DESIGN AND SIMULATION OF PROTECTION TECHNIQUES IN SWITCHED MODE POWER SUPPLY CIRCUIT

By

SITI NOORAIN BINTI ISHAK

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

DESIGN AND SIMULATION OF PROTECTION TECHNIQUES IN SWITCHED MODE POWER SUPPLY CIRCUIT YOUR

by

Siti Noorain Binti Ishak

A project dissertation submitted to the
Department of Electrical & Electronic Engineering
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

Approved:

____

Dr. Nor Zaihar bin Yahaya
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

Siti Noorain Binti Ishak

ABSTRACT

Power supply is important to provide sufficient and stable power needed by the load. In order to provide power with high reliability, it is important to maintain the stability of the operation. Therefore, the internal circuitry of the power supply should be included with a protection system. In this project, overvoltage, overcurrent and switching protection will be installed in AC-to-DC Switched Mode Power Supply (SMPS). The SMPS is developed by combining a 3-phase full-bridge rectifier with a flyback converter. The multiple outputs isolated SMPS topology can be obtained by using three sets of transformer's secondary winding. To improve the power efficiency and reduce the switching losses, zero current switching (ZCS) and zero voltage switching (ZVS) circuit will be implemented at the controlling switch of the converter. The crowbar circuit will be used to protect the circuits from overvoltage whilst for overcurrent, a sensor will be used to sense the overcurrent having a high resistance path to limit the current. It is found that by applying the overvoltage protection, the voltage that exceeds 240 V can be reduced to around 12 V.

ACKNOWLEDGEMENTS

I would like to thank my supervisors, Dr. Nor Zaihar B. Yahaya and Ms Zalilah Bt May for their supports and guidance all this time. They had helped me with their brilliant ideas and never stop to correct the mistakes I made in order for me to achieve the objectives of this project. When I was down and lost, they helped me to realize and open my eyes to see the direction of this project. It was very helpful to me. Studying about SMPS really makes me happy as I learnt a lot from this project.

Thanks to my family and friends, who always give me encouragement and supports to complete this project. Their love had made me stronger and more encouraged to finish this project. Their patience and advices when I am complaining about the obstacles and challenge that I faced in order to complete this project, make me feel less burdened and comforted. It is really helpful to be among them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Power supply is an important part in electronic system. Without power, not even one electrical appliance is able to operate. However, the power supply is normally neglected in electronic systems and often designed without proper concerns or brought in after the system is complete, and improperly placed which is often too small or has inadequate ventilation for cooling purpose. The circuit designer normally focuses on designing the electronic system circuitry compared to the power supply. The best is to provide sufficient power to the load and can maintain its power reliability and efficiency while protecting its circuitry and the loads [1].

In order to protect the load, the power supplied to the load should be stable. Otherwise, some of the electronic components such as transistors and diodes might be damaged and thus affects the reliability of the power supply. When the power supplied is exceeding the rated power that the electronic components can withstand, the heat dissipated will affect the operation.

$$\text{Power supplied} = IV \qquad (1)$$

$$\text{Power dissipated} = I^2R \qquad (2)$$

From Eq. (1), when the power suddenly increases, the current and voltage supplied will increase as well. When the current exceeds the maximum rating that the components can handle, the heat dissipated by the components in Eq. (2) will increase. This increases the thermal level which may reduce the component's lifespan.

The designers usually want to avoid fault from occurring. Therefore, the specifications for the power supply normally include high safety margins. However, the safety margins are sometimes over-specified, and consequently, the power supply unit becomes considerably larger, heavier and more expensive [2].

In this project, a multiple output level AC-DC Switched Mode Power Supply (SMPS) will be designed using a flyback converter with the protection circuit for overvoltage and overcurrent. This SMPS will be able to supply 5 V, 12 V and 24 V outputs. Most of the commercially available multiple outputs Switched Mode Power Supplies (SMPS) use multiple number of DC-DC converters that have increased the cost and complexity of the system and reduce reliability [3]. So, an isolated type of SMPS is chosen. The protection circuit will be used to maintain reliability of the loads.

1.2 Problem Statement

Without proper consideration in designing the power supply, this might affect the stability of the loads. The problems, such as overvoltage and overcurrent are the main factors. It is important to design a protection system in ensuring the reliability of the power delivered and its efficiency

1.3 Objectives and Scope of Study

- To understand about SMPS
- To acquire the knowledge about the protection system needed for SMPS
- To apply the protection system to the SMPS for the application of a remote control car charger, closed-circuit television (CCTV) and spotlight.
- To simulate and validate the circuit.

5 V output will be used for remote control car battery charger. This application needs 2 A of current while for 12 V output, it will be used for CCTV and the current rating is 5A. For 24 V output, it will be used for a 24 V spotlight with a current of 3.75 A to light up the spotlight.

CHAPTER 2
LITERATURE REVIEW

This section discusses about the type of power supplies, the converter and the protection system in order to achieve objective 1 and 2. At the end of this chapter, the type of the converter that will be used will be decided.

2.1 Type of Power Supply

There are two types of power supplies that are usually used. One is linear power supply and the other one is switched mode power supply (SMPS).

2.1.1 What is Linear Power Supply

Linear power supply or also known as linear regulator uses a transistor that operates in linear mode; not as a switch. Linear power supply has a bulky steel or iron laminated transformer. This transformer has two purposes which are to provide a safety barrier for the low voltage output from the AC input and to reduce the input from typically 115 V or 230 VAC to a much lower voltage [4].

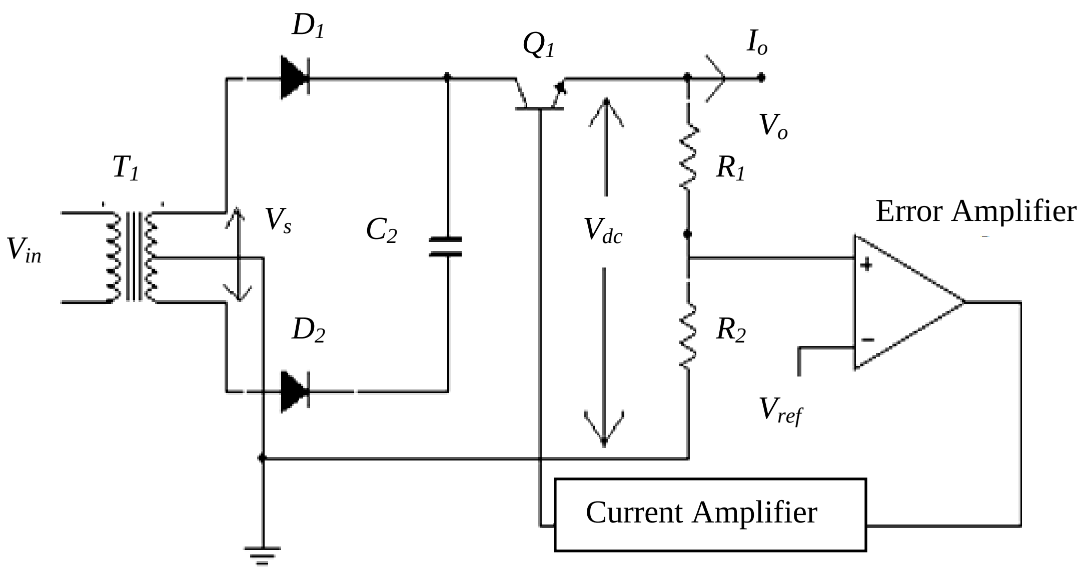

Figure 1   The Basic Circuit of Linear Regulator

Figure 1 shows an example of a linear regulator which consists of rectifiers, transformer T_1, storage capacitor C_1, resistors R_1 and R_2, and capacitor Q_2 which operates in the linear mode. From Figure 1, the output voltage, V_o is the difference between the secondary winding voltage, V_s and the unregulated DC voltage V_{dc} rectified from the transformer *T1*.

In order to control output voltage $V_{o,}$ V_{dc} should be controlled by means of the input from the error amplifier feeding base current to the transistor [5]. The base current to the transistor is controlled by controlling the reference voltage, V_{ref} of the error amplifier.

2.1.2 What is SMPS

The basic concept behind SMPS is the fact that the output regulation is undertaken by using a switching regulator. This uses a series of switching element that turns the current supply on and off [6]. By controlling the duty cycle of the switching, the output voltage of SMPS can be controlled. Usually, power MOSFET is used as the switching device rather than using power BJT [7]. To control the duty cycle of the switch, sometimes a sample of the output voltage is used as the feedback signal to the switch drive circuit to achieve regulation [8].

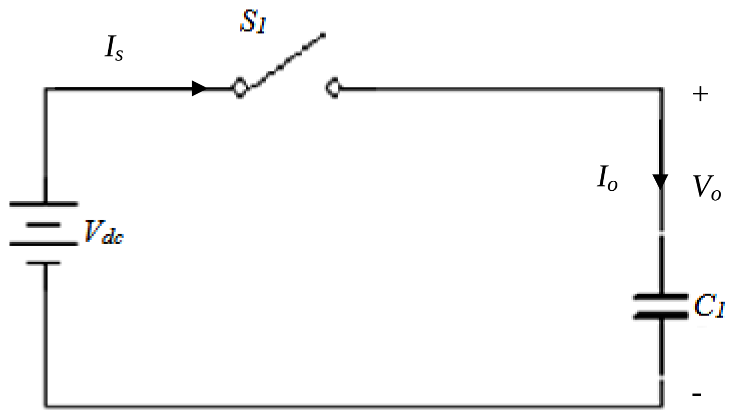

Figure 2 The Basic Circuit of SMPS

From Figure 2, when the switch S_1 is on, the current I_s and voltage V_{dc} from the source will flow to the capacitor C_1 and charge it. When the switch S_1 is turned off, the current I_s will stop flowing and the capacitor C_1 will discharge the energy from it as shown in Figure 3. By controlling the duty cycle of the switch S_1, the voltage V_o or current I_s flowing to the capacitor C_1 can be controlled [9] to obtain the required current I_o.

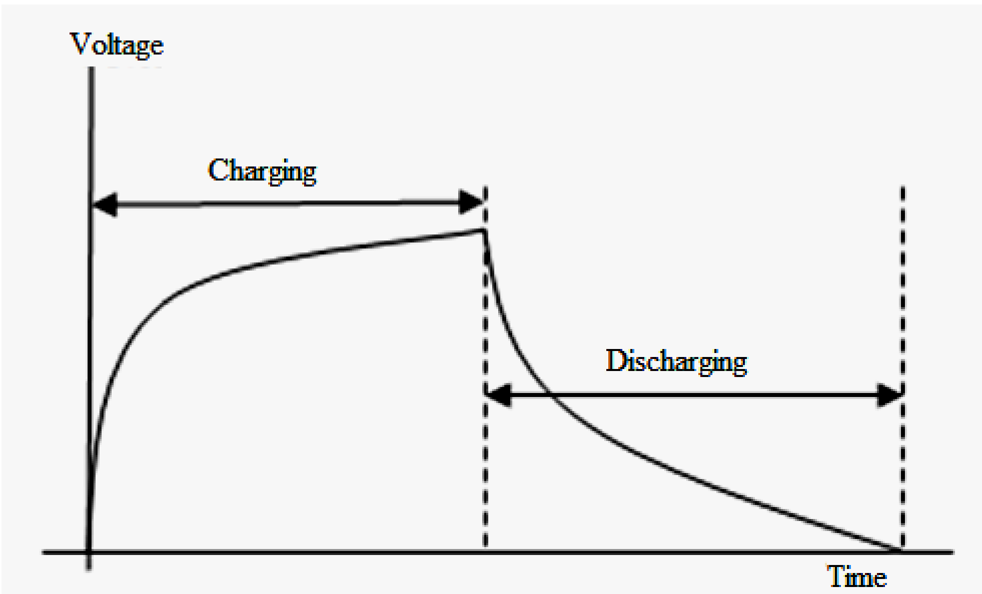

Figure 3 The Charging and Discharging of Capacitor

2.1.3 The advantages and disadvantages of SMPS and Linear Regulator

The most significant advantage of SMPS inhibits a greater efficiency because the switching transistor dissipates little power as it functions as a switch. When the transistor acts like a switch, it is either has a negligible voltage drop across it or a negligible current through it. Other advantage is lower heat generation due to higher efficiency compared to linear power supply.

Despite having higher efficiency, the design of SMPS is more complex compared to linear regulator. It also generates high-amplitude, high-frequency energy that needs to be blocked by the low-pass filter to avoid electromagnetic interference (EMI), and a ripple voltage during the switching [10].

Table 1 Comparison between SMPS and Linear Power Supply [11]

Features	**SMPS**	**Linear Power Supply**
Efficiency	65-75 %	25-50 %
Temperature rise	20-40^{o}C	50-100^{o}C
Ripple value	Higher 25-50 mV	Even 5 mV possible
Overall regulation	0.3 %	0.1 %
RF interference	Can cause problem if not properly shielded	None
Magnetic material	Ferrite core	Stalloy or CRGO core
Weight	About 60 W\kg	20-30 W\kg
Reliability	Depends on the switches	More reliable
Transient response	Slower	Faster
Complexity	More	Less

From Table 1, the efficiency of SMPS is higher than the linear power supply and this leads to a lower temperature rise for SMPS as the heat is less dissipated. Table 1 also shows that for 1 kilogram of SMPS, 60 kW of power can be generated. However, for a linear power supply, it can only generate 20 kW for each kilogram. In other words, for the same power generated by both power supplies, SMPS will have a lighter weight compared to linear power supply. As an example, if both power supply generate 120 W, SMPS only weighs 2 kg while linear power supply will at least becomes 40 kg. Due to this, SMPS is chosen for this project instead of linear power supply.

2.1.4 Type of SMPS

SMPS can be divided into three types depending on the topologies. The topology is the arrangement of the energy storage inductors and capacitors as well as transistors and rectifiers in the circuit network. The three types of SMPS are isolated, non-isolated and quasi-resonant switch.

An isolated SMPS has transformer-coupling between the output and the input whereas non-isolated does not have transformer. The quasi-resonant switch is basically a conventional semiconductor power-switching device with an LC circuit incorporated into a circuit to shape either current flowing through the device or the voltage across it [12].

