Study and Design, Simulation of PWM based Buck converter for Low Power Application

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Abstract: *Now a day's dc-dc switching converters are widely used for sophisticated application. By using these converters with given dc input voltage a stabilised output voltage can be obtained by using Buck (lower), Boost (higher) or Buck –Boost (generic) topology which improves the efficiency of dc-dc converter as compared to linear regulators. Most used technique to control switching power supply is pulse width modulation (PWM). In this way a particular dc-dc converter is designed by keeping the typical application in mind. A properly designed dc-dc converter provide low ripple, better noise rejection, reliable and efficient converter. For some typical application like powering LED needs constant current supply for constant illumination, hence feedback based closed loop converters becomes better choice. In the present thesis for low power application a PWM based closed loop dc-dc buck converter has been designed, analysed and simulated. A MOSEFET has been used as switching device and components has been designed for low ripple and low noise. With variation in load and variation in input power supply output supply voltage has been obtained as constant value by using PID controller. The performance of PID controller and switching frequency has been adjusted such that the output voltage maintain at 8 V. By rigorous simulation procedure it has been obtained that for load resistance in the range of 10Ω to 35Ω and with the value of P = 8, I = 20 and at a switching frequency of 100 KHz, the output voltage provides a constant value at 7.995 V approximately. The maximum ripple value obtained is 4%.*
MATLAB has been used as a tool for simulation. The performance of converter has been analysed by controlling PID controller.

Keyword: - *Linear Regulator, Switching Regulator, Ripple/Noise, Converter, transistor switch, capacitor, diode, inductor, pulse-width modulating controller etc.*

I. Introduction

Linear regulators are great for powering very low powered devices. They are easy to use and cheap, and therefore are very popular. However, due to the way they work, they are extremely inefficient.

A linear regulator works by taking the difference between the input and output voltages, and just burning it up as waste heat. The larger the difference between the input and output voltage, the more heat is produced. In most cases, a linear regulator wastes more power stepping down the voltage than it actually ends up delivering to the target device. With typical efficiencies of 40%, and reaching as low as 14%, linear voltage regulation generates a lot of waste heat which must be dissipated with bulky and expensive heat sinks. This also means reduced battery life for your projects. A switching regulator works by taking small chunks of energy, bit by bit, from the input voltage source, and moving them to the output. This is accomplished with the help of an electrical switch and a controller which regulates the rate at which energy is transferred to the output. The energy losses involved in moving chunks of energy around in this way are relatively small, and the result is that a switching regulator can typically have 85% efficiency. Since their efficiency is less dependent on input voltage, they can power useful loads from higher voltage sources.
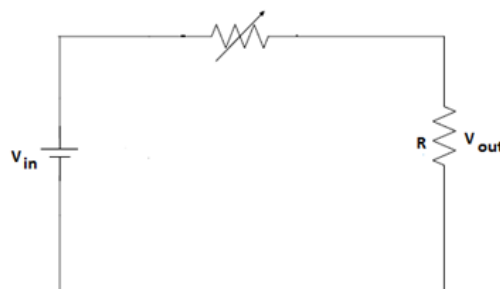

Linear Regulator

A simple Linear Regulator. If we consider an example, where V_{in}= 12V and we want to have a V_{out}= 8V. In this case we need to drop 4 volts across the regulator.

Using standard power equation: $\qquad$ P = V*I

If the output current = 10A, this will result in 10 A * 4 V = 40 W.

Now the regulator must dissipate 40 W of heat energy. This results in a mere 66.6% 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 2 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 50 KHz to 100 KHz) as show
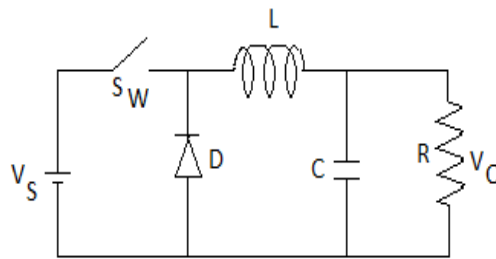
Switching Regulator

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

$$\text{Duty Cycle} = \frac{V_{out}}{V_{in}}$$

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.

Comparison between Linear Regulator and Switching Regulator

	Linear	Switching
Function	Only step down; input voltage must be greater than output.	Step up, Step down, or inverts
Complexity	Low, which usually requires only the regulator and low value bypass capacitors.	Medium to high, which usually requires inductor, diode, an filter caps in addition to the IC; for high power circuits, external FFTs are needed
Ripple/Noise	Low; no ripple, better noise rejection.	Medium to high, due to ripple at switching rate.
Efficiency	Low to medium, But actual battery life depends on load current and battery voltage over time; high if V_{in}-V_{out} difference is small.	High, except at very low load currents(μA), where switch mode quiescent current is usually higher
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.
Waste heat	High, if average load and/or input/output voltage difference are high.	Low as components usually run cool for power levels below 12W

DC-DC Converter

DC-DC converters are electronic devices that are used whenever we want to change DC electrical power efficiently from one voltage level to another. In the previous chapter we mentioned the drawbacks of doing this with a linear regulator.

Types of Converters

Currently, dc/dc converters can be divided into two broad categories:
*   Non-isolated dc/dc converters
*   Isolated dc/dc converters

Non-Isolated DC/DC Converters

The non-isolated converter usually employs an inductor, and there is no dc voltage isolation between the input and the output. The vast majority of applications do not require dc isolation between input and output voltages. The non-isolated dc-dc converter has a dc path between its input and output. Battery-based systems that don't use the ac power line represent a major application for non-isolated dc-dc converters. Point-of-load dc-dc converters that draw input power from an isolated dc-dc converter, such as a bus converter, represent another widely used non-isolated application. Most of these dc-dc converter ICs use either an internal or external synchronous rectifier. Their only magnetic component is usually an output inductor and thus less susceptible to generating electromagnetic interference. For the same power and voltage levels, it usually has lower cost and fewer components while requiring less pc-board area than an isolated dc-dc converter. For lower voltages (12V) non-isolated buck converters can be used.

Isolated DC/DC Converters

For safety considerations, there must be isolation between an electronic system's ac input and dc output. Isolation requirements cover all systems operating from the ac power line, which can include an isolated front-end ac-dc power supply followed by an isolated "brick" dc-dc converter, followed by a non-isolated point-of-load converter. Typical isolation voltages for ac-dc and dc-dc power supplies run from 1500 to 4000V, depending on the application. An isolated converter employs a transformer to provide dc isolation between the input and output voltage which eliminates the dc path between the two.

