DOKUZ EYLUL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ON THE DESIGN OF SWITCH MODE POWER SUPPLY DESIGN

by
Buket TURAN

July, 2007
IZMIR

ON THE DESIGN OF SWITCH MODE POWER SUPPLY DESIGN

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We have read the thesis entitled **"ON THE DESIGN OF SWITCH MODE POWER SUPPLY DESIGN"** completed by **BUKET TURAN** under supervision of **ASSOC. PROF. DR. UĞUR ÇAM** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ON THE DESIGN OF SWITCH MODE POWER SUPPLY DESIGN

ABSTRACT

In this thesis, switch mode power supplies, differences between linear power supplies and switch mode power supply types are discussed. Widely used types of DC-DC converters depending on the input-output wave forms and circuit simulations using Pspice and B2 Spice are notably examined. Each type of DC-DC converter has DC input signal, switch, energy storage and filter elements. Filter elements smooth the ripple of the output. Without using filter elements, the output will be more unregulated. This is discussed by simulation of a basic type of converters. Every converter can be simulated by using a switch that is controlled by pulses. Although using filter elements, controlling the switch by pulses will comprise an unregulated output. There occur some losses because of the switching and components used in converters. To obtain more regulated output, some control circuits should be used. Pulse Width Modulation is the most important type. Some types of DC-DC converters are simulated by adding PWM control circuits. Diodes that are used in switch mode power supplies are reverse or forward biased depending on the condition of the switch. If a forward biased diode is suddenly switched to reverse bias, the conduction will continue in the reverse direction for a short interval called the reverse recovery time. Therefore, they should be selected with minimal recovery times. Ideal diode should have no reverse recovery time, but practically this can not be possible. The aim of choosing proper diode is to minimize this reverse recovery time.

Keywords: switch mode power supplies, linear power supplies, DC-DC converters, filter capacitor, pulse width modulation, diode reverse recovery

ANAHTARLAMALI GÜÇ KAYNAĞI TASARIMI

ÖZ

Bu arastırmada, anahtarlamalı güç kaynakları, lineer güç kaynakları arasındaki farklılıkları ve anahtarlamalı güç kaynakları çeşitleri anlatılmaktadır. Giriş–çıkış dalgalanma durumuna bağlı olarak çoğunlukla kullanılan DC-DC dünüştürücüler ve Pspice ve B2 Spice kullanılarak yapılan basit devre simulasyonları üzerinde özellikle durulmuştur. Her bir DC-DC dönüştürücü temel olarak DC giriş sinyali, anahtar, depolama ve filtreleme elemanları kullanılarak oluşturulmuştur. Filtre elemanları dalgalanmayı azaltmak için kullanılmıştır. Filtre elemanları olmadan çıkış daha düzensiz olarak elde edilir. Bu durum temel dönüştürücü örneğiyle gösterilmiştir. Darbe verilerek anahtarlama yapılmıştır. Filtre elemanları kullanıldığı halde darbe sinyali verilerek yapılan kontrolde düzensiz çıkış elde edilir. Anahtarlamadan ve devre elemanlarından ötürü oluşan kayıplar meydana gelir. Daha düzenli bir çıkış elde etmek için bazı kontrol devreleri kullanılmaktadır. Bunlardan en önemlisi darbe genlik modüsyonu ile kontroldür. Bazı dönüştürücü çeşitlerinin simülasyonları darbe genlik modülasyon kontrol devreleri kullanılarak yapılmıştır. Anahtarlama konumuna göre diyotlar iletim yönünde yada tıkama yönündedir. Buna bağlı olarak tıkanma süreleri olabildiğince kısa seçilmelidir. İdeal diyotta bu süre sıfırdır fakat pratik olarak bu mümkün değildir. Uygun diyot seçmenin amacı bu süreyi kısaltmaktır.

Anahtar kelimeler: Anahtarlamalı güç kaynakları, lineer güç kaynakları, DC-DC dönüştürücüler, filtre kapasitörleri, darbe genlik modülasyonu, diyot toparlanma süresi

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CHAPTER ONE
INTRODUCTION

Theory of switch mode power supplies have been known for many years until the first bipolar junction transistor was produced lately 1940s. However, usages of switching techniques were very rare in those days. In 1952 G. W. BRYAN expressed a low power high voltage DC supply using a transistor in an oscillator at flyback mode. This ensured switching power supplies to be widely used. After the production of switching power transistors in 1967, switching power supplies became more available and popular. Recently, they are the most important and effective techniques of power applications. (Steve Watkins, 1998) Switch mode power supplies are used in personal computers, television receivers, video cassette recorders, DVD Recorder**,** telephone systems, and many other varied applications requiring the conversion of signals from one format to another.

Linear and switch mode power supplies are the main types of power supplies. Switch mode power supplies can be used in high frequency applications. Also they are smaller and cheaper beside their higher efficiency. On the other hand, linear power supplies are simpler to design, and they don't produce unwanted signals. The regulating components of linear power supplies generate heat, to dissipate this heat; large heat-sinks are required**.** When the properties of power supplies are discussed, switching power supplies offer greater flexibility to the designer than linear power supplies do.

Switching power supplies topologies depending on the input-output wave forms have four types:

1) DC Input-AC Output Power Supplies:

Inverters are the power supplies, which have DC input voltage and convert this voltage to AC output voltage. Firstly, the AC supply line voltage is converted to DC voltage by using bridge and filter. After that, the voltage converted to the variable voltage that has high frequency by using the three-phase inverter bridge is connected to the load. Uninterrupted power supplies, induction heating and emergency lighting systems are some of the applications.

1) AC Input-AC Output Power Supplies:

Cycloconverters are AC Input-AC Output power supplies. The technique of cycloconversion was known in Germany in the 1930's. They are used to convert the ac power frequency to a lower or upper frequency. There is not dc stage during the conversion. Input and output of the converter can be one or three phase. They are mainly used to start the AC motors.

2) AC Input-DC Output Power Supplies:

Rectifier and off-line converters convert AC input signal to the DC output signal. Rectifiers are divided into two groups which are half wave rectifier and full wave rectifier. In an half wave rectifier, the positive cycle of the AC signal remains same and the diode is forward biased, but the negative part is eliminated and the diode in negative cycle is reverse biased. In a full wave rectifier, the circuit converts AC to DC voltage in both half cycles. On the other hand, off-line converters convert AC voltage to DC voltage directly.

3) DC Input-DC Output Power Supplies:

There are ten types of DC-DC power supplies. These are; Buck (step down),Boost (step down), Buck-Boost (inverting), Ćuk Converter, SEPIC (Single-Ended Primary Inductance Converter), Flyback Converter, Forward Converter, Push-Pull Converter, Half Bridge Converter, Full Bridge Converter. In the third chapter the characteristic properties of these converters are mentioned.

The aim of DC-DC power supplies is to obtain regulated output voltage, but finding exact output voltage is very difficult. By using some components and methods, we can obtain more regulated output voltage. Controlling the switch by pulse width modulation and using filter are some of the methods. The Pspice and B2

Spice simulations and components that effect the stabilization of output are discussed in the fourth chapter.

In the fifth chapter, reverse recovery characteristic of the diode is investigated. The reverse current and voltage of the diode is simulated. The reverse recovery time of the diode is a certain time the minority carriers require to be neutralized. Schottky diodes are chosen for DC-DC converter applications due to low recovery time. Junction capacitance is the capacitance associated with the charge variation in the depletion layer. For reverse bias condition C_J decreases with increasing reverse bias.

In the last chapter, conclusion is given.

CHAPTER TWO
DC POWER SUPPLIES

Power supply is a device used to convert the power, generally raw input power to a controlled, regulated or stabilized output power, to meet specified requirements.

A typical DC power supply is designed by using transformer, rectifier, filter and regulator. Transformer converts the AC supply voltage, typically 120Vrms, to the essential AC voltage. Rectifier converts the AC Voltage to DC Voltage. This DC Voltage has fluctuations. Filter provides an unregulated DC voltage. By using filter, fluctuation amplitude decreases. Regulator provides the constitution of full wave rectified DC voltage.

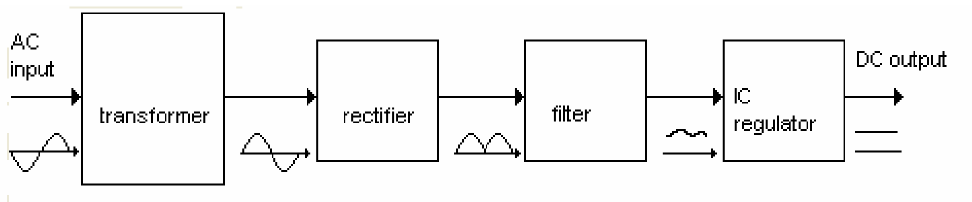

Figure2.1: Block diagram of a DC power supply

2.1 Linear Power Supplies

Linear power supplies are used to reduce the input voltage (e.g. 127V or 220V) to the proper output voltage (e.g. 12 V) with the help of transformer. They are used in low power applications like cordless phones and video games consoles. Since linear power supplies still use 60 Hz (or 50 Hz, depending on the country) frequency from the power grid, which is a very low frequency , the transformer and the capacitor sizes are very big.

Basic linear power supply is shown in the figure 2.2. In this circuit, line voltage is reduced by the transformer. Rectifier and capacitor smooth the DC voltage. Although these elements smooth the ripple at the output, there still exists a ripple at the output voltage.

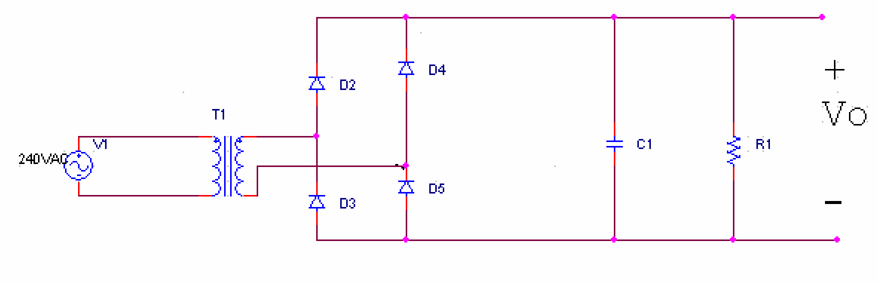

Figure 2.2 Basic Linear power supply

To reduce the ripple, some kinds of linear regulators are used as in figure 2.3. Linear regulator is a voltage regulator based on an active device (such as a bipolar junction transistor, field effect transistor) operating in its "linear region" or passive device like a zener diode operated in its breakdown region. Purpose of regulating device is to create a variable resistor effect.

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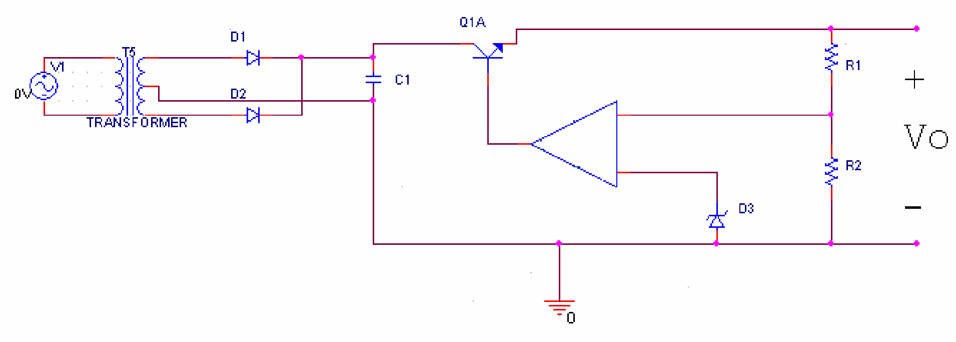

Figure2.3 Linear power supply with regulator

Linear power supplies were widely used by designers to achieve a regulated output voltage because of their simple design techniques. Nowadays, since efficiency is very important for designers and can be obtained by switched mode power supplies, linear power supplies are not popular as before because of their low efficiency.

