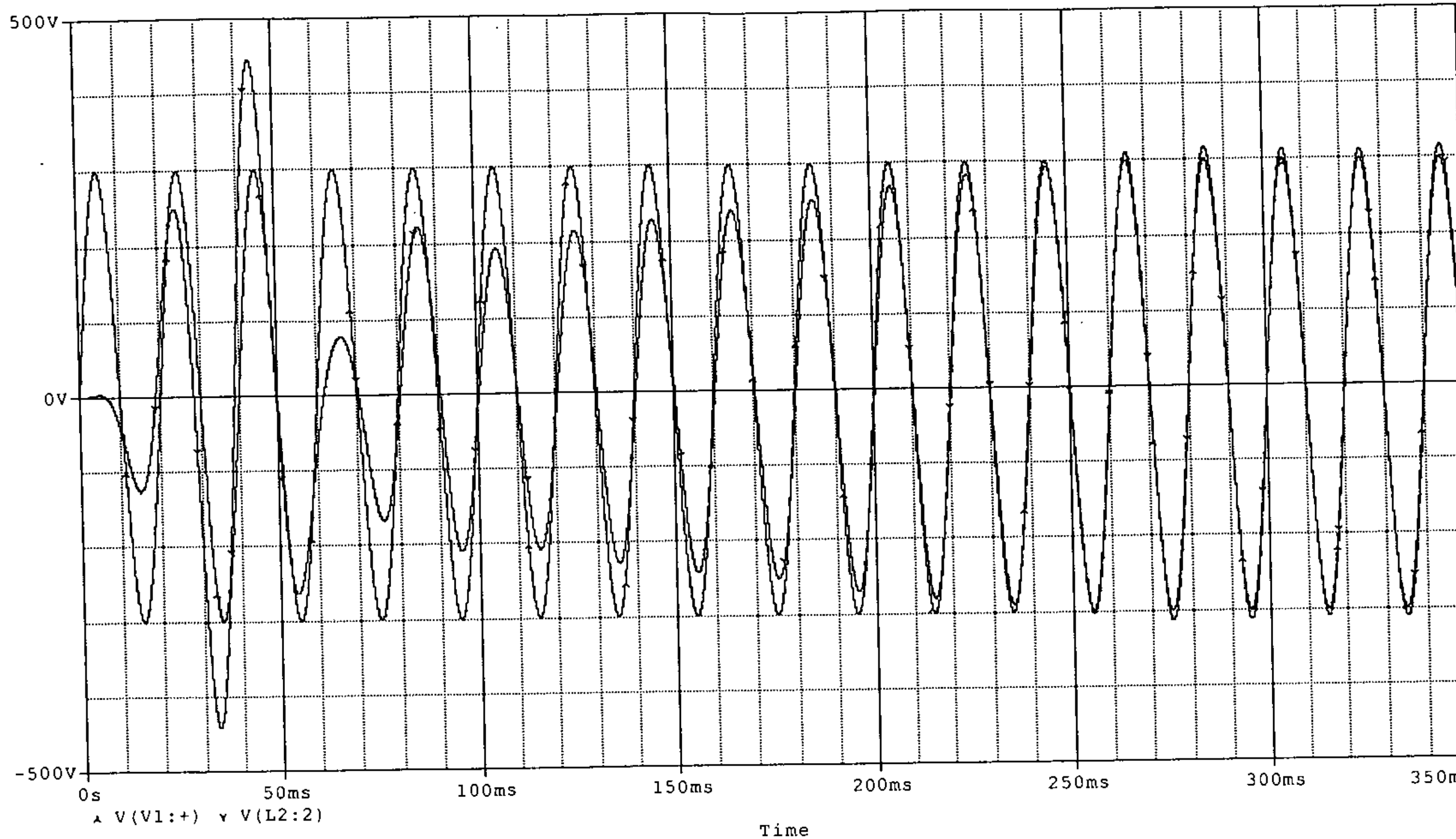


Figure-72 Input/output voltage waveforms when input voltage is 300V and load 70 ohm.
V(V1:+)--Input voltage = 300V.
V(L2:2)--Output voltage = 300V.

* Input power = 2600 watts. Output power = 650 watts. Power loss inside IGBT-1 = 1100 watts, IGBT-2 = 475 watts, snubber resistor R2 = 19 watts, R3 = 11 watts.

** Voltage regulation = -1.67%.

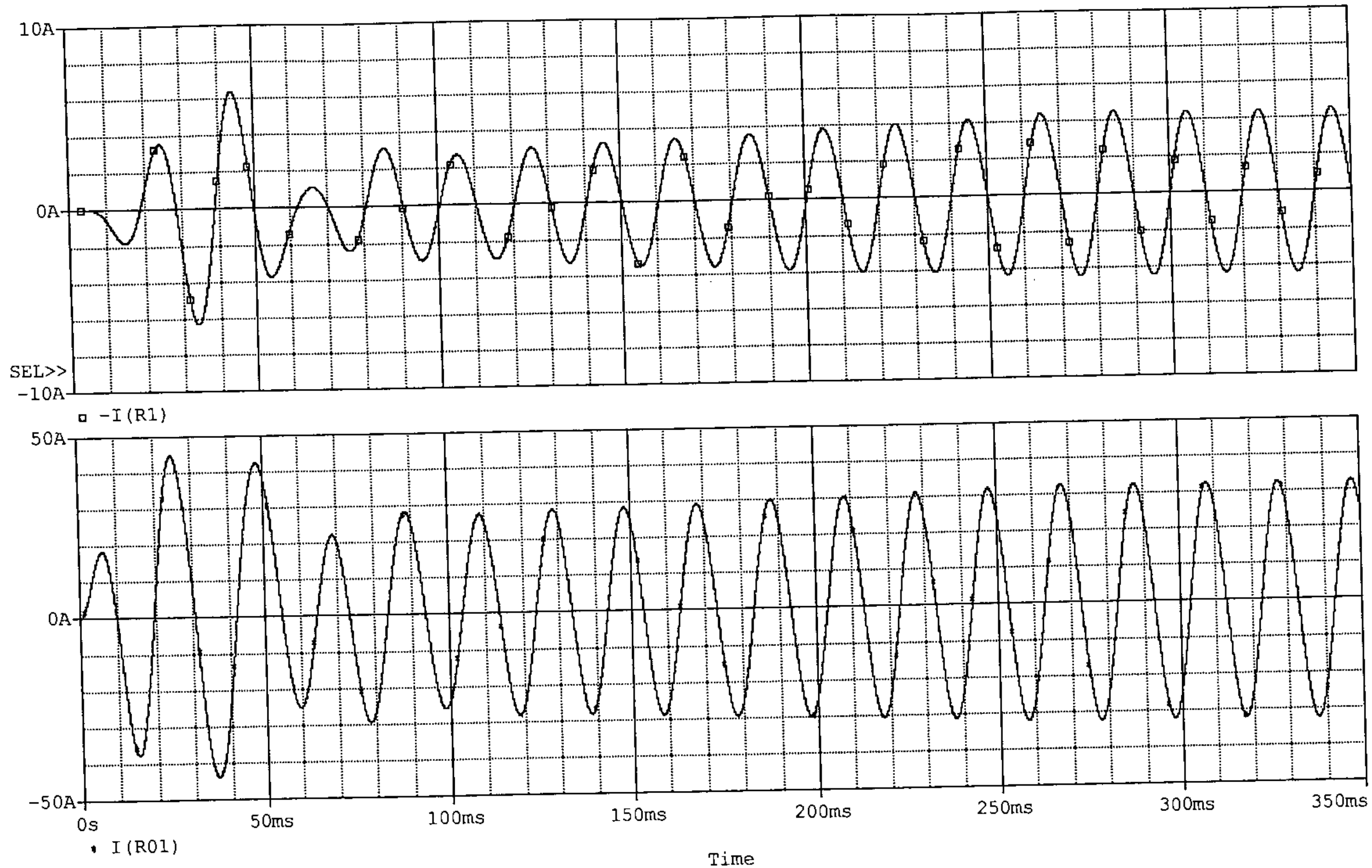


Figure-73. Input/output current waveforms when input voltage 300V and load 70 ohm.
I(R01)--Input current.
I(R1)--Output current.

