POWER FACTOR IMPROVEMENT OF VARYING LAGGING LOAD BY PWM SWITCHED SINGLE CAPACITOR

by

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ABSTRACT

In this thesis, an important overview has been given about the need for power factor improvement, the history of power factor correction by capacitors and the review of static power factor correction methods.

A new method is proposed which improves the power factor automatically of varying lagging loads to unity using one single large shunt capacitor instead of using a bank of switching capacitors. Basically, this control scheme is a static power factor improvement method by continuous voltage or current control of a capacitor. In this work, the voltage across the capacitor is being changed by a bi-directional switch to control the magnitude of compensating capacitor current and thereby attaining unity power factor. The switching device is turned on-off by a pulse width modulated signal having moderately high frequency (several times of source frequency) to produce a current which is equal to the reactive component of load current in magnitude but is directed in opposite direction. As a result line current will be in phase with source voltage.

The control scheme is involved in detecting the power factor angle of the load and also the magnitude of the load current and then making the capacitor voltage is changed automatically according to the var compensation of the load to improve line power factor..

The scheme is simple in the sense that it uses only one static bi-directional switch controlled by an electronic control circuit. The electronic control circuit is also simple that uses only analog ICs and some discrete digital components.

CHAPTER – 1

INTRODUCTION

1.1 INTRODUCTION

Reactive power is recognized as an essential factor in the design and good operation of power systems. Real and reactive power on a transmission line in an integrated network is governed by the line impedance, voltage magnitudes, the angle of difference at the line ends, and the role the line plays in maintaining network stability under dynamic contingencies. Reactive power (VAR) compensation or control is an essential part in a power system to minimize power transmission losses, to maximize power transmission capability, and to maintain the supply voltage within desired level.

Static reactive power compensation is becoming one of the most economic and effective solutions to both traditional and new problems in power transmissions systems. It is a well established practice to use reactive power compensation to control the magnitude of the voltage at a particular bus bar in any electric power system. In the past, synchronous condensers, mechanically switched capacitors and inductors, and saturated reactors have been applied to control the system voltage in this manner. Since the late 1960s, thyristor controlled reactor (TCR) devices together with fixed capacitors (FCs) or thyristor switched capacitors (TSCS) have been used to inject or absorb reactive power.

In an ideal electro energetic system, the voltage and frequency in the various points of power distribution must be constant, presenting only the fundamental component (harmonics contents nil) and a near-unity power factor. In particular, these parameters must be independent of the size and characteristics of the consumer loads; this can be obtained only if these loads are equipped with reactive power compensators to make the network independent from probable changes that appear in the distribution points. Compensation of the loads is one of techniques for the controlling reactive power, so to improve the quality of the energy in the ac transmission lines; this technique is generally used for the compensation of individual or a group of loads.

This has three essential objectives:

1. Power factor correction
2. Improvement of the voltage regulation
3. Load balancing

It is noted that power factor correction and load balancing are the desired even when the supply voltage is virtually constant and independent of the load.

Power factor correction is the capacity of generating or absorbing the reactive power –[1] to a load without the use of the supply. The major industrial loads have inductive loads (they absorb reactive power); hence the current tends to go beyond the necessary value to active power absorption alone. But active power is usually used for the power conversion, and an excessive load current represents a loss for the consumer, who not only pays for the over-dimensioning of the cable but also for the excess power loss in the cables. The electric companies do not want to transport the useless reactive power of the alternators toward the loads, and the distribution network cannot be used at high efficiency. The voltage regulation in the various points becomes complicated. The pricing used by electric companies always penalize the low power factor of the clients; hence the development of systems for power-factor improvement for industrial processes is necessary.

1.2 NEED FOR POWER FACTOR IMPROVEMENT :

There are three categories of electrical loads in an electrical system:

- Resistive - Resistive loads offer only a resistance to current flow. The load itself does not affect the current or voltage waveforms of the incoming power supply. Examples would be electric heating and incandescent lights.

- Inductive - Inductive loads tend to affect the phase angle of the incoming power supply, such that the current drawn will lag the voltage supplied. Examples include electric motors, transformers, and lighting ballasts.

- Non linear - Non linear loads affect the shape of the electric voltage and current waveforms. Examples include high-tech equipment, including computers, printers, and electronic lighting ballasts.

Power factor is the name given to the ratio of the real or usable power measured in kilowatts (kW) to the total power supplied measured in kilo volt-amperes(kVA). Inductive loads contribute to a reduced power factor.

A pure resistive load gives a power factor of 100%. At a power factor below 100%, the utility must supply additional reactive power, which increases the costs of the electrical system. Allowing some leeway, most utilities require that a customer's power factor be maintained above 90%. Those customers below 90% are surcharged in proportion to the amount of additional reactive power required.

Power factor can be corrected by installing power factor correction capacitors. Capacitors have a parallel but opposite effect on the power source as the inductive loads, so the two effects cancel one another. There are two product categories, static capacitors (lower cost, appropriate when the required correction stays within a reasonably narrow range) and switching capacitors (able to respond to changing correction requirements when, for example, significant motors come on and off). Additionally, the building owner will often have to decide whether the capacitors should be placed where the relevant equipment is supplied, or at the service entrance. That decision is made based on the type of equipment and power quality found in the building. The more non-linear loads and the more harmonic distortion found, the more appropriate it will be to install the capacitors near the loads. In highly sensitive applications, various means of isolation have to apply.

1.3 REVIEW OF POWER FACTOR CORRECTION BY CAPACITOR : [2]

Shunt capacitors were first applied for power factor correction in 1914. Their use, however, was limited during the next twenty years because of high cost per kVAR, large size and weight. Prior to 1932 all capacitors employed oil as the dielectric. At about this time the introduction of chlorinated aromatic hydrocarbon impregnating compounds (askarels) and other advances in the capacitor construction brought about sharp reductions in size and weight.

The acceptance of capacitors has been due to the following:

1. Reduction in selling price.

2. Improved design and manufacturing methods resulting in small size and weight.

3. Development of outdoor, pole-type units and standardized mounting brackets.

4. Reduction in failures.

5. Better understanding of system benefits that acquire from their use.

1.4 REVIEW OF STATIC POWER FACTOR CORRECTION METHODS :

1.4.1 INTRODUCTION

The industrial loads such as induction motors and induction furnaces account for most of the reactive power drawn from the AC supply. The transformers used in power transmission and distribution and others, which may form part of the load or the supply consumer reactive power owing to the magnetizing current drawn by them. Besides, the household loads such as fluorescent lights, fans and other appliances using fractional horsepower induction motor draw reactive power from the AC supply system. The loads are usually not balanced in the three phases of the three-phase supply network. The negative sequence component, which arises due to the unbalanced loads, is also considered as a sort of the reactive current from the AC supply system. Thus, the demand for the reactive power from the supply network terminal increases to a large amount. This increased reactive power causes the system to operate at low power factor. The supply power factor is critical for an economical design, and efficient and reliable operation of power systems.

Some of the disadvantages of low supply power factor are the following:

- It causes an increase in current in utility lines and hence results additional loss (proportional to I^2) of active power in all the elements of power system from power station down to the utilization devices.

- It causes overheating of the system component as large current flows to meet certain active power demand.

- The cross-sectional area of bus-bars and switch-gears (ie conductor size) have to be increased to transmit or distribute a certain amount of power.

- It requires larger kVA rating of equipments (transformers, alternators etc) than necessary to meet certain active power demand.

- It causes poor voltage regulation at the load and hence power transfer capability is adversely affected.

- It increases the investment in system facilities per kW of load as the supply power factor decreases.

These disadvantages can be overcome to a large extent if the power factor is improved externally. In fact, it is a practice since the inception of AC power transmission to install reactive power compensators, for power factor improvement. The reactive power compensators are external devices, which supply and compensate the lagging reactive power consumed by the load thereby relieving the burden on the AC supply. These compensators are also known as power factor correcting devices. The reactive power compensators are connected across the supply terminals to relieve the transmission lines from the excess current. Hence, they are called shunt compensators. Thus the function of the shunt compensator is to minimize the voltage fluctuation at a given terminal and to improve the supply power factor by compensating the load reactive power. In general, the problem of compensation by reactive power compensators is viewed from two aspects, load compensation and voltage support.

1.4.2 LOAD COMPENSATION

The objective is to reduce or cancel the reactive power (VAR) demand of large, and fluctuating industrial loads, such as electric arc furnaces, rolling mills, etc. and to balance the real power drawn from the AC supply lines. These types of heavy industrial loads are normally concentrated in one plant and supplied from one network terminal, and therefore can be handled best by a local compensator connected to the same terminal.

1.4.3 VOLTAGE SUPPORT

This is generally related to the voltage at a given terminal of a transmission line. The objective is to balance the voltages of the three phases, regulate or control the voltage at a given terminal whenever it deviates from a reference value due to the disturbances of both loads and generation. Because of the complex interconnected AC network – it may not be possible or practical to measure the quantities that would meaningfully characterize the load. Instead, the transmission line voltage is regulated by the shunt compensators because it determines the transmittable power. The transmission network compensation is achieved in a manner different from that of the load compensation although both compensation schemes are fundamentally the same in respect of compensation of the load reactive power. Here the compensation currents are expressed in terms of the terminal voltages, and the impedance of the AC system plays a significant role in the transmission network compensation.

With the passage of time, the shunt compensators have gone through several modifications with the rapid developments in the power system as regards the increase in the operating voltage level and complex interconnections of large networks. In what follows, a review of such reactive shunt compensators has been presented chronologically.

1.5 SHUNT REACTIVE POWER COMPENSATORS : - [3]

1.5.1 FIXED CAPACITOR BANKS

A review of fixed capacitor bank shunt capacitors is made in section 1.3.

The selection of shunt capacitors is dependent on many factors. The most important is the amount of lagging VAR taken by the load. In case of widely fluctuating loads, the VAR of the load also varies over wide limits. Thus a fixed capacitor bank may often lead to either over-compensation or under-compensation resulting in lower power factor in the AC power supply system.

1.5.2 SWITCHED CAPACITORS

The wide range of variation in lagging VAR on the system has caused the necessity for controlled compensation of the reactive power to achieve desired power factor at all load conditions. This is usually achieved by using switched capacitors. Depending on the total VAR requirement, a number of capacitors are used which can be switched into or switched out of the system individually. The control is accomplished by continuously sensing the load VAR. If more compensation is required, then the required numbers of capacitors are switched into the circuit so as to take the extra VAR. Conversely, the required numbers of capacitors are switched out if the load VAR falls. The smoothness of control is solely dependent on the number of capacitor switching units used. A very fine control of the power factor can be achieved at the expense of economy by using a large number of such small units. The switching is conventionally accomplished using relays and magnetic contractors. One such method uses a master control relay in addition to a time-delay relay for each unit. For one-step automatic control the master relay energizes the closing element of the time delay relay and if the master-relay contacts stay closed for the time required for the time delay relay contacts to make, then the operating circuit is energized and the capacitor breaker closes. A similar process reverse trips the capacitor breaker. For more accuracy and reliability, multi step control is preferred. However, these methods using mechanical switches and relays invariably suffer from the drawback of being sluggish, introducing switching transients and requiring frequent maintenance. With the advent of high power solid state devices, thyristors have replaced the mechanical switches. The rugged electronic circuits have made the system highly reliable. Thyristor switching of a static capacitor has made it possible to achieve virtually continuous control of reactive power generation on a large scale. Each small unit of capacitors is switched on and off individually using thyristors as switching elements as shown in **Fig. 1.5.2. (a)** The supply current is also shown neglecting the commutation interval. The switching-on transients are avoided by selecting the switching-on instant, at the time when the network voltage corresponds in magnitude and polarity to the capacitor voltage. Switching off transients is not a problem since turning-off of the thyristors occurs at the next current zero after the removal of the gate pulse. The capacitor then remains charged to either positive or negative peak value of the network voltage and is prepared for a new switching-on, which will be free from transients. The time required for switching on or off is made up of the time to detect the magnitude of the desired, change in the reactive power(one-half cycle), plus variable time (maximum of one-half cycle) waiting for suitable switching conditions. Switching-on or off is therefore achieved within one cycle of the power frequency. Usually, a step-down transformer, as shown in **Fig.1.5.2(a)** is necessary to suit the voltage ratings of thyristors and capacitors. Switched inductors working on the same principle are also used in transmission systems for direct compensation of the charging capacitance of a transmission line. Such a scheme is illustrated in **Fig.1.5.2 (b)** along with the supply voltage and current waveforms.

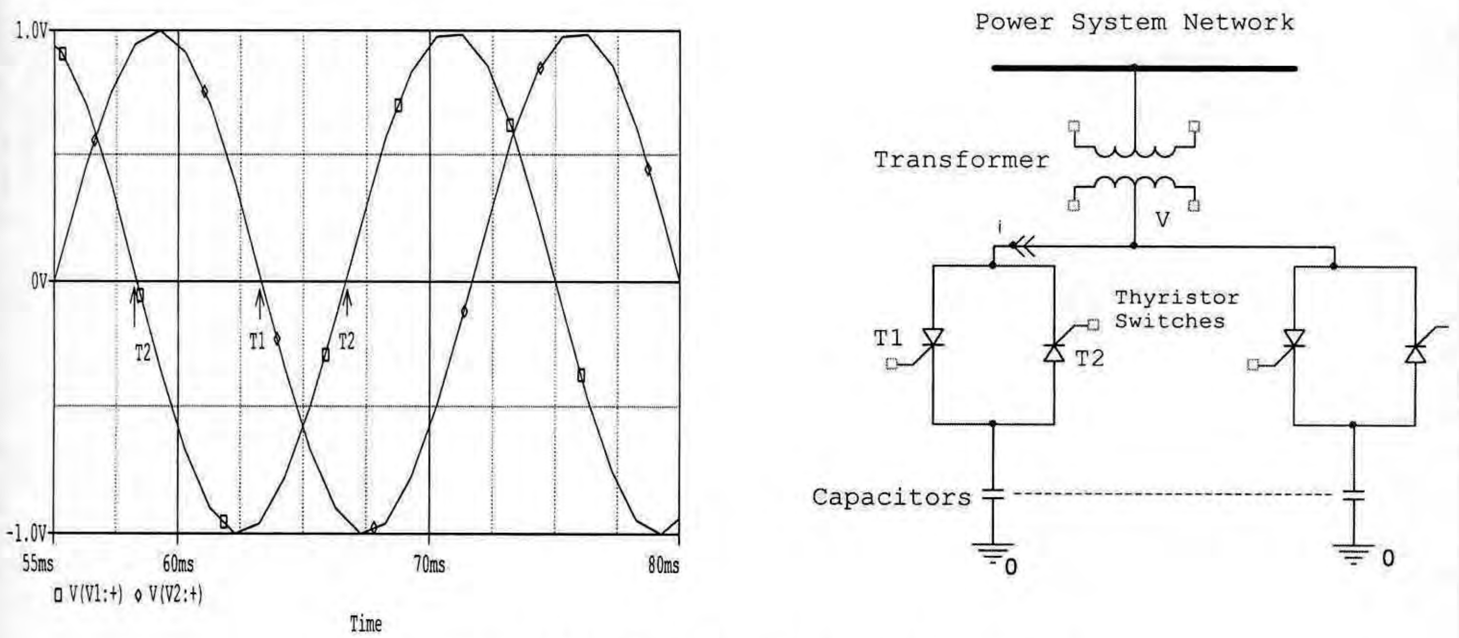


Figure : 1.5.2- (a) Thyristor switched capacitors

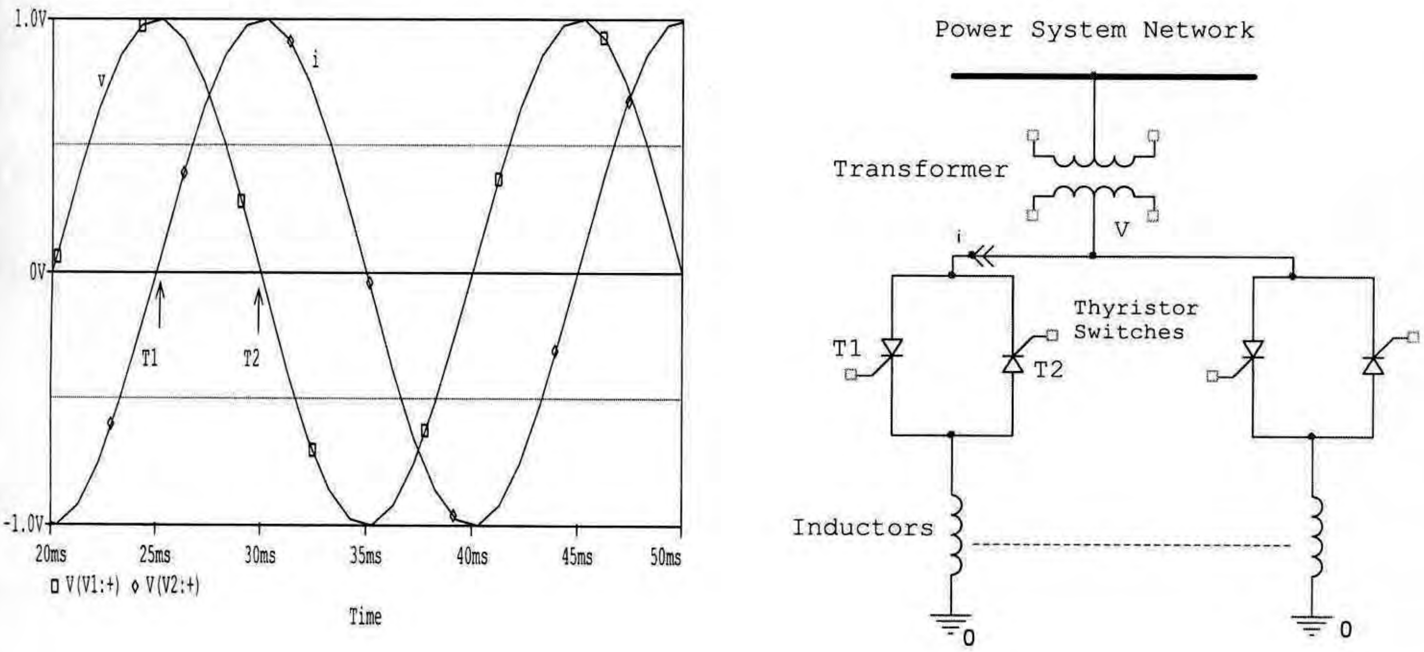


Figure : 1.52 (b) - Thyristor switched inductors

1.5.3 SYNCHRONOUS CONDENSER

The synchronous machine when over-excited, draws leading current from the supply system. This characteristic particularly makes it useful as a dynamic power factor correction device. The machine can provide continuous VAR balance when used with proper automatic exciter control system. The short time overload capacity of synchronous condenser is larger than that of capacitor. The synchronous condenser has also greater stabilizing effect upon the system voltage. However, it has also many drawbacks as, compared to the shunt capacitors. The losses in the synchronous condensers are much greater than for the shunt capacitors. For synchronous condensers the full load losses vary from about 1.5 percent to 3 percent of the kVA rating whereas for capacitors the losses are about 0.33 percent of the kVA rating. The capacitors are more effective since they lend themselves to distribution at several locations closer to the load throughout the network. It will be very costly to distribute small synchronous condensers throughout the system. The VAR (reactive volt-amperes loading) rating of a capacitor installation can be easily changed with a variation in the load and system requirements day by day which is impractical with the synchronous condensers. The failure of a synchronous condenser compared to a single unit in a bank of capacitors is less likely to occur. However, any such failure in a synchronous condenser completely affects entire ability to produce VAR. This is not so in the capacitor banks since there are several other capacitors in a bank even if a particular unit fails. Synchronous condensers increase the short-circuit current of a system and thus the breakers of higher rating are required. The response of the synchronous condenser is slow due to the inherent mechanical inertia.

1.5.4 STATIC VAR COMPENSATOR :

STATIC REACTOR COMPENSATOR : [3]

The aim is to achieve fine control over the entire VAR range as in the case of the synchronous condenser without sacrificing the advantages of static capacitors has been fulfilled by the development of the static reactor compensator. This essentially consists of a controllable reactor in parallel to a shunt capacitor as shown in Fig. 1.5.4

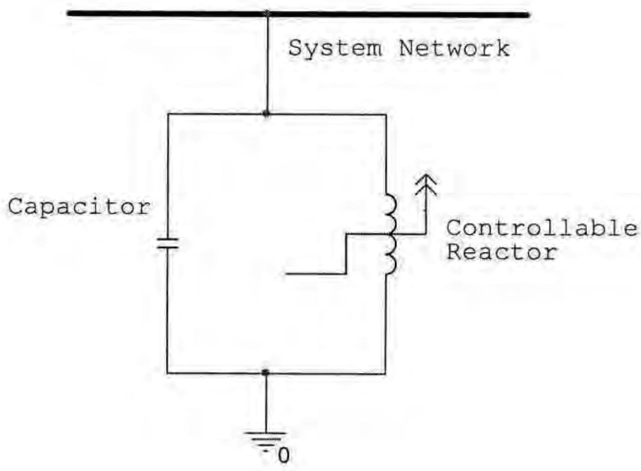


Figure : 1.5 .4 - Basic static reactor compensator

By choosing proper values for the capacitor and the inductor, it is possible to achieve smooth and stepless control of VAR from lagging to leading over a wide range to compensate for the wide variations in the load VAR. This is accomplished by a continuous control of the effective fundamental reactance of the inductor. Since there is a greater requirement for the leading VAR, preferably a number of capacitors are switched in steps to provide a wide range of leading VAR.

MODERN STATIC VAR COMPENSATOR [4-19]

In the past, synchronous condensers, mechanically switched capacitors and inductors, and saturated reactors have been applied to control the system voltage in this manner. Since the late 1960s, thyristor-controlled reactor (TCR) devices together with fixed capacitors (FCs) or thyristor-switched capacitors (TSCs) have been used to inject or absorb reactive power.

Series compensation is the control of the equivalent line impedance of a transmission line. The induction of external components (either capacitive or inductive) is used to change the apparent reactance of the line. A controllable series compensator such as the thyristor-controlled series compensation (TCSC) has been developed to change the apparent impedance of a line by either inductive or capacitive compensation, facilitating active power transfer control. The thyristors control the conduction period of the reactor to vary the overall effective Z of the circuit. The TCSC suffers from the disadvantage that it generates low-order harmonic components into the power system.

TCSCs are usually connected in series to conventional line series capacitors. They may consist of one or several identical modules. Each module has a small thyristor-controlled reactor in parallel to the segment series capacitor. Although the TCSC is primarily used for regulating the power flow, though varying its effective reactance inserted in series with the transmission line, it may also be used for voltage stabilization. In this case, the o/p reads terminal voltage within a tight band.

Voltage source converters using GTO thyristor have been developed to operate as static VAR compensators. These are known as ASVCs. Such converters may resemble the operation of synchronous condensers, but in a static manner. For these devices, a converter transformer is always needed to complement the function of the P.E. switches to perform system VAR compensation and may also be used to connect the device to the HV bus. The converter supplies reactive power to the network by increasing the synthesized inverter o/p voltage. Similarly, the ASVC absorbs VARs from the network by reducing the o/p voltage below the network voltage, i.e., no large power components such as capacitor banks or reactors are used. Only a small capacitor is employed to provide the required reference voltage level to the inverter. In contrast to the TCR/FC or

TCR/TSC schemes, bulky and experimental passive elements are not required. The possibility of PWM voltage source converters with high switching frequency for reactive power compensation has also been reported. However, the high-switching-frequency operation of GTOs is not available. In order to apply large-scale reactive power compensation, new svc systems with low-switching-frequency PWM operation have been reported.

The conventional GTO inverters have dc link voltage limitations of about 2 kV. Hence, the series connections of the existing GTO thyristors have been essential in realizing high voltage, about 4 kV. So there has been great interest in the multilevel level inverter topology, which can overcome series connection problems. The multilevel level inverters are able to generate multiple level outputs line to line voltage without output transformers or reactors, i.e., the harmonics components of the phase voltage are fewer than those of the conventional two-level inverter at the same switching frequency.

1.6 ADVANTAGES AND DISADVANTAGES OF DIFFERENT TYPES OF COMPENSATING EQUIPMENT

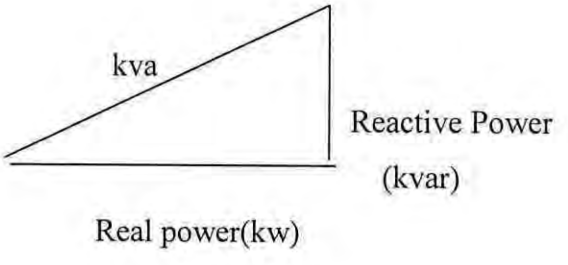
mpensating uipment	Advantages	Disadvantages
ʼitched Shunt actor	• Simple in principle and construction	• Fixed in value
ʼitched Shunt pacitor	• Simple in principle and construction	• Fixed in value • Switching transients
ies Capacitor	• Simple in principle • Performance relatively insensitive to location	• Requires over voltage protection and sub harmonic filter
ıchronous ndenser	• Has useful overload capability • Fully controllable • Low harmonics	• High maintenance requirement • Slow control response • Performance sensitive to location • Requires strong foundations
lyphase urated actor	• Very rugged construction • Large overload capability • No effect on fault level • Low harmonics	• Essentially fixed in value • Performance sensitive to location • Noisy
yristor ntrolled ıctor (TCR)	• Fast response • Fully controllable • No effect on fault level • Can be rapidly repaired after failures	• Generates harmonics • Performance sensitive to location
yristor itched ɔacitor (TSC)	• Can be rapidly repaired after failures • No harmonics	• No inherent absorbing capability to limit over voltages • Complex bus-work and controls Low frequency resonance with system

1.7 VAR COMPENSATION

An inexpensive source of reactive power (leading VARs) are power capacitors. The VARs are proportional to the square of the applied voltage. The reactance of the capacitor bank varies inversely with the frequency.

$$X_{cap} = 1 / 2\pi fc$$

So, if the frequency is high the impedance is low. The capacitors draw a leading current which gives a voltage rise through the inductive reactance of the power system and it raises the operating voltage level. The reactive power and voltage cannot be controlled by themselves. So, they must be switched in groups to provide variable reactive power.



1.8 STATIC VAR COMPENSATION (SVC)

Static means unlike the synchronous condenser, have no moving parts. These devices employ fixed banks of capacitors with controlled switches like thyristors, MOSFETs. Static VAR compensation maintains voltage levels, reduces voltage flicker, improves power factor, corrects phase imbalance and improves system stability.

In conventional SVC, the reactive power is provided by physical circuit elements such as capacitors or inductors. Here a particular SVC, which consists of two thyristor switched capacitor (TSC) stages to provide the VARs, and a thyristor controlled reactor (TCR) stage to provide lagging VARs.

1.9 OBJECTIVE OF THE THESIS :

In industrial applications, usually banks of shunt capacitors are used for power factor correction. In our research, our first objective is to improve the power factor manually by using a single large shunt capacitor without using the shunt capacitor banks. Then our second objective is to develop a power factor improvement method, which will automatically improve the power factor by using the same single large shunt capacitor. To do this, our first target was to develop a control circuit which will measure the lagging angle (the angle difference of voltage and current because of the inductive load, i.e. motors) and which will also generate a switching signal to the shunt capacitor in proportion with that lagging angle and thus making the power factor improved to our desirable limit. So the objective is mainly static power factor improvement by continuous control of the capacitor, which is to be done by the pulse width modulation(PWM) control of capacitor voltage by using series bi-directional switch.

A shunt capacitor is used because a shunt capacitor improves load voltage by neutralizing the part of the lagging current in a circuit, thereby reducing the line current and the voltage drop. The amount of power factor correction increases with capacitor kvar rating, the shunt capacitor corrects power factor to a greater extent. Shunt capacitors must be switched in one or more groups to keep within the desired voltage limits as load varies. It should be mentioned that shunt capacitors do not reduce light flicker because they cannot be switched on and off fast enough to counteract rapid fluctuations in voltage. But for increasing the source power factor as well as improve voltage, shunt capacitors at or near the load offer the best solution.

In this work, the voltage across the single capacitor is being changed by a bi-directional switch to control the magnitude of compensating capacitor current and thereby attaining the required power factor correction. The control scheme is involved in detecting the power factor of the load and the magnitude of the load current. The control circuit then provides a reference voltage, which is the product of load current and power factor. This reference is compared with a saw-tooth wave to generate a train of pulses, which in turn switches ON/OFF the bi-directional switch to control the capacitor voltage. The reference voltage changes with load and thereby makes the capacitor voltage change automatically by varying the widths of the pulses.

1.10 OUTLINE OF THE THESIS :

This thesis consists of three chapters, which are chapter one, chapter two and chapter three respectively. Chapter one deals with introduction and need for power factor improvement. The brief history of power factor correction by capacitor and the review of static power factor correction methods are also discussed in chapter one. It also includes the objectives of the thesis.

Chapter two basically describes the detailed study of unity power factor attainment by using single PWM switched capacitor by continuous control of capacitor voltage and current. To make it easier to understand and to introduce the final approach (with practical switch and feedback control) chapter two introduces many topics step by step. To implement and describe the working procedure of different approaches a lot of wave shapes of voltages and currents are given in many figures of chapter two.

Chapter three concludes the thesis with summary and achievements. It also gives some important suggestions and the recommendations of future works.

CHAPTER –2

ANALYSIS AND DEVELOPMENT OF COMPENSATOR CIRCUIT

2.1 MATHEMATICAL DERIVATION :

A single-phase load of impedance $Z_l=R_l+jX_l$ supplied from a voltage V. The load current is I_l and

$$I_l = V/Z_l = V/(\sqrt{R_l^2 + X_l^2} < \Phi) \qquad [\Phi = \tan^{-1}(X_l/R_l)]$$

$$= I_l < -\Phi$$

$$= I_l \cos\Phi - j\, I_l \sin\Phi$$

Or,

$$I_l = VG_l + j\,VB_l = I_R + j\,I_x \qquad \text{-----------} \; \mathbf{(2.1.1)}$$

Both V and I_l are phasors. **Equation (2.1.1)** is represented in the phasor diagram (**Figure- 2.1)** in which V is the reference phasor.

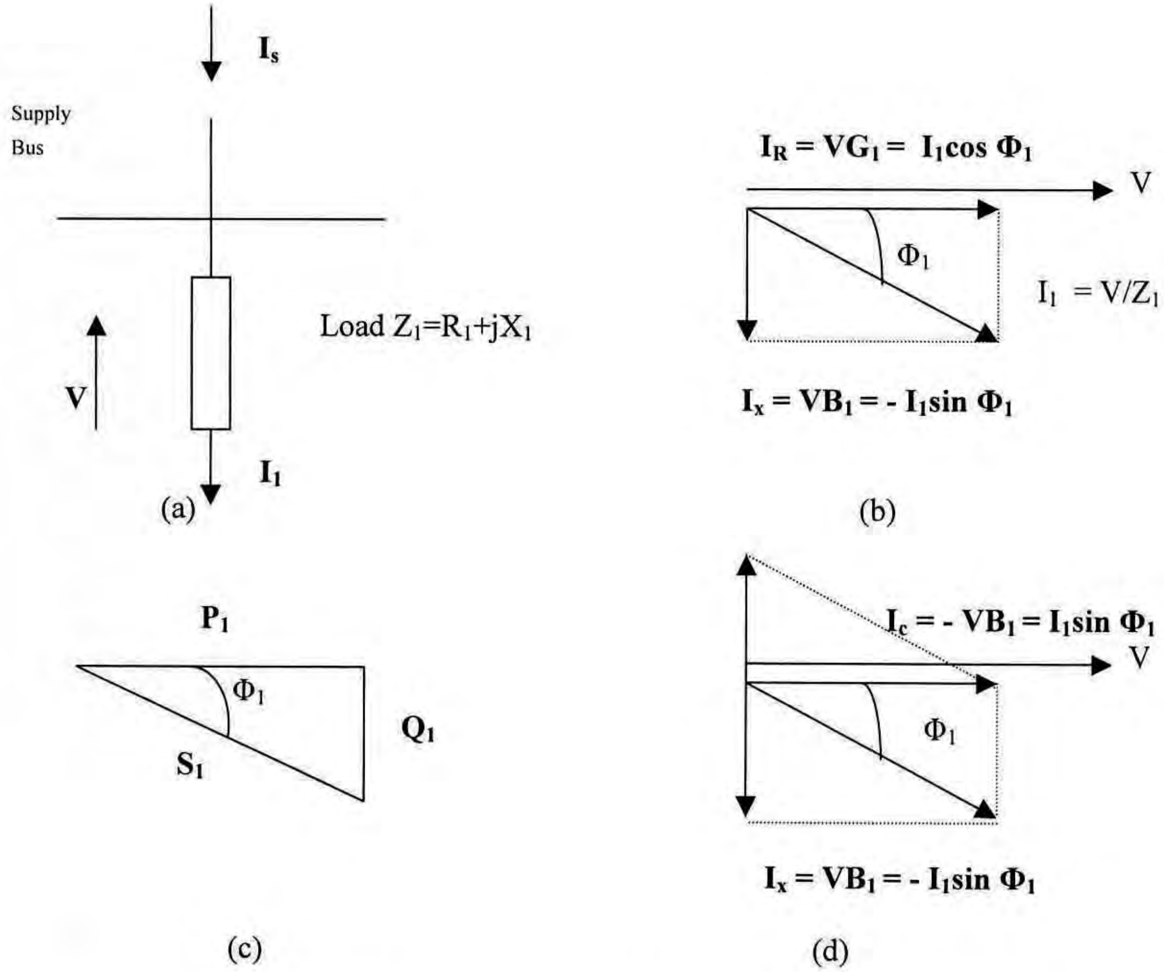


Figure- 2.1 : Phasor diagram of Power-Factor Correction

I_R = Resistive component of load current in phase with V.

$= VG_l$

I_X = Reactive component of load current in phase quadrature with V.

$= VB_l$

Φ = Angle between V and I_l.

For an inductive load I is lagging ; I is negative

The apparent power supplied to the load is –

$$S_l = V I_l^*$$

$$=V(I_l \cos \Phi + j I_l \sin \Phi)$$
$$=V^2G_l - j V^2B_l$$
$$= P_l + j Q_l$$

P_l = Real component of apparent power.

Q_l = Reactive component of apparent power.

For lagging load B_l is negative and Q_l is positive (by convention)

The current $I_S = I_l$ supplied by the power system is larger than is necessary to supply the real power alone, by the factor

$$I_l / I_R = 1/ \cos \Phi$$

Here, $\cos \Phi = P_l / S_l$

= Power factor i,e fraction of the apparent power which can be usefully converted into other forms of energy.

By connecting a compensator (in parallel with the load) which will supply the current of magnitude $I_l \sin \Phi$

Then Supply current, $I_S = I_l + I_C$

$$= I_l \cos \Phi - j I_l \sin \Phi + j I_l \sin \Phi$$
$$= I_l \cos \Phi$$
$$= I_R$$

Which is in phase with V, making the overall power factor unity. Figure- 2.1(d) shows the phasor relationships. The supply current I_S now has the smallest value capable of supplying full power P_l at the voltage V, and all the reactive power required by the load is supplied locally by the compensator, the load is thus totally compensated.

I_C = compensator current

$= j\, I_l \sin \Phi = - j\, VB_l$

The apparent power exchanged with the supply system is,

$S_C = P_C + j\, Q_C = j\, V^2\, B_l = -jVI_l \sin \Phi$

Thus $P_C = 0$ and $Q_C = V^2 B_l = IV \sin \Phi = -Q_l$

Therefore the compensator requires no mechanical power input for an inductive load capacitive compensation is required.(B_C positive and Q_C negative) – [1]

The implementation of sin is complex. So for easier implementation we have considered sin Φ as Φ . From mathematical analysis we know that for small value of the angle $\sin \Phi \approx \Phi$. So from our analysis we find that for small value of Φ, experimental result resembles to the theoretical value.

2.2 : CALCULATION OF CAPACITANCE OF THE COMPENSATING CAPACITOR

Consider an inductive load taking a lagging current I at a power factor $\cos\Phi_1$. In order to improve the power factor of this circuit, the remedy is to connect such an equipment in parallel with the load which takes a leading reactive component and partly or fully cancels the lagging reactive component of the load. **Figure 2.2(a)** shows a capacitor connected across the load.

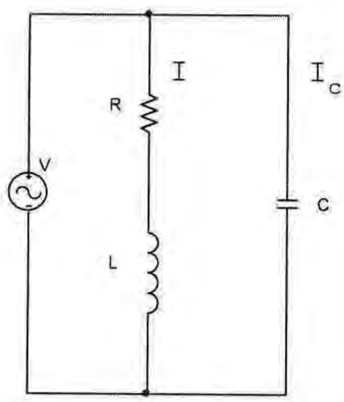


Figure : 2.2(a) – A lagging load with compensating capacitor

The capacitor takes a current I_c which leads the voltage V by 90^0. The current I_c partly cancels the lagging reactive component of the load current as shown in the vector diagram in **Figure 2.2(b)** .

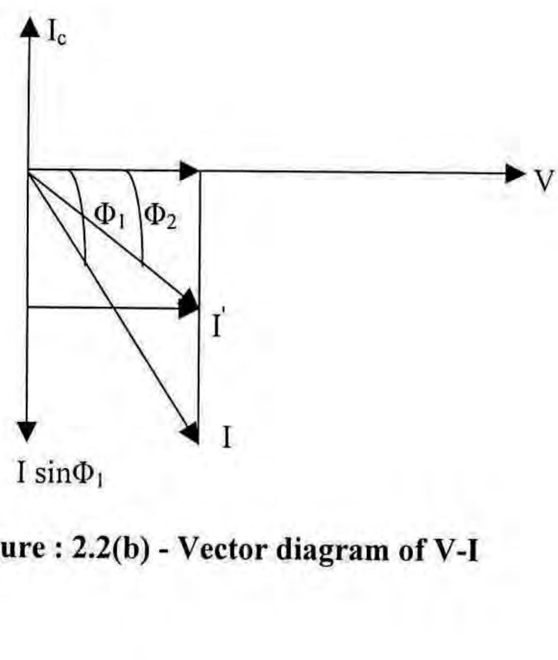


Figure : 2.2(b) - Vector diagram of V-I

The resultant circuit current becomes I' and its angle of lag Φ_2 . It is clear that Φ_2 is less than Φ_1 so that new power factor cos Φ_2 is more than the previous p.f. cos Φ_1.

From the vector diagram, it is clear that after power factor correction, the lagging reactive component of the load is reduced to $I' \sin \Phi_2$.

Obviously, $I' \sin \Phi_2 = I \sin\Phi_1 - I_c$

Or $\quad I_c = I \sin\Phi_1 - I' \sin \Phi_2$ --------------- **(2.2.1)**

We know, $X_c = V / I_c = 1 / \omega C$

Therefore, Capacitance of the compensating capacitor to improve power factor from $\cos\Phi_1$ to $\cos \Phi_2$

$C = I_c / \omega V$ ------------------ **(2.2.2)**

Now the capacitance of the compensating capacitor to make the power factor unity for the circuit given below- **Figure : 2.2 (c)**

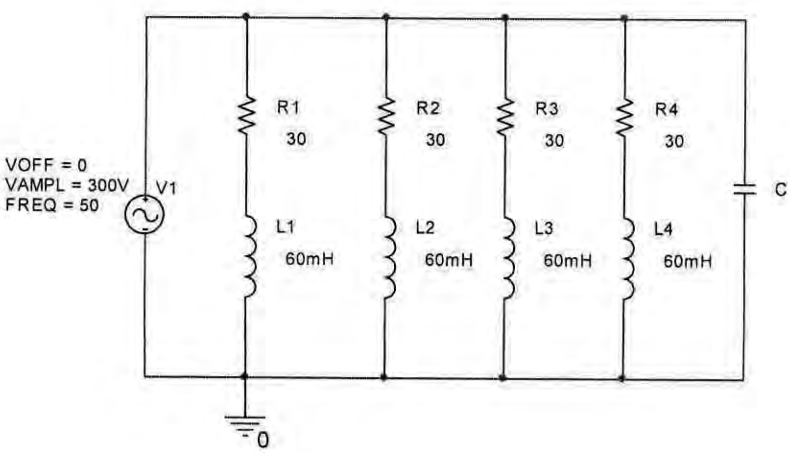


Figure: 2.2 (c) –For theoretical calculation of the capacitance of the required capacitor to attain unity power factor

Here four lagging loads of equal magnitudes in parallel are considered. The equivalent impedance Z_e of the lagging loads is given by:

$$1/Z_e = 1/Z_1+1/ Z_2 +1/ Z_3 +1/ Z_4$$

Here, $Z_1 = Z_2 = Z_3 = Z_4 = 30+j\ (2*\pi*50*60*.001) = 30+j\ 18.85 = Z$ (say)

Now,

$$1/Z_e = 1/Z+1/Z+1/Z+1/Z = 4/Z$$

Therefore, $Z_e = Z/4$

$$= 1/4(\ 30+j\ 18.85)$$

$$=1/4(35.43 < 32.14^0)$$

$$= 8.86 < 32.14^0$$

The Inductive lagging current

$$I = V/Z_e$$

$$= 300< 0^0 / 8.86 < 32.14^0$$

$$= 33.86 < - 32.14^0$$

Here

Existing power factor = $\cos \Phi_1 = \cos < 32.14^0 = 0.85$

Desired power factor = $\cos \Phi_2 = 1$

Now

$$I \sin \Phi_1 = I \surd [1- (0.85)^2] = 33.86 * \surd [1- (0.85)^2] = 17.84 \text{ Amps}$$

$I' \sin \Phi_2 = 0$ [As $\Phi_2 = 0^0$]

So, From Equation (1)

$I_c = I \sin\Phi_1 - I' \sin \Phi_2$

$= 17.84$ Amps

Therefore, From Equation (2) the value of the compensating capacitor is

$C = I_c / \omega V$

$= 17.84 / (2*\pi*50*300)$

$= 189\ \mu F$ **--------------------(2.2.3)**

If we simulate the circuit of **Figure:2.2 (c)** considering the same load and the value of the compensating capacitor **C = 200 μF** , we get the following result which shows full compensation ie the power factor is improved to unity.

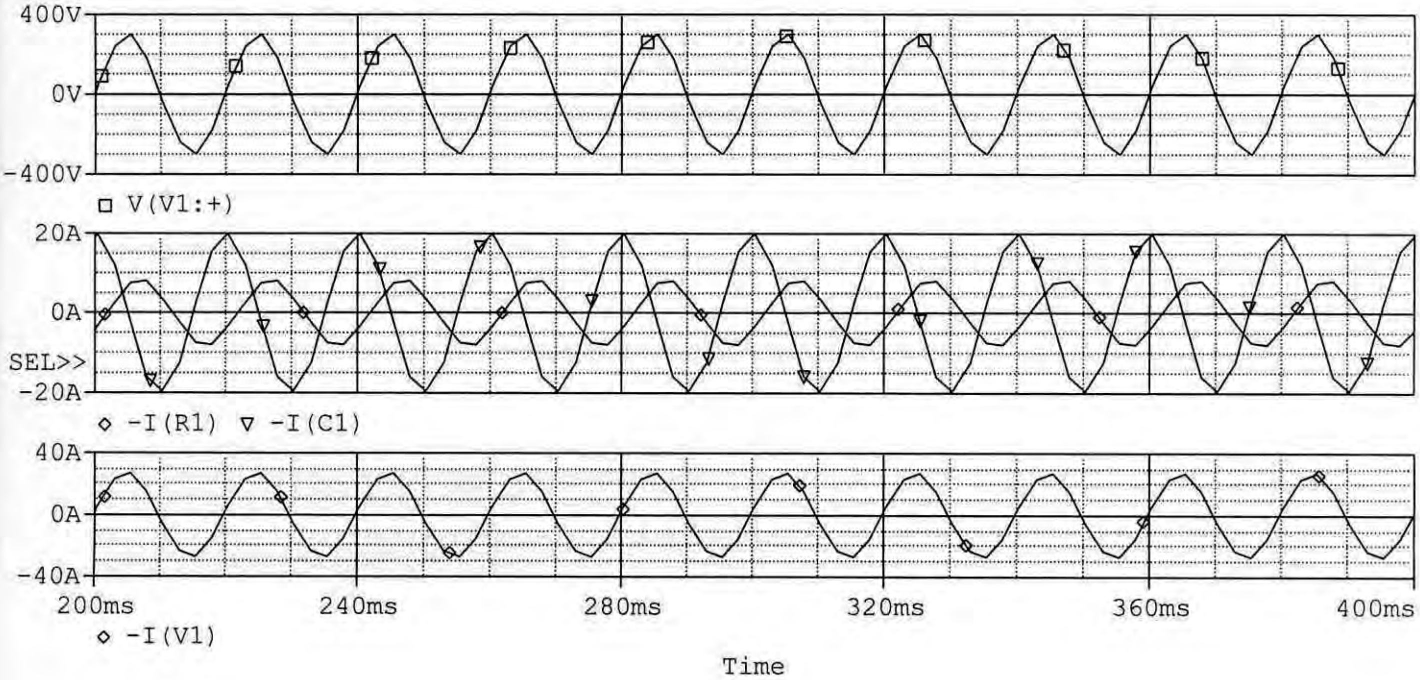


Figure : 2.2 (d) – Wave forms showing input current and voltage after compensation attaining unity power factor

So the value of the capacitance of the compensating capacitor is almost equal to the theoretical value.

2.3 BASIC COMPENSATOR :

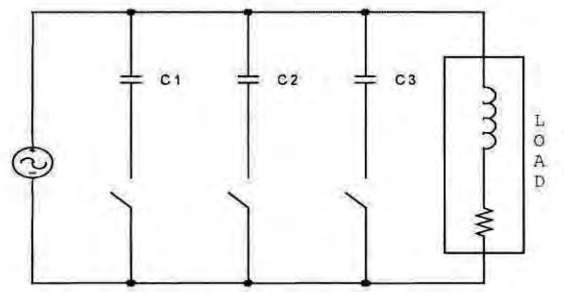


Figure:2.3 (a) - Basic compensator

The quadrature phase lagging current of an inductive load can be compensated with the help of compensating current supplied from a bank of capacitors connected in parallel which can be controlled by switching as required. In practical implementation switching devices like thyristors, MOSFETS etc can be used.