Isolated dc-dc converters use a switching transformer whose secondary is either diode-or synchronous-rectified to produce a dc output voltage using an inductor capacitor output filter. This configuration has the advantage of producing multiple output voltages by adding secondary transformer windings. For higher input voltages (48V) transformer isolated converters are more viable
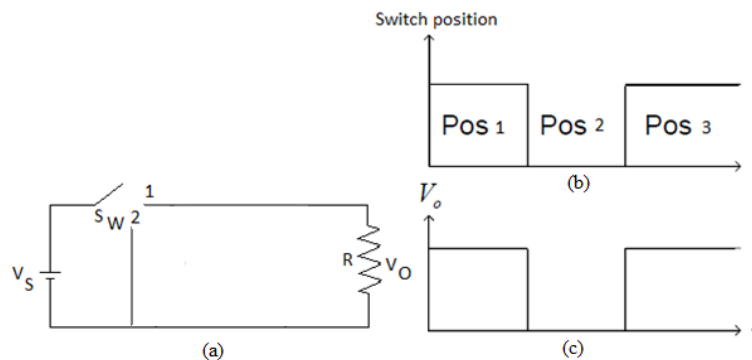
Buck Converter – Theory of Operation

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. Figure 3 shows a simplified non-isolated buck converter that accepts a dc input and uses pulse-width modulation (PWM) of switching frequency to control the output of an internal power MOSFET. An external diode, together with external inductor and output capacitor, produces the regulated dc output.
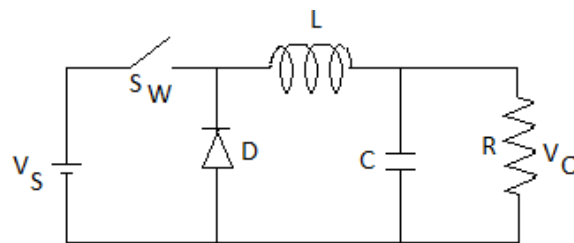

Non isolated Buck Regulator

The buck converter here onwards is introduced using the evolutionary approach. Let us consider the circuit in Figure 4(a), containing a single pole double-throw switch.


Buck Converter

The output voltage equals the input voltage when the switch is in position 1 and it is zero when the switch is in position 2. By varying the duration for which the switch is in position 1 and 2, it can be seen that the average output voltage can be varied, but the output voltage is not pure dc. The circuit in (a) can be modified as shown in belwo by adding an inductor in series with the load resistor. An inductor reduces ripple in current passing through it and the output voltage would contain less ripple content since the current through the load resistor is the same as that of the inductor. When the switch is in position A, the current through the inductor increases and the energy stored in the inductor increases. When the switch is in position 2, the inductor acts as a source and maintains the current through the load resistor. During this period, the energy stored in the inductor decreases and its current falls. It is important to note that there is continuous conduction through the load for this circuit. If the time constant due to the inductor and load resistor is relatively large compared with the period for which the switch is in position 1 or 2, then the rise and fall of current through inductor is more or less linear, as shown in Figure 5.
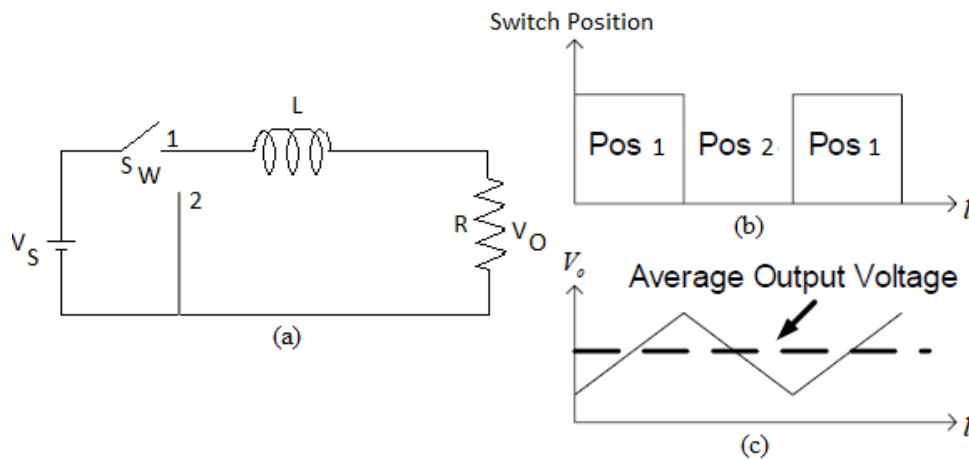
Effect of an Inductor

A capacitor reduces the ripple content in voltage across it, whereas an inductor smoothes the current passing through it. The combined action of LC filter reduces the ripple in output to a very low level.
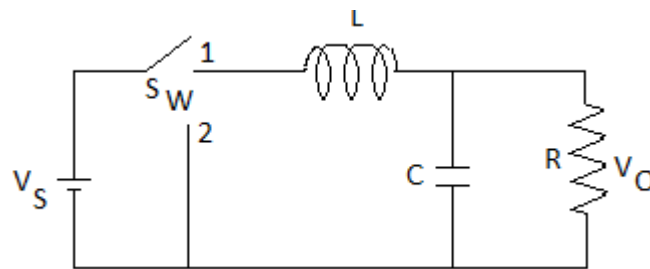
Circuit with an LC Filter

With the circuit in Figurer it is possible to have a power semiconductor switch to correspond to the switch in position 1 and a diode in position 2. The circuit that results is shown in Figure 7. When the switch is in position 2, the current will pass through the diode. The important thing now is the controlling of the power semiconductor switch.
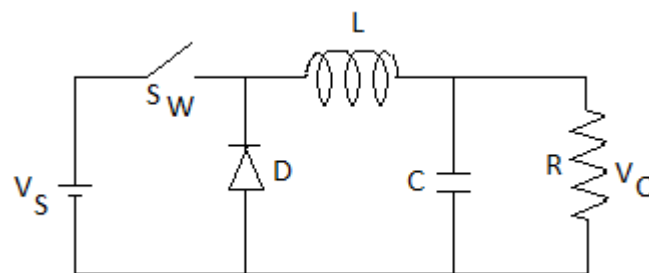
Buck converter without feedback

The circuit in Figure Bulk converter without feedback can be regarded as the most elementary buck converter without a feedback. The Buck Converter transfers small packets of energy with the help of a power switch, a diode, and an inductor and is accompanied by an output filter capacitor and input filter. All the other topologies such as the Boost, Buck-Boost Converter etc, vary by the different arrangement of these basic components.

This circuit can be further modified by adding the feedback part which is integral for a stabilizes the output. Such a circuit is shown in the Figurers below.
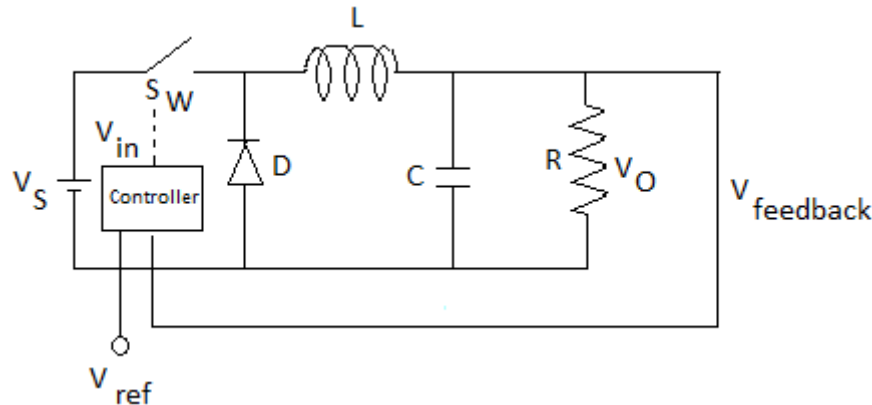
Step down Buck Converter with feedback

The PWM Controller above figure compares a portion of the rectified dc output with a voltage reference (V_{ref}) and varies the PWM duty cycle to maintain a constant dc output voltage. If the output voltage wants to increase, the PWM lowers its duty cycle to reduce the regulated output, keeping it at its proper voltage level. Conversely, if the output voltage tends to go down, the feedback causes the PWM duty cycle to increase and maintain the proper output. A buck converter or step-down switch mode power supply can also be called a switch mode regulator

Different components in the Buck Converter

Buck converter consists of five standard components:
➢ transistor switch (active switch)
➢ capacitor
➢ diode (passive switch)
➢ inductor
➢ pulse-width modulating controller

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.