In this work, an isolated topology incorporated with transformer will be designed to obtain multiple output voltage. The input and the output will be electrically isolated from each other. Usually, this requirement is needed to keep the mains voltage well apart from the voltage at the load. The turn ratio of the transformer can be chosen to provide a various different output voltages from the input.

2.1.5 Type of Isolated SMPS

There are several types of isolated SMPS that are commonly used. They are flyback, forward, half-bridge, and full-bridge converters. The configurations of the components in the converter are different from each other. This section discusses about the different types of isolated SMPS that can be used for this project.

2.1.6 Buck Converter

Figure 4 shows a conventional buck converter. It consists of a switching device S_1, a freewheeling diode D_1, a capacitor C_1 and an inductor L_1. The switching device can be a transistor. During the on period of the switch, S_1, the DC voltage from the source, V_{dc} will flow through S_1 to L_1 and charge it before flowing to the resistor R_1 . When S_1 is off, the energy from the L_1 will be discharged. D_1 is used to provide a path for the current flow during the off period of the switch. Without D_1, the highly induced emf in L_1 and the current discharges from the L_1 may damage S_1.

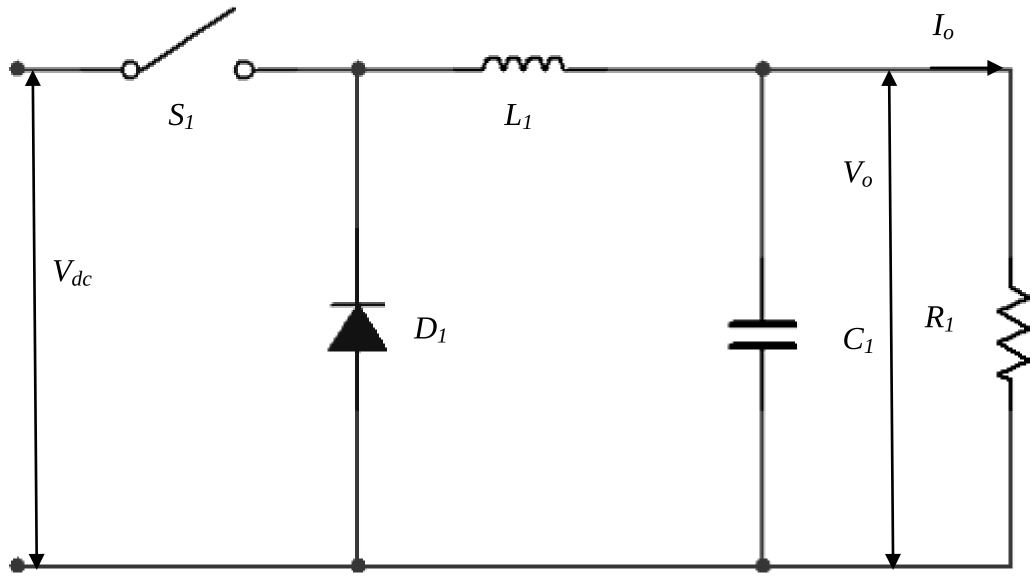

Figure 4 Buck Converter

When V_s is lower than the output voltage V_o, the current will flow in reverse direction from V_o to V_s. This reverse current will cause D_1 in the rectifying circuit to become reversely biased and blocked the current. So the current become nearly to zero simply because buck converter cannot operate when V_{dc} is higher than V_o.

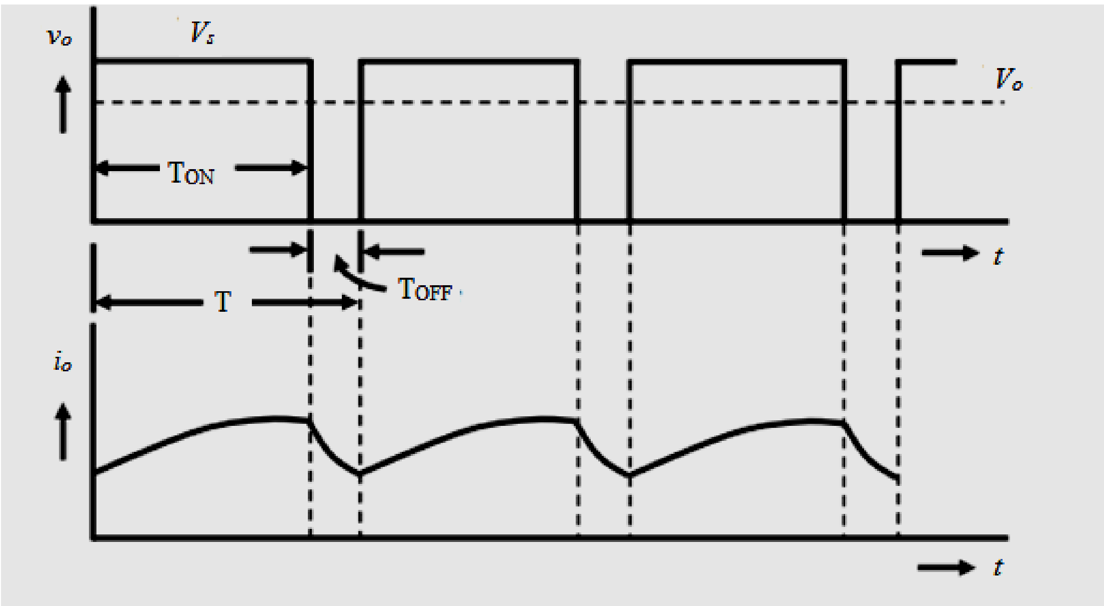

Figure 5   Output Voltage and Current Waveforms [13]

The instantaneous output voltage v_o and current i_o are shown in Figure 5. When the switch S_1 is on, L_1 will be charged i_o will be increasing. Once S_1 is off, the induced emf in L_1 will be discharged and i_o will be flowing through the D_1 and keep on reducing until the S_1 is on again.

2.1.7 Boost Converter

Boost converter is a step up converter. It is mainly used for regulating DC power supplies and regenerative braking of DC motor. The output voltage of boost converter is higher than the input voltage. The input to the converter is DC. So, if the available input is AC, the rectifying circuit is needed to rectify AC input to DC.

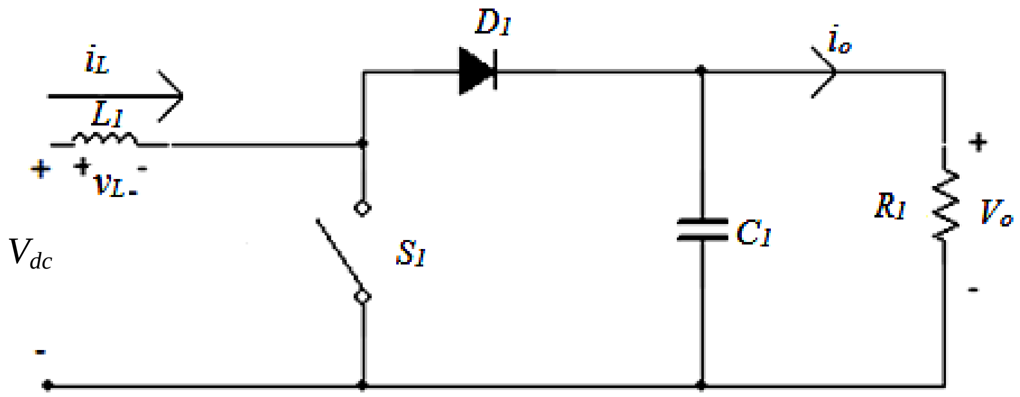

Figure 6 Boost Converter

Boost converter is shown in Figure 6. When the switch S_1 is on, the current in inductor L_1 will flow through the switch S_1 as the resistance of S_1 is lower compared to the resistance of the diode D_1. The direction of the current flow is shown by i_1 in Figure 7. As there is no current flowing through D_1, the energy stored in the capacitor, C_1, will be discharged. So, the output current i_o will flow in anticlockwise, causing D_1 to be reverse-biased and makes the output become isolated as shown in Figure 7. The input will supply energy to L_1 and the current in the inductor i_L will increase as L_1 is charging.

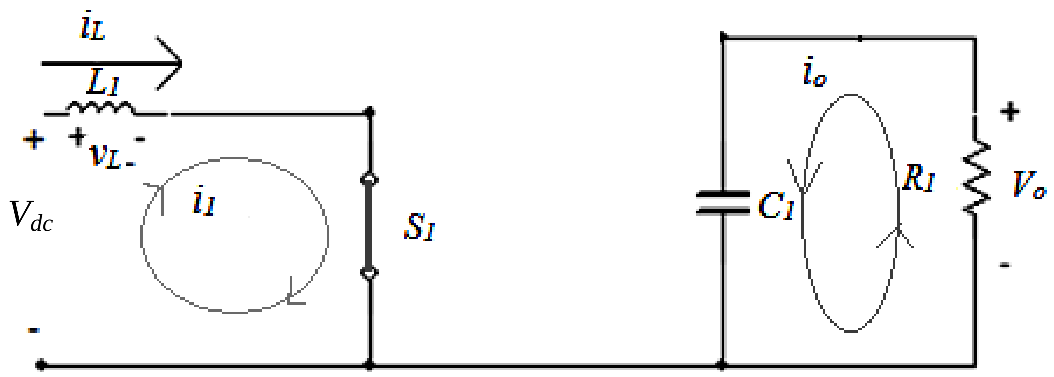

Figure 7 Switch is On for Boost Converter

Once the switch is off, the energy in L_1 will be discharged. The operation of the boost converter during the off period is shown by Figure 8. The input voltage, V_{dc} as well as the voltage from L_1 will make the diode D_1 become forward biased and the output current i_o flow through D_1 to the output as shown in Figure 8. The output current i_o flows through the output resistance R_1 while the capacitor current i_C flows through the filtering capacitor C_1. The capacitor C_1 will store the energy flowing across it. The filtering capacitor C_1 is assumed to be sufficiently large to ensure a constant magnitude of output voltage of V_o.

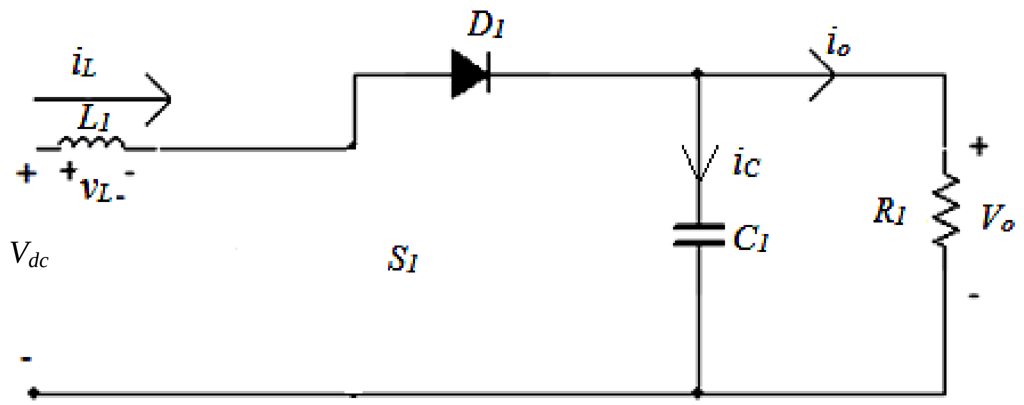

Figure 8 Switch is Off for Boost Converter

2.1.8 Flyback Converter

Flyback converter is usually used for low power application SMPS where the output voltage needs to be isolated from the input main supply. The overall electronic component arrangement of this converter is significantly simpler than other SMPS circuits [14]. Input to the circuit is generally unregulated DC voltage achieved by rectifying the utility AC voltage followed by a simple capacitor filter to smoothen the ripples of the rectified output voltage.

The circuit can offer single or multiple isolated output voltages and can function over wide range of input voltage variation. In terms of energy efficiency, flyback power supplies are poorer to many other SMPS circuits but this simple topology and low cost makes it widely used in low output power range.

The flyback converter is based on the buck-boost converter [15]. The derivation of flyback converter from buck-boost converter is illustrated in Figure 9. Figure 9(a) shows the basic buck-boost converter, with the using of MOSFET and diode as the switches. In Figure 9(b), the winding of the inductor is made of two wires, with a 1:1 turn ratio. The basic function of the inductor is not changed, and the parallel windings are equal to a single winding made of larger wire. In Figure 9(c), the connections between both windings are broken. One winding is used while the transistor Q_1 conducts, while the other winding is used when diode D_1 is conducting. The total current in the two windings is unchanged from the circuit in Figure 9(b).

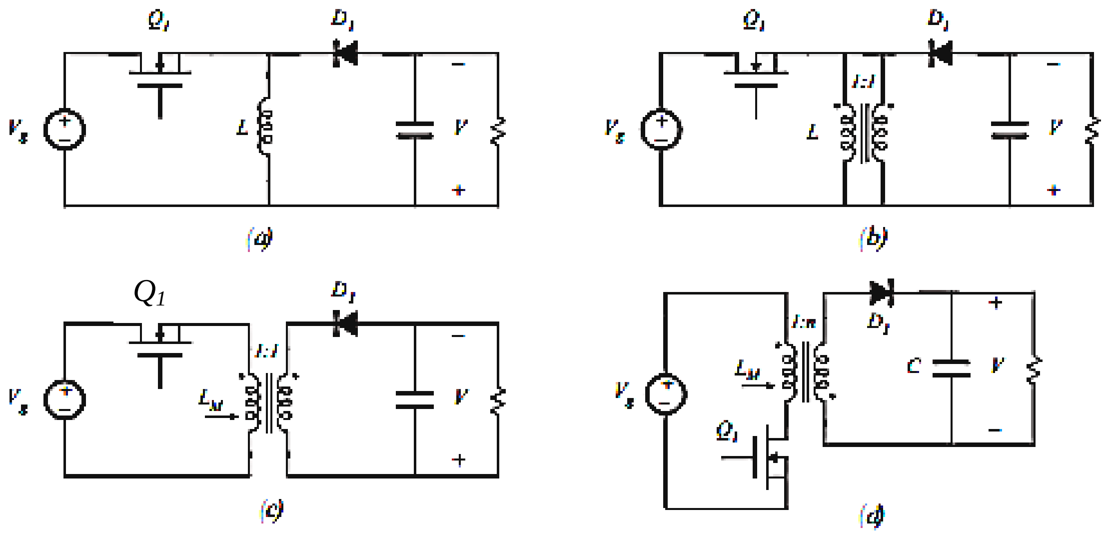

Figure 9 The derivation of flyback converter [16]

However, the distribution of the current between the windings is not equal even though the magnetic fields inside the inductor in both cases are equal. Although the two-winding magnetic device is represented using the same symbol as the transformer, it is actually more like an inductor that has two windings than a transformer.

