

STUDY ON DESIGNING THE FEEDBACK LOOP CONTROL OF BUCK CONVERTER



A THESIS REPORT

**SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
AND
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THE DEGREE
OF**

**BACHELOR OF SCIENCE (B.sc) in ELECTRICAL & ELECTRONICS
ENGINEERING (EEE)**

BY

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DECLARATION

We hereby declare that research work titled “*Study on designing the Feedback loop control of buck converter*” is our own work. The work has not been presented elsewhere for assessment.

Where material has been used from other sources it has been properly acknowledged/ referred.

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ABBREVIATION:

| | |
|--------|---|
| BJT | Bipolar Junction Transistor |
| CCM | Continuous Conduction Mode |
| CMC | Current Mode Control |
| CMOS | Complementary MOS |
| DC | Direct Current |
| DCM | Discontinuous Conduction Mode |
| DCR | Direct Current Resistance |
| ESL | Equivalent Series Inductance |
| ESR | Equivalent Series Resistance |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| NFET | Negative Channel Field Effect Transistor |
| PDA | Personal Digital Assistants |
| PWM | Pulse Width Modulation |
| SMPS | Switch Mode Power Supplies |
| SRBC | Synchronous Rectifier Buck Converter |
| VMC | Voltage Mode Control |

ABSTRACT:

Direct current to direct current (DC-DC) converters are power electronics circuits that convert direct current (DC) voltage input from one level to another. DC-DC converters are also known as switching converters, switching power supplies or switches. DC-DC converters are important in portable devices such as cellular phones and laptops. In this project, the configuration of DC-DC converter chosen for study was buck configuration. Buck converter converts the DC supply voltage to a lower DC output voltage level. The buck converter is suitable for low power application due to the low voltage level at the output. The control method chosen to maintain the output voltage from the buck converter in this thesis was voltage-mode control. Voltage-mode control technique compares the actual output voltage with the reference voltage. The difference between both voltages will drive the control element to adjust the output voltage to a fixed voltage level. At last we used some hardware control tools along with MATLAB Simulink to have the desired output voltage level.

THESIS PAPER

TABLE OF CONTENTS

| | |
|----------------------|-----|
| DECLARATION..... | I |
| ACKNOWLEDGEMENT..... | II |
| ABBREVIATION..... | III |
| ABSTACT..... | IV |

1. CHAPTER01

Page

| | |
|--|----|
| 1.1 Introduction..... | 01 |
| 1.2 Why use a switching regulator..... | 03 |
| 1.3 What are SMPS..... | 05 |
| 1.4 Why working on Buck converter..... | 06 |
| 1.5 Motivation for thesis..... | 06 |
| 1.6 Thesis objective..... | 06 |
| 1.7 Workflow of the thesis..... | 07 |

2. CHAPTER02

| | |
|--------------------------------------|----|
| 2.1 Operation of buck converter..... | 08 |
| 2.2 Design specification..... | 09 |
| 2.3 Component values..... | 14 |
| 2.4 Transfer function..... | 15 |
| 2.5 P-spice simulation..... | 16 |

3. CHAPTER03

| | |
|--|----|
| 3.1 Controller design..... | 19 |
| 3.2 PWM controller..... | 20 |
| 3.3 Comparator and voltage to PWM converter..... | 21 |
| 3.4 Stability criteria..... | 23 |
| 3.5 Compensator network..... | 25 |

4. CHAPTER 04

| | |
|---|----|
| 4.1 Feedback circuit design and analysis..... | 29 |
| 4.2 Controlling the output voltage..... | 30 |
| 4.3 Compensator design..... | 31 |
| 4.4 Transfer function of the compensator..... | 33 |
| 4.5 Bode plot of the compensator..... | 34 |
| 4.6 Simulation of the complete circuit..... | 35 |

5. CHAPTER05

| | |
|---|----|
| 5.2 Hardware design and implementation..... | 37 |
| 5.3 Future scopes..... | 39 |
| 5.4 Conclusion..... | 40 |
| 5.5 References..... | 41 |

LIST OF FIGURE

| | Page # |
|--|---------------|
| 1.1: Interdisciplinary nature of Power Electronics | 01 |
| 1.2: Power Supply Tree..... | 02 |
| 1.3: Linear Regulator..... | 03 |
| 1.4: Switching Regulator..... | 04 |
| 2.1: Buck Converter..... | 08 |
| 2.2: When the switch is closed..... | 08 |
| 2.3: When the switch is open..... | 08 |
| 2.4: Pspice simulation of Buck converter..... | 15 |
| 2.5: Waveform of the output voltage..... | 15 |
| 2.6: Inductor current wave form..... | 16 |
| 2.7: Diode voltage waveform..... | 16 |
| 2.8: Inductor voltage waveform..... | 17 |
| 2.9: Output current waveform..... | 17 |
| 3.1: Block diagram for voltage mode control..... | 18 |
| 3.2: PWM Signal..... | 20 |
| 3.3: Voltage Reference Comparator..... | 20 |
| 3.4: PWM Comparator Signals..... | 21 |
| 3.5: Definitions of the crossover frequency, phase and gain margins..... | 23 |
| 3.6: A general compensated error amplifier..... | 24 |
| 3.7: Type I Compensation..... | 25 |
| 3.8: Type II Compensation..... | 26 |
| 3.9: Type III Compensation..... | 27 |
| 4.1: Feedback circuit block with buck converter..... | 28 |
| 4.2: Methodology to control output voltage..... | 29 |

| | |
|--|----|
| 4.3: Bode plot of buck converter transfer function..... | 31 |
| 4.4: Compensator bode plot..... | 34 |
| 4.5: Simulation of the feedback controlled buck in P-sim software..... | 35 |
| 4.6: Output voltage with variable load correction..... | 35 |
| 5.1: V_{out} vs V_{in} graph of Buck converter..... | 38 |

LIST OF TABLE

1.1: Comparison between Linear and Switch-Mode Regulators.....05

2.1: Buck converter components values.....14

5.1: Vin and Vout Values.....38

CHAPTER 01

1.1 INTRODUCTION

Over the years as the portable electronics industry progressed, different requirements evolved such as increased battery lifetime, small and cheap systems, brighter, full-color displays and a demand for increased talk-time in cellular phones.

An ever increasing demand from power systems has placed power consumption at a premium. To keep up with these demands engineers have worked towards developing efficient conversion techniques and also have resulted in the subsequent formal growth of an interdisciplinary field of Power Electronics. However it comes as no surprise that this new field has offered challenges owing to the unique combination of three major disciplines of electrical engineering: electronics, power and control [1].

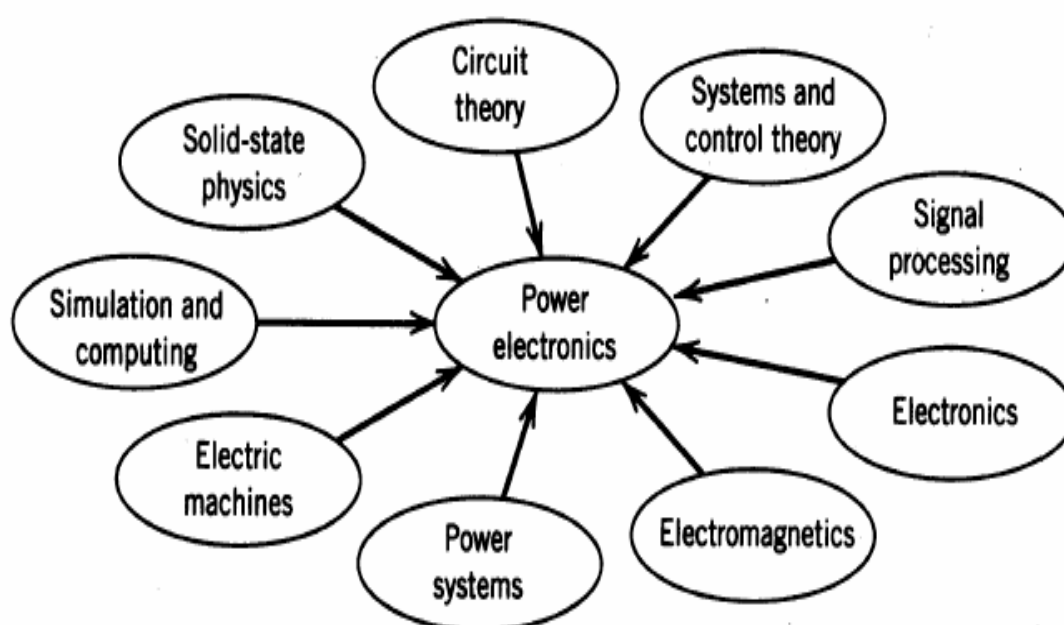


Figure 1.1: Interdisciplinary nature of Power Electronics [2]

These multi-discipline technologies, as highlighted in Figure 1.1, have involved control theory, filter synthesis, signal processing, thermal control, and magnetic components design [3].

Applications of power electronics range in size from a switched mode power supply in an AC adapter, battery chargers, audio amplifiers, fluorescent lamp ballasts, through variable frequency drives and DC motor drives used to operate pumps, fans, and manufacturing machinery, up to giga watt-scale high voltage direct current power transmission systems used to interconnect electrical grids. Power electronic systems are found in virtually every electronic device.

However, DC/DC converters are used in most mobile devices (mobile phones, PDA etc.) to maintain the voltage at a fixed value whatever the voltage level of the battery is. These converters are also used for electronic isolation and power factor correction. A power optimizer is a type of DC/DC converter developed to maximize the energy harvest from solar photovoltaic or wind turbine systems.

This thesis looks at the design issues associated with designing dc/dc converters (Figure 1.2).

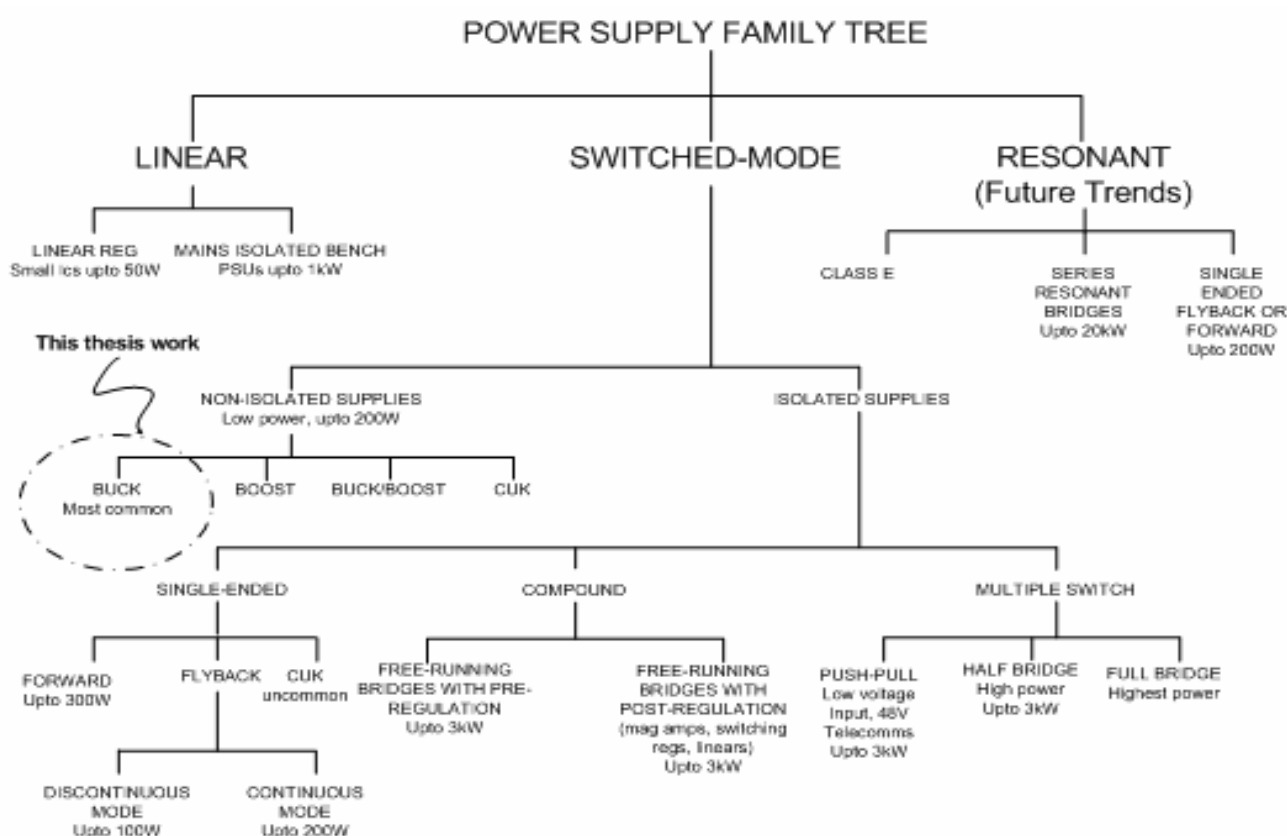


Figure 1.2: Power Supply Tree [4]