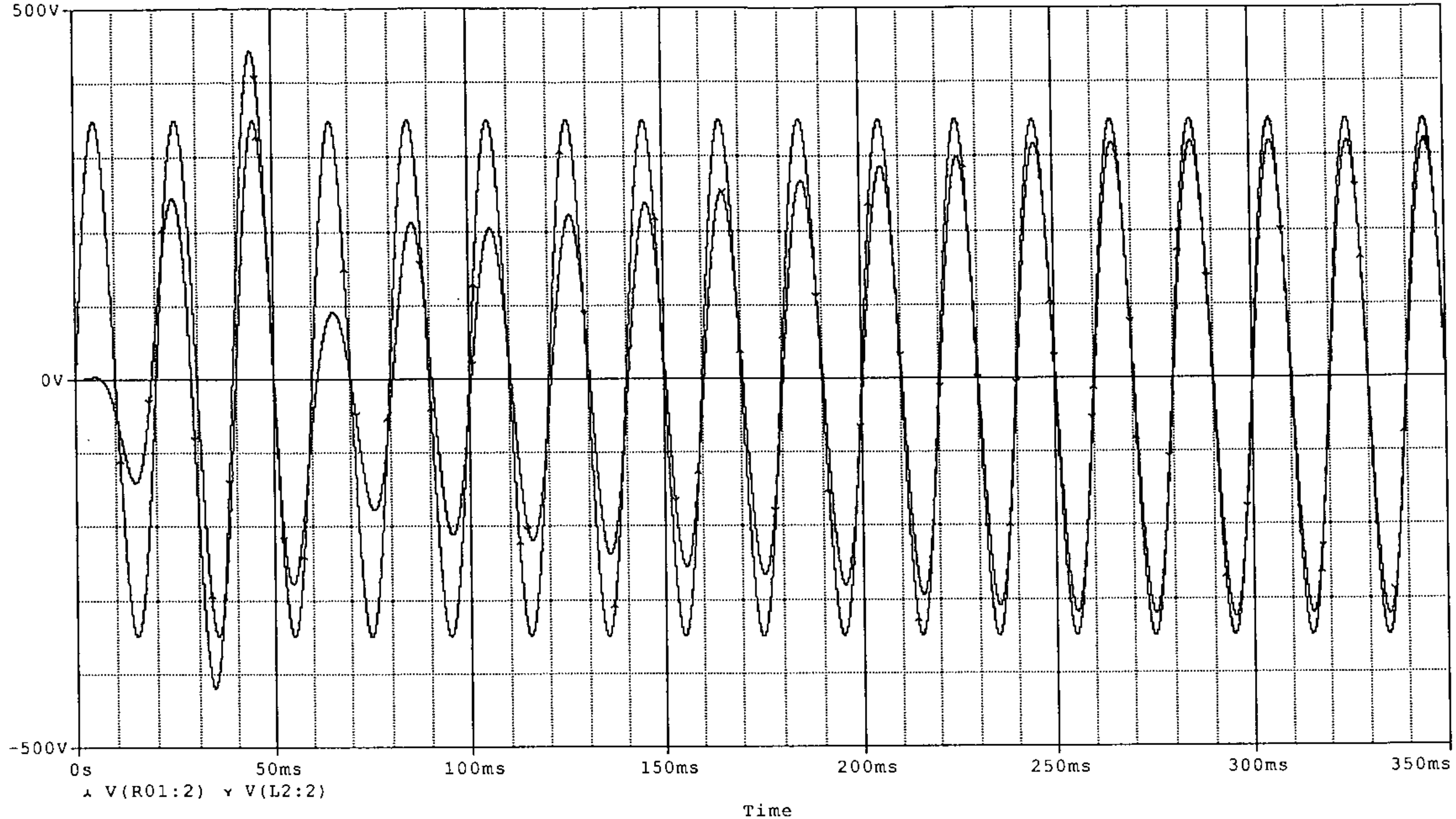


Figure-74 Input/output voltage waveforms when input voltage is 350V and load 50 ohm.
V(V1:+)--Input voltage = 350V.
V(L2:2)--Output voltage = 300V.

* Input power = 3250 watts. Output power = 1000 watts. Power loss inside IGBT-1 = 1500 watts, IGBT-2 = 600 watts, snubber resistor R2 = 22 watts, R3 = 12 watts.

** Voltage regulation = -5%.

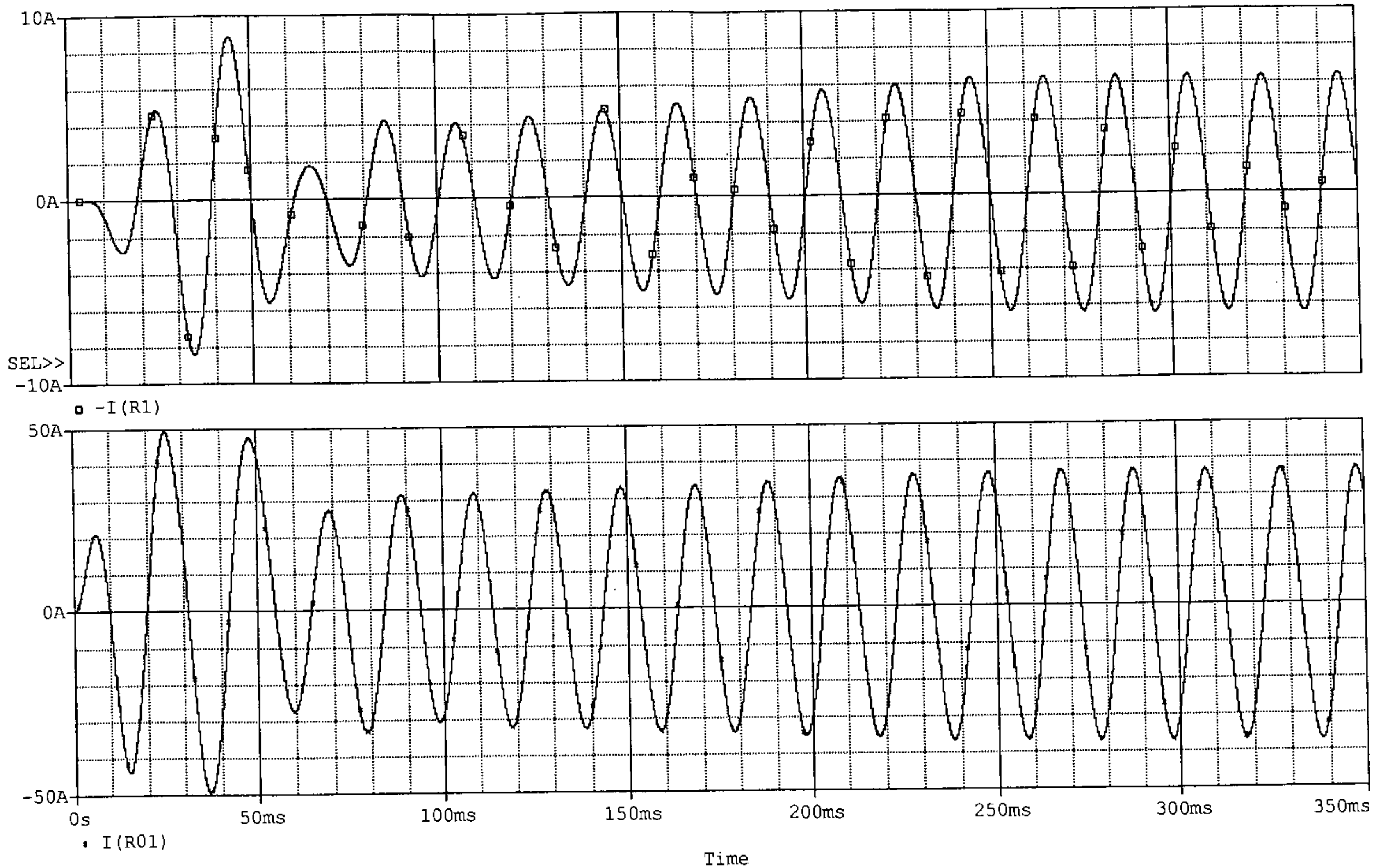


Figure-75. Input/output current waveforms when input voltage 350V and load 50 ohm.
I(L1)--Input current.
I(R1)--Output current.