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 miniaturisation trends in electronic and computer systems.

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.
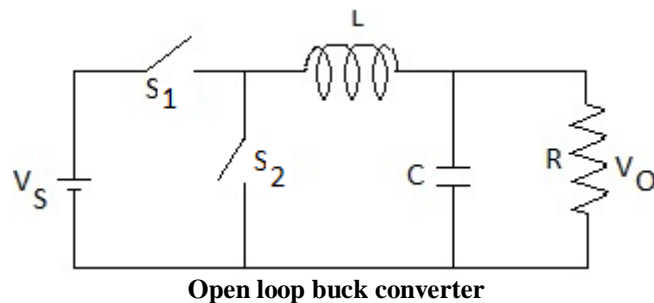
Inductor

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.

Pulse-width modulating controller

Pulse Width Modulation (PWM)
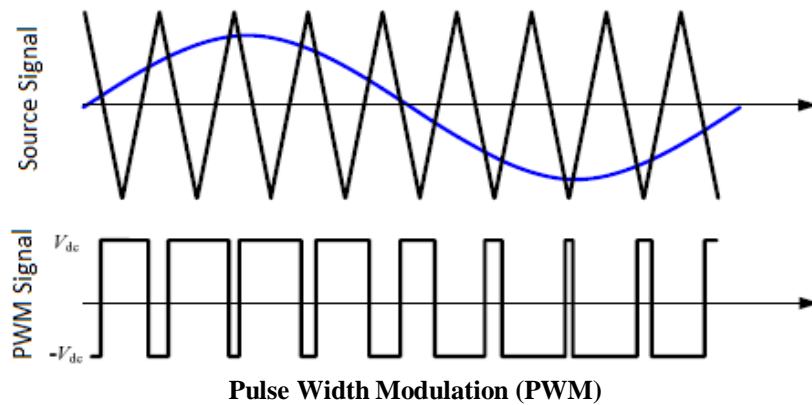
Design and analysis of Buck Converter

The buck converter is used for step down operation. A buck converter with its output filter area

Open loop buck converter

When the switch S_1 is on and S_2 is off, the input voltage appears across the inductor and current in inductor increases linearly. In the same cycle the capacitor is charged. When the switch S_1 is on and S_2 is off, the voltage across the inductor is reversed. However, current in the inductor cannot change instantaneously and the current starts decreasing linearly. In this cycle also the capacitor is also charged with the energy stored in the inductor.

Continuous Mode / Discontinuous Mode

During the ON state and then the subsequent OFF state the Buck Converter can operate in Continuous Mode or Discontinuous Mode. The difference between the two is that in CCM the current in the inductor does not fall to zero.

(a) Continuous mode　　**(b) Discontinuous mode**
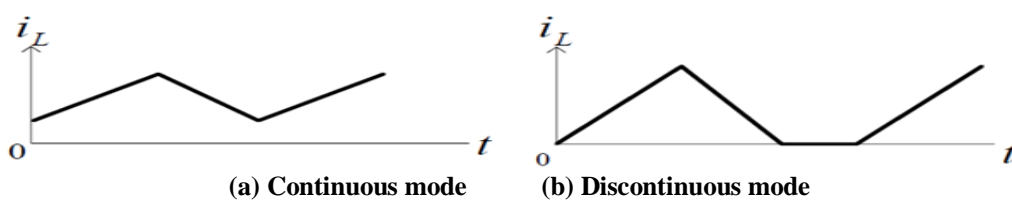
Calculation for Duty Ratio

For calculation of the duty ratio we will first of all assume that the converter is in steady state. The switches are treated as being ideal, and the losses in the inductive and the capacitive elements are neglected. Also it is important to point out that the following analysis does not include any parasitic resistances (all ideal case). The analysis also has the assumption that the converter is operating in Continuous conduction mode only i.e. $i_L(t) > 0$.When the switch is on for time duration t_{on} , the switch conducts the inductor current and the diode becomes reverse biased. This results in a positive voltage $v_L = V_d - V_o$ across the inductor in Figure 12 (a). This voltage causes a linear increase in the inductor current i_L. When the switch is turned off, because of the inductive energy storage, i_L continues to flow. This current now flows through the diode, and $v_L = -V_o$ in Figure. Since in steady-state operation waveform must repeat from one time period to the next, the integral of the inductor voltage L v over one time period must be zero, where $T_s = t_{on} + t_{off}$.

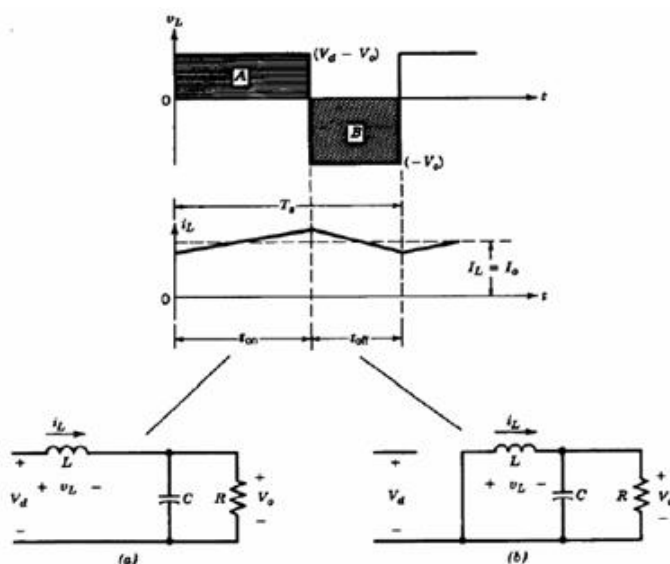$$\int_0^{Ts} vL\, dt = \int_0^{ton} vL\, dt + \int_{ton}^{Ts} vL\, dt = 0$$

It implies that areas A and B must be equal. Therefore,

$$(V_d - V_o)t_{on} = V_o(T_s - t_{on})$$

or

$$\frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D\ (Duty\ Ratio)$$

Hence in this mode, the voltage output varies linearly with the duty ratio of the switch for a given input voltage and does not depend on any other circuit parameter.