2.2 Switch Mode Power Supply

Switch mode power supplies are used for transferring electric power from a source to a load in high frequencies. Switch mode power supplies are used as replacements for the linear power supplies when higher efficiency, smaller size or lighter weight is required. On the other hand, switch mode power supplies are more complicated to be designed. Switch mode power supplies can be classified as rectifier (ac to dc converter), inverter (dc to ac converter), chopper (dc to dc converter), and ac power controller (ac to ac at same frequency). Isolated and non-isolated power supplies are the two groups corresponding to isolation characteristics. Isolated power supplies are very important in high power and high input voltage, because of isolation; load is protected from the harmful effects of the input voltage. Isolated power supplies contain transformers, on the other hand non-isolated power supplies contains inductors.

Period of the on-off conditions that controls the switch can be adjusted by giving a pulse. But with this control, fully regulated output can not be obtained. Controlling the switch by some methods enables the output to be fully regulated as desired. These are Pulse Width Modulation (PWM), current-mode control and feed forward. PWM is the most effective technique to obtain analog electrical value or signal, which are wanted to be generated at the output, by controlling the width of the pulses that will be produced. PWM is used for controlling the converter's output voltage through feedback control of the switching transistor. Transistor operates as a switching component; it is closed and opened by PWM that uses a square wave whose duty cycle is modulated by variation of output voltage.

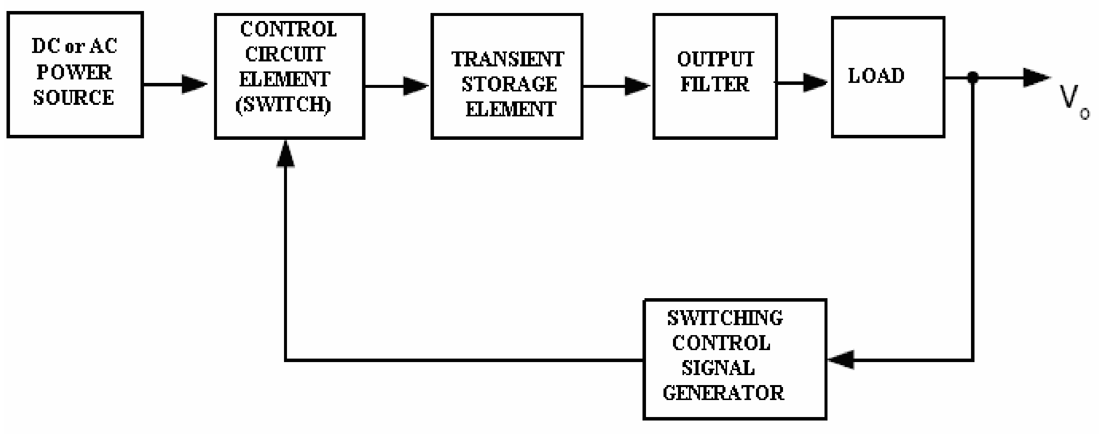

Figure2.4 Block diagram of switched mode power supply

In Figure 2.4, basic block diagram of switched mode power supply is given. Power transistors such as MOSFETs and thyristors are the examples of switching elements. Due to switching periods, storage elements such as inductor and transformer are used to store the magnetic energy and then maintain the energy to the output. Output filters are used to reduce the harmonic level to an acceptable magnitude or to smooth the output voltage level. Switching control circuit is used to reduce distortion of the output.

2.3 Differences between SMPS and Linear Power Supply

There are two main types of regulated power supplies: SMPS and Linear. The reasons for choosing a type can be summarized as follows:

Size and weight of power supplies: Switch mode power supply operates at high frequencies. As a result of operating in high frequencies, size of the transformer and electrolytic capacitor become smaller. Smaller size provides lower cost.

Efficiency and power dissipation of power supplies: Linear power supplies have big size and high initial voltage. To obtain the required output voltage, components consume the input voltage by heat. Therefore excess power, which is defined as the multiplication of the voltage drop in control component and the current flows through the component, releases as heat. Efficiency of linear power supplies is between 30 to 50 percent. On the other hand efficiency of switch mode power supplies is between 70 to 90 percent. An inefficient supply must generate more heat to obtain the same power to the load. Therefore, an SMPS will produce less heat.

Complexity of power supplies: SMPS circuits are more complicated than linear power supplies. A linear power supply circuit contains IC regulator and filter to obtain regulated outputs. On the other hand, switch mode power supplies have control elements and components in high frequency. For example capacitors must be choosen carefully because some of them have large values in circuits while operating in high frequencies. SMPSs often require the use of custom-made transformers and inductors. Transformers in SMPSs can not be connected directly to the line; they must be connected through the electronic circuit. Also, some filters are used for dissipating the noise in SMPS. SMPS’s behaviour may be significantly affected by the layout of components on the circuit board.

Radio frequency interference: Linear PSUs, generally do not produce interference and are used to supply power where radio interference must not occur (wikipedia, 2007). SMPSs produce radio frequency interference that is defined as any “unwanted” signal received by a device. In SMPS circuits; the components like inductor and capacitor generate undesirable electromagnetic interference in high frequencies. There are some methods for solving electromagnetic problems. For example, the isolation distance shouldn’t be shorter than 7mm. Sometimes slits are made onto printed circuit board to obtain the desired distance. Also some filters are used for reducing the interference.

Electronic Noise at the Output Terminals: Linear power supplies have ripple at the output in milivolts. By the help of the filter capacitor and linear regulator, this ripple can be suppressed but can not be dissipated. In contrast, SMPSs don’t exhibit ripple. Beside this, output of the SMPS generates more noise than linear power supply does.

Power Factor: Power factor is the ratio of the real power to the apparent power, and its value is between 0 and 1. Circuits containing inductive or capacitive elements often have a power factor below 1.0; generally about 0.6. Power factor is a power distribution problem. This problem occurs in SMPSs more than linear power supplies. Power factor correction (PFC) circuits can reduce this problem.

CHAPTER THREE
SWITCHING - MODE OUTPUT POWER SUPPLIES

DC to DC converters convert a DC voltage to another DC voltage level. DC-DC converters are divided into two groups depending on the isolation. Non-Isolated converters are buck (step down), boost (step down), buck-boost (inverting), Ćuk and SEPIC (single-ended primary inductance converter) converters. Isolated converter types are flyback, forward, half bridge, and full bridge converters. DC power supply and battery charger are some of the examples of DC-DC converters.

Block diagram of a basic DC-DC converter from line to the load is given in Figure 3.1. Firstly the line voltage is rectified and filtered to obtain unregulated DC voltage. This unregulated DC voltage is converted to another dc voltage level. Switching circuit is used to produce high frequency while converting. Transformer is used where isolation is needed. High frequency rectifier and filter is used to smooth the ripple at the output. Feedback control is used to obtain required exact DC voltage level.

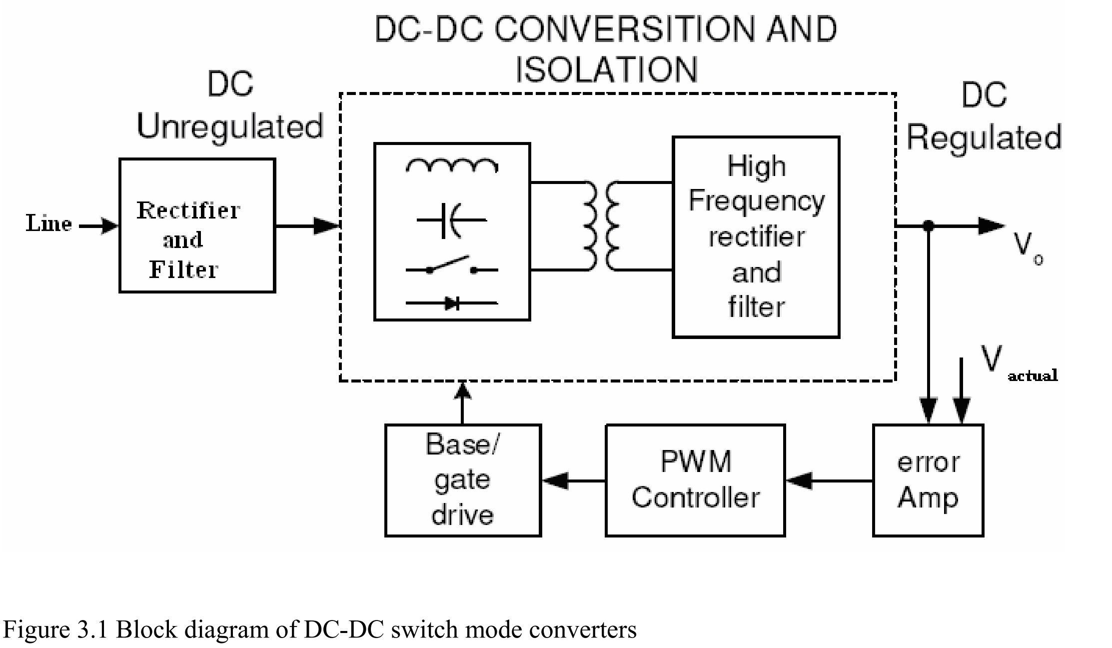

Figure 3.1 Block diagram of DC-DC switch mode converters

3.1 Buck (Step Down) Converters:

As in linear power supply, the aim of the buck converter is providing a lower output voltage. However, buck converter has higher efficiency. Buck converters are mainly used in regulated dc power supplies, dc motors and battery powered applications.

Basic circuit schematic is shown in Figure 3.2. The switch is controlled by periodic pulses. Switch has on and off conditions. When the switch is on, the current flows through the inductor. Because of the flowing current, the energy is stored in the inductor. In the off state, the storage energy discharges and inductor maintains current flow through the load. Inductor smoothes the ripple of the load current. The inductor current specifies the mode of the converter. Discontinuous mode is the situation that the inductor current reaches zero and stay zero for a short time. But when the current does not stay at zero, this is called continuous mode. The capacitor is used to reduce the ripple of the load voltage whereas the diode is used to specify the path of the current.