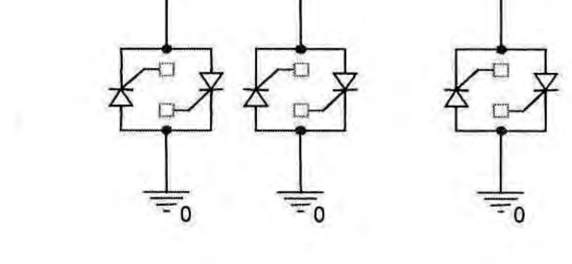


Figure : 2.3(b) - A TSC arrangement

2.4 DEVICE MODELING :

To implement our proposed compensation technique described by above mathematical derivation we need a compensational block, which will first determine the compensating current out of the compensator. Then this current will be compared with a high frequency saw-tooth wave to generate the PWM pulses – **[4]** to drive the bi-directional switch of the compensator. There will be control over the modulation index to vary the pulse width in the PWM pattern for determining appropriate compensating current out of the compensator. Therefore the proposed compensating system may be as shown in **Figure-2.4**

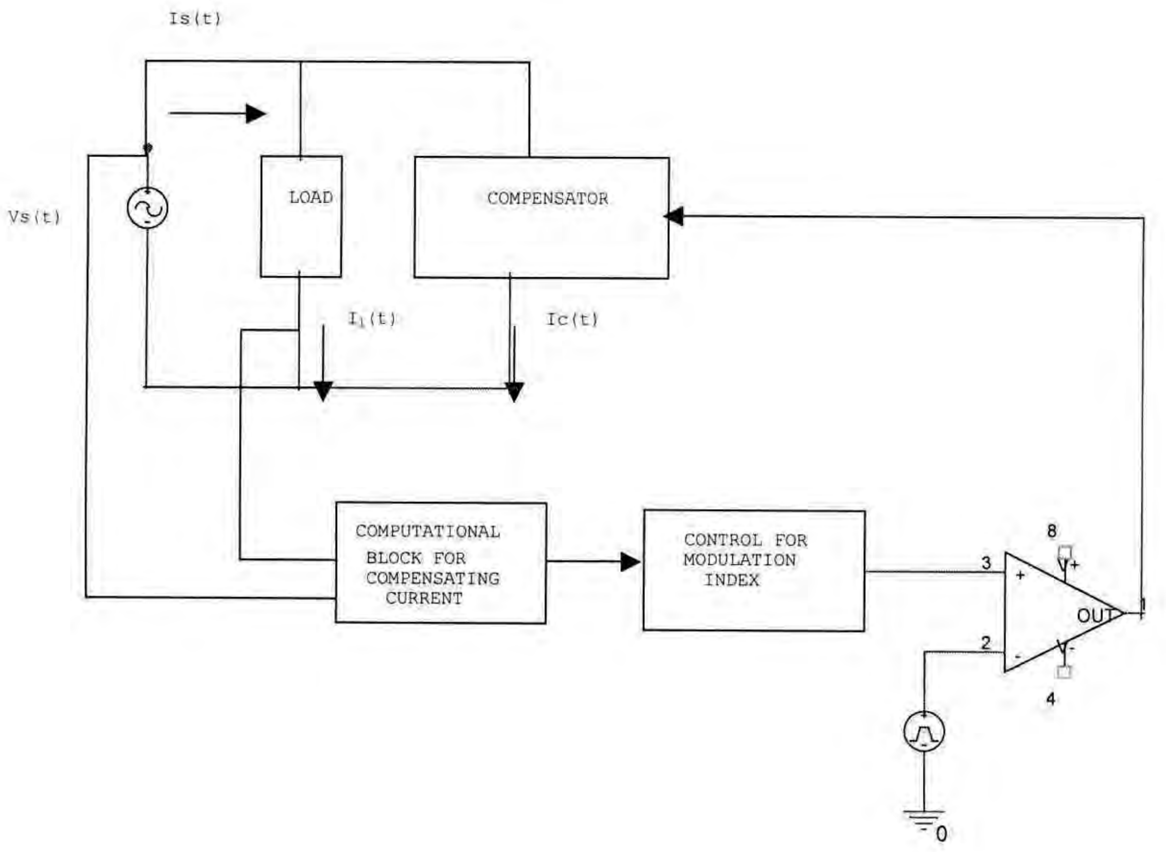


Figure : 2.4 - Proposed Arrangement for compensation (With feedback control)

2.5 FIRST APPROACH :

For a particular load, we need a constant magnitude of compensating current to compensate the reactive component of load current. Considering the total load comprising of four equal impedances in parallel at the same time. Pulse Width Modulated (PWM) signals are supplied to the Switches S1 and S2 to control the voltage of the capacitor i.e. the compensating current to attain Unity power factor. The required PWM signal is generated by comparing a high frequency saw-tooth wave with a specified dc voltage for the particular load. In this approach we took eight cases for which the dc voltage is varied from 1V to 8 V to have eight different PWM signals for switching the switches, and in each case we attained unity power factor i.e, the input voltage and input current are in phase. The voltage across the switches and the capacitor are within the limit but the current through the switches and the capacitor are very high. A practical switch with such an excessive current bearing capacity is not available and it is also not feasible. So we adopt another approach where the current through the switch and the capacitor are within limit.

From **Equation – 2.2.3 (For Figure:2.2(c))** we got the theoretical value of the capacitance of the compensating capacitor to have total compensation i.e unity power factor for four equal loads in parallel. In this case the theoretical value of the capacitance of the capacitor is **189μF**. Now taking the value of the capacitance of the compensating capacitor to its round figure i.e **200 μF** and after simulation we found that the lagging load current is fully compensated that means unity power factor is attained (the input voltage and input current are in phase). First we will consider the fixed load that comprises four loads of equal impedances in parallel then we will gradually develop a controlled circuit where unity power factor will be attained in each case while varying the no. of parallel loads at a time.

A low-pass filter –[4] is used to smooth out the compensating current which in turn smoothes out the supply current. We simulate the **Figure 2.5** and observed the various values of the circuit parameters which is given in **TABLE-2.5**

From the **TABLE-2.5** We see that PWM signals generated for the switches S1 and S2 are opposite in nature, i.e the width of the PWM signal to S1 increases as the dc voltage is increased. On the other hand the width of the PWM signal to S2 decreases as the dc voltage is increased which fulfills to our requirements.

This circuit arrangement performs the compensating task successfully for a particular load, since there is no direct relation between load and PWM generation circuit. The performance of the circuit is questionable with load variations. We have to design a flexible circuit arrangement that will effectively work in spite of load variation. For a generalized purpose we need some modification in the present circuit **(Fig. 2.5)** which will be designed in the next approach.

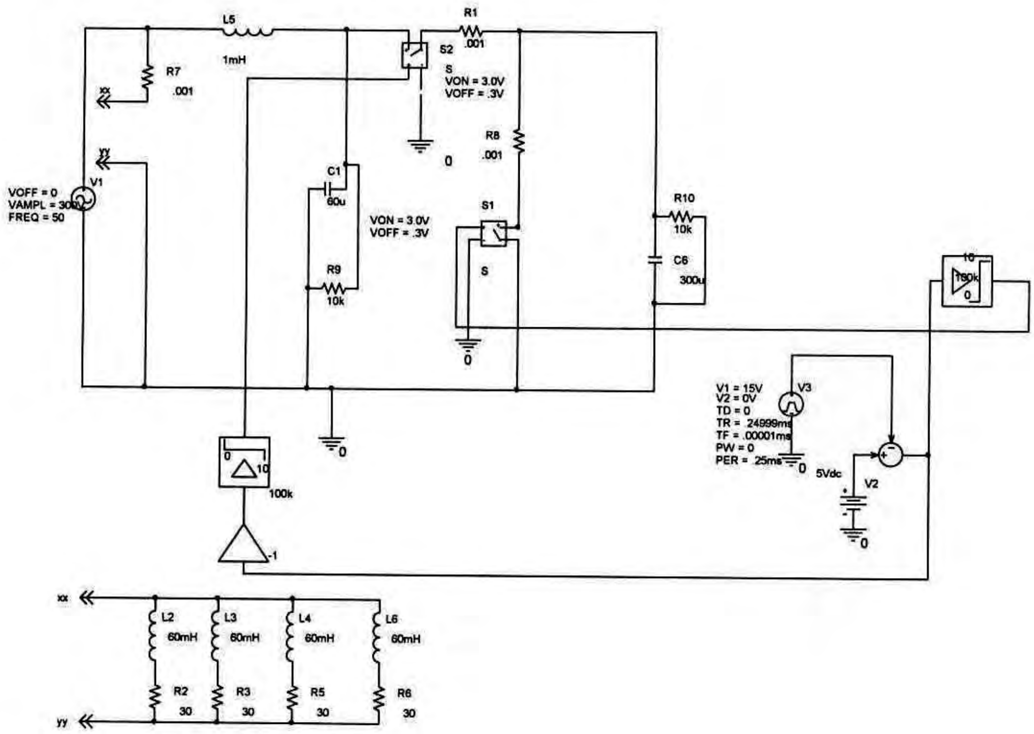


Figure : 2.5 - Circuit arrangement for First Approach to attain unity power factor

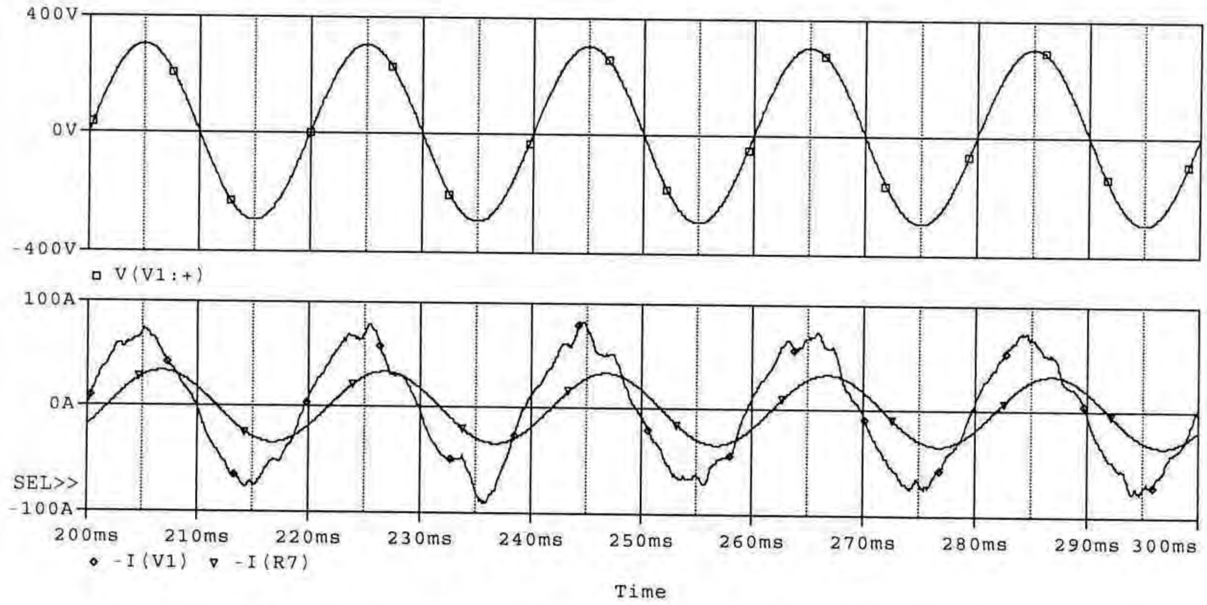


Figure: 2.5 (a) – Unity power factor attained for V_{dc} = 1V [First Approach]

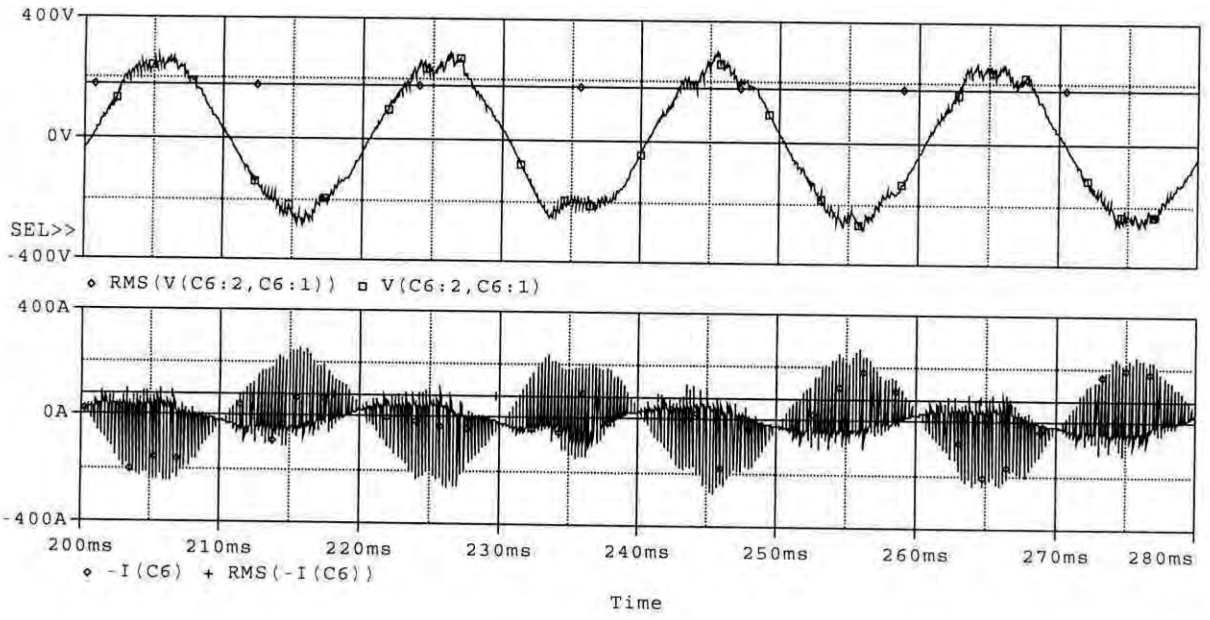


Figure: 2.5 (b) – Voltage against and current through the capacitor for V_{dc} = 1V [First Approach]

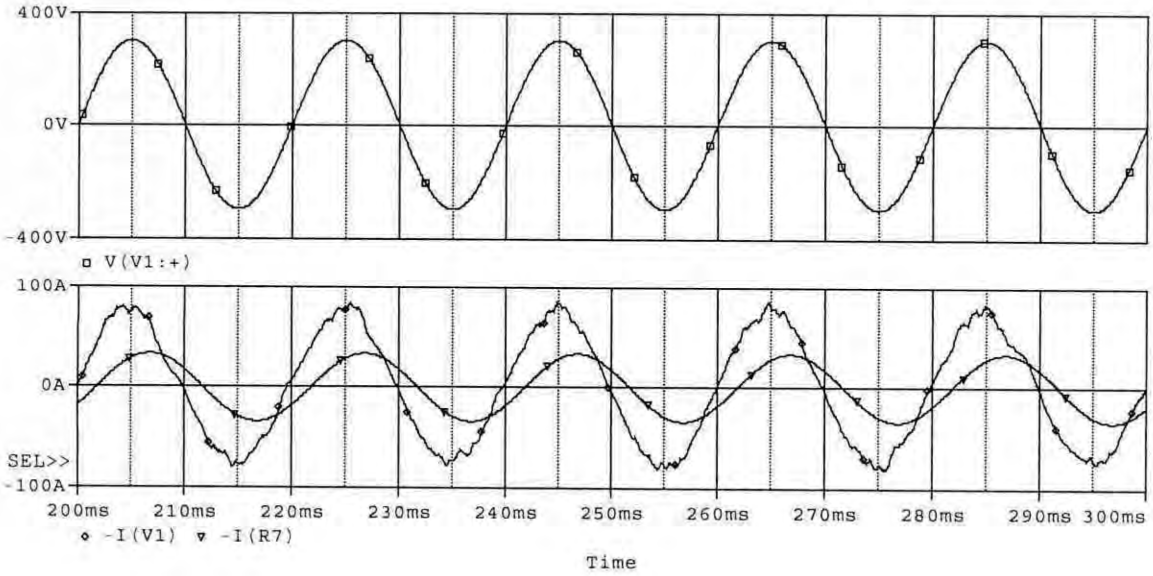


Figure : 2.5 (a1) – Unity power factor obtained for V_{dc} = 2 V [First Approach]

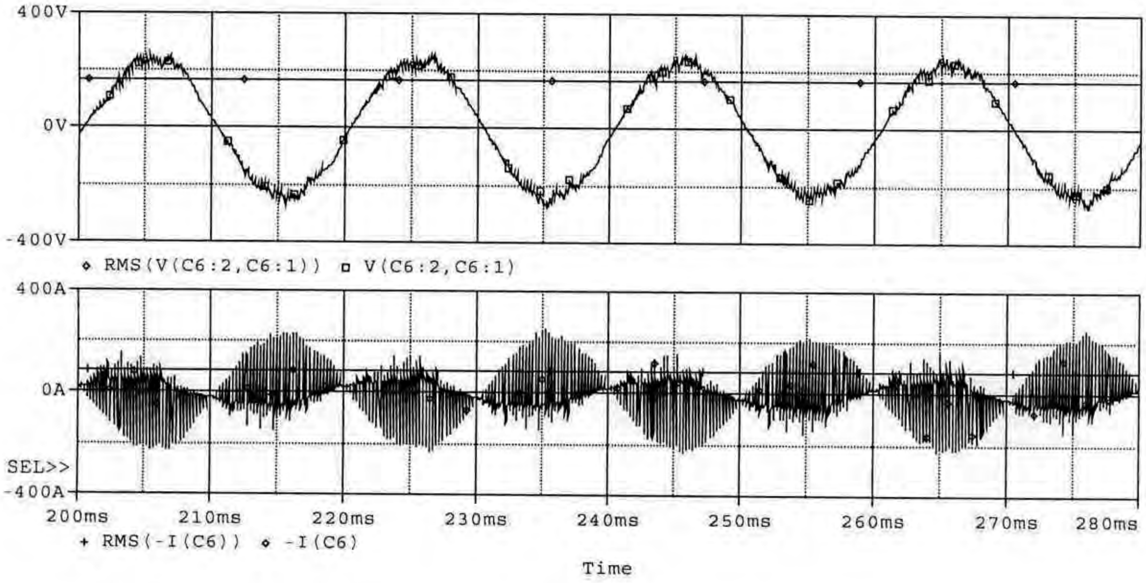


Figure: 2.5 (b1) – Voltage against and current through the capacitor for V_{dc} = 2V [First Approach]

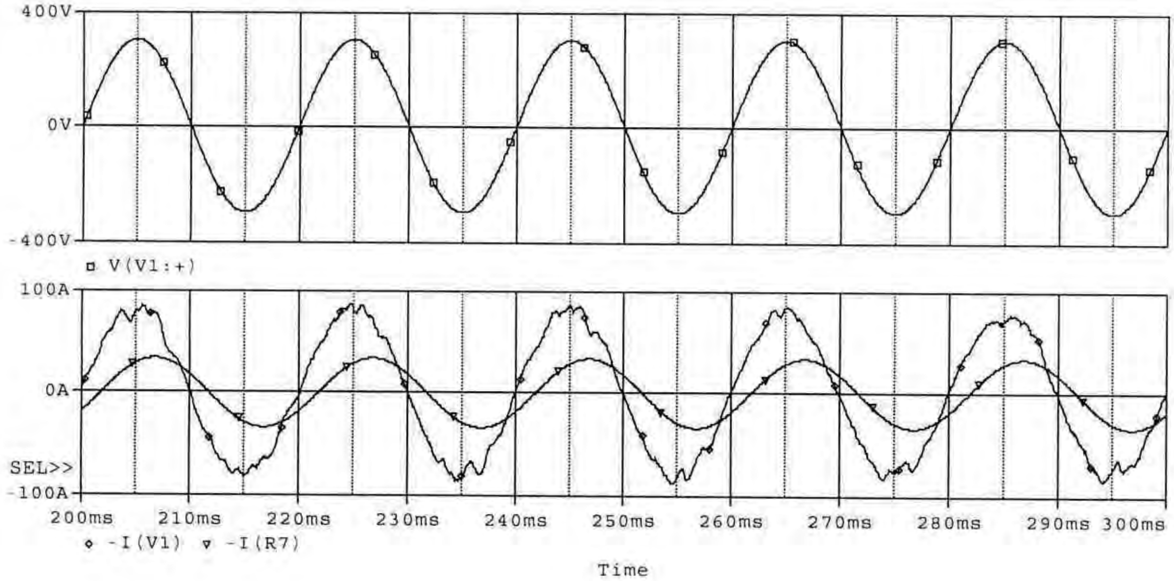


Figure : 2.5 (a2) – Unity power factor obtained for $V_{dc} = 3$ V [First Approach]

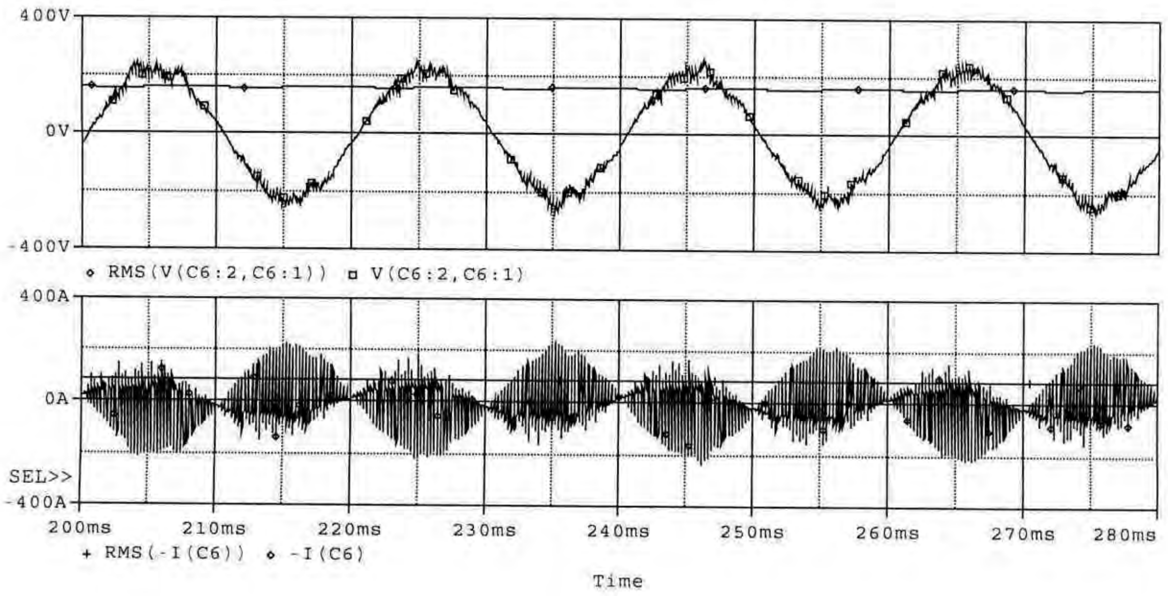


Figure: 2.5 (b2) – Voltage against and current through the capacitor for $V_{dc} = 3$V [First Approach]

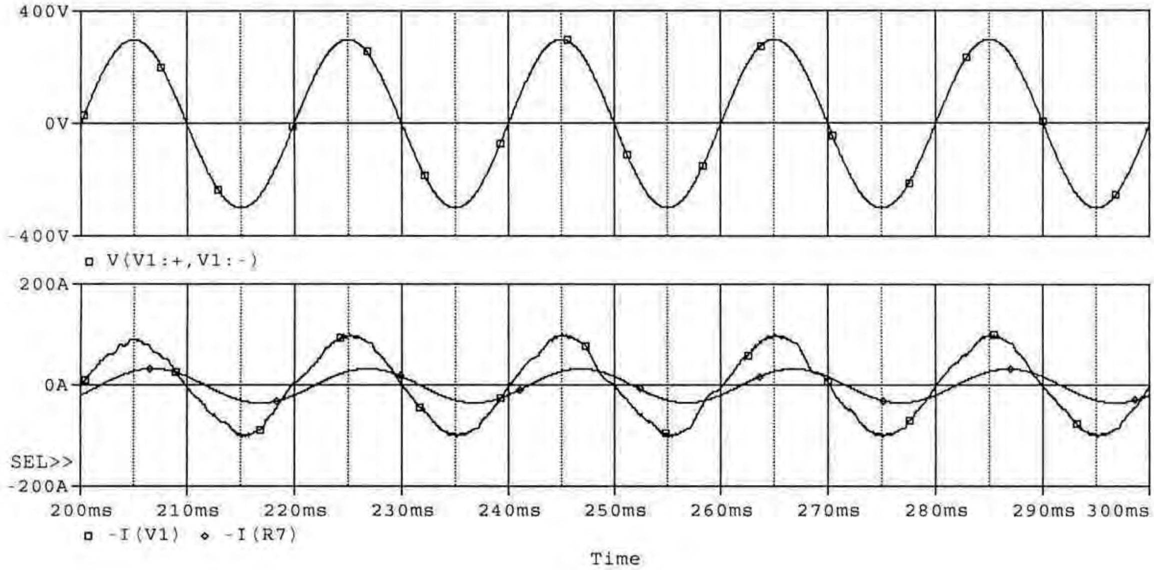


Figure : 2.5 (a3) – Unity power factor obtained for V_{dc} = 4 V [First Approach]

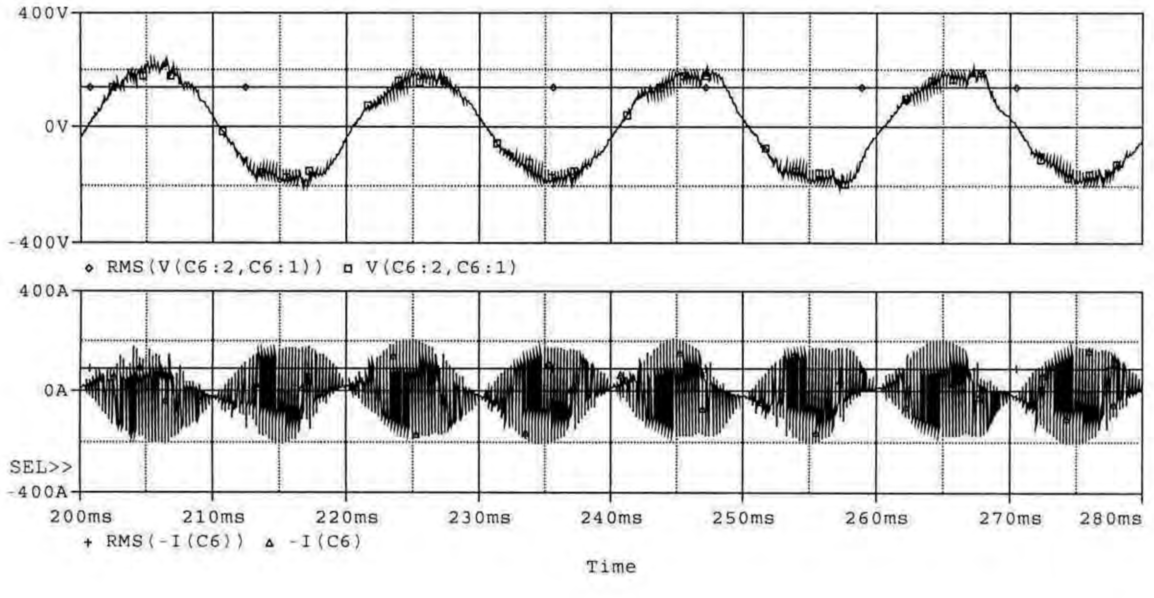


Figure: 2.5 (b3) – Voltage against and current through the capacitor for V_{dc} = 4V [First Approach]

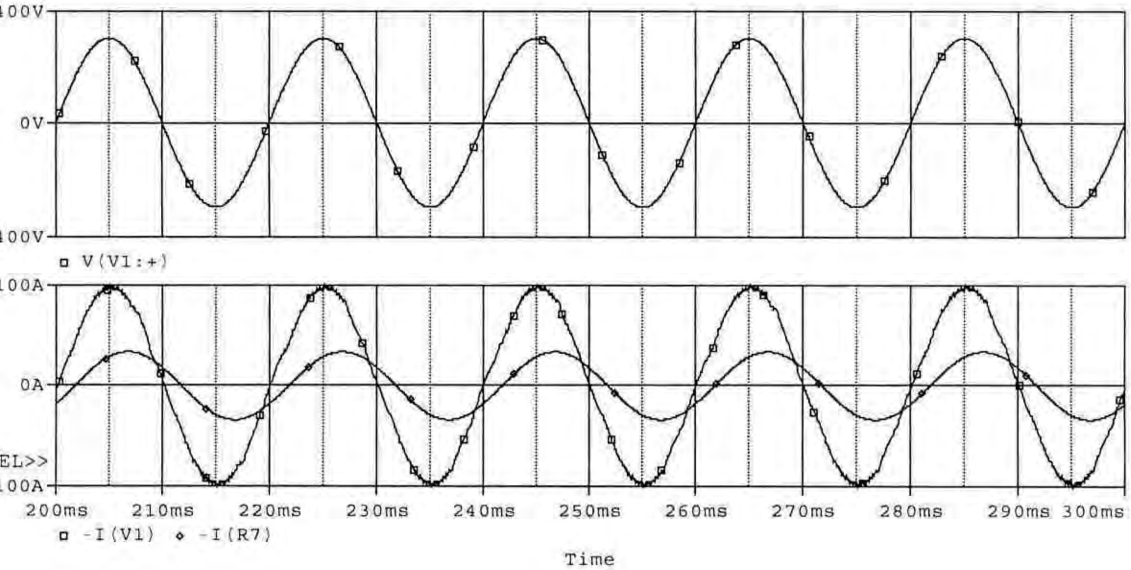


Figure : 2.5 (a4) – Unity power factor obtained for V_{dc} = 5 V [First Approach]

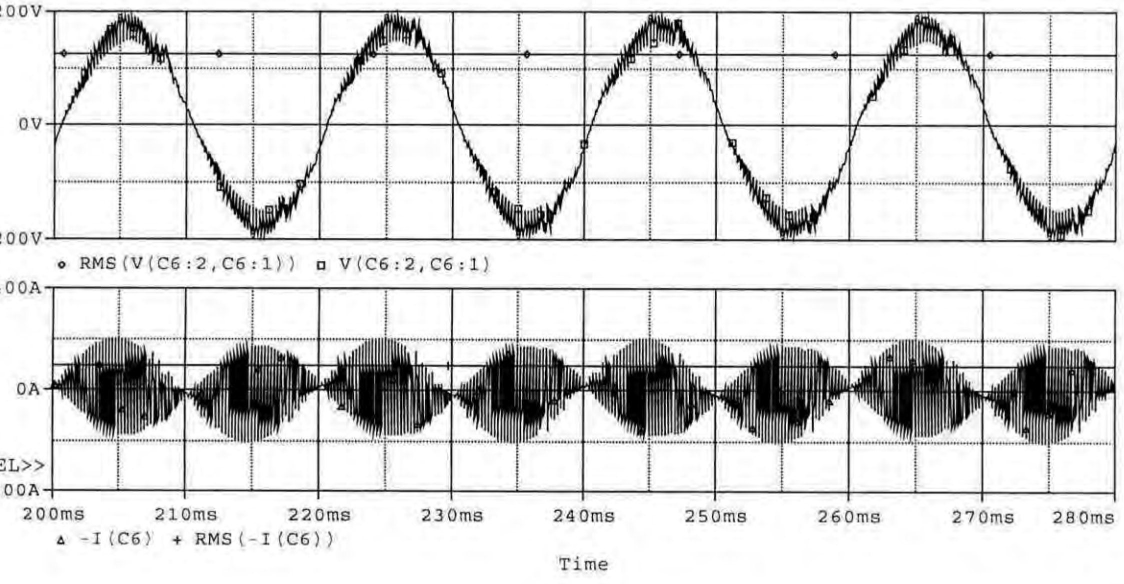


Figure: 2.5 (b4) – Voltage against and current through the capacitor for V_{dc} = 5V [First Approach]

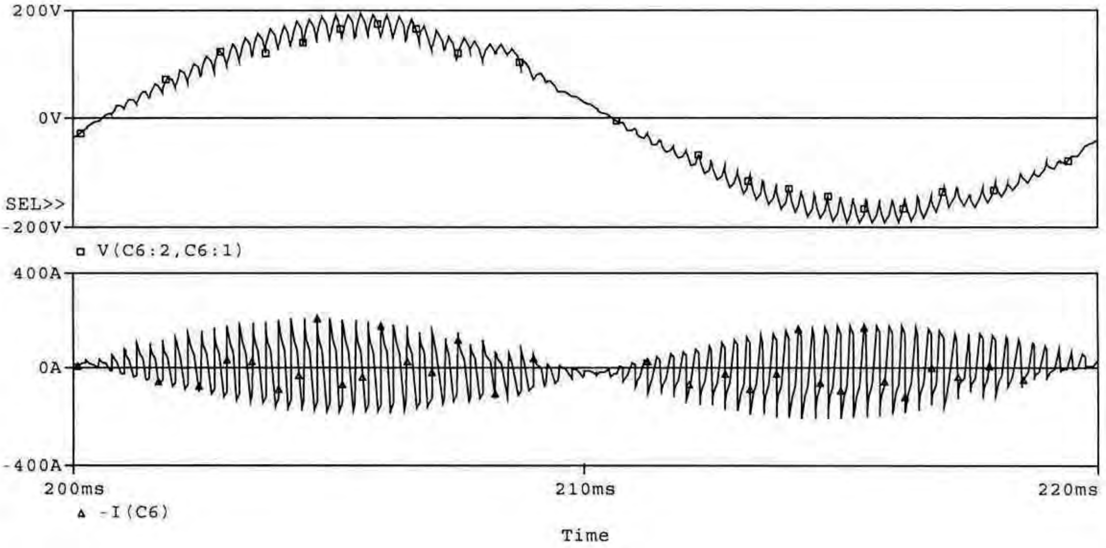


Figure : 2.5 (a4.1) – Voltage and current profile of the capacitor for V_{dc}=5V [First Approach]

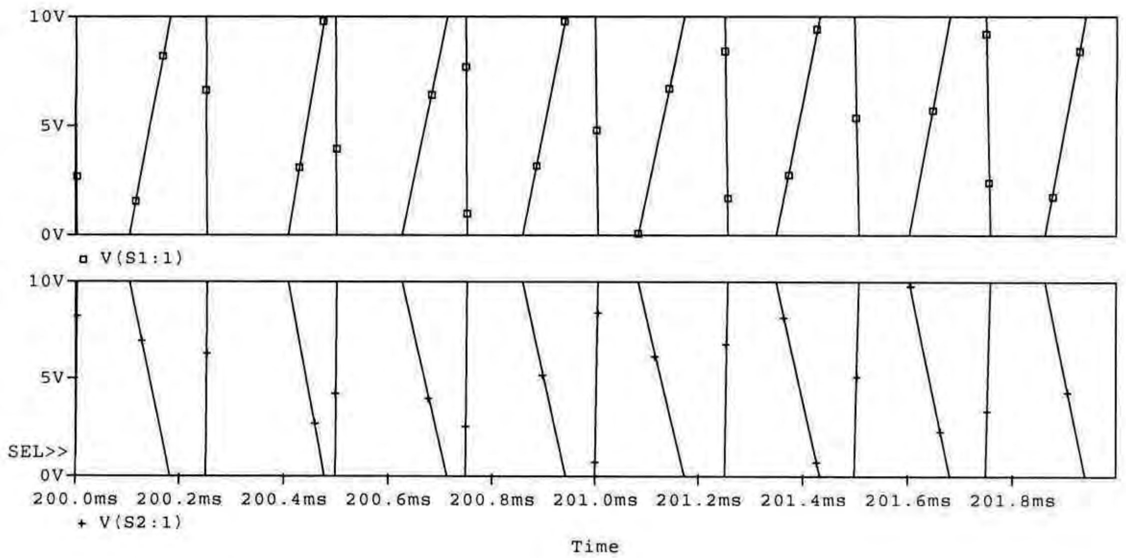


Figure : 2.5 (b4.1) – PWM signals supplied to switches S1 and S2 for V_{dc}=5V [First Approach]

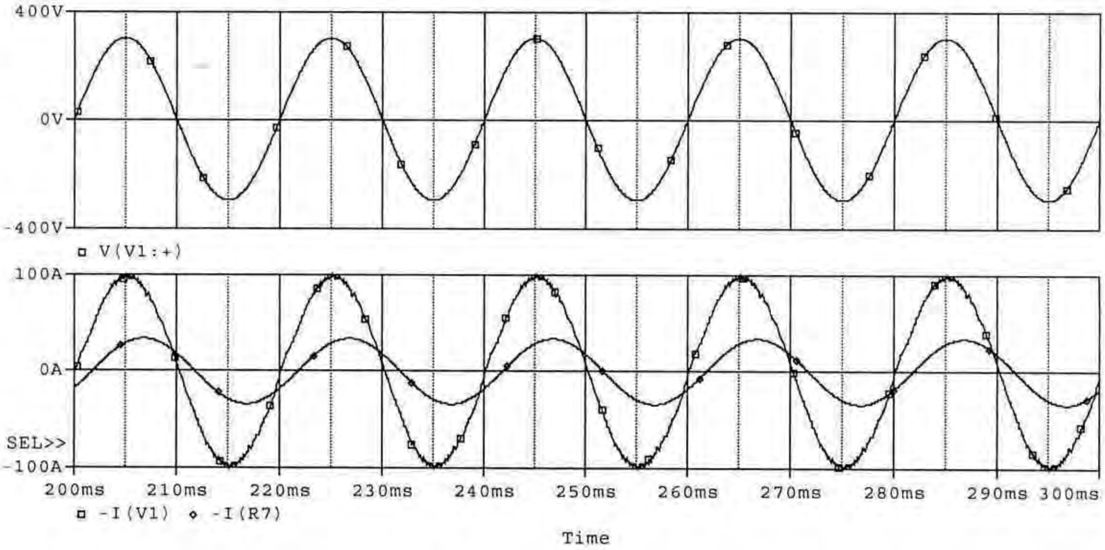


Figure : 2.5 (a5) – Unity power factor attained for V_{dc}=6V[First Approach]

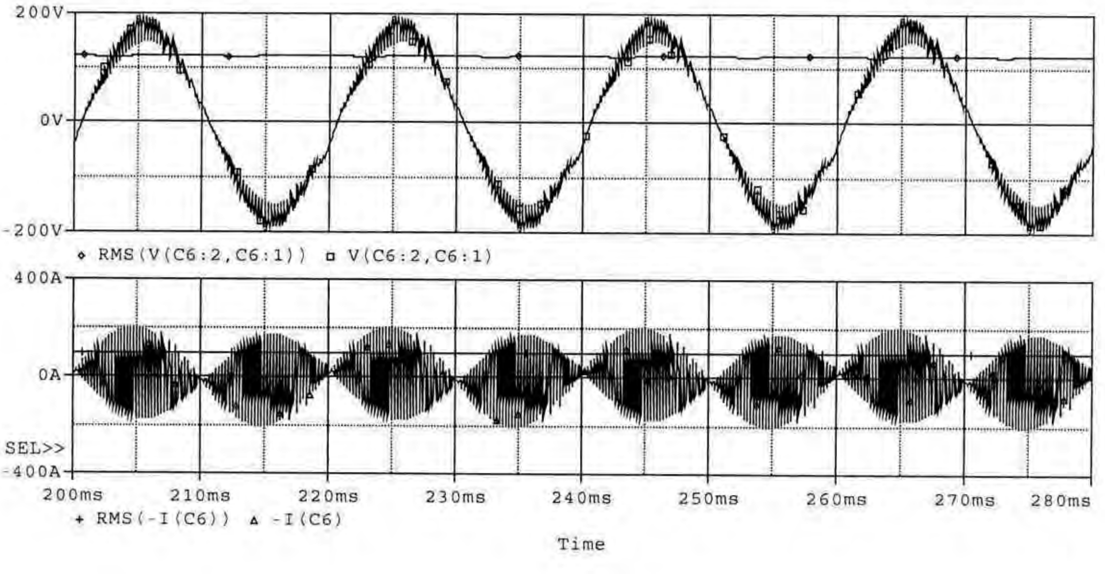


Figure : 2.5 (b5) – Voltage across and current through the capacitor for V_{dc}=6V [First Approach]

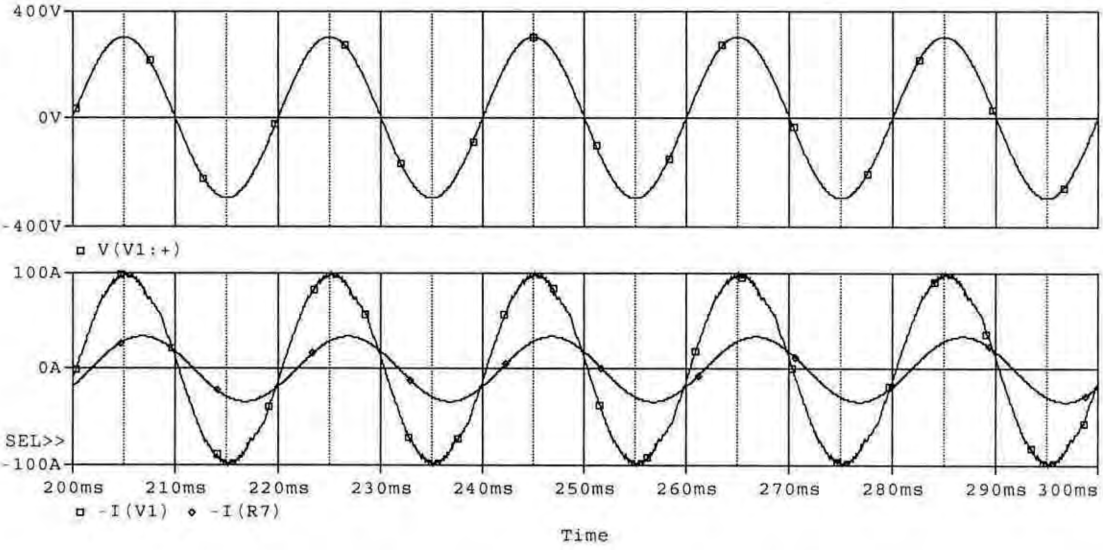


Figure : 2.5 (a6) – Unity power factor attained for V_{dc}=7V [First Approach]

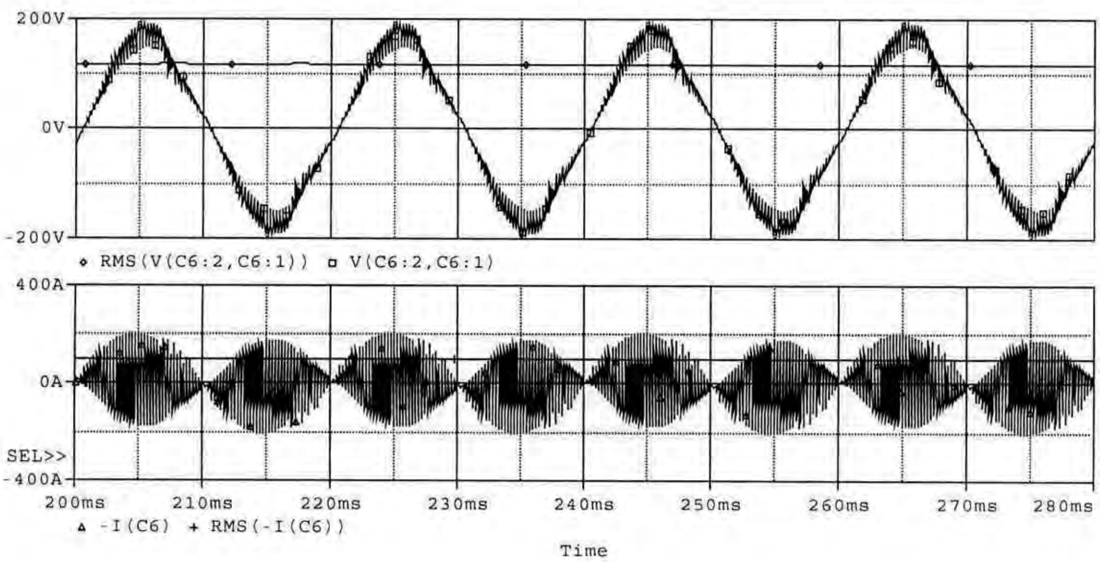


Figure : 2.5 (b6) – Voltage across and current through the switch for V_{dc}=7V [First Approach]

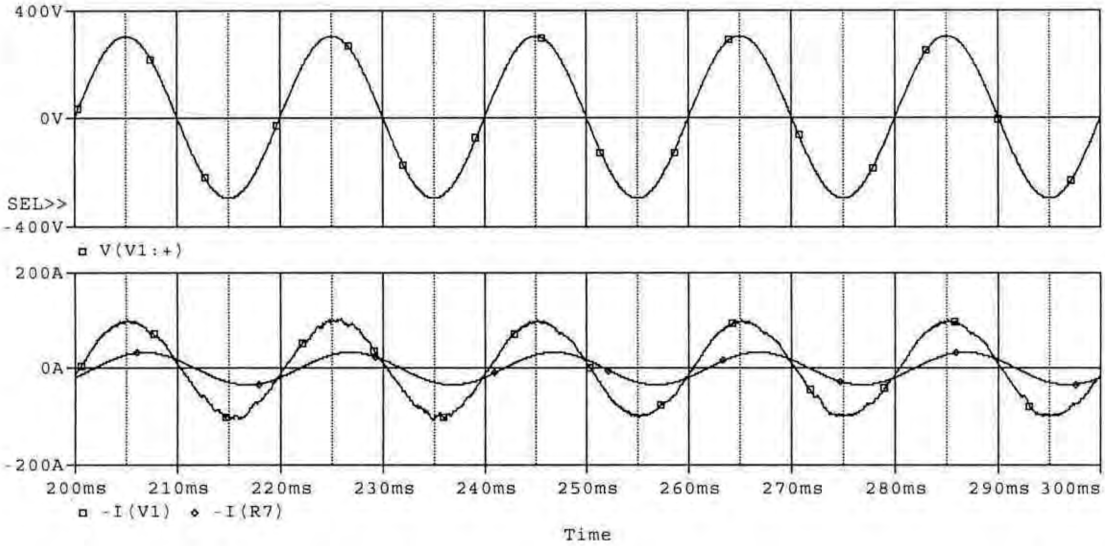


Figure : 2.5 (a7) – Unity power factor attained for V_{dc}=8V [First Approach]

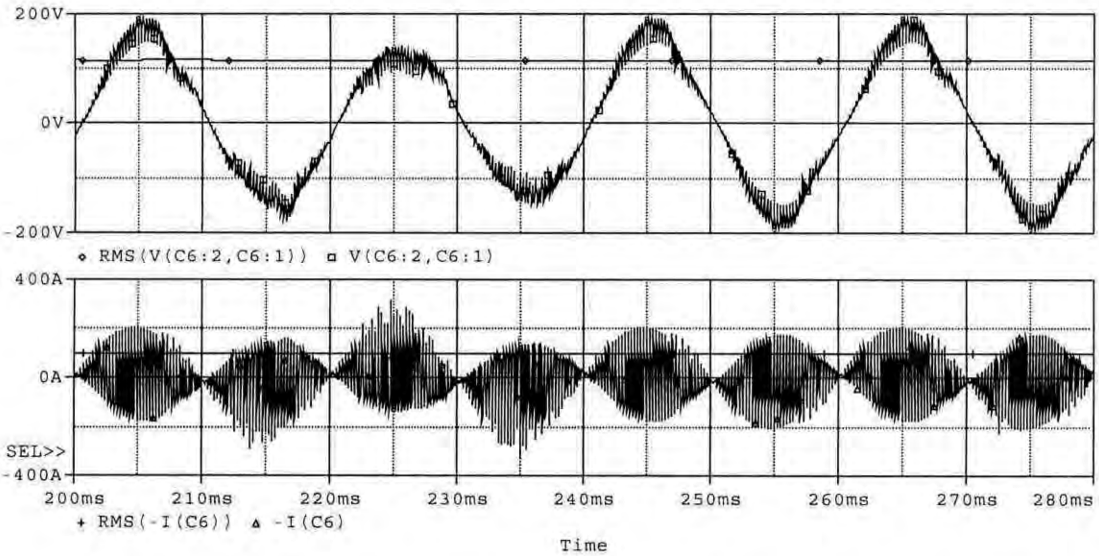


Figure : 2.5 (b7) – Voltage across and current through the capacitor for V_{dc}=8V [First Approach]