Step down converter circuit states for CCM mode: (a) Switch on; (b) Switch off

Calculation for Inductor

We can derive a simplified differential equation based on the assumption that the voltage across the load, and thereby across the capacitor, is fairly constant. The differential equation in terms of the current through the inductor, when the switch is closed, may now be written as

$$\frac{Li_L(t)}{dt} = V_d - V_o - - - - - - - - - - - - (1)$$

Assuming that the circuit has assumed steady state hence there may already be some current in the inductor, I_{Lmin} , just prior to the closing of switch S. Hence for a time interval $0 \leq t \leq T_{on} = DT$, gives:

$$i_L(t) = \frac{V_d - V_o}{L}t + I_{L,min} - - - - - - - - - - - -(2)$$

The inductor current increases linearly with time and attains its maximum value $I_{l,max}$ as $t \rightarrow T_{ON} = DT$ such that

$$I_{L,max} = \frac{V_d - V_o}{L}DT + I_{L,min} \ - - - - - - - - - - -(3)$$

Defining the change in the current from its minimum to maximum value as the peak-to-peak current ripple ΔI_L, the equation 4-6 yields an expression for ΔI_L, as

$$\Delta I_L = I_{L,max} - I_{L,min} = \frac{V_d - V_o}{L}DT - - - - - - - - - - -(4)$$

Note that the current ripple is directly proportional to D, the duty cycle, upon which we may not have any control because of the output voltage requirement. However, it is inversely proportional to the inductance L upon which we can exert some control. Thus, the current ripple can be controlled by a proper selection of the inductor.

Let us now analyze the circuit when the switch is in its open position. The inductor current completes its path through the lower side MOSFET and the corresponding differential equation, for OFF $0 \le t \le T_{OFF}$, is

$$L\frac{di_L(t)}{dt} = -V_o - - - - - - - - - - - - (5)$$

From the solution of the above first-order differential equation, we obtain
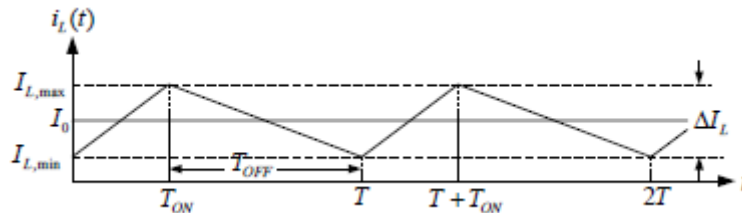
$$i_L(t) = -\frac{V_o}{L}t + I_{L,max} - - - - - - - - - (6)$$

Where $I_{L,max}$ is the maximum value of the current in the inductor at the opening of the switch or the beginning of the off period. As $t \to T_{off} = (1-D)T$, the inductor current decreases to its minimum value $I_{L,min}$ such that

$$I_{L,min} = -\frac{V_o}{L}(1-D)T + I_{L,max} - - - - - - - -(7)$$

The Eq. 7 yields another expression for the peak-to-peak current ripple as

$$\Delta I_L = I_{L,max} - I_{L,min} = \frac{V_o}{L}(1-D)T - - - - - - - -(8)$$

Inductor Current

The current through the inductor as given by Eq. 2 during the on time and by Eq. 6 during the off time is sketched in the Figure 13. The average current in the inductor must be equal to the dc current through the load. That is,
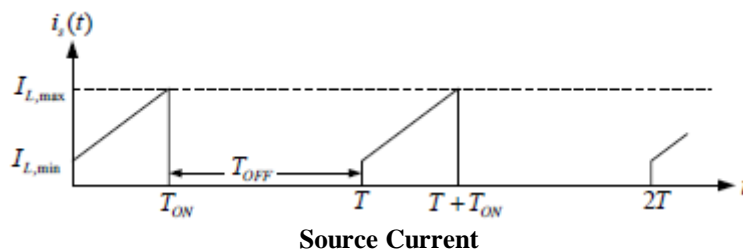
$$I_{L,avg} = I_o = \frac{V_o}{R} - - - - - - - -(9)$$

The expressions for the maximum and minimum currents through the inductor may now be written as

$$I_{L,max} = I_{L,avg} + \frac{\Delta I_L}{2} = \frac{V_o}{R} + \frac{V_o}{2L}(1-D)T - - - - - - - (10)$$

$$I_{L,min} = I_{L,avg} - \frac{\Delta I_L}{2} = \frac{V_o}{R} - \frac{V_o}{2L}(1-D)T - - - - - (11)$$

The current supplied by the source varies from $I_{L,min}$ to $I_{L,max}$ during the time the switch is closed and is zero otherwise as shown in Figure 14.

Source Current

When the switch, the inductor, and the capacitor are treated as ideal elements, the average power dissipated by them is zero. Consequently, the average power supplied by the source must be equal to the average power delivered to the load. That is,

$$V_d I_d = V_o I_o = DV_s I_s - - - - - -(12)$$

This equation helps us express the average source current in terms of the average load current as $I_s = DI_o$ the current through the lower side MOSFET is shown in Figure 15. Its average value is

$$I_{Ls} = (1 - D)I_o - - - - - - - -(13)$$

Current through low side of Mosefet
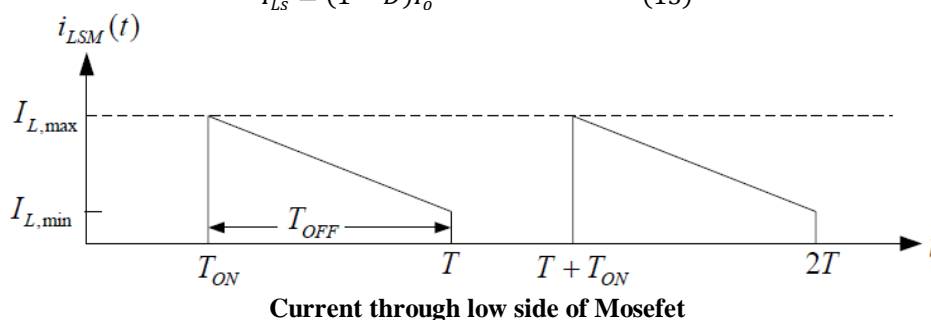
We know the fact that the buck converter can either operate in its continuous conduction mode or discontinuous mode. When it operates in the continuous conduction mode, there is always a current in the inductor. The minimum current in the continuous conduction mode can be zero. Consequently, there is a minimum value of the inductor that ensures its continuous conduction mode. It can be obtained from Eq. 11 by setting $I_{L\,min}$ to zero as

$$\frac{V_o}{R} - \frac{V_o}{2L_{min}}(1 - D)T = 0 - - - - - - - (14)$$

Hence,

$$L_{min} = \frac{1 - D}{2}RT = \frac{1 - D}{2f}R - - - -(15)$$

Calculation for Capacitor

The output capacitor is assumed to be so large as to yield $v_o(t)=V_o$. However, the ripple in the output voltage with a practical value of capacitance can be calculated by considering the waveforms shown in Figure 16 for a continuous conduction mode of operation. Assuming that all of the ripple component in i_L flows through the capacitor and its average component flow through the load resistor, the shaded area in Figure 16 represents an additional charge ΔQ.
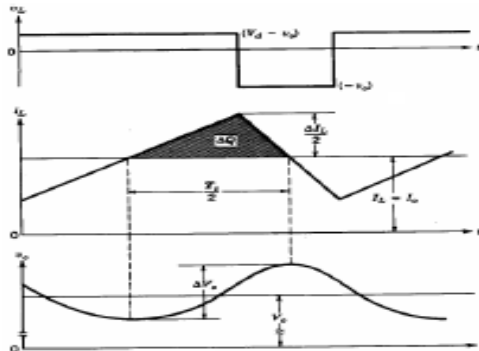
Output Voltage ripple in a step down Converter