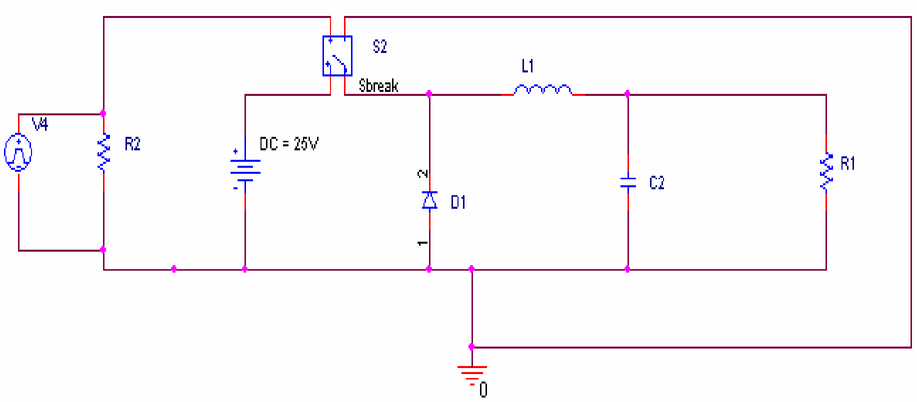

Figure 3.2 Circuit schematic of buck converter

If we assume the voltage across the capacitor and the load is constant, we can identify the voltage across the inductor;

$$V_L = V_{in} - V_o = L\frac{d_{iL(t)}}{d_t} \tag{3.1}$$

When the switch is ON, diode is reverse biased and acts as an open circuit. The inductor current increases till the end of the ON period. This increase is defined as;

$$\int_0^{t_{on}} d_{iL(t)} = \int_0^{t_{on}} \frac{V_{in} - V_o}{L} d_t \tag{3.2}$$

$$i_{L(ton)} - i_{L(0)} = \frac{V_{in} - V_o}{L} t_{on} \tag{3.3}$$

When the switch is OFF, the diode is forward biased and completes the path for the inductor's current to flow across the load. Inductor current decreases and maintains current flow till the end of the OFF period. This decrease is defined as;

$$\int_{t_{on}}^{T} d_{iL(t)} = \int_{ton}^{T} \frac{V_{in} - V_o}{L} d_t \tag{3.4}$$

$$i_{L(T)} - i_{L(ton)} = \frac{-V_o}{L}(T - t_{on}) \tag{3.5}$$

The energy stored in each component is the same at the beginning of one period and at the end of that period, because of the steady state condition. Current inductor specifies the stored energy. This causes inductor current to be the same at the beginning and end of the period:

$$i_{L(0)} = i_{L(T)} \tag{3.6}$$

$$i_{L(0)} = i_{L(t_{on})} - \frac{V_{in} - V_o}{L} t_{on} \tag{3.7}$$

$$i_{L(T)} = i_{L(t_{on})} - \frac{-V_o}{L}(T - t_{on}) \tag{3.8}$$

$$\frac{V_{in} - V_o}{L} t_{on} = \frac{V_o}{L}(T - t_{on}) \tag{3.9}$$

Duty cycle is the ratio of the on time to the period of one cycle ($D = \frac{t_{on}}{T}$). If we put DT instead of t_{on} in equation (3.9), input output relationship is then expressed as:

$$V_{in}.D = V_o \tag{3.10}$$

The output voltage depends on the duty cycle and input voltage as given by (3.10). Duty cycle can not be bigger than 1, hence output voltage is smaller than input voltage.

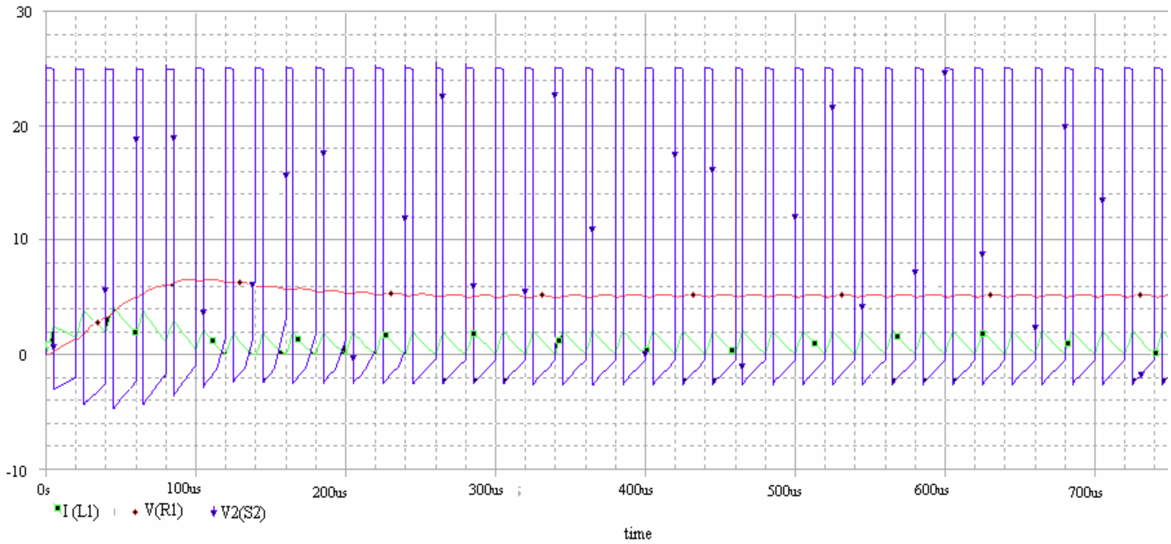

Figure 3.3 Simulation of Buck Converter

In Figure 3.3, simulation of Buck Converter is given. One period is 20µs; on period is 5µs and off period is 15µs. In theoretical result; output voltage is equal to the duty ratio multiplied by input voltage. In simulation, we obtain that the output satisfies the equation (3.10).We give 25 volt DC to the input and obtain 5.5 volt DC at the output. It is an expected result; there are some losses because of the circuit elements and diode is neglected while the mathematical equation of the output is found. Output voltage is stepped down by the circuit.

3.2 Boost (step up) Converter:

Boost converter steps up the input voltage to the desired output voltage. Basic boost converter has the same components like buck converter, but the configuration is different to obtain greater output voltage than input voltage. Beside, capacitor is used as a filtering element.

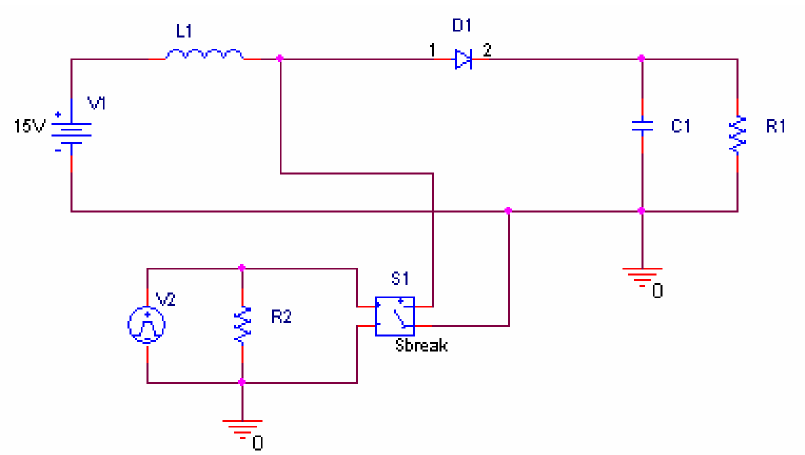

Figure 3.4 Circuit Schematic of Boost Converter

A basic schematic of boost converter is shown in Figure 3.4. As in boost converter, when the switch is on, the current through the inductor increases and the current is stored as magnetic flux. During the on period diode is reverse biased to isolate the output stage. Capacitor provides current to the load during on state. The increase of the inductor's current during the on period is equal to:

$$\int_0^{t_{on}} d_{i(L)} = \frac{V_{in} d_t}{L} \tag{3.11}$$

$$i_{L(on)} = \frac{V_{in}.t_{on}}{L} \tag{3.12}$$

When the switch is off, the inductor is discharging and the current flows through the diode and load. The current of inductor while discharging is defined as:

$$\int_{t_{on}}^{T} d_{i(L)} = \frac{(V_O - V_{in}) d_t}{L} \tag{3.13}$$

$$i_{L(off)} = \frac{(V_o - V_{in})T}{L} - \frac{(V_o - V_{in})t_{on}}{L} \tag{3.14}$$

In continuous mode sum of the current at the beginning and the end of one period is equal to zero:

$$i_{L(on)} + i_{L(off)} = \frac{V_{in}.t_{on}}{L} + \frac{(V_o - V_{in}).T}{L} + \frac{(V_o - V_{in})t_{on}}{L} = 0 \tag{3.15}$$

Substituting $t_{(on)} = D.T$ yields:

$$\frac{(V_o - V_{in})T}{L} - \frac{V_o.D.T}{L} = 0 \tag{3.16}$$

$$V_O = \frac{V_{in}}{(1-D)} \tag{3.17}$$

Equation (3.17) shows that the output voltage is greater than input voltage since the duty cycle is always smaller than 1. In figure 3.5, simulation of a basic boost converter is given. As it is seen in figure, output voltage is approximately 17 volt and when on period is 4µs and input voltage is 15 volt. There are some differences between theoretical and simulation results. Some losses occur by switching and component's characteristics. Also diode voltage is neglected in mathematical expression.

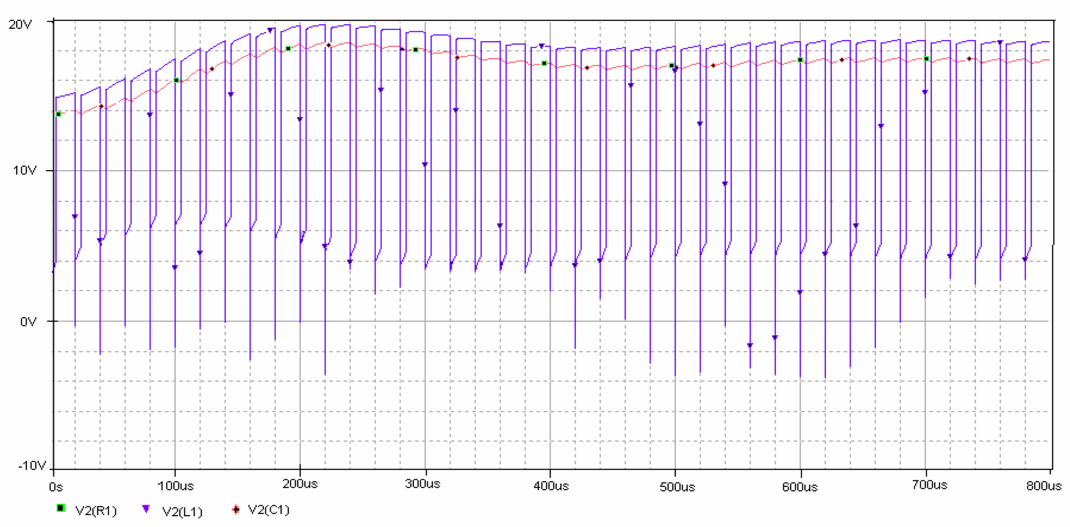

Figure 3.5 Simulation of Boost Converter

3.3 Buck-Boost (inverting):

Buck-Boost converters are used both for step up and step down applications. Duty cycle of the switching transistor identifies the output voltage. Duty cycle changes between 0 and 1. For a duty cycle under 0.5, the conversion works in step down mode;

for a duty cycle over 0.5, the converter then operates in the step up mode. We assume the diode is ideal.