1.2 WHY USE A SWITCHING REGULATOR?

Voltage regulation conventionally has been done by Linear Regulators but slowly is being replaced with Switching Regulators. To realize the importance of a switching regulator we will first compare its efficiency with a linear regulator. The resistance of the linear regulator varies in accordance with the load resulting in a constant output voltage [5]

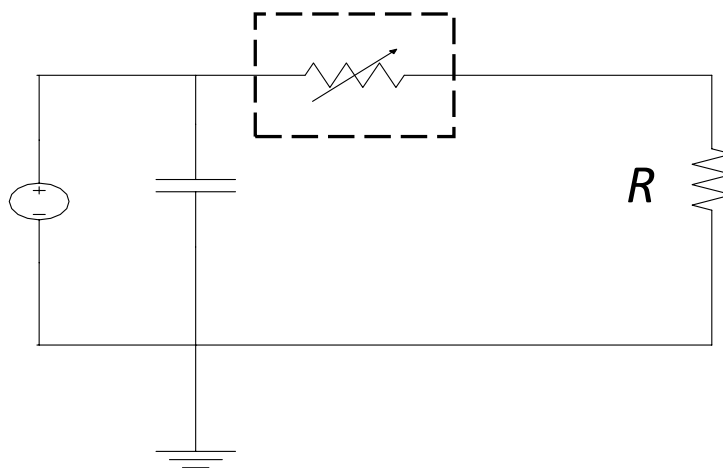


Figure 1.3: Linear Regulator

Figure 1-3 shows a simple Linear Regulator. If we consider an example, where $V_{in} = 12\text{v}$ and we want to have a $V_{out} = 5\text{v}$. In this case we need to drop 7 volts across the regulator.

Using standard power equation, $P = I \times V$ (1)

If the output current = 5A, this will result in $5\text{ A} * 5\text{ V} = 25\text{ W}$.

Now the regulator must dissipate 25 W of heat energy. This results in a mere 50% efficiency for the linear regulator and a lot of wasted power which is normally transformed into heat. Provision for heat sinks for cooling makes the regulator bulky and large. Hence, where size and efficiency are critical, linear voltage regulators cannot be used.

Figure 1-4 is a very basic switching regulator. The switching regulator is a simple switch (and hence ideally no resistance or very low resistance). This switch goes on and off at a fixed rate (usually between 10 KHz to 100 KHz) as shown in Figure 1-4.

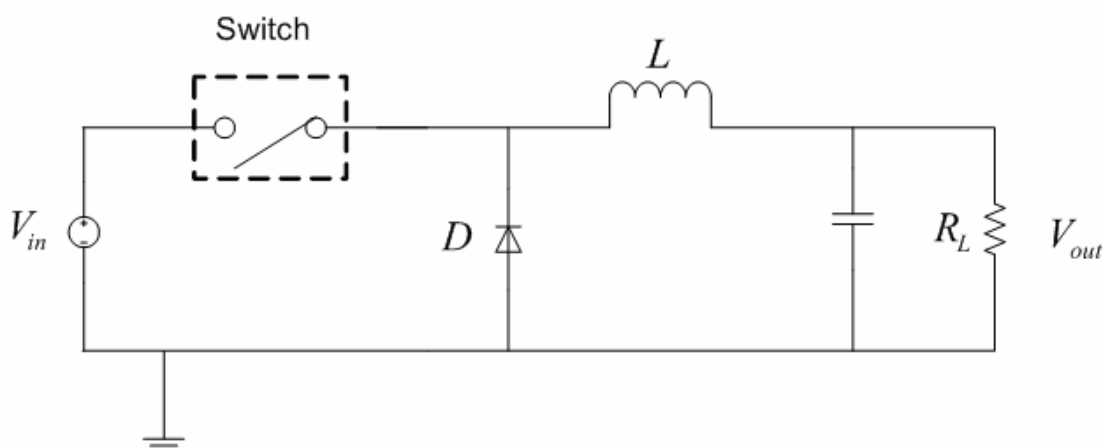


Figure 1.4: Switching Regulator

The Duty Cycle for the switch is determined by the Eq. 1.2.

$$\text{Duty cycle} = \frac{V_{out}}{V_{in}} \dots\dots\dots (1.2)$$

The time that the switch remains closed during each switch cycle is varied to maintain a constant output voltage. The switching regulator is much more efficient than the linear regulator achieving efficiencies as high as 80% to 95% in some circuits. In contrast, the linear regulator usually exhibits only 50% to 60% efficiency. With higher efficiency smaller heat sinks will be required because lesser heat is dissipated. This further result in SMPS that can be packaged in a fraction of the size of linear regulators.

There is also another advantage of Switching Regulators and that is that the energy stored by inductor & capacitor can be transformed to output voltages that can be greater than input (boost), negative (inverter), or can be transferred through a transformer to provide electrical isolation with respect to the input.

Unlike linear regulators, switched power supplies can step up or step down the input voltage [6].

All of our discussion can be summarized with a comparison in Table 1.1 described next :

TABLE 1.1

| | Linear | Switching |
|---------------------|--|--|
| Function | Only steps down ; input voltage must be greater than output. | Steps up, steps down, or inverts |
| Efficiency | Low to medium , but actual battery life depends on load current and battery voltage | High , except at very low load currents (μA), where switch-mode quiescent current is usually higher. |
| Waste Heat | High , if average load and/or input/output voltage difference are high | Low , as components usually run cool for power levels below 10W |
| Complexity | Low , which usually requires only the regulator and low-value bypass capacitors | Medium to high , which usually requires inductor, diode, and filter caps in addition to the IC; for high-power circuits, external FETs are needed |
| Size | Small to medium in portable designs, but may be larger if heat sinking is needed | Larger than linear at low power, but smaller at power levels for which linear requires a heat sink |
| Total Cost | Low | Medium to high , largely due to external components |
| Ripple/Noise | Low ; no ripple, low noise, better noise rejection. | Medium to high , due to ripple at switching rate |

Table 1: Comparison between Linear and Switch-Mode Regulators [7]

So, that is why we chose to work with Switch mode buck converter for our thesis.

1.3 WHAT ARE SMPS ?

High frequency switching converters are power circuits in which the semiconductor devices switch at a rate that is fast compared to the variation of the input and output waveforms. The difference between the switching frequency and the frequency of the external waveforms is large enough to permit the use of low-pass filters to remove the unwanted switching frequency components. High frequency switching converters are used most often as interfaces between dc systems of different voltage levels. These converters are known as high-frequency dc/dc converters, and examples of their use are the power supplies in computers and other electronic equipment.

1.4 WHY WORKING ON A BUCK CONVERTER ?

The buck converter is the most widely used dc-dc converter topology in power management and microprocessor voltage-regulator (VRM) applications. Those applications require fast load and line transient responses and high efficiency over a wide load current range. They can convert a voltage source into a lower regulated voltage. For example, within a computer system, voltage needs to be stepped down and a lower voltage needs to be maintained. For this purpose the Buck Converter can be used [8]. Furthermore buck converters provide longer battery life for mobile systems that spend most of their time in “stand-by”. Buck regulators are often used as switch-mode power supplies for baseband digital core and the RF power amplifier (PA) [9].

1.5 MOTIVATION FOR THE THESIS:

When we want to use a device with low voltage level, if we connect the device such as laptop or charger directly to the rectified supplied from the socket at home, the device might draw too much voltage and will waste energy as a result.

Therefore to avoid unnecessary power wastage, we would need to convert the voltage level to suitable voltage level for the equipment to function properly as well as save energy. Whether there are changes in the load, the output voltage will always be fixed. That is why we choose to do our thesis on designing feedback controlled buck converter which will always give a fixed output voltage irrespective of load change.

1.6 THESIS OBJECTIVE:

The main objective of this project is to design a buck converter to convert the input DC voltage to lower DC output voltage level for low power applications to solve the problem of voltage regulation and high power loss of the linear regulator circuit. The converter uses switching scheme operates the switches such as MOSFET in cut-off and saturation region to reduce power loss across the transistor or switch. The output voltage level is then regulated by the voltage-mode control circuit to a desired output voltage level as in the design specification.

1.7 WORKFLOW OF THE THESIS :

The workflow of this Thesis is:

- I. Study the operation and design of buck converter.
- II. Study the operation of voltage-mode control circuit.
- III. Simulation of buck converter frequency response.
- IV. Deriving the transfer function of the converter circuit.
- V. Choosing an appropriate feedback controller circuit for the converter circuit.
- VI. Deriving the values of the components of the controller circuit.
- VII. Designing the controller circuit.
- VIII. Simulation of controller circuit frequency response.
- IX. Simulation of the converter circuit with the feedback controller circuit
- X. Designing the hardware with arduino and matlab simulink.
- XI. Observing the steady output voltage from the hardware circuit.

CHAPTER 02

2.1 OPERATION OF BUCK CONVERTER:

The name “Buck Converter” presumably evolves from the fact that the input voltage is bucked/chopped or attenuated, in amplitude and a lower amplitude voltage appears at the output. A buck converter, or step-down voltage regulator, provides non-isolated, switch-mode dc-dc conversion with the advantages of simplicity and low cost.

The operation of the buck converter is simple, with an inductor and two switches (usually a MOSFET and a diode) that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging the inductor into the load.

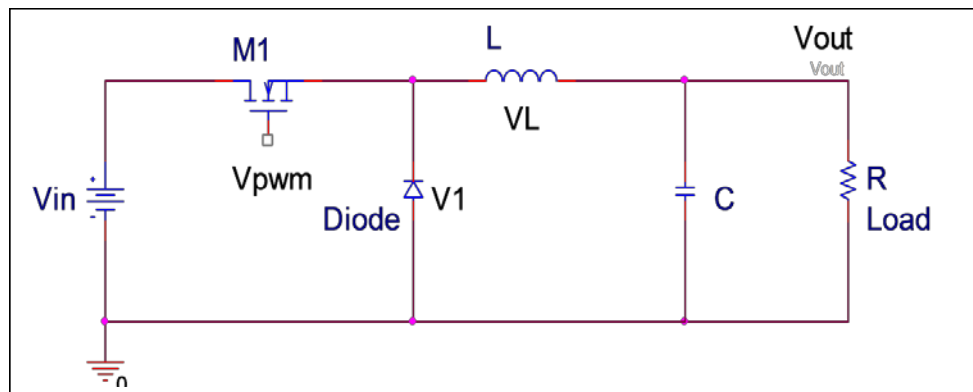


Figure 2.1: Buck Converter

Figure 2.1 shows the circuit diagram of a Buck-converter. The MOSFET M1 operates as the switch, which is turned on and off by a pulse width modulated (PWM) control voltage VPWM. The ratio of the on time (t_{on}) when the switch is closed to the entire switching period (T_{sw}) is defined as the duty cycle $D = t_{on} / T_{sw}$.