Transformer does not have the ability to store energy however the inductor can. This device is sometimes known as a “flyback transformer”. For flyback transformer, current does not flow simultaneously in both windings not like the normal transformer [17].

Figure 9(d) illustrates the typical configuration of the flyback converter. The MOSFET Q_1, source is connected to the primary-side ground, to simplify the gate drive circuit. The MOSFET, Q_1, is usually controlled by a PWM circuit. To get a positive output voltage, the transformer polarity is reversed.

From Figure 10, when current is fired to the gate of Q_1, Q_1 will be on. Thus, the current, i_1, will flow at primary winding of the transformer but the current, i_2, at secondary is zero. This is because the flyback transformer acts differently than the normal transformer. During this time, the voltage drop at Q_1 is zero thus the voltage at the primary winding, V_{pri} is equal to V_{dc}. Once the switch is off, the current i_2, will flow at the secondary winding due to $L_2 \frac{dv_{sec}}{dt}$.

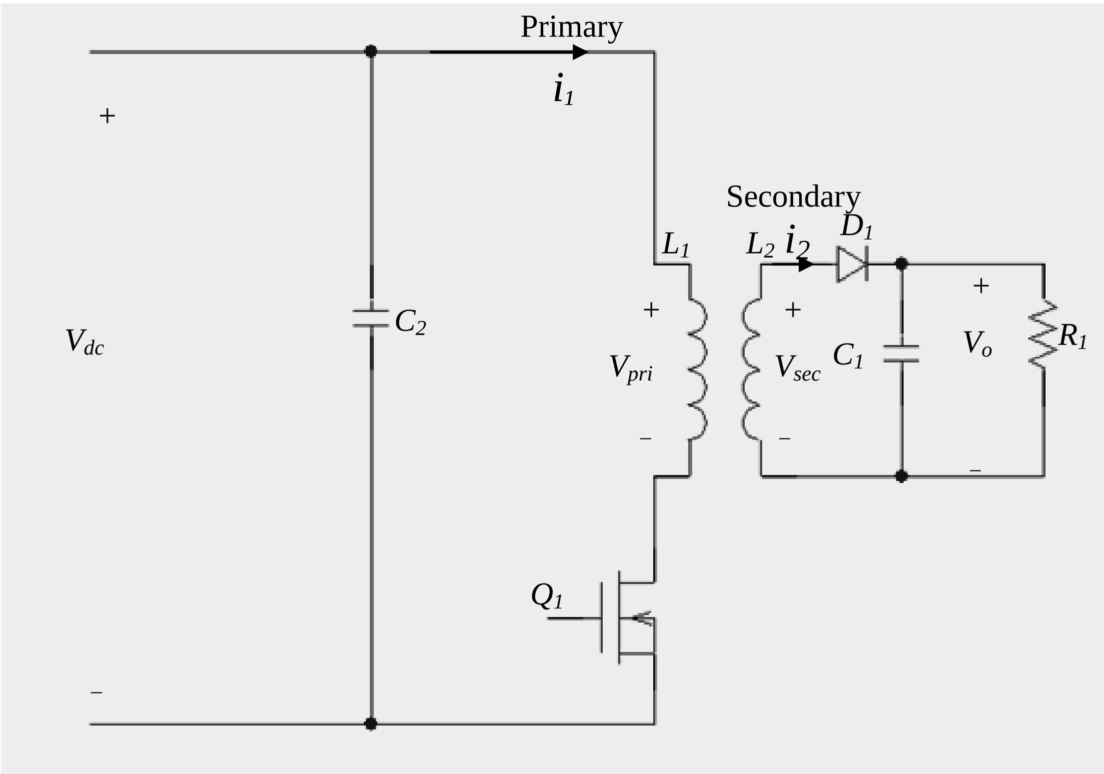

Figure 10   Flyback Converter

The turn ratio of the flyback transformer can be manipulated. However, unlike the normal transformer, the turn ratio does not manipulate the voltage but the current at the primary and secondary of the transformer does. The ampere-turns at the primary and secondary winding must be the same [18]. As an example, if L_1 has 100 turns and the current is 1 Ampere, the ampere-turns will be 100 ampere-turns. So, during off period, L_2 will also have 100 ampere-turns. If the L_2 has 10 turns, then i_2 will be 10A. The output voltage will simply be the current times the load resistance, R_1.

2.1.9 Forward Converter

Another popular SMPS circuit is forward converter. It is used for producing isolated and controlled DC voltage from the unregulated DC input supply. As in the case of flyback and forward converter, the input DC supply is often derived after rectifying and a little filtering of the utility AC voltage. The forward converter, when compared with the flyback circuit, is generally more energy efficient and is used for applications requiring little higher power output generally up to 200W [19].

However the topology of the circuit, especially the filtering circuit at the output is not as simple as in the flyback converter. As an example, by comparing the flyback converter in Figure 10 with the forward converter in Figure 11, only one diode is needed in flyback converter circuit whereas forward converter needs two. This shows that, flyback converter needs lesser components at the filtering part compared to forward converter.

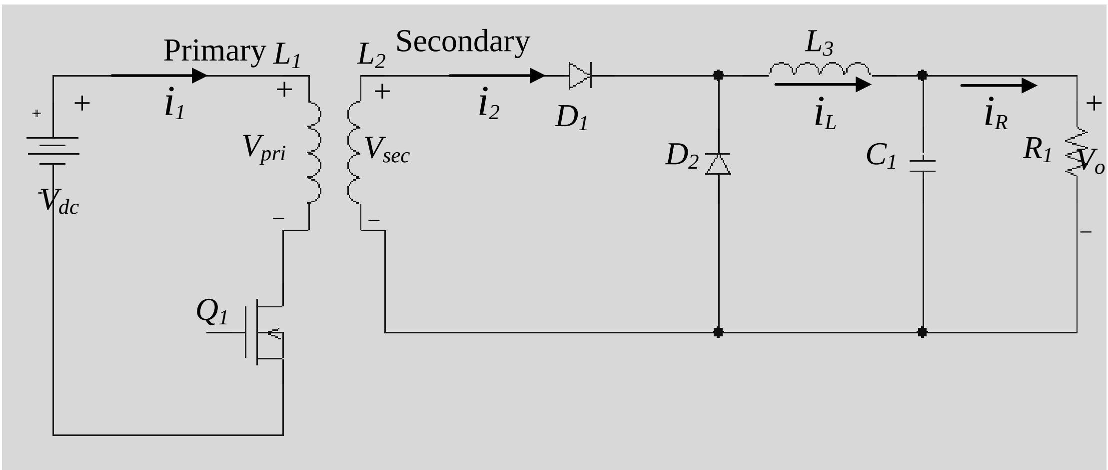

Figure 11 Basic Topology of Forward Converter

When the gate of Q_1 is triggered, Q_1 turned on. Then, the DC voltage from the source, V_{dc} will be applied to the primary winding, L_1 of the transformer T_1 and simultaneously a scaled voltage, V_{sec} will appear at the secondary winding, L_2. The dotted sides of both windings have positive polarity. The diode D_1 becomes forward biased so the current i_2 will flow through D_1 and then through the low pass filter preceding the load. The current i_1 at L_1 flows into the dot whilst the current i_2 at L_2 flows out of the dot. The ratio of i_1 and i_2 are inversely of the turns-ratio of L_1 and L_2 [20].

When the Q_1 is turned off, i_1 as well as i_2 are brought to zero. However, the current through the inductor, i_L and the current through the load, i_R are still flowing. The diode D_2 provides a freewheeling path for these currents to flow. The required emf to maintain the continuity of the current flowing through L_1 and the current to maintain the bias of D_2 is provided by L_1 itself. The inductor current, i_L will be decaying as it flows in opposite of the output voltage, V_o. However, due to the presence of a relatively large filter capacitor, C_1, the output voltage V_o become relatively constant.

From the various type of converter, the type of converter that was decided to be used in this project is flyback converter. This decision was made because the input and output voltage of flyback converter is isolated, thus when there is fault at the input, the output will not be affected. Furthermore, it is easier to configure multiple outputs level with flyback converter as it only takes two more secondary windings to obtain three levels of output voltage. Moreover, flyback converter topology is simpler compared to other converter. Forward converter also has isolated input and output. However, flyback has lesser components compared to forward converter.

2.2 Protection System

It is important to protect the load against overvoltage because overvoltage in power supply could easily damage the circuit it is powering. It is normal to simply shut down the power supply if an overvoltage is detected except for transient.

Most power supplies have some forms of current limiting protection, such that if the load current rises above a preset level such as the current rating of the circuit, the output voltage reduces to limit the current to a safe level. The protection from overcurrent is important to limit the dissipation in the regulator component to safe values and thereby prevent damage to the components.

In order to decrease the volume and weight of a DC-DC converter, higher switching frequency must be chosen. Increasing the switching frequency leads to increased switching losses which in turn reduces the converter efficiency [21]. Due to that, some auxiliary circuit will need to be included to improve the switching frequency and to reduce the electromagnetic interference (EMI) to the switch. Therefore, some LC resonant circuit will be needed.

2.2.1 Method of Protection

To protect the SMPS from overvoltage, instead of shutting down the system instantly when during fault, alternatively, a “crowbar” circuit may be used, where a thyristor is triggered if the voltage at the gate of the thyristor rises above the threshold voltage, putting a short circuit across the output, hence, clamping the output voltage low, with the current controlled by the current limit circuit. SCR is usually used as the in the circuit [22]. Figure 12 shows an example of crowbar thyristor circuit.

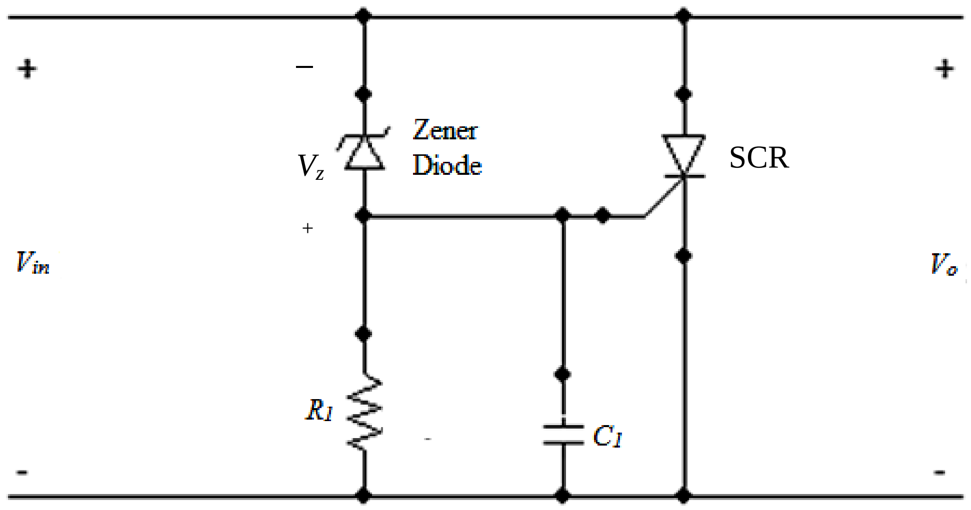

Figure 12 Crowbar circuit

In Figure 12, the thyristor used is a Silicon-controlled rectifier (SCR). When the voltage at the input V_{in} exceeded the breakdown voltage of the zener diode, the voltage, V_z will flow through zener diode in reverse direction. If V_z is more than the threshold voltage of the SCR, the SCR will be triggered. Hence, the output voltage, V_o will be shorted. By using this method, the system can still operate even when the voltage has exceeded the limit.

For overcurrent protection, normally circuit breaker and fuse will be used to protect the circuits. However, in this project electronics component will be used to protect the circuit from overcurrent.

The normal method of providing current limiting in a power supply is to provide an output current sensor driving a feedback path that is used to control the output current. When the output current is below the critical threshold level, the feedback does not affect the output current, but above the threshold, a high resistance path is introduced into the circuit to control the current.

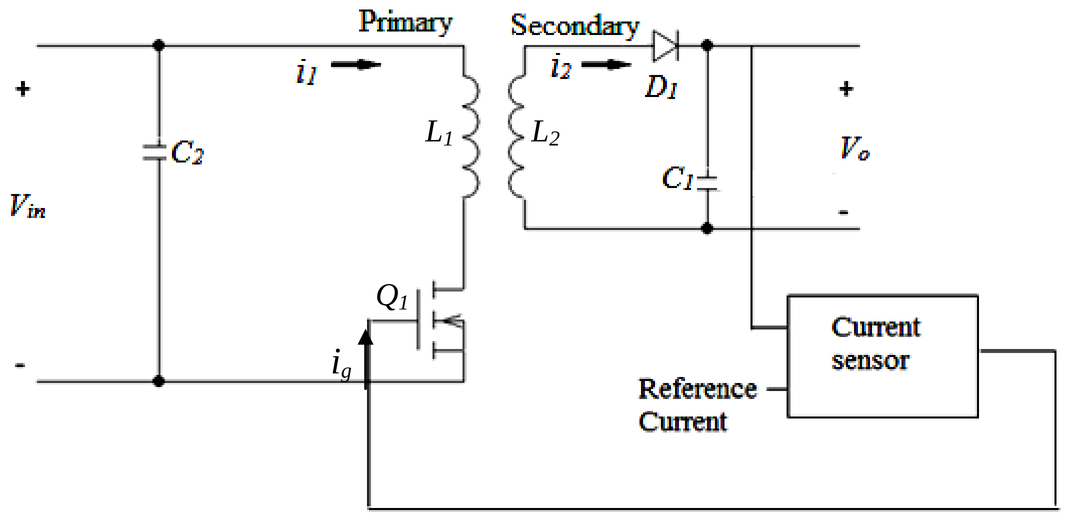

Figure 13 Flyback converter with overcurrent protection

Theoretically, the current sensor will be feeding the switching components of the flyback converter to limit the current transferred to the secondary winding of the flyback transformer as shown in Figure 13. When the current i_2 flows through the current sensor, the current i_2 will be compared with the reference current. If i_2 is less than the reference current, the frequency of the current feeding the gate of Q_1, i_g will be reduced to limit the amount of current transferred to the secondary winding, L_1.