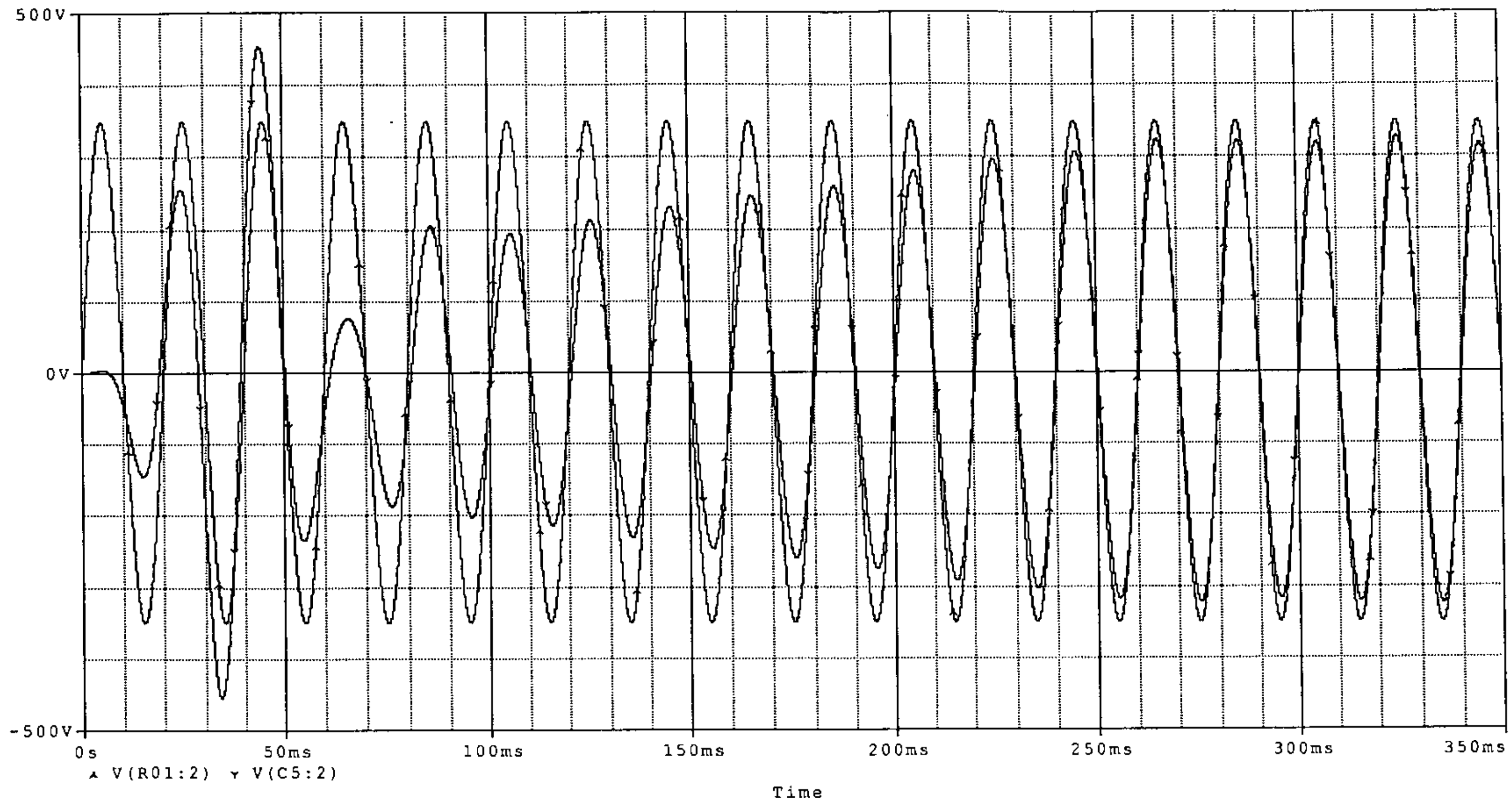


Figure-76 Input/output voltage waveforms when input voltage is 350V and load 60 ohm.

V(V1:+)--Input voltage = 350V.

V(L2:2)--Output voltage = 300V.

* Input power = 3050 watts. Output power = 900 watts. Power loss inside IGBT-1 = 1400 watts, IGBT-2 = 550 watts, snubber resistor R2 = 22 watts, R3 = 12 watts.

** Voltage regulation = -6.66%.

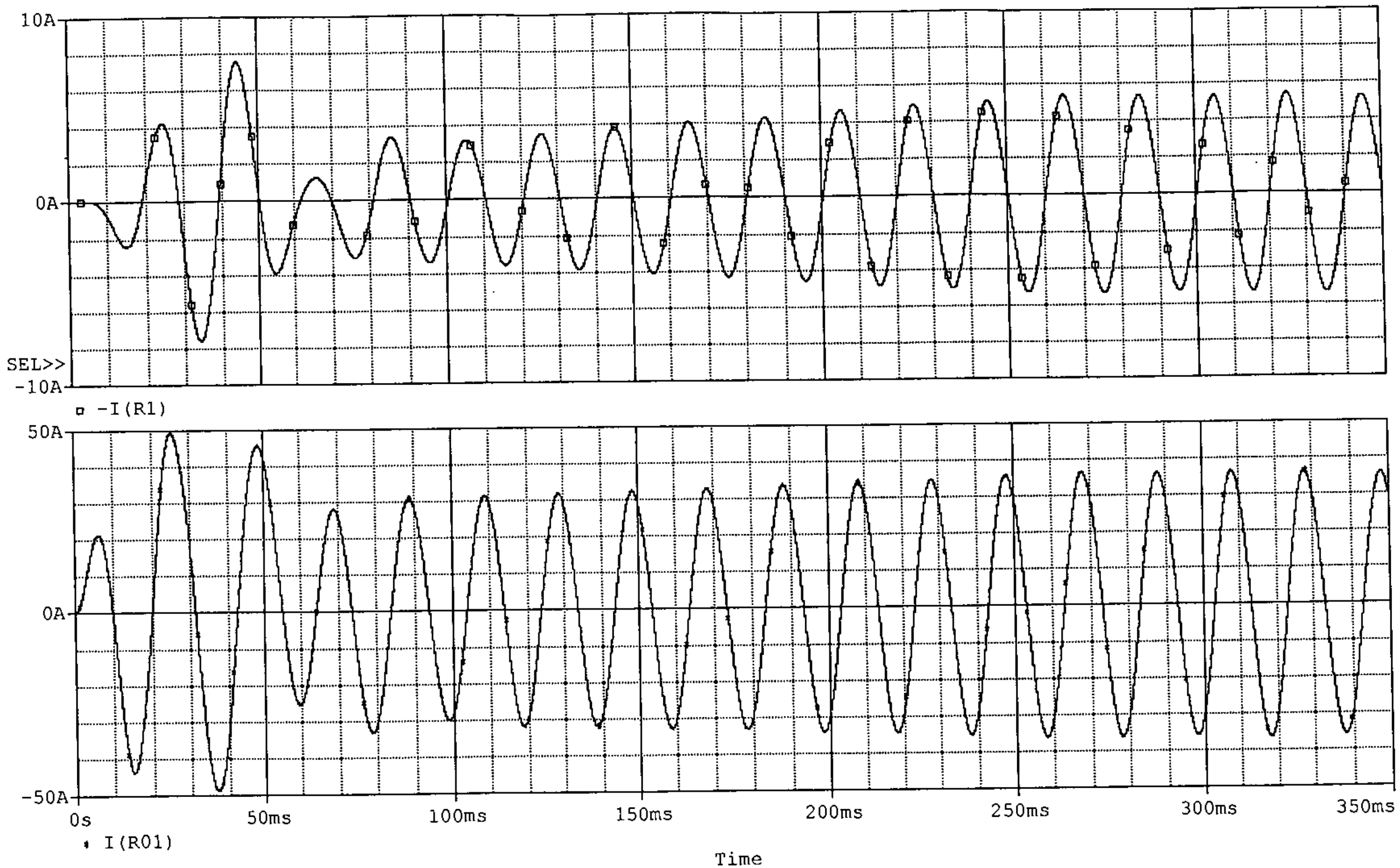


Figure-77. Input/output current waveforms when input voltage 350V and load 60 ohm.
I(R01)--Input current.
I(R1)--Output current.