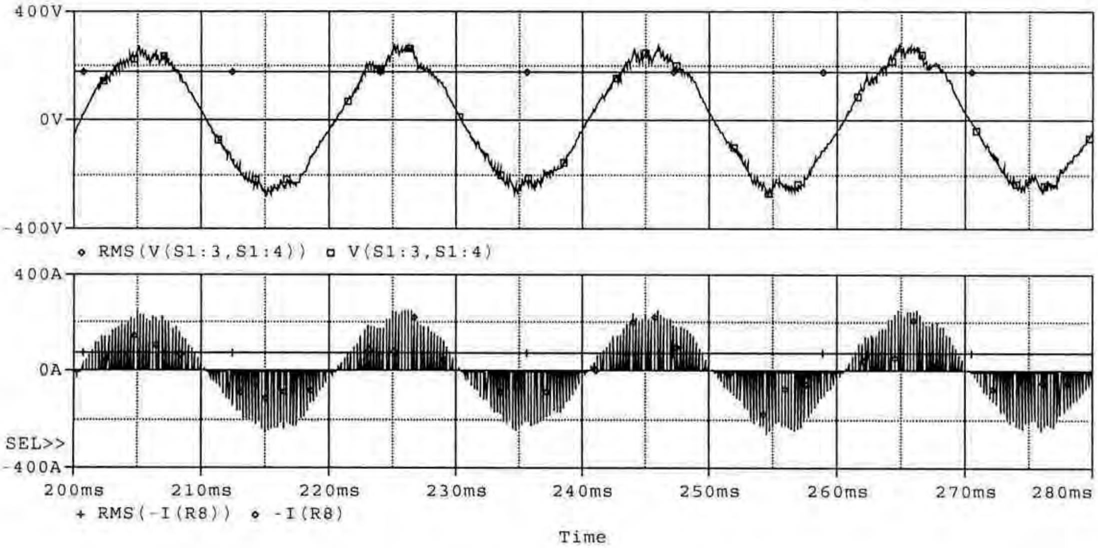


Figure: 2.5 (c) – Voltage across and current through the switch (S1) for V_{dc}= 1V [First Approach]

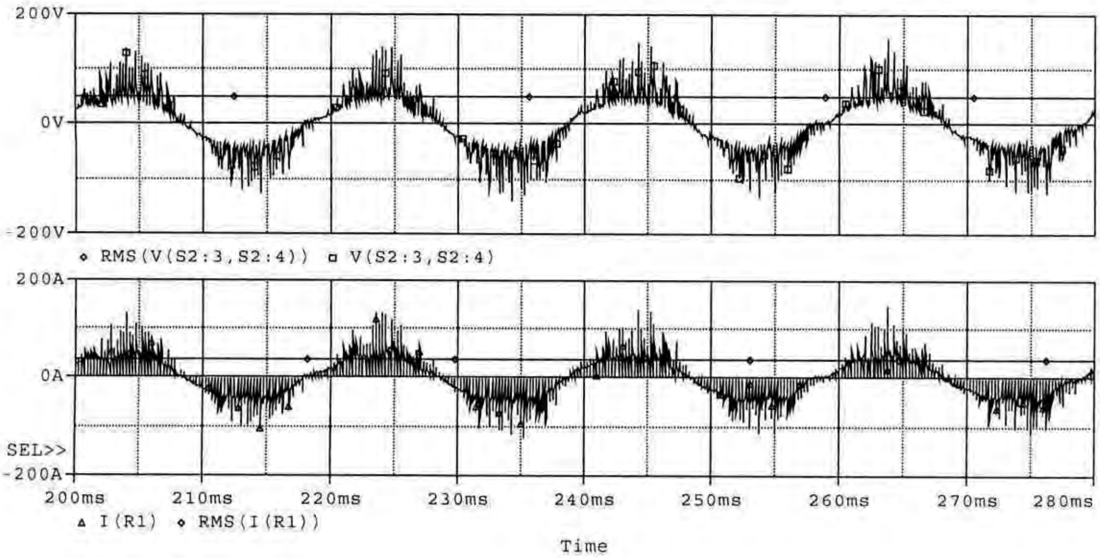


Figure : 2.5 (d) – Voltage across and current through the switch (S2) for V_{dc}= 1V[First Approach]

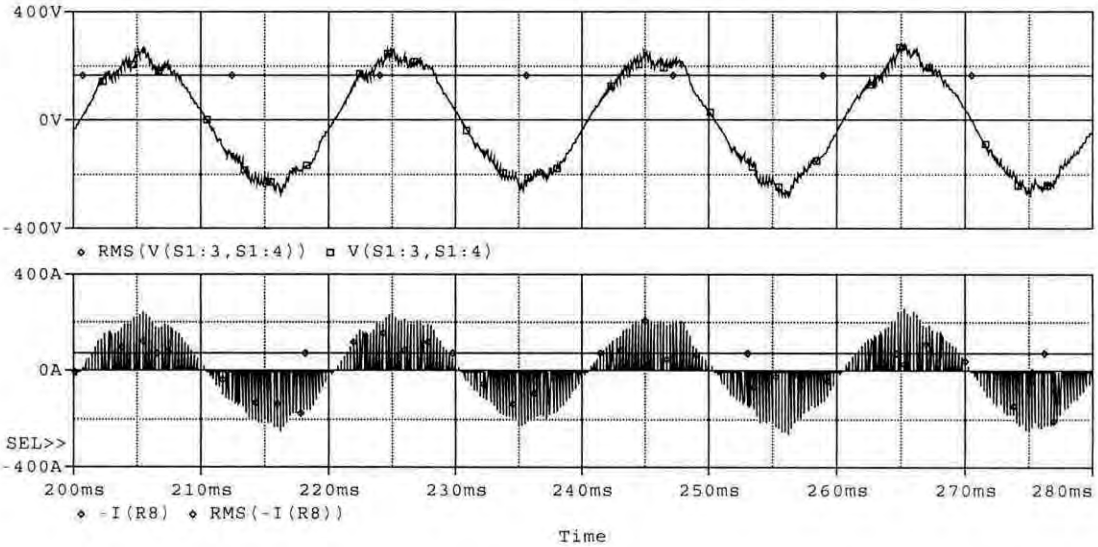


Figure: 2.5 (c1) – Voltage across and current through the switch (S1) for V_{dc}= 2V [First Approach]

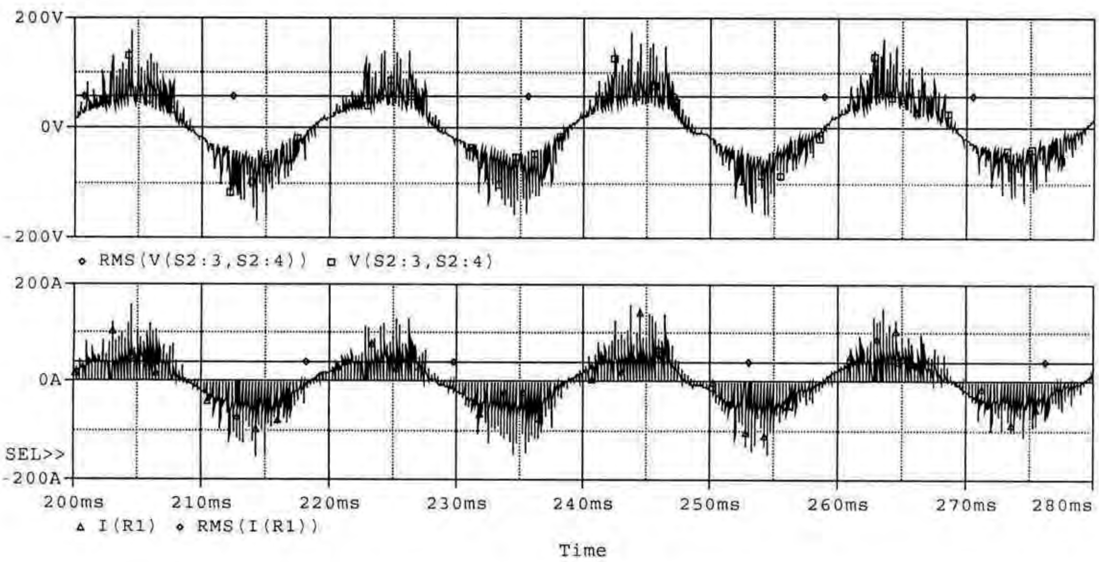


Figure : 2.5 (d1) – Voltage across and current through the switch (S2) for V_{dc}= 2V [First Approach]

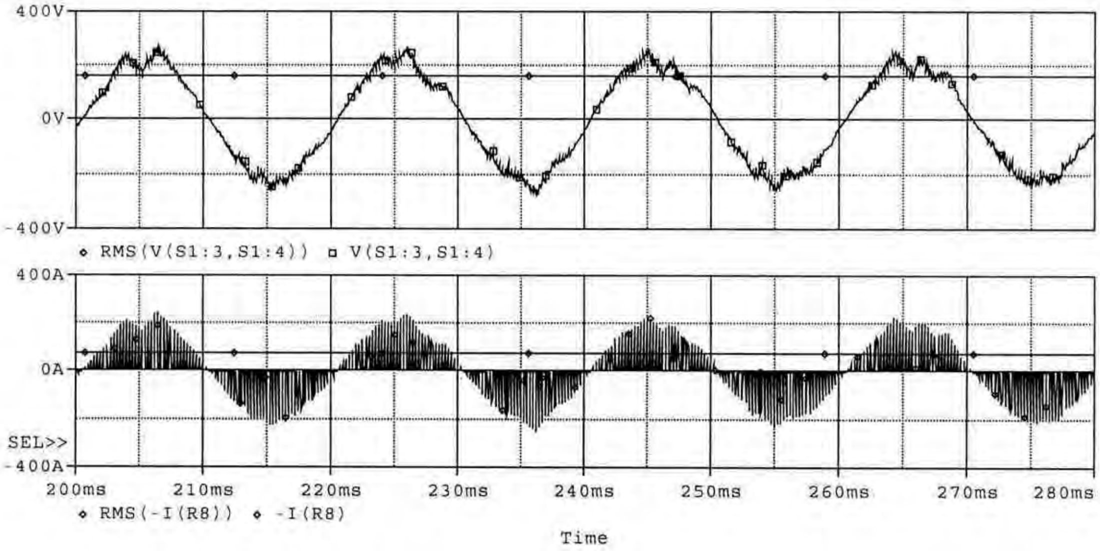


Figure: 2.5 (c2) – Voltage across and current through the switch (S1) for V_{dc}=3V [First Approach]

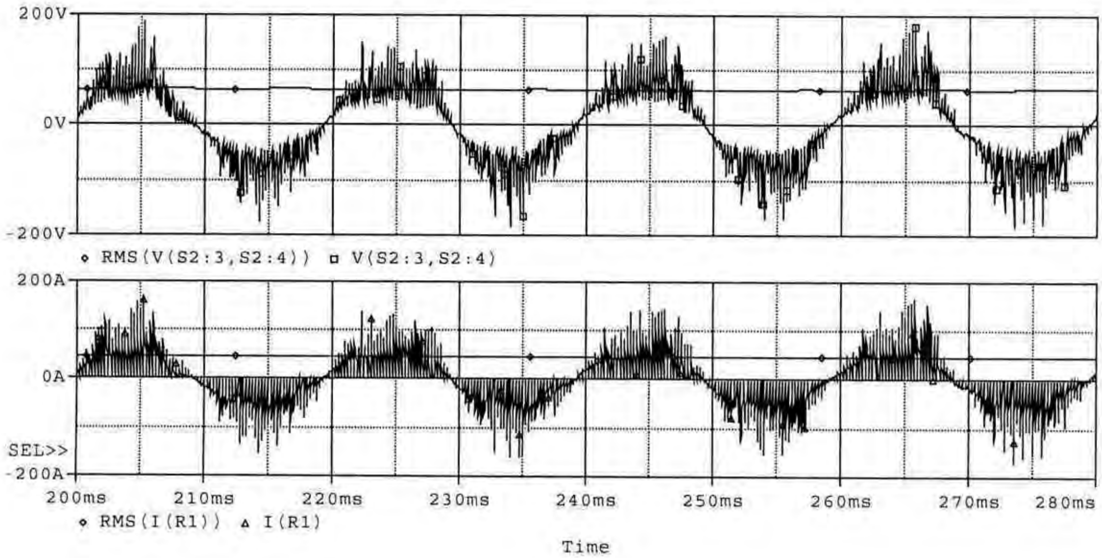


Figure : 2.5 (d2) – Voltage across and current through the switch (S2) for V_{dc}= 3V [First Approach]

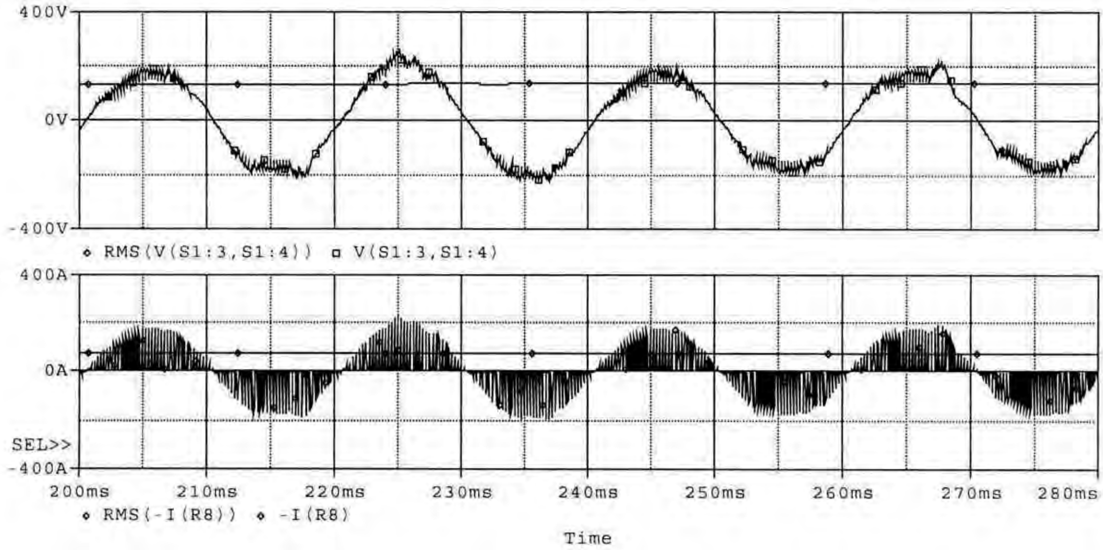


Figure: 2.5 (c3) – Voltage across and current through the switch (S1) for V_{dc}= 4V [First Approach]

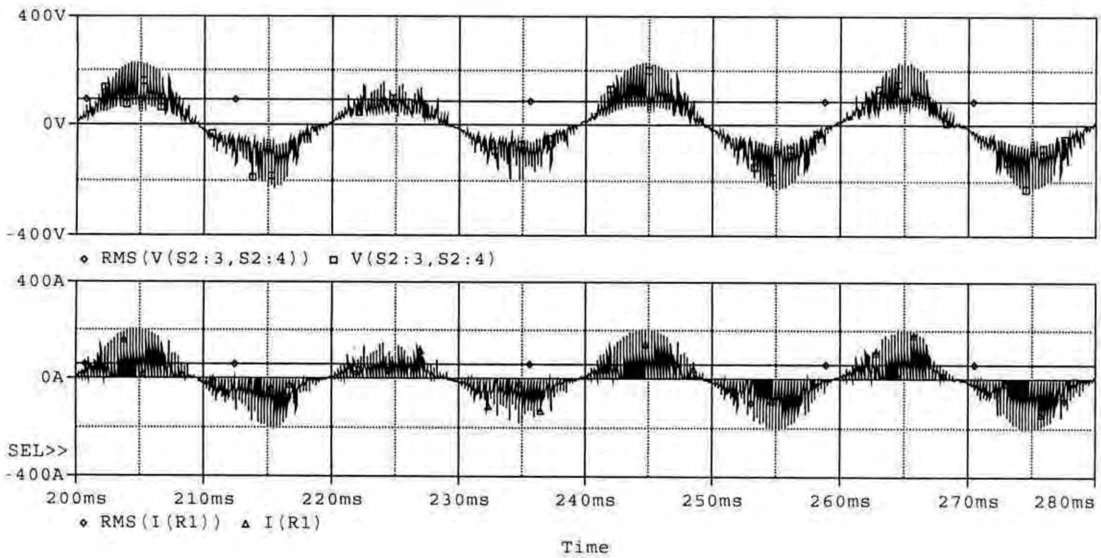


Figure : 2.5 (d3) – Voltage across and current through the switch (S1) for V_{dc}= 4V

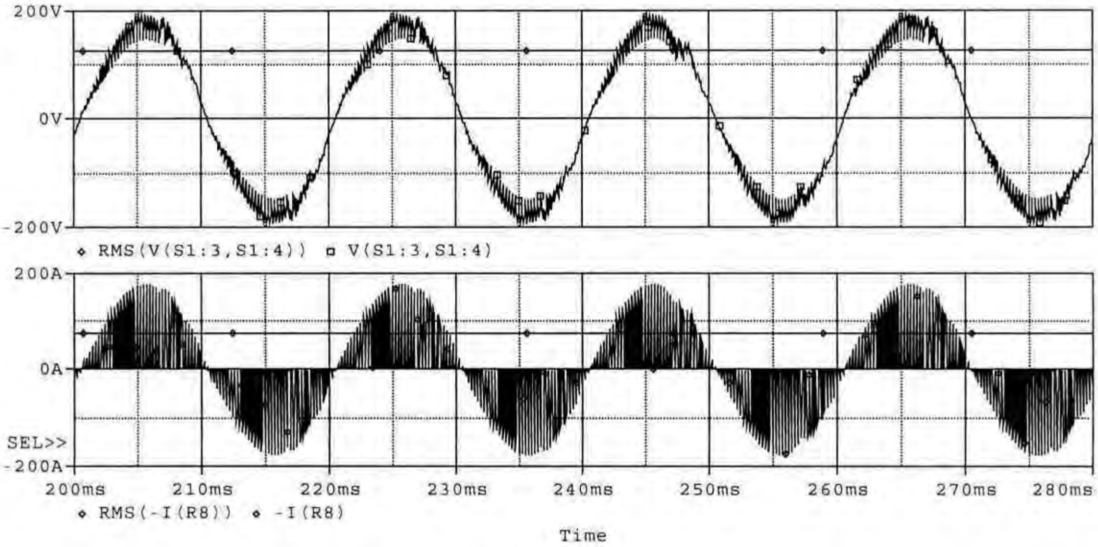


Figure: 2.5 (c4) – Voltage across and current through the switch (S1) for V_{dc}= 5V [First Approach]

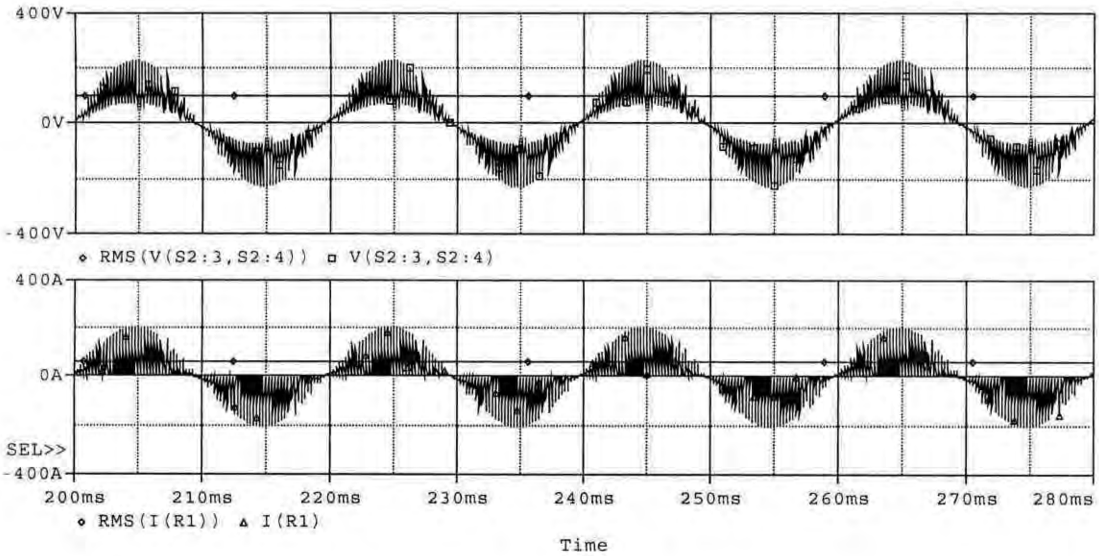


Figure : 2.5 (d4) – Voltage across and current through the switch (S2) for V_{dc}= 5V [First Approach]

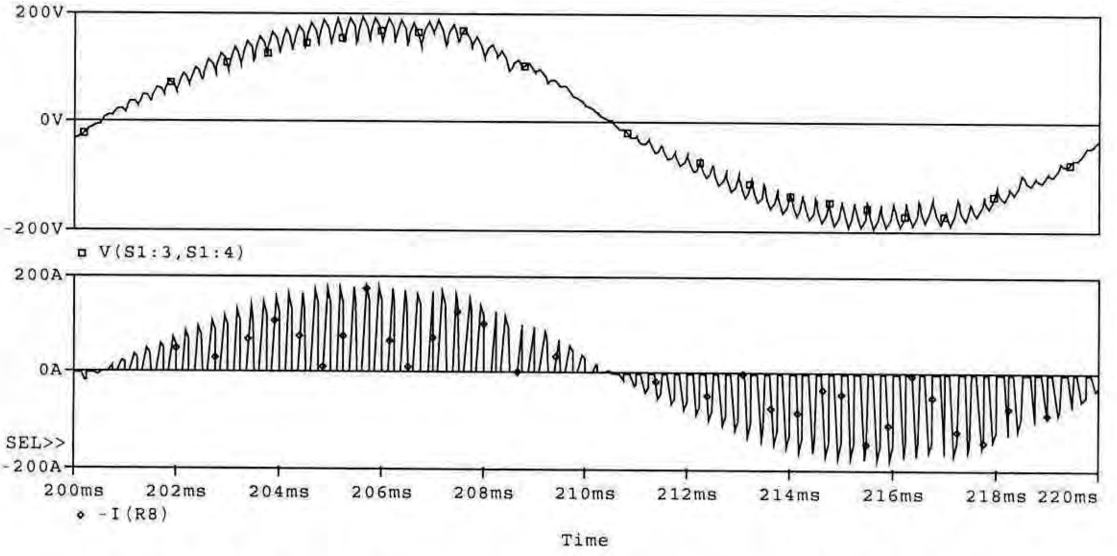


Figure : 2.5 (c4.1) - Voltage and current profile of the Switch (S1) for V_{dc}=5V [First Approach]

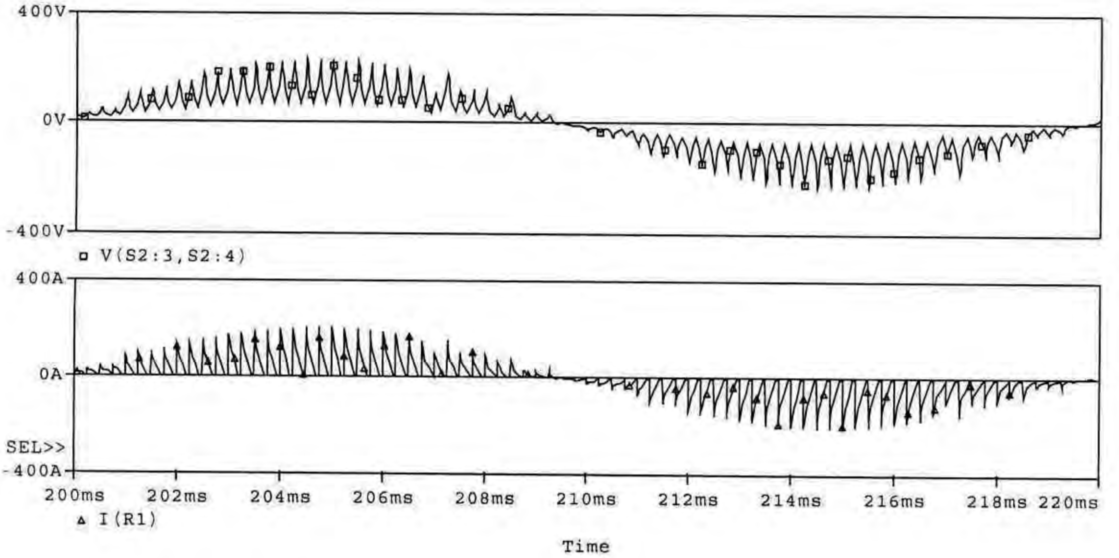


Figure : 2.5 (d4.1) - Voltage and current profile of the Switch (S2) for V_{dc}=5V

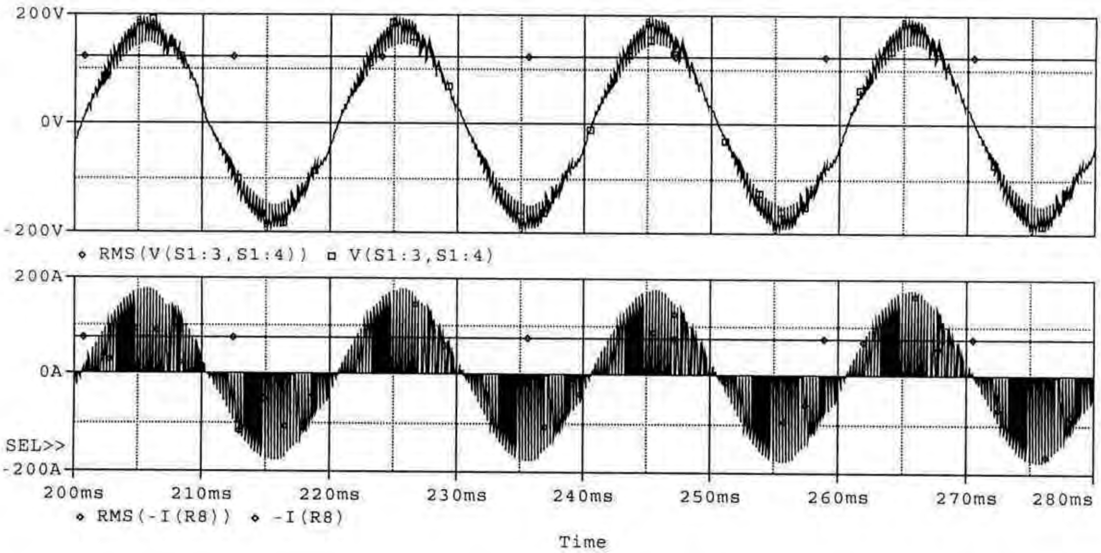


Figure: 2.5 (c5) - Voltage across and current through the switch (S1) for V_{dc}= 6V [First Approach]

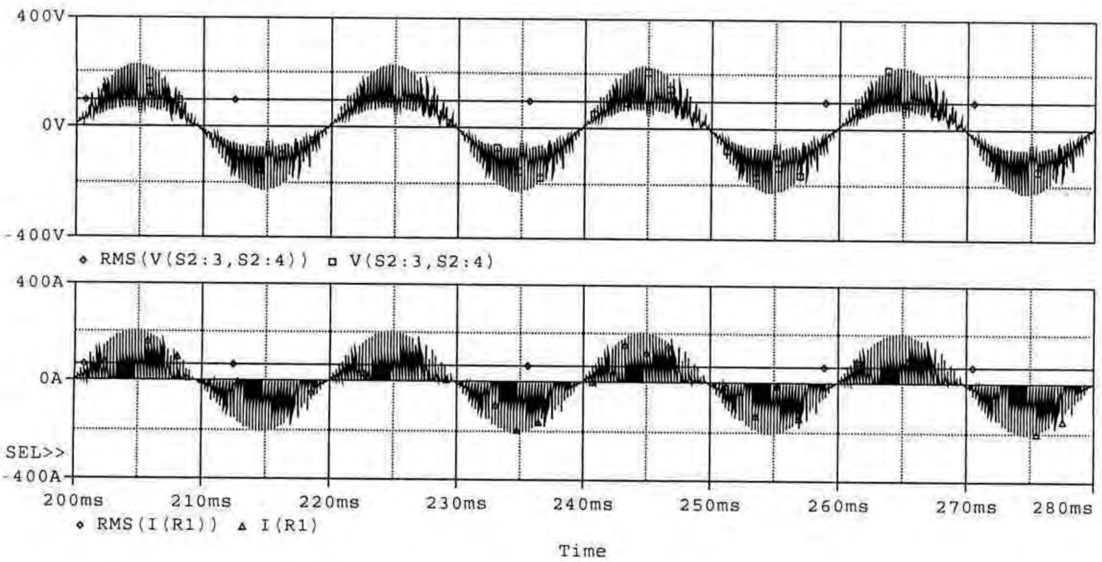


Figure : 2.5 (d5) – Voltage across and current through the switch (S2) for V_{dc}= 6V

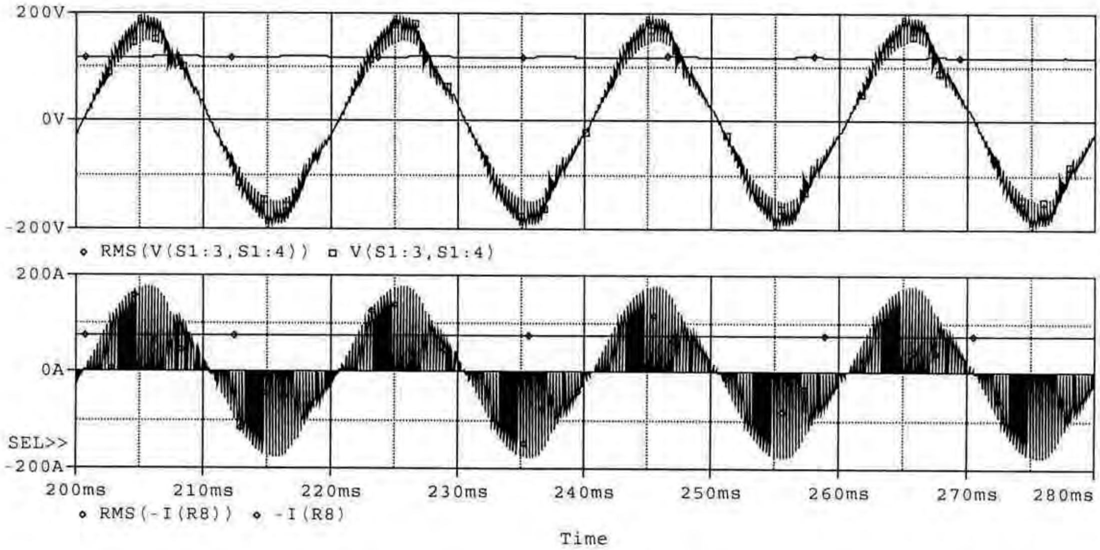


Figure: 2.5 (c6) – Voltage across and current through the switch (S1) for V_{dc}= 7V[First Approach]

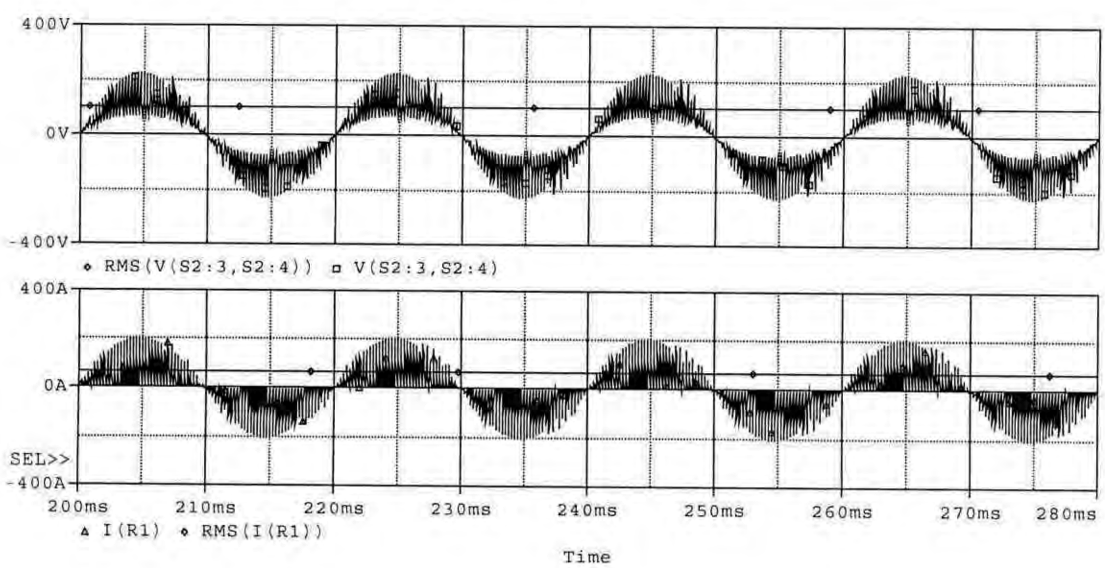


Figure : 2.5 (d6) – Voltage across and current through the switch (S2) for V_{dc}= 7V [First Approach]

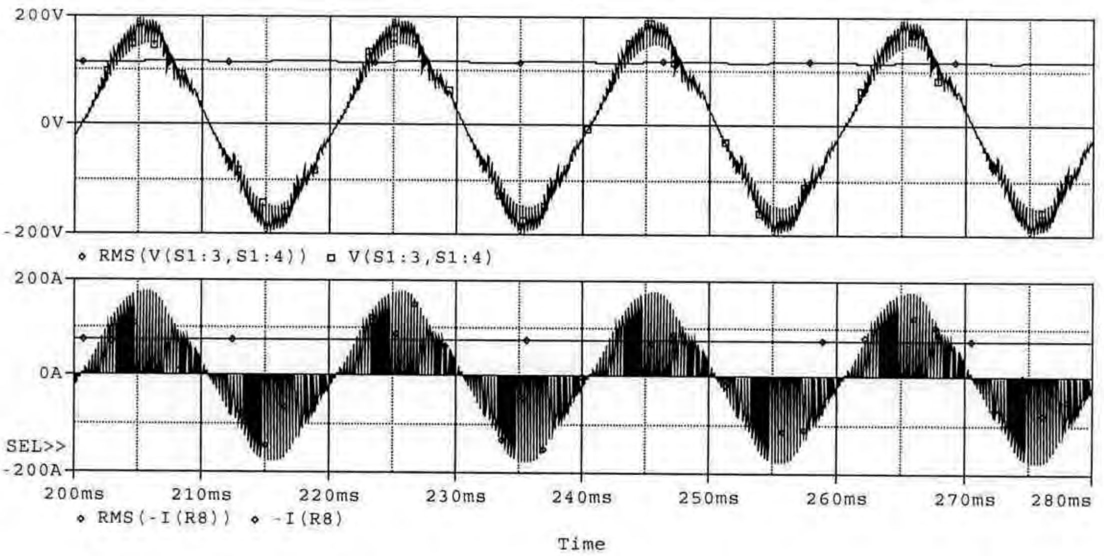


Figure: 2.5 (c7) – Voltage across and current through the switch (S1) for V_{dc}= 8V [First Approach]

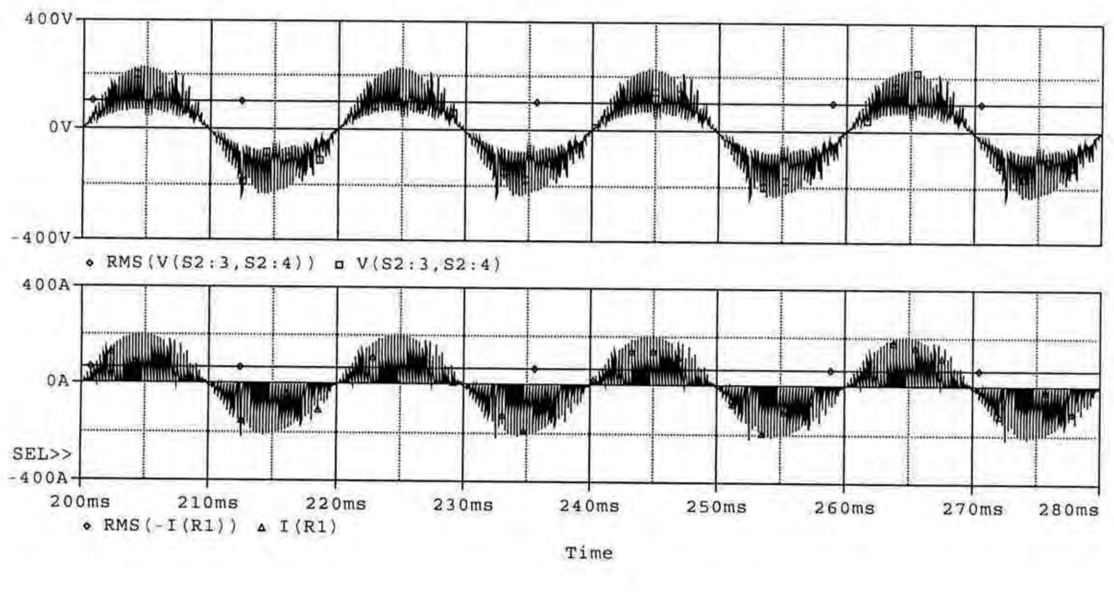


Figure : 2.5 (d7) – Voltage across and current through the switch (S2) for V_{dc}= 8V [First Approach]

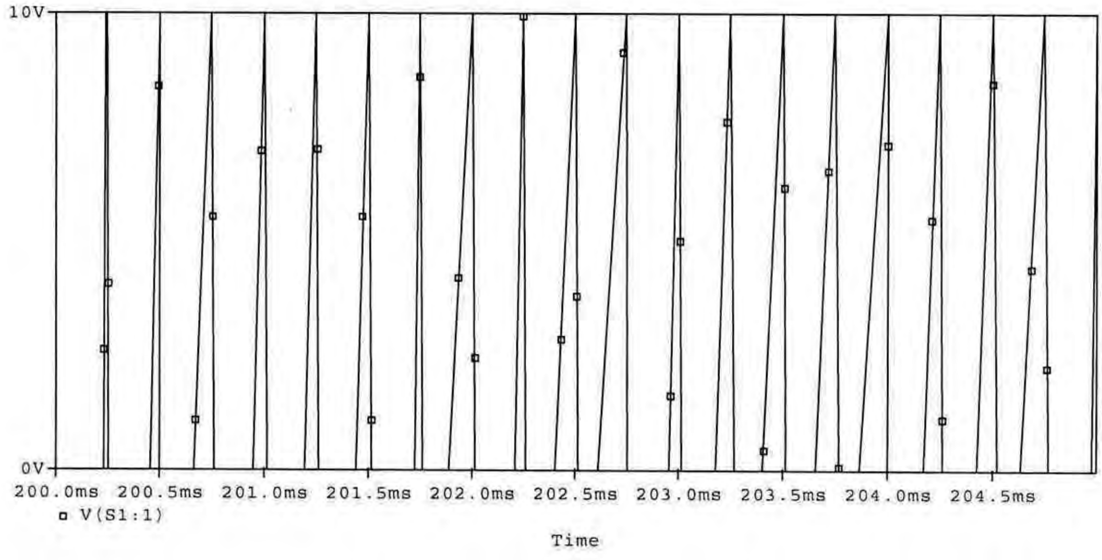


Figure : 2.5 (e) – PWM signals supplied to the switch S1 for V_{dc}= 1V [First Approach]

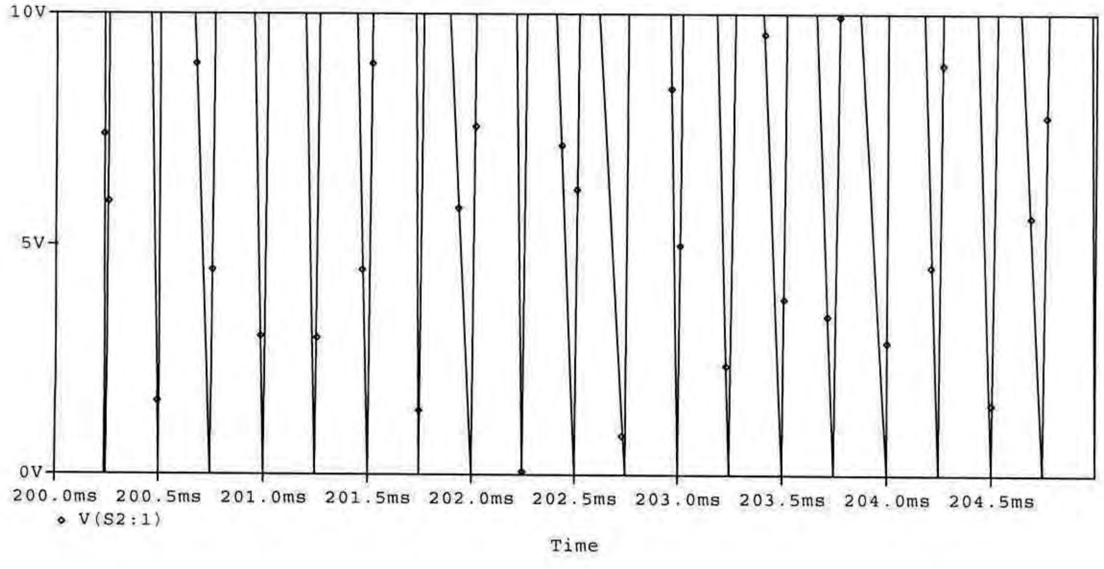


Figure : 2.5 (f) – PWM signals supplied to the switch S2 for V_{dc}= 1V [First Approach]

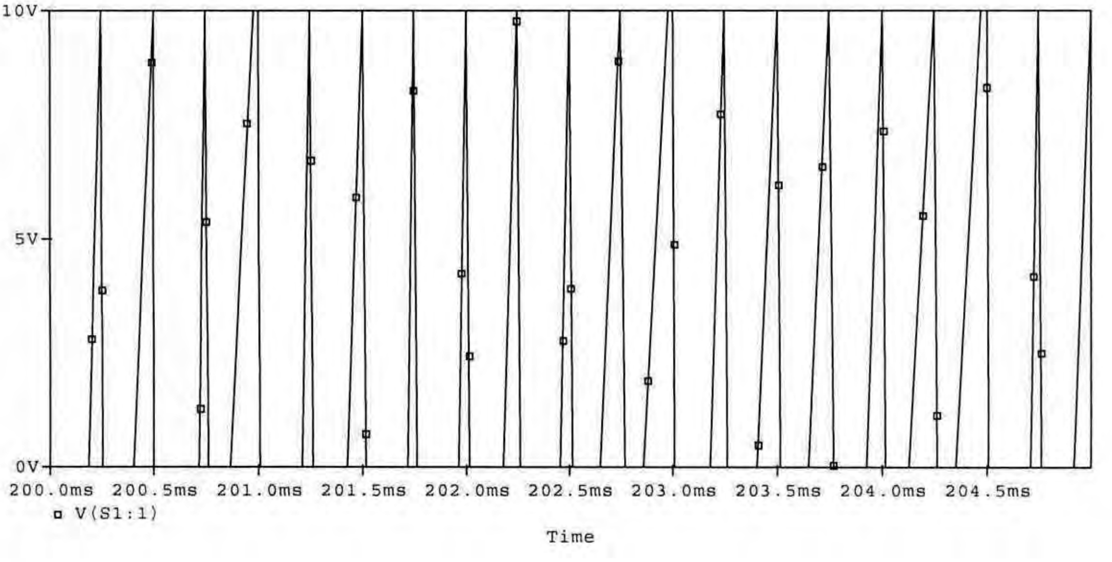


Figure : 2.5 (e1) – PWM signals supplied to the switch S1 for V_{dc}= 2V [First Approach]

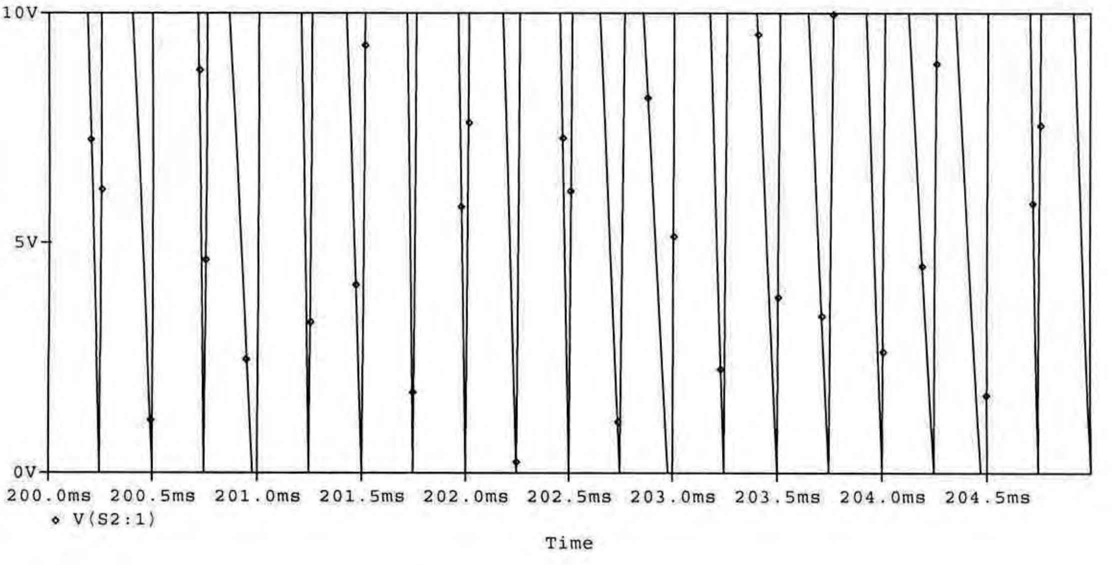


Figure : 2.5 (f1) – PWM signals supplied to the switch S2 for V_{dc}= 2V [First Approach]

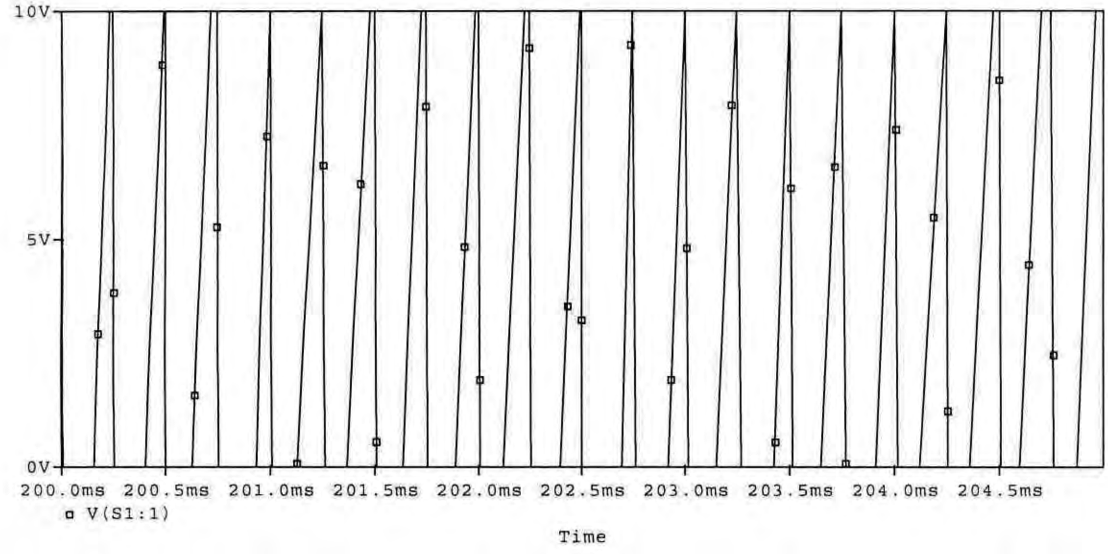


Figure : 2.5 (e2) – PWM signals supplied to the switch S1 for V_{dc}= 3V [First Approach]