To improve the switching frequency and to reduce EMI; which is mainly contributed by resonance [23] to the switch, zero current switching (ZCS) and zero voltage switching (ZVS) can be used and combined together. The ZVZCS means mixed operation of ZVS for leading-leg switches and ZCS for lagging-leg switches [24]. ZCS topology is where the switch turns off at zero current. The peak resonant current flows through the switch but the peak switch voltage remains the same as in its switch-mode counterpart.

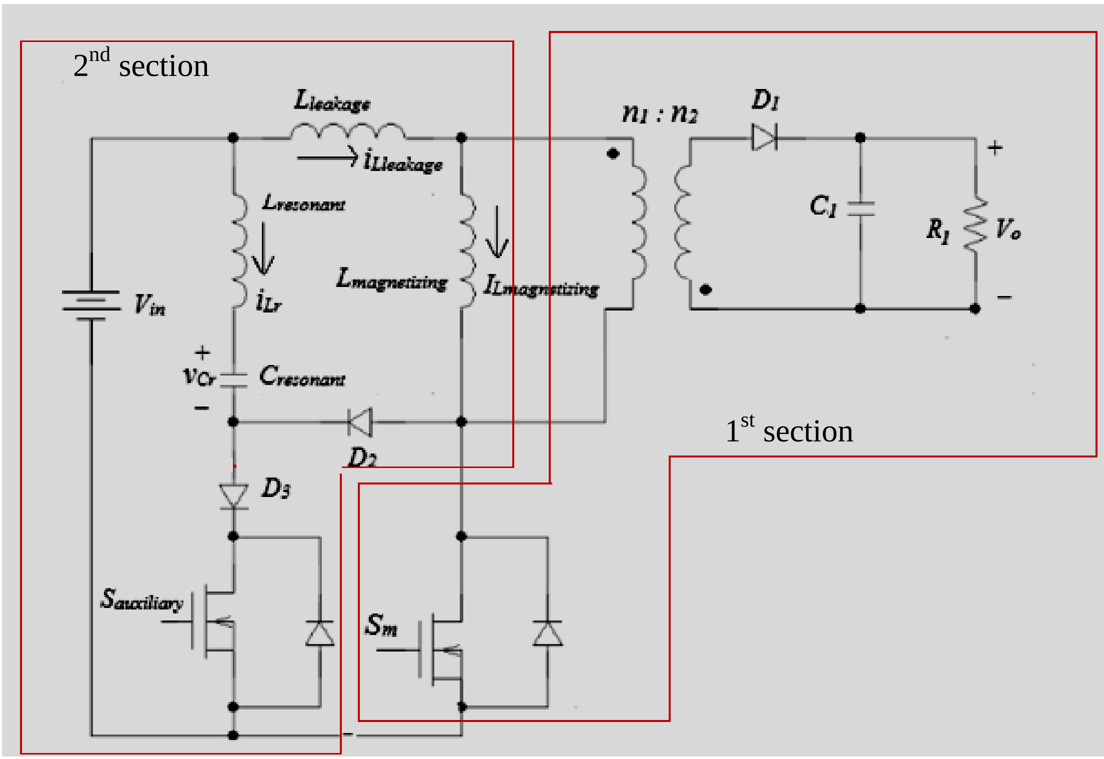

Figure 14 Example of ZCS in Flyback Converter

Figure 14 shows a ZCS in a flyback converter. The circuit can be divided into two sections. The first section is a conventional flyback converter. It is responsible for transferring power to the load. The converter comprises of a transformer, a switch S_m, a diode D_1 and an output filter C_o. The second section comprises of the auxiliary diodes D_2, D_3, the resonant inductor $L_{resonant}$, the resonant capacitor $C_{resonant}$, and the auxiliary switch $S_{auxiliary}$. This section is the ZCS commutation cell to provide ZCS to the switch S_m. The auxiliary switch $S_{auxiliary}$ in this section does not need the photocoupler or the pulse transformer as the isolated drive since both switches have common ground. So, the control circuit is simple [25].

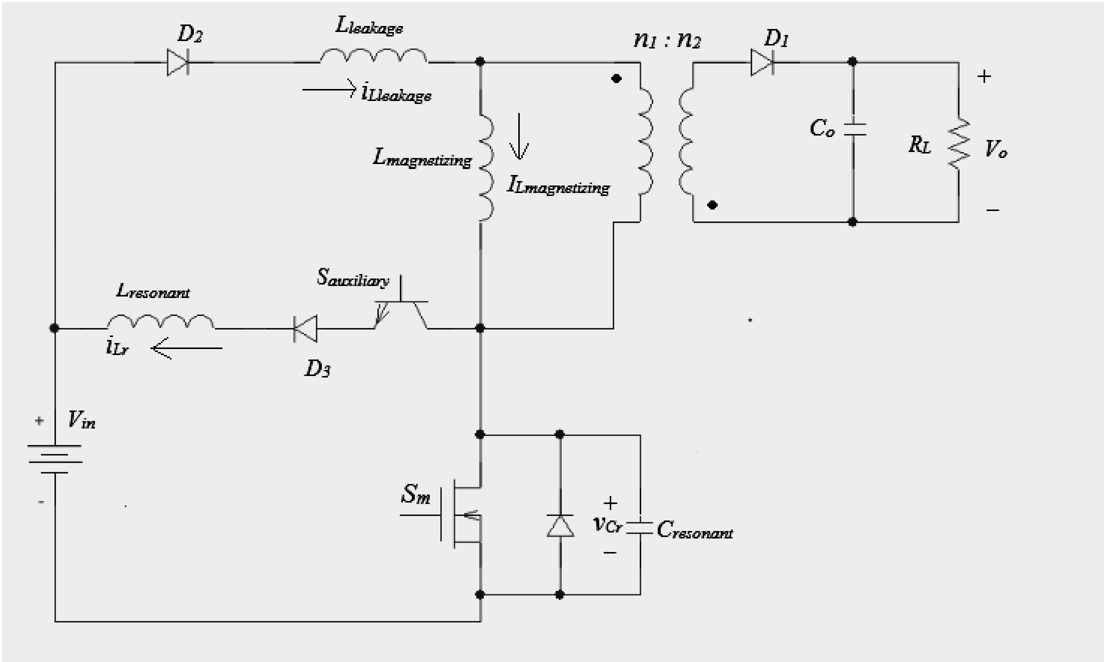

Figure 15 Example of ZVS-PWM in Flyback Converter

ZVS topology is where the switch turns on and turns off at zero-voltage. ZVS in a flyback converter is shown in Figure 15. The main switch S_m and the other semiconductor devices in the design are operated at ZVS turn-on and turn-off condition except for the auxiliary switch, $S_{auxiliary}$. The auxiliary switch, $S_{auxiliary}$, operates at ZCS turn-on and turn-off condition. The ZVS-PWM flyback DC/DC converter has no additional current stress in comparison to the hard switching flyback DC/DC converter counterpart. The energy used to assist in the ZVS operation of the S_m is not dissipated, but is instead delivered to V_{in} [26].

The power stage diagram of the proposed ZVS-PWM flyback DC/DC converter is shown in Fig. 15. The circuit can be divided in two sections. The first section is a conventional flyback converter. It comprises a main switch S_m, a diode D_1, an isolated transformer, and output filter capacitor C_o. $L_{magnetizing}$ and $L_{leakage}$ are the magnetizing inductor and leakage inductor of the isolated transformer, respectively. This section performs the operation of the conventional flyback dc/dc converter. The second section is a ZVS-PWM commutation cell to provide the zero-voltage-switching on all semiconductors in the circuit of the first section. It comprises of the auxiliary diodes

D2, D3, the resonant inductors $L_{resonant}$, the resonant capacitors $C_{resonant}$, and auxiliary switch $S_{auxiliary}$, which are rated for a small power when compared to the output power.

2.3 The Preliminary Design of the SMPS

2.3.1 Number of Output

Usually, +5 volt output is required for logic circuits, but frequently other voltage levels are required as well.

The SMPS designed will be used for multiple loads which mean the output levels will be more than one. However, regulation of all the outputs using a single converter is difficult [27].

In order to produce multiple outputs with a simple converter topology, flyback converter was chosen instead of forward converter. Besides, the arrangements of the components are simpler compared to other topologies and the output is isolated from the input. So, it is easier to design multiple outputs with flyback converter for low power applications.

However, the flyback converter is only applicable for DC input [28]. So, in order to provide DC input to the converter, the AC input must be rectified and then fed to the flyback converter.

2.3.2 Full-Bridge Rectifier.

In industrial applications where three-phase AC voltages are available, it is prefered to use three-phase rectifier circuits, compared to a single-phase rectifier, because of their lower ripple content in the waveforms and a higher power handling capability [29]. However, the rectifiers are the largest source of loss within switching power supplies [30]. So, it is important to choose the type of rectifier correctly.

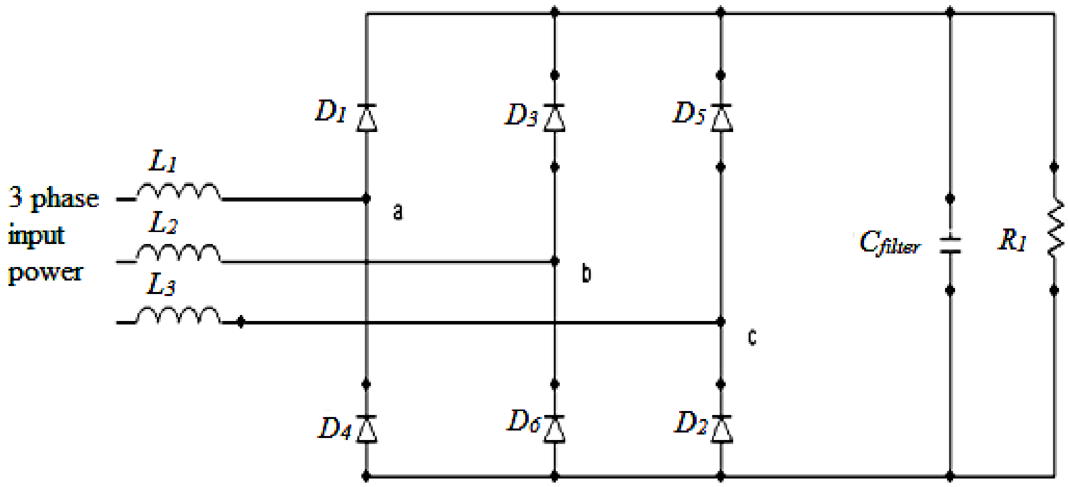

Figure 16 Three-phase full-bridge rectifier

From Figure 16, to construct a three-phase full-bridge rectifier, the number of diodes needed is 6 as for each phase there are two diodes running in positive and negative cycle respectively. As an example, when voltage at phase ‘a’ and phase ‘c’ are positive, the current from phase ‘a’ and phase ‘c’ will flow through D_1 and D_5 respectively, to the load and come back through D_6 which is at phase ‘b’.

If the voltage at phase ‘b’ and phase ‘c’ are positive, the current from phase ‘b’ and phase ‘c’ will flow through D_3 and D_5 respectively, to the load and come back through D_4 which is at phase ‘a’.

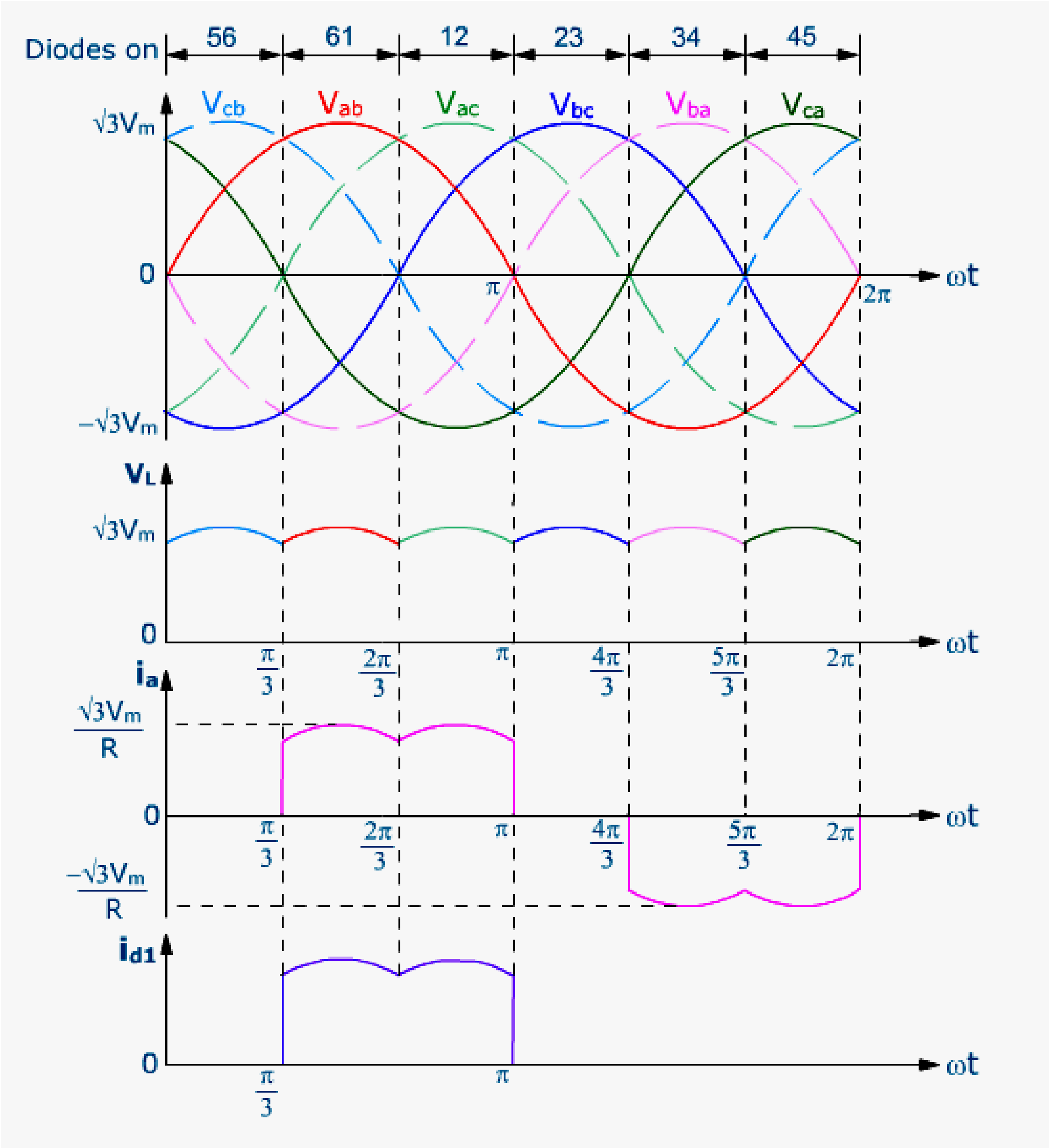

Figure 17 Three-phase full-bridge rectifier [31]