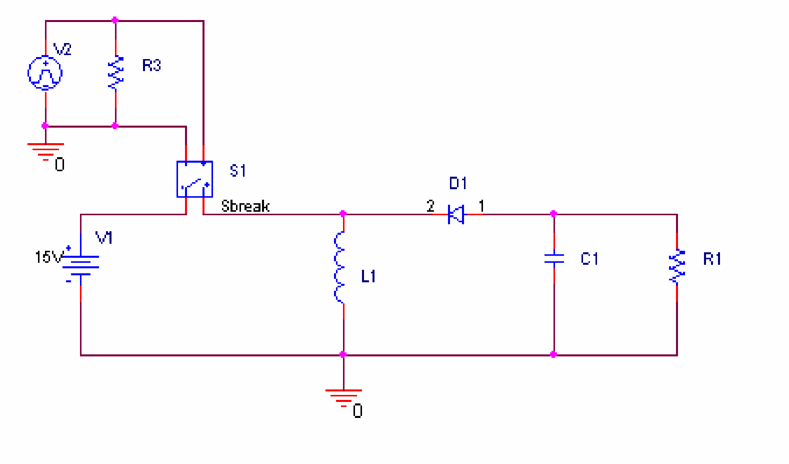

Figure 3.6 Circuit Schematic of Buck-Boost Converter

As in buck and boost converters, the switch has on and off conditions and controlled by periodic pulses. When the switch is on, diode is reversed biased. The current flows through the inductor and energy is stored by the inductor. By the effect of the diode reverse biased condition, the current depending on the input voltage does not flow through output load, only the capacitor supplies the energy through the output load. The voltage across the inductor is equal to the input voltage for the on condition;

$$V_{in} = V_L = \int_0^{t_{on}} L \frac{di}{dt} \tag{3.18}$$

$$i_{t_{on}} - i_0 = \int_0^{t_{on}} \frac{V_{in}.dt}{L} = \frac{V_{in}}{L} t_{on} \tag{3.19}$$

When the switch is off, diode is forward biased. The stored energy of the inductor is discharged and the inductor's current flow through the load. The voltage across the inductor is equal to the output voltage;

$$V_o = V_L = \int_{t_{on}}^{T} L \frac{di}{dt} \tag{3.20}$$

$$i_T - i_{t_{on}} = \int_{t_{on}}^{T} \frac{V_o.dt}{L} = \frac{V_o}{L}.T - \frac{V_o}{L}.t_{on} \tag{3.21}$$

The inductor's current is the same at the beginning and end of one period, consequently the total variation of the current must be zero. Substituting $t_{(on)} = D.T$ after equalizing the total current to zero yields:

$$i_T - i_{t_{on}} + i_{t_{on}} - i_0 = 0 \tag{3.22}$$

$$\frac{V_o}{L}T - \frac{V_o}{L}DT + \frac{V_{in}}{L}DT = 0 \tag{3.23}$$

$$V_o = -\frac{V_{in}D}{(1-D)} \tag{3.24}$$

Buck-Boost converter's polarity is differing from output to input. While the input voltage is positive, the output voltage is negative.

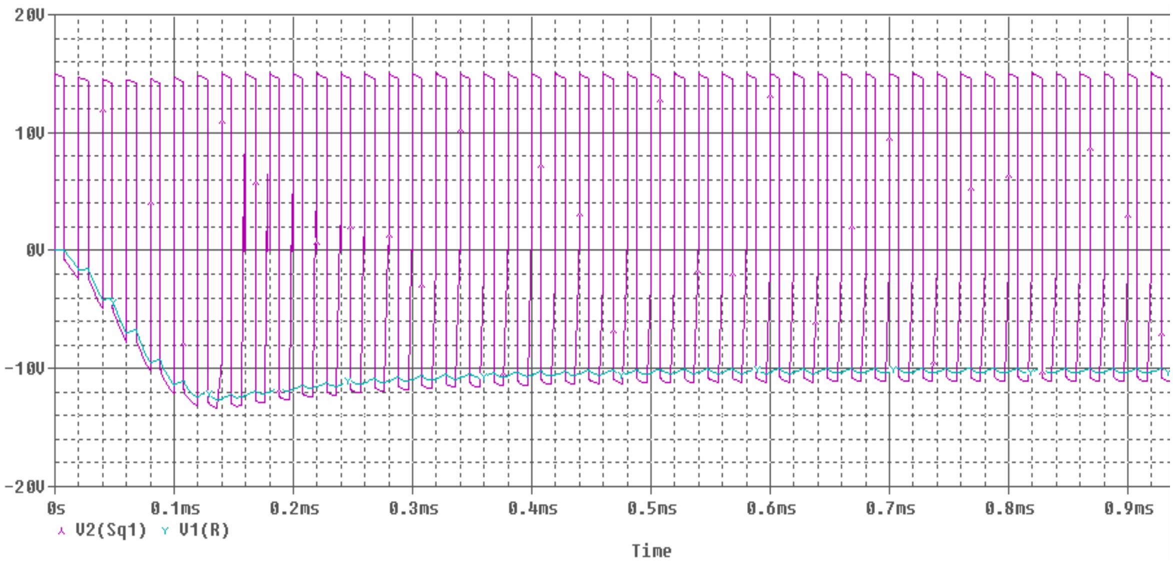

Figure 3.7 Simulation of Buck-Boost Converter

Simulation of basic Buck-Boost converter is shown in Figure 3.7. When 15 volt DC input voltage is applied, we obtain approximately 10.7 volt DC with negative polarity. Magnitude of output voltage is smaller than input voltage. Time of on period is 8μs, which is smaller than the half of the total period. This buck-boost converter is operating as a step down converter. If we calculated output by using the equation (3.24), we obtain -10volt. Theocratic result is obtained by neglecting the diode, hence they are compatible.

3.4 Ćuk Converter:

Like buck-boost converter, Ćuk converter's output voltage magnitude can be either greater than or less than the input voltage magnitude depending on the duty cycle. It is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design of this converter. This converter has minimum ripple by the effect of the second capacitor and inductor. In other words, these elements are used for amplifying the effect of filtering.

There are two operation modes in Ćuk converters depending on the switch condition. When the switch is on, first inductor is charged by the input voltage. Diode is reverse biased in this mode. The capacitive energy that is stored in C_1 capacitor maintains the current flowing through the load. The voltages across the inductors during t_{on} are equal to:

$$V_{L_1} = V_{input} \text{ and } V_{L_2} = V_{out} - V_c \tag{3.25}$$

The discharge value of C_1 capacitor when the switch is on:

$$V_C = \int_0^{t_{on}} \frac{I_{L_2} dt}{C} \tag{3.26}$$

$$V_{Ct_{on}} = \frac{I_{L_2} t_{on}}{C}$$

(3.27)

When the switch is off; C_1 capacitor is charged by the first inductor and input voltage. Diode is forward biased in this mode. During t_{off} , the voltages across the inductors and capacitor C_1 are:

$$V_{L_1} = V_{input} - V_C \tag{3.28}$$

$$V_{L_2} = V_{out} \tag{3.29}$$

$$V_{Ct_{off}} = \int_{t_{on}}^{T} \frac{I_{L_1} dt}{C} = \frac{I_{L_1}}{C}(T - t_{on}) \tag{3.30}$$

For steady state condition, the net change of charge associated with C_1 of one period must be equal to zero and the energy of on condition must be equal to the off condition.

$$\frac{I_{L_2} t_{on}}{C} - \frac{I_{L_1}}{C}(T - t_{on}) = 0 \tag{3.31}$$

$$\frac{I_{L_2} DT}{C} - \frac{I_{L_1}}{C}(T - DT) = 0 \tag{3.32}$$

$$\frac{I_{L_2}}{I_{L_1}} = \frac{1-D}{D} = \frac{I_o}{I_i} \tag{3.33}$$

$$P_{in} = P_{out} \tag{3.34}$$

$$\frac{V_{output}}{V_{input}} = \frac{D}{1-D} \tag{3.35}$$

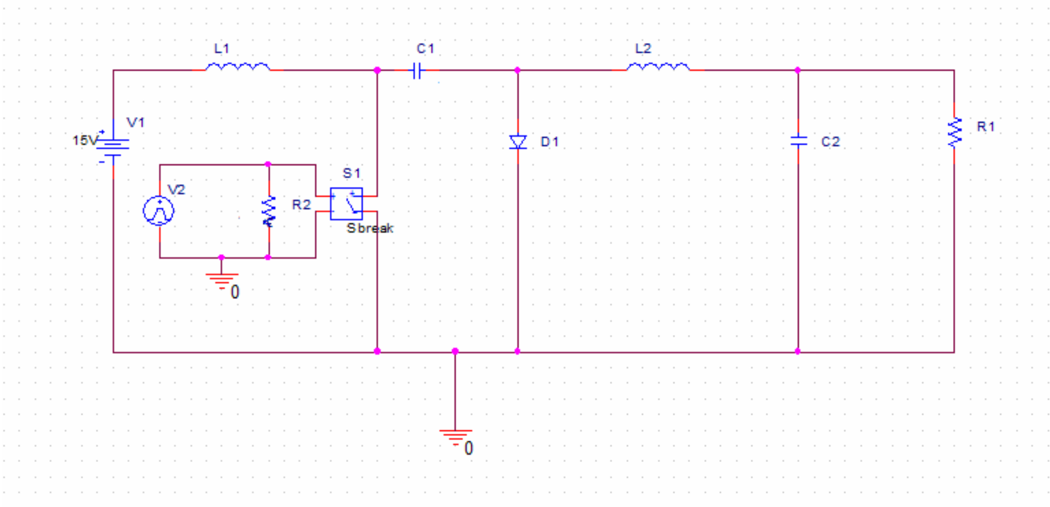

Figure 3.8 Circuit Schematic of Ćuk Converter

As it is seen in Figure 3.9 when we simulate the basic Ćuk Converter, we obtain a smaller output voltage because on period of the switch of this circuit is 3µs which is not bigger than half of the total cycle. The output is negative because of the reference polarity of the output (L2 supplies the current flow from ground through the output load).

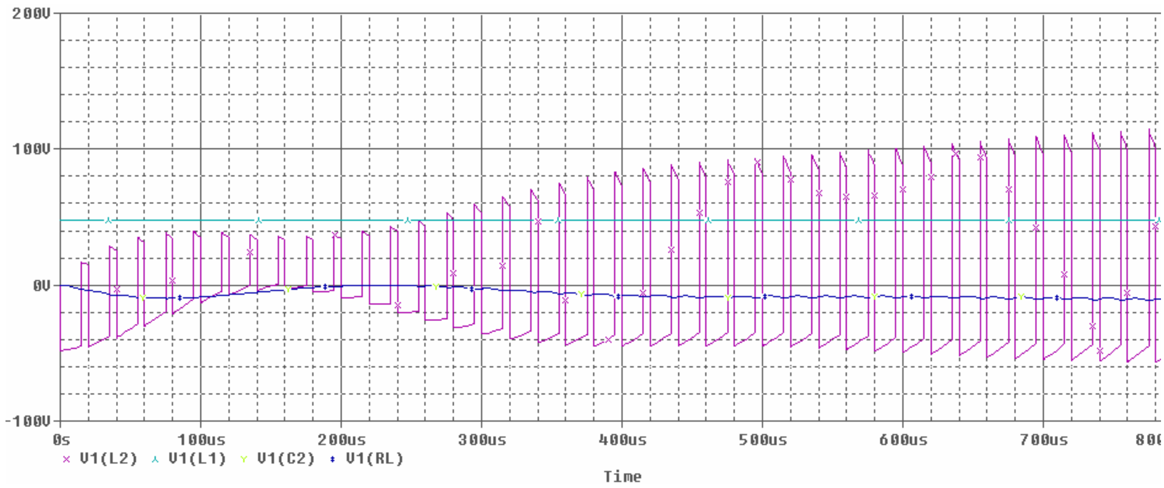

Figure 3.9 Simulation of Ćuk Converter

3.5 Flyback Converter:

This type of converter is similar to buck-boost converter, but transformer is used instead of inductor in flyback converter and also Flyback converter has galvanic isolation. They are used in cell phone charger, standby power supply in PCs, lasers, copiers etc.