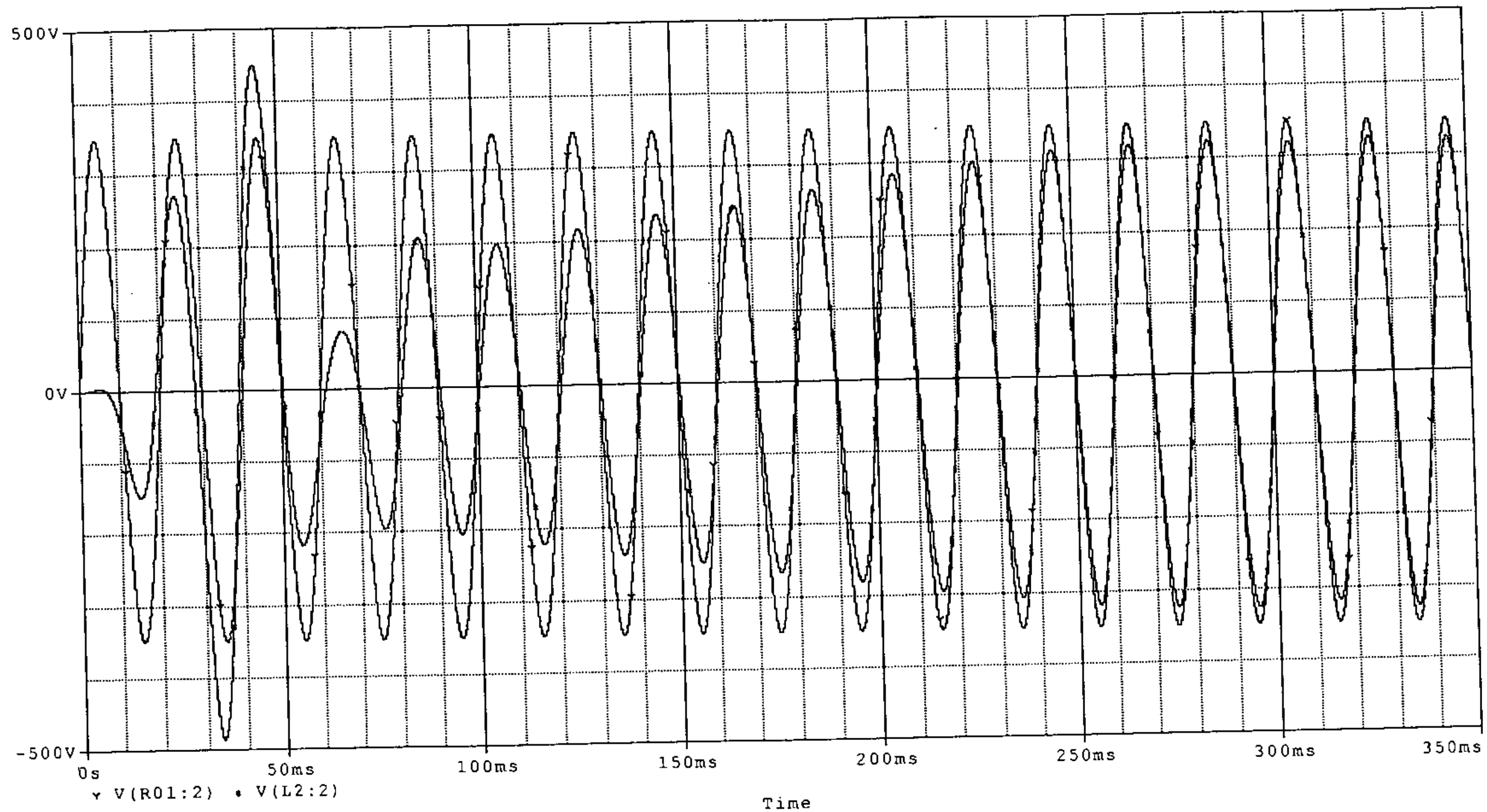


Figure-78 Input/output voltage waveforms when input voltage is 350V and load 70 ohm.
V(V1:+)--Input voltage = 350V.
V(L2:2)--Output voltage = 300V.

* Input power = 2900 watts. Output power = 750 watts. Power loss inside IGBT-1 = 1300 watts, IGBT-2 = 500 watts, snubber resistor R2 = 22 watts, R3 = 12 watts.

** Voltage regulation = -8.33%.

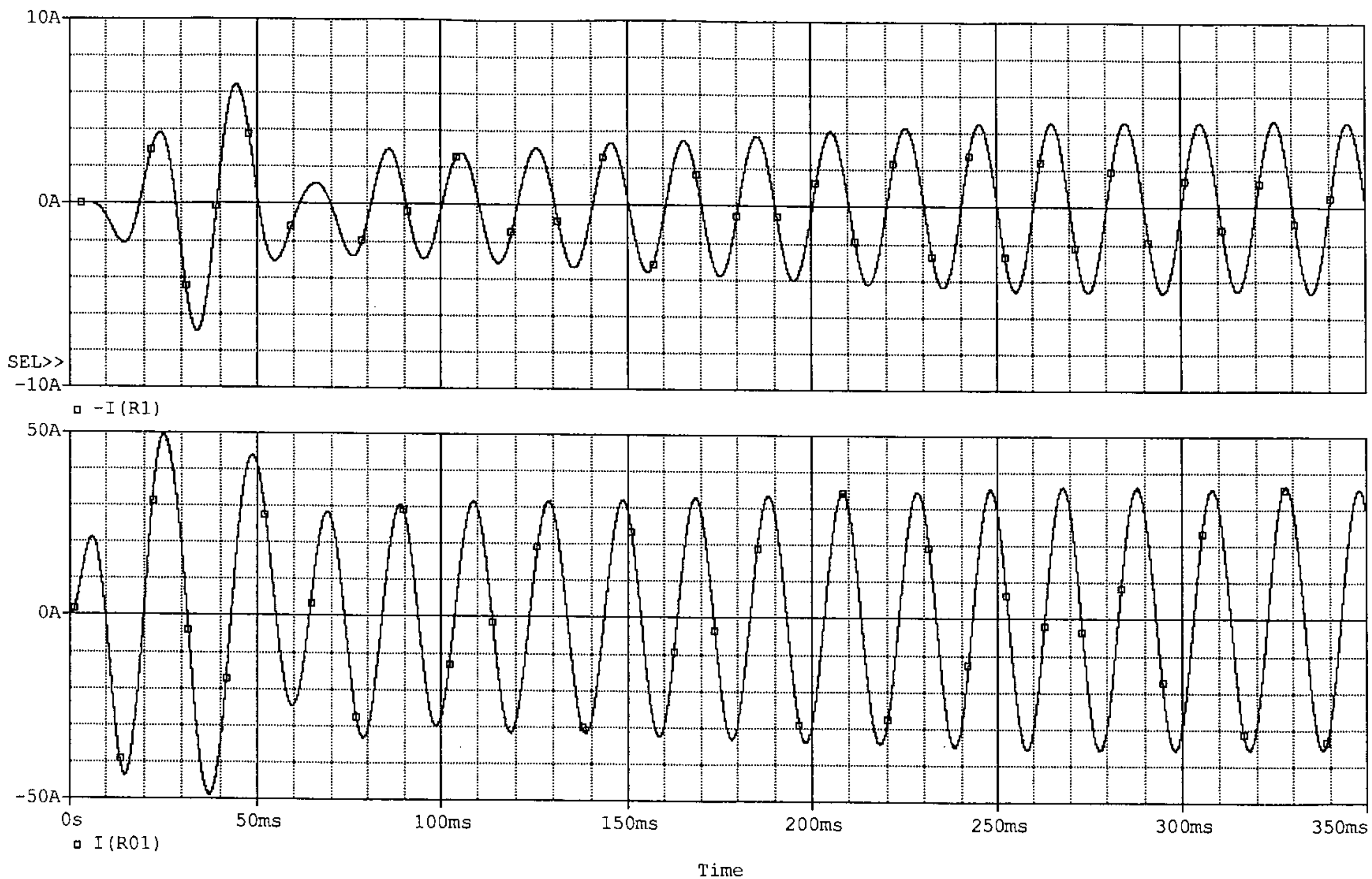


Figure-79. Input/output current waveforms when input voltage 350V and load 70 ohm.
I(L1)--Input current.
I(R1)--Output current.

2.4 CONTROL OF INPUT CURRENT

In AC C^uk regulator so far we have studied, input current is high in comparison to the load current but less than earlier thesis [5]. This is not desirable for a instrument to practical purpose. As such after extensive research and studied with necessary modification of the circuitry input current is reduced to about 30 ampere (peak). Further reduction is possible by applying the input filter circuit.

2.4.1 INPUT FILTER CIRCUIT

The Input current waveforms in fig-61, fig-64 and fig-67 shows that input current always lag input voltage by about 45 degree. The average current we may consider is about 35 ampere (peak) from mathematical calculation we can find out the var component of the current is 25 ampere. Thus a capacitor is to be provided to the input of the circuit which will draw 25 ampere. After calculation the value of the capacitor we get nearly 270 micro farad. The AC C^uk regulator circuit with input capacitor filter is shown in fig-80. The current waveforms with different load is shown in fig-81, fig-83 and fig-85, it shows that input current is reduced considerably to 20 ampere (peak), which is equivalent to 14 rms ampere only. After applying input filter circuit the input output voltage remains the same as before and are shown in fig-82, fig-84 and fig-86.