Figure 17 shows the voltage and current waveforms of three-phase full-bridge rectifier based on the circuit shown in Figure 16. V_m is the peak of the phase voltage while i_a is the phase current and i_{d1} is the current flowing through D_1. From 0 to $\frac{1}{3}\pi$, D_5 and D_6 are conducting so the load voltage is equal to the maximum voltage as shown in Eq. 3. From $\frac{1}{3}\pi$ to $\frac{2}{3}\pi$, D_6 and D_1 are conducting resulting the same voltage at the load as the maximum voltage. From $\frac{2}{3}\pi$ to π, D_1 and D_2 are conducting.

$$V_{max} = \sqrt{3}V_m \tag{3}$$

The average voltage for full-wave is as Eq. (4)

$$V_{av} = \frac{3\sqrt{3}V_m}{\pi} \tag{4}$$

where solving

$$V_{rms} = \sqrt{\frac{6}{2\pi}\int_{-\frac{\pi}{6}}^{\frac{\pi}{6}}(\sqrt{3}V_m \cos\omega t \, d(\omega t)} \tag{5}$$

yields

$$V_{rms} = [\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}]^{1/2} V_m = 1.6554 \, V_m \tag{6}$$

In this project, the load of the rectifier is the flyback transformer. So, the load is of resistance-inductance (RL) type. For RL load, the average voltage will be different as now the inductance is present.

The instantaneous output voltage of this rectifier is

$$v_L = \sqrt{3}V_m \sin\omega t \;\; for \; \frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3} \tag{7}$$

The load current can be obtained by solving the Eq. (7) below

$$L\frac{di}{dt} + Ri_L + E = \sqrt{3}V_m \sin\omega t \tag{8}$$

which results to

$$i_L(t) = \frac{\sqrt{3}V_m}{Z}\sin(\omega t - \theta) + Ce^{-(\frac{R}{L})} - \frac{E}{R} \tag{9}$$

where Z is the load impedance given by

$$Z = \sqrt{R^2 + \omega^2 L^2} \tag{10}$$

while

$$\theta = tan^{-1}\left(\frac{\omega L}{R}\right) \tag{11}$$

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

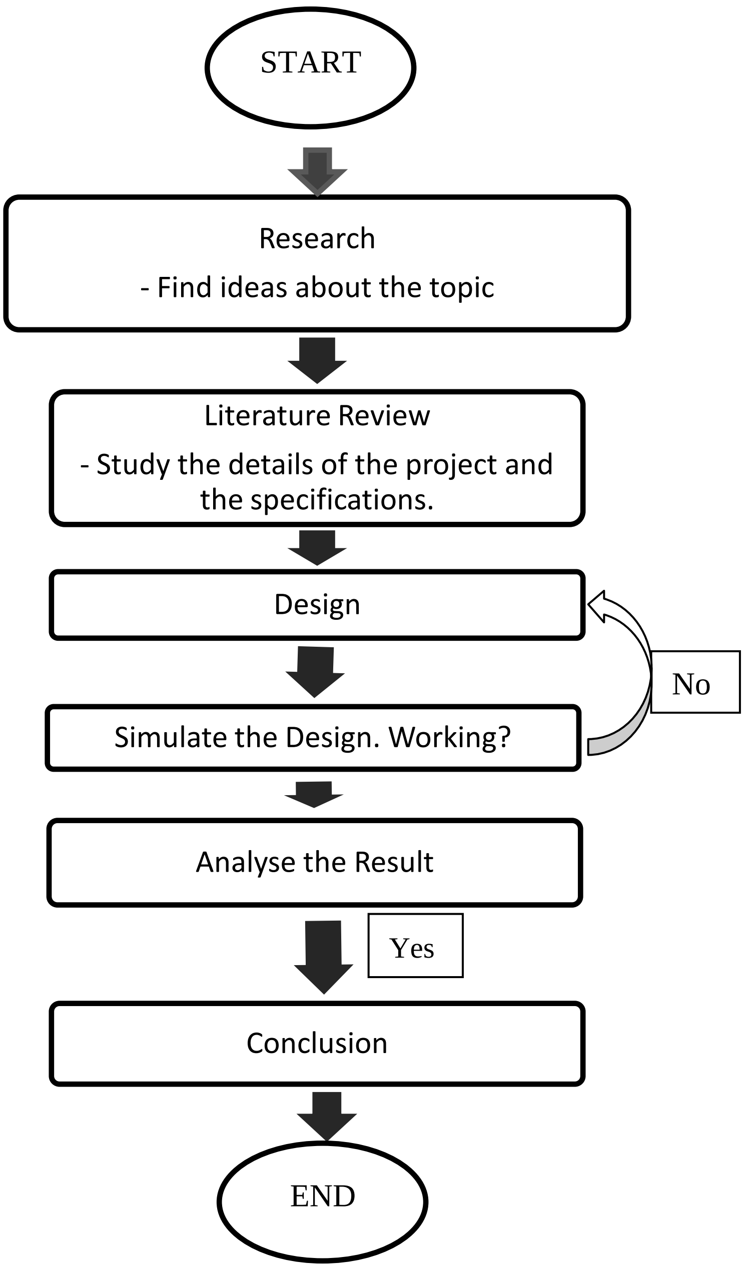

Figure 18 Research methodology flow chart

Figure 18 shows the flow chart of the research methodology for FYP1 and FYP 2. The project started by researching to find the ideas of the project title given. It is important to understand the direction of the project to make sure that the project objectives and purposes can be achieved.

After that, some important information is gathered by doing literature review. This stage is very important as it will determine the methods and solutions used in the designing process.

After that, the designing process will be commenced. Along this process, the literature still needs to be reviewed to enhance the knowledge and increase the information in order to solve the problems.

This process continues until the desired output is achieved. Once the result is obtained, it can be analyzed for conclusion.

3.2 Research and literature review

For FYP 1, the project focused on research by reading and comparing the information from the related journals and books about SMPS. Later, more literatures are reviewed to have a better understanding about it and also the protection method used.

There was a lot of information gathered about SMPS including the topologies and the suggested converter type used for multiple loads. To protect the SMPS from overvoltage and overcurrent, several methods can be used. So, the best method to implement the multiple output voltage SMPS needs to be identified.

The reading materials of the literature review consist of books and published journals and also lecture notes from a number of universities have been referred to gain some additional information. Some websites were also referred.

FYP 2 is the continuation of FYP 1 and will be focusing on designing and simulation of the designed circuit. In order to get the correct output, the value of the components used need to be calculated.

Other than that, the selection of the components will also depend on the requirement of the circuit. As an example, the diodes for the rectifying circuit must be able to withstand high voltage up to 415 V. So, from the various types of diode, only the diodes that can withstand that amount of voltage will be chosen. In order to find the most suitable components, the datasheets of the components need to be referred.

3.3 Gantt Chart

Table 2 Gantt Chart for FYP I

Details	Week												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Title selection and confirmation	■	■											
2. Preparation of extended proposal			■	■	■								
3. Extended proposal submission						■							
4. Preparation for proposal defense							■						
5. Proposal defense and progress evaluation								■					
6. Preparation for Interim report									■	■	■		
7. Draft of Interim report submission												■	
8. Improve the Interim report													■
9. Interim report submission													■

Table 2 shows the Gantt chart for FYP 1. For the first 2 weeks, the title of the project was selected and then confirmed with FYP 1 coordinator. Once the title was confirmed, 3 weeks from week 3 to week 5 was given to prepare the extended proposal to be submitted to the supervisor. The submission of extended proposal is on week 6 and the preparation for proposal defense was done on week 7. On week 8, the proposal defense was conducted and evaluated by the supervisor and also an internal examiner from Electrical and Electronics Engineering Department. From week 9 to week 11, an interim report was prepared and the submission is on week 13.

Table 3 Gantt Chart for FYP II

Details	Week																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Design the circuit and run the simulation	■	■	■	■	■	■	■	■	■	■							
2. Preparation of progress report						■	■	■									
3. Progress report submission								■									
4. Preparation for ELECTREX									■	■	■						
5. ELECTREX											■						
6. Preparation for draft report and technical report											■	■					
7. Draft of final report submission													■				
8. Final report(soft cover) and technical paper submission														■			
9. Preparation for viva													■	■			
10. Viva														■			
11. Final report (hard cover) submission																	■

Table 3 shows the Gantt chart for FYP II. It takes some times to familiarize with PSpice and for designing, even Multisim is used to run the simulation. However, due to student version of Multisim, only a limited number of components are allowed to be used for each circuit. So, Multisim is not suitable for designing a complex circuit such as the SMPS.

By using PSpice, the rectifying circuit was simulated. Started from week 6, the preparation for the progress report is done by getting the results of the simulation while doing some more research on the components to be used.

The progress report needs to be submitted on week 8 and continue on the preparation for ElectrEx that will be held on week 11. This exhibition was only for Electrical and Electronics Engineering students. For this exhibition, presentation should be done by the help of a poster and the simulation of the circuit. The evaluators will evaluate the project.

On week 11 and week 12, the students are expected to prepare the draft of final report and the technical report to be submitted on week 13. On week 14, the final report (soft cover) and the technical report are to be submitted. Viva will also be held on week 14 on 20th and 21st of December 2012. The final report (hard cover) will be required for submission on week 17 after the completion of the examinations.

3.4 Software

Throughout the project, the software like PSpice and Matlab are used to design and simulate the circuit. Matlab is needed to do the calculation of the value of the components used whereas PSpice is needed to do circuit design and simulation. Other than using PSpice, Microsim was also used. In Student Version of PSpice, the components available in the library are limited. So, in order to solve the problem, Microsim was used.

3.5 Design and Simulation

The next step after doing the literature review is the design stage. The SMPS will be divided into several parts. At first, the most important part which is the rectifying circuit will be designed. The designed circuit will then be simulated to get the output. Meanwhile, the expected output current at the load will be calculated using the formula of 3-phase full-bridge rectifying circuit with RL load given by Eq. 9. The ampere-turns at primary and secondary winding are the same.

3.5.1 Rectifying circuit

Figure 19 shows the designed circuit for rectifying circuit. The output of this circuit will later be connected to the flyback converter. So, the rectified voltage from the rectifier can be controlled by using DC-DC converter. The simulation is done for a 3 phase full-bridge rectifier with the line-to-line voltage of 415 V and phase voltage of 240 V as shown in Table 4.

By knowing the input voltage is 240 V, the diodes used for the rectifying circuit should able to handle a minimum of 240 V.

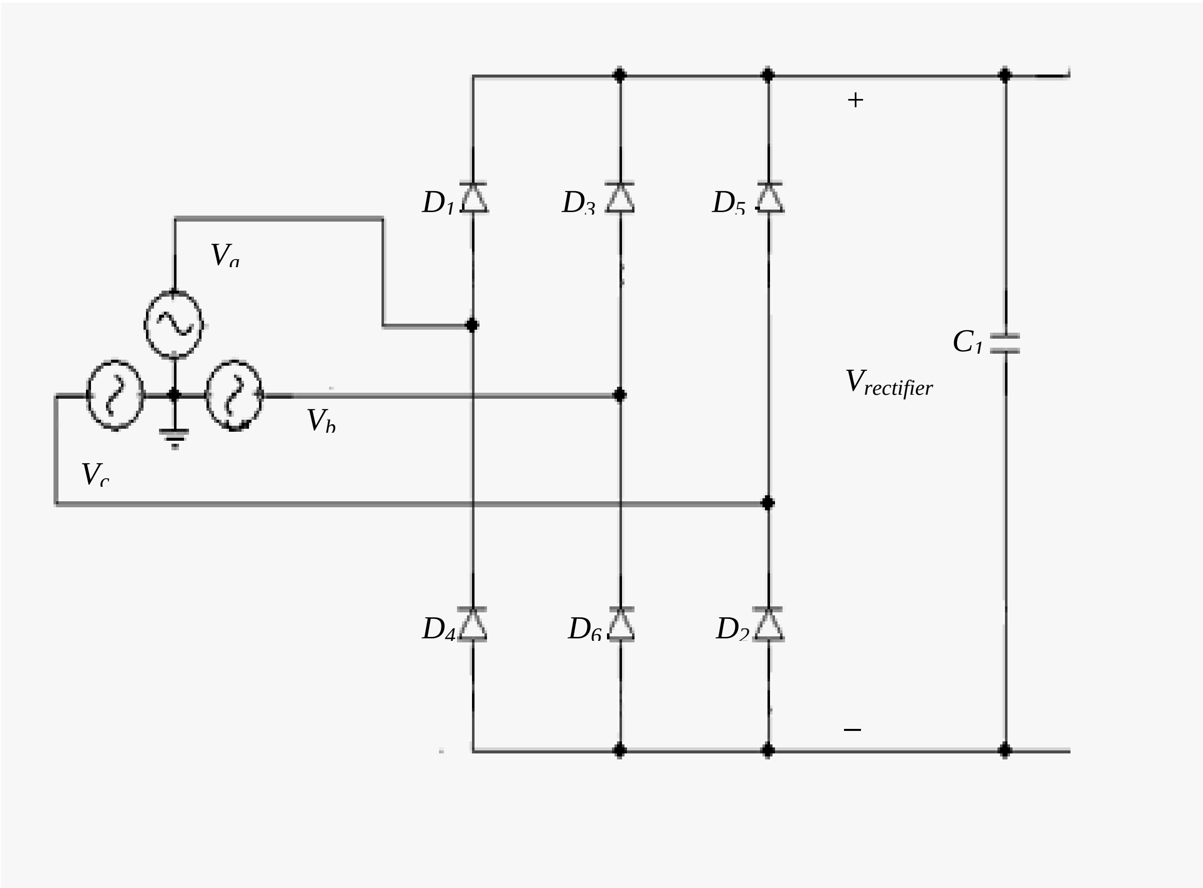

Figure 19 The Basic Rectifier Circuit

Table 4 shows the parameters for the circuit in Figure 19. The voltage sources are made to be 120^0 apart from each other in order to create 3-phase input.