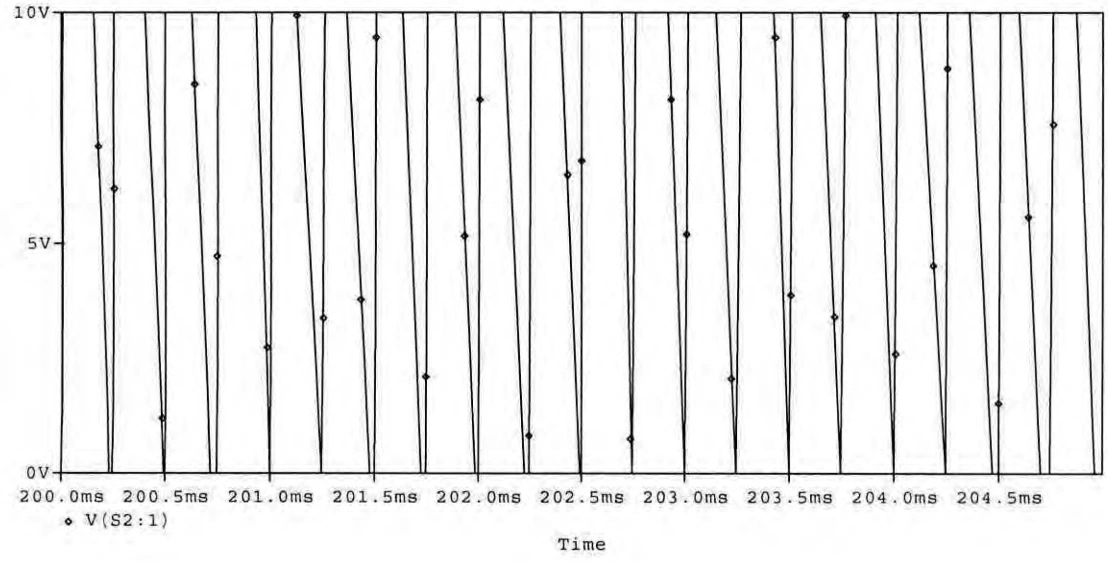


Figure : 2.5 (f2) – PWM signals supplied to the switch S2 for V_{dc}= 3V [First Approach]

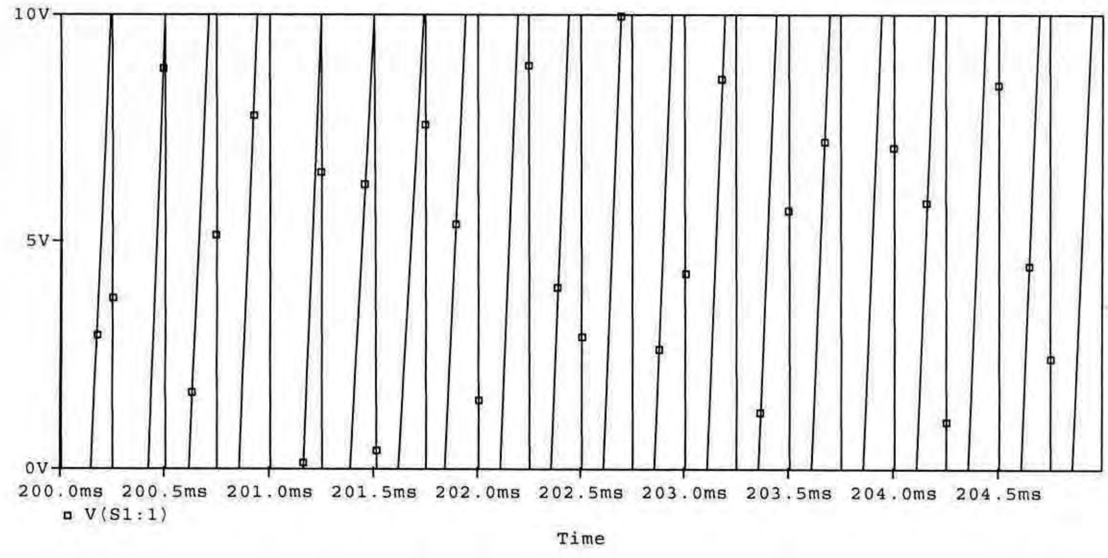


Figure : 2.5 (e3) – PWM signals supplied to the switch S1 for V_{dc}= 4 V [First Approach]

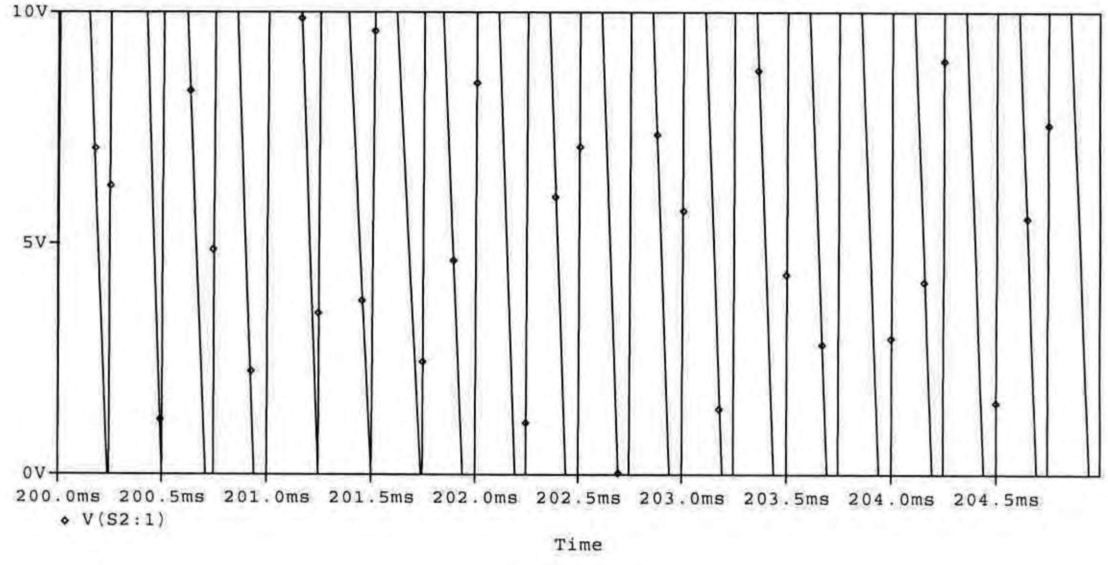


Figure : 2.5 (f3) – PWM signals supplied to the switch S2 for V_{dc}= 4 V [First Approach]

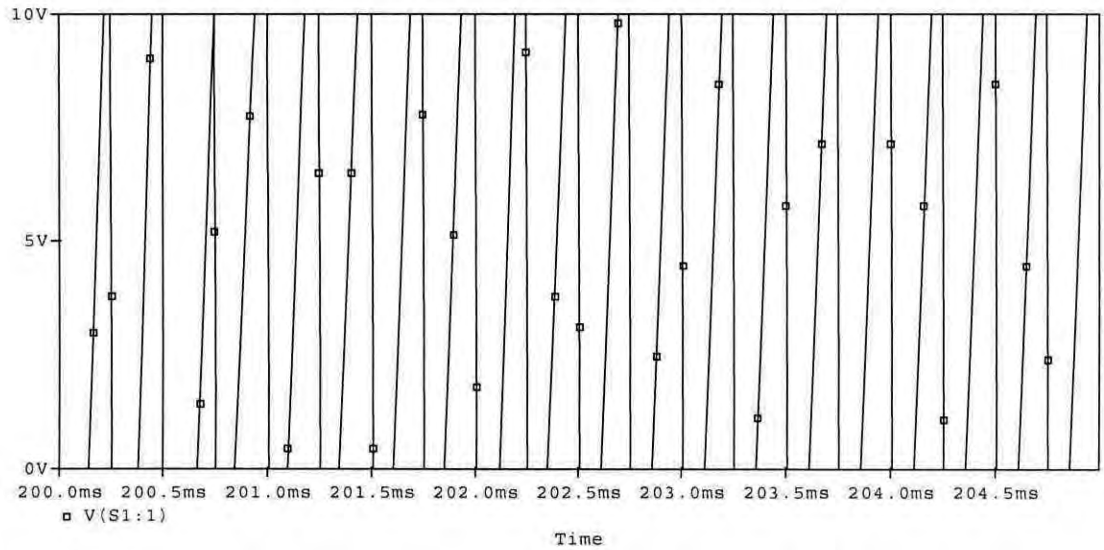


Figure : 2.5 (e4) – PWM signals supplied to the switch S1 for V_{dc}= 5 V [First Approach]

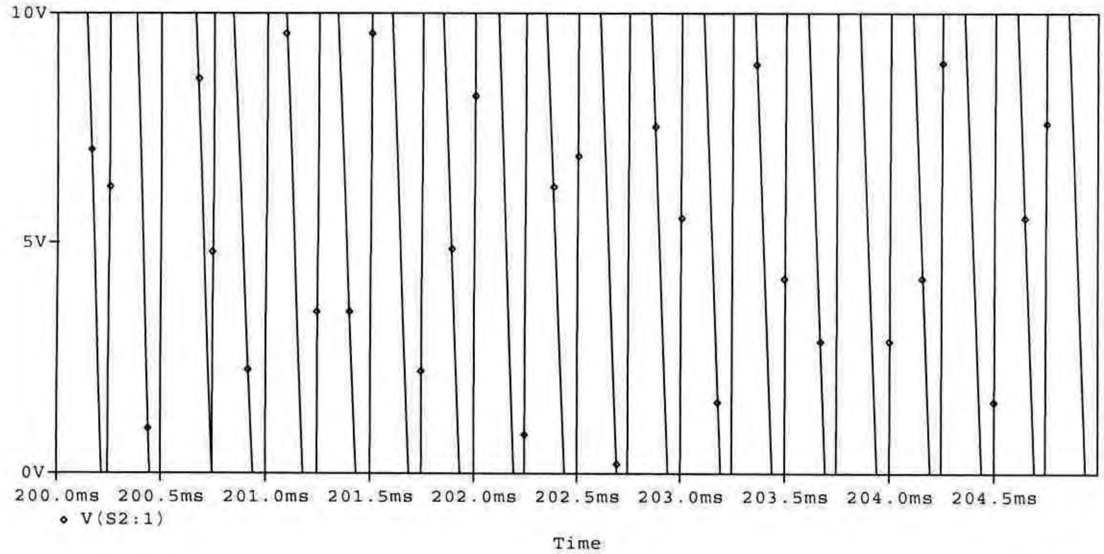


Figure : 2.5 (f4) – PWM signals supplied to the switch S2 for V_{dc}= 5 V [First Approach]

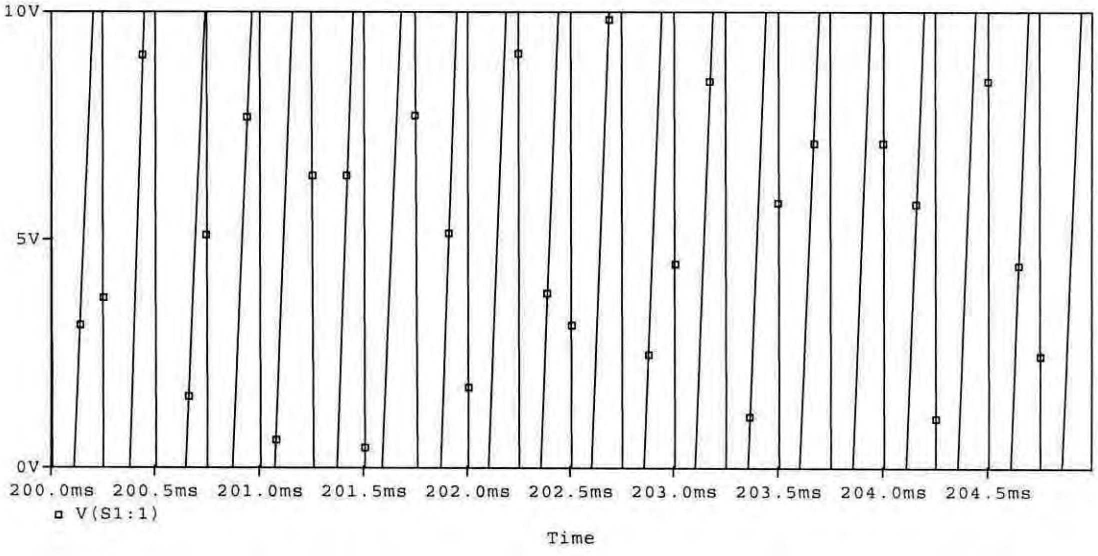


Figure : 2.5 (e5) – PWM signals supplied to the switch S1 for V_{dc}= 6 V [First Approach]

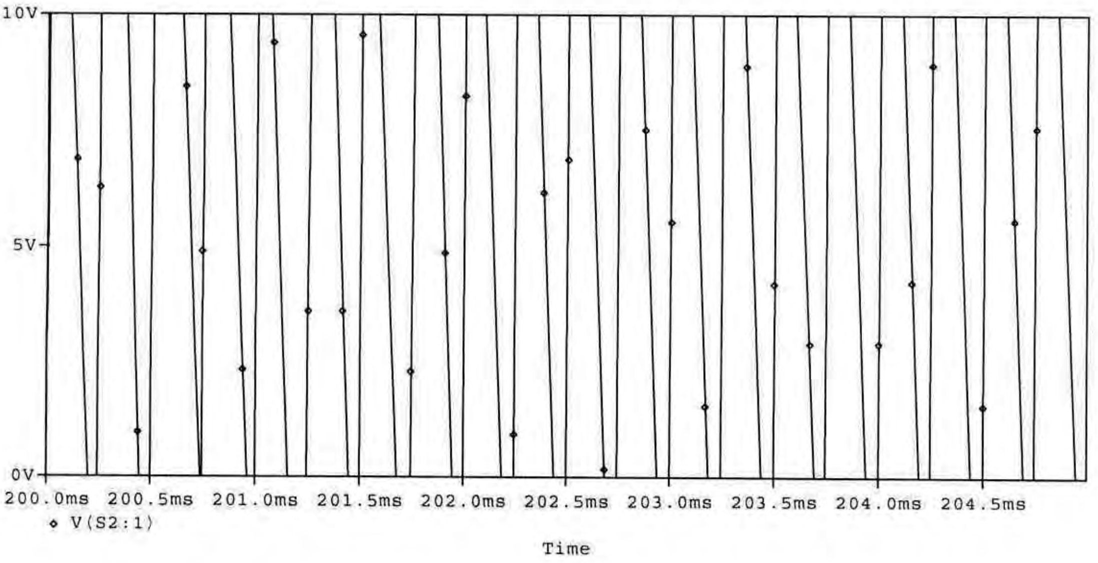


Figure : 2.5 (f5) – PWM signals supplied to the switch S2 for V_{dc}= 6 V [First Approach]

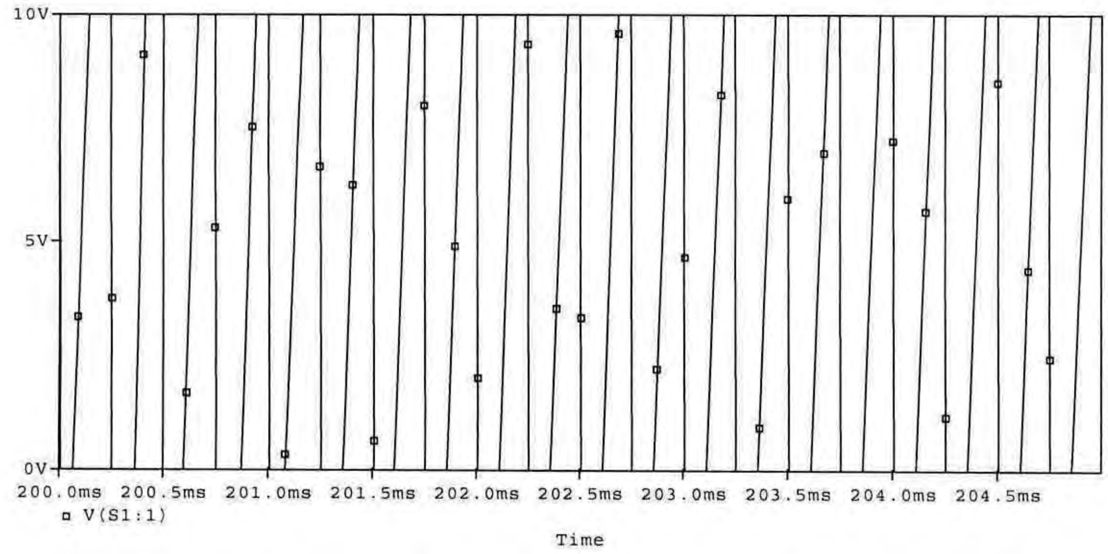


Figure : 2.5 (e6) – PWM signals supplied to the switch S1 for V_{dc}= 7 V [First Approach]

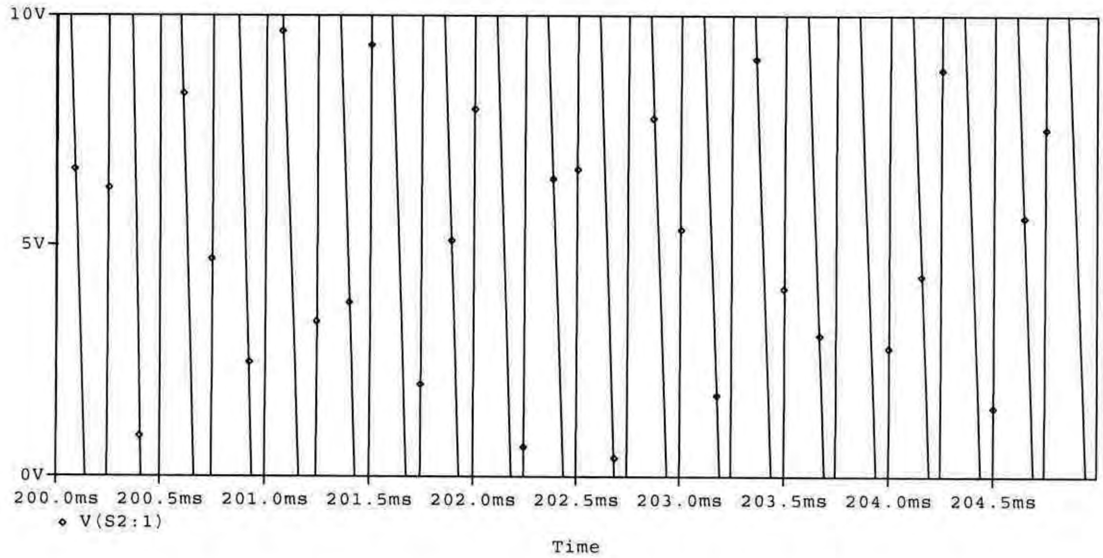


Figure : 2.5 (f6) – PWM signals supplied to the switch S2 for V_{dc}= 7 V [First Approach]

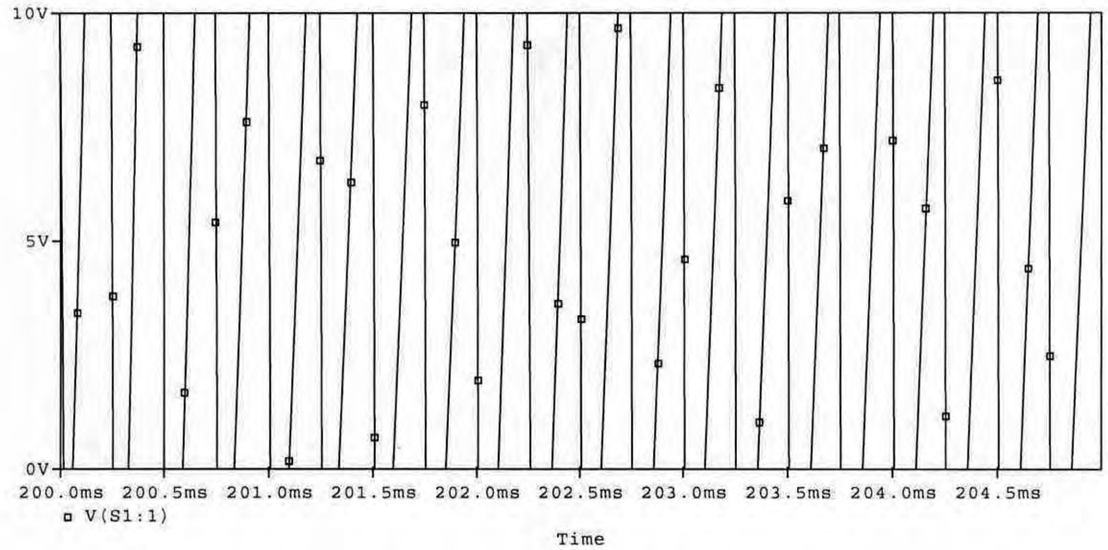


Figure : 2.5 (e7) – PWM signals supplied to the switch S1 for V_{dc}= 8 V [First Approach]

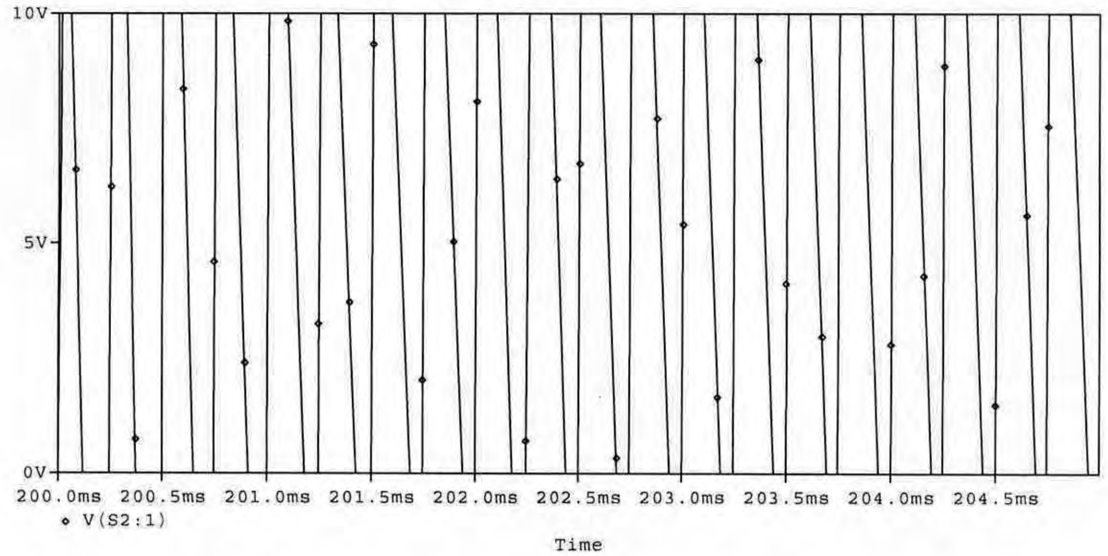


Figure : 2.5 (f7) – PWM signals supplied to the switch S2 for V_{dc}= 8 V [First Approach]

TABLE – 2.5

Hc	SWITCH S1		SWITCH S2		CAPACITOR		PULSE WIDTH (μs)		REMARKS
lt	V(RMS) Volt	I(RMS) Amps	V(RMS) Volt	I(RMS) Amps	V(RMS) Volt	I(RMS) Amps	S1	S2	
	178	72	50	36	178	81	43	211	Unity Power factor obtained
	169	74	57	41	169	84	45	209	Unity Power factor obtained
	160	76	66	46	160	87	85	169	Unity Power factor obtained
	138	76	89	58	138	95	86	161	Unity Power factor obtained
	127	76	98	63	127	99	89	158	Unity Power factor obtained
	122	76	101	65	122	100	104	144	Unity Power factor obtained
	119	76	105	65	119	100	136	111	Unity Power factor obtained
	115	76	110	67	115	100	140	105	Unity Power factor obtained

Figure : 2.5 (g) – TABLE 2.5 – Various parameters of the Figure – 2.5 for the First approach

2.6 SECOND APPROACH :

In this approach in order to limit the current through the capacitor and the switch we made some modification to the circuit of the first approach. At first we take the four loads of equal magnitude in parallel at a time and found that by varying the dc voltages of the PWM generator from **5V to 12V** the power factor in each case becomes unity. Here the current through the switch and the capacitor are within tolerable limit. A switch of such a limit is practically feasible.

Now We are going to vary the loads one by one and in each case we determine the dc voltage required for the generation of the PWM signals to operate the switch to have the unity power factor.

We prepared a table **[TABLE-2.6 (A)]** where the value of the various parameters of the circuit (**Figure 2.6)** are taken for different values of dc voltages **(5 – 12V)** . From this table we find that the width of the PWM signals increases as the dc voltage increase.This satisfies our requirements.

We again made a table **[TABLE 2.6 (B)]** where the loads are taken one by one and determine the required dc voltage for each case to attain unity power factor. Here the value of the dc voltage for the generation of the PWM signal increases as the number of parallel loads increases. The width of the corresponding PWM signals also increases as the no. of loads increase which satisfies our desired conditions.

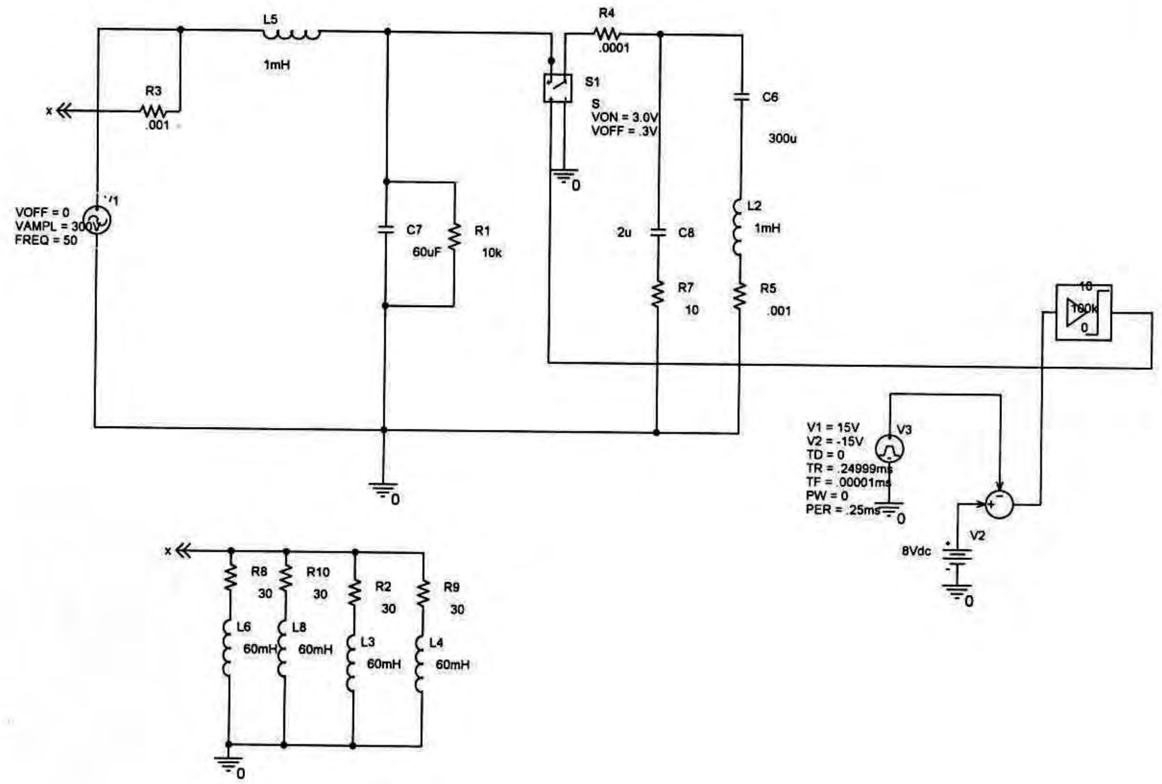


Figure: 2.6 - Circuit arrangement for Second Approach to attain unity power factor

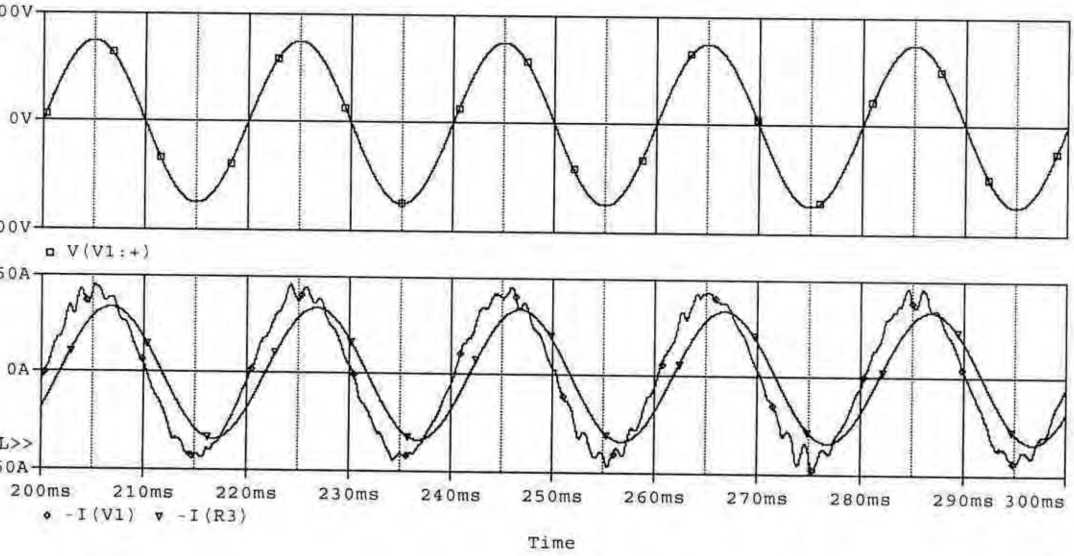


Figure : 2.6 (a1) : Unity power factor attained for V_{dc}= 5V [Second Approach]

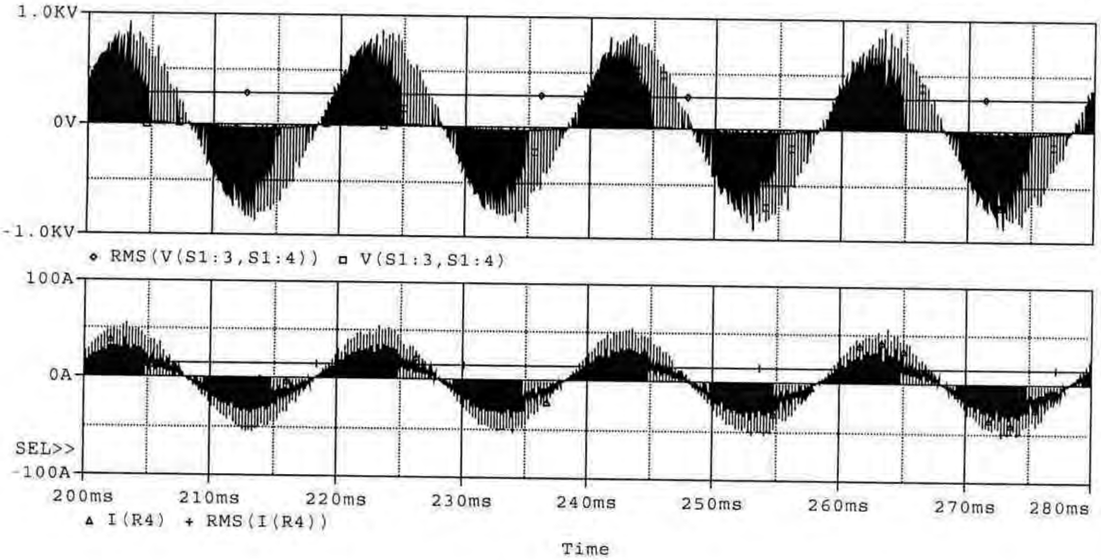


Figure : 2.6 (b1) – Voltage across and current through the switch for V_{dc}= 5V to attain unity power factor [Second Approach]

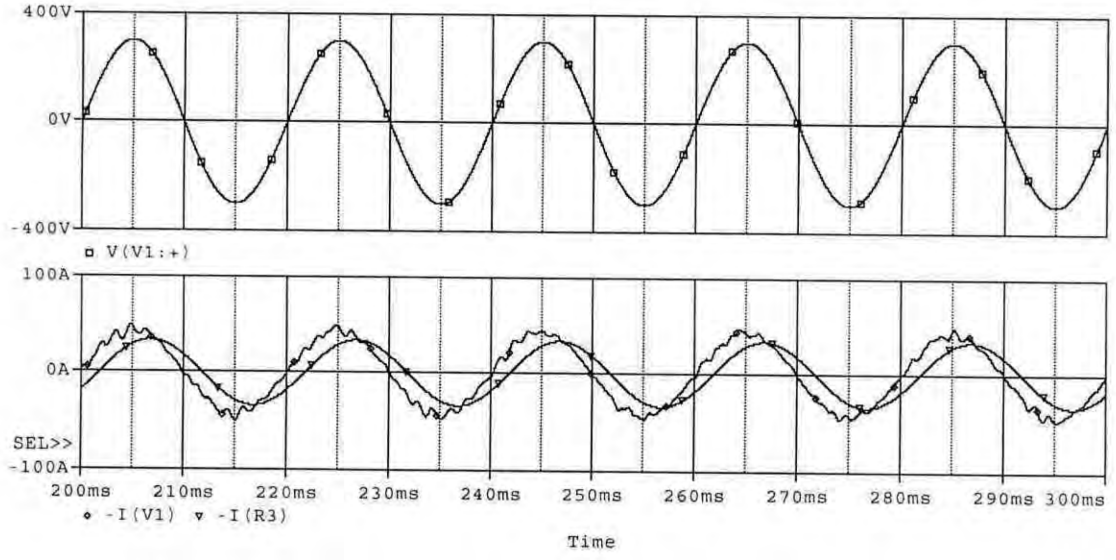


Figure : 2.6 (a2) : Unity power factor attained for V_{dc}= 6V [Second Approach]

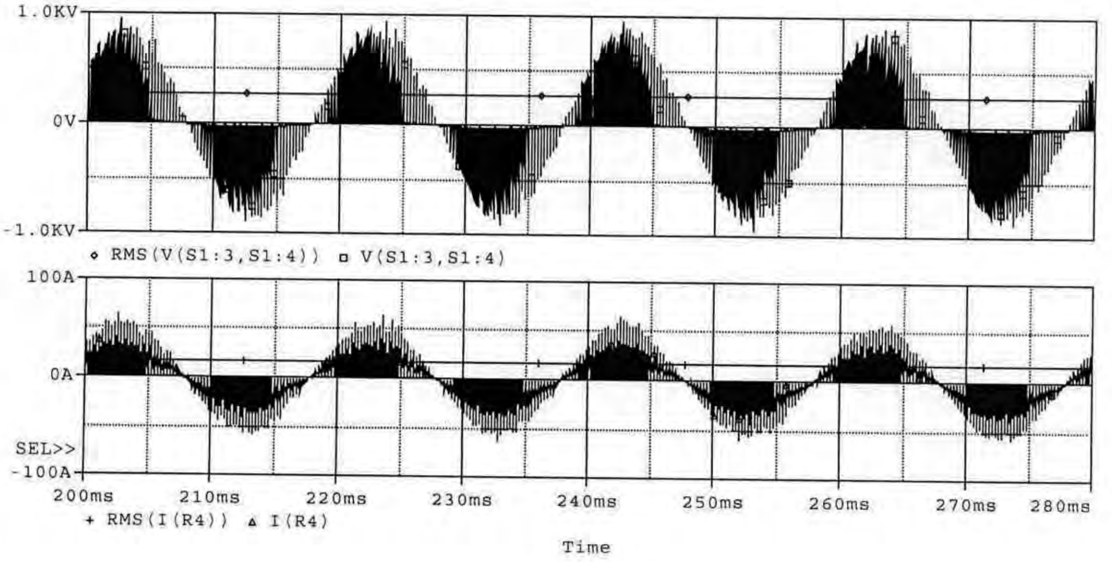


Figure : 2.6 (b2) – Voltage across and current through the switch for V_{dc}= 6V to attain unity power factor [Second Approach]

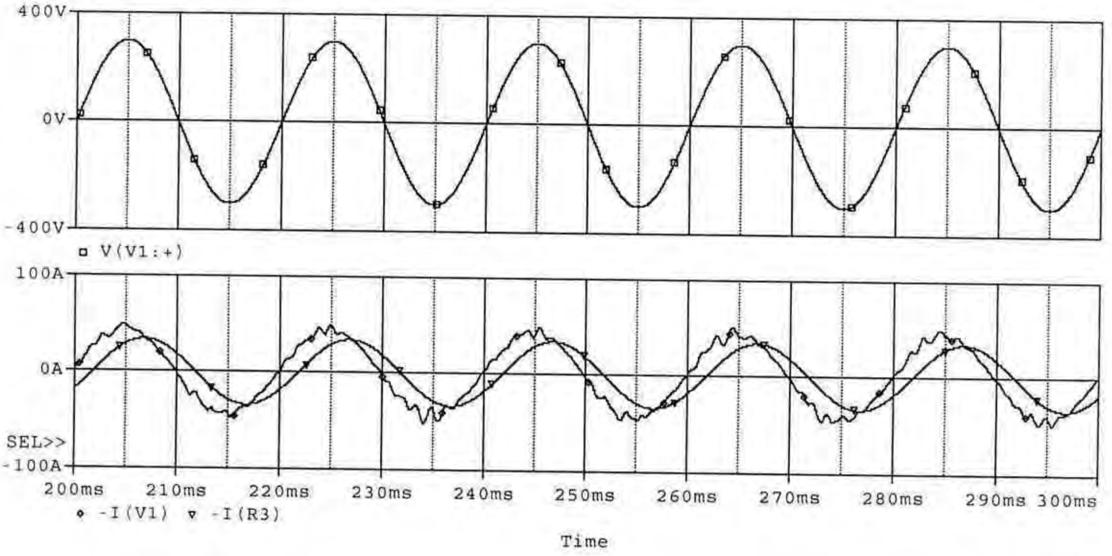


Figure : 2.6 (a3) : Unity power factor attained for V_{dc}= 7V [Second Approach]

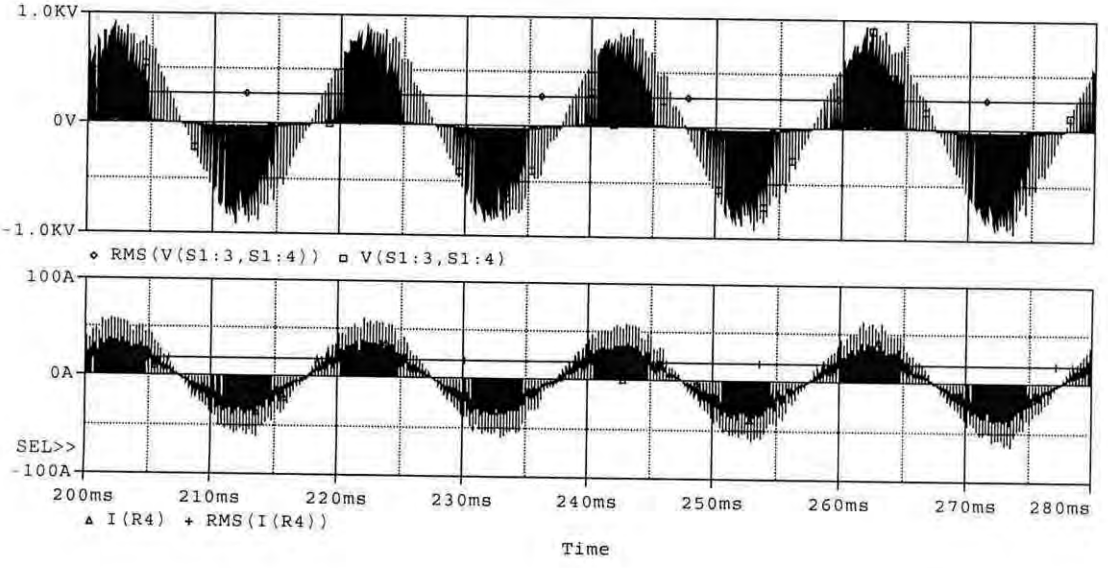


Figure : 2.6 (b3) – Voltage across and current through the switch for V_{dc}=7V to attain unity power factor [Second Approach]

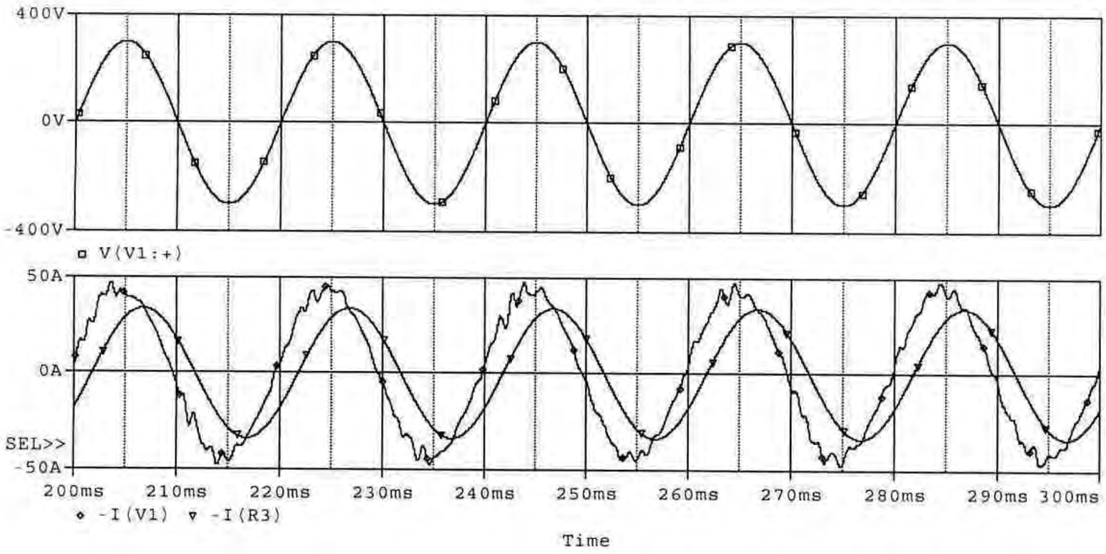


Figure : 2.6 (a4) : Unity power factor attained for V_{dc}= 8V [Second Approach]

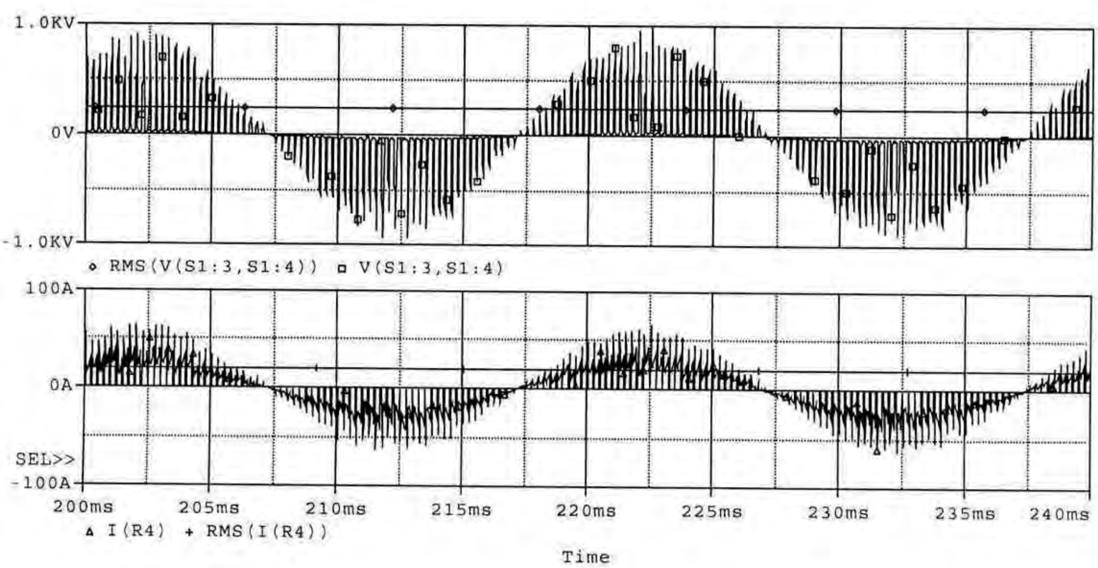


Figure : 2.6 (b4) – Voltage across and current through the switch for V_{dc}= 8V to attain unity power factor [Second Approach]

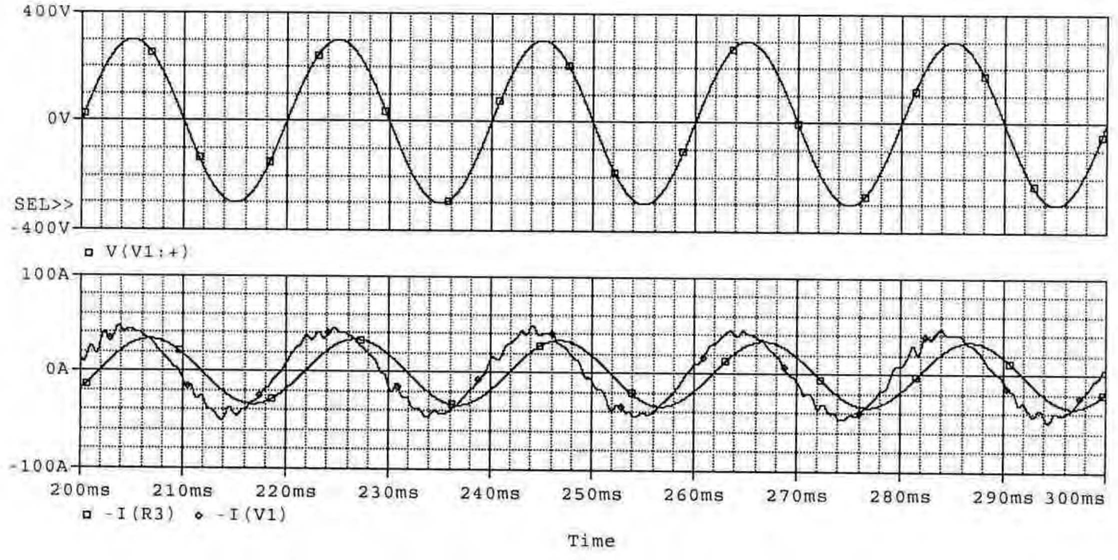


Figure : 2.6 (a5) : Unity power factor attained for V_{dc}=9V [Second Approach]