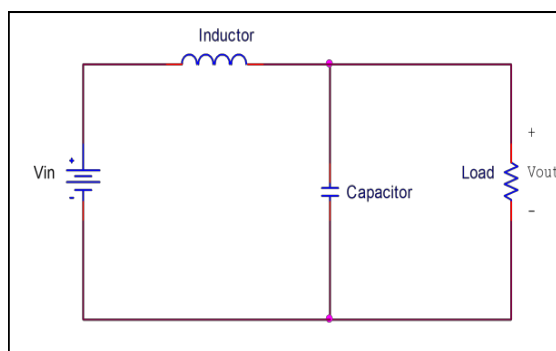


Figure 2.2: When the switch is closed

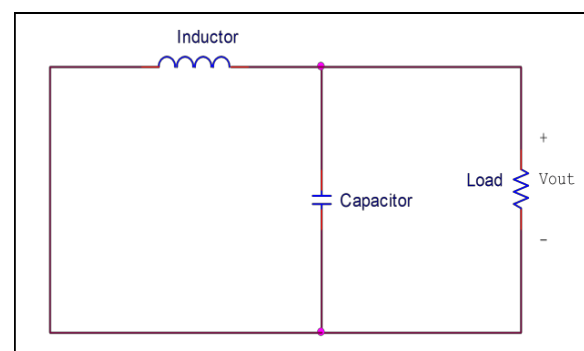


Figure 2.3: When the switch is open

The equivalent circuit in Figure 2.2 is valid when the switch is closed. The diode is reverse biased, and the input voltage supplies energy to the inductor, capacitor and the load. When the switch is open as shown in Figure 2.3 the diode conducts and the capacitor supplies energy to the load, and the inductor current flows through the capacitor and the diode. The output voltage is controlled by varying the duty cycle. In steady state, the ratio of output voltage to the input voltage is “D”, given by V_{out}/V_{in} .

2.2 DESIGN SPECIFICATION:

As just seen in the previous section that any basic switched power supply consists of five standard components:

- pulse-width modulating controller
- transistor switch (active switch)
- inductor
- capacitor
- diode (passive switch)

Now we will look into more detail as to the selection and the functioning of these components.

SWITCH

In its crudest form a switch can be a toggle switch which switches between supply voltage and ground. But for all practical applications which we shall consider we will deal with transistors. Transistors chosen for use in switching power supplies must have fast switching times and should be able to withstand the voltage spikes produced by the inductor. The input on the gate of the transistor is normally a Pulse Width Modulated (PWM) signal which will determine the ON and OFF time. Sizing of the power switch is determined by the load current and off-state voltage capability.

The power switch (transistor) can either be a MOSFET, IGBT, JFET or a BJT. Power MOSFETs are the key elements of high frequency power systems such as high-density power Supplies. Therefore MOSFETs have now replaced BTJ's in new designs operating at much higher frequencies but at lower voltages. At high voltages MOSFETs still have their limitations. The intrinsic characteristics of the MOSFET produce a large on-resistance which increases excessively when the devices' breakdown voltage is

raised. Therefore, the power MOSFET is only useful up to voltage ratings of 500V and so is restricted to low voltage applications or in two-transistor forward converters and bridge circuits operating off-line. At high breakdown voltages ($>200\text{V}$) the on-state voltage drop of the power MOSFET becomes higher than that of a similar size bipolar device with similar voltage rating. This makes it more attractive to use the bipolar power transistor at the expense of worse high frequency performance [10]. As improvements in fabrication techniques, new materials, device characteristics take place than MOSFETs are likely to replace BJTs.

Another new device likely to displace the BJT in many high power applications is the Insulated Gate Bipolar Transistor (IGBT). This device combines the low power drive characteristics of the MOSFET with the low conduction losses and high blocking voltage characteristics of the BJT. Therefore the device is highly suited to high power, high voltage applications. However, since current transport in the device is by the same process as the BJT, its switching speed is much slower than the MOSFET, so the IGBT is at present limited to lower ($<50\text{kHz}$) applications.

OPERATING FREQUENCY

The operating frequency determines the performance of the switch. Switching frequency selection is typically determined by efficiency requirements. There is now a growing trend in research work and new power supply designs in increasing the switching frequencies. The higher is the switching frequency, the smaller the physical size and component value. The reason for this is to reduce even further the overall size of the power supply in line with miniaturization trends in electronic and computer systems.

However, there is an upper frequency limit where either magnetic losses in the inductor or switching losses in the regulator circuit and power MOSFET reduce efficiency to an impractical level. Higher frequency also reduces the size of the output capacitor. We chose 10 KHz as switching frequency and crossover frequency is 1/5 th of switching frequency which is 2 KHz. Time Period, $T_s = (\frac{1}{F_s}) = 0.0001 \text{ s}$.

Duty cycle, $D = (\frac{V_{out}}{V_{in}}) = 0.4167$

INDUCTOR

The function of the inductor is to limit the current slew rate (limit the current in rush) through the power switch when the circuit is ON. The current through the inductor cannot change suddenly. When the current through an inductor tends to fall, the inductor tends to maintain the current by acting as a source. This limits the otherwise high-peak current that would be limited by the switch resistance alone. The key advantage is when the inductor is used to drop voltage, it stores energy. Also the inductor controls the percent of the ripple and determines whether or not the circuit is operating in the continuous mode.

Peak current through the inductor determines the inductor's required saturation- current rating, which in turn dictates the approximate size of the inductor. Saturating the inductor core decreases the converter efficiency, while increasing the temperatures of the inductor, the MOSFET and the diode. The size of the inductor and capacitor can be reduced by the implementation of high switching frequency, multi-phase interleaved topology, and a fast hysteric controller

A smaller inductor value enables a faster transient response; it also results in larger current ripple, which causes higher conduction losses in the switches, inductor, and parasitic resistances. The smaller inductor also requires a larger filter capacitor to decrease the output voltage ripple.

A DC-DC converter transfers energy at a controlled rate from an input source to an output load, and as the switching frequency increases, the time available for this energy transfer decreases. For example, consider a buck converter operating at 500 kHz with a 10 μ H inductor. For most DC-DC converters, changing the frequency to 1 MHz allows use of exactly one half the inductance, or 5 μ H. we calculated the value of critical inductance , $L_c = \left[\frac{(1-D)RI}{2F_S} \right] = 29.16\mu\text{H}$, hence Inductance, $L = \left[(V_{in}-V_{out}) \times \left(\frac{D}{F_S} \right) \times \left(\frac{1}{\Delta I} \right) \right] = 194\mu\text{H}$.

CAPACITOR

Capacitor provides the filtering action by providing a path for the harmonic currents away from the load. Output capacitance (across the load) is required to minimize the voltage overshoot and ripple present at the output of a step-down converter. The

capacitor is large enough so that its voltage does not have any noticeable change during the time the switch is off. Large overshoots are caused by insufficient output capacitance, and large voltage ripple is caused by insufficient capacitance as well as a high equivalent-series resistance (ESR) in the output capacitor. The maximum allowed output-voltage overshoot and ripple are usually specified at the time of design. Thus, to meet the ripple specification for a step-down converter circuit, we must include an output capacitor with ample capacitance and low ESR.

The problem of overshoot, in which the output-voltage overshoots its regulated value when a full load is suddenly removed from the output, requires that the output capacitor be large enough to prevent stored inductor energy from launching the output above the specified maximum output voltage.

Since switched power regulators are usually used in high current, high- performance power supplies, the capacitor should be chosen for minimum loss. Loss in a capacitor occurs because of its internal series resistance and inductance. Capacitors for switched regulators are partly chosen on the basis of Effective Series Resistance (ESR). Solid tantalum capacitors are the best in this respect [11]. For very high performance power supplies, sometimes it is necessary to parallel capacitors to get a low enough effective series resistance. We calculated the capacitor value by this equation

$$\text{Capacitance, } C = \left[\frac{\Delta I \times T_s}{8 \times \Delta V} \right] = 416.66 \mu\text{F}$$

DIODE/ TRANSISTOR

Since the current in the inductor cannot change suddenly, a path must exist for the inductor current when the switch is off (open). This path is provided by the freewheeling diode (or catch diode).

The purpose of this diode is not to rectify, but to direct current flow in the circuit and to ensure that there is always a path for the current to flow into the inductor. It is also necessary that this diode should be able to turn off relatively fast. Thus the diode enables the converter to convert stored energy in the inductor to the load. This is a reason why we have higher efficiency in a DC-DC Converter as compared to a linear regulator. When the switch closes, the current rises linearly (exponentially if resistance

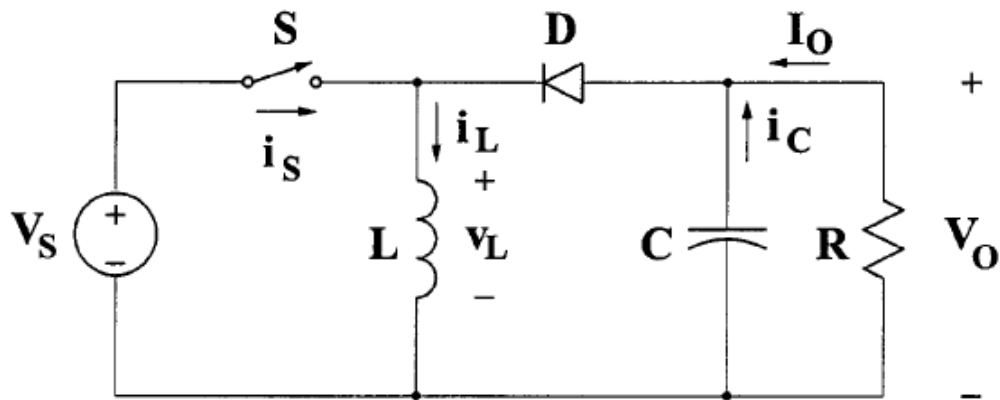
is also present). When the switch opens, the freewheeling diode causes a linear decrease in current. At steady state we have a saw tooth response with an average value of the current.