Table 4 The Parameters of the Rectifier

Components	Parameters		
Voltage source(VA, VB, and VC)	Type : VSIN	Frequency = 50Hz	Vamp = 240V
Diodes	Type : 1N3900		

3.5.2 The Combination of Rectifier and Flyback Converter.

Figure 20 shows the rectifying circuit was combined with a single output flyback converter. From this single output, the three outputs of the power supply will be derived. This method is used due to the unavailability of a transformer with three secondary windings in PSpice. The transformer shown in Figure 20 is the main transformer used for controlling the output of the flyback transformer. The maximum output voltage for the application of this SMPS is 24 V. So, as long as the voltage at the secondary winding is more than 24 V then it is acceptable. Therefore, the output of the converter at this stage is made to be halved of the input voltage.

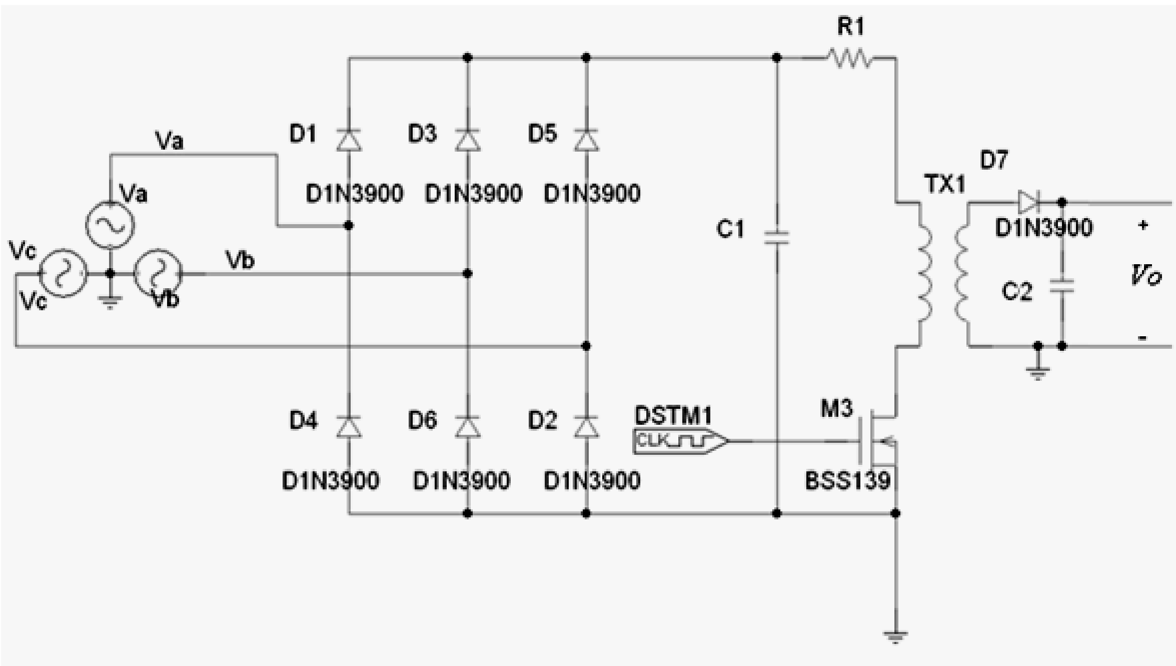

Figure 20 The Rectifying Circuit with the Flyback Converter.

Table 5 contains the parameters used for the circuit in Figure 20. Circuit in Figure 20 is the continuation of the circuit in Figure 19. So, some of the design parameters are already stated in Table 4 and are not going to be stated in Table 5.

Table 5 The Parameters of the Rectifier and the Converter

Components	Parameters		
C1	Value = 0.1F		
C2	Value = 10uF		
R1	Value = 10Ω		
M3	D = 0.5	T_{ON} = 5ms	T_{OFF} = 5ms
Transformer, TX1	Coupling = 1	L1 = 1H	L2 = 1H
Diodes	Type = D1N3900		

The value of the filter capacitor is calculated using the formula

$$Q = CV \qquad (12)$$

where Q = charge , C = filter capacitor size and V = voltage drop

$$Q = \int I\, dt \qquad (13)$$

Where I = current and t = time.

So, by solving the integral in Eq. (13), the result is

$$Q = It \qquad (14)$$

Therefore, by equating the charge, Q in Eq. (12) and Eq. (14), the value of the capacitance is

$$C = \frac{It}{V} \qquad (15)$$

The magnetizing inductance of L_1 and L_2 of the transformer were made to be the same in order to make the calculations of the impedance become easier as the ratio of L_1 and L_2; N_1:N_2 is 1.

From the circuit in Figure 20, when the switch, M3 is on, only the circuit at the primary side of the flyback transformer, TX1 is operating. So, the value of the resistor, R1 is calculated based on this operation. At steady state condition, where the DC voltage from the rectifier is steady, the capacitor C1 can be considered as open circuited as it is fully charged. So, only the resistor, R1 and inductor of primary winding, L2, will be considered for the calculation.

By using the equation

$$V = IZ \tag{16}$$

where

$$Z = R1 + \omega L1 \tag{17}$$

the value of R1 and L1 will be obtained.

The switch that controls the operation of the converter is controlled by a clock, DSTM1. The values of the components were calculated and chose to be suitable for the operation of the SMPS.

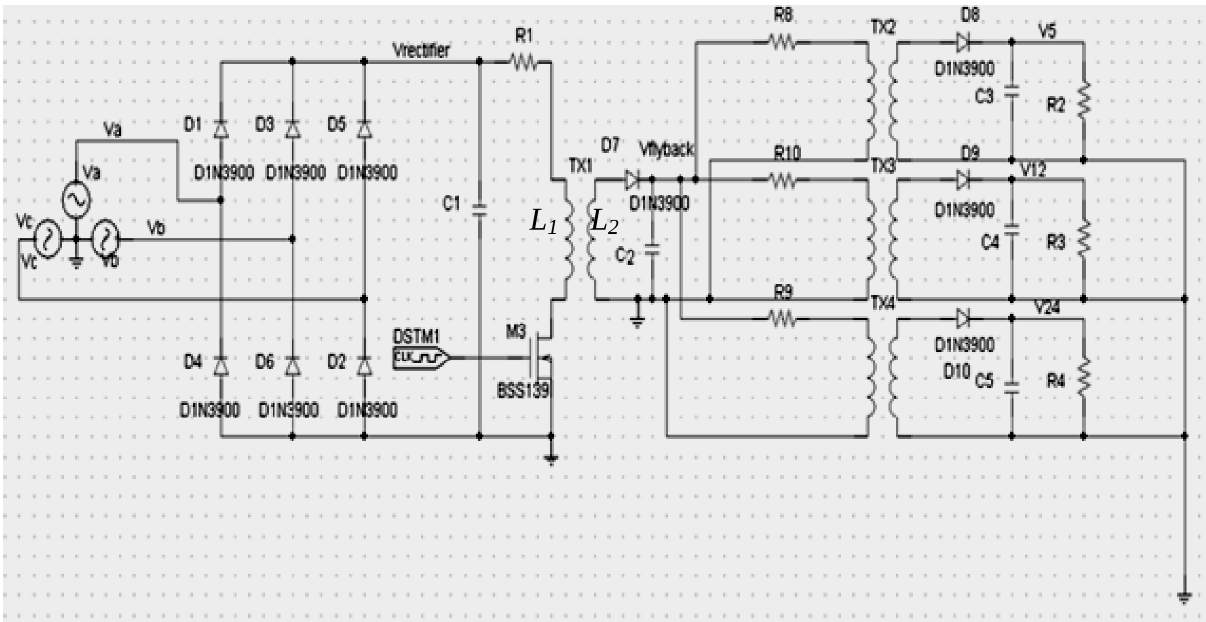

Figure 21 The Rectifying Circuit with Three Outputs of Flyback Converter.

Figure 21 shows the combination of the rectifier with the flyback transformer. The output voltage of the transformer is then cascaded with three similar transformers in order to obtain three different output voltages. The turns-ratio of all three transformers were made to be the same whilst the filter capacitor and the resistance at the output were calculated to get three different outputs.

The value of C3, C4 and C5 were calculated using Eq. 12, 13 and 15 whilst the value of R2, R3, and R4 were calculated using Eq. 16 and 17.

The parameters of the circuit in Figure 21 are available in Table 6. However, some of the parameters are already stated in Table 4 and Table 5. So, they are not stated in Table 6.

Table 6 The Parameters of the Converter

Components	Parameters		
Capacitor	C3: Value = 900uF	C4: Value = 1000uF	C5: Value = 900uF
Resistor	R2: Value = 67	R3: Value = 230 Ω	R4: Value = 970 Ω
	R8: Value = 600Ω	R9: Value = 600Ω	R10: Value = 600Ω
Transformer, TX2, TX3, TX4	Coupling = 1	L1 = 1H	L2 = 1H
Diodes	Type = D1N3900		

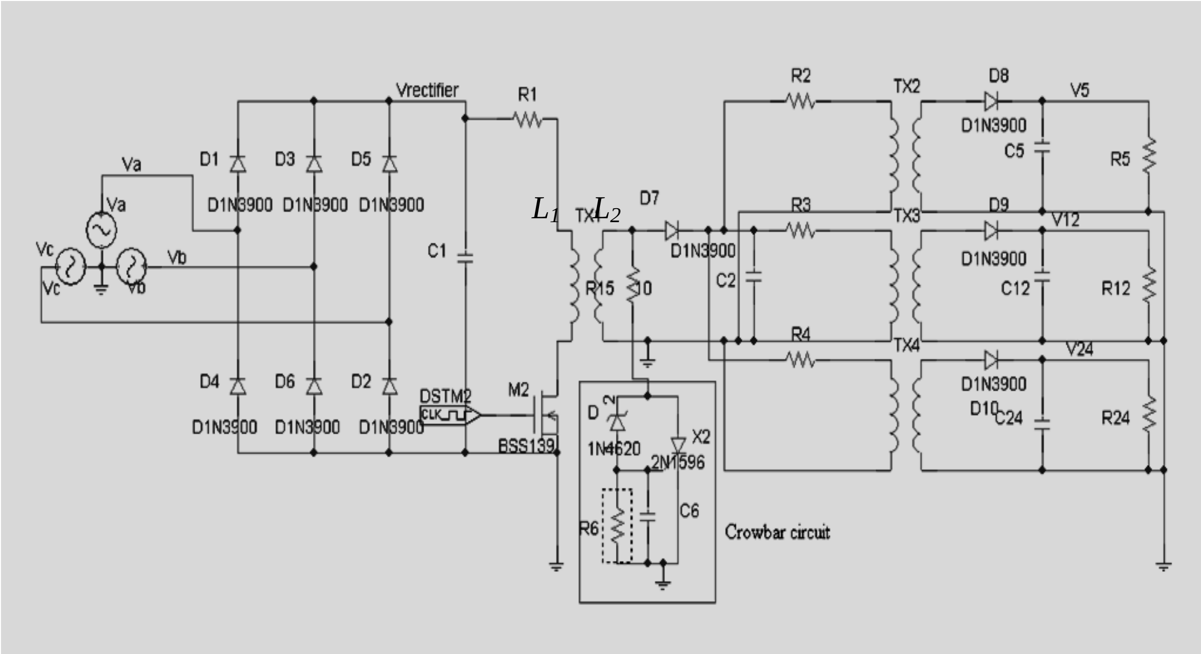

Figure 22 The SMPS with Overvoltage Protection

Figure 22 is the combination of previous circuit with a crowbar circuit to protect the SMPS from overvoltage. The crowbar circuit is connected in parallel with the circuit at L_2 of main transformer, TX1. Table 7 contains the details and the parameters of the components used for the circuit in Figure 22.

Table 7 The Parameters of The Crowbar Circuit

Components	Parameters
C1	Value = 1uF
SCR, X2	Model = 2N1596
R1	Value = 10Ω
Zener Diode, D	Type = 1N4620

CHAPTER 4
SIMULATIONS RESULTS AND DISCUSSIONS

In this chapter, the results of the simulations will be discussed. The results will be divided into two sections which are result of the power supply and result of the protection circuit.

4.1 Results of the Power Supply

Under this subtopic, there are two parts which are results of the rectifier and the results of the flyback converter. Once both results are obtained, the next step of applying protection circuit to the power supply will be done.

4.1.1 Results of Rectifier

Figure 23 shows the voltage of the rectifying circuit before the ripples are filtered and smoothen by the filtering capacitor.