When the switch is on, the energy is stored in the first winding of the transformer. Magnetic flux increases in the inductor core of the primary part during on condition. A corresponding voltage is induced at the secondary. Diode is reverse biased in this mode; hence the current passing through the load is supplied only by the capacitor. Capacitor is discharged through the load. The voltage that occurs in the first winding is described by;

$$V_{L_1} = V_{input} \tag{3.36}$$

The current flowing through the first winding in on period with an initial value at t_o is:

$$i_{L_{(on)}} = \int_{t_0}^{t_{(on)}} \frac{V_{input}}{L_1} dt \tag{3.37}$$

$$i_{L_{(on)}} = \frac{V_{input}}{L_1} t_{(on)} - \frac{V_{input}}{L_1} t_0 = \frac{V_{input}}{L_1} t_{(on)} - i_0 \tag{3.38}$$

If we assume the ripple of the voltage by choosing a large capacitor, the voltage at the output load in the on period is equal to;

$$V_{output} = i_C . R_L \tag{3.39}$$

When the switch is off, the current of the switch goes to zero and energy stored in the first winding of the transformer causes the current to flow in the secondary winding of the transformer through the diode and the load. Diode is forward bias in this mode. In the off period, if we take turn ratio of the transformer $\frac{N_1}{N_2}$, the current flowing in the first winding during off period is:

$$i_{L_{(off)}} = \frac{N_1}{N_2} \int_{t_{(on)}}^{t_T} \frac{V_o}{L_1} dt \tag{3.40}$$

$$i_{L_{(off)}} = \frac{V_o}{L_1} \frac{N_1}{N_2} t_T - \frac{V_o}{L_1} \frac{N_1}{N_2} t_{(on)} \tag{3.41}$$

The current at the end of the on period is equal to the current at the end of the off period because of the continuous mode characteristic. Therefore the initial value of the inductor core flux is equal to the end value. Then:

$$i_T = \frac{V_{input}}{L_1} t_{(on)} - i_0 - \left(\frac{V_o}{L_1}\frac{N_1}{N_2} t_T - \frac{V_o}{L_1}\frac{N_1}{N_2} t_{(on)}\right) \tag{3.42}$$

$$0 = \frac{V_{input}}{L_1} t_{(on)} - \left(\frac{V_o}{L_1}\frac{N_1}{N_2} t_T - \frac{V_o}{L_1}\frac{N_1}{N_2} t_{(on)}\right) \tag{3.43}$$

Calculating equation (3.43) by putting duty cycle D instead of the ratio of the on period to the one period:

$$V_{input}.D = V_o \cdot \frac{N_1}{N_2}(1-D) \tag{3.44}$$

$$V_o = V_{input} \cdot \frac{D}{(1-D)}\frac{N_2}{N_1} \tag{3.45}$$

This shows that in flyback converter the output is proportional to the both duty cycle and winding numbers of the primary and secondary side. If the number of turns N_1 and N_2 are very different, then the coupling between primary and secondary will be bad and this leads to a low efficiency of about 65-70%. This occurs generally at the low output voltages. If the number of turns N_1 and N_2 are approximately equal, the efficiency can be > 90% and coupling will be good.

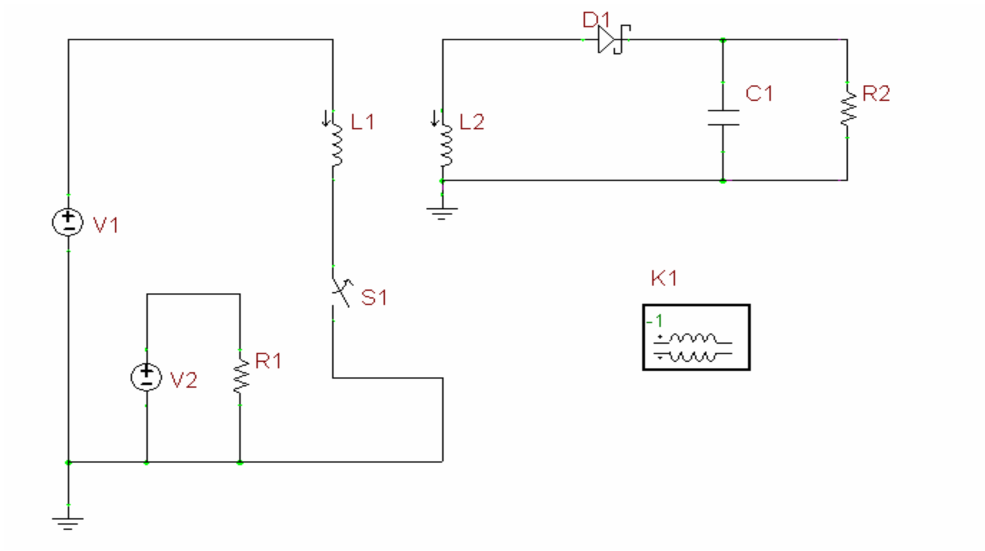

Figure 3.10 Circuit Schematic of Flyback Converter

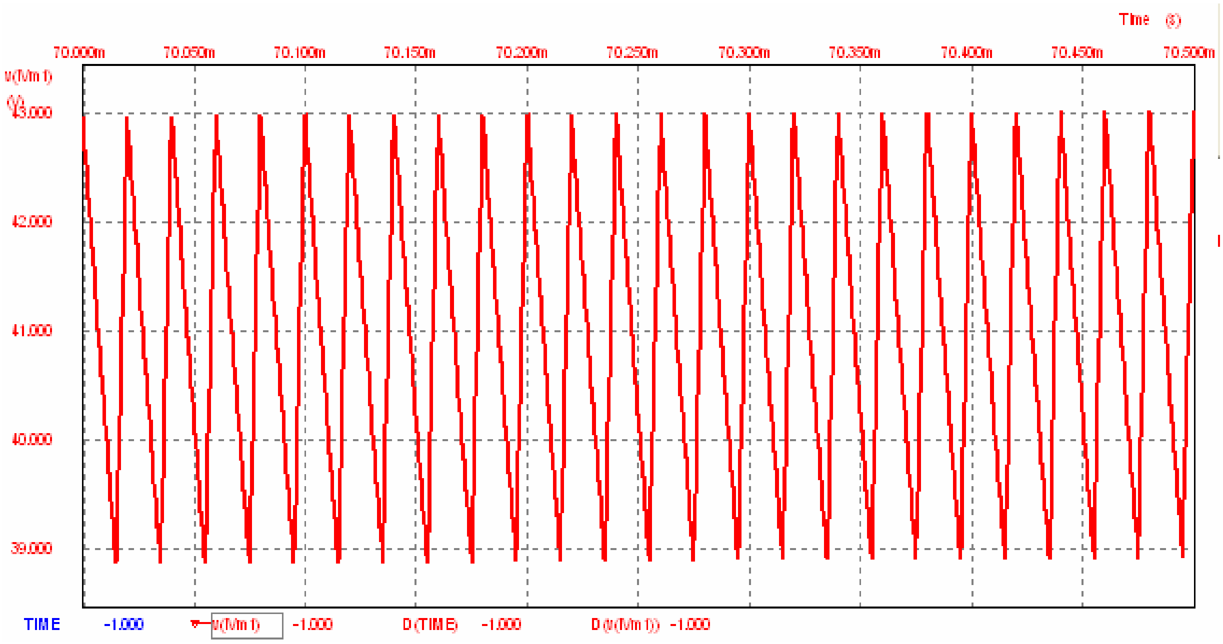

Figure 3.11 Simulation of output voltage on R_2 of flyback converter

In figure 3.11, simulation of basic flyback converter is given. In figure 3.11 the output that occurs on the resistor R_2 is given time interval between 70milisecond and 70.5 millisecond. Input is equal to 15 volt DC. Total period is 20μs and on period is 15μs. In theocratical calculation output should be 45volt DC. In simulation the output is approximately 41 volt DC. In simulation result, there fluctuations, output is not exactly regulated and it is not same with theocratical result. This difference is allowable, since efficiency, losses and diode voltage effect the output. The output can be regulated by using some more filter elements and snubber circuit.

3.6 SEPIC (Single-Ended Primary Inductance Converter):

In Single-Ended Primary Inductance Converter are used both step up and step down the voltage like flyback converter. SEPIC converter smoothes more ripple than flyback converter. SEPICs are used in battery-powered applications.

Basic schematic of SEPIC is given in Figure 3.11. Input capacitor is used to reduce the effects of the parasitic inductance and internal resistance of the power supply. C1 capacitor is used to block any DC component between input and output; as a result this capacitor isolates the input from the output. This capacitor is used to protect the circuit against a short circuit too. L1 and L2 inductors are used to store the energy during on and off periods. These inductors should have the same number of turns. If winding voltages are identical, they generate equal and additional current incline. If they are different, voltage across the two windings will differ and C1 capacitor will act as a short circuit to the difference. In addition, identical inductors tend to have lower cost than two separate inductors. Output capacitor is used to average the current pulses supplied by the diode during off period.

When the switch is on, current of the first inductor is increased. Diode is reverse biased in this period. The polarity of the C1 capacitor and second inductor are opposite. One side of the capacitor is at V_{in} and the other at 0 V because there is no Vdc across L_1

or L_2. The current of the second inductor flows through the C1. C2 capacitor supplies the current through the output. The voltage that is seen on the inductor during the on period is:

$$V_{L1_{t(on)}} = \int_{0}^{t_{on}} V_{input} d_t \tag{3.46}$$

When the switch is off, current of the first inductor flows through the C1 capacitor, the diode and the load. And the second inductor's current flows through the diode and the load. Hence, the load's current is supplied by the inductors' current. During the off period, the voltage seen across L1 inductor is:

$$V_{L1_{t(off)}} = \int_{t_{off}}^{T} (V_{out} + V_{C1} - V_{in}) d_t \tag{3.47}$$

The voltage seen across L1 during the on period is exactly compensated by the voltage seen during off period by neglecting the diode voltage:

$$V_{input}.t_{(on)} = (V_{out} + V_{C1} - V_{in})T - (V_{out} + V_{C1} - V_{in})t_{(off)} \tag{3.48}$$