2.3 COMPONENTS VALUES:

Table 2.1

| Topology | Values |
|------------------------------------|---------------|
| DC input voltage (V_{in}) | 12 V |
| Output voltage (V_{out}) | 5 V |
| Switching Frequency (F_s) | 10kHz |
| Time Period, T_s | 0.0001 s |
| Duty cycle, D | 0.4167 |
| Switch ON time , t_{on} | 41.6 μ S |
| Load Resistance, (R_L) | 1 Ohm |
| Load current (I_L) | 5 A |
| Output current ripple , ΔI | 1.5 A |
| Output voltage ripple, ΔV | 45 mV |
| Critical inductance, L_c | 29.16 μ H |
| Inductance, L | 194 μ H |
| Capacitance, C | 416 μ F |
| Crossover Frequency | 2 KHz |

2.4 TRANSFER FUNCTION :



$$\begin{aligned}
 \text{TF} = \frac{V_o}{d} &= \frac{V_{in}}{LC} \times \frac{1+SrC}{s^2+s\left(\frac{1}{RC}+\frac{r}{L}\right)+\frac{1}{LC}} \\
 &= \frac{(17.73 \times 10^3 + s)}{6.94 \times 10^{-5} s^2 + 0.2305 s + 1.477 \times 10^3}
 \end{aligned}$$

2.5 PSPICE SIMULATIONS

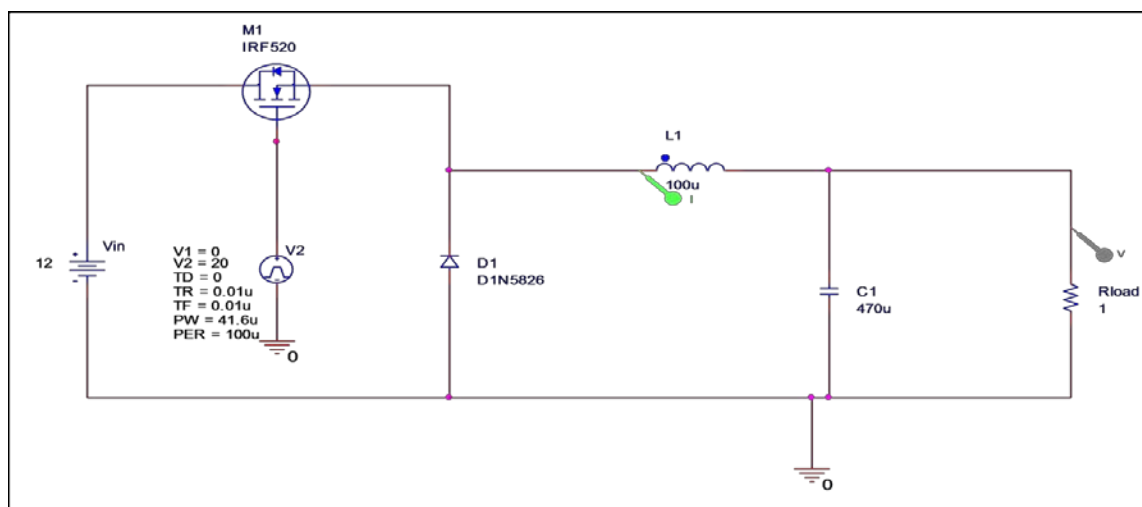


Figure 2.1: Pspice simulation of Buck converter.

Figure 2.1 shows the simulation circuit of buck converter. We used IRF 520 mosfet as a switch and a normal D1N5826 diode. We used 100 micro henry inductor and 470 micro farad capacitor with an internal resistance of 0.1 ohm and load resistance of 1 ohm.

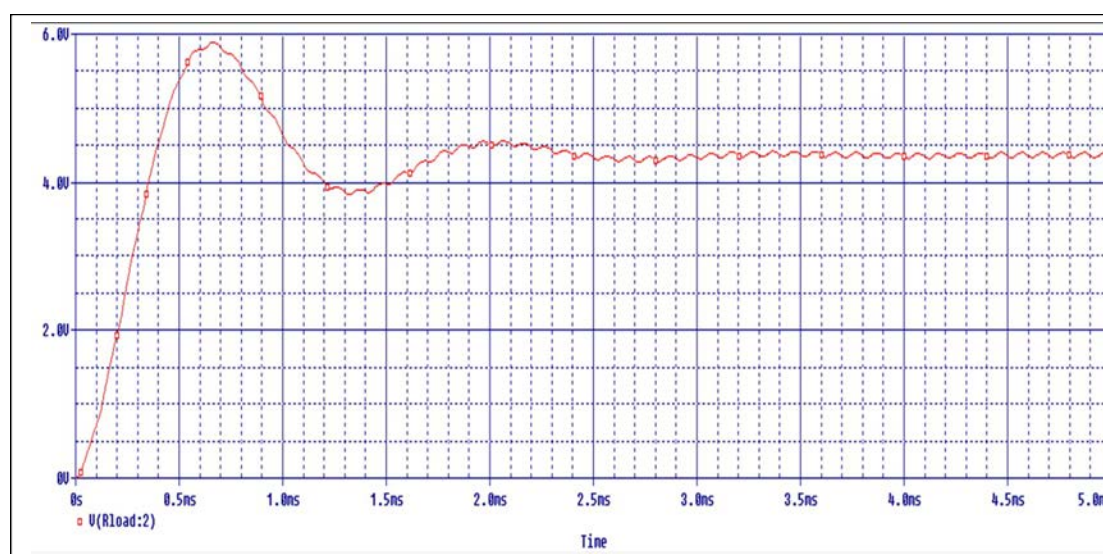


Figure 2.2: Waveform of the output voltage

Here, figure 2.2 shows the output voltage waveform which at the beginning was a bit fluctuating but after some time it became steady at 5v which is a desired value.

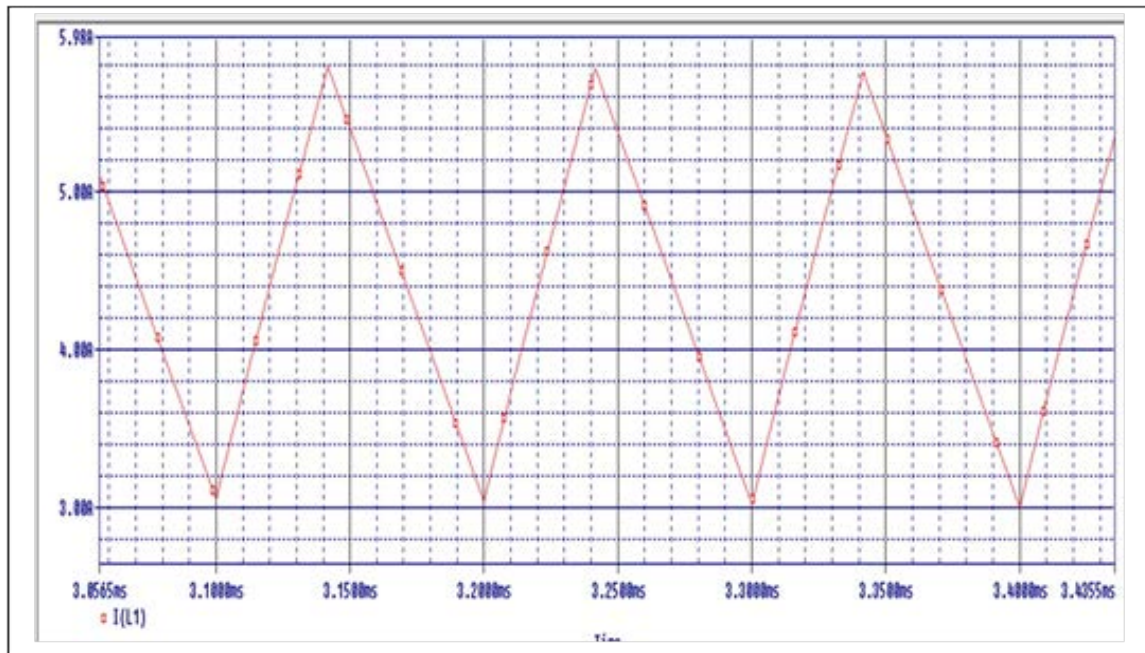


Figure 2.3 : Inductor current wave form

Here, figure 2.3 shows the inductor current waveform which is fluctuating between 3A to 5A which is also a desired value.

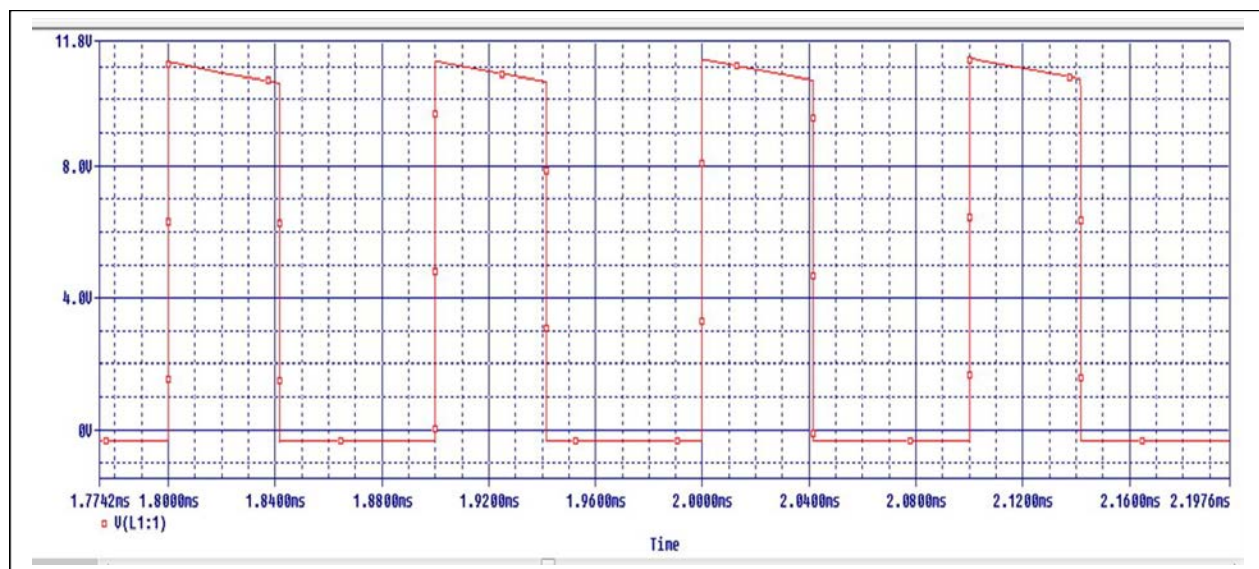


Figure 2.4 : Diode voltage waveform.

Figure 2.4 shows the diode voltage waveform which is fluctuating between 0v to 11v which is also a desired value.

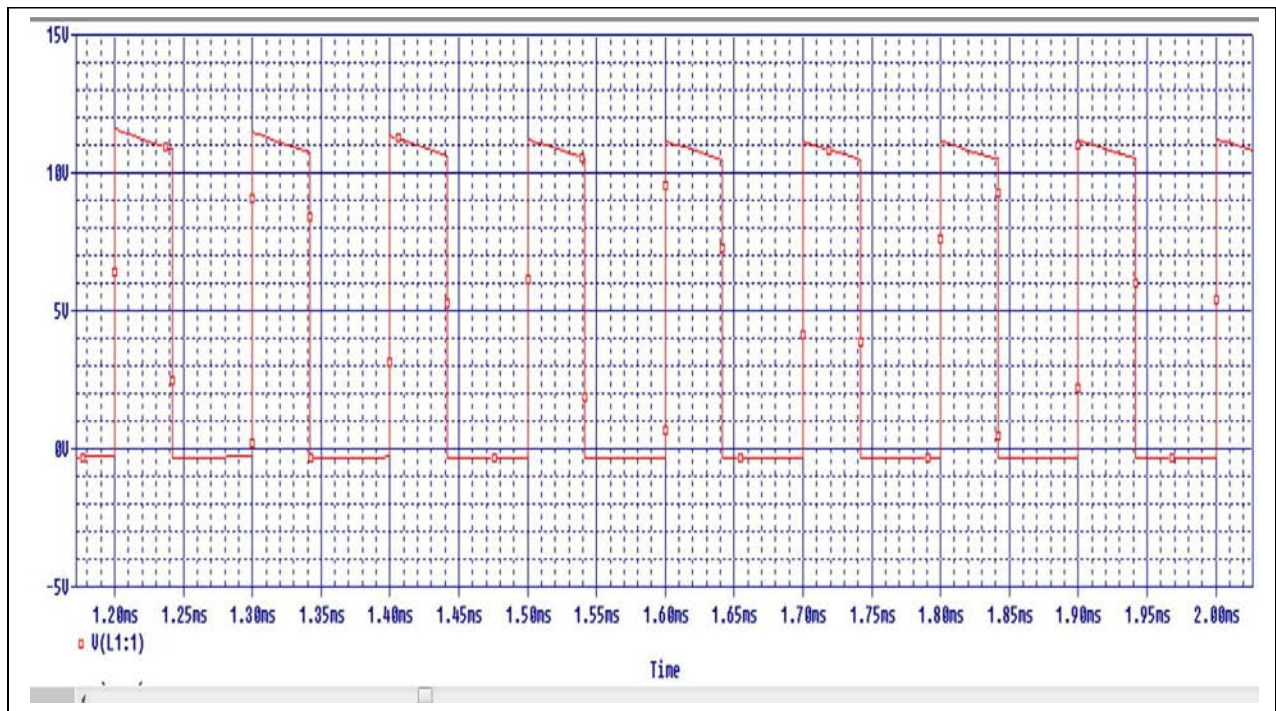


Figure 2.5 : Inductor voltage waveform

Here, figure 2.5 is showing the inductor voltage waveform which is fluctuating between 0v to 12v which is very much desired value for an input voltage of 12V.