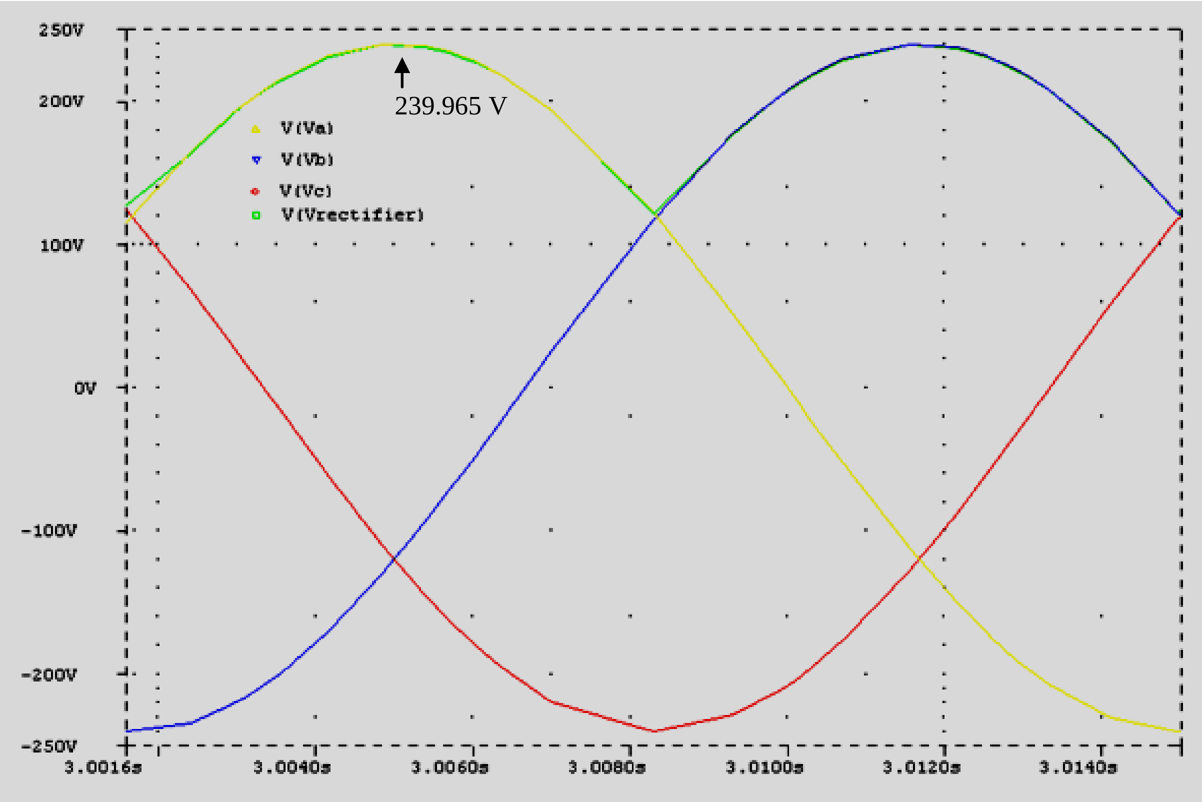

Figure 24   The source voltages and the output voltage

The output voltage of the rectifier is measured to make sure that the designed circuit operates correctly and the output of it is the same as the expected output.

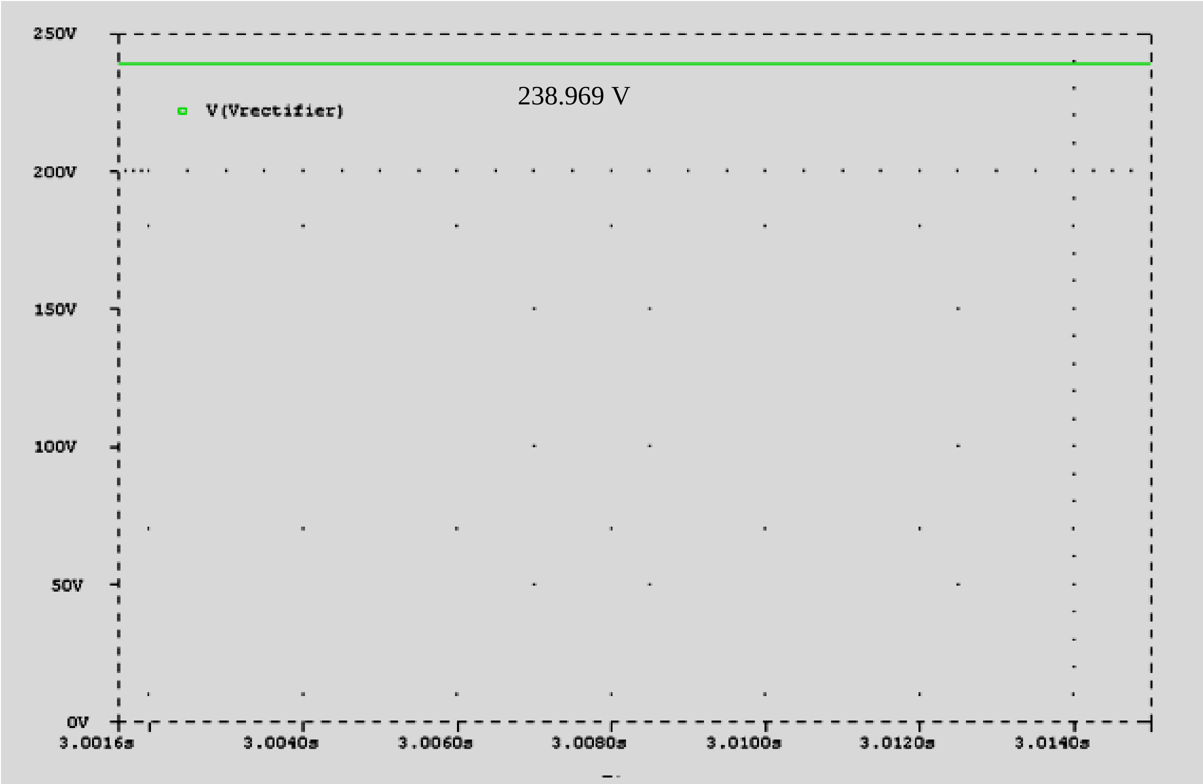

Figure 25 The Output of the Rectifier after being Filtered

With a capacitor of 0.1F, the ripples of the rectifier output can be smoothen to almost a straight line as shown in Figure 24. The capacitor size is chosen to be large enough to filter the ripples. The value of the capacitance is calculated using the equation in Eq. (14) and Eq. (15).

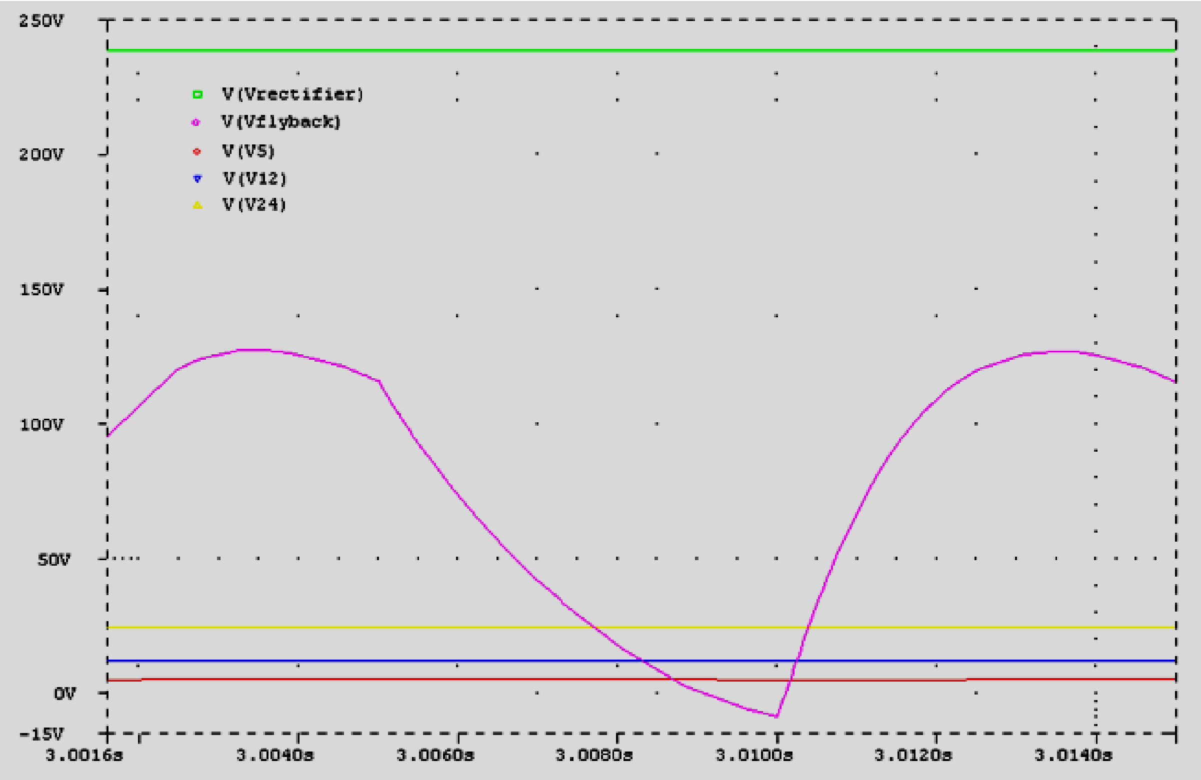

Figure 26 The Comparison of the Rectifier and Flyback Outputs.

From Figure 25, the Vrectifier is the output of the rectifier after it was filtered while Vflyback is the output of the flyback converter before the voltage is separated into three levels. V5 is the voltage waveform for the output of 5 V while V12 is the voltage waveform for the output voltage of 12 V and V24 is for 24 V output. As shown in Figure 25, the ripples of the flyback converter are quite big. However, after it is filtered after the second stage transformer, the ripples become smoother as shown in Figure 26 for 5 V, 12 V and 24 V.

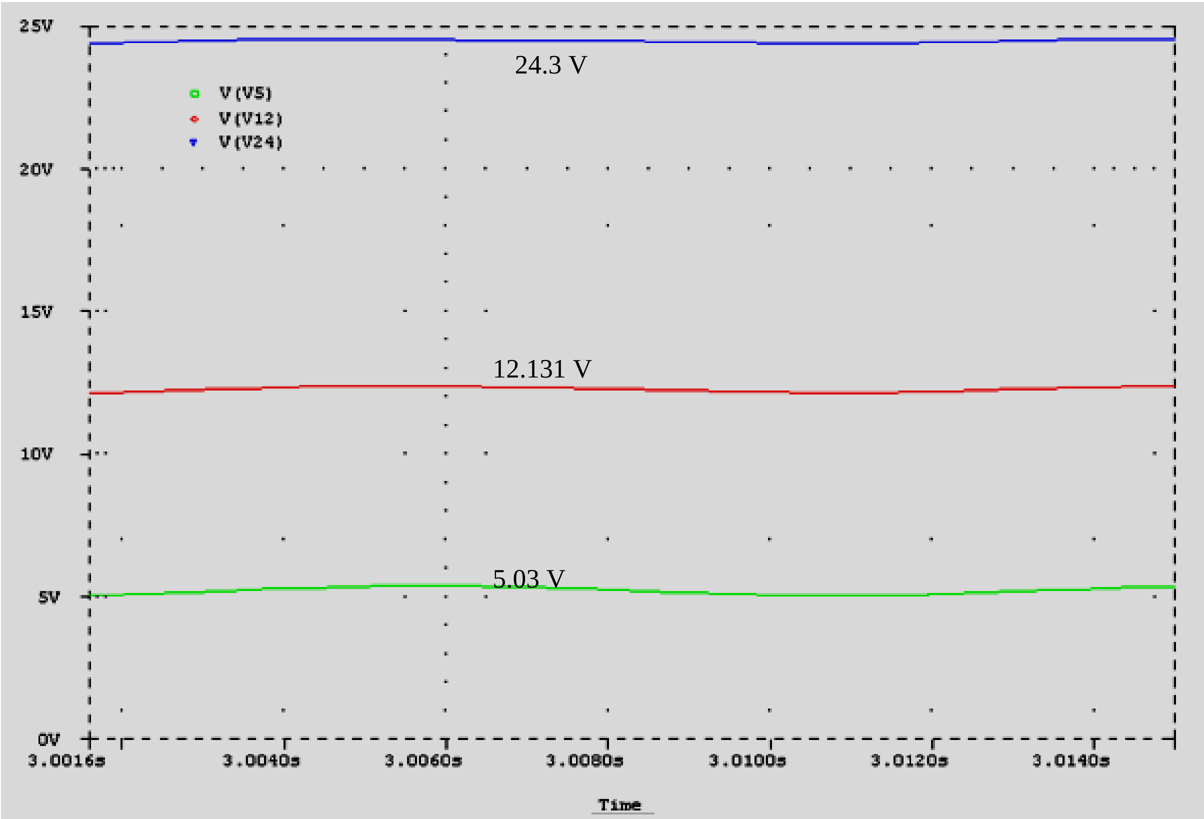

Figure 27 The Outputs of the Converter

As shown is Figure 26, the blue waveform is the waveform of 24 V output. The average voltage for 24 V output is around 24.3 V. It is good enough as it is 1.25% difference than the required voltage. The red waveform shows the voltage of the converter for 12 V output. The average of the voltage is around 12.131 V. The percentage of difference is about 1.1%. The third waveform which is in green color is the output voltage waveform for 5 V. The average voltage is 5.03 V and it is about 0.6% difference.

4.2 Results of Overvoltage Protection

Overvoltage usually occurs at the secondary winding of the transformer when the switch is on. It is because during that time, the rate of change of the voltage over time is very high.