By putting duty cycle instead of the time periods and the value in equation (3.46) instead of the C1 capacitor voltage we obtain this:

$$\frac{V_{out}}{V_{input}} = \frac{D}{1-D} \tag{3.49}$$

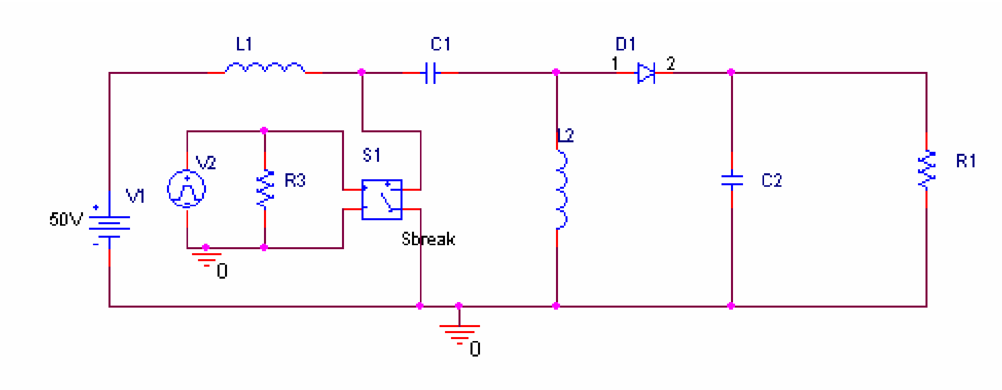

Figure 3.12 Circuit Schematic of SEPIC Converter

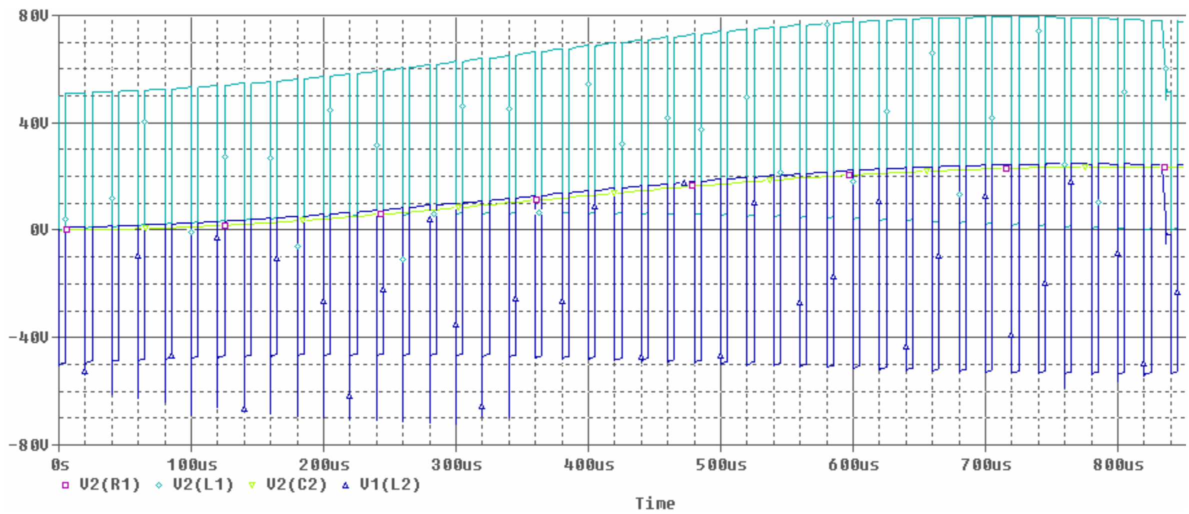

Figure 3.13 Simulation of SEPIC Converter

Simulation of SEPIC Converter is given in Figure 3.13. 50 volt DC is applied to the input. As it is calculated in equation (3.49), the output is depending on the duty ratio. On period of this circuit is 5µs. Voltages of the first inductor and second inductor are equal with reverse polarities. And the load voltage is equal to the second capacitor's voltage as it is proved in the calculations above.

3.7 Forward Converter:

This converter is similar to flyback converter. The difference is that forward converter is based on the direct converter; however flyback converter is based on the indirect converter. As a result, when the switch is on inductor stores the energy on the primary side, the storage energy in the first inductor is seen on the secondary part lossless in off period. Load maintains the current from this storage energy. D1 is forward biased and D2 is reverse biased in the on period. On the other hand, D1 is reversed biased and D2 is forward biased in the off period.

The voltage of the second inductor at the end of the on period is:

$$V_{L2_{t(on)}} = \int_0^{t_{(on)}} (\frac{N_2}{N_1}V_{in} - V_O)dt = \frac{N_2}{N_1}V_{in}t_{(on)} - V_O t_{(on)} \tag{3.50}$$

When the switch is off, the current of the inductor flows through the load, and second diode. The current flowing through the second inductor at the end of the off period is:

$$V_{L2_{t(off)}} = \int_{t_{on}}^{T} -V_o dt = -V_o T - -V_o t_{(on)} \tag{3.51}$$

The voltage of the inductor during on period is equal and has reverse polarity to the voltage of the inductor during off period to compensate the voltage.

$$(\frac{N_2}{N_1}V_{in}t_{(on)} - V_O t_{(on)}) + (-V_o T - -V_o t_{(on)}) = 0 \tag{3.52}$$

$$V_{output} = \frac{N_2}{N_1}V_{in}D \tag{3.53}$$

This result is the same with buck converter. The main difference of buck converter and forward converter is isolation. Forward converter is an isolated buck converter.

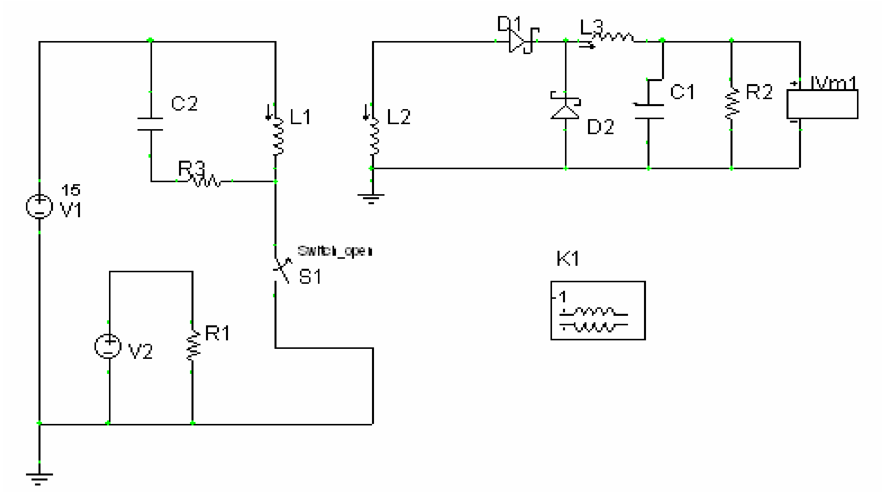

Figure 3.14 Circuit schematic of forward converter

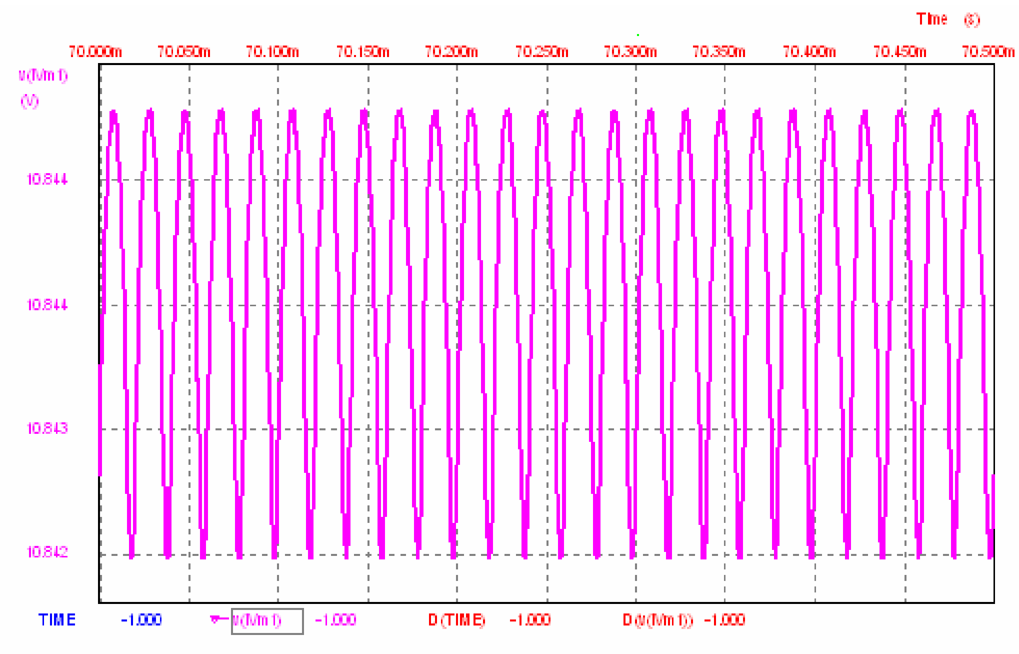

Figure 3.15 Simulation of forward converter output voltage on R_2

In figure 3.14 basic forward converter that is seen in figure 3.13 is simulated. Numbers of windings of inductors are same, and coupling coefficient is equal to -1. 15volts DC is applied to the input. Total period is 20µs and on period is 15µs. For the equation (3.53) output should be 11.25. In simulation result output is approximately 10.8volt. The difference occurs because of the voltage of the diodes. Therefore simulation result and mathematical result are similar. This shows us, that forward converter acts like an isolated buck converter.

CHAPTER FOUR
STABILITY OF DC-DC CONVERTERS

DC-DC converters are used to obtain more regulated DC outputs in required DC voltage level. There are some factors that effect this regulation. In this chapter, output capacitors and PWM controller's effect are introduced .These are simulated with Pspice.

4.1 Effect of output Capacitor

A capacitor can store energy when disconnected from its charging circuit; therefore it can be used like a temporary battery. In switch mode power supplies, due to switch condition energy of load is supplied by the storage energy of the capacitor. As a result of this storage energy of capacitor, the ripple that is seen at the output load is smoothed. They are used as filter elements. Filter capacitor's value must be high enough to supply current to the load continuously and to store enough energy. If capacitor's value is not sufficiently high, and if the capacitor can not be charged fast enough, the voltage will decrease while the current passing through the load increases. The voltage across the load is required to be constant. Hence, the load current should be constant.

In figure 3.3, buck converter is simulated with appropriate capacitor value. On the other hand, in figure 4.1, buck converter is simulated with inappropriate capacitor. This capacitor's value is not enough to supply an unregulated load voltage. Since the capacitors value is low, the storage energy in the capacitor is low. Therefore, when capacitor maintains the load, the current is not sufficiently high to obtain constant voltage.

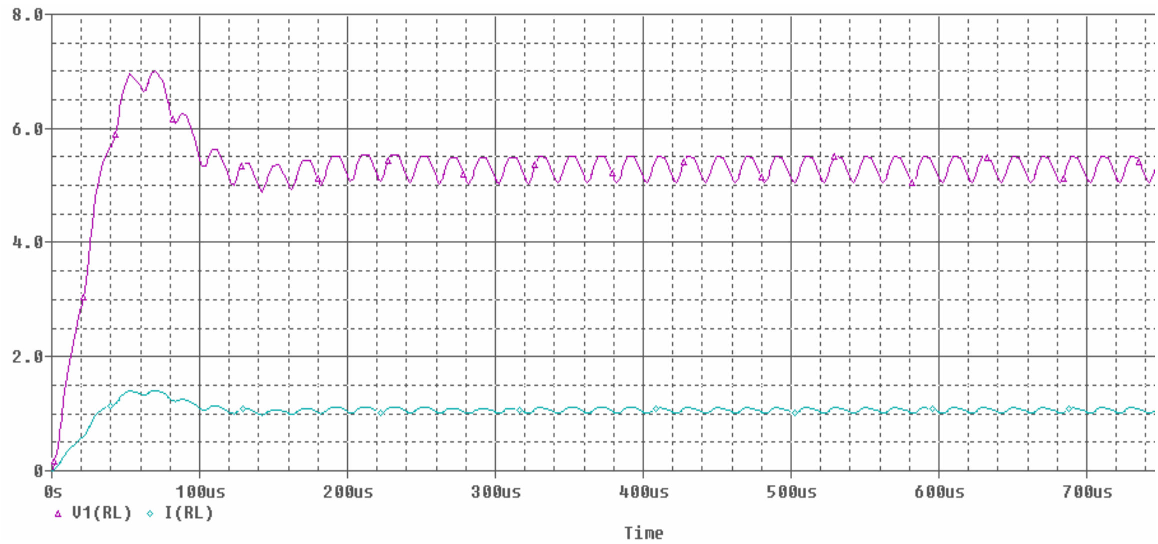

Figure 4.1 Output voltage and load current with low capacitor value in buck converter

4.2 Duty ratio Control by Pulse Width Modulation:

For basic converters in third chapter, on and off periods of switches are controlled by giving pulse. For obtaining more regulated output, on and off periods of switch should be controlled by PWM controller. PWM is a square wave. PWM control system should be applied to circuit for maintaining an exact required output voltage regardless of varying input and load conditions. This is made by adjusting the duty cycle of the PWM to determine the output voltage equal to the actual voltage that is required at the output by voltage mode control.