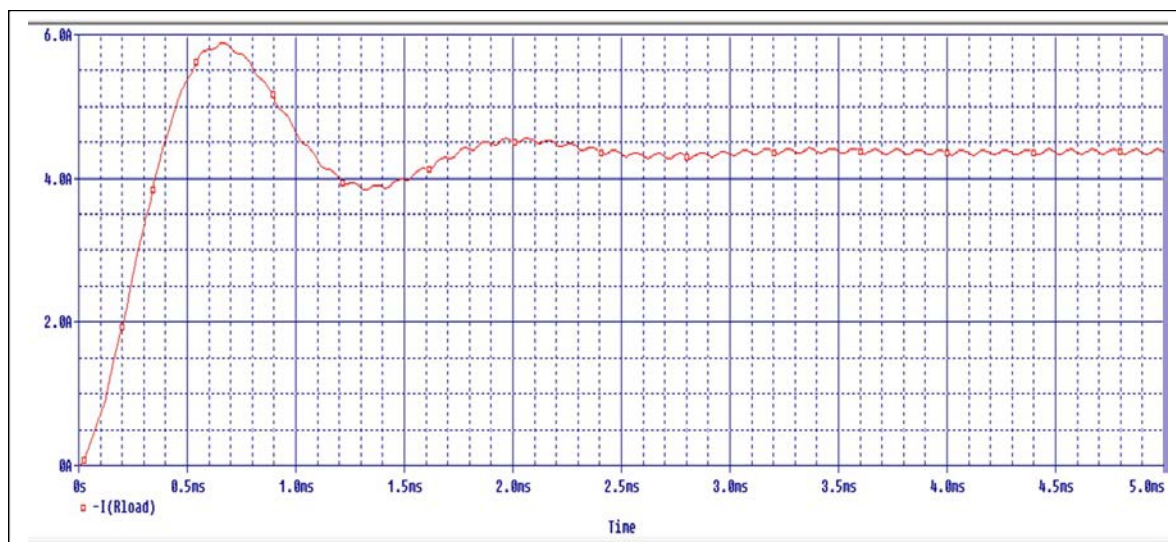


Figure 2.6 : Output current waveform

Here in the figure 2.6, is the wave form of output current which is same as output voltage waveform fluctuating at the beginning but reached to a stable value of 5V.

CHAPTER 03

3.1 CONTROLLER DESIGN:

The buck converter is the most widely used dc-dc converter topology in power management and microprocessor voltage-regulator (VRM) applications. These applications require fast load and line transient responses and high efficiency over a wide range of load current. They can convert a voltage source into a lower regulated voltage source. For example within a computer system, voltage needs to be stepped down and a lower voltage needs to be maintained. For this purpose the Buck Converter can be used. Furthermore buck converters provide longer battery life for mobile systems that spend most of their time in “stand-by”. Buck regulators are often used as switch-mode power supplies for baseband digital core and the RF power amplifier.

Suppose we want to use a device with low voltage level and if devices such as laptop or charger is directly connected to the rectified supplied from the socket at home, the device might not function properly or it might be broken due to over current or overvoltage. Therefore to avoid unnecessary damage to the equipment's and devices, we would need to convert the voltage level to suitable voltage level for the equipment's to function properly.

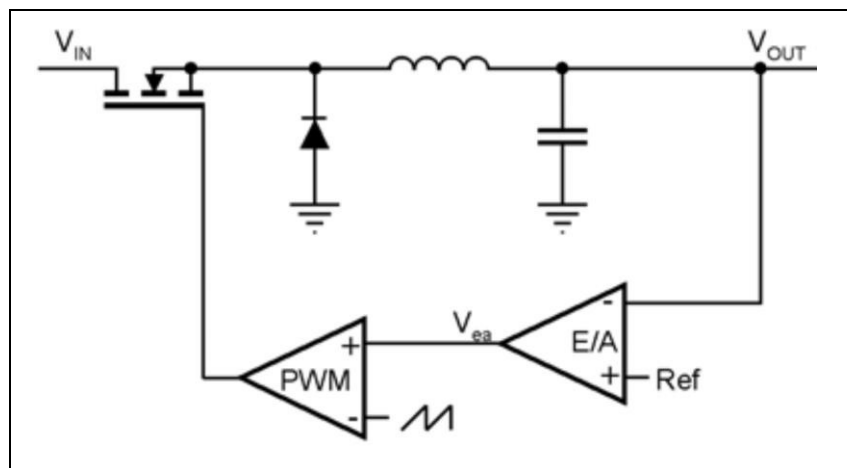


Figure 3.1: Block diagram for voltage mode control

The control method chosen to maintain the output voltage from the buck converter is

voltage-mode control and is shown in figure 3.2. Voltage mode has a single voltage feedback path with pulse width modulation performed by comparing the voltage error signal with a constant ramp waveform. The difference between both the voltages will drive the control element to adjust the output voltage to a desired voltage level. This is called as output voltage regulation. Voltage regulation is very important in electronic circuit to ensure that the load or the connected device can operate properly and to avoid damage to the equipment from overvoltage and overcurrent.

3.2 PWM CONTROLLER

The heart of a switching power supply is its switch control circuit (controller). One of the key objectives in designing a controller for the power converter is to obtain tight output voltage regulation under different line and load conditions [12]. Often, the control circuit is a negative-feedback control loop connected to the switch through a comparator and a Pulse Width Modulator (PWM). The switch control signal (PWM), controls the state (on or off) of the switch. This control circuit regulates the output voltage against changes in the load and the input voltage.

PWM is the method of choice to control modern power electronics circuits. The basic idea is to control the duty cycle of a switch such that a load sees a controllable average voltage. To achieve this, the switching frequency (repetition frequency for the PWM signal) is chosen high enough that the load cannot follow the individual switching events and they appear just a “blur” to the load, which reacts only to the average state of the switch.

With pulse-width modulation control, the regulation of output voltage is achieved by varying the duty cycle of the switch, keeping the frequency of operation constant. Duty cycle refers to the ratio of the period for which the power semiconductor is kept ON to the cycle period. A clearer understanding can be acquired by the Figure 3.2.

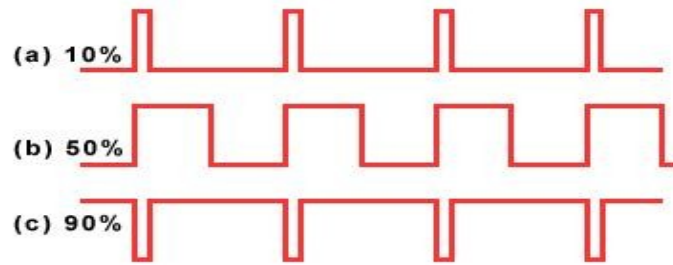


Figure 3.2: PWM Signal

The Figure 23 shows PWM signals for 10% (a), 50% (b), and 90% (c) duty cycles. Usually control by PWM is the preferred method since constant frequency operation leads to optimization of LC filter and the ripple content in output voltage can be controlled within the set limits.

3.3 COMPARATOR AND VOLTAGE TO PWM CONVERTER

Switching power supplies rely on negative feedback to maintain the output voltages at their specified value. To accomplish this, a differential amplifier is used to sense the difference between an ideal voltage (the reference voltage) and the actual output voltage to establish a small error signal ($v_{control}$).

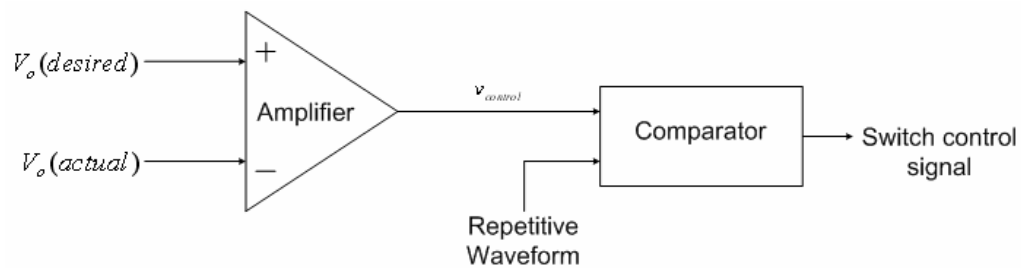


Figure 3.3: Voltage Reference Comparator [1]

The PWM switching at a constant switching frequency is generated by comparing a signal level control voltage with a repetitive wave form.

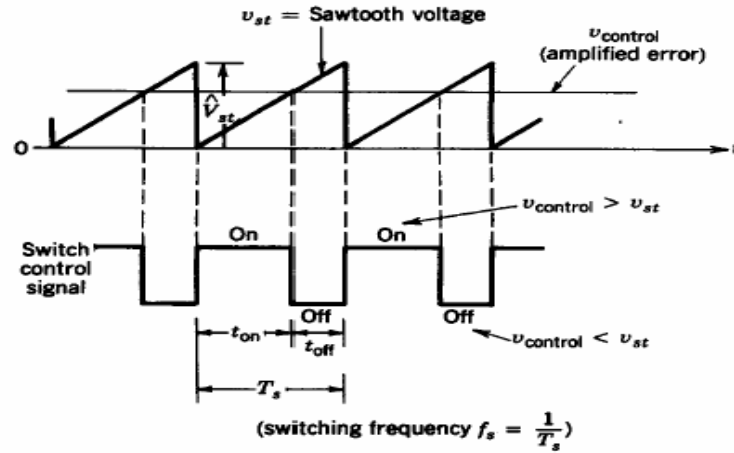


Figure 3.4: PWM Comparator Signals [1]

The frequency of the repetitive waveform with a constant peak, which is shown to be a saw tooth, establishes the switching frequency. This frequency is kept constant in a PWM control and is chosen to be in a few hundred kilohertz range. When the amplified error signal, which varies very slowly with time relative to the switching frequency, is greater than the saw tooth waveform, the switch control signal becomes HIGH, causing the switch to turn on. Otherwise, the switch is off. So when the circuit output voltage changes $V_{control}$ also changes. Causing the comparator threshold to change. Consequently, the output pulse width also changes. This duty cycle change then moves the output voltage to reduce to error signal to zero, thus completing the control loop. In terms of $v_{control}$ and the peak of the saw tooth waveform V_{st} in Figure 25, the switch duty ratio can be expressed as :

$$D = \frac{T_{on}}{T_s} = \frac{V_{control}}{V_{st}}$$

3.4 STABILITY CRITERIA

It is the desire of all designers of power supplies, whether they are switching or not, for accurate and tight regulation of the output voltage(s). To accomplish regulation we need to add a feedback loop. The feedback loop can cause an otherwise stable system to become unstable. Even though the transfer function of the original converter might not contain any right hand poles but after feedback it is possible that right hand poles may be introduced. Also we need to introduce a high DC gain. But with high gain again comes the possibility of instability.