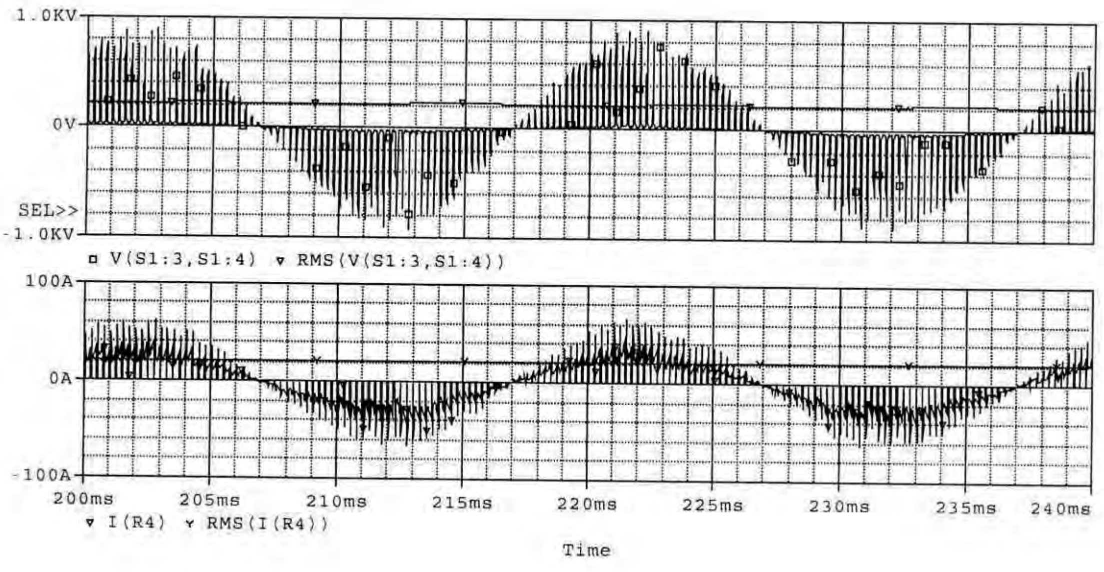


Figure : 2.6 (b5) – Voltage across and current through the switch for V_{dc}= 9V to attain unity power factor [Second Approach]

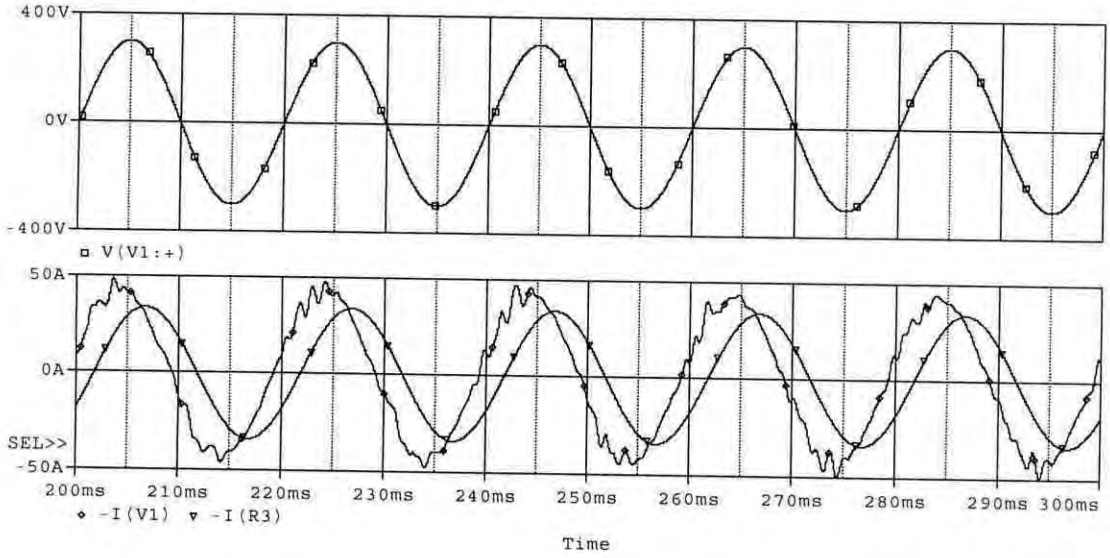


Figure : 2.6 (a6) : Unity power factor attained for V_{dc}= 10V [Second Approach]

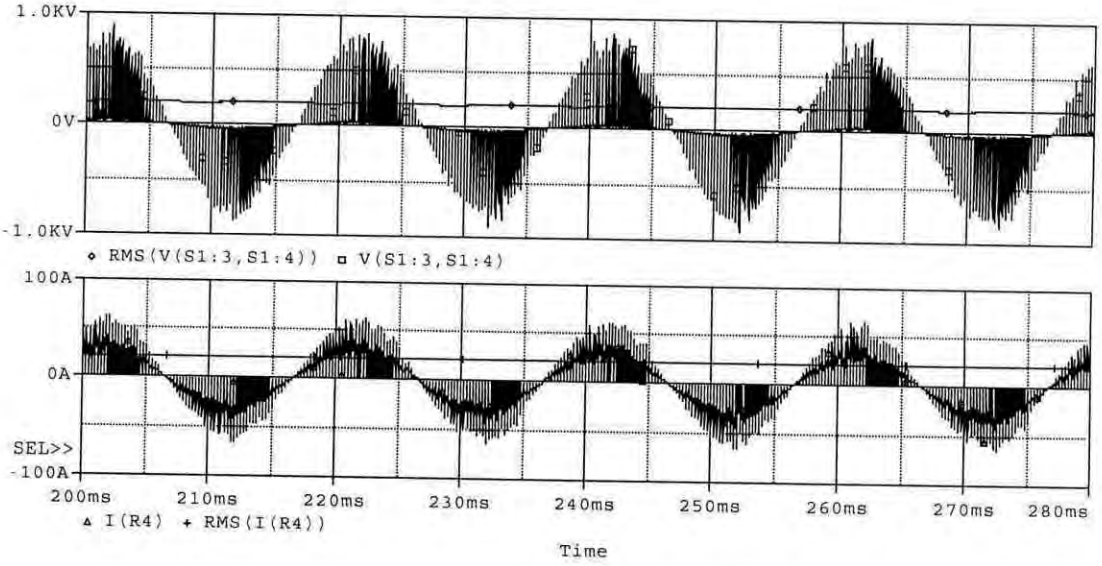


Figure : 2.6 (b6) – Voltage across and current through the switch for V_{dc}=10V to attain unity power factor [Second Approach]

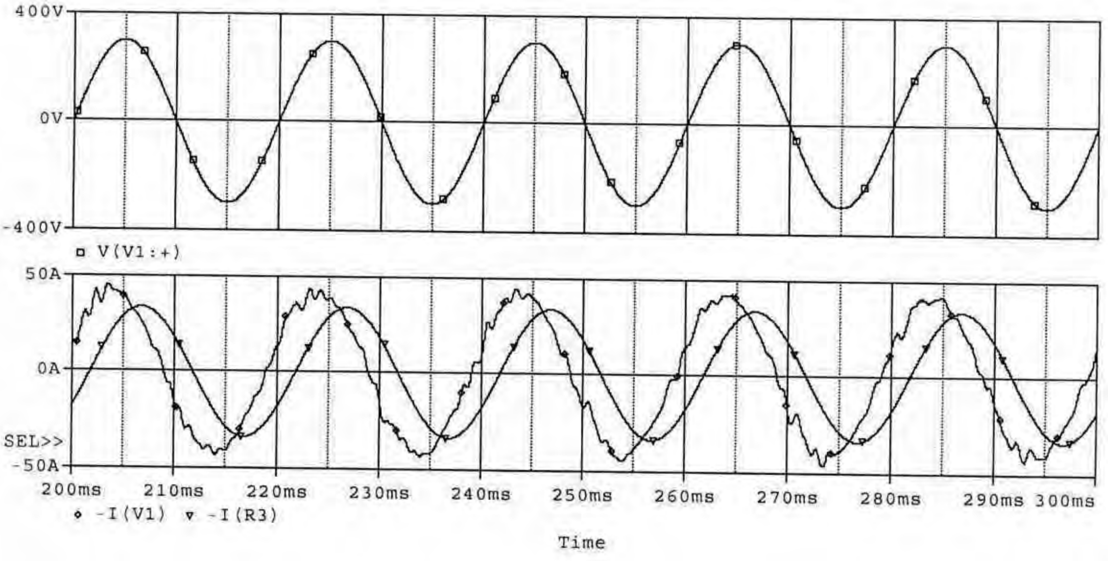


Figure : 2.6 (a7) : Unity power factor attained for V_{dc}= 11V [Second Approach]

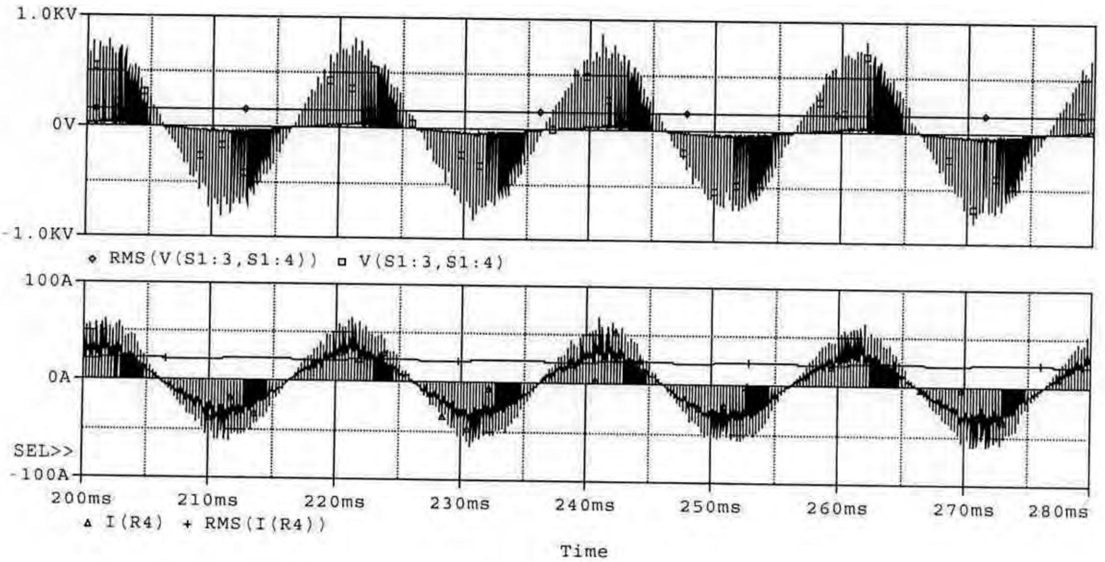


Figure : 2.6 (b7) – Voltage across and current through the switch for V_{dc}= 11V to attain unity power factor [Second Approach]

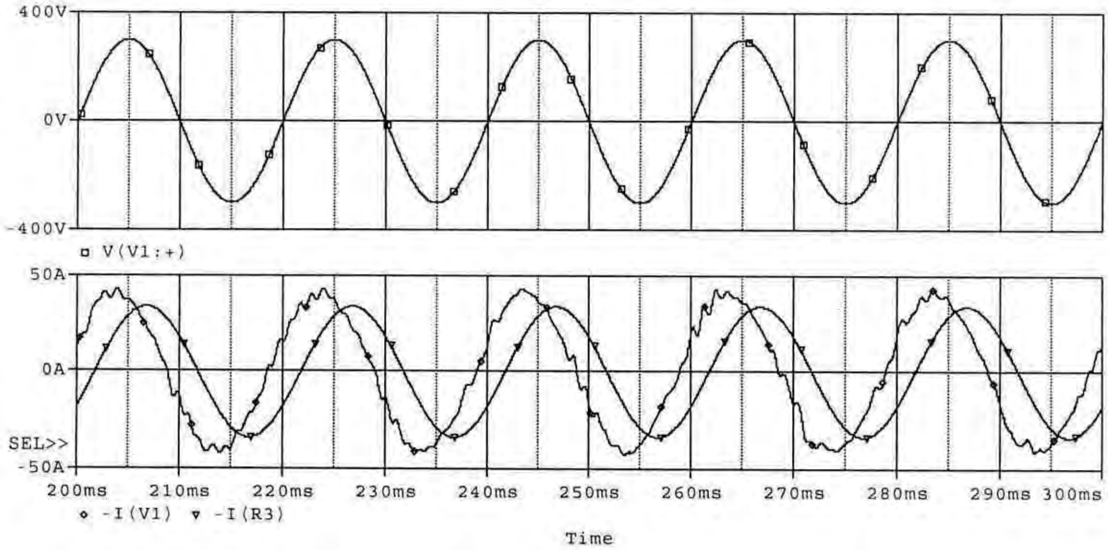


Figure : 2.6 (a8) : Unity power factor attained for V_{dc}= 12V [Second Approach]

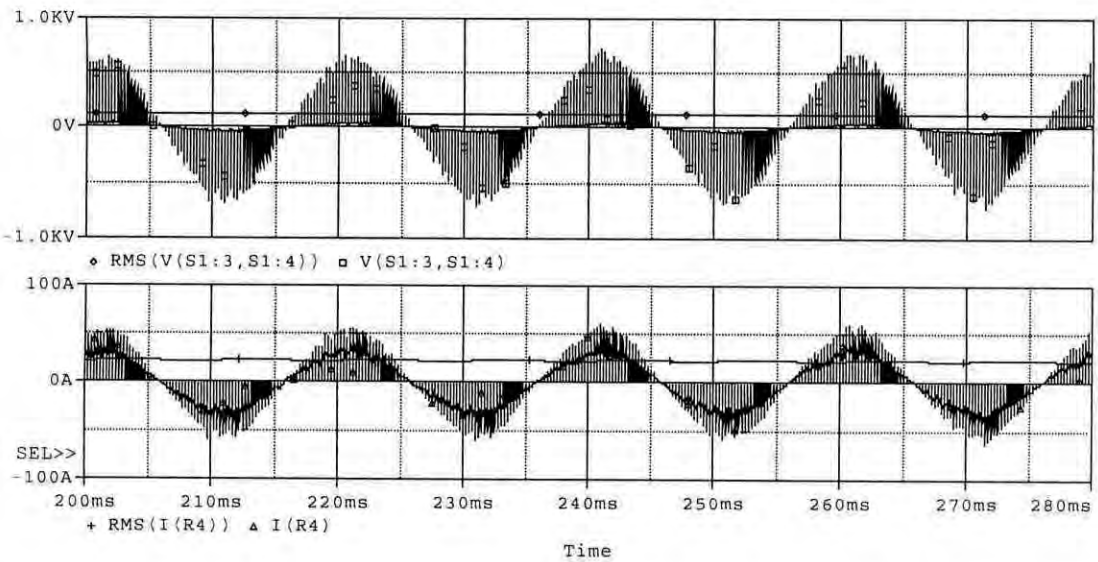


Figure : 2.6 (b8) – Voltage across and current through the switch for V_{dc}= 12V to attain unity power factor [Second Approach]

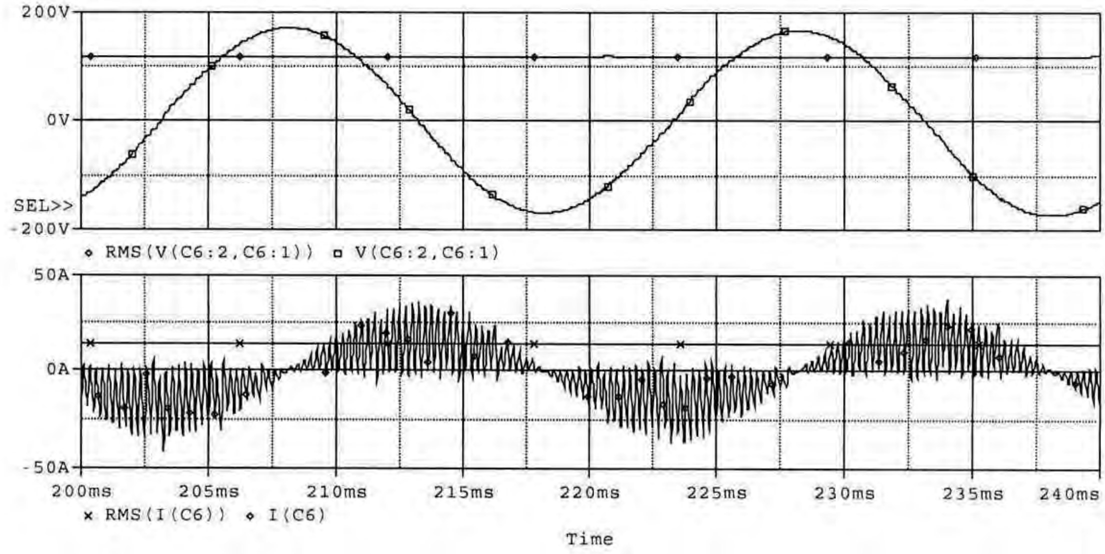


Figure : 2.6 (c1) – Voltage across and current through the capacitor for V_{dc}= 5V to attain unity power factor [Second Approach]

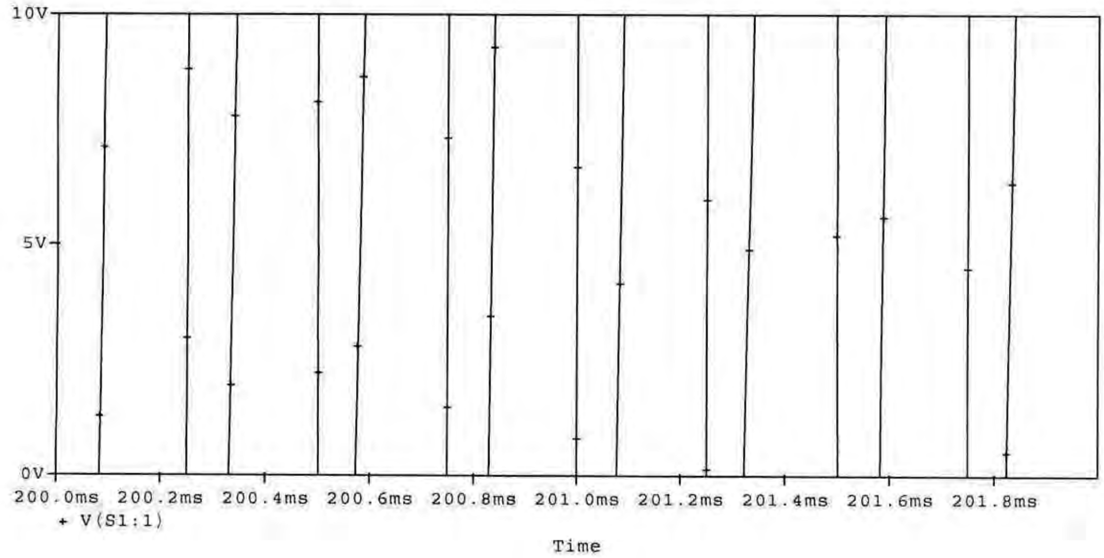


Figure : 2.6 (d1) – PWM signal supplied to the switch for V_{dc}= 5V to attain unity power factor [Second Approach]

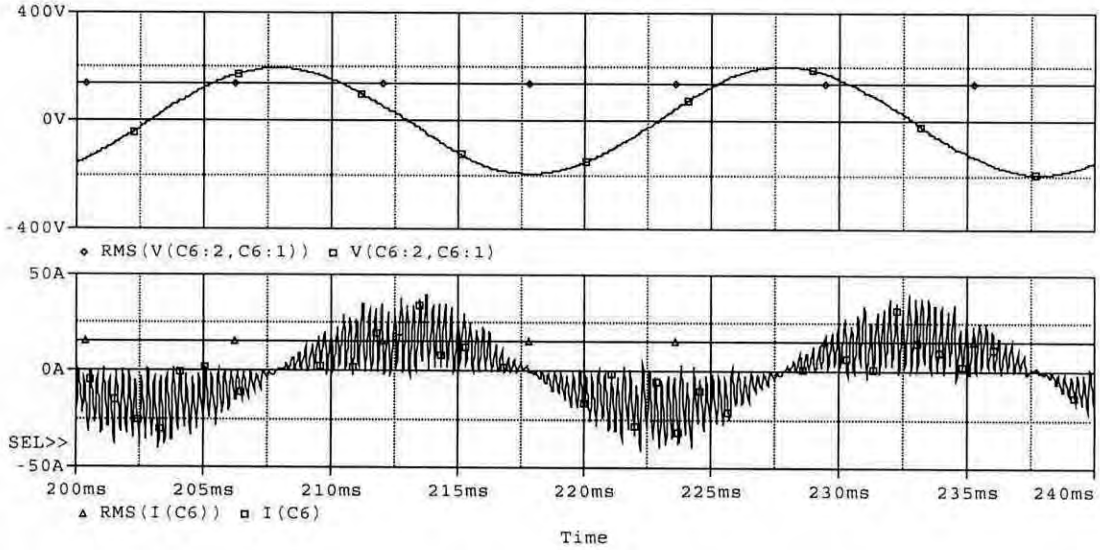


Figure : 2.6 (c2) – Voltage across and current through the capacitor for V_{dc}= 6V to attain unity power factor [Second Approach]

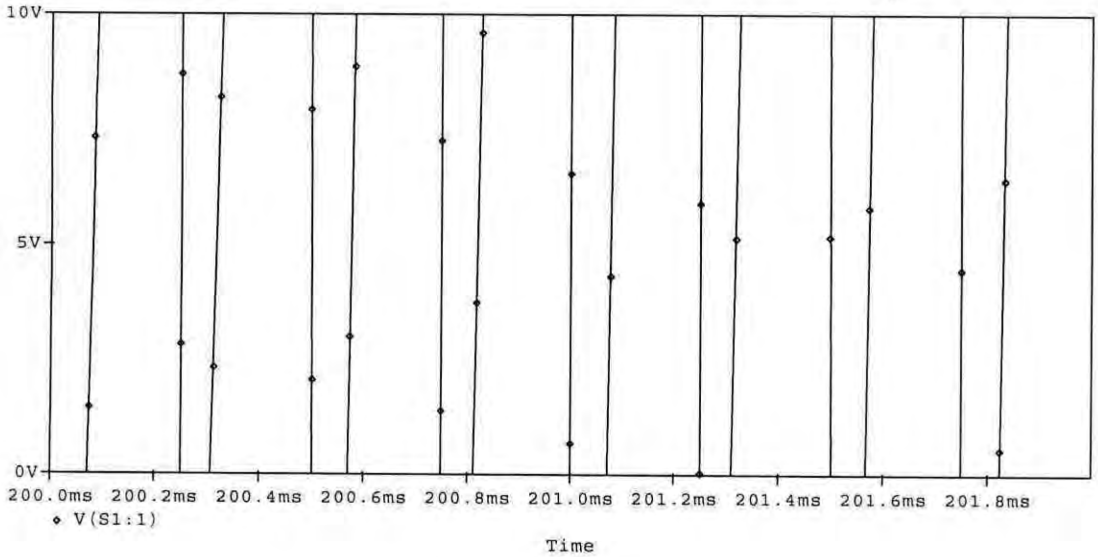


Figure : 2.6 (d2) – PWM signal supplied to the switch for V_{dc}= 6V to attain unity power factor [Second Approach]

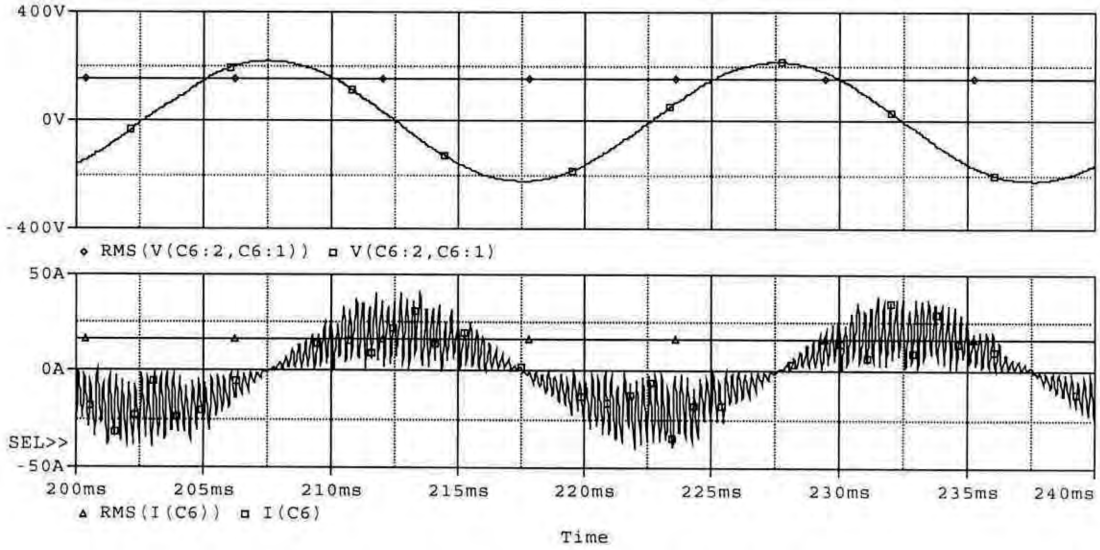


Figure : 2.6 (c3) – Voltage across and current through the capacitor for V_{dc}= 7V to attain unity power factor [Second Approach]

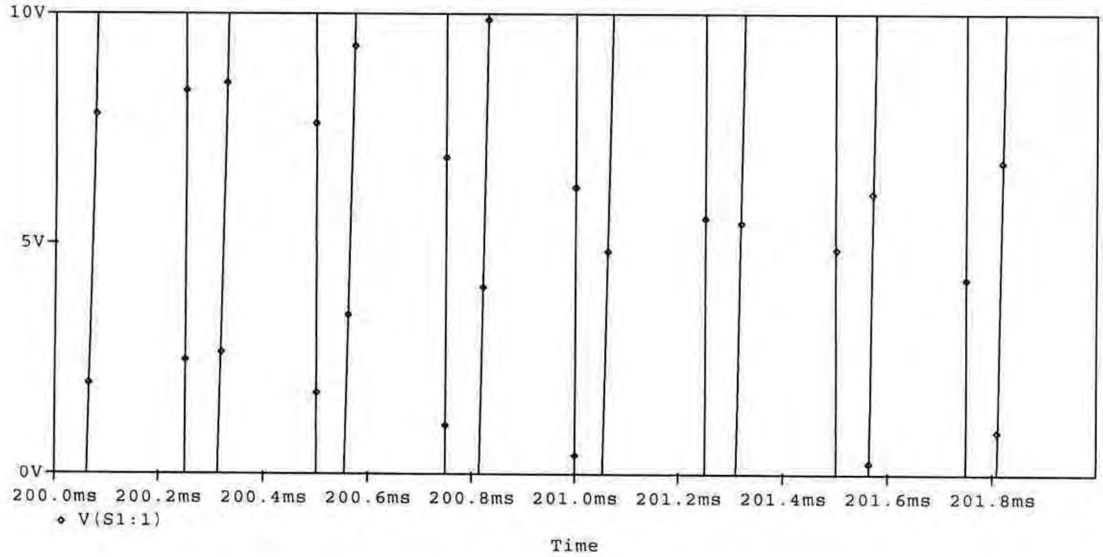


Figure : 2.6 (d3) – PWM signal supplied to the switch for V_{dc}= 7V to attain unity power factor [Second Approach]

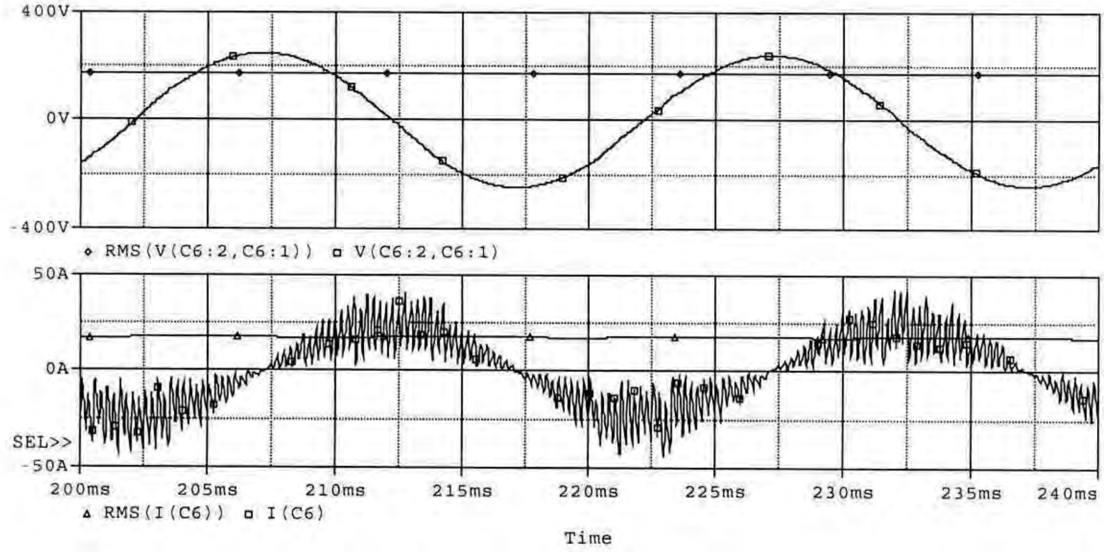


Figure : 2.6 (c4) – Voltage across and current through the capacitor for V_{dc}=8V to attain unity power factor [Second Approach]

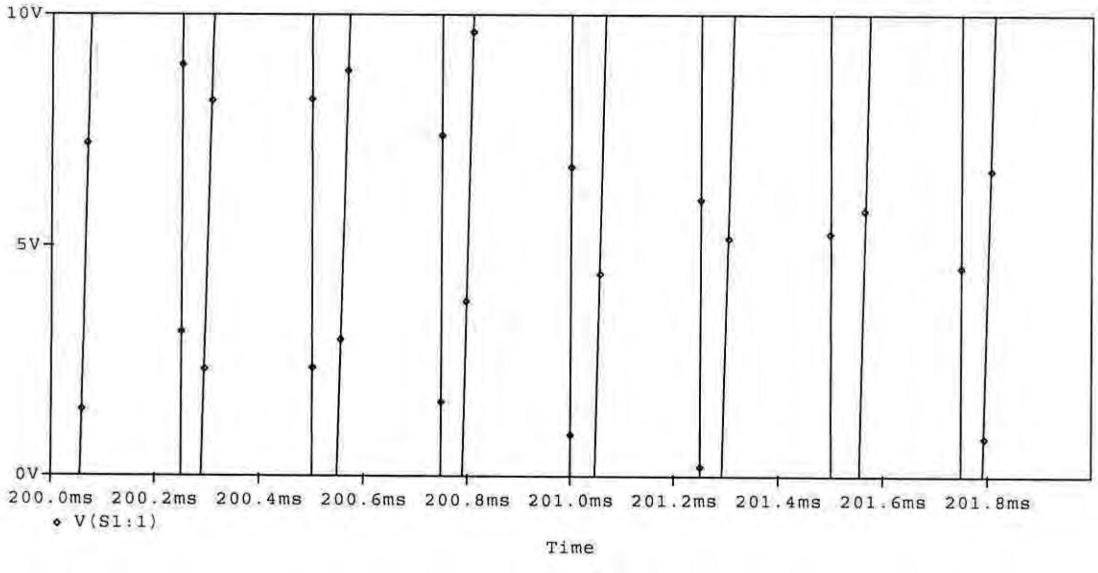


Figure : 2.6 (d1) – PWM signal supplied to the switch for V_{dc}= 8V to attain unity power factor [Second Approach]

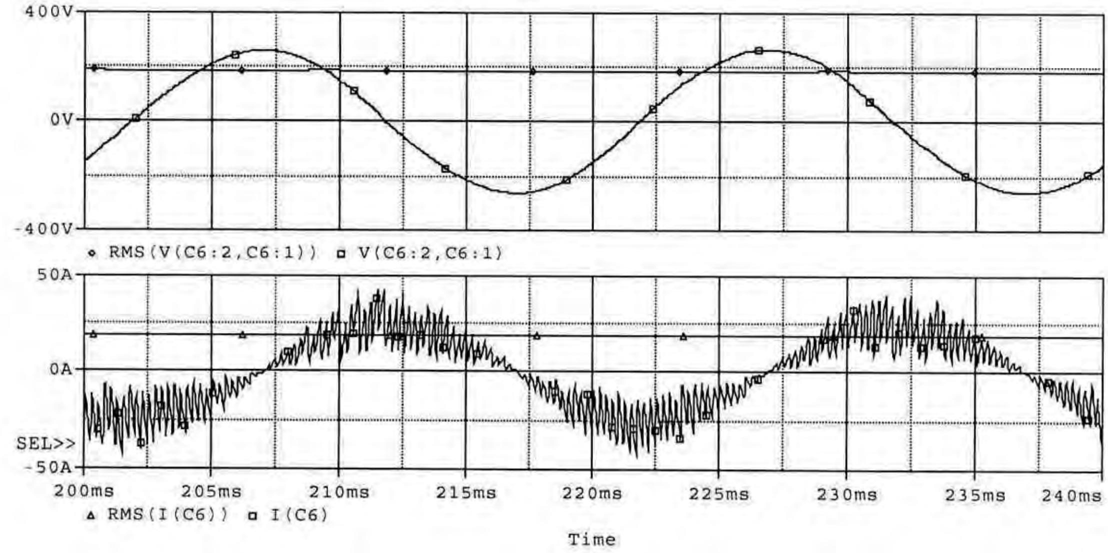


Figure : 2.6 (c5) – Voltage across and current through the capacitor for V_{dc}=9V to attain unity power factor [Second Approach]

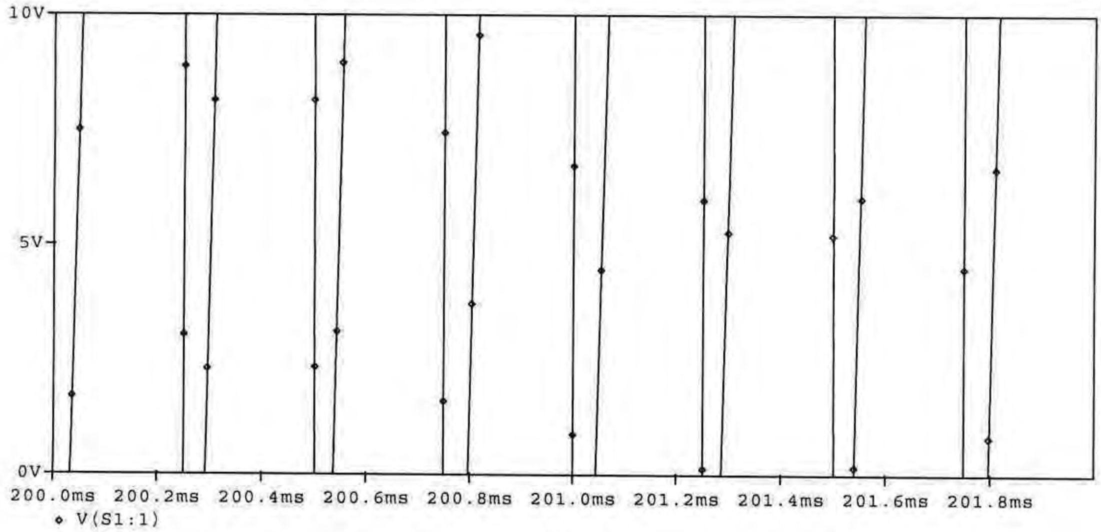


Figure : 2.6 (d5) – PWM signal supplied to the switch for V_{dc}= 9Vto attain unity power factor [Second Approach]

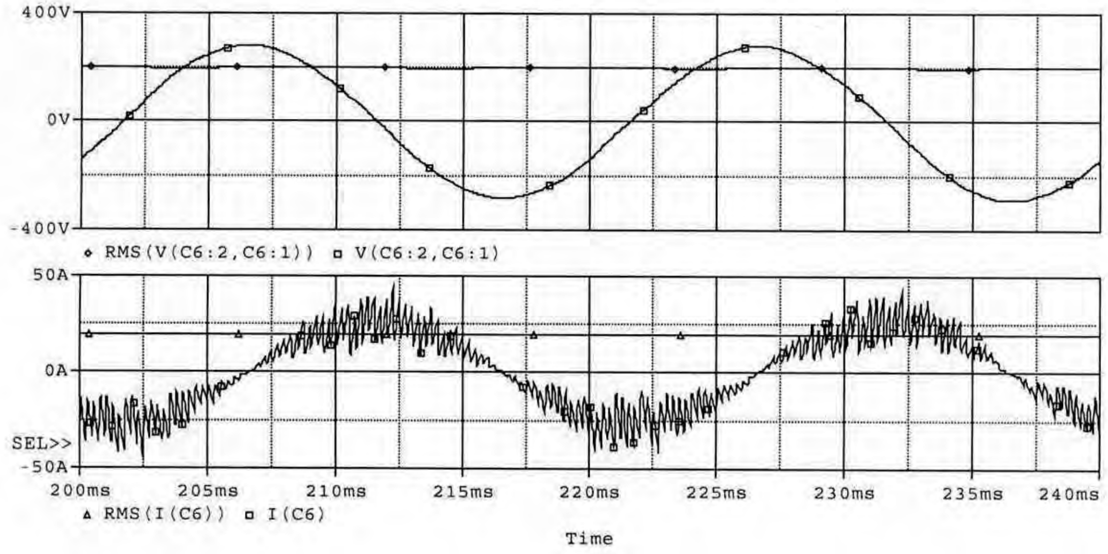


Figure : 2.6 (c6) – Voltage across and current through the capacitor for V_{dc}=10V to attain unity power factor [Second Approach]

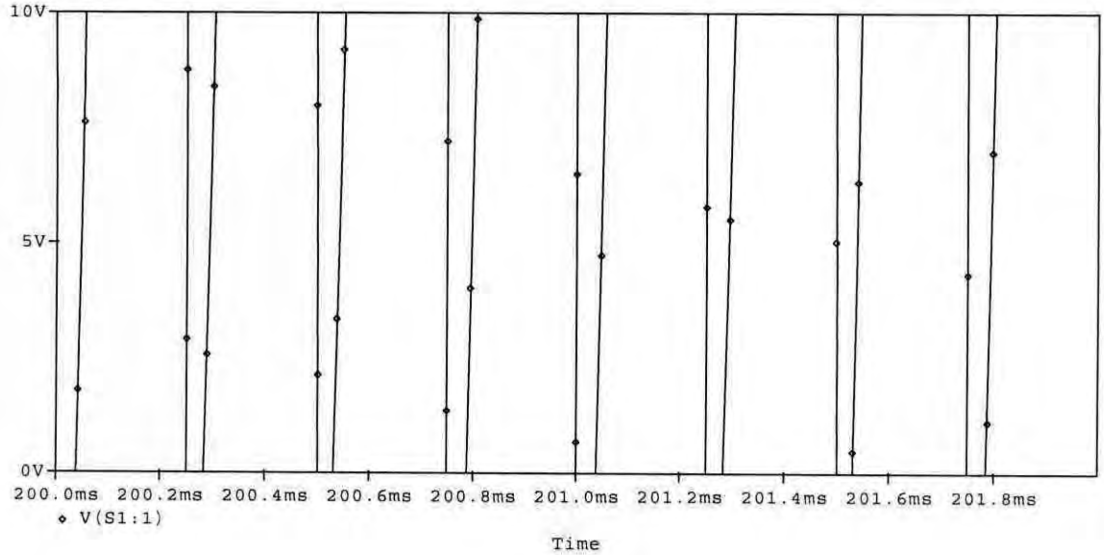


Figure : 2.6 (d6) – PWM signal supplied to the switch for V_{dc}= 10V to attain unity power factor [Second Approach]

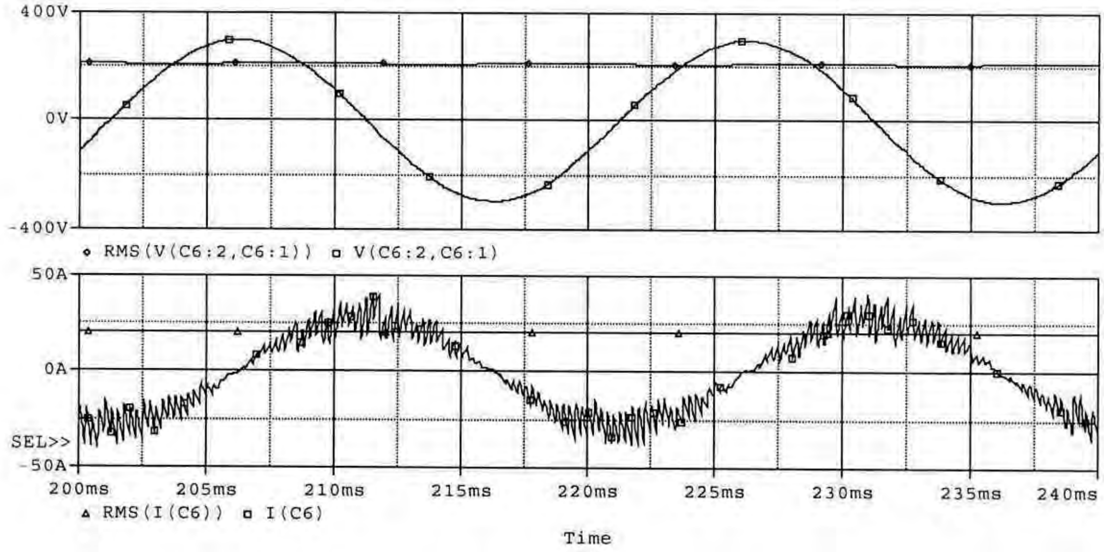


Figure : 2.6 (c7) – Voltage across and current through the capacitor for V_{dc}=11Vto attain unity power factor [Second Approach]

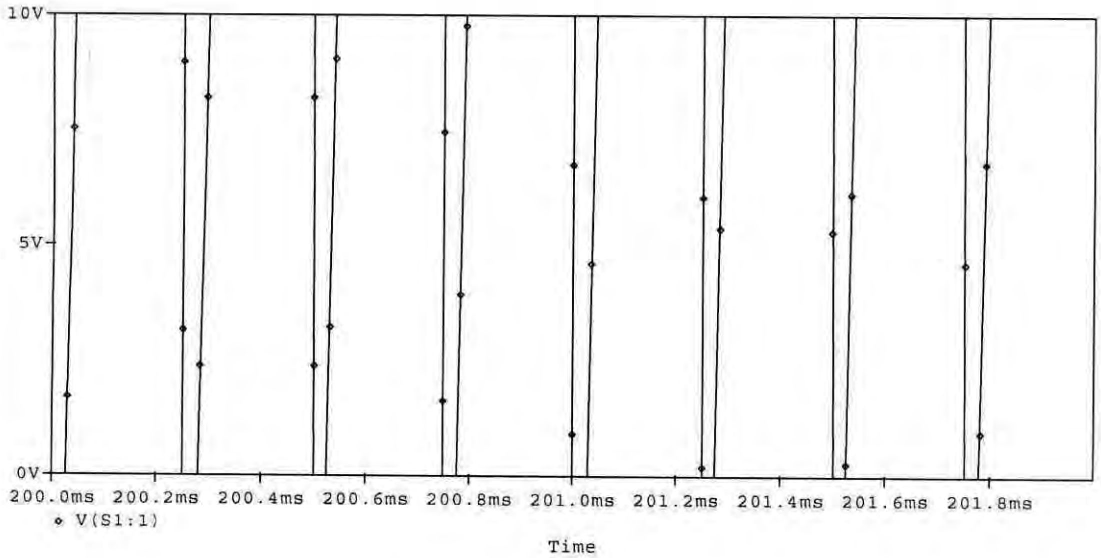


Figure : 2.6 (d7) – PWM signal supplied to the switch for V_{dc}= 11V to attain unity power factor [Second Approach]

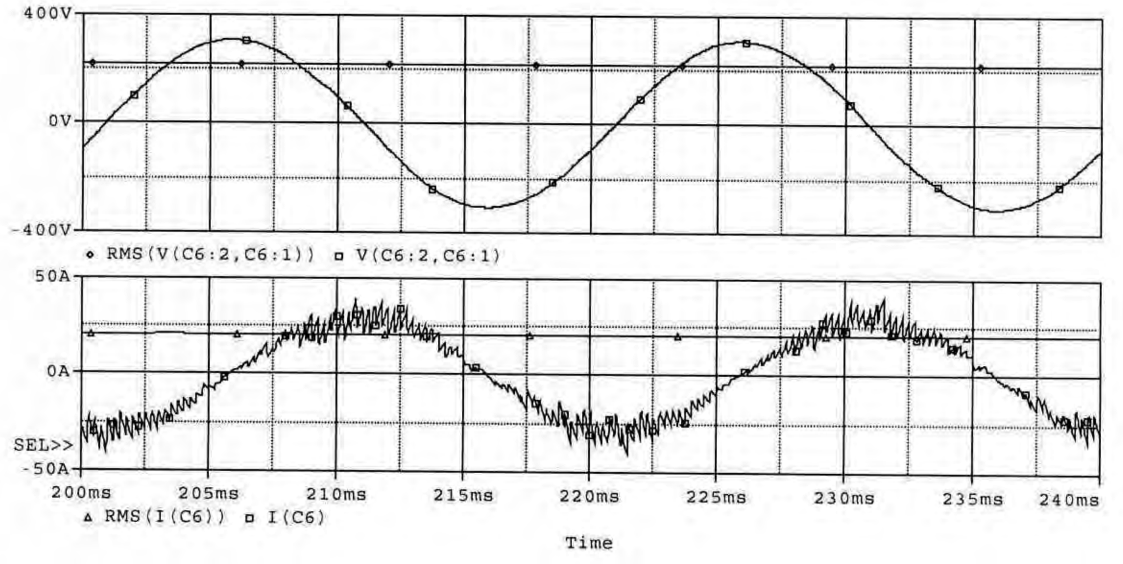


Figure : 2.6 (c8) – Voltage across and current through the capacitor for V_{dc}= 12V to attain unity power factor [Second Approach]

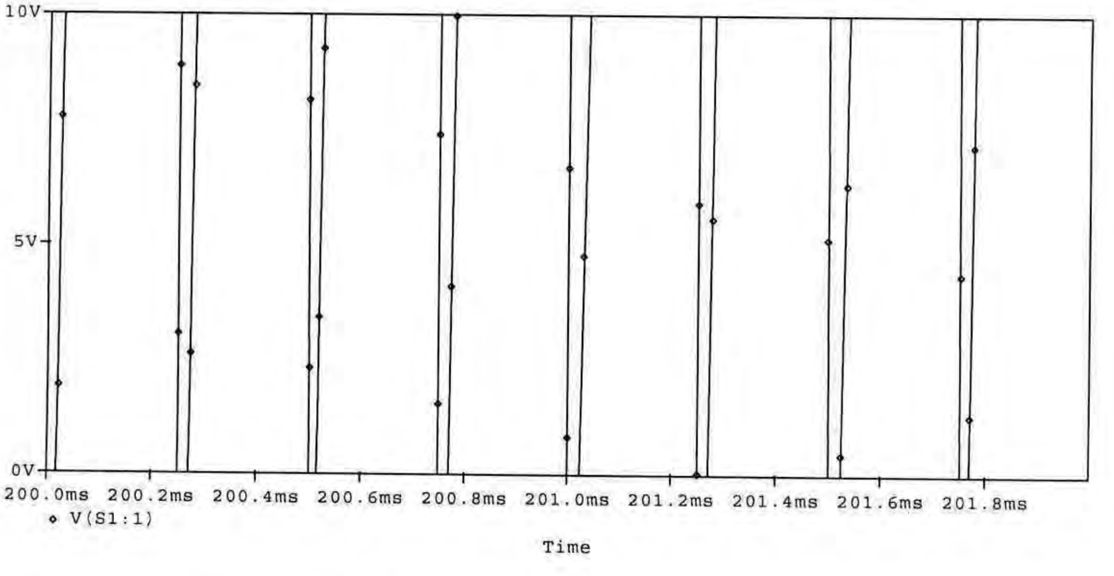


Figure : 2.6 (d8) – PWM signal supplied to the switch for V_{dc}= 12V to attain unity power factor [Second Approach]