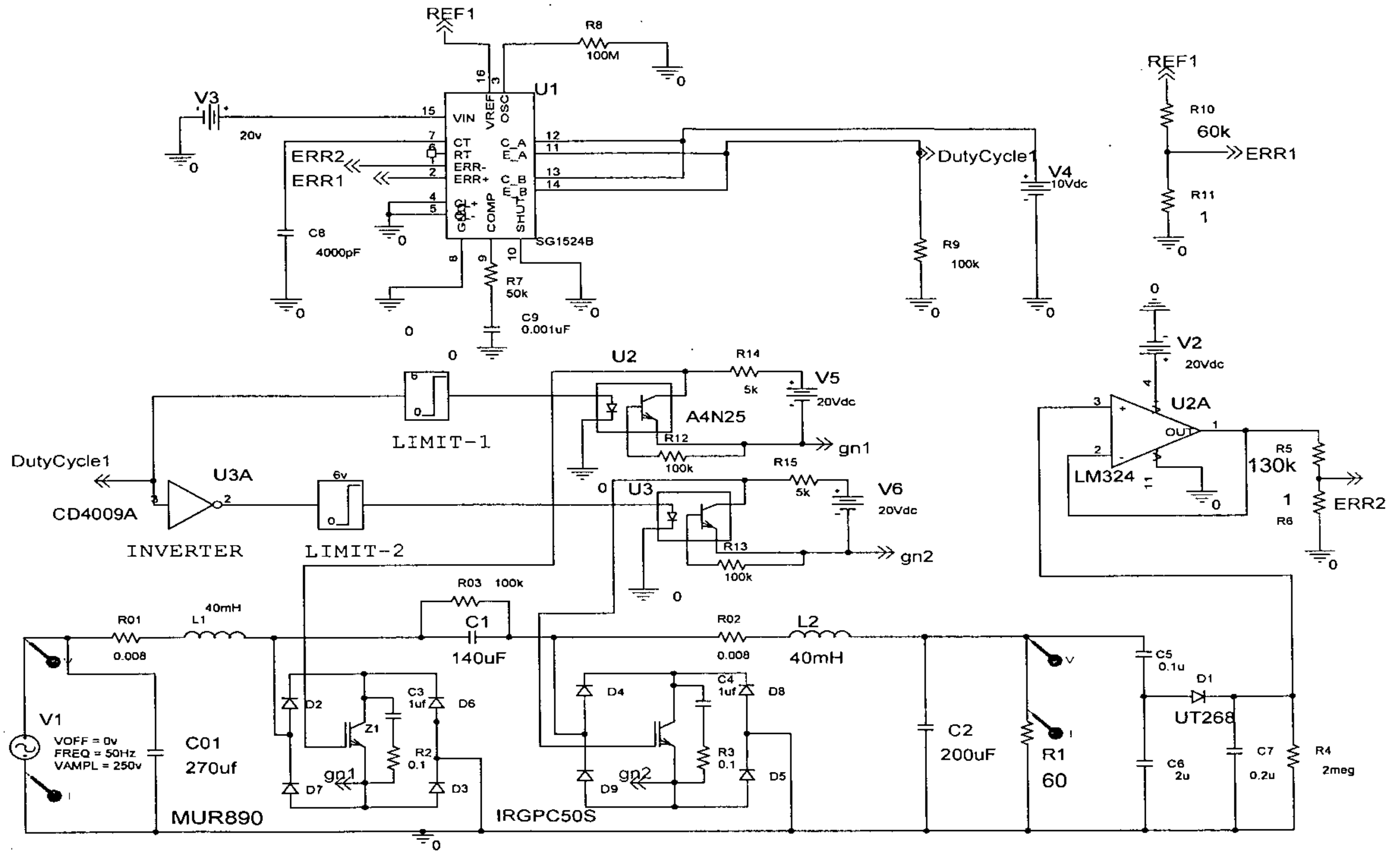


Figure-80. Automatic contol AC C^uk regulator circuit with input filter (practical switch implementation).

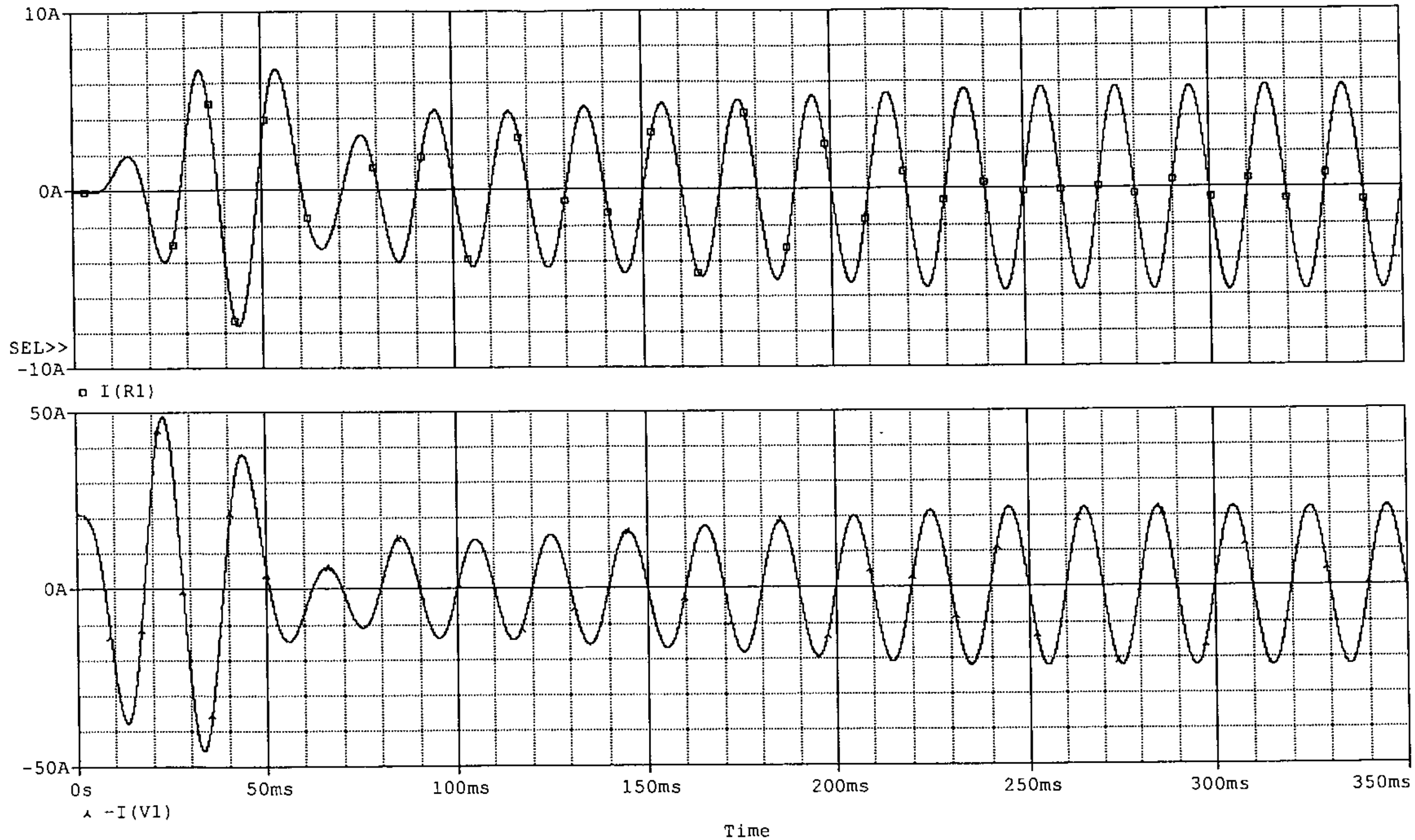


Figure-81. Input output current waveforms when input voltage 250V, load 50 ohm.
I(V1)--Input current.
I(R1)--Output current.