These two issues determine the need to have stability criteria for a power supply. Hence, feedback compensation design involves selection of a suitable compensation circuit configuration and positioning of its poles and zeros to yield an open loop transfer function. Certain very important parameters need to be taken in to account when calculating the stability of the power supply.

- Variations in input voltage do not cause instability.
- Allow for variations in the peak-to-peak oscillator voltage.
- Error amplifier (which we will discuss in the next section) has sufficient attenuation at the switching frequency so that it does not amplify the output voltage ripple and cause sub-harmonic oscillations.
- Mid-frequency gain is greater than zero to prevent a large overshoot at turn-on and during transient conditions.
- Error amplifier has the drive capability to drive the feedback network properly.
- High gain at low frequency region to provide tight output voltage regulation and minimize the steady-state error in the power supply output.
- The phase margin determines the transient response of the output voltage in response to sudden changes in the load and the input voltage. The difference between 180° and the actual phase when the gain reaches unity gain. (In this case it is approaching zero.) Phase margins of 45° to 60° (360° degree minus the total closed-loop phase lag) are considered

safe values that yield well-damped transient load responses. The recommended value is 45° to 60° [2].

- Gain Margin is the difference between unity gain (zero dB) and the actual gain when the phase reaches 180° . (In this case it is a positive number.) The recommended value is -6dB to -12 dB.
- A crossover frequency (or bandwidth), f_c , of between one tenth and one fourth of a switching frequency for a system to respond sufficiently fast to transients, such as a sudden change of load.

A commonly used derivative from the above definitions is that if the slope of the gain response as it crosses the unity-gain axis is not more than -20 dB / decade, the phase margin will be greater than 45° and the system will be stable.

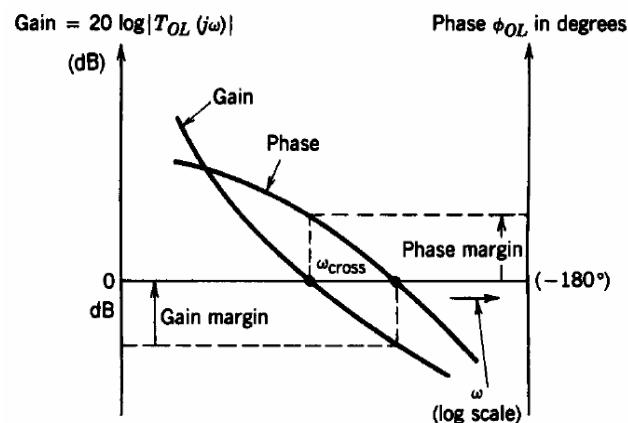


Figure 3.5: Definitions of the crossover frequency, phase and gain margins [2]

3.5 COMPENSATOR NETWORK:

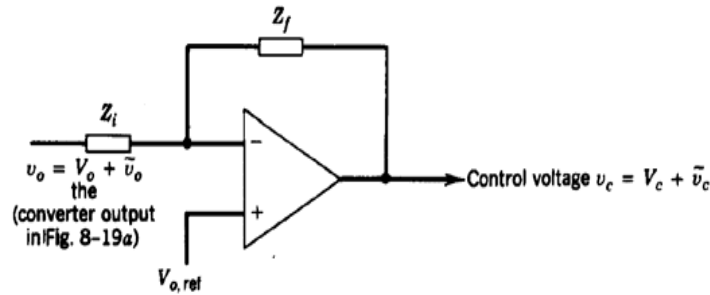


Figure 3.6: A general compensated error amplifier

After the values for external filter components are chosen (according to our requirements) than only the power stage is complete. The original filter of the buck converter by itself has a very low phase margin which needs to be increased. A better phase margin can be included by adding a suitable controller in a closed loop configuration. Proper compensation of the system will allow for a predictable bandwidth with unconditional stability. In most cases, a Type II or Type III compensated network will properly compensate the system. The ideal Bode plot for the compensated system would be a gain that rolls off at a slope of -20dB/decade, crossing 0dB at the desired bandwidth and a phase margin greater than 45° for all frequencies below the 0dB crossing. According to [13] the designer must compensate the power supply to ensure that the overall loop response is stable. The purpose of adding compensation to the error amplifier is to counter act some of the gains and phases contained in the control-to-output transfer function that could jeopardize the stability of the power supply. Obviously, the ultimate goal is to make the overall closed loop transfer function (control-to-output cascaded with the error amplifier) satisfy the stability criteria. This is to avoid having the closed-loop phase any closer to 360° than the desired phase margin anywhere where the gain is greater than 1 (0 dB). It is also desirable to have the slope of the gain curve at the crossover point with a value of -20 dB/decade. The overall frequency-response loop has two parts. The first includes a power-stage with driver and PWM comparator and the second is the compensation. The compensation circuit based on an error- amplifier with the R and C external components shapes the required feedback- loop frequency response.

TYPE I COMPENSATION

Dominant pole compensations, or single pole compensation, are referred to as a Type I Compensation. This type of compensation is used for converter topologies that exhibit a minimal phase shift prior to the anticipated gain crossover point. These include forward-mode regulators such as the buck, push- pull, and half- and full-bridge using either voltage or current mode control techniques. These converters exhibit a relatively low phase shift below the pole contributed by the output filter. This compensation yields, though, a relatively poor transient response time because the gain crossover frequency occurs at a low frequency. Its load regulation is very good, though, since its DC gain is very high.

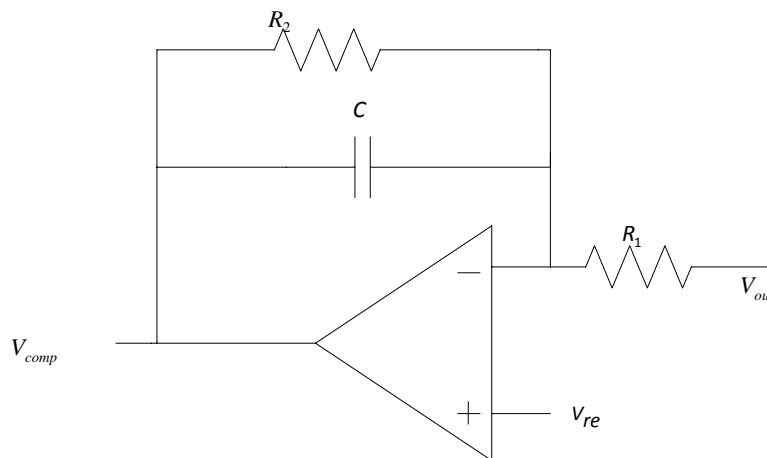


Figure 3.7: Type I Compensation [13]

Transfer is given by :

$$K(s) = -\frac{V_{out}(s)}{V_{in}(s)} = \frac{R_2}{R_1(1+R_2C2S)}$$

This method of error amplifier compensation is generally not used if a rapid transient load response time is desired.

TYPE II COMPENSATION

The Type II network helps to shape the profile of the gain with respect to frequency and also gives a 90° boost to the phase. This boost is necessary to counteract the effects of the resonant output filter at the double pole

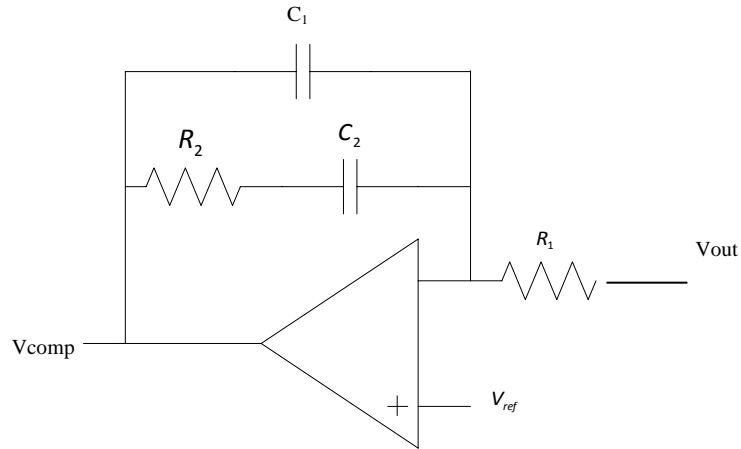


Figure 3.8: Type II Compensation

Transfer function is given by : $K(s) = \frac{1 + sR_2C_1}{sR_1(C_1 + C_2)(1 + sR_2(\frac{C_1C_2}{C_1 + C_2}))}$

TYPE III COMPENSATION

Type III network shapes the profile of the gain with respect to frequency in a similar fashion to the Type II network, but utilizes two zeroes to give a phase boost of 180° . This boost is necessary to counteract the effects of an under damped resonance of the output filter at the double pole. The Type III compensation circuit has two poles, with two zeros and a pole at its origin providing an integration function for better DC accuracy. Optimal selection of the compensation circuit depends on the power-stage frequency response.

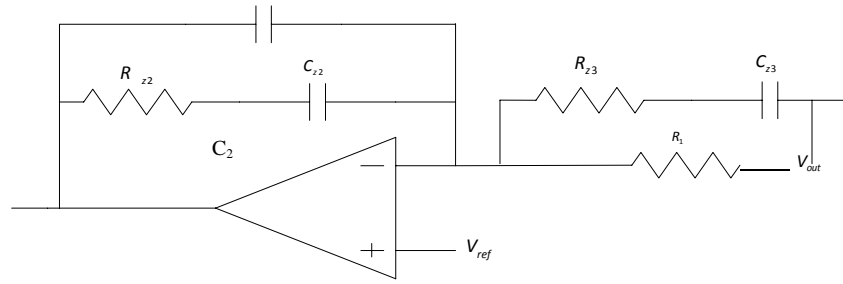


Figure 3.9: Type III Compensation

Transfer function of the type 3 compensator is given by :

$$K(s) = \frac{R1 + R3}{R1 \times R3 \times C1} \times \frac{\left(s + \frac{1}{R2 \times C2}\right) \left(s + \frac{1}{(R1 + R3)C3}\right)}{s \times \left(s \times \frac{C1 + C2}{R2 \times C1 \times C2}\right) \left(s + \frac{1}{R3 \times C3}\right)}$$

CHAPTER 04

4.1 FEEDBACK CIRCUIT DESIGN AND ANALYSIS:

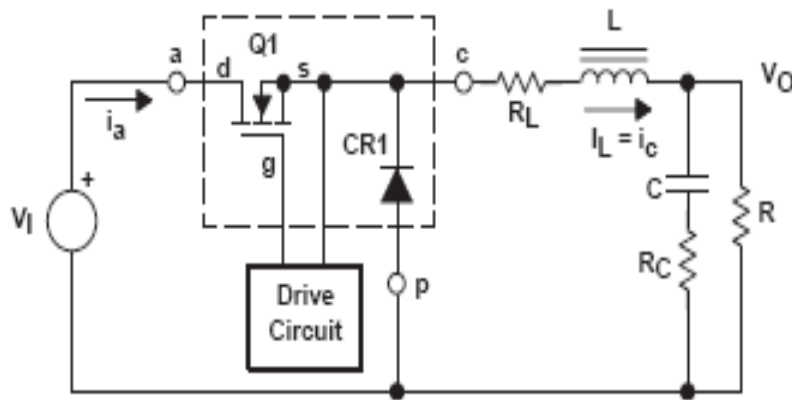


Figure 4.1: Feedback circuit block with buck converter

During normal operation of the buck power stage, Q1 is repeatedly switched on and off with the on and off times governed by the control circuit. This switching action causes a train of pulses at the junction of Q1, CR1, and L which is filtered by the L/C output filter to produce a dc output voltage, V_O .