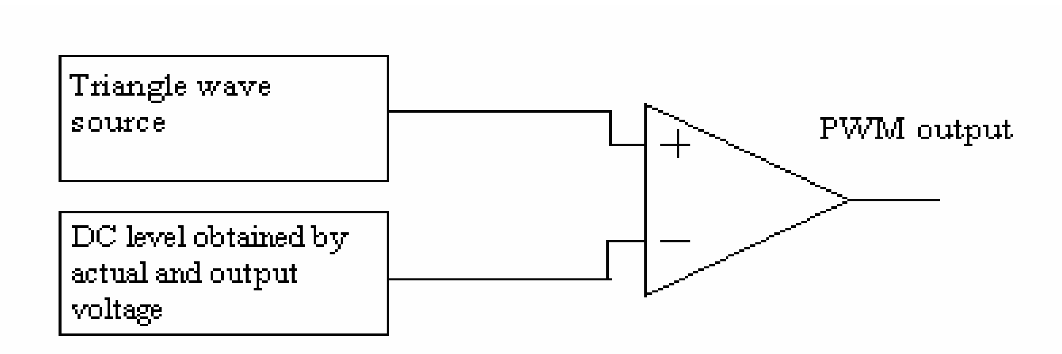

Figure 4.2 Block diagram of PWM generator

In figure 4.2 block diagram of a PWM controller is given. DC level is obtained by using an error amplifier. PWM output is obtained by comparing the DC level and triangle wave source.

The error amplifier integrates the error signal. The difference between actual voltage and required voltage multiplied by the gain is seen at the output of the error amplifier. The control voltage that is obtained by error amplifier is used to drive the PWM. When the control voltage is equal to the output voltage, there is no problem. When actual voltage is smaller than output voltage, output of the error amplifier is negative and duty cycle must be decreased to obtain the needed output voltage. When control voltage is bigger than output voltage, output of the error amplifier is positive and duty cycle must be increased.

Mainly, control voltage is applied to the non inverting node of the comparator and triangle wave is applied to the inverting node of the comparator to obtain PWM output. The frequency of triangular wave depends on the value of the load and capacitor. The output of the comparator is a rectangular pulse whose duration depends upon the reference voltage. The lower the actual voltage, the wider the pulse width of the output voltage of comparator.

In figure 4.3, Buck converter is simulated by using PWM control circuit. 15 volt DC input voltage is supplied. On and off periods are setting by the PWM controller. In figure 3.2 there is a small time that output’s value is over the expected value. On the other hand, in figure 4.3 to reduce the unexpected voltage rise, on period is controlled by PWM. Since the output is equal to the duty cycle multiplied by the input voltage, on period is reduced by PWM controller to obtain required output.

Spice Program of the buck converter with PWM control is;

```
*BUCK CONVERTER WITH PWM CONTROL
* INPUT VOLTAGE
Vin    1      0      DC     15
*
* BASIC BUCK CONVERTER
Switch   1 3    11 0   SW
Diode  0      3      DSCH
L1     3      4      50UH
CL     4      6      200UF
R_ESR  6      0      0.1
*
* LOAD
RL     4      0      5
*
* VOLTAGE MODE CONTROL
* REFERENCE VOLTAGE
VREF   12     0      PWL (0US 0V 10US 0V  200US 5V 450US 5V)
*
* ERROR AMP
G_ERR  0 10   12 5   0.003
Rinerror 5 10 6k
Re 4 5 2k
*
RGAIN       10      0        700K
CGAIN       10      0        10PF
* TRIANGLE WAVE FOR PWM
VTriangle   9      0      PULSE (0V 5V 0 5US 5US 0.1US 10US)
R9     9      0      1MEG
```

```
*
* PWM COMPARATOR
ECMP    11    0      TABLE {V (10, 9)} = (-5MV 0V) (5MV, 5V)
R11     11    0      1MEG
*
*
.MODEL SW      VSWITCH(VON=5V VOFF=0V RON=0.1 ROFF=100K)
.MODEL DSCH D (IS=0.0002 RS=0.05 CJO=5e-10 TT=2NS)
*
* ANALYSIS
.TRAN   1US 450US
*
* VIEW RESULTS
.PRINT TRAN    V (1) V (4)
.PROBE
.END
```

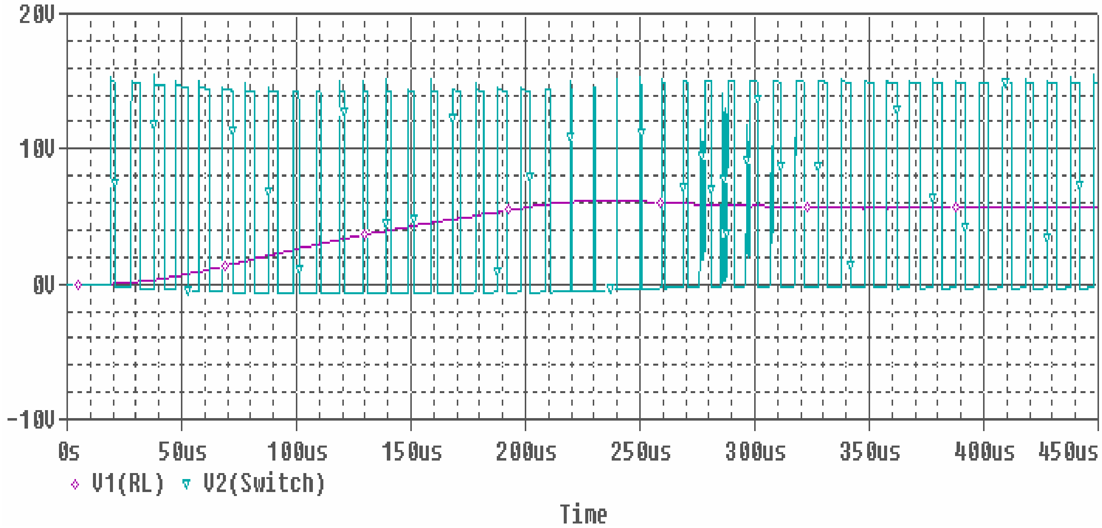

Figure 4.3 Switch signal and load voltage of buck converter with PWM voltage mode control

CHAPTER FIVE
DIODE REVERSE RECOVERY EFFECT

Diodes that are used in switching power supplies applications is called catch diode or freewheeling diodes. For decreasing the switching losses, these diodes should be selected with minimal recovery times and adequate current ratings for lower optimum operating temperatures. Ideal diode should have no reverse recovery time, but practically this can not be possible in manufacturing.

Semiconductor diodes occur by getting together p-type and n-type semiconductors. In n-type semiconductors, there are electrons, and p-type semiconductors involve holes. If a positive voltage is applied to the p-side of the junction. the pn junction is forward biased. When diode is forward biased, majority carrier electrons from n-region diffuse into the p-region and majority carrier holes from p-region diffuse into the n-region. As the majority carriers cross into the opposite regions, they become minority carriers in those regions, causing the minority carrier concentration to increase. When the forward current is reduced to zero, reverse bias occurs. The diode continues to conduct due to minority carriers which remain stored in the p-n junction and bulk semiconductor material. The minority carriers require a certain time to be neutralized. This time is called the reverse recovery time of the diode. Reverse recovery have two different types depending on the reverse recovery characteristic. These are soft recovery and abrupt recovery. Soft recovery hass longer reverse recovery time than abrupt recovery. In soft recovery, peak reverse current is long. In abrupt recovery this time is short. The peak reverse current can be expressed in reverse $\frac{d_i}{d_t}$ as;

$$I_{RR} = t_a \frac{d_i}{d_t} \tag{3.54}$$

t_a is the time between the zero crossing and the peak reverse current.

Softness factor is defined as;

$$t_{rr} = \frac{t_b}{t_a} \tag{3.55}$$

Where t_b is the time needed for reverse current change from peak reverse current to zero. t_b depends on the charge storage in the bulk semiconductor material.

There are some types of diodes depending on the reverse characteristic. Standard diodes have high reverse recovery time, and are used in low frequency applications. Fast recovery diodes have low recovery time and are used in DC-DC and AC-DC converters. These diodes are rated with reverse recovery of 500ns or less. Schottky diodes have very low recovery time beside fast recovery diodes and are used in high current and low voltage DC power supplies.

The typical parameters of the diode specify the output voltage's graphic. For modeling the diode; saturation current, series resistance, reverse breakdown voltage, reverse breakdown current, zero bias p-n capacitance and transit time are examined.

V_T is the thermal voltage . Thermal voltage is defined as;

$$V_T = \frac{kT}{q} \tag{3.56}$$

K is the boltzmann's constant (1.3806x10^{-23}) J per K

T is the absolute temperature in kelvin.

And q is the electron charge (1.6022x10^{-19}) coulombs

Since T is the variable parameter of the thermal voltage, thermal voltage is directly proportional to the absolute temperature in kelvin.

When diode is in forward bias region, saturation current can be found as shown below, where I_S is the saturation current and V_D is the forward voltage;

$$I_D = I_S(e^{\frac{V_D}{\eta V_T}} - 1) \approx I_S e^{\frac{V_D}{\eta V_T}} \tag{3.57}$$

Rashid (1995) describe η as the emission coefficient (or ideality factor) depending upon the material and the physical construction of diodes, whose value varies from 1 to 2, but it should ideally be 1.

When the diode is in reverse bias region, it can be expressed as shown below;

$$I_R = I_S(e^{\frac{-|V_R|}{\eta V_T}} - 1) \approx -I_S \tag{3.58}$$

In practical diodes, the reverse current increases with the reverse voltage. Also reverse voltage affects the junction capacitance; consequently junction capacitance has an effect on the output regulation. Equation of depletion capacitance at zero bias is given below. The capacitance associated with the charge variation in the depletion layer is called the junction capacitance. For reverse bias condition, V_D is negative so that C_J decreases with increasing reverse bias.

$$C_J = \frac{C_{j0}}{(1 - \frac{V_D}{V_j})^m} \tag{3.59}$$

V_j is the junction potential, this potential depends on the type of the diode, for example for a silicon diode $V_j \approx 0.5$V to 0.9V and for a germanium diode, $V_j \approx 0.2$V to 0.6V. C_{j0} is the zero bias junction capacitance.

Schottky diodes typically have a significantly higher junction capacitance than other rectifiers and lower reverse voltage. One of the reasons that schottky diode is stated as better choice in switch mode power supplies, is that their junction capacitance is high, consequently fast recovery is achieved.