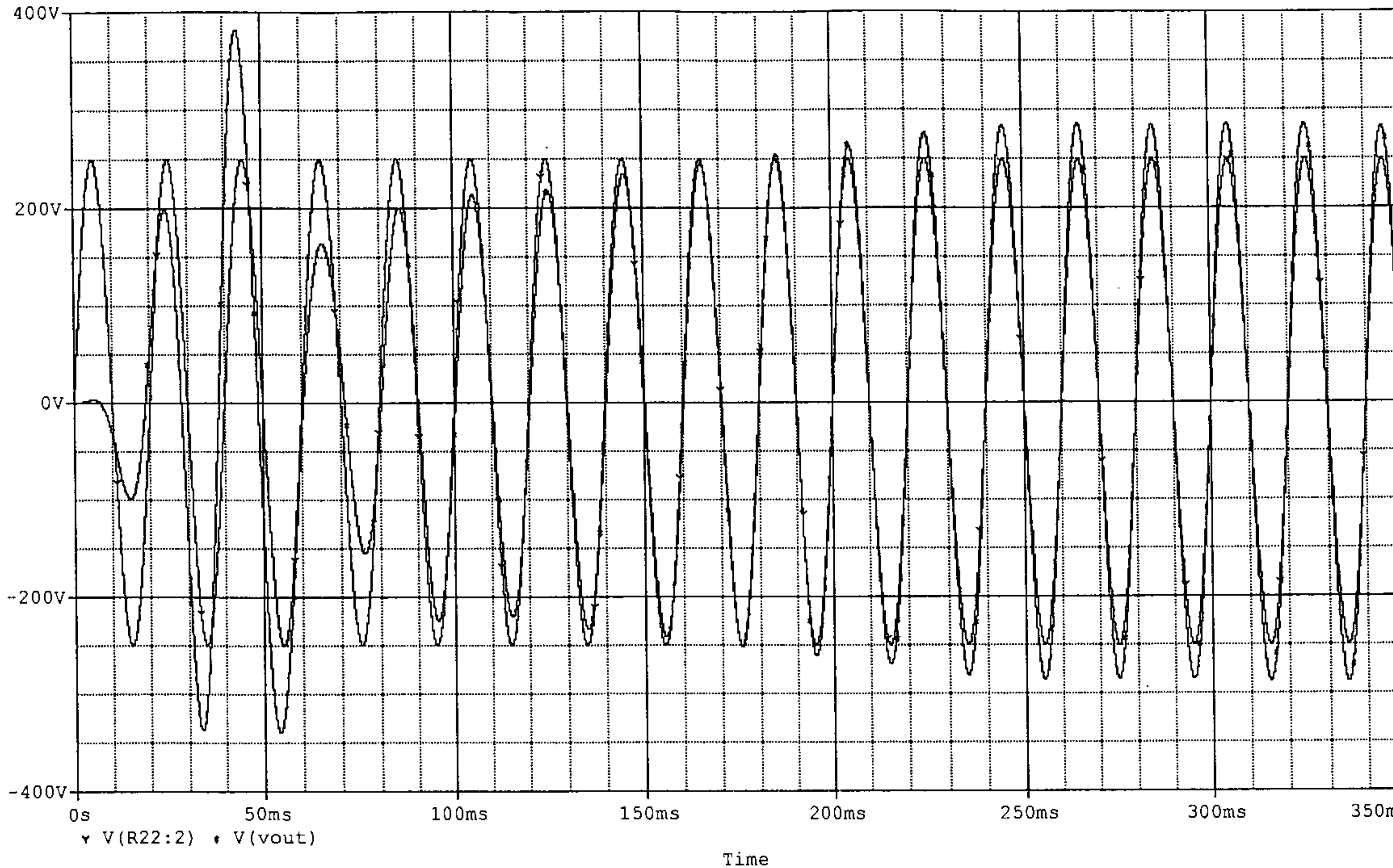


Figure-82. Input output voltage waveforms when input voltage 250V, load 50 ohm.
V(R22:2)--Input voltage=250V.
V(vout)--Output voltage=300V.

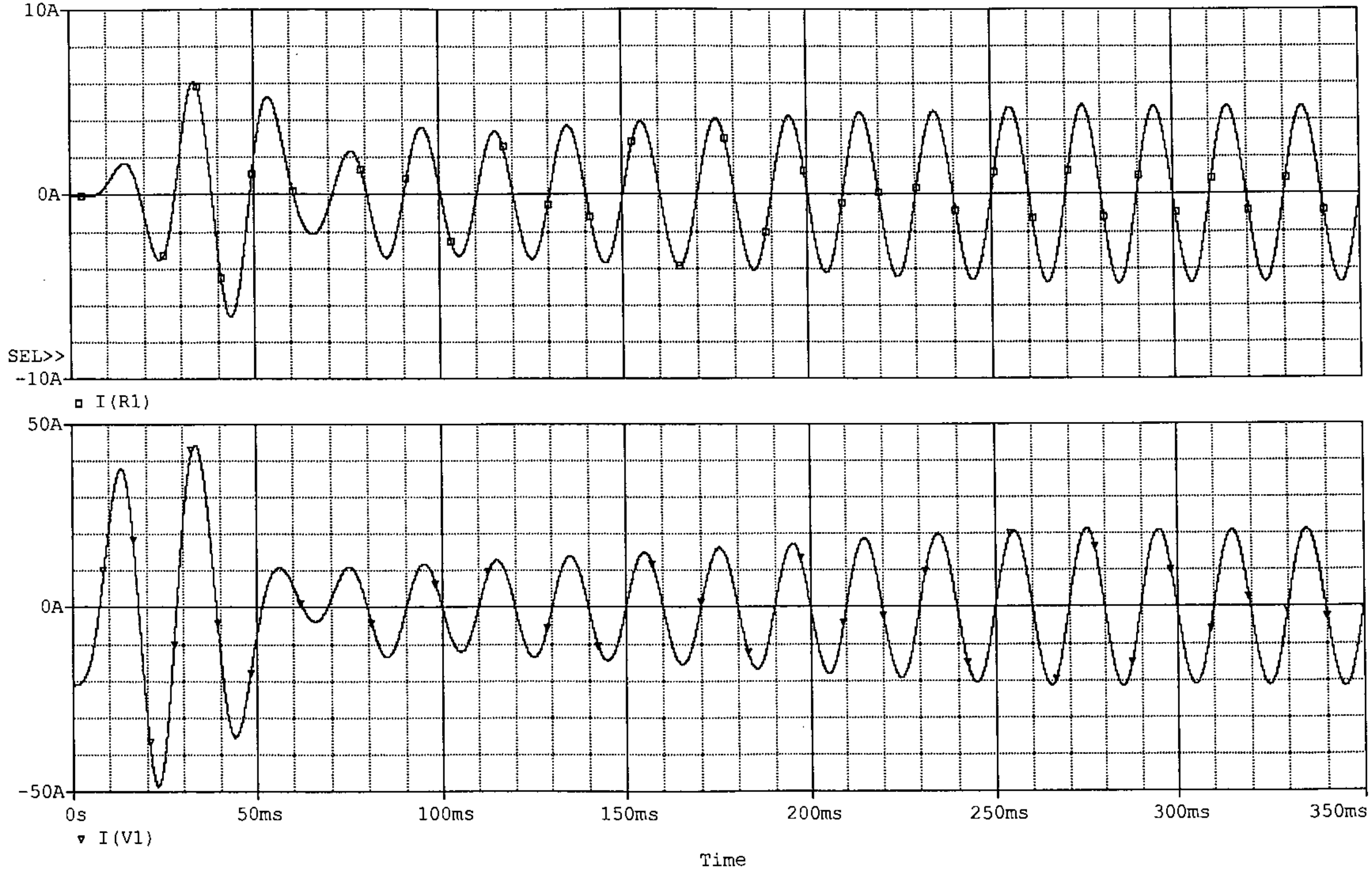


Figure-83. Input output current waveforms when input voltage 250V, load 60 ohm.
I(V1)--Input current.
I(R1)--Output current.