4.2 CONTROLLING THE OUTPUT VOLTAGE:

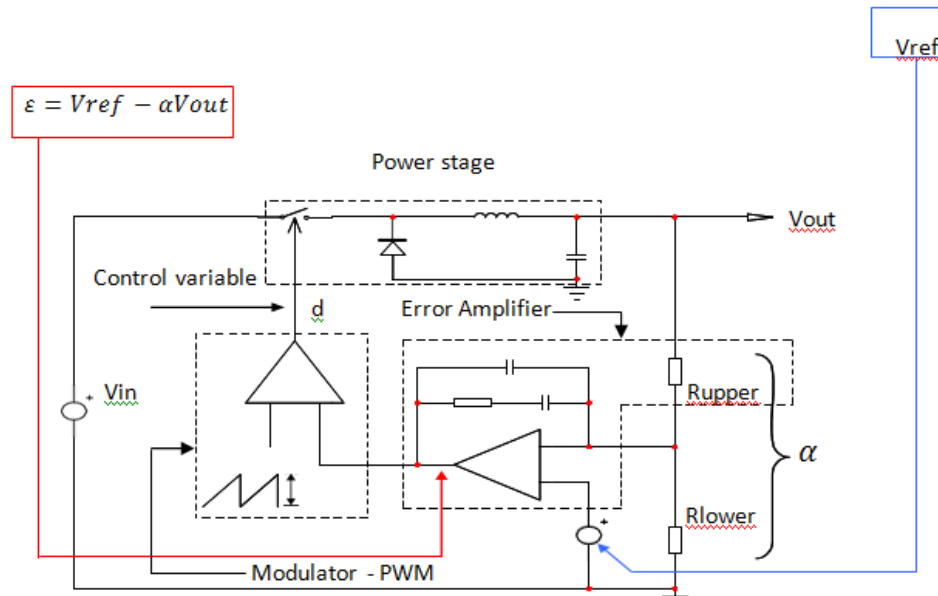


Figure 4.2: Methodology to control output voltage

- V_{out} is permanently compared to a reference voltage V_{ref} .
- The reference voltage V_{ref} is precise and stable over temperature.
- The error, $\varepsilon = V_{ref} - \alpha \times V_{out}$ is amplified and sent to the control input.
- The power stage reacts to reduce ε as much as it can.

STABILIZING THE CONVERTER :

- Selecting the crossover frequency f_c (2 kHz).
- Provide a high dc gain for a low static error.
- Shoot for at least 45° phase margin at f_c .
- Evaluate the needed phase boost at f_c to meet.

We are considering type 2 compensator to construct our feedback circuit.

4.3 TYPE II COMPENSATOR DESIGN

BODE PLOT OF THE FILTER CIRCUIT:

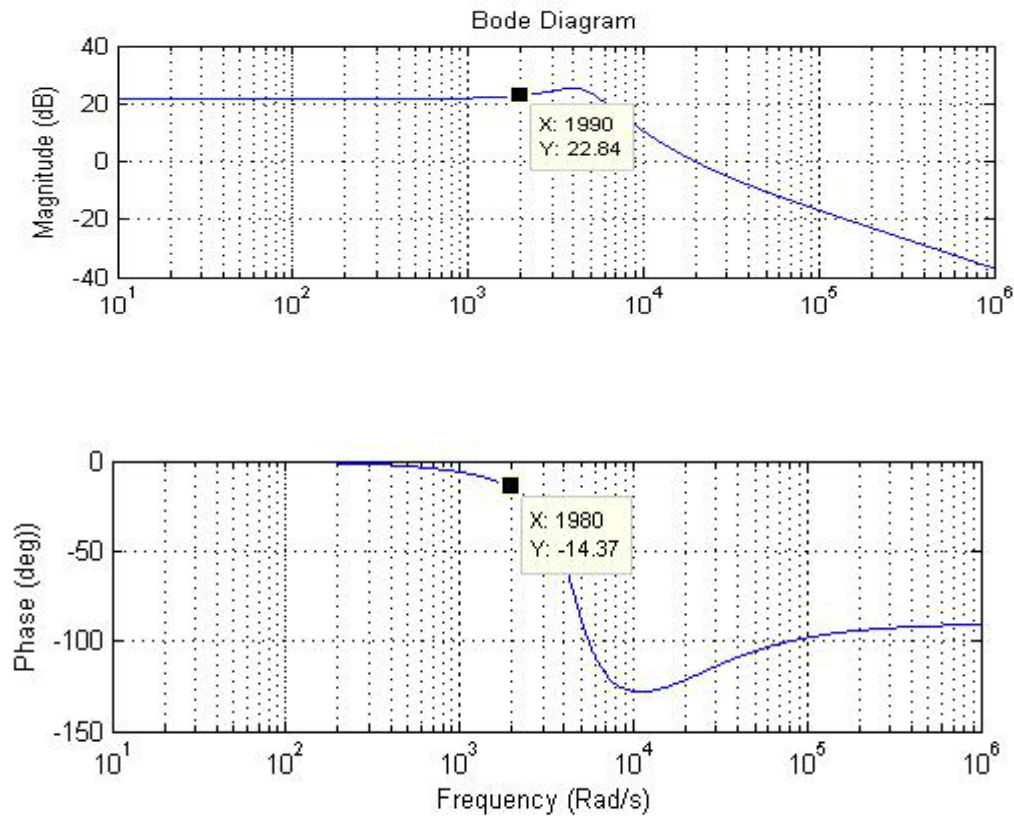


Figure 3.1: Bode plot of buck converter transfer function

Switching frequency , $F_{sw} = 10 \text{ kHz}$

Crossover frequency, $F_{co} = (1/5)$ of $F_s = 2 \text{ KHz}$

At 2 KHz, filter gain is 22.84dB and phase is -14.37° .

Pulse of PWM , $V_p = 3$

PWM gain = $1/V_p = -9.54 \text{ dB}$

Combined gain = $(-9.54 + 22.84) \text{ dB} = 13.3 \text{ dB}$

So, compensator gain should be -13.3 dB to make the overall gain 0 [13].

$-13.3 = 20 \log (V_c/V_o)$

$(V_c/v_o) = 0.216$

So, the magnitude of the mid frequency gain is,

$$(R2/R1) = 0.216$$

$$R1 = 1k$$

$$R2 = 0.216 k$$

$$\theta_{comp} = \theta_{phase} - \theta_{filter}$$

$$= 45^\circ - (-14.37^\circ)$$

$$= 59.37^\circ$$

$$K = \tan\left(\frac{\theta_{comp}}{2}\right) = 0.57$$

$$C1 = \frac{K}{2\pi f_{co} R2} = 210 \text{ nF}$$

$$C2 = \frac{1}{K 2\pi f_{co} R2} = 646 \text{ nF}$$

4.4 TRANSFER FUNCTION OF THE COMPENSATOR

$$\begin{aligned}\text{Type II compensator transfer function} &= \frac{1+sR_2C_1}{sR_1(C_1+C_2)(1+sR_2(\frac{C_1C_2}{C_1+C_2}))} \\ &= \frac{S+22.03 \times 10^3}{18.85S+6.454 \times 10^{-4}S^2}\end{aligned}$$

MATLAB CODE TO GENERATE THE BODE PLOT:

```
clc;
close all;
clear all;
numTF=[0 1 22.03*10^3];
denomTF=[6.454*10^-4 18.85 0];
w=0:10:10e5;
Y=freqs(numTF,denomTF,w);
y1=abs(Y);
y2=angle(Y);
subplot(2,1,1)
semilogx(w,20*log10(y1))
grid on
ylabel('Magnitude (dB)')
title('Bode Diagram')
subplot(2,1,2)
semilogx(w,y2*(180/pi))
grid on
ylabel('Phase (deg)')
xlabel('Frequency (Rad/s)')
```