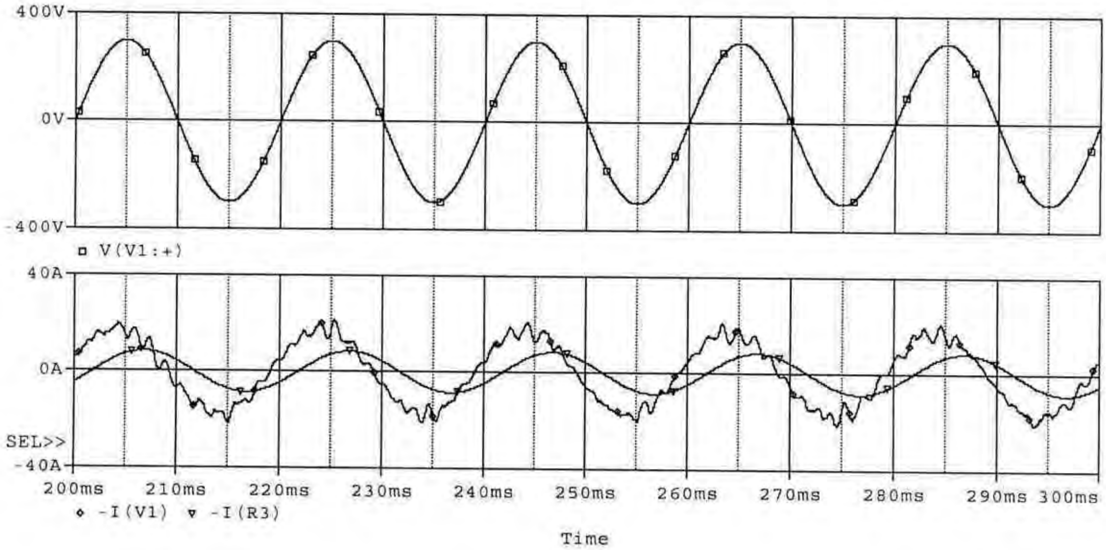


Figure : 2.6 (aa1) – Unity power factor attained for V_{dc}=2.35V for single load [Second Approach]

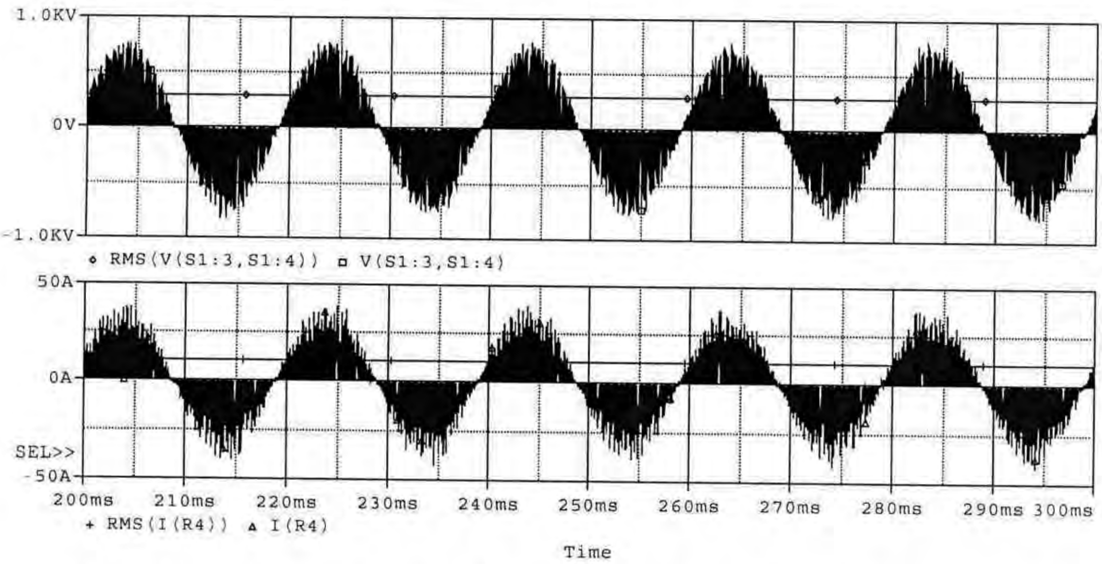


Figure : 2.6 (bb1) – Voltage across and current through the switch for V_{dc}=2.35V for single load to attain unity power factor [Second Approach]

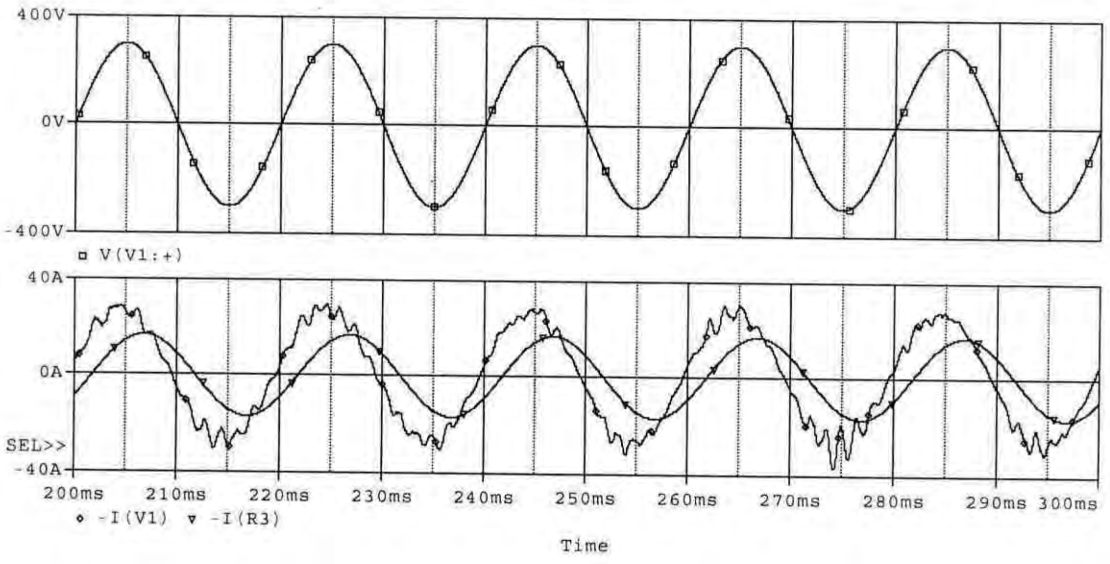


Figure : 2.6 (aa2) – Unity power factor attained for V_{dc}=4.60 V for two loads [Second Approach]

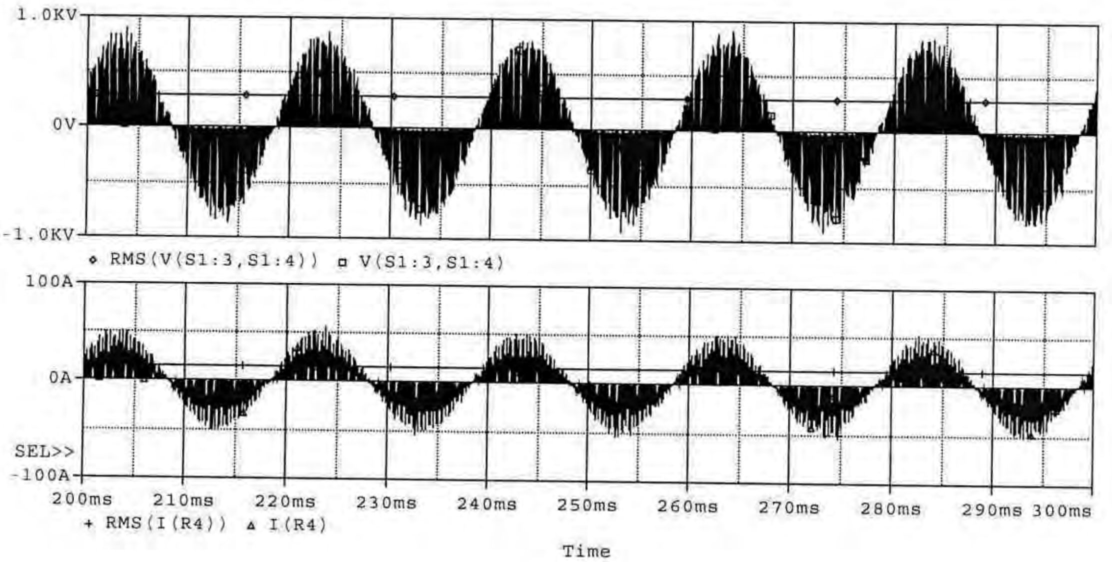


Figure : 2.6 (bb2) – Voltage across and current through the switch for V_{dc}=4.60 V for two loads to attain unity power factor [Second Approach]

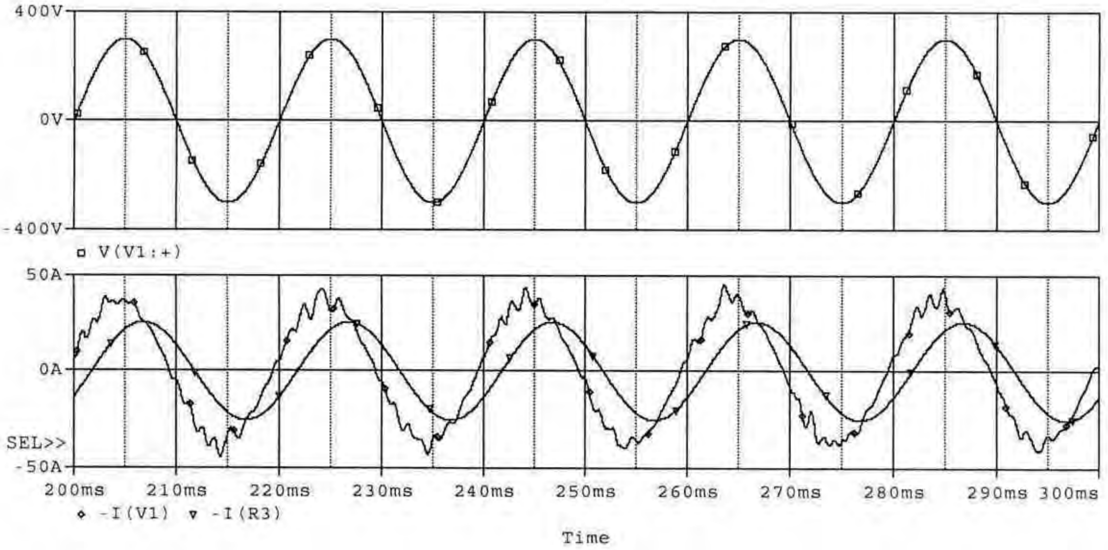


Figure : 2.6 (aa3) – Unity power factor attained for V_{dc}=7.0V for three loads [Second Approach]

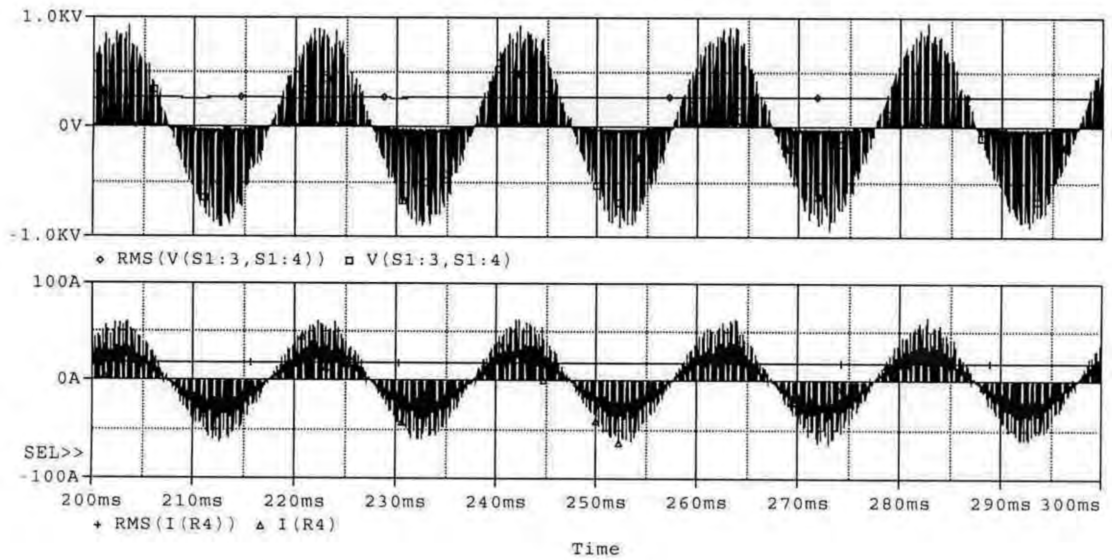


Figure : 2.6 (bb3) – Voltage across and current through the switch for V_{dc}=7.0 V for three loads to attain unity power factor [Second Approach]

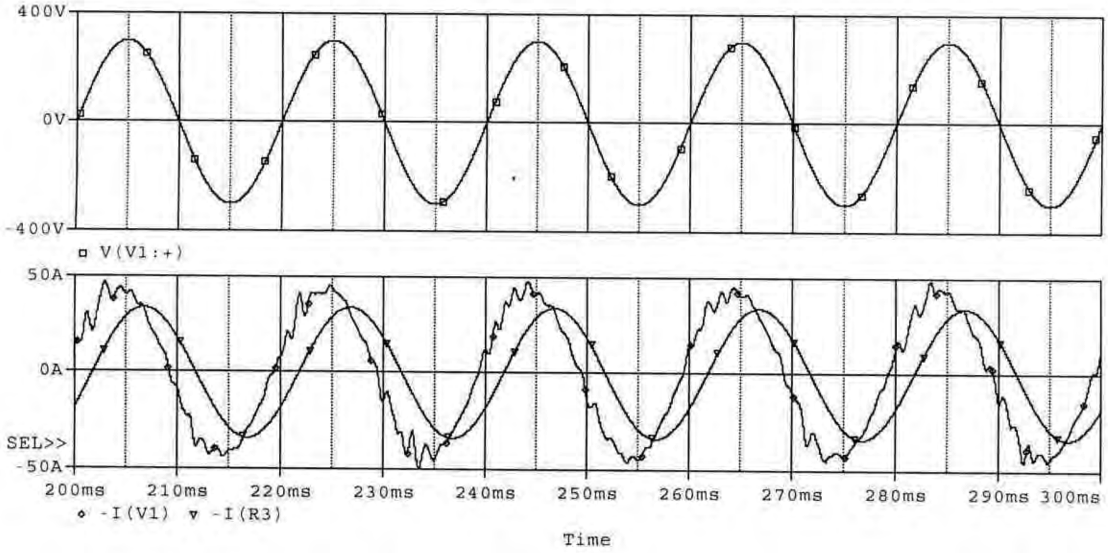


Figure : 2.6 (aa4) – Unity power factor attained for V_{dc}=9.50 V for four loads [Second Approach]

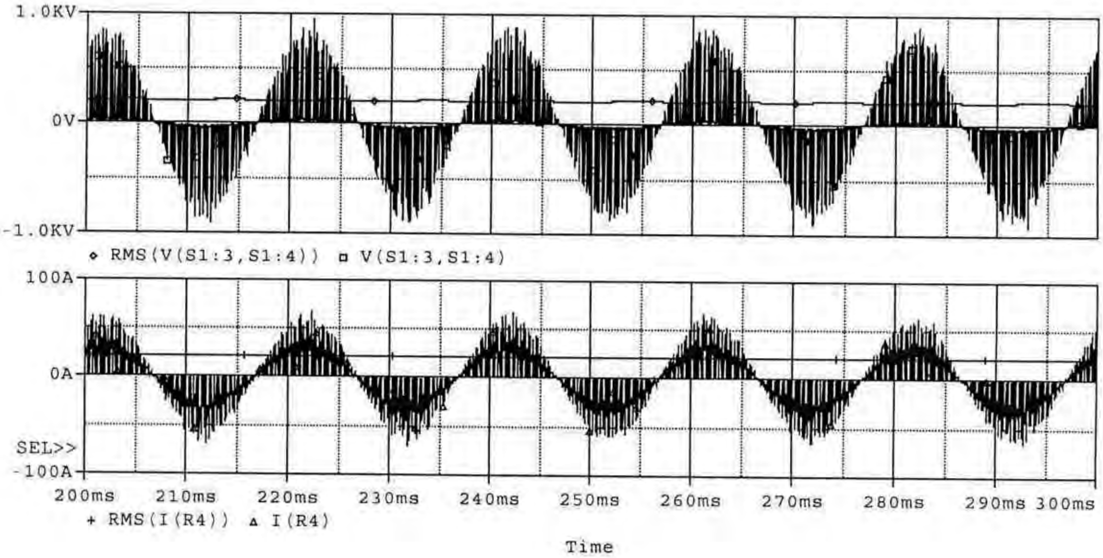


Figure : 2.6 (bb4) – Voltage across and current through the switch for V_{dc}=9.50 V for four loads to attain unity power factor [Second Approach]

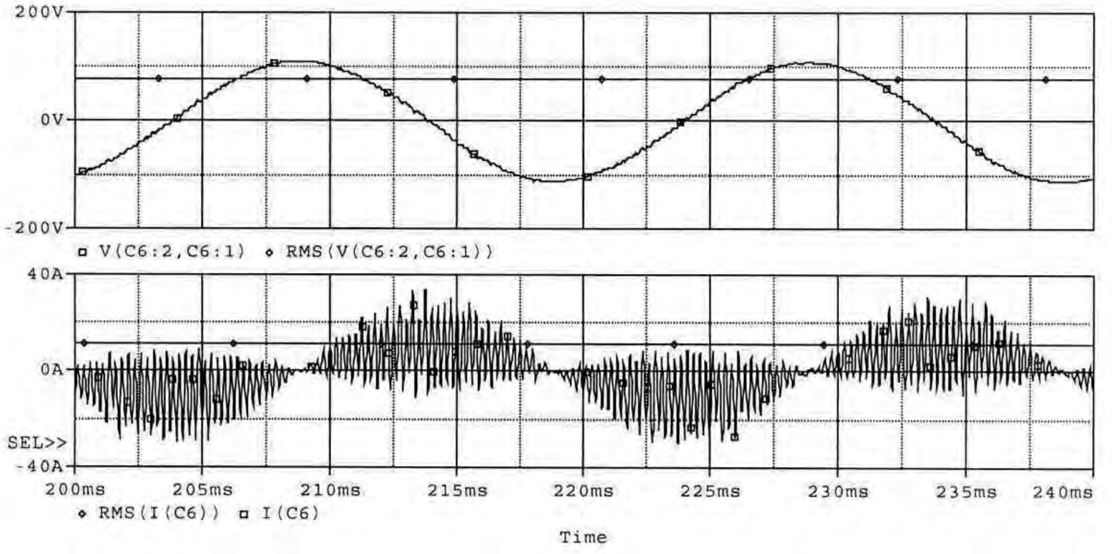


Figure : 2.6 (cc1) – Voltage across and current through the capacitor for V_{dc}=2.35V and for single load to attain unity power factor [Second Approach]

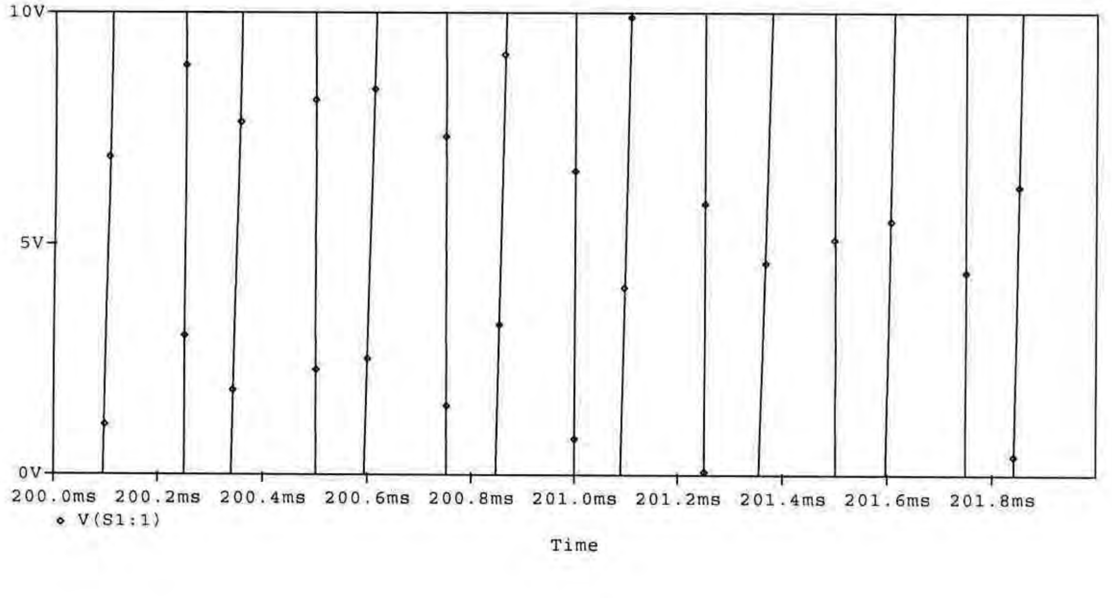


Figure : 2.6 (dd1) – PWM signal supplied to the switch for V_{dc}= 2.35V and for single load to attain unity power factor [Second Approach]

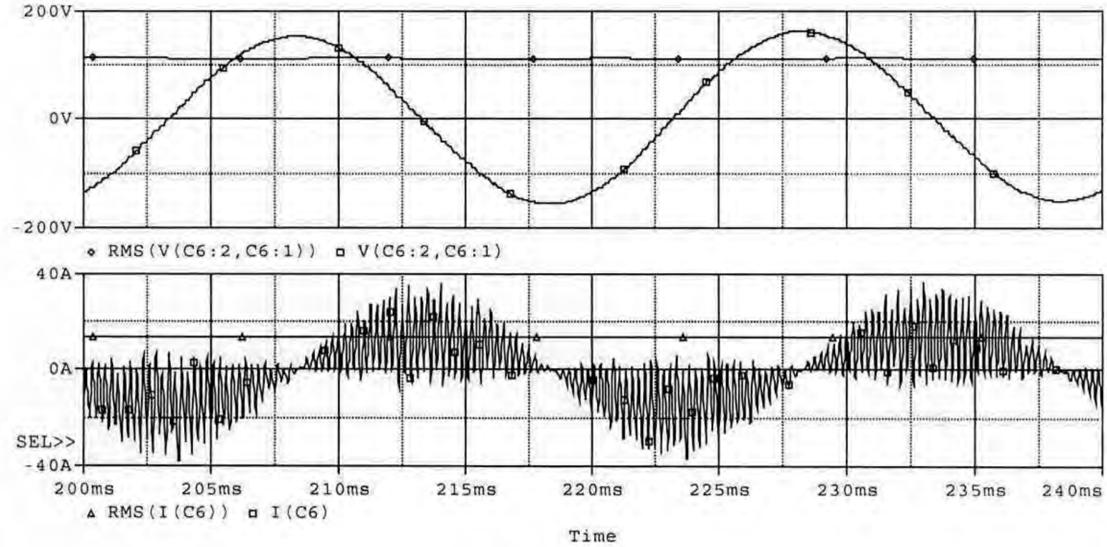


Figure : 2.6 (cc2) – Voltage across and current through the capacitor for V_{dc}=4.60 V and for two loads to attain unity power factor [Second Approach]

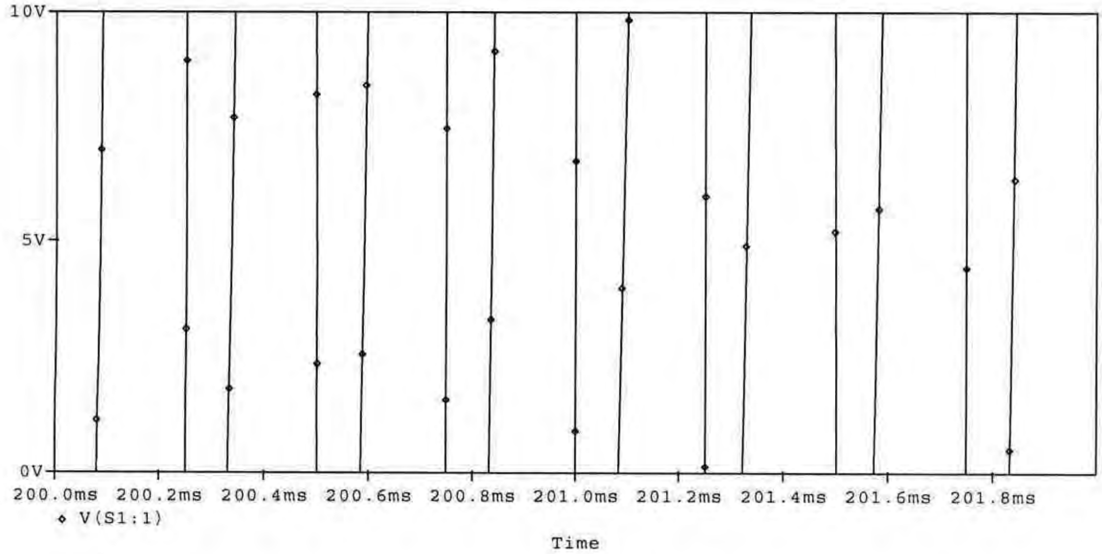


Figure : 2.6 (dd2) – PWM signal supplied to the switch for V_{dc}= 4.60 V and for two loads to attain unity power factor[Second Approach]

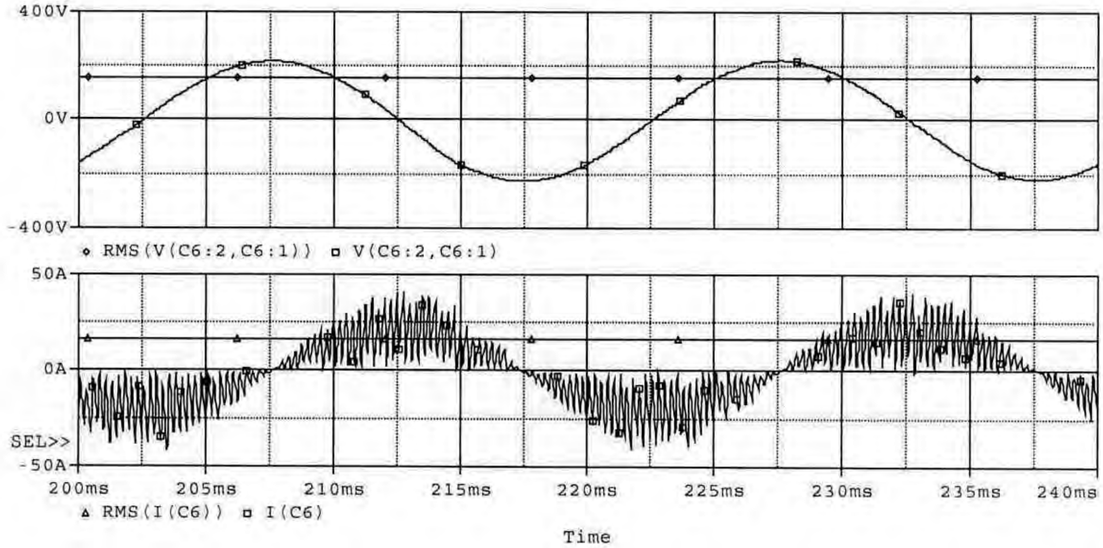


Figure : 2.6 (cc3) – Voltage across and current through the capacitor for V_{dc}=7.0 V and for three loads to attain unity power factor [Second Approach]

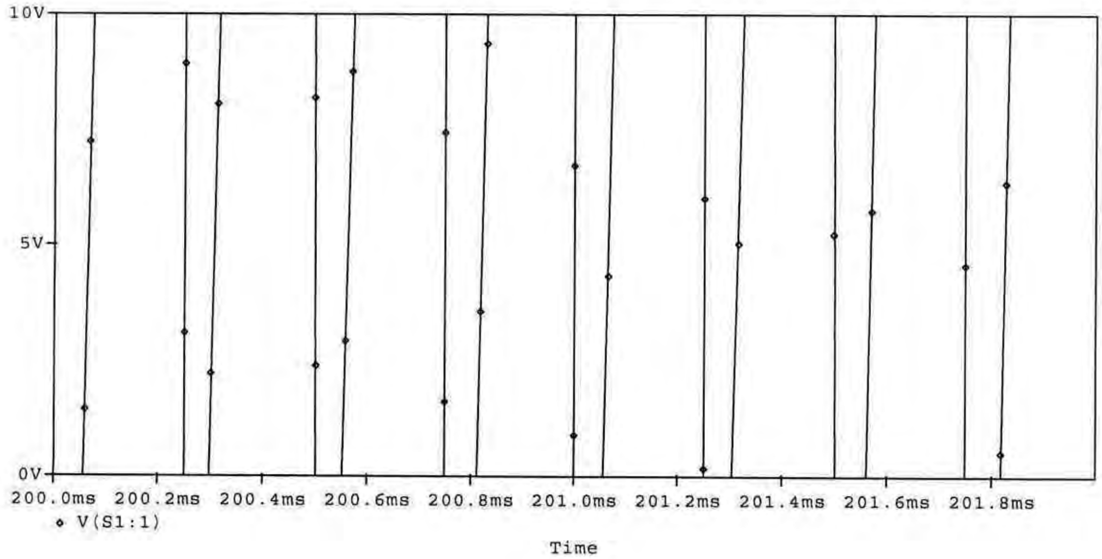


Figure : 2.6 (dd3) – PWM signal supplied to the switch for V_{dc}= 7.0 V and for three loads to attain unity power factor [Second Approach]

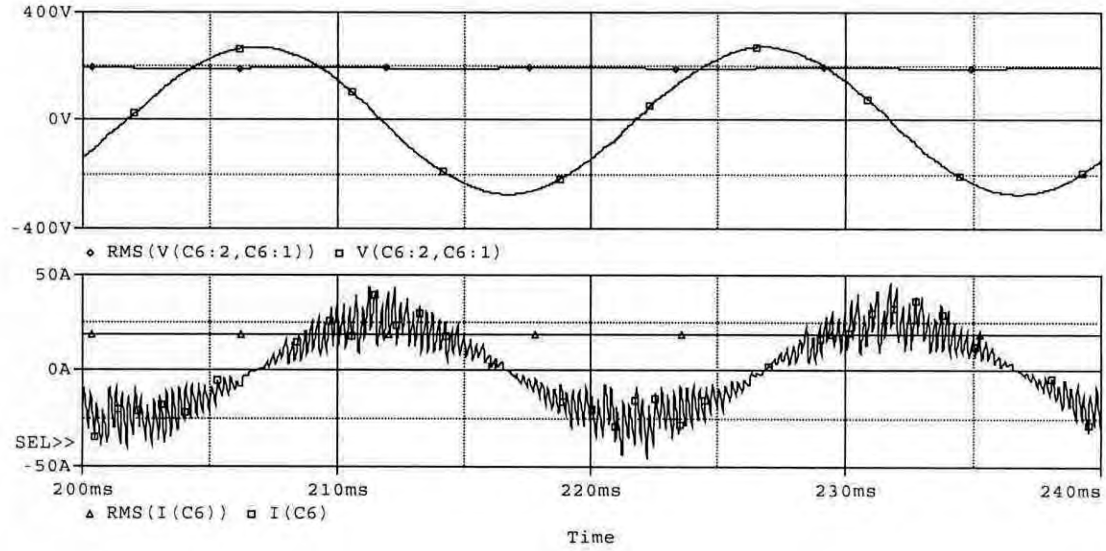


Figure : 2.6 (cc4) – Voltage across and current through the capacitor for V_{dc}=9.50 V and for four loads to attain unity power factor [Second Approach]

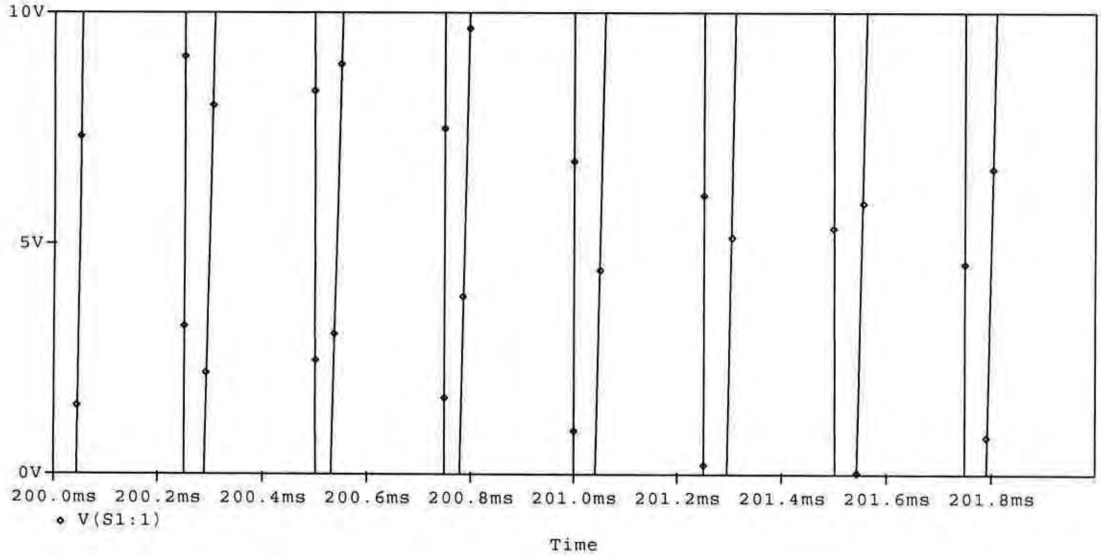


Figure : 2.6 (dd4) – PWM signal supplied to the Switch for V_{dc}= 9.50 V and for four loads to attain unity power factor [Second Approach]

TABLE - 2.6 (A)

V(dc)	SWITCH		CAPACITOR		Pulse Width	Remarks
Volt	Voltage (RMS) Volt	Current (RMS) Amp	Voltage (RMS) Volt	Current (RMS) Amp	(μs)	
5	291	15.25	119	13.90	165	Unity p.f obtained
6	282	17.25	141	15.50	170	Unity p.f obtained
7	272	18.65	156	16.50	176	Unity p.f obtained
8	253	20.00	173	17.70	185	Unity p.f obtained
9	227	21.05	186	18.50	200	Unity p.f obtained
10	199	22.00	199	19.45	208	Unity p.f obtained
11	164	22.40	211	20.30	218	Unity p.f obtained
12	127	22.50	217	20.70	224	Unity p.f obtained

Figure : 2.6 (e) – TABLE – 2.6 (A) – Various parameters of Figure : 2.6 to attain unity power factor varying the dc voltage from 5 to 12 V

TABLE - 2.6 (B)

No. of Loads	V(dc)	SWITCH		CAPACITOR		Pulse Width	Remarks
	Volt	Voltage (RMS)	Current (RMS) Amp	Voltage (RMS) Volt	Current (RMS) Amp	(μs)	
ONE	2.35	295	11	79	11	119	Unity power factor obtained
TWO	4.60	294	15	113	14	152	Unity power factor obtained
THREE	7.00	271	19	158	17	176	Unity power factor obtained
FOUR	9.50	213	22	193	19	200	Unity power factor obtained

Figure : 2.6 (f) – TABLE – 2.6 (B) – Various parameters for Figure : 2.6 to attain unity power factor for varying the loads

2.7 THIRD APPROACH :

In this approach we added a control circuit to the previous circuit (**FIGURE-2.6**)where the signals proportional to the magnitude of the load current and the angle of the power factor are multiplied to produce a signal proportional to **Iθ** (where I is the magnitude of the load current and θ is the power factor angle). This signal is compared with a triangular wave to produce PWM signals to drive the switches which varies the voltage across the capacitor to supply the required compensating current to make the power factor unity. As load varies the magnitude of the load current with its power factor angle varies as a whole their product varies. So if we change the loads one by one we get different valued dc voltages to produce the PWM .

A table **[TABLE – 2.7]** is prepared to have the required dc voltage (proportional to the product of load current and power factor angle) for the various numbers of loads to have unity power factor . In this table the values of all the required parameters of the circuit **[Figure- 2.7]** are shown. The width of the PWM signals increases with the increase in the no. of loads as well as increase of the dc voltage for the production of PWM signals to attain unity power factor in each case.

From the **TABLE-2.7** the required value of the dc voltages to produce the PWM is same as that of from **TABLE-2.6** which means the control circuit works properly. In the next and final approach we designed a controlled circuit same as **Figure- 2.7** only replacing the conventional switch by a practical bi-directional switch.

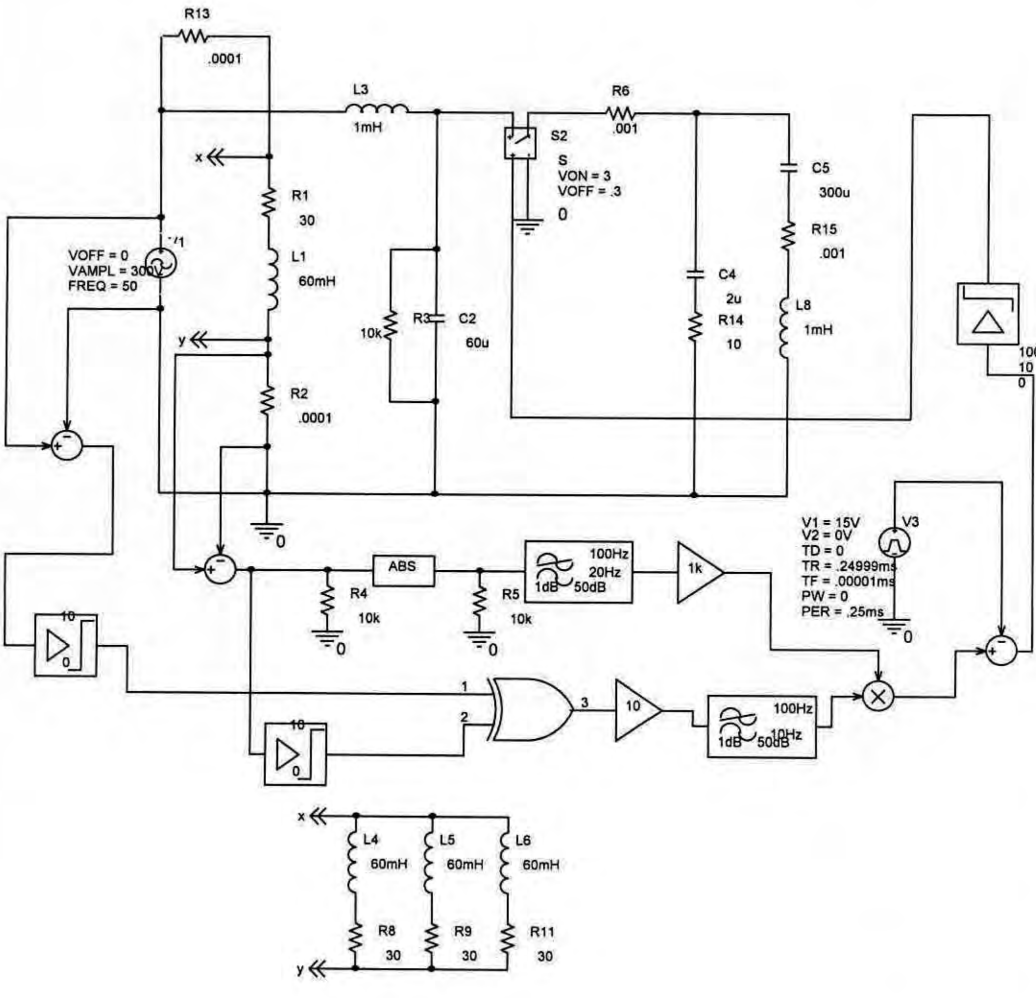


Figure : 2.7 – Circuit arrangement for Third Approach to attain unity power factor for varying loads with control

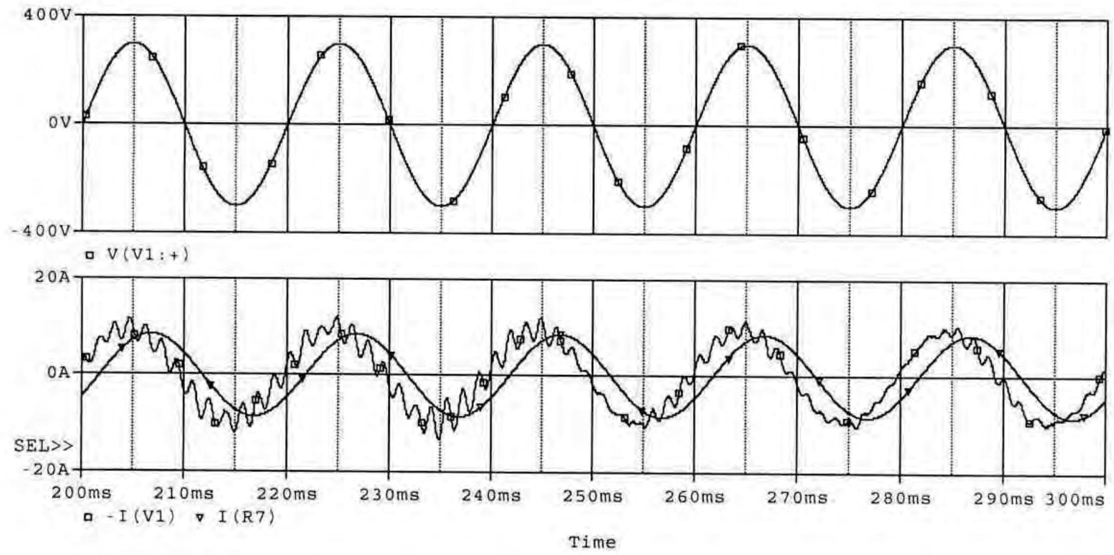


Figure : 2.7 (a1) - Unity power factor attained for single load with controlled circuit [Third Approach]

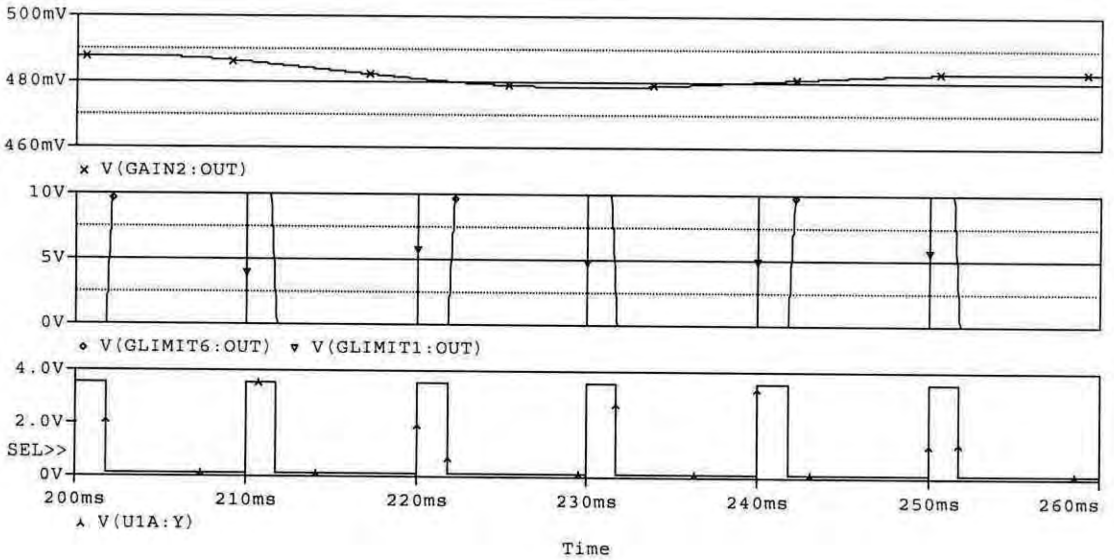


Figure : 2.7 (a1.1) – Power factor angle and equivalent of load current for single load with controlled circuit to attain unity power factor [Third Approach]

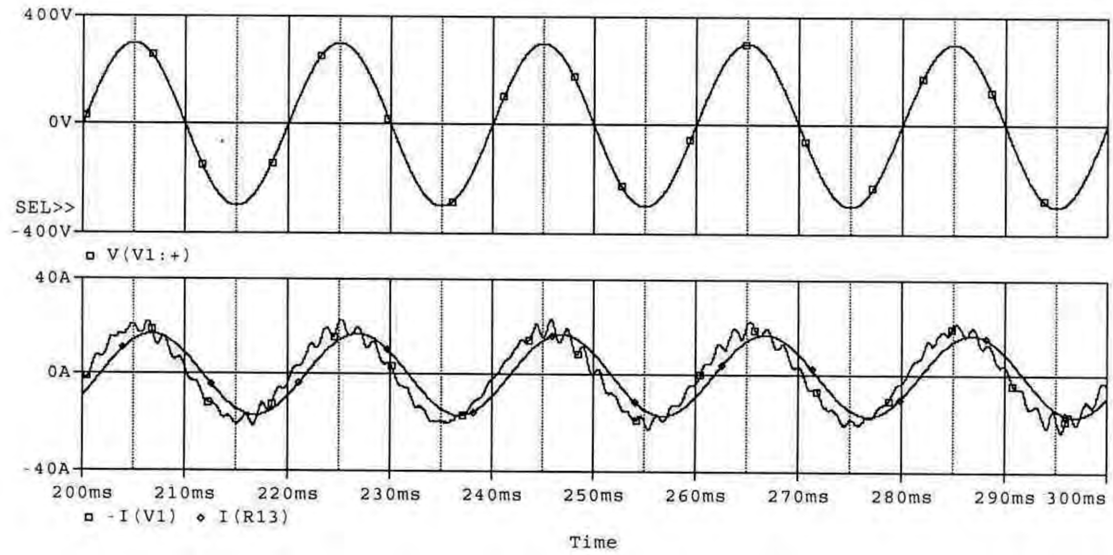


Figure :2.7 (a2) - Unity power factor attained for two loads with controlled circuit [Third Approach]

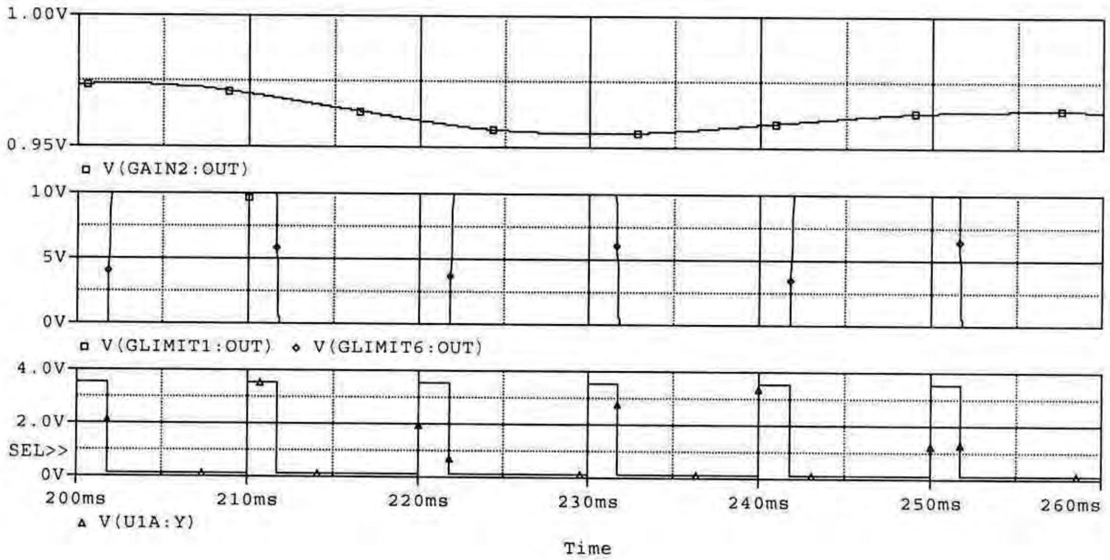


Figure : 2.7 (a2.1) – Power factor angle and equivalent of load current for two loads with controlled circuit to attain unity power factor [Third Approach]