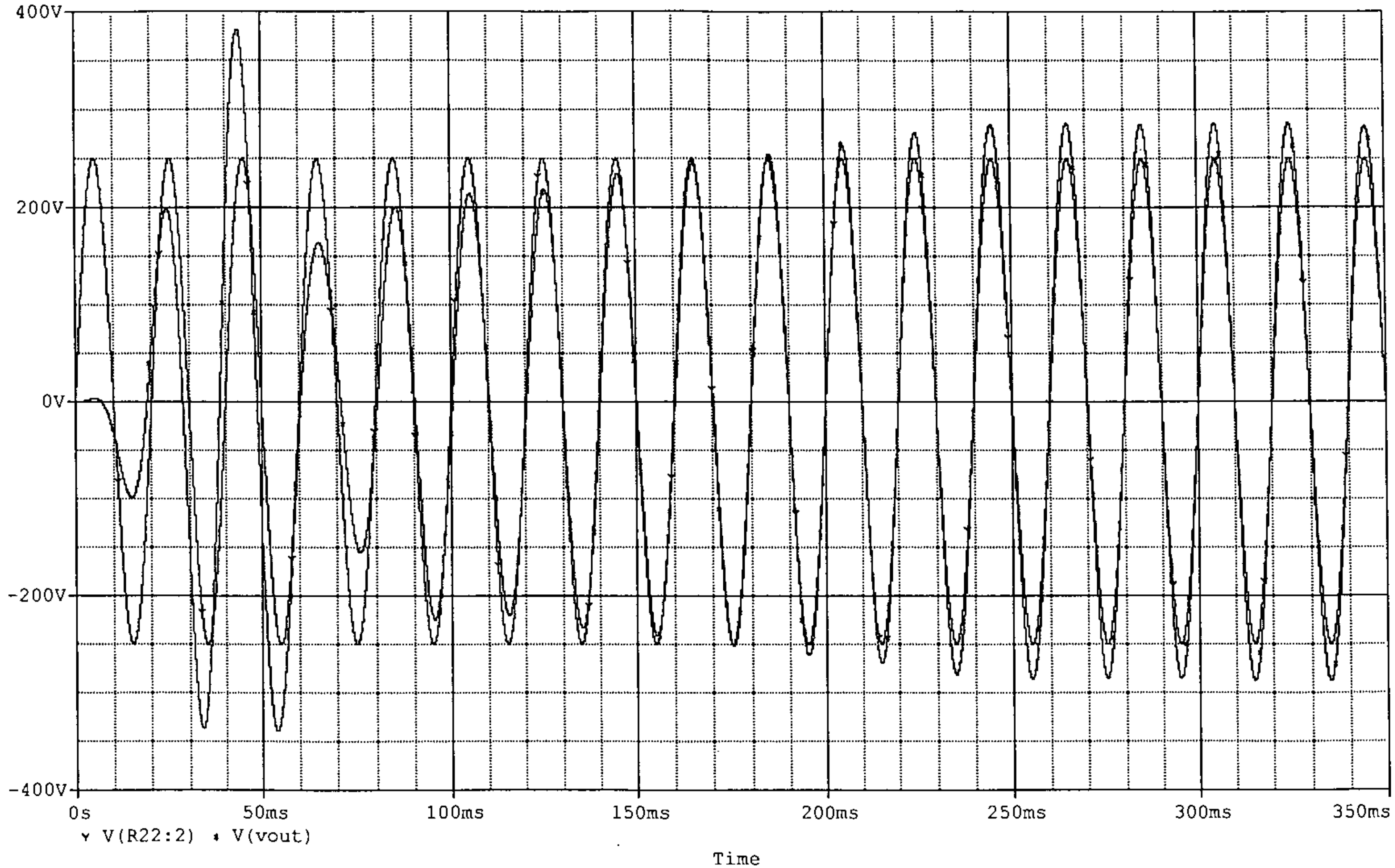


Figure-84. Input output voltage waveforms when input voltage 250V, load 60 ohm.
V(R22:2)--Input voltage=250V.
V(vout)--Output voltage=300V.

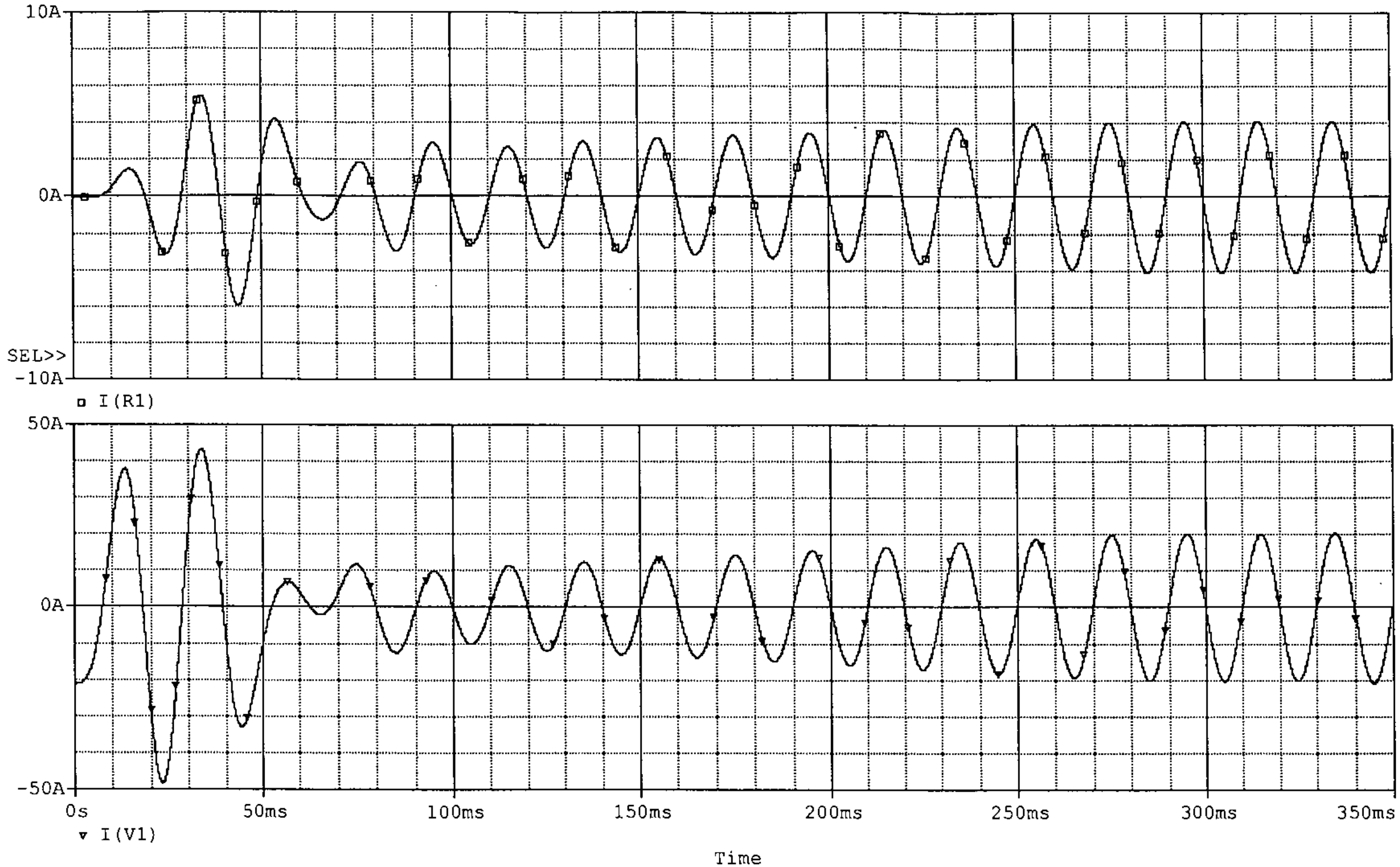


Figure-85. Input output current waveforms when input voltage 250V, load 70 ohm.
I(V1)--Input current.
I(R1)--Output current.