4.5 BODE PLOT OF THE COMPENSATOR:

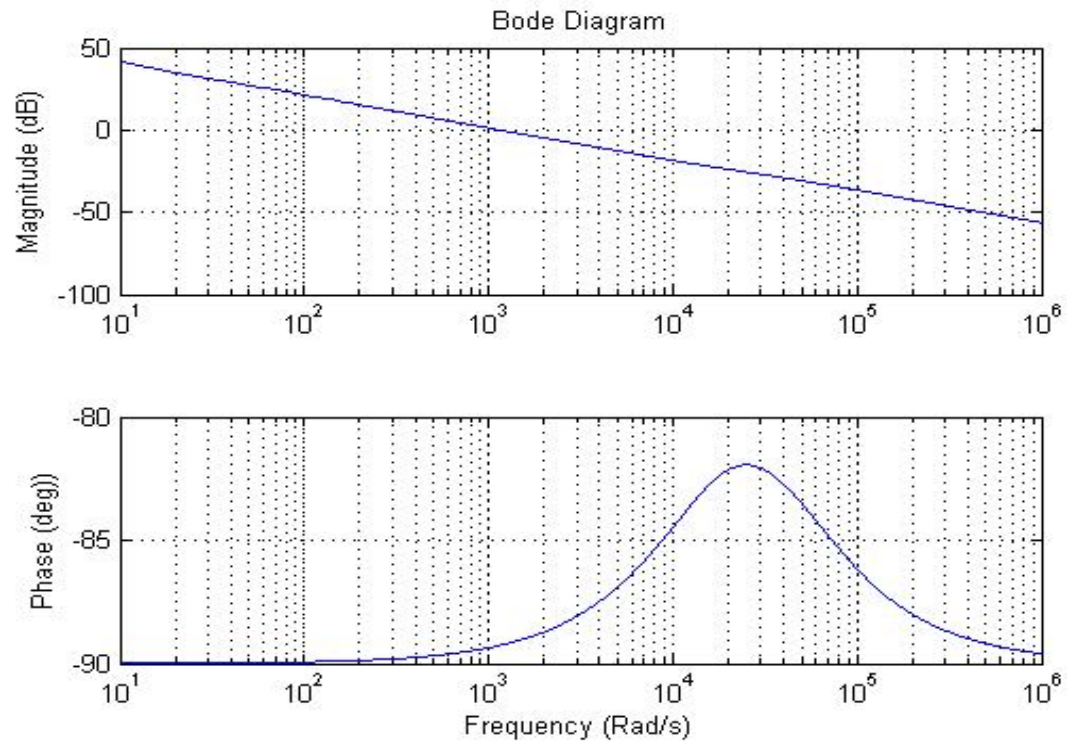


Fig 4.3 : Compensator bode plot

4.6 SIMULATION OF THE FEEDBACK WITH FILTER NETWORK

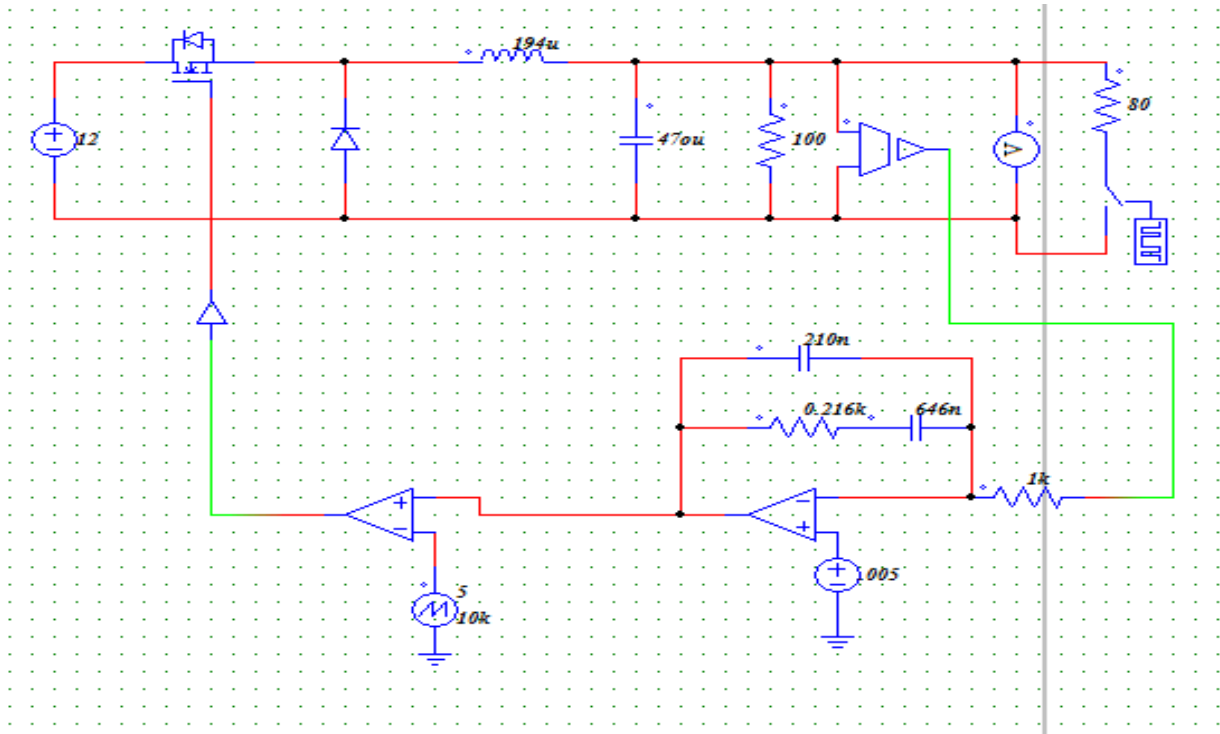


Figure 4.4 : Simulation of the feedback controlled buck in P-sim software

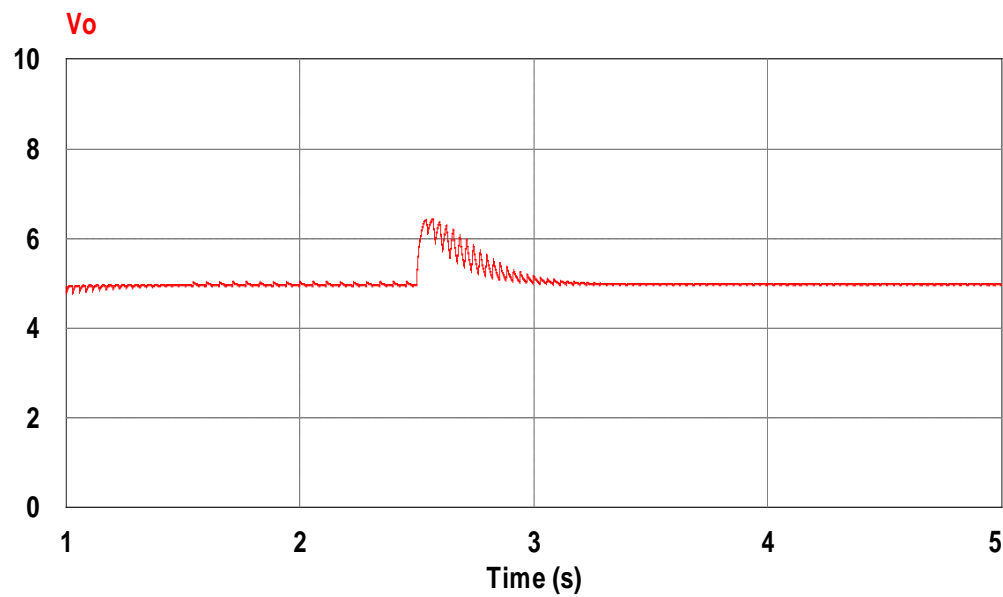
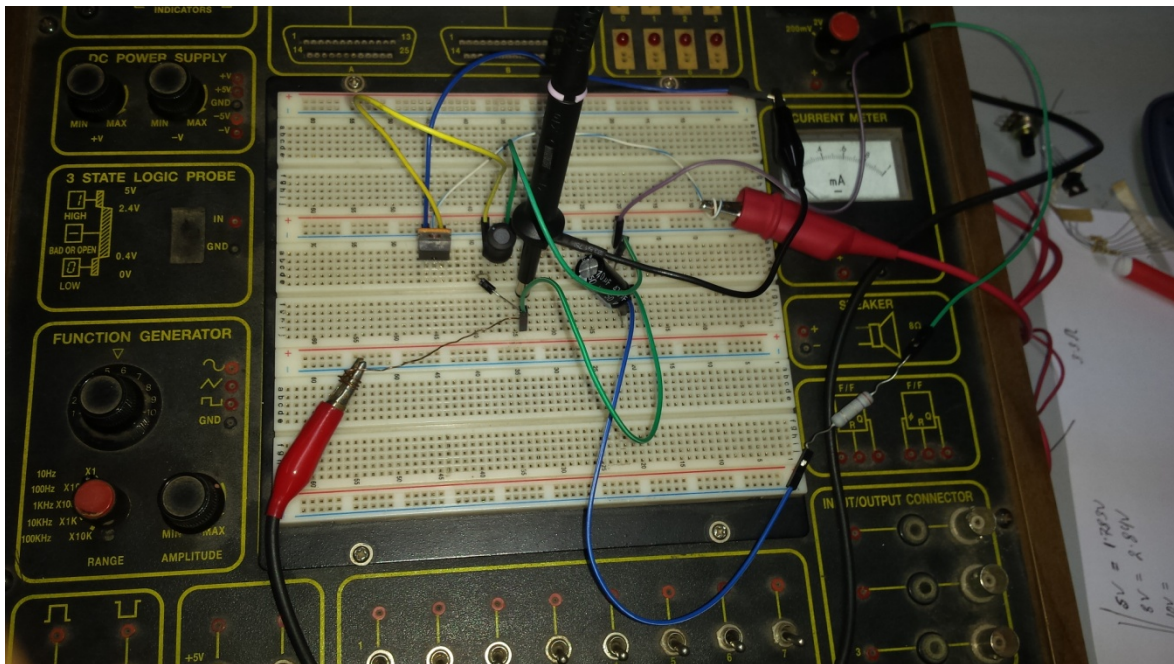


Figure 4.5: Output voltage with variable load correction

As we can see from the figure 4.4 and 4.5 that our design of the buck converter feedback circuit have given the desired constant output of 5v with adjustment to load variation. Now, we would like to implement the design on hardware. The next chapter deals with the basic design and implementation of the circuit on hardware with the help of matlab simulink.

CHAPTER 05

5.1 HARDWARE DESIGN AND IMPLEMENTATION



Though we would like to implement the hardware feedback control part with matlab-simulink coordination with arduino but the buck converter design is the most easier and convenient one as we have achieved our desired output voltage of 5V for an input of 12V but it changes with the load and input variation which is solved by our feedback controller circuit simulation on Psim software. We are hoping that in near future will design the feedback controller circuit with matlab – simulink coordination with arduino board so, that the whole thing can be controlled digitally.

The following table and graph shows the relationship between input voltage and output voltage of the buck converter open loop system that we got by implementing it in hardware.

| Vin | Vout |
|-----|-------|
| 5V | 1.84V |
| 8V | 3V |
| 10V | 3.94V |
| 12V | 4.88V |

Table 5.1 :Vin and Vout Values

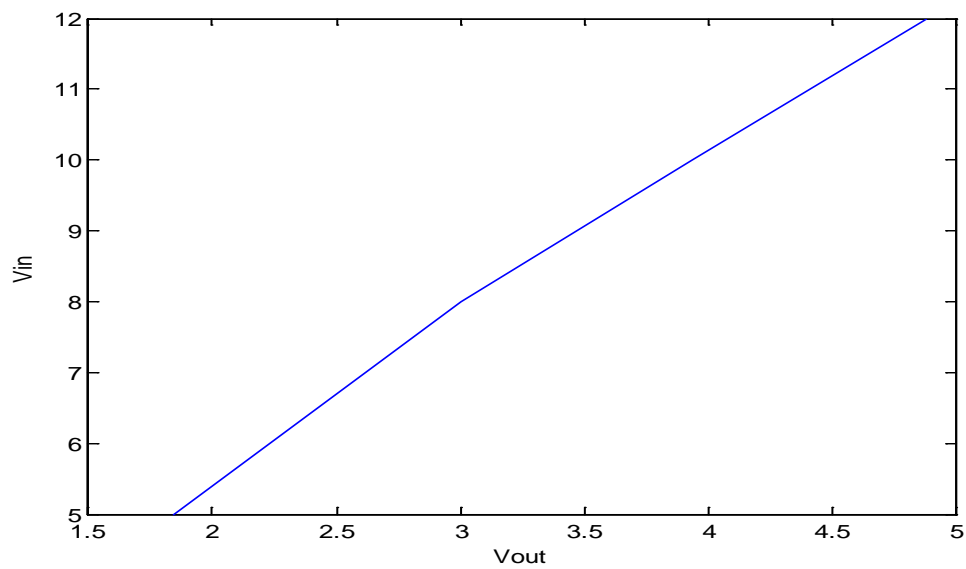


Fig 5.1: Vout vs Vin graph of Buck converter

5.2 FUTURE SCOPE:

Even though the proposed objectives have been met, there are still many improvements that could be done for this project. The project is far from completed since much improvement could be done to increase the reliability and accuracy of the converter.

Because the technology is still improving over the years, there are many types of configuration for buck converter control available in the market. For instance, there are synchronous buck converter, peak-current control buck converter and etc.

Thus, this project could be expanded by implementing peak-current mode control or synchronous buck configuration into the voltage-mode control buck converter for improvement in the controlling the output voltage. By improving the control method for the buck converter, the complexity of the design will arise, thus it will needs some study to be done in the future for such improvement.

Finally, even after such improvement, there will be more studies that could be done to improve the efficiency and reliability of the converter. The method of controlling the MOSFET by using pulse-width modulation generated by the microcontroller is one such study that could be done in the future.

5.3 CONCLUSION:

As conclusion, this project had successfully achieved its main objectives which is to develop a voltage-mode control buck converter. The closed-loop circuit simplifies the tedious work of controlling the output by automatically adjusting the duty cycle to regulate the output voltage at a particular level.

Voltage-mode control is chosen for this project since its design process is not very complex and not to mention, cheap. The controlling method is also easy to understand since it detects the voltage change through sense network and feed the signal back to the controller circuit for regulation process.

Last but not least, this project had also taught us many things in handling problems, providing and implementing solutions to solve them. Time management is also very important as last minute work can be very pressuring and tiring. Good time management is crucial since it ensures that this project can be finished on time with good quality of work.

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