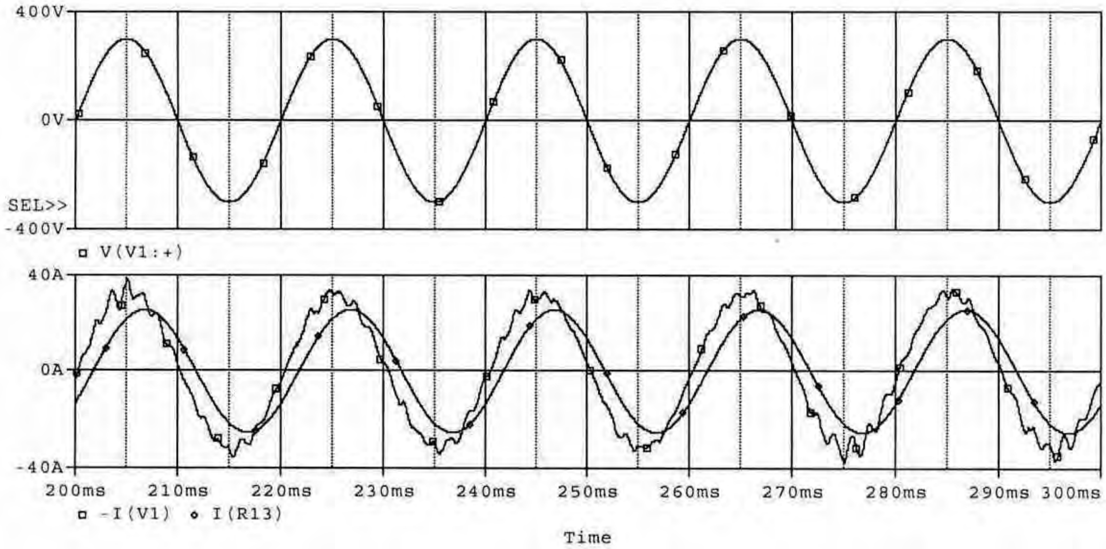


Figure : 2.7 (a3) - Unity power factor attained for three loads with controlled circuit [Third Approach]

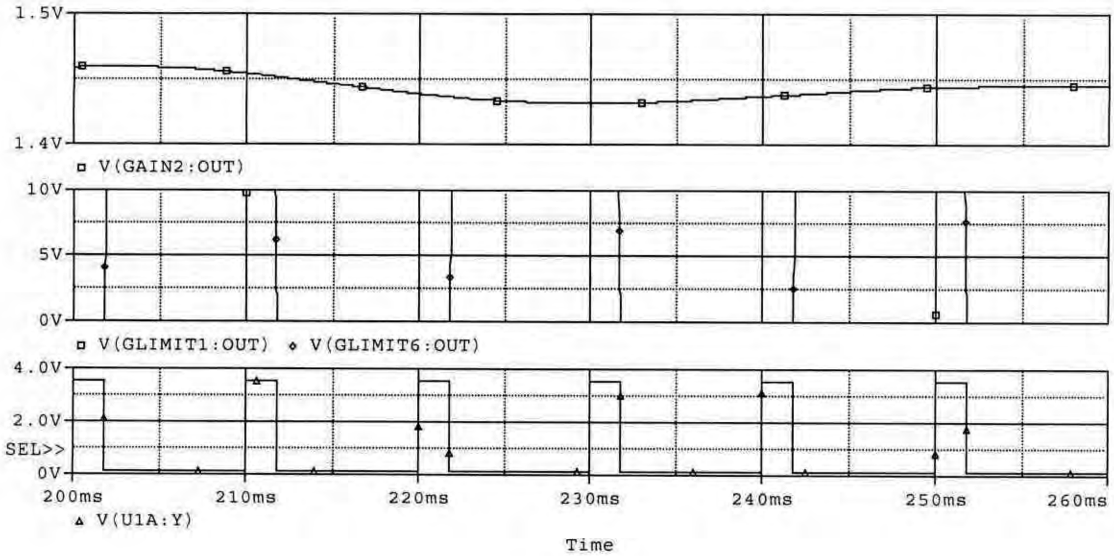


Figure : 2.7 (a3.1) – Power factor angle and equivalent of load current for three loads with controlled circuit to attain unity power factor [Third Approach]

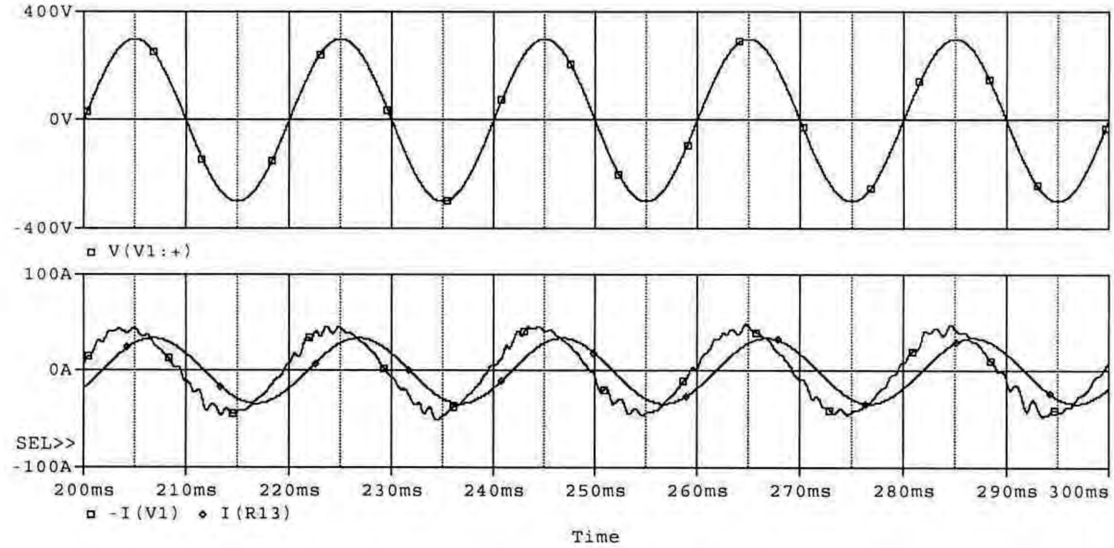


Figure : 2.7 (a4) - Unity power factor attained for four loads with controlled circuit [Third Approach]

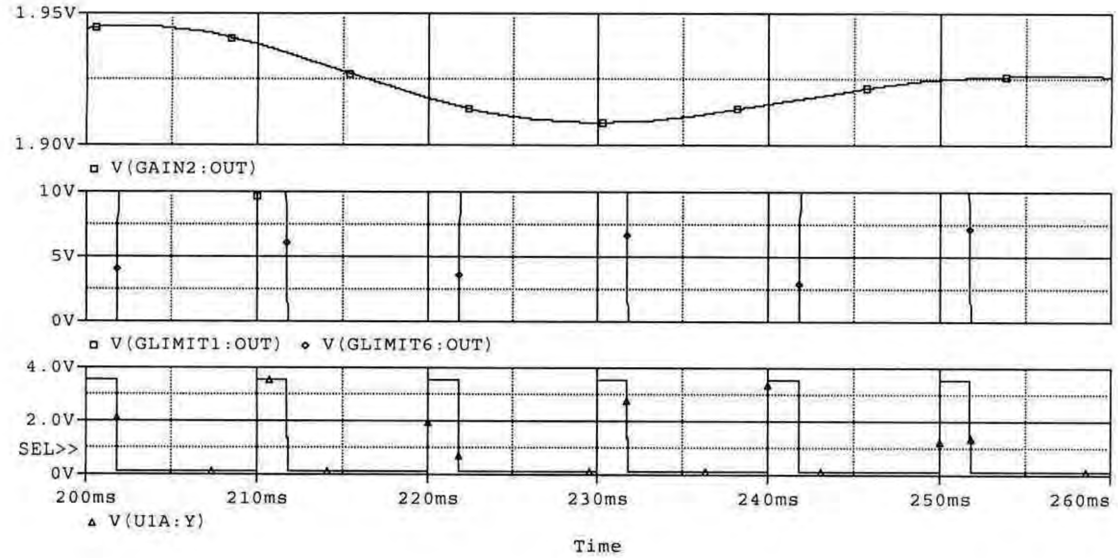


Figure : 2.7 (a4.1) – Power factor angle and equivalent of load current for four loads with controlled circuit to attain unity power factor [Third Approach]

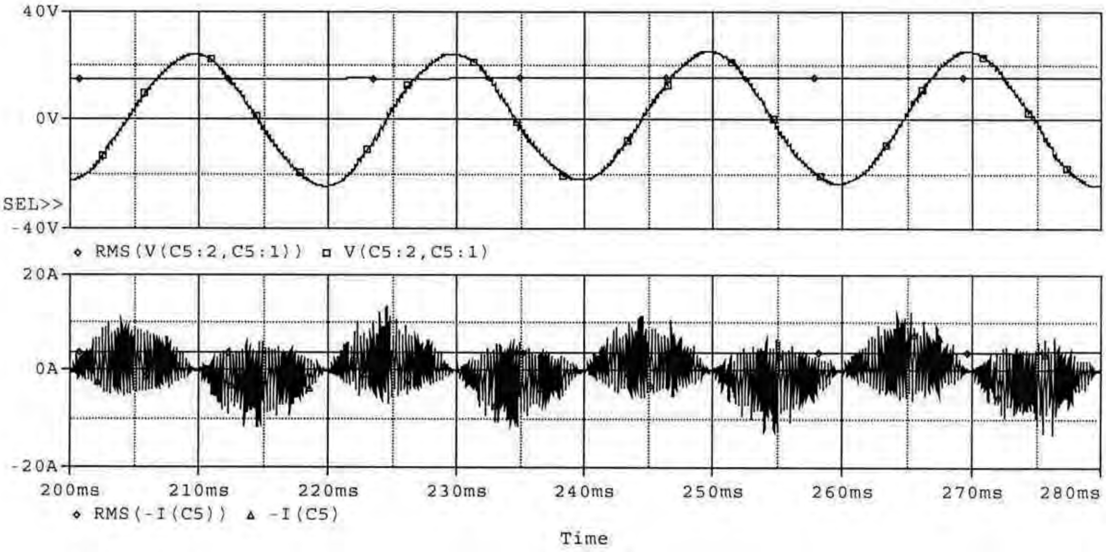


Figure : 2.7 (b1) – Voltage across and current through the capacitor to attain unity power factor for single load with control circuit [Third Approach]

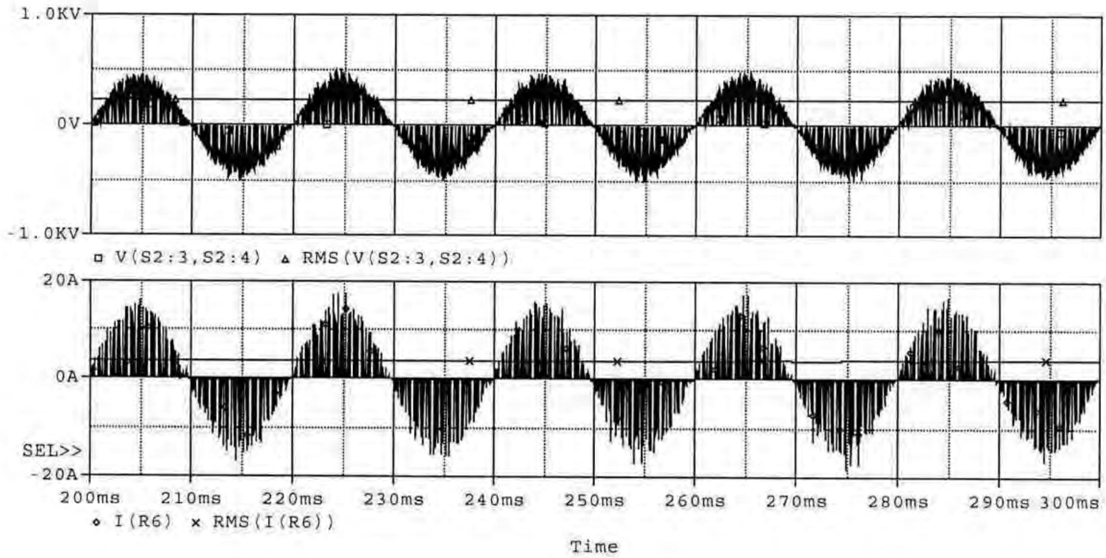


Figure : 2.7 (c1) – Voltage across and current through the switch to attain unity power factor for single load with control circuit [Third Approach]

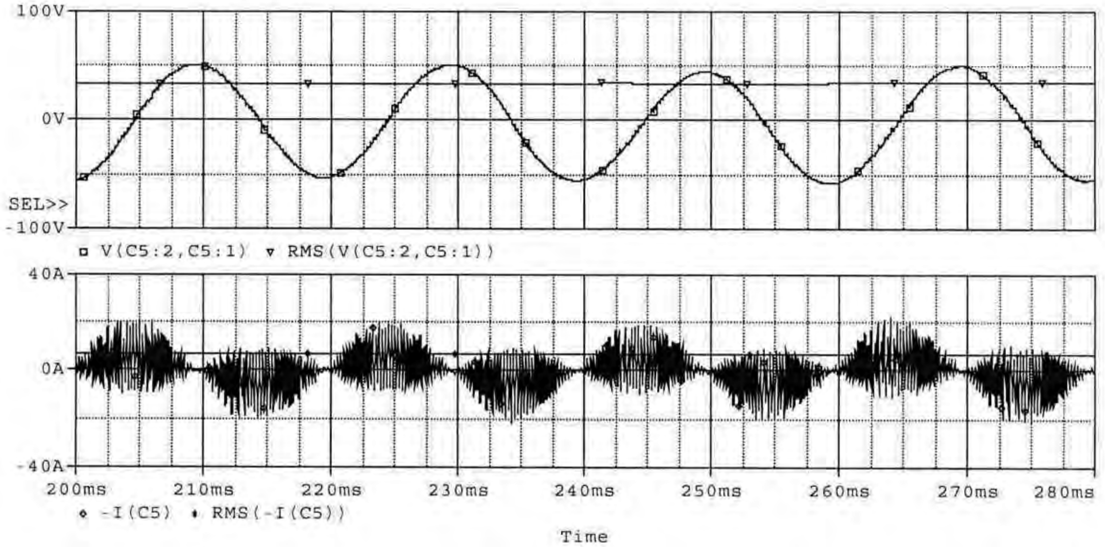


Figure : 2.7 (b2) – Voltage across and current through the capacitor to attain unity power factor for two loads with control circuit [Third Approach]

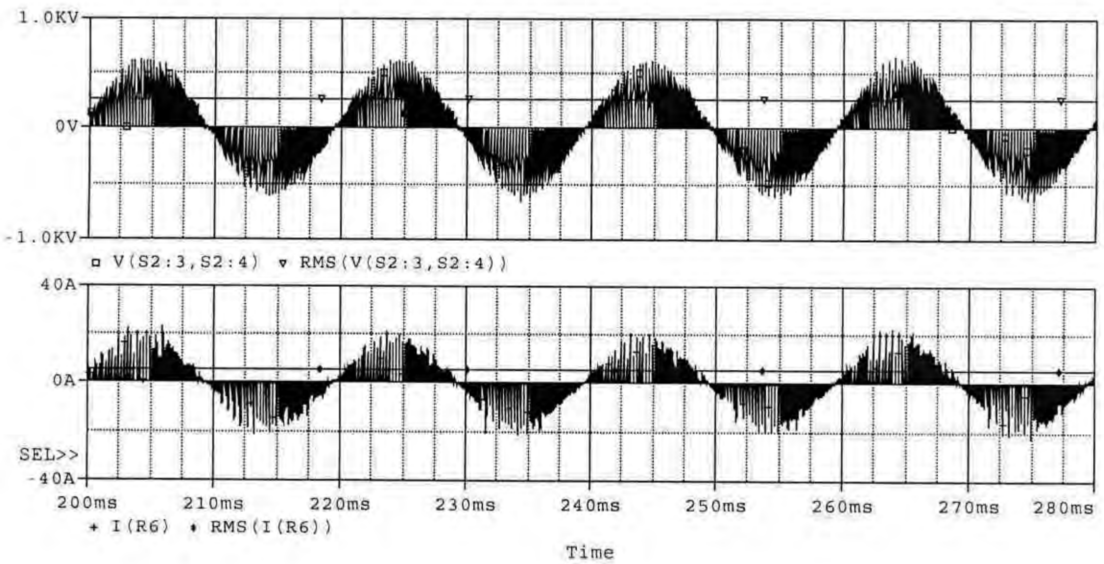


Figure : 2.7 (c2) – Voltage across and current through the switch to attain unity power factor for two loads with control circuit [Third Approach]

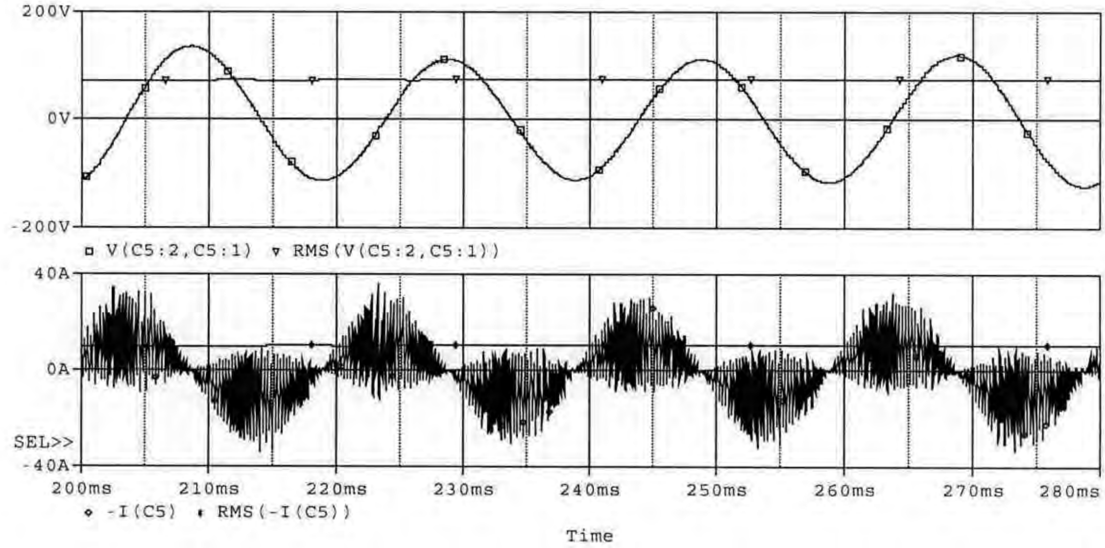


Figure : 2.7 (b3) – Voltage across and current through the capacitor to attain unity power factor for three loads with control circuit [Third Approach]

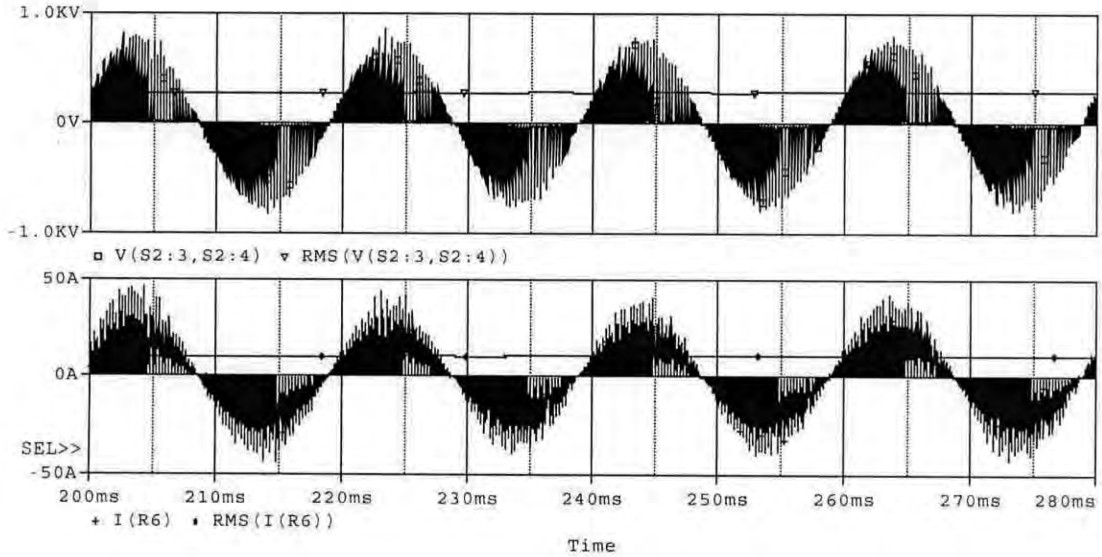


Figure : 2.7 (c3) – Voltage across and current through the switch to attain unity power factor for three loads with control circuit [Third Approach]

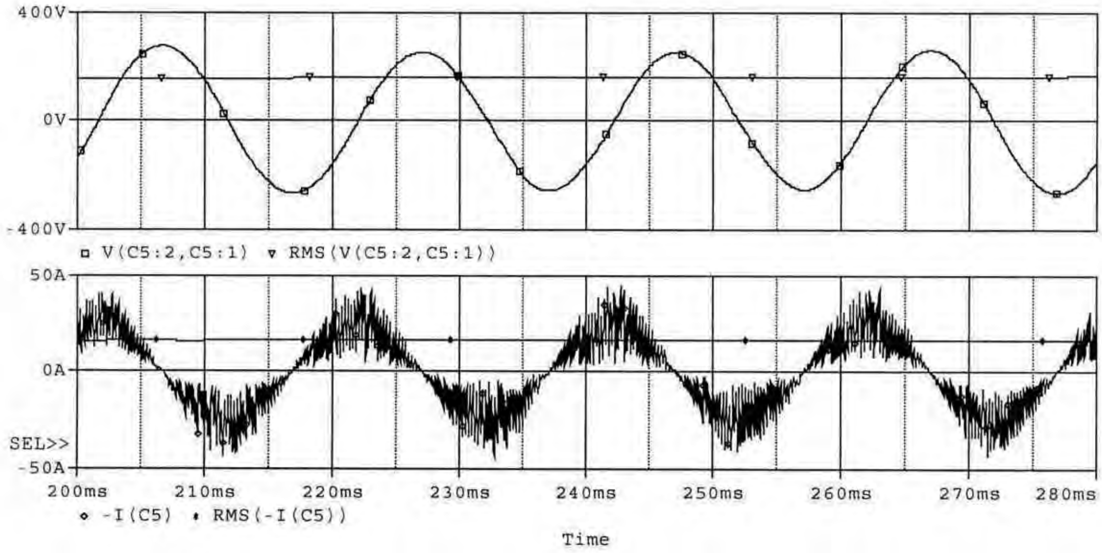


Figure : 2.7 (b4) – Voltage across and current through the capacitor to attain unity power factor for four loads with control circuit [Third Approach]

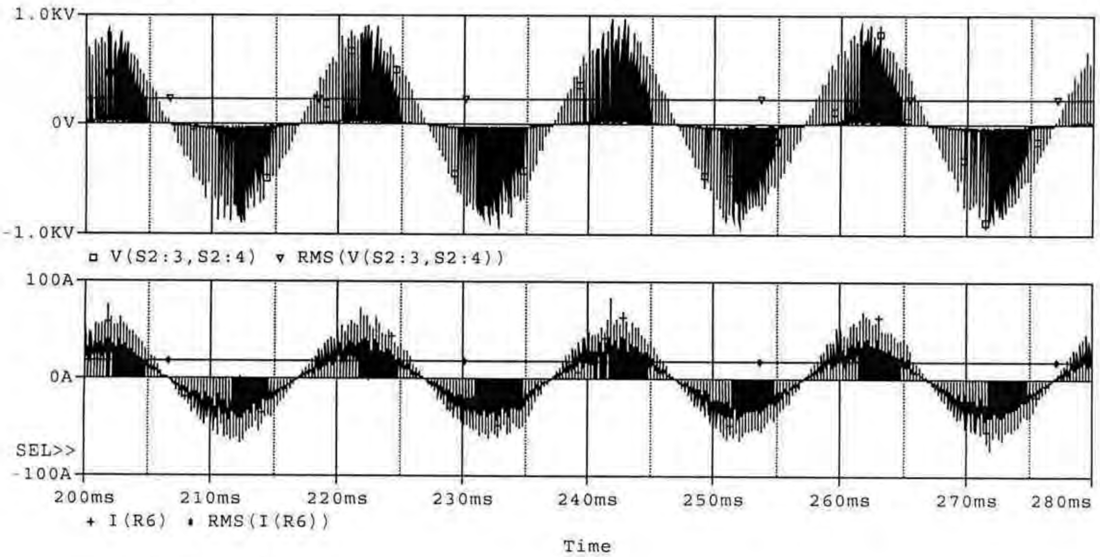


Figure : 2.7 (c4) – Voltage across and current through the switch to attain unity power factor for four loads with control circuit [Third Approach]

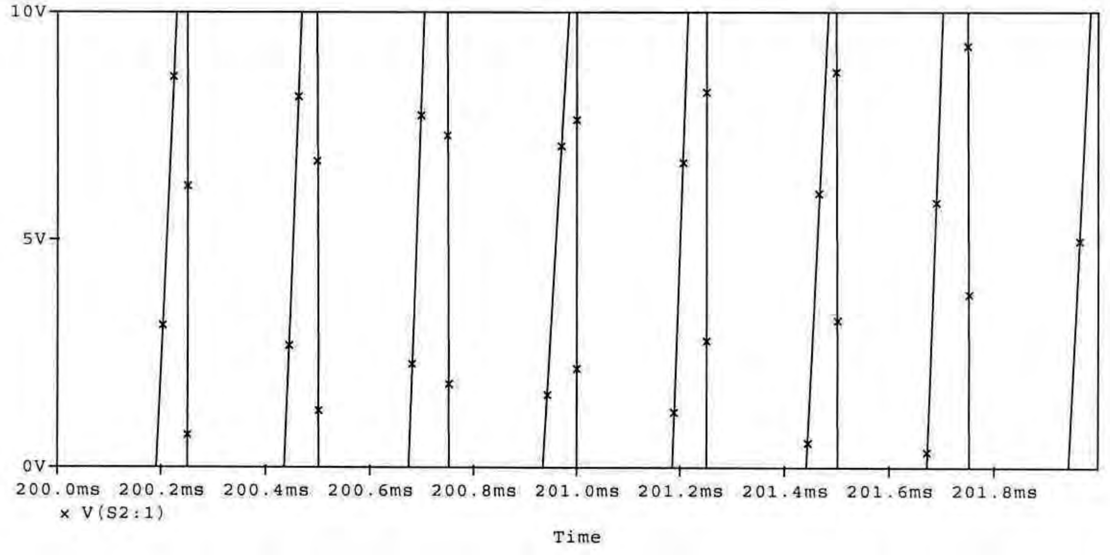


Figure : 2.7 (d1) - PWM signal supplied to the switch to attain unity power factor for single load [Third Approach]

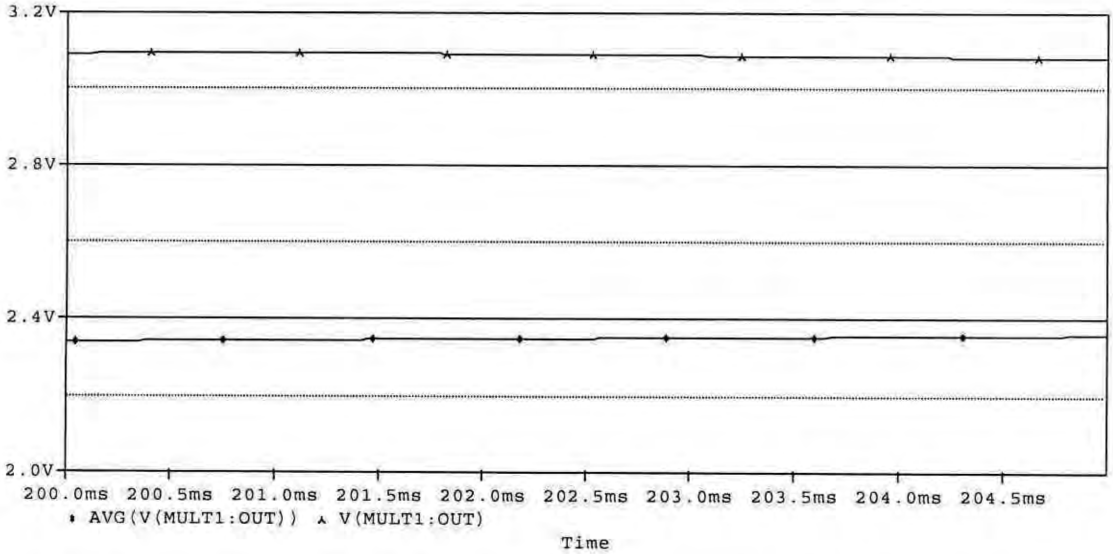


Figure : 2.7 (e1) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for single load [Third Approach]

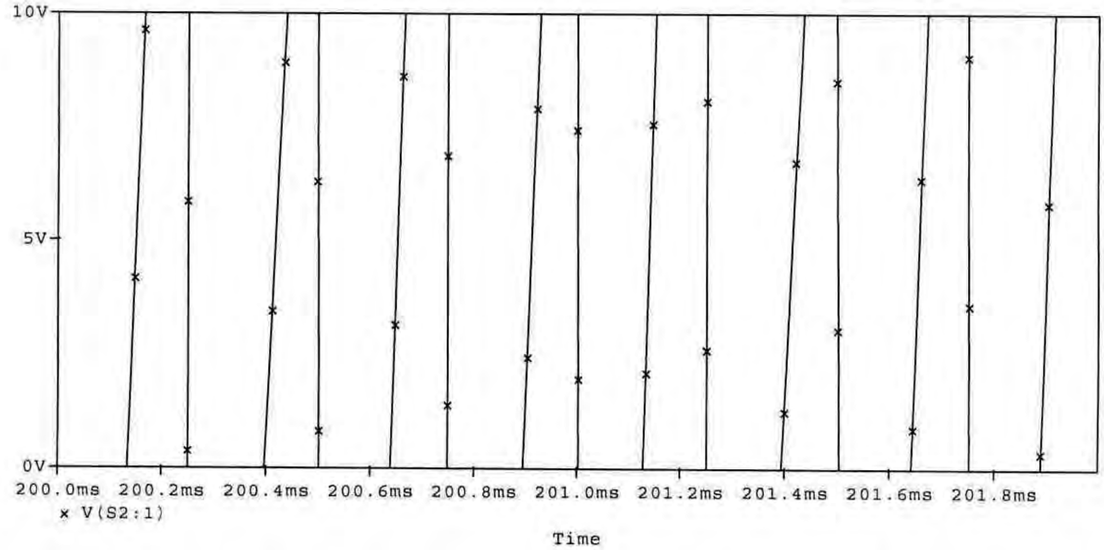


Figure : 2.7 (d2) - PWM signal supplied to the switch to attain unity power factor for two loads [Third Approach]

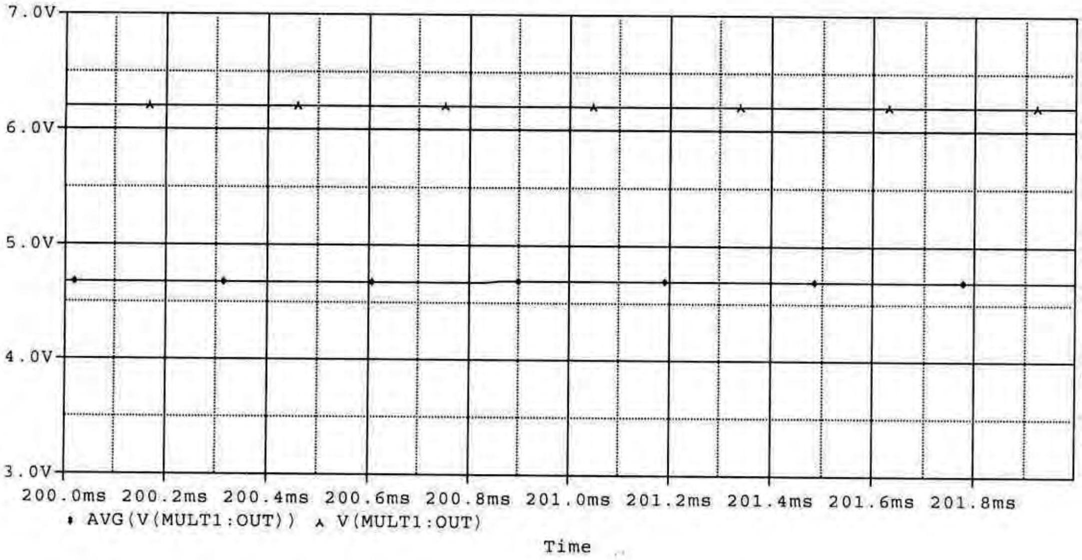


Figure : 2.7 (e2) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for two loads [Third Approach]

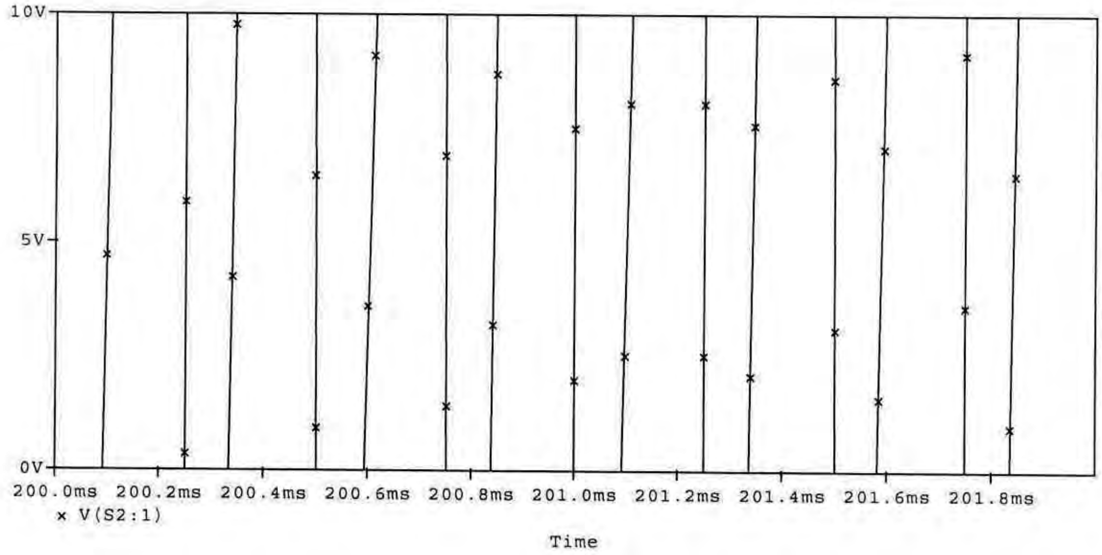


Figure : 2.7 (d3) - PWM signal supplied to the switch to attain unity power factor for three loads [Third Approach]

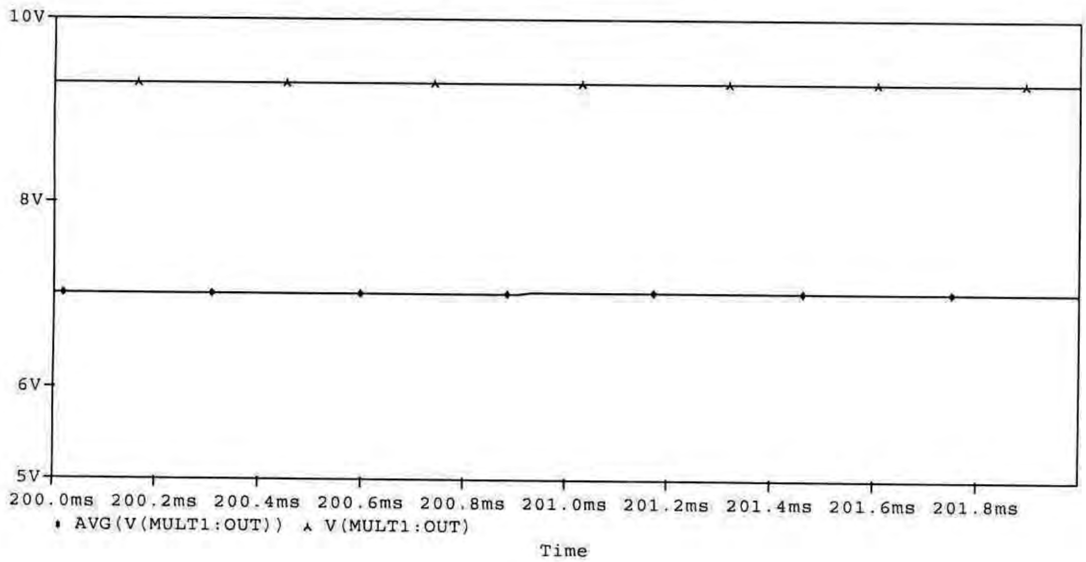


Figure : 2.7 (e3) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for three loads [Third Approach]

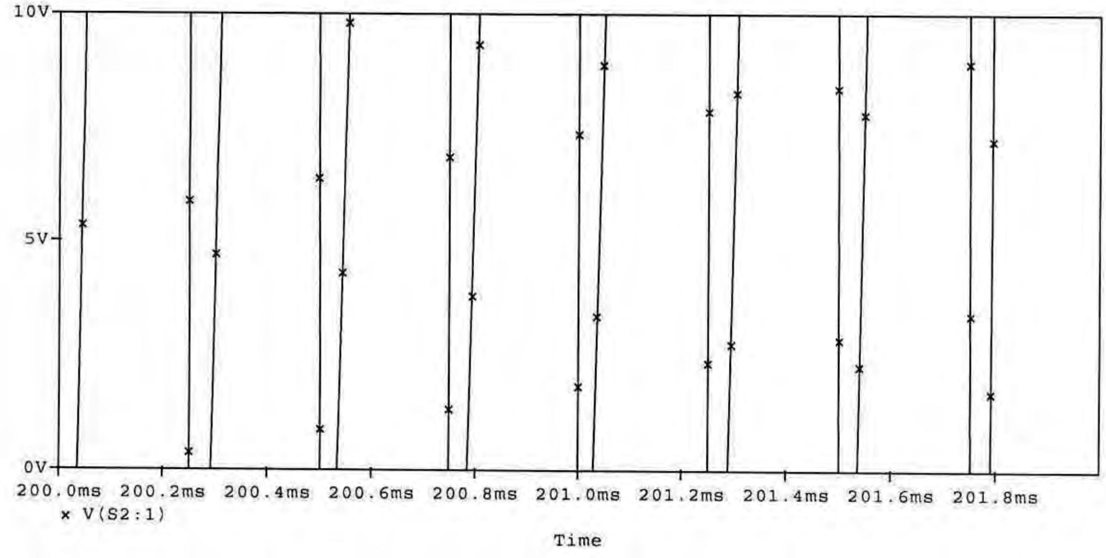


Figure : 2.7 (d4) - PWM signal supplied to the switch to attain unity power factor for four loads [Third Approach]

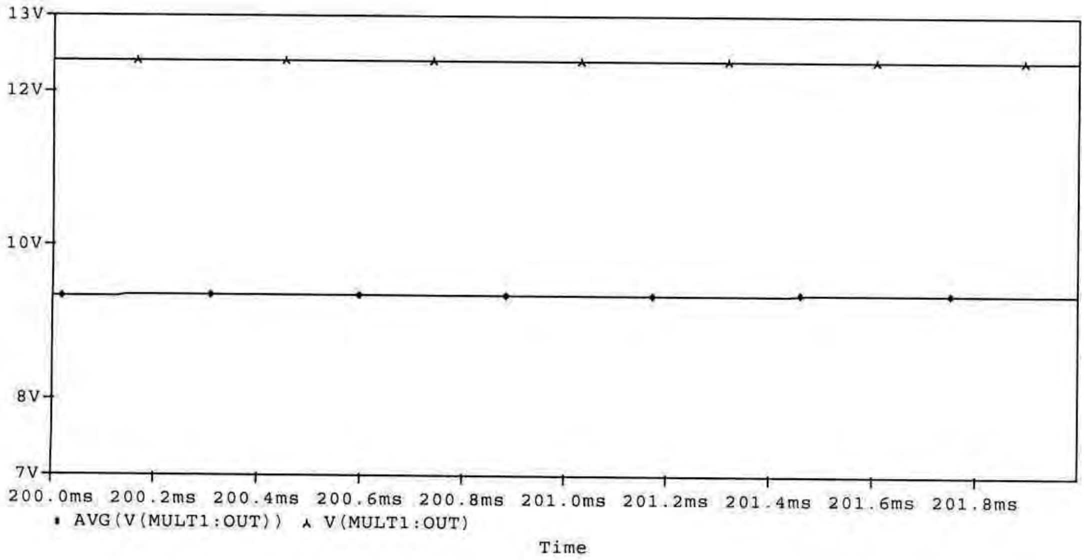


Figure : 2.7 (e4) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for four loads [Third Approach]

TABLE – 2.7

No. of Loads	CAPACITOR		SWITCH		PULSE WIDTH	DC VOLTAGE FOR PWM	VOLTAGE PROPORTI-ONAL TO LOAD CURRENT	REMARKS
	V(RMS) Volt	I(RMS) AMP	V(RMS) Volt	I(RMS) AMP	(μs)	V (AVG) Volt	V Volt	
ONE	**16**	**4**	**132**	**4**	**18**	**2.35**	**0.48**	Unity P.f obtained
TWO	**34**	**7**	**250**	**6**	**82**	**4.68**	**0.95**	Unity P.f obtained
THREE	**76**	**11**	**284**	**11**	**140**	**7.00**	**1.45**	Unity P.f obtained
FOUR	**164**	**17**	**285**	**19**	**201**	**9.50**	**1.95**	Unity P.f obtained

Figure : 2.7 (f) – TABLE –2.7 - Various parameters of Figure : 2.7 to attain unity power factor for varying the loads

2.8 FINAL APPROACH :

In this approach we only replaced the conventional switch by a practical bi-directional switch . The generated PWM is supplied to the switch through optocoupler - **[4]** which isolates the control or gate signal with respect to ground.

Here a table **[TABLE – 2.8]** is shown where all required parameters of the circuit of **Figure-2.8** are available. Comparing this table with **[TABLE –2.7]** and **[TABLE-2.6].** we see that the controlled circuit with practical switch works effectively.