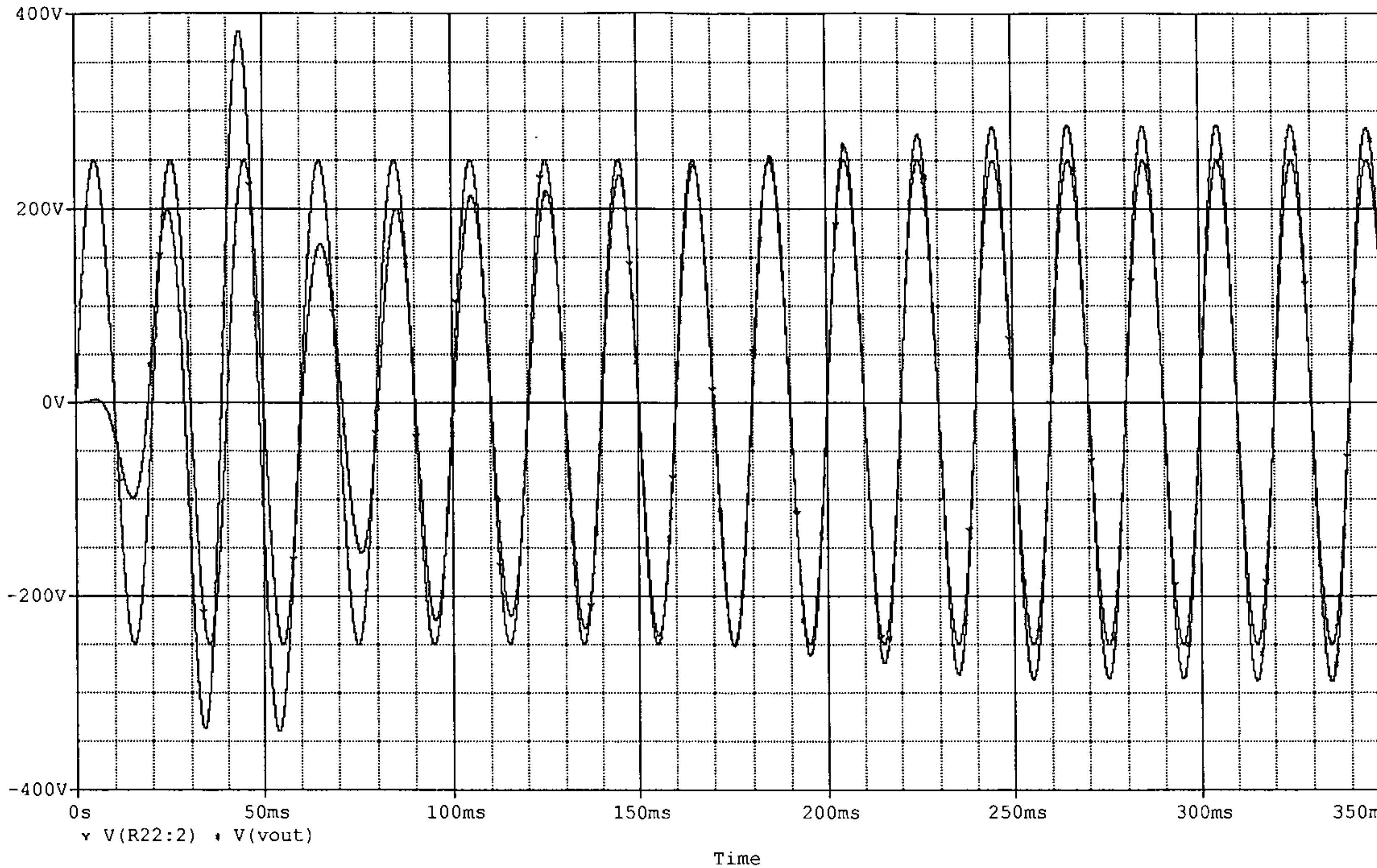


Figure-86. Input output current waveforms when input voltage 250V, load 70 ohm.
I(V1)--Input current.
I(R1)--Output current.

2.5 INPUT /OUTPUT RELATIONSHIP

2.5.1 IDEAL RELATIONSHIP

The Ideal relationship between input and output means that the losses associated with the inductors, capacitors, the switches and the diodes are not take into account. The relationship is derived for any half cycle of C^uk regulator and assumed to hold for other half cycle of AC C^uk regulator. The relationship of Input and Output voltage and current already derived in chapter-1 in case DC to DC C^uk converter in eqs.-(1.32) and (1.33).

$$V_a = \frac{-KV_s}{1-K} \quad (1.32)$$

$$I_s = \frac{KI_a}{1-K} \quad (1.33)$$

Equation (1.32) & (1.33) show the ideal relationship of input-output voltage and input-output current respectively. Voltage and current quantities are in time varying form.

2.5.2 NON IDEAL RELATIONSHIP

The parasitic in a C^uk regulator are due to non-ideal inductor, capacitor, the switch and the diode. The parasitic elements have significant impact on the voltage conversion ratio, efficiency and the stability of the switch mode converters. The effect of these parasitic elements can be modeled in the circuit simulation programs for designing such converter.

Parasitic Effect on Voltage Gain and Efficiency:

Inclusion of lossy elements in the converter analysis is necessary, since otherwise the results may be qualitatively misleading. The voltage gain of the C^uk converter as obtained in equation (1.32) becomes infinitely large when the duty cycle ratio K approaches 1, which is not achievable practically. Inclusion of lossy elements in the analysis, such as the parasitic resistance of the inductor, corrects this problem. The efficiency also reduces from the ideal 100 %, because of the loss on the inductor resistance and other components of the regulator. The losses mostly occur in the circuit of AC C^uk regulator is inside IGBTs, this is due to improper switching time of the PWM gate signals.

We know,

$$Efficiency = \frac{P_{out}}{P_{out}+P_{loss}}$$

P_{loss} = Loss occurs in IGBTs, diode D2 to D9, inductor L1, L2, capacitor C1, C2, and also inside the components of Auxiliary circuits. These losses are very small but due to improper switching these losses are sometimes very high, as such efficiency of this regulator is not 100%, though ideally it can be considered 100 % efficient.

2.6 DRAWBACKS OF AC C^UK REGULATOR

(a) Efficiency is less:

For 6 ampere (peak), equivalent to 4.25 ampere rms output current, input current is 14 rms ampere, so for 1100 watt output power input power is 2500 watt, Therefore efficiency of this regulator is about 44%. Though the circuit provides automatic voltage regulation the efficiency is very poor and needs to be investigated for further improvement.

CHAPTER – 3

CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

Power quality describes the quality of voltage and current of power system and is one of the most important considerations in domestic, industrial and commercial applications today. Power quality faced by industrial operations includes transients, sags, surges, outages, harmonics and impulses. Voltage sags are one of the most important power quality problems affecting domestic, industrial and commercial customers. Voltage sag is the momentary decrease or increase in the rms voltage magnitude, usually caused by faults or sudden loading on the power system. Equipment used in modern industrial plants is becoming more sensitive to voltage fluctuations as the complexity of the equipment increase. Increasing use of loads supplied by electronic power converters has led to growing problems in the quality of power supplies. Computers, adjustable speed drives and automated manufacturing processes are very susceptible to voltage sags and brief outages.

DC to DC converters with isolation transformers can have multiple outputs of various magnitudes and polarities. The regulated power supply of this type has wide applications, particularly in computer system, where, a low voltage high current power supply with low output ripple and fast transient response are mandatory. An essential feature of efficient electronic power processing is the use of semiconductor devices in a power supply in switch mode (to achieve low losses) to control the transfer of energy from source to load through the use of pulse width modulated techniques. Inductive and capacitive energy storage elements are used to smooth the flow of energy while keeping losses at a low level. As the frequency of switching increases, the size of the capacitive elements decreases in a direct proportion. Because of their superior performance they are replacing conventional linear power supplies.

This thesis has proposed a AC- AC C^uk regulator for ac power applications. The function of AC- AC C^uk regulator is to keep output voltage constant either for a input voltage increase or decrease and also during load changes. If the output voltage remains constant equipment life time increases and outages and maintenance are reduced. The AC- AC C^uk regulator are studied for ideal and practical with ground isolation switches. It has been observed that in the controlled AC C^uk regulator when input voltage is 200V, 250V, 300V, 350V and 400V then output voltage is always maintained at 300V corresponding to 230V rms. To maintain constant output voltage PWM control is used. By varying pulse width of output of the control signals On/Off time to switch automatically through electronic circuit have achieved the goal of maintaining the constant output voltage across load. Due to freewheeling path surge voltage appears across the switches in the manual control circuit. In this work snubbers are used as a remedy to this problem. However this problem does not arise when regulator uses IGBTs as switches in practical circuit. Input current is very high of this regulator but after extensive research necessary modification is done on the circuitry. Input current is greatly reduced from 60 ampere of earlier thesis [5] to 14 rms ampere. Filter circuit is used to smooth the output. As a starting work towards obtaining a practical light weight, efficient and reliable AC to AC voltage regulator the proposed C^uk regulator show promising aspects. Moreover by implementation of IC chip (SG1524B) the circuit design is compact and commercially more acceptable.

3.2 RECOMMENDATION OF FURTHER WORK

The proposed AC C^uk regulator should be implemented practically in laboratory in future works. Also the drawbacks listed in chapter 2.6 are needed to be rectified after further research. The recommendation for those are given below:

(a) Ffficiency is less:

The switching losses of the different components uses in the circuits are the inherent properties of those components, it is not possible to reduced them but the additional losses occur due to improper selection of switching time can be minimized after further research.

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