Therefore, the peak-to-peak voltage ripple ΔV_o can be written as

$$\Delta V_o = \frac{\Delta Q}{C} = \frac{1}{C}\left(\frac{1}{2}\right)\left(\frac{\nabla I_L}{2}\right)\left(\frac{T_s}{2}\right) - - - - - - - - - (16)$$

From Figure 16 during t_{off}

$$\Delta I_L = \frac{V_o}{L}(1-D)T_s - - - - - - - - (17)$$

Therefore, substituting ΔI_L from Eq. 17 into the Eq. 16 gives

$$\Delta V_o = \frac{T_s}{8C}\left(\frac{V_o}{L}\right)(1-D)T_s - - - - - - - (18)$$

$$\frac{\Delta V_o}{V_o} = \frac{1}{8}\frac{T_s^2(1-D)}{LC} = \frac{\pi^2}{2}(1-D)\left(\frac{f_c}{f_s}\right)^2 - - - - - - - (19)$$

Where switching frequency $f_s = 1/T$ and

$$f_c = \frac{1}{2\pi\sqrt{LC}} - - - - (20)$$

Equation 19 shows that the voltage ripple can be minimized by selecting a corner frequency fc of the low pass filter at the output such that fc <<fs. Also, the ripple is independent of the output load power, so long as the converter operates in the continuous-conduction mode. We should note that in switch-mode dc power supplies, the percentage ripple in the output voltage are usually specified to be less than, for instance, 1%.

The analysis carried out above assumes ideal components and if we were to make the analysis using all the non-ideal components it would make the derivation a bit more complex with a lot of other parameters included in the final equation. But for the calculation of initial values of the components the above approximations does result in reasonable values. It is also important to realize here that the ESR and ESL are also important and can even dominate. More about how the non-ideality can affect the overall system can be found on [6].

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 [7]. 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

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.
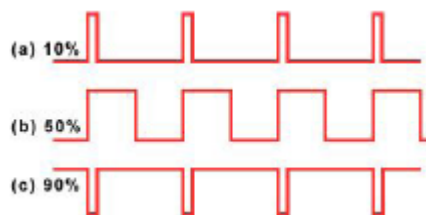
Comparator and Voltage to PWM Converter

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).
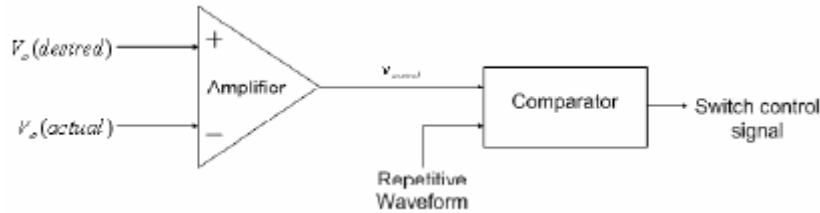
Voltage Reference Controller

The PWM switching at a constant switching frequency is generated by comparing a signal-level control voltage v control with a repetitive waveform as shown in Figure 18.
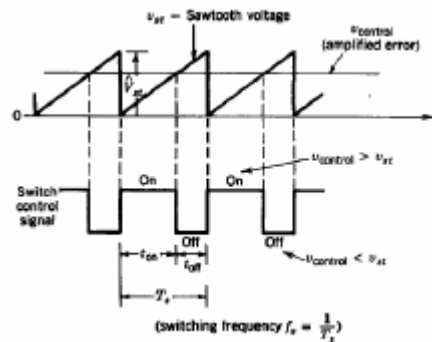

PWM Comparator Signals

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 Vst in the switch duty ratio can be expressed as

$$D = \frac{t_{on}}{T_s} = \frac{V_{control}}{V_{st}} - - - - - - (21)$$

PID Controller

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs.