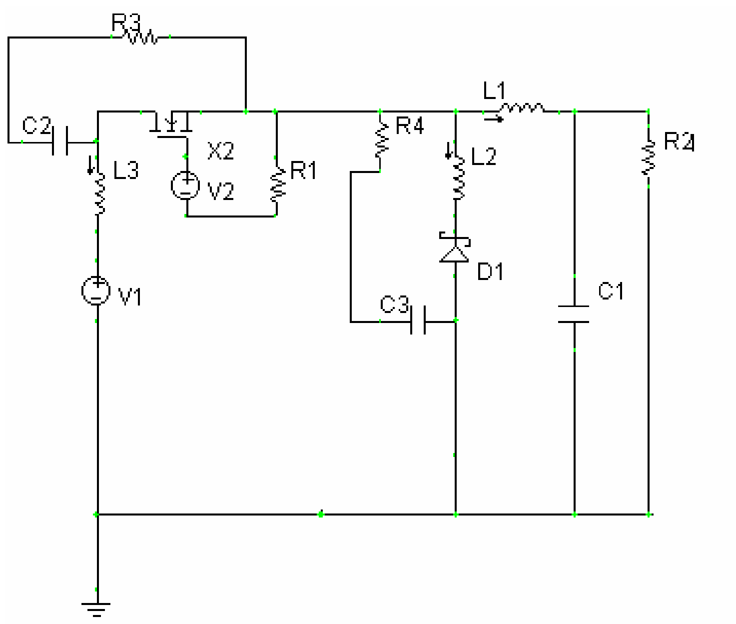

Figure 5.1 Circuit schematic of buck converter by using schottky diode

Buck converter in figure 5.1 is simulated. Voltage and current graph of the diode time interval between 15.78 millisecond and 15.8 millisecond is given related with the condition of the switch. While the diode is passing from forward to the reverse condition, it is expected to reach zero in a short time. Practically this is not possible.

Here, $\frac{d_v}{d_t}$ is minimized by using schottky diode. Consequently, there occurs a little delay which can be neglected by switching while the diode is in reverse bias.

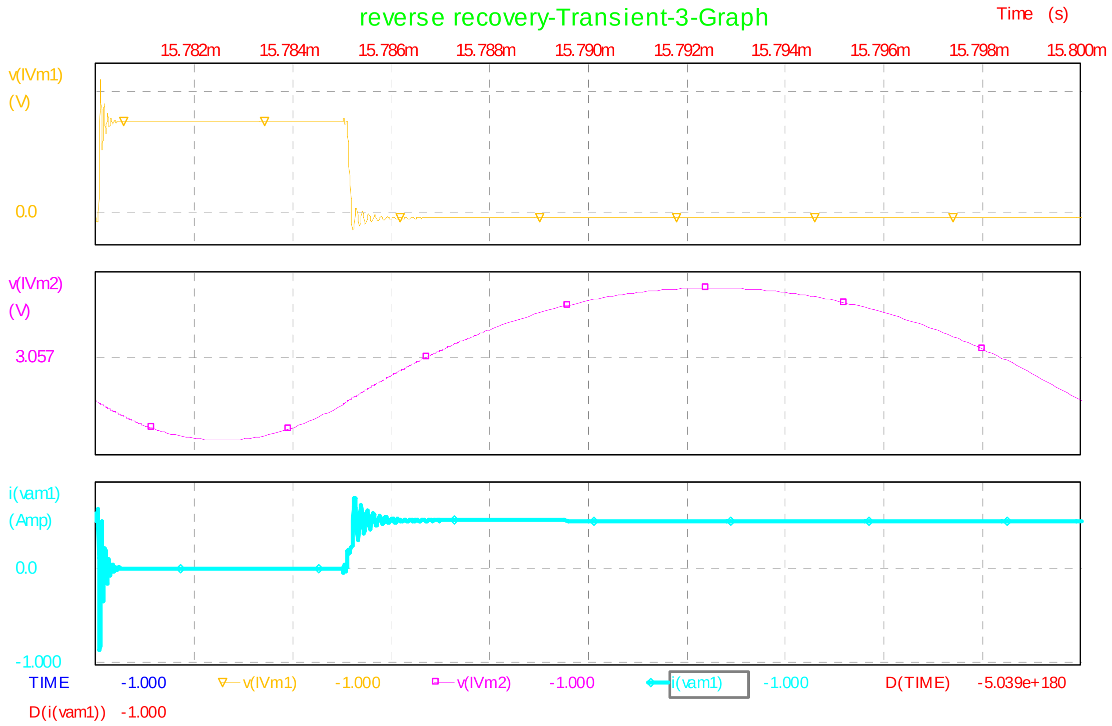

Figure 5.1 Simulation result of buck converter by using schottky diode

CHAPTER SIX
CONCLUSION

Nowadays, consumers need power at dc or ac at the same, higher or lower voltages or variable frequency. A switched mode power supply system is an interface between the utility system and consumer load to satisfy this need. They offer many advantages such as high efficiency, low power loss and small size, though their designs are complicated. Isolation is important in some applications. On this occasion transformers are used to achieve isolation in SMPS. SMPS are used widely in some areas like computers, televisions, uninterrupted power supplies, induction heating and emergency lighting systems, driving AC motors.

The aim of my thesis is to examine the input-output relationship of DC-DC converters, and the factors that effect the stability of output voltage. There are different types of DC-DC converters depending on the required voltage level. Also isolation specifies the types of DC-DC converters. In DC-DC converters isolation is made by using transformer.

In mathematical calculations performed for basic DC –DC converters, to find input-output relations diode is stated as ideal and losses are not taken into consideration. These calculations are carried out assuming that the circuits are in steady state and the voltage seen at the output is constant. But, in the simulations I have performed, it is seen that even if we obtained results close to the calculated values, exact the same results haven't been obtained. This is caused by the losses of some components in the circuit simulations and the characteristics of the diode.

One of the parameter to reduce the ripple is using capacitor at the output. From my simulation results, it is seen that, if the capacitor's value is less than the needed value, too much ripple occurs. The simulation shows that, % 20 ripple is occurred. Because the capacitor used here maintains the current flowing through the load. The capacitor's value which is not high enough causes the ripple current flowing through the load is multiplied by the load resistance; there occurs a ripple in the output voltage.

In the result of simulation which we do using suitable capacitor value, the ripple seen at the output decreases, but fully regulated output is still not obtained. In this situation, I ensured the output to be more regulated using PWM control. When the output voltage is less than or greater than the desired value, PWM control changes the charging and discharging times of circuit's storage elements by changing the on and off period of the switch. Pulse width modulation control is very important to obtain regulated outputs.

Switch mode power supplies operate in high frequencies, that's why choosing diodes for a switch mode power supply circuit is important. Ideally, when the diode is reverse biased, it is expected to reach zero immediately. But in practice this is not possible. In reverse bias, diode continues to conduct due to minority carriers which remain stored in the diode. This is shown related with diode characteristics in the simulation of buck converter. With respect to the simulation results time is needed for current to change situation when a diode is getting reverse biased. We can determine this time with reverse recovery time. As the simulation result is investigated, it is seen that peak reverse current decreases when $\frac{d_i}{d_t}$ decreases. This enables the diode to get in reverse region faster depending on the on and off position of the switch, in the simulation shortening this time is achieved by using schottky diode.

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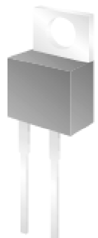
APPENDIX

FAIRCHILD SEMICONDUCTOR®

MBR1035 - MBR1060

Features

- Low power loss, high efficiency.
- High surge capacity.
- For use in low voltage, high frequency inverters, free wheeling, and polarity protection applications.
- Metal silicon junction, majority carrier conduction.
- High current capacity, low forward voltage drop.
- Guard ring for over voltage protection.



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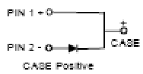
TO-220AC



Schottky Rectifiers

Absolute Maximum Ratings* T_A = 25°C unless otherwise noted

Symbol	Parameter	Value				Units
		1035	1045	1050	1060	
V_{RRM}	Maximum Repetitive Reverse Voltage	35	45	50	60	V
$I_{F(AV)}$	Average Rectified Forward Current	10				A
I_{FSM}	Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave	150				A
T_{stg}	Storage Temperature Range	-65 to +175				°C
T_J	Operating Junction Temperature	-65 to +150				°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	2.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	60	°C/W
$R_{\theta JL}$	Thermal Resistance, Junction to Lead	2.0	°C/W

Electrical Characteristics T_A = 25°C unless otherwise noted

Symbol	Parameter	Device				Units
		1035	1045	1050	1060	
V_F	Forward Voltage I_F = 10 A, T_C = 25°C	-		0.80		V
	I_F = 10 A, T_C = 125°C	0.57		0.70		V
	I_F = 20 A, T_C = 25°C	0.84		0.95		V
	I_F = 20 A, T_C = 125°C	0.72		0.85		V
I_R	Reverse Current @ rated V_R T_A = 25°C	0.1				mA
	T_A = 125°C	15				mA
I_{RRM}	Peak Repetitive Reverse Surge Current 2.0 us Pulse Width, f = 1.0 KHz	1.0		0.5		A

Typical Characteristics

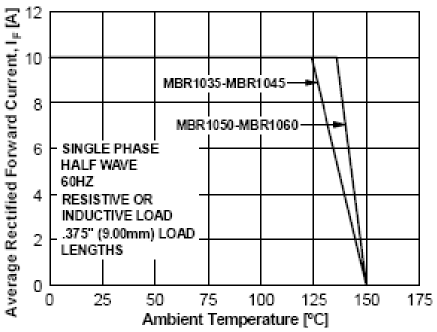


Figure 1. Forward Current Derating Curve

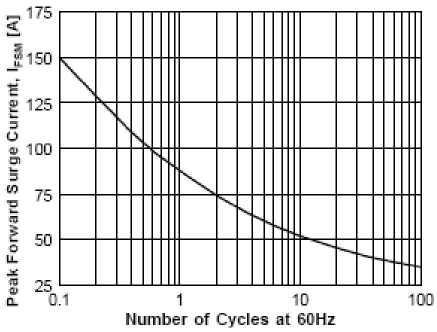


Figure 2. Non-Repetitive Surge Current

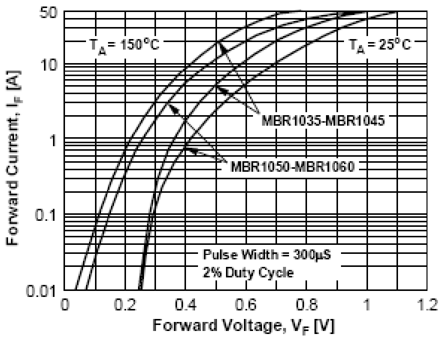


Figure 3. Forward Voltage Characteristics

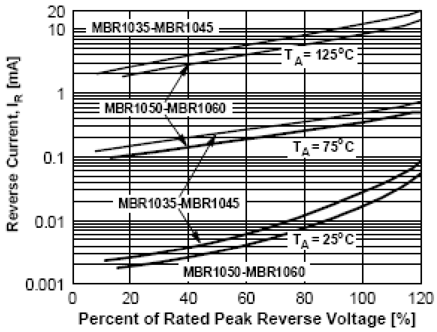


Figure 4. Reverse Current vs Reverse Voltage

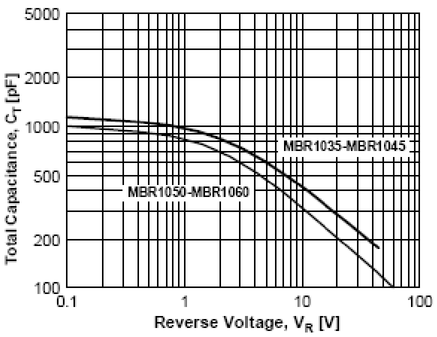


Figure 5. Total Capacitance

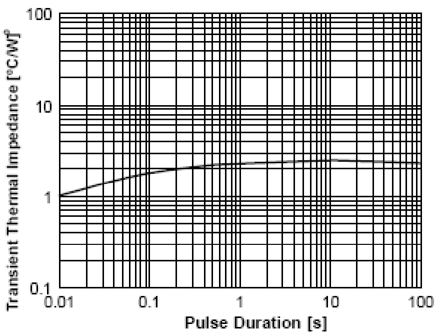


Figure 6. Thermal Impedance Characteristics