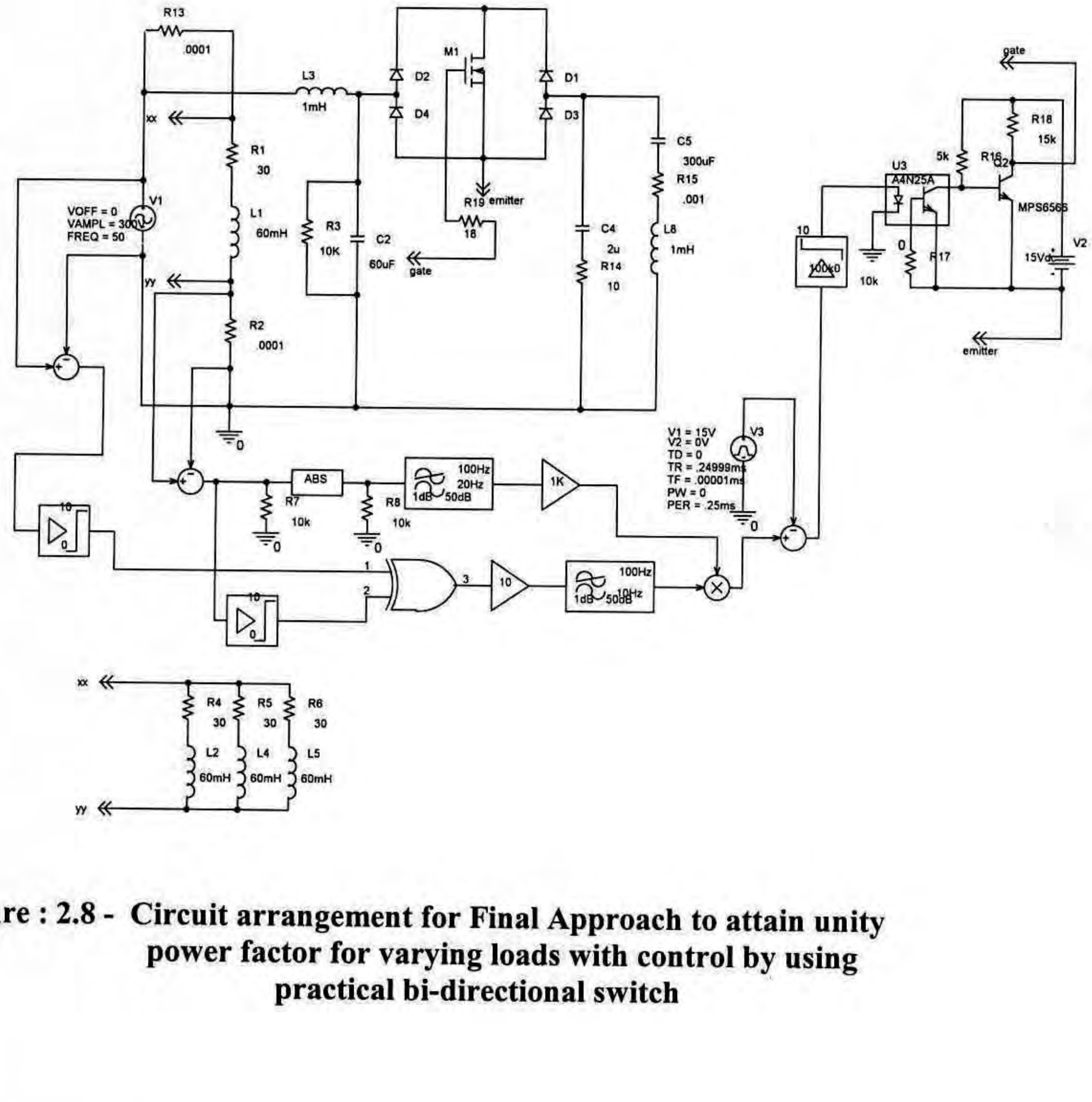


Figure : 2.8 - Circuit arrangement for Final Approach to attain unity power factor for varying loads with control by using practical bi-directional switch

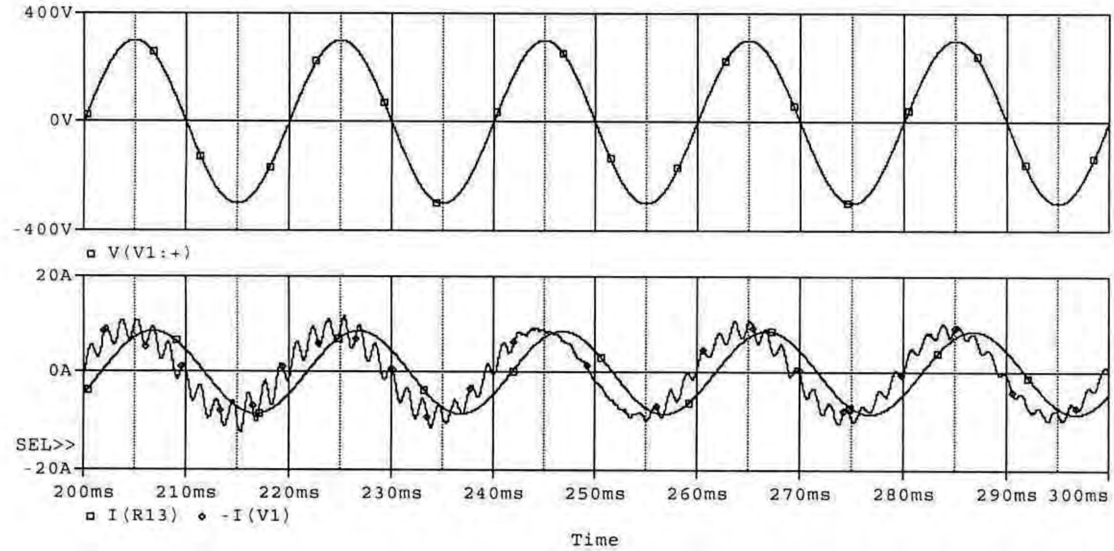


Figure : 2.8 (a1) - Unity power factor attained for single load with controlled circuit by using practical switch [Final Approach]

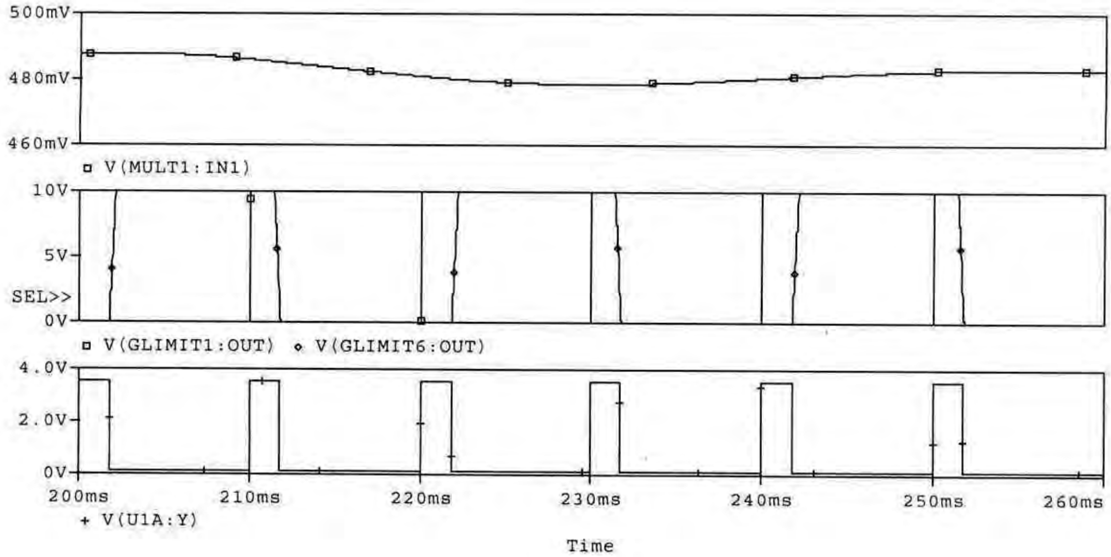


Figure : 2.8 (a1.1) – Power factor angle and equivalent of load current for single load with controlled circuit by using practical switch [Final Approach]

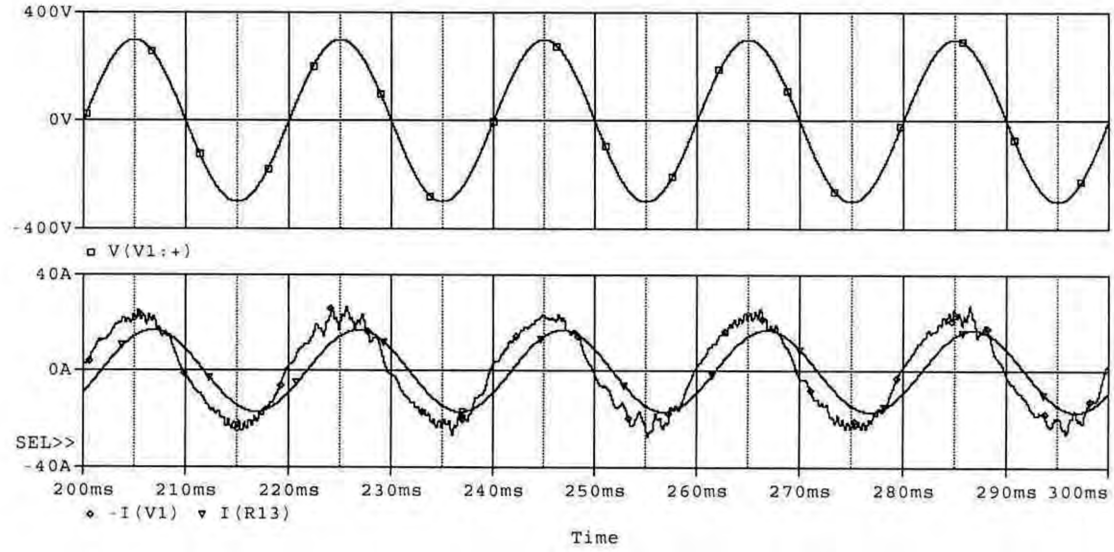


Figure : 2.8 (a2) - Unity power factor attained for two loads with controlled circuit by using practical switch [Final Approach]

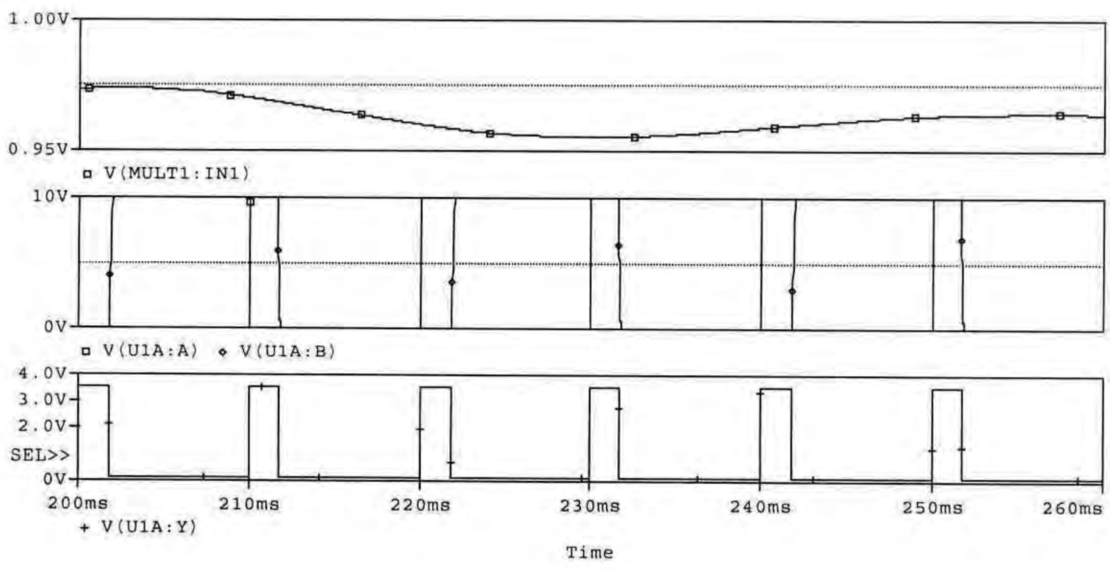


Figure : 2.8 (a2.1) – Power factor angle and equivalent of load current for two loads with controlled circuit by using practical switch [Final Approach]

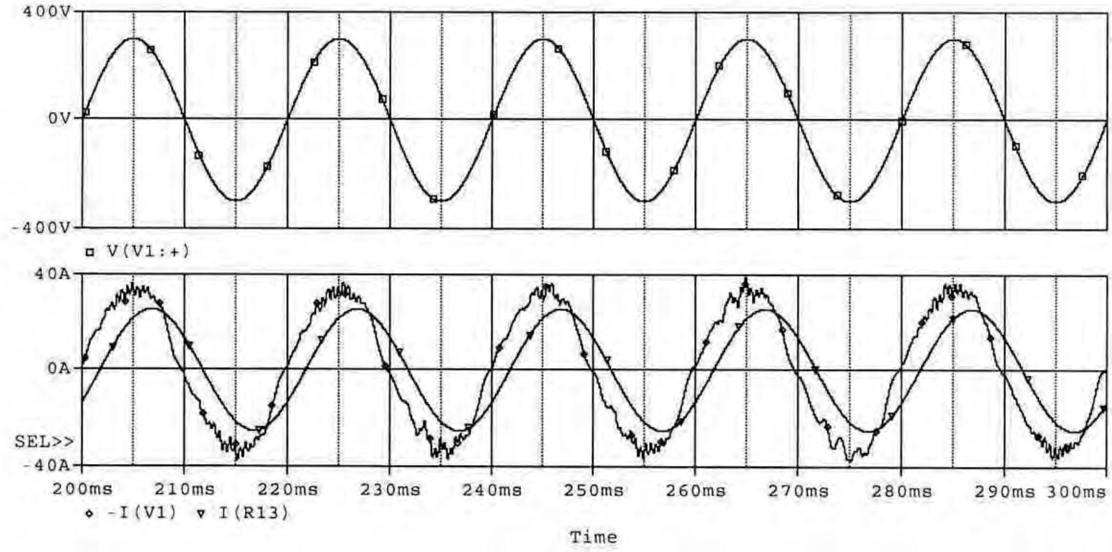


Figure : 2.8 (a3) - Unity power factor attained for three loads with controlled circuit by using practical switch [Final Approach]

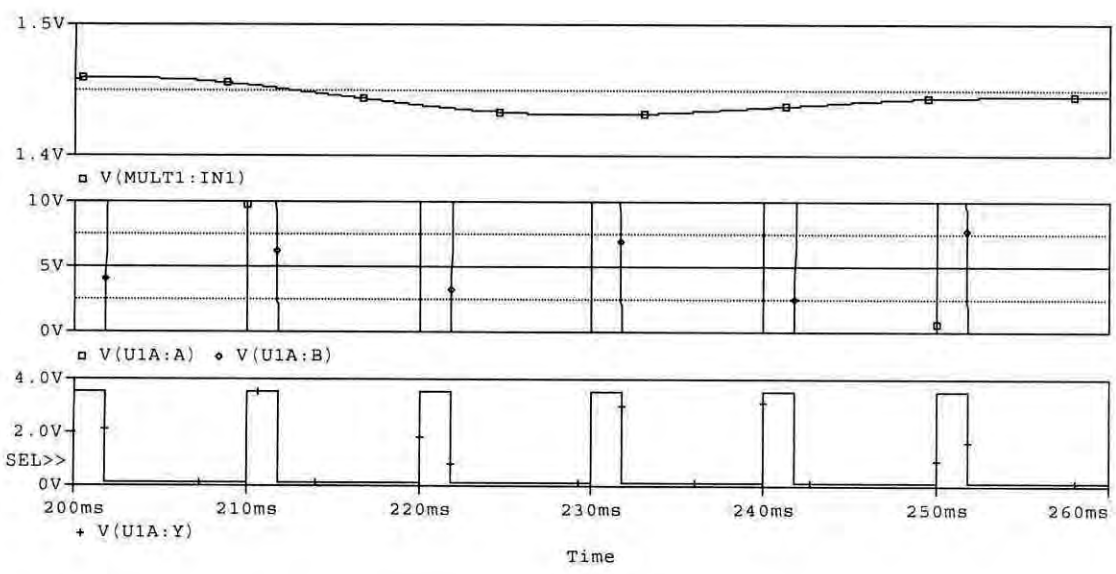


Figure : 2.8 (a3.1) – Power factor angle and equivalent of load current for three loads with controlled circuit by using practical switch [Final Approach]

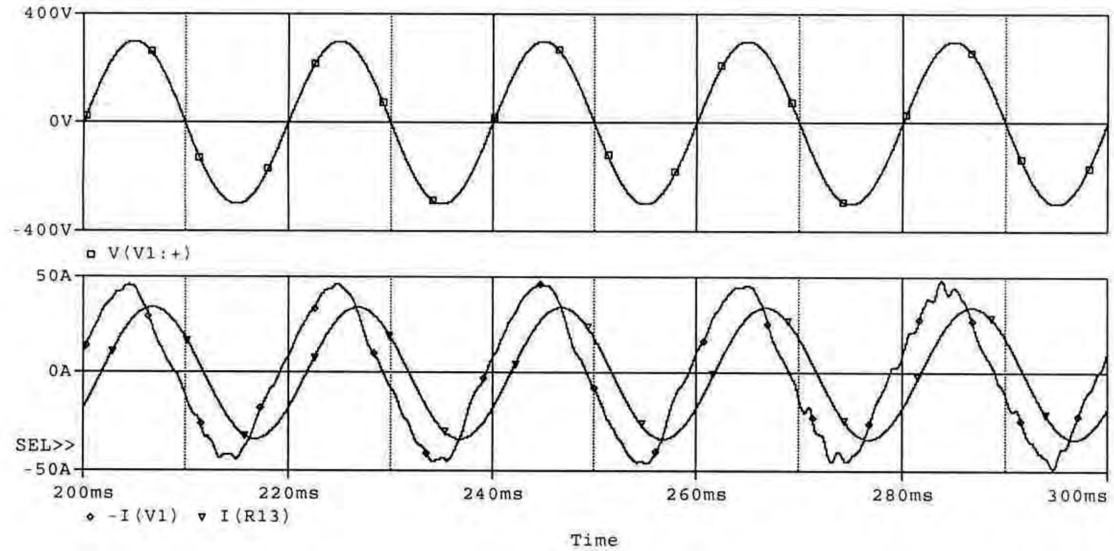


Figure : 2.8 (a4) - Unity power factor attained for four loads with controlled circuit by using practical switch [Final Approach]

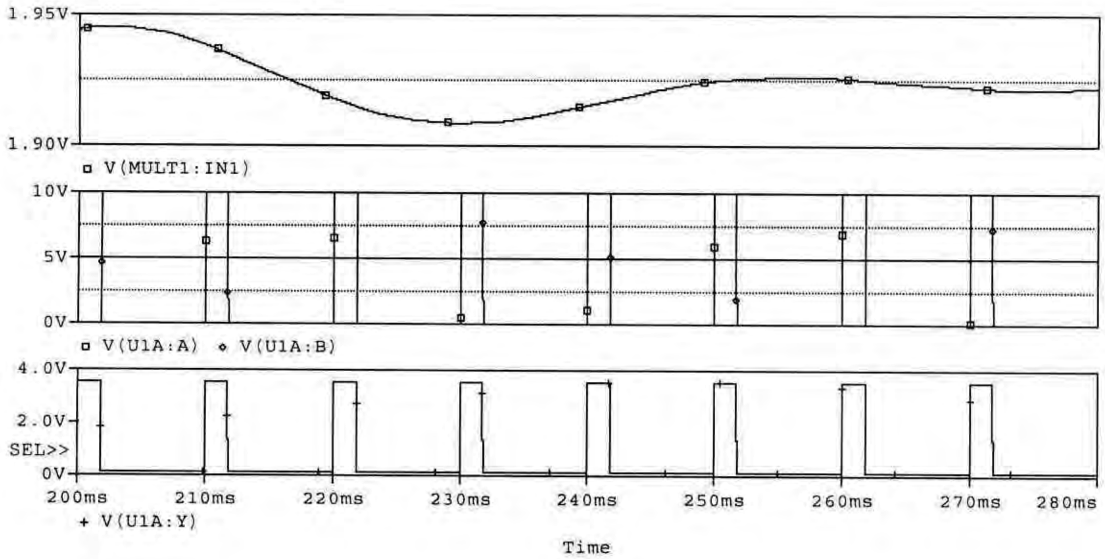


Figure : 2.8 (a4.1) – Power factor angle and equivalent of load current for four loads with controlled circuit by using practical switch [Final Approach]

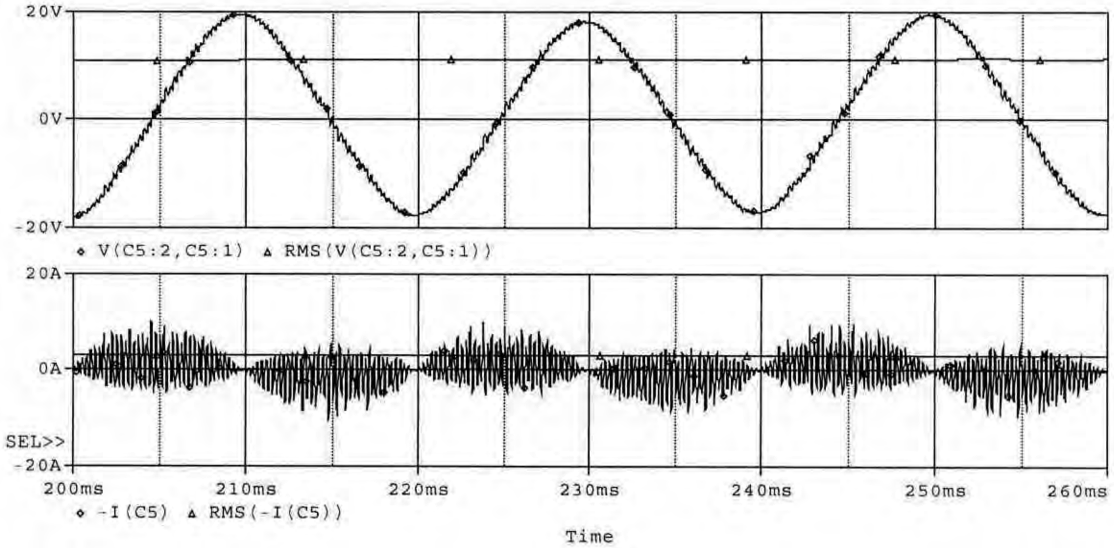


Figure : 2.8 (b1) – Voltage across and current through the capacitor to attain unity power factor for single load with control circuit by using practical switch [Final Approach]

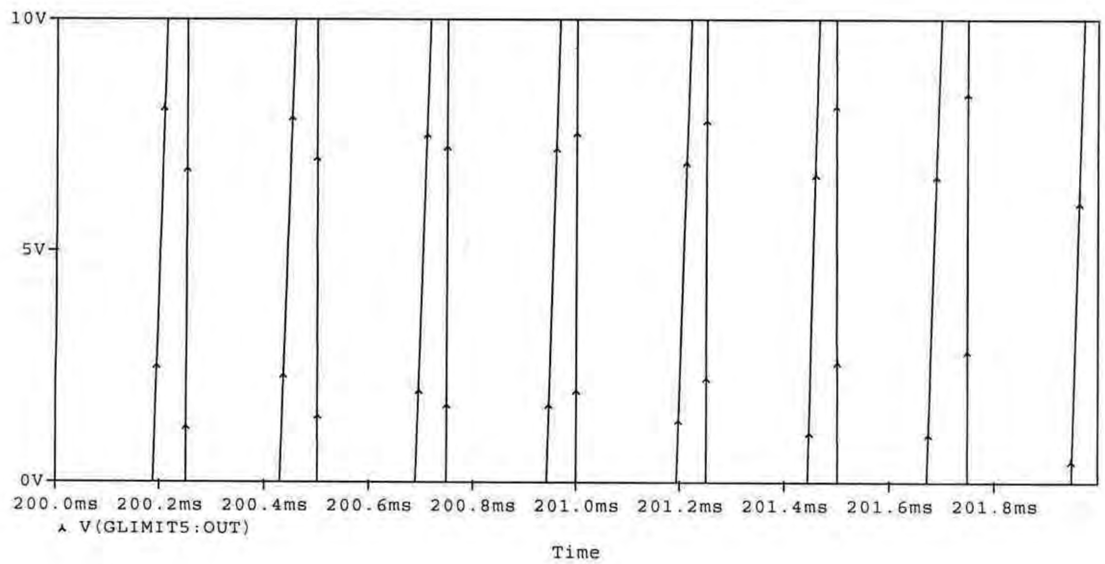


Figure : 2.8 (c1) - PWM signal supplied to the switch to attain unity power factor for single load [Final Approach]

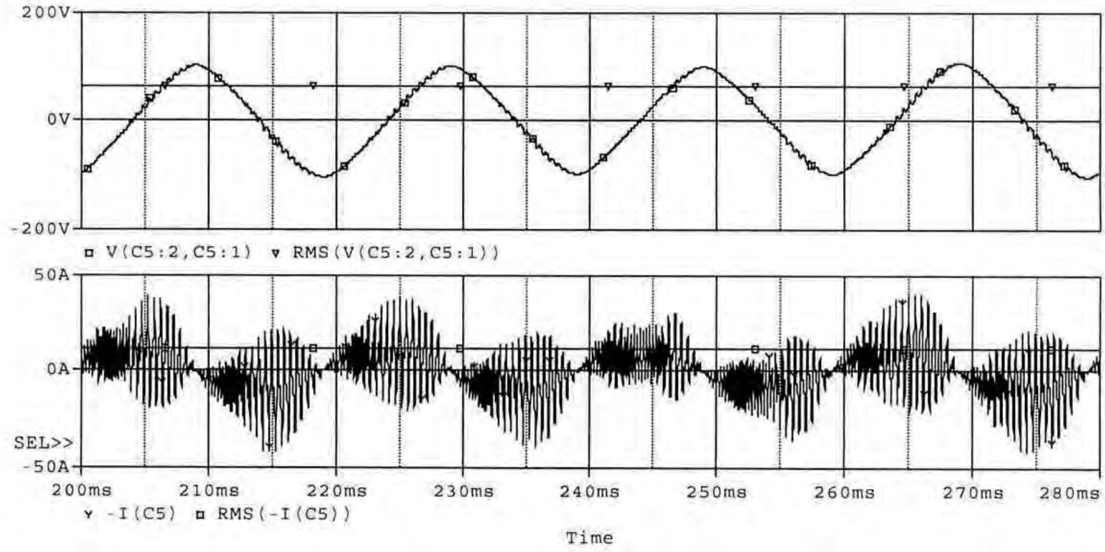


Figure : 2.8 (b2) – Voltage across and current through the capacitor to attain unity power factor for two loads with control circuit by using practical switch [Final Approach]

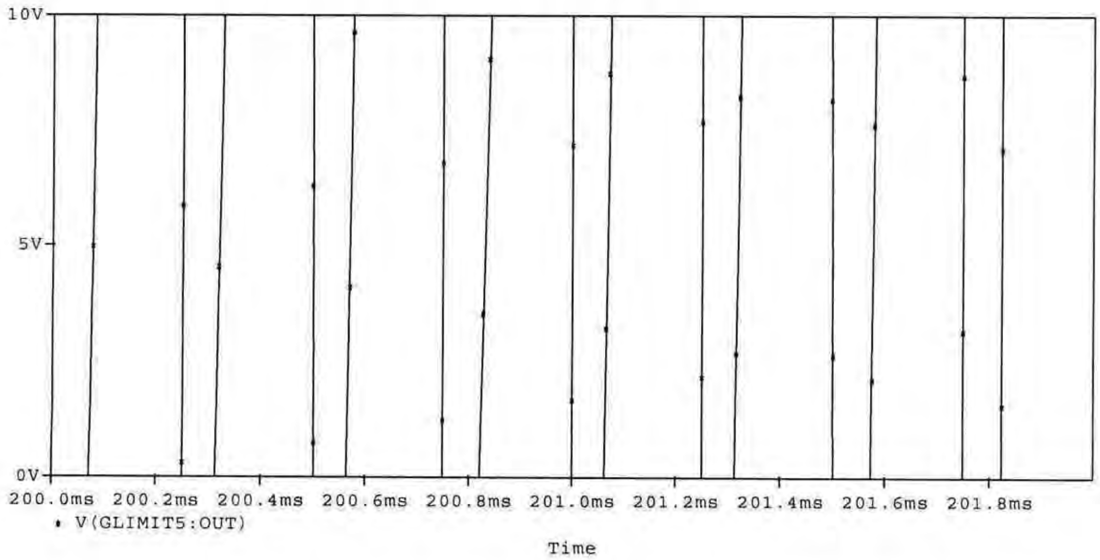


Figure : 2.8 (c2) - PWM signal supplied to the switch to attain unity power factor for two loads [Final Approach]

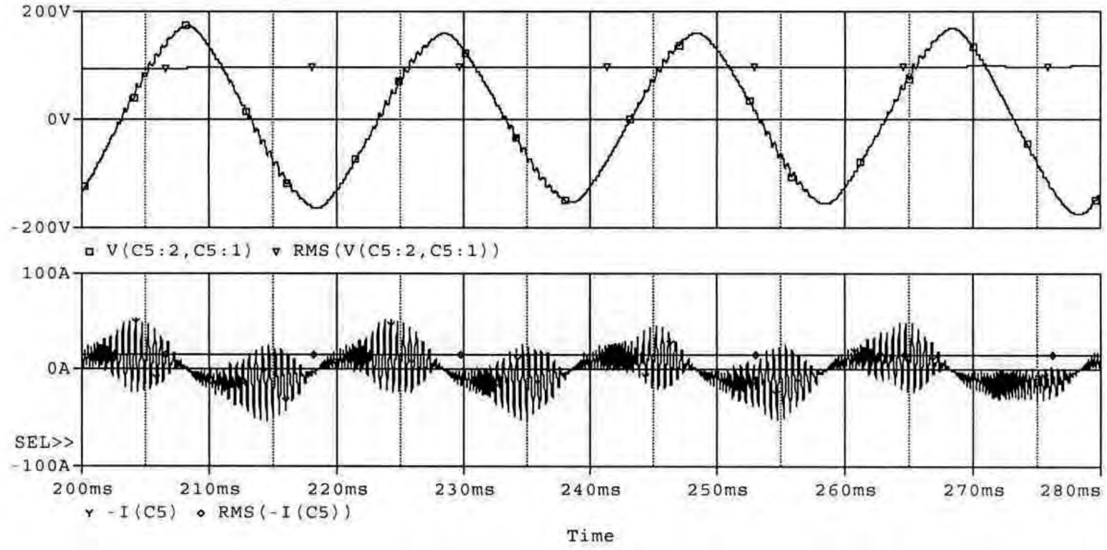


Figure : 2.8 (b3) – Voltage across and current through the capacitor to attain unity power factor for three loads with control circuit by using practical switch [Final Approach]

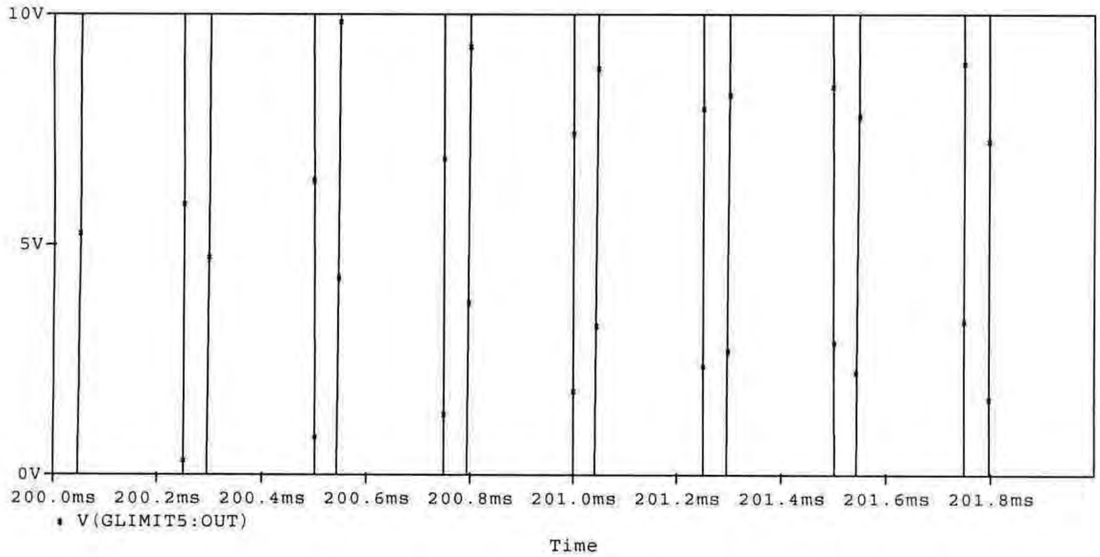


Figure : 2.8 (c3) - PWM signal supplied to the switch to attain Unity power factor for three loads [Final Approach]

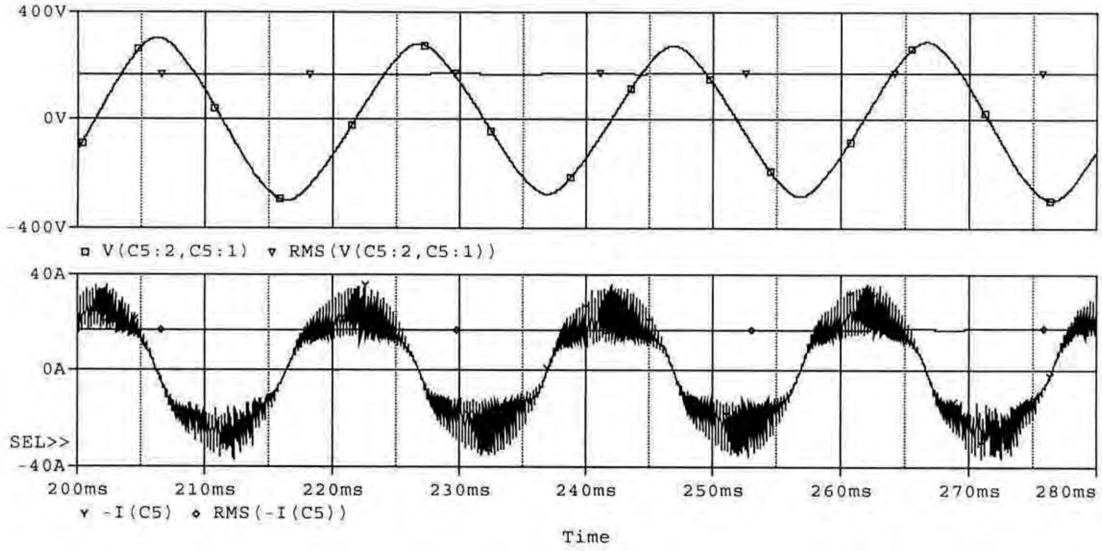


Figure : 2.8(b4) – Voltage across and current through the capacitor to attain unity power factor for four loads with control circuit by using practical switch [Final Approach]

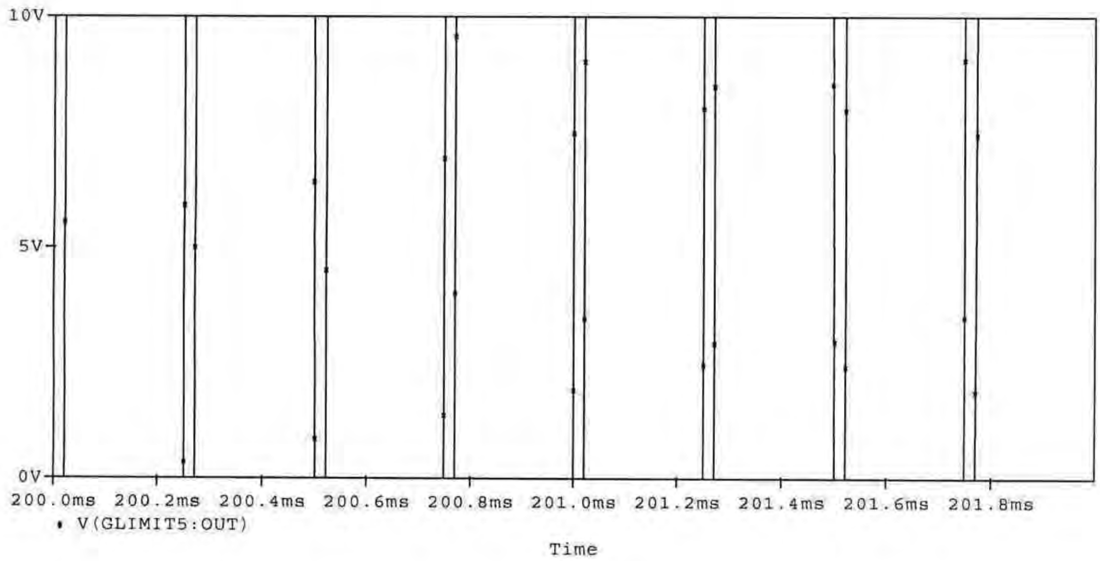


Figure : 2.8 (c4) - PWM signal supplied to the switch to attain Unity power factor for four loads [Final Approach]

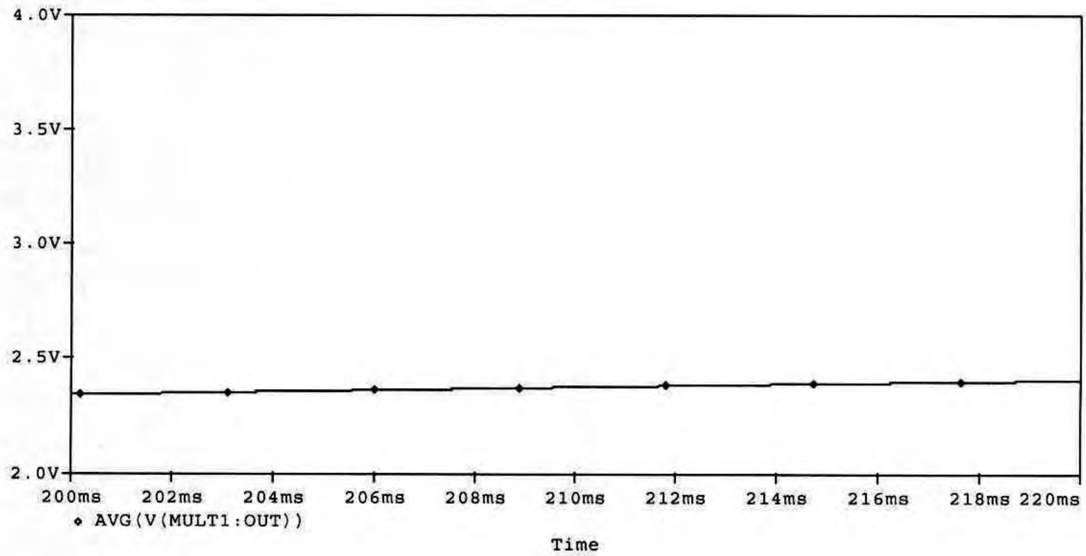


Figure : 2.8 (d1) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for single load with practical switch [Final Approach]

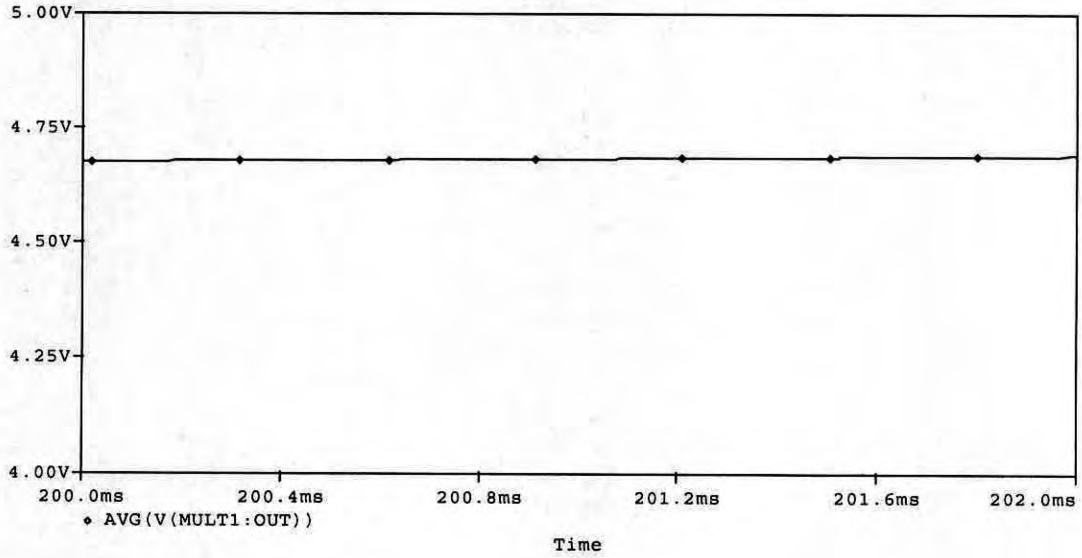


Figure : 2.8 (d2) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for two loads with practical switch [Final Approach]

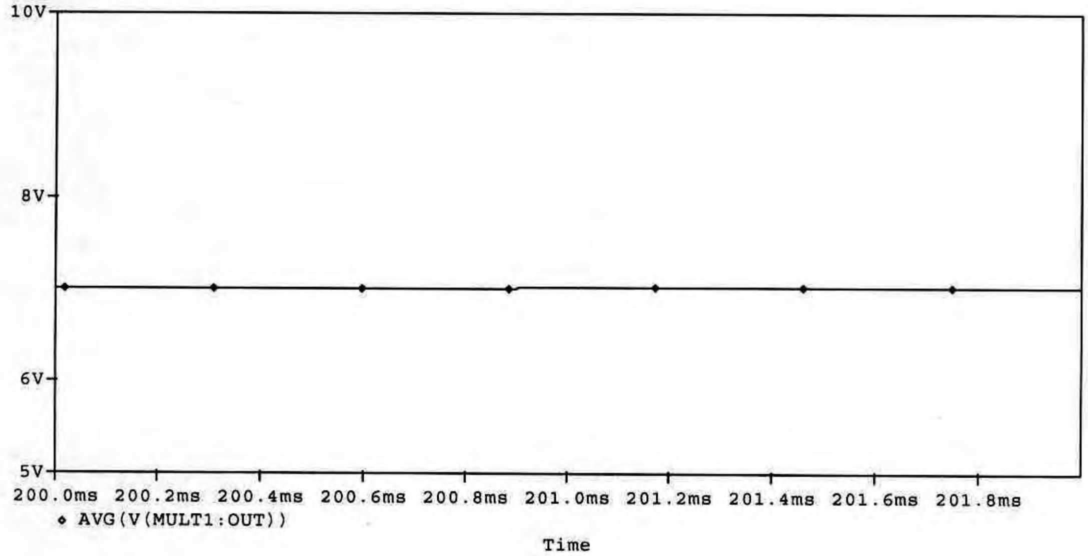


Figure : 2.8 (d3) - Value of the dc voltage which is proportional to the product of lLoad current and the power factor angle to attain unity power factor for three loads with practical switch [Final Approach]

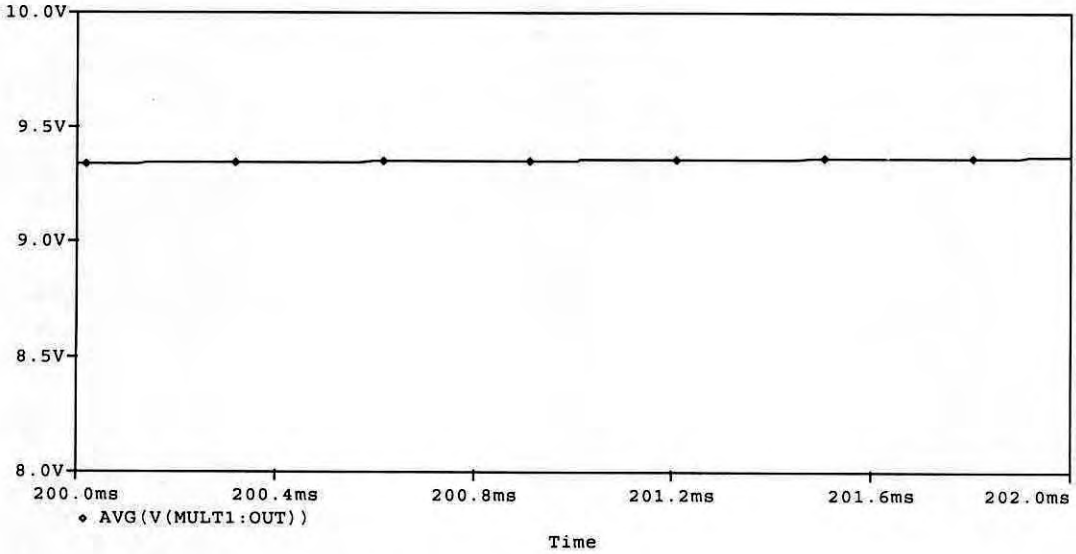


Figure : 2.8 (d4) - Value of the dc voltage which is proportional to the product of load current and the power factor angle to attain unity power factor for four loads with practical switch [Final Approach]

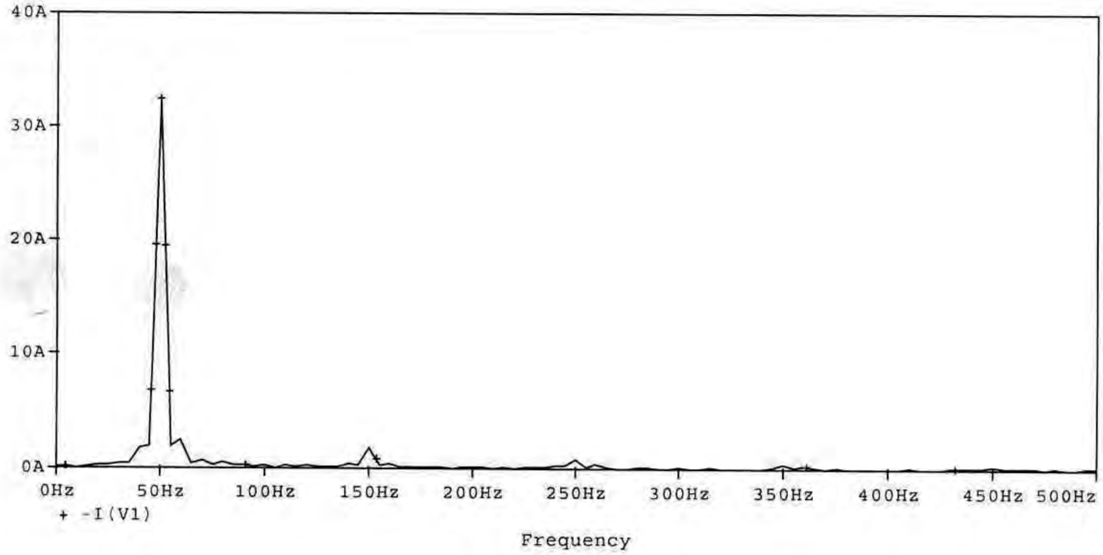


Figure : 2.8 (e) – Frequency spectrum of input current (line current) after compensation for Figure- 2.8 [Final Approach]

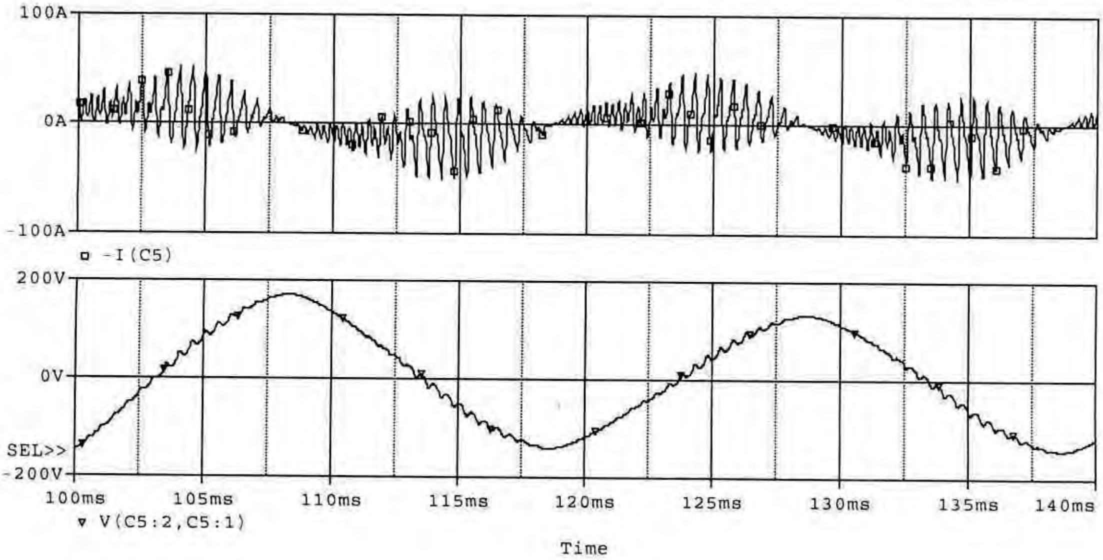


Figure : 2.8 (f) – Current and voltage profile of the capacitor after compensation for Figure- 2.8 [Final Approach]

TABLE – 2.8

No. of Loads	CAPACITOR		PULSE WIDTH	DC VOLTAGE FOR PWM	VOLTAGE PROPORTIONAL TO LOAD CURRENT	REMARKS
	V(RMS) Volt	I(RMS) AMP	(μs)	V (AVG) Volt	V Volt	
ONE	**12**	**3**	**39**	**2.35**	**0.48**	Unity Power factor obtained
TWO	**64**	**12**	**164**	**4.68**	**0.95**	Unity Power factor obtained
THREE	**100**	**15**	**194**	**7.00**	**1.45**	Unity Power factor obtained
FOUR	**172**	**18**	**226**	**9.50**	**1.95**	Unity Power factor obtained

Figure : 2.8 (g) – TABLE – 2.8 – Various parameters Various parameters of Figure : 2.8 to attain unity power factor for varying the loads

CHAPTER- 3

CONCLUSION

3.1 GENERAL :

Power factor improvement and harmonics elimination are essential in power lines of all capacities. Our proposed circuit is an attempt to suggest a simple controlled compensating circuit for a medium voltage line. A reactive current component cancellation principle is proposed, which is found to be very effective to improve power factor.

In our proposed scheme the compensating current required to compensate the reactive component of the load current is controlled by varying the voltages across the capacitor which is switched by switches . The switches are switched by PWM signals which is generated by comparing a dc voltage with a triangular wave with high frequency. The dc voltage is made proportional to the product of load current and the power factor angle by using a control circuit.

The scheme studied in this thesis may replace switching capacitors in medium power application providing accurate VAR compensation in continuous control mode. The scheme is simple in the sense that it uses only one static bi-directional switch controlled by an electronic control circuit.

The electronic control circuit is also simple. It uses only analog ICs and some discrete digital components. Since the control circuit is hybrid in nature, it tracks the power factor and magnitude of load current online and provides the compensation signal without any computer computation intensive controller. As a result, the proposed circuit can be manufactured for medium power application and marketed easily.

The control circuit will generate a dc voltage which will be equal to the value of the product of load current and the power factor angle. This dc voltage is compared with the triangular wave to generate the PWM signals to switch the switches which vary the voltage across the capacitor. The compensating current varies automatically to attain unity power factor.

Full compensation of the reactive component of load current has been achieved with some high frequency harmonics. To eliminate these harmonics a filter is used which will suppresses the higher harmonics and almost sinusoidal line current is obtained. When the switch is turned on-off several times spikes in the voltage appears. These spikes are reduced by using R-C snubber circuit with the compensating capacitor.

3.2 RECOMMENDATION FOR FUTURE WORK

Reviewing the proposal and contributions made in this thesis, we recommend some future works to be done to achieve the same or related goals.

- Research can be done further on minimizing the capacitor current spikes in the compensator circuit.

- It will be easier to implement the circuit using a digital micro controller. The micro controller will monitor the load current and the phase angle between source voltage and load current using a data acquisition system. Then it will generate the appropriate gate pulse to drive the compensator.

- The power factor of a remote utility system can be controlled by the SCADA processing technique.

- A digital computer controlled system can be designed which will determine the current at the compensator circuit and generate the required PWM gate pulses to drive the switch of the compensator. The compensator will monitor the load current and control the modulation index until the required compensation takes place.

- The proposed scheme may be field verified through practical implementation.

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