With the use of PI controller the output voltage of the buck converter set to a desired value. In this chapter we vary the value of P and I so that our desired output will be achieved. For this first we set the value of P=0, and then vary the value of I=0, 10, 20, 30, 40 and so on. Then change the value of P=3, and then vary the value of I=0, 10, 20, 30, 40 and so on. Similar process will be repeated such that our desired value will not achieve.
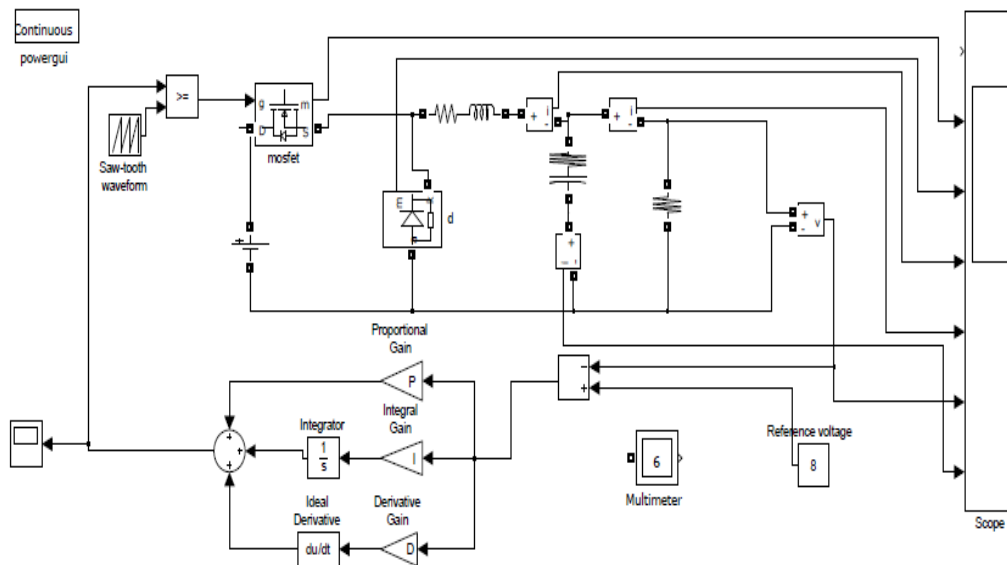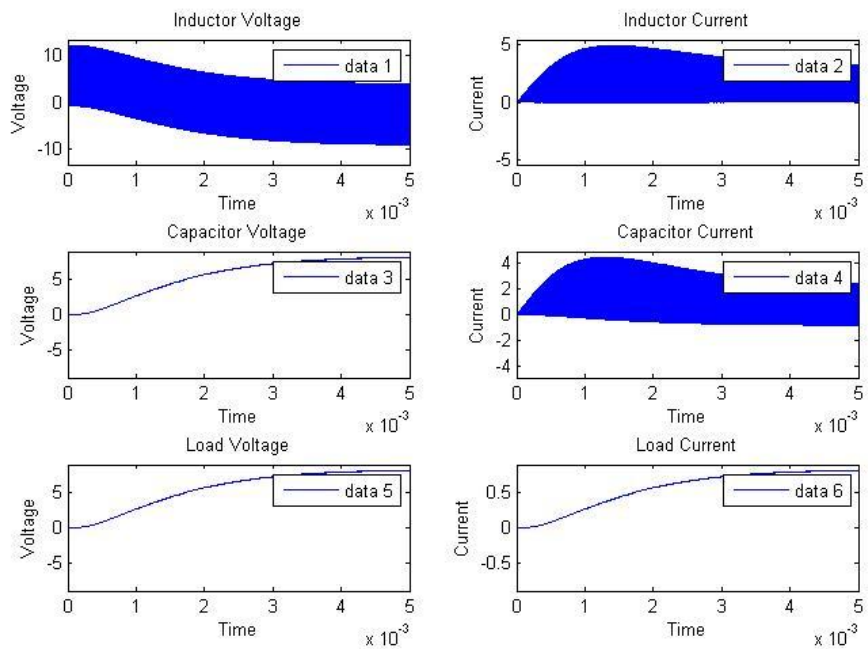
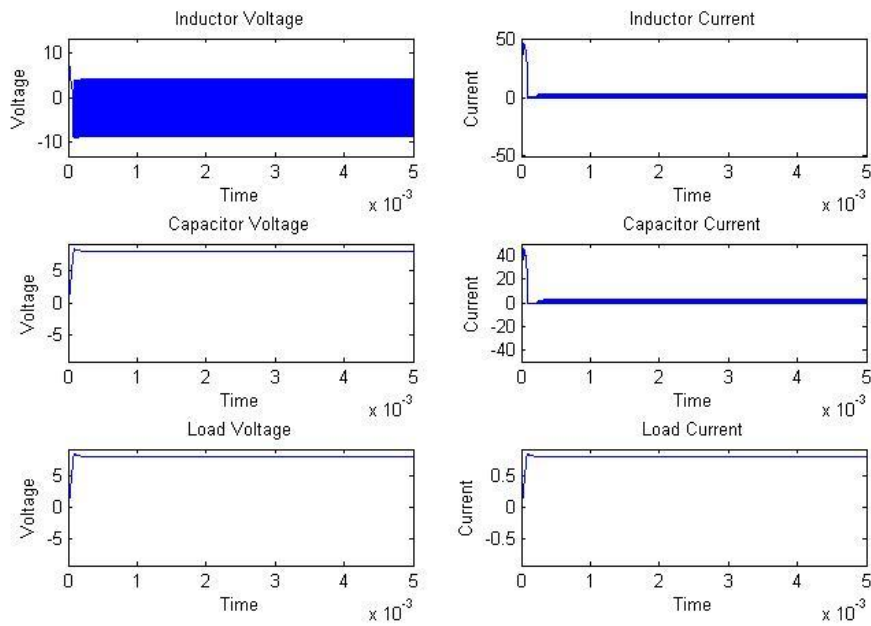**Closed loop Buck Converter Shim Power Simulation Diagram**
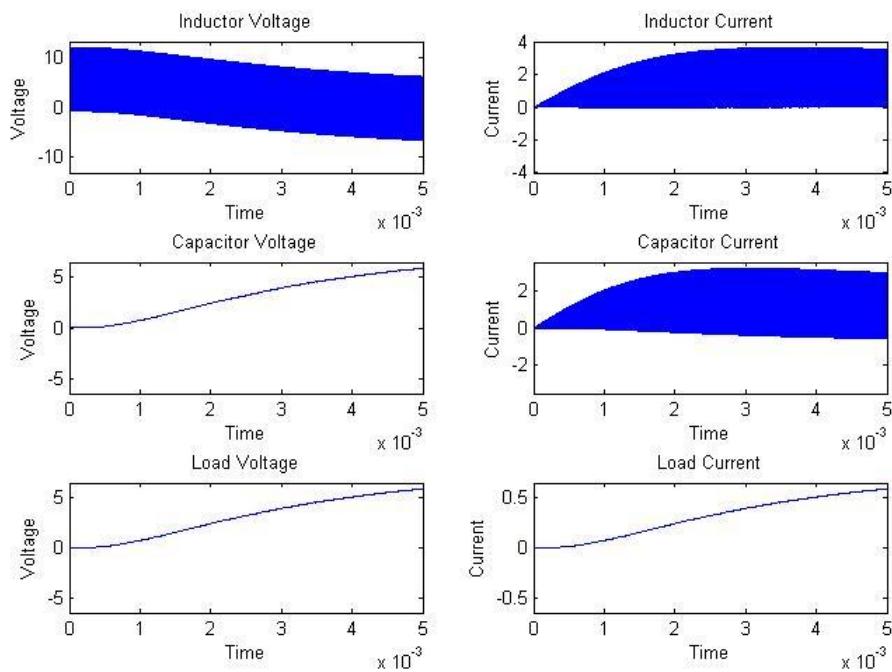
Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when P=0 and I=10
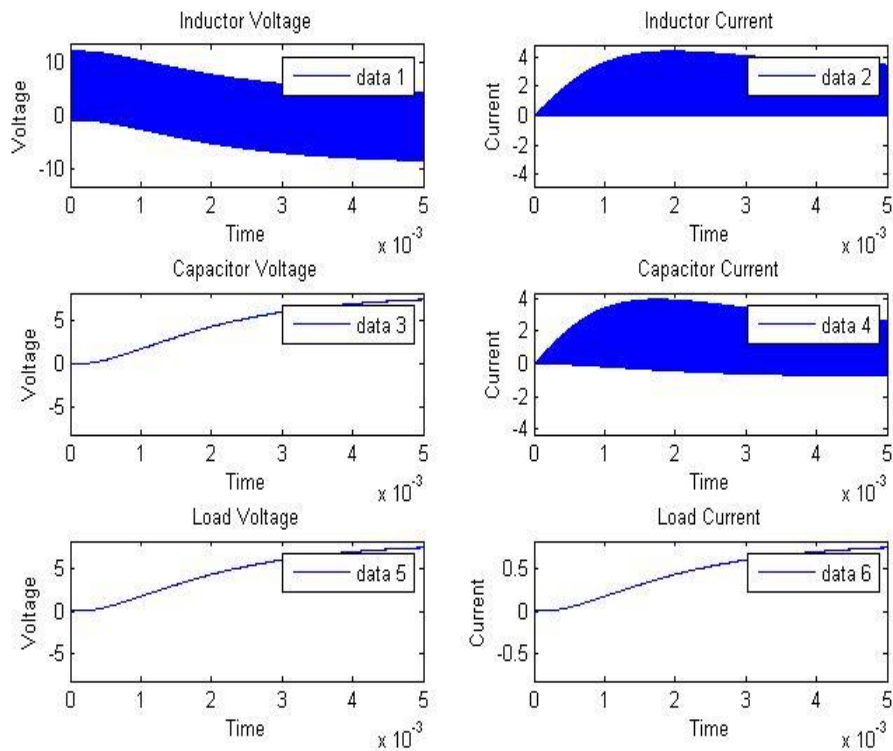
Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when P=0 and I=20