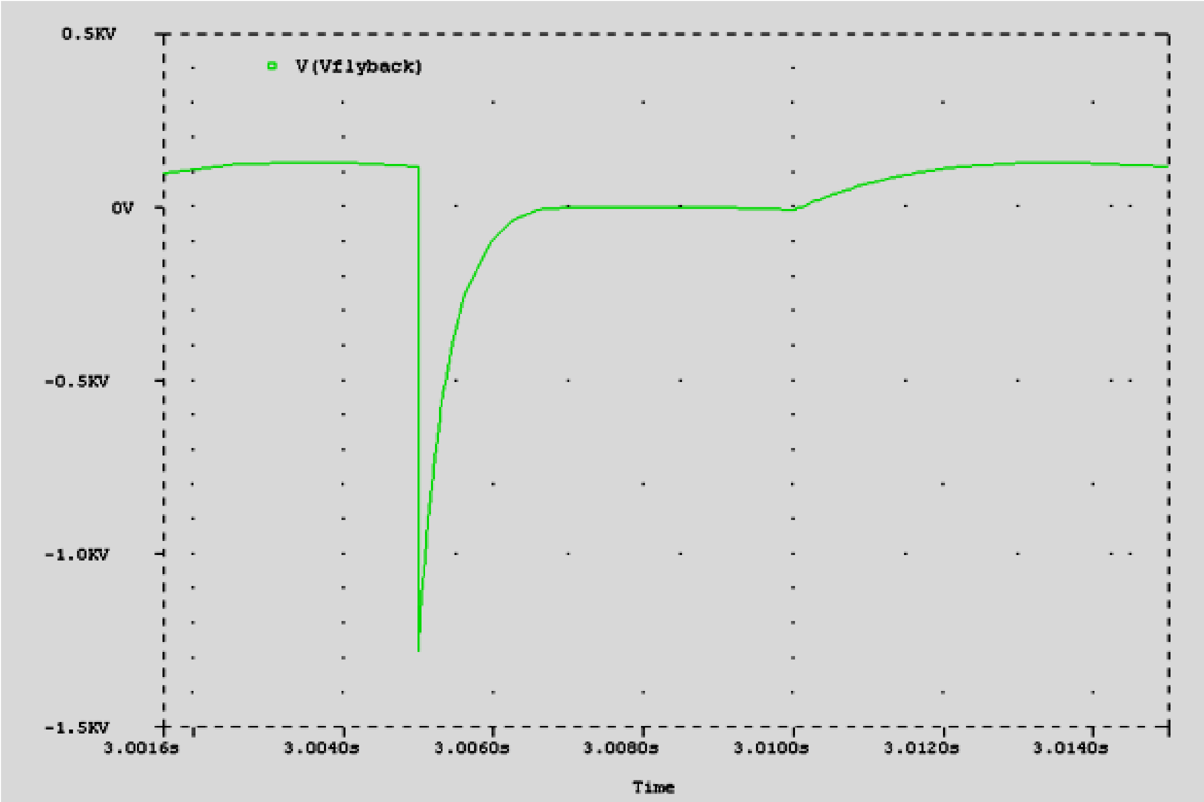

Figure 28 Overvoltage at the Secondary Winding of the Transformer before Implementing Crowbar Circuit

Referring to Figure 27, during overvoltage, the voltage might be exceeding 1kV and this much of voltage will surely damage the circuit. However, by implementing crowbar circuit at the secondary winding of the transformer, the overvoltage can be reduced to about 3V or 4V as shown in Figure 28.

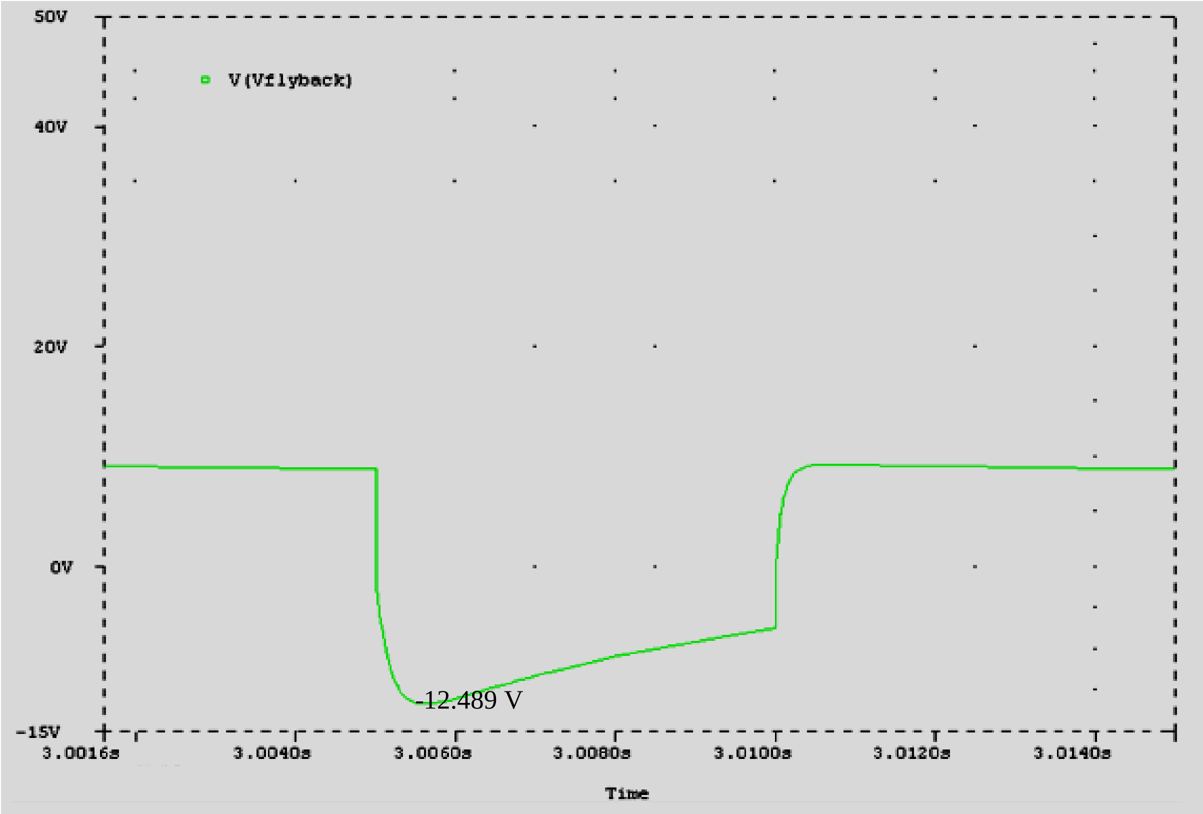

Figure 29 The Voltage at the Secondary Winding of the Transformer with Crowbar Circuit

The overvoltage is now reduced to less than 15 V. This shows that the crowbar circuit can be implemented for overvoltage protection.

CHAPTER 5
CONCLUSION

In the end, the expectation of the SMPS to have three output levels which are 5V, 12V and 24V are met. In this project, overvoltage protection is installed in AC-to-DC Switched Mode Power Supply (SMPS). The SMPS is developed by combining a 3-phase full-bridge rectifier with a flyback converter. With isolated SMPS topology, the multiple output level can be obtained by using three sets of secondary winding. The crowbar thyristor circuit is used to protect the circuits from overvoltage. After crowbar is configured to the SMPS, the overvoltage that had exceeded 240 V is reduced to 12.489 V. This shows that the crowbar circuit configured to the SMPS is working.

REFERENCES

[1] H. W. Whittington, B. W. Flynn. & D. E. Macpherson, “Switched Mode Power Supply: Design and Construction” Edition: 2. Somerset, England : Research Studies Press Ltd. 1997

[2] S. S. Ang, and A. Oliva “Power-Switching Converters”. Edition: 3. New York: CRC Press. 2010

[3] S. Singh, G. Bhuvaneswari, and B. Singh, "Multiple Output SMPS with Improved Input Power Quality" in *5th International Conference on Industrial and Information Systems, ICIIS.*, 2010, pp. 382-387. Jul 29 - Aug 01 2010.

[4] National Instrument. Linear Versus Switch Mode Power Supply. Retrieved on 31 Oct 2012 from : http://digital.ni.com/public.nsf/ad0f282819902a1986256f79005462b1/7438e77138bddf1b86256f660008e9cc/$FILE/linear_versus_switching.pdf

[5] A. I. Pressman, K. Billings & T. Morey, “Switching Power supply Design” Edition: 3. USA: The McGraw-Hill Companies. 2009.

[6] I. Pool, Switch Mode Power Supply Basics Tutorial. Retrieved on 31 Oct 2012 from http://www.radio-electronics.com/info/power-management/switching-mode-power-supply/basics-tutorial.php

[7] H. B. Kotte, R. Ambatipudi, and K. Bertilsson, "High Speed Cascode Flyback Converter Using Multilayered Coreless Printed Circuit Board (PCB) Step-Down Power Transformer" in *ECCE Asia, 2011. IEEE 8th*,pp. 1856-1862, 30 May - 3 June 2011.

[8] Engineers Garage, SMPS (Switched Mode Power Supply). Retrieved on 10 Nov 2012 from http://www.engineersgarage.com/articles/smps-switched-mode-power-supply.

[9] L. Rozenblat, Electronics Infoline, SMPS Block Diagram, Basic Concepts, Theory of Operation. (15 Nov 2008). Retrieved on 10 Nov 2012 from http://www.electronicsinfoline.com/Projects/Electronics/Power_Supply_and_Battery/Switch_Mode/smps_block_diagran_basic_concepts_theory_of_operation.shtml.

[10] Sinrace Technology (Shenzhen) Co. Ltd, Advantages and Disadvantages of SMPS. Retrieved on 31 Oct 2012 from http://www.power-supply-manufacturers.com/en/knowledge-base/572-advantages-and-disadvantages-of-smps.html

[11] Engineers Garage, SMPS (Switched Mode Power Supply). Retrieved on 10 Nov 2012 from http://www.engineersgarage.com/articles/smps-switched-mode-power-supply?page=6

[12] H. S. Walter, Lecture notes for the subject of Analogue Circuit Design Switching Power Supplies. Flyback Converter. Darmstadt University.

[13] Lecture notes: Module 3. DC-to-DC Converters. Lesson 17: Types of Basic Converter, Indian Institute of Technology (IIT), Kharagpur. 2012

[14] R. Negele, (2009, November) Flyback Converter and Snubber Design : Every application has its special need. Retrieved on 10 Nov 2012 from http://negal.ch/download/BP_11_09_Negal.pdf

[15] G. Ledwig, (1998) DC-DC Converter Basic. Retrieved on 11 Nov 2012 from http://www.otherpower.com/images/scimages/1431/buck_boost_basics.pdf

[16] P. Sensarma, Lecture notes: "The Flyback Converter". Department of Electrical, Computer and Energy Engineering, University of Colorado. Computer and Energy Engineering, University of Colorado. 2011

[17] Lecture notes: Module 3. DC-to-DC Converters. Lesson 22: Flyback Type Switched Mode Power Supply, Indian Institute of Technology (IIT), Kharagpur.

[18] Buttle Winding, (2012) Flyback and Transformer Theory. [Online] Available : http://www.butlerwinding.com/store.asp?pid=28336

[19] Mouser Electronics, (2012) Power Supply Technology : Forward DC/DC Converters. [Online] Available : http://my.mouser.com/applications/power-supply-topology-forward/

[20] D. M. Bellur, M. K. Kazimierczuk, "Review Of Zero-Current Switching Flyback PWM DC-DC Converter". Wright State University. pp. 1-8

[21] Lecture notes: Module 3. DC-to-DC Converters. Lesson 23: Forward Type Switched Mode Power Supply, Indian Institute of Technology (IIT), Kharagpur.

[22] DC Power Supply Handbook, Agilent Technologies. 2000, pp. 11

[23] M. Kchikach, R. Lee, H. F. Weinner, Y. Zidani. Y. S. Yuan, and Z. M. Qian, "Study of Resonance Phenomenon in Switching Mode Power Supply (SMPS)". *IEEE Power Electronics Specialist Conference*., 2004, pp. 3016-3018

[24] J. G. Cho, J. W. Baek, C. Y. Jeaong, and G. H. Rim. "Novel Zero-Voltage and Zero-Current Switching Full-Bridge PWM Converter Using a Simple Auxiliary Circuit". *IEEE Transactions on Industry Applications*., 1999, vol. 35, pp. 15 - 20

[25] J. B.V. Reddy, G. Bhuvaneswari, and B. Singh, “A Single DC-DC Converter Based Multiple Output SMPS with Fully Regulated Isolated Outputs”. *IEEE Indicon 2005*, 2005, pp. 585 - 589

[26] C. M. Wang, J. H. Su, and C. H. Yang, "A Novel ZCS-PWM Flyback Converter With A Simple ZCS-PWM Auxiliary Circuit" in *International Conference on Power Electronics and Drive System, PEDS.*, 2005, pp. 805 - 810

[27] C. M. Wang, J. H. Su, and C. H. Yang, "A Novel ZVS-PWM Flyback Converter With A Simple ZCS-PWM Auxiliary Circuit" in *IEE Proceedings*.,2006,Vol. 153, pp. 116 - 122

[28] M. H. Rashid, “Power Electronics Circuits, Devices, and Applications” Edition:3. New Delhi: Prentice-Hall of India Private Limited.2006

[29] N. Mohan, T. M. Undeland, W. P. Robbins, “Power Electronics : Converters, Applications and Design.” Edition : 3. USA, : Wiley & Sons, Inc.2003

[30] SWITCHMODE™ Power Supply Reference Manual, ON Semiconductor. 1999

[31] R. D. Four, (2001) Three-Phase Bridge Rectifier Retrieved on 15 Nov 2012 from http://www.eng.uwi.tt/depts/elec/staff/rdefour/ee33d/s3_3pbr.html

APPENDICES

APPENDIX A

DIODES' DATASHEET

For 1N3900

Microsemi Catalog Number	Working Peak Reverse Voltage	Repetitive Peak Reverse Voltage
1N3899*	50V	50V
1N3900*	100V	100V
1N3901*	200V	200V
1N3902*	300V	300V
1N3903*	400V	400V

*Add the Suffix R for reverse polarity

App. A1 The Maximum Rating of the Diodes.

Electrical Characteristics			
Average forward current	$I_{F(AV)}$	20 Amps	T_C = 100°C, Square wave, $R_{\theta JC}$ = 1.8°C/W
Maximum surge current	I_{FSM}	225 Amps	8.3 ms, half sine T_C = 100°C
Max peak forward voltage	V_{FM}	1.40 Volts	I_{FM} = 63A T_J = 25° C*
Max peak reverse current	I_{RM}	6 mA	V_{RRM}, T_J = 150°C
Max peak reverse current	I_{RM}	50 μA	V_{RRM}, T_J = 25°C
Max reverse recovery time	t_{RR}	200 ns	I_F = 1A dc, V_R = 30V, di/dt = 25A/μs
Max junction capacitance	C_J	150 pF	V_R = 10V, f = 1Mhz, T_J = 25°C

*Pulse test: Pulse width 300 μsec, Duty cycle 2%

App. A2 The Electrical Characteristics of the Diodes.

APPENDIX B
MOSFET'S DATASHEET

For BSS 139

Maximum Ratings

Parameter	Symbol	Values	Unit
Drain-source voltage	V_{DS}	250	V
Drain-gate voltage, R_{GS} = 20 kΩ	V_{DGR}	250	
Gate-source voltage	V_{GS}	± 14	
Gate-source peak voltage, aperiodic	V_{gs}	± 20	
Continuous drain current, T_A = 25 °C	I_D	0.04	A
Pulsed drain current, T_A = 25 °C	$I_{D\ puls}$	0.12	
Max. power dissipation, T_A = 25 °C	P_{tot}	0.36	W
Operating and storage temperature range	T_j, T_{stg}	– 55 … + 150	°C

App. B1 The Maximum Rating of the MOSFET.