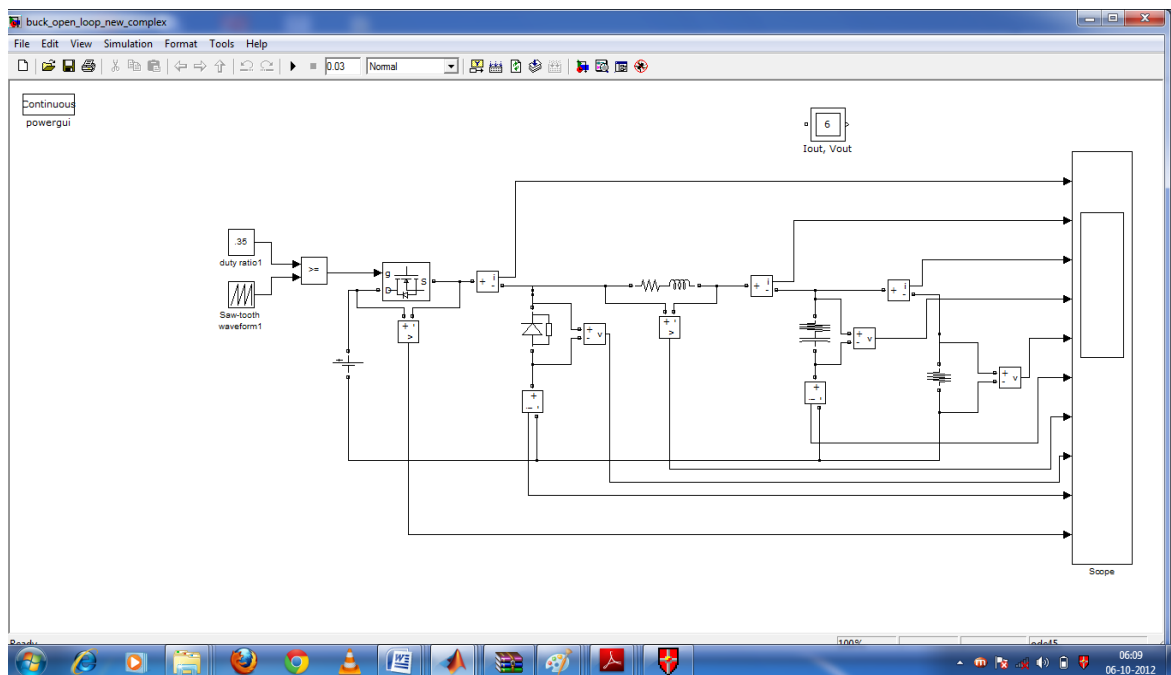**Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when P=0 and I=30**

Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when P=3 and I=0

Different Values of $V_L, I_L, V_C, I_C, V_O, I_O$ when P=0 and I=10 to 40

I	V_O	I_O	V_L	I_L	V_C	I_C
10	7.298	0.7298	0.8606	0.2055	7.298	0.5243
20	7.699	0.7699	1.05	0.213	7.699	0.5569
30	7.833	0.7833	0.7386	0.2154	7.833	0.5679
40	7.896	0.7896	1.205	0.2183	7.896	0.5714

Simulation of dc-dc buck converter for open loop :-

Simulate the open loop dc-dc buck converter and getting the output response.first we vary the load resistance keeping the supply voltage constant and then vary the supply voltage by keeping the load resistance constant.the output response is show.

Open loop Buck Converter SimPower Simulation Diagram
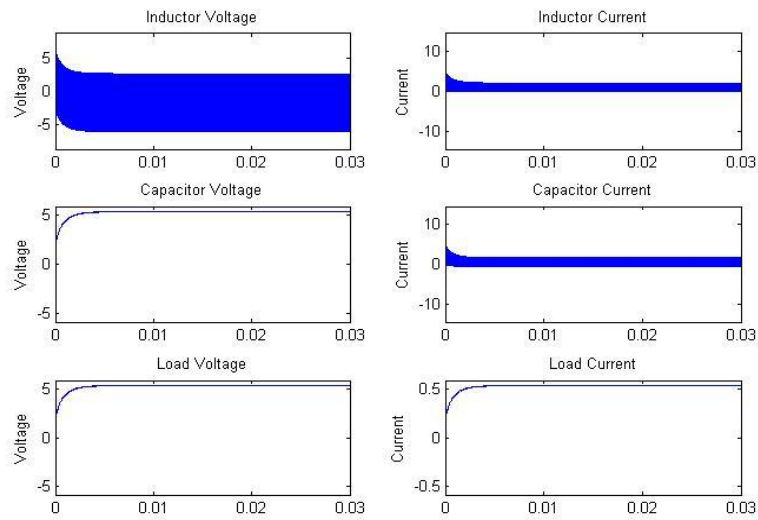
Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when Load=10Ω
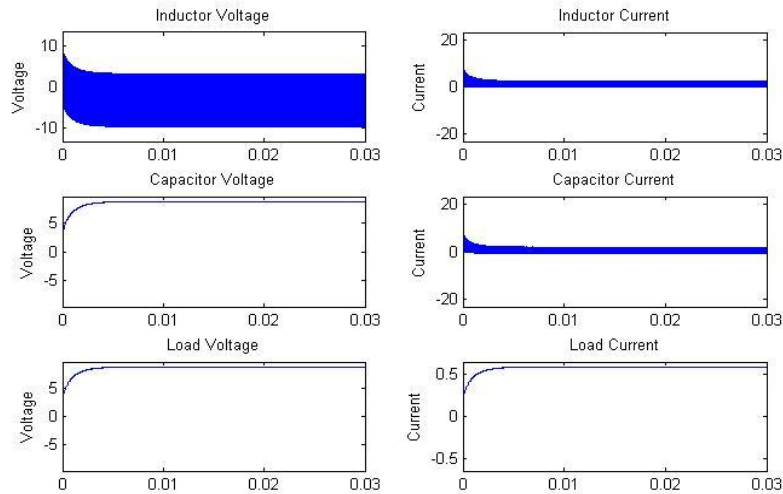
Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when Load =15Ω

Waveform of $V_L, I_L, V_C, I_C, V_O, I_O$ when Supply Voltage V_S=12V

Open loop Buck Converter Simulated Values vs. Load Resistance R

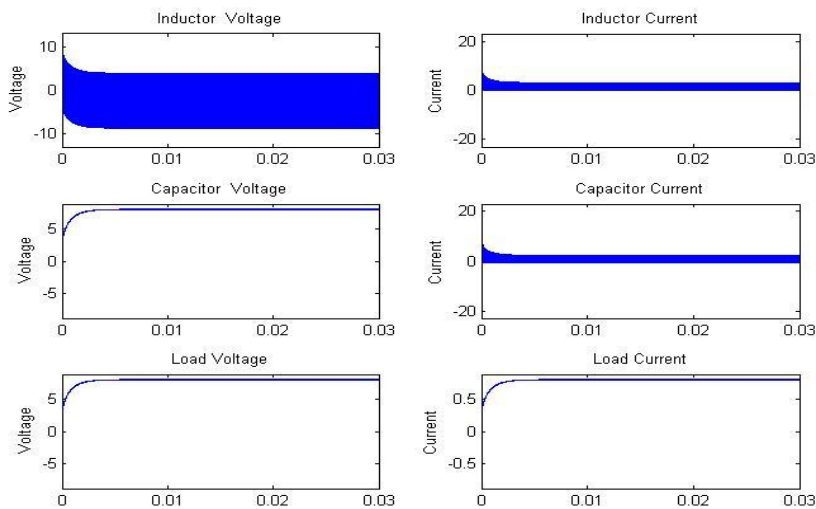| R	V_O	I_O	V_L	I_L	V_C	I_C
10	5.232	0.5233	1.879	0.09876	5.232	0.4244
15	8.662	0.5775	1.26	0.09143	8.662	0.4861
20	9.108	0.4554	4.013	0.1036	9.108	0.3518
25	9.433	0.3773	3.969	0.09374	9.433	0.2836
30	9.677	0.3226	4.046	0.08731	9.677	0.2352
35	9.863	0.2818	3.859	0.08169	9.863	0.2001
40	10.03	0.2508	3.756	0.07387	10.03	0.1769
45	10.15	0.2256	3.828	0.06937	10.15	0.1562
50	10.24	0.2047	3.871	0.06758	10.24	0.1371

Open loop Buck Converter Simulated Values vs. Supply Voltage V_S

V_S	V_O	I_O	V_L	I_L	V_C	I_C
8	5.232	0.5232	1.879	0.09876	5.232	0.4244
8.5	5.566	0.5566	1.101	0.09785	5.566	0.4588
9	5.91	0.591	0.1577	0.08391	5.91	0.5071
9.5	6.239	0.6239	0.5234	0.0916	6.239	0.5323
10	6.568	0.6568	0.4543	0.09439	6.568	0.5625

Closed loop Buck Converter Sims Power Simulation Diagram

Closed loop Buck Converter Simulated Values v/s. Load Resistance R

R	V_O	I_O	V_L	I_L	V_C	I_C
10	7.955	0.7955	1.188	0.04656	7.955	0.7489
15	7.969	0.5312	1.262	0.03165	7.969	0.4996
20	7.978	0.3989	1.093	0.02438	7.978	0.3745
25	7.986	0.3194	1.236	0.02064	7.986	0.2988
30	7.992	0.2664	1.316	0.01675	7.992	0.2496
35	7.998	0.2285	1.299	0.01505	7.998	0.2135
40	8.003	0.2001	1.294	0.01318	8.003	0.1869
45	8.007	0.1779	1.257	0.01227	8.007	0.1657
50	8.012	0.1602	1.332	0.01127	8.012	0.140

Closed loop Buck Converter Simulated Values v/s Supply Voltage

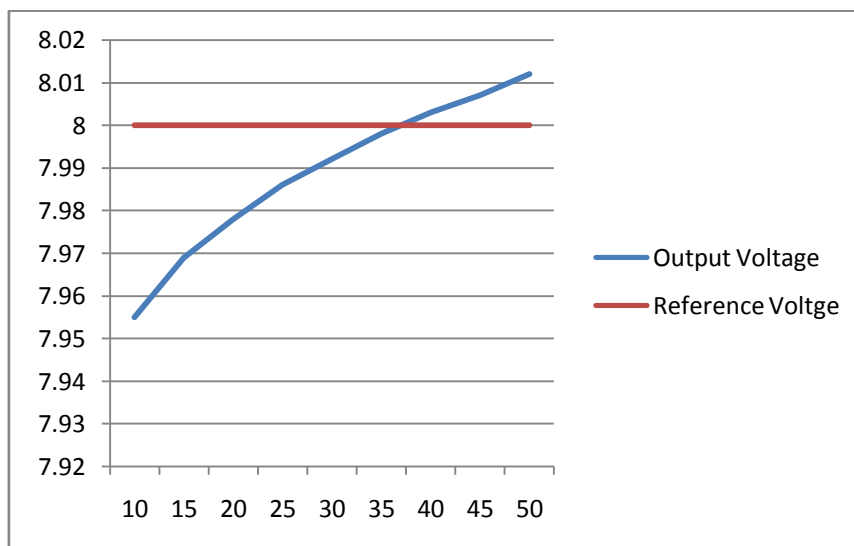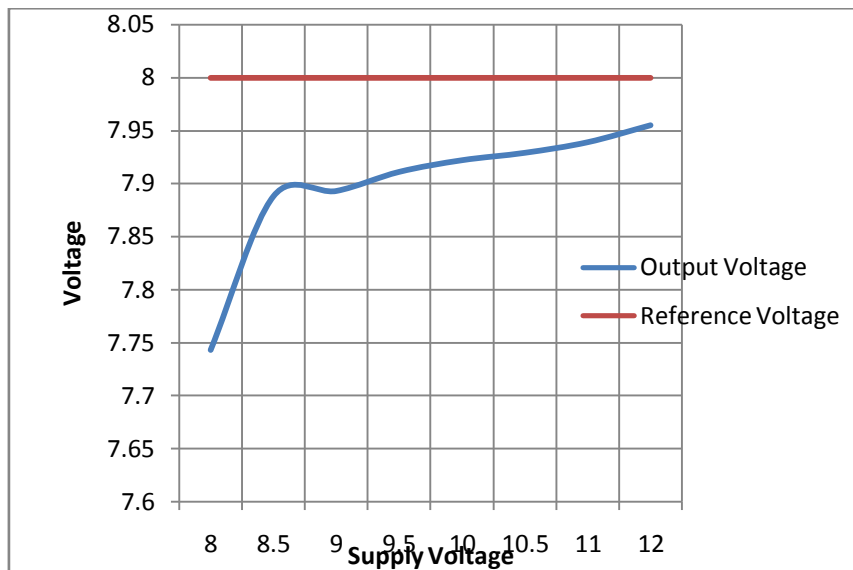| V_S	V_O	I_O	V_L	I_L	V_C	I_C
8	7.743	0.7743	0.1186	1.364	7.743	0.5901
8.5	7.888	0.7888	0.4903	0.1228	7.888	0.666
9	7.893	0.7893	0.06857	0.08389	7.893	0.7055
9.5	7.911	0.7911	0.135	0.05655	7.911	0.7345
10	7.922	0.7922	0.2823	0.04702	7.922	0.7452

Figure 58 Graph for Output voltage and reference Voltage vs Load

Graph for Output voltage and reference Voltage vs Supply Voltag

II.   Result and Conclusion
Of variation of load as well as variation in supply voltage. The simulation result shows that the output voltage vary only maximum up to 3% if we vary increase the load resistance by 250% and lower the supply voltage by 66.6%. The converter can be utilised for low power application such as to drive light

Future scope
1.   In the present thesis we use asynchronous buck converter, by using the synchronous buck converter efficiency can be improved.
2.   Here we design for low power applications, by changing the parameter of buck converter, high power application can be done.
3.   By the variation of supply voltage, load and constant parameter (P & I) output voltage can be set for a particular application where it is desired.

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