EN2110 - Electronics III

Simulation Exercise 1

Switching Circuits

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150684U
W.A.D.N. Wickramarachchi

Content

1. DC – DC Converters

Switch mode DC to DC converter are used to convert unregulated dc input into a controlled dc output at desired voltage level. The average output voltage is controlled by controlling the switch on off ratio, which is known as the duty ratio. In this assignment only non-isolated coveters are used and these converters are analyzed in the steady state.

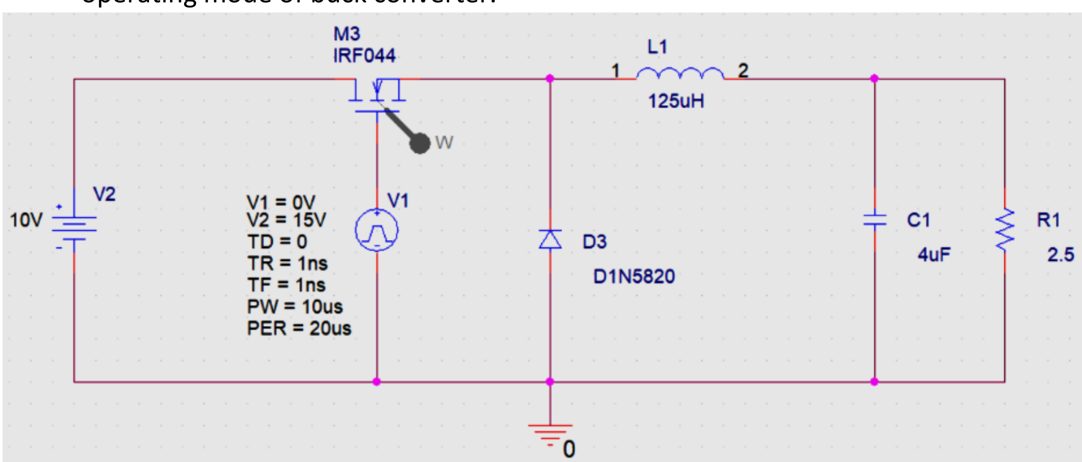
Following assumptions are carried out when designing the switching circuits Switches are treated as ideal components with no inductive or capacitive elements. DC input voltages to the converter contains no internal impedances and source is a low ripple dc voltage source. Output supplied to the load can be represented by equivalent resistance.

2. Buck Converter

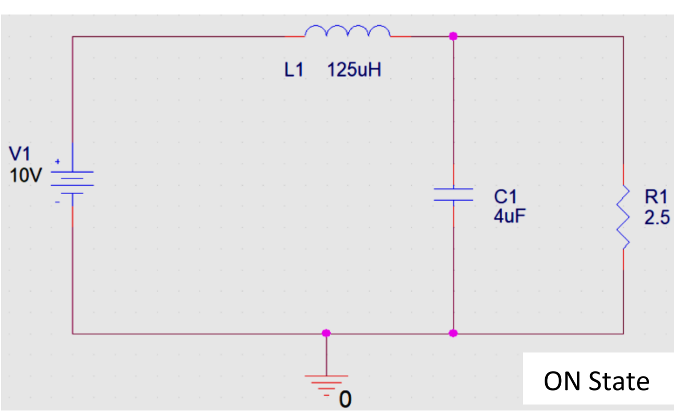
i. Introduction

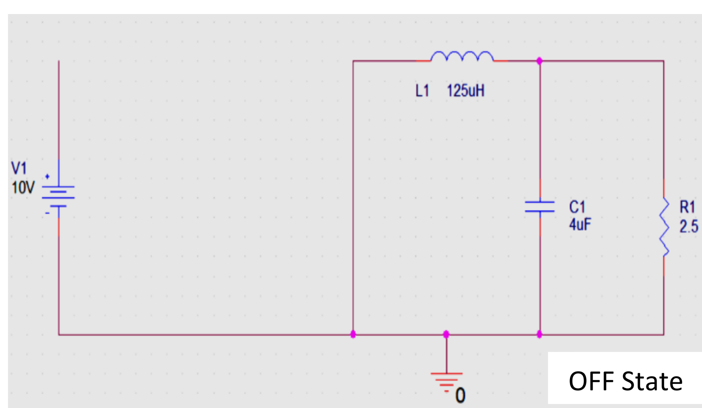
Buck converter is a step-down converter that produces a lower average output voltage than the input voltage. It is mainly used in regulated DC power supplied and Motor Controllers.

Output voltage of the buck converter is controlled by varying the duty ratio and average output voltage ratio varies linearly with control voltage. When buck converter component values are determined Continuous Conduction Mode is taken as the operating mode of buck converter.



ii. Circuit behaviors in ON-OFF states





iii. Calculations

- **Duty Ratio(D)**

For Steady State operation; waveform must repeat from one time period to another and integral of inductor voltage over one time period must be zero.(Inductor Voltage Balance)

$$\int_{T_s}^{.} V_L dt = \int_{T_{ON}}^{.} V_L dt + \int_{T_{OFF}}^{.} V_L dt = 0$$

$$(V_{in} - V_{out})T_{ON} + (-V_{out})T_{OFF} = 0$$

$$(V_{in} - V_{out})DT_s + (-V_{out})(1 - D)T_s = 0$$

$$V_{in}D + (-V_{out}) = 0$$

$$\boldsymbol{V_{out} = D.V_{in}}$$

Where D is the duty cycle,

$$D = \frac{T_{ON}}{T_s}$$

According to Buck Converter Requirements.

$$V_{out} = D.V_{in}$$

$$D = \frac{V_{out}}{V_{in}} = 0.5$$

- **Inductor Value(L)**

Considering the power output of the load,

$$P = V_{DC}.I_{DC}$$

$$I_{DC} = \frac{P}{V_{DC}} = 2A$$

Finding the current ripple corresponding to 20% of I_{DC},

$$\frac{\Delta I}{I_{DC}} = 20\% \rightarrow \Delta I = 0.2I_{DC} = 0.4A$$

Consider voltage across inductor,

$$L\frac{di}{dt} = V_L$$

$$L\frac{\Delta I}{\Delta t} = V_L$$

Considering the OFF state

$$L\frac{\Delta I}{(1 - D).T_s} = V_{out}$$

$$L = \frac{(1 - D).V_{out}}{\Delta I \ .f_s} = 125\mu H$$

Where f_s is the switching frequency of the converter is $50kHz$,

$$f_s = \frac{1}{T_s}$$

- ## Capacitor Value(C)

From Charge Balance of the Capacitor within a period,

$$\int_{T_s}^{.} i\, dt = 0$$

Assume that the ripple component of the inductor current flow completely through the capacitor,

$$\frac{1}{2}\left(\frac{T_s}{2}\right)\left(\frac{\Delta I}{2}\right) = \Delta Q$$

For output voltage ripple,

$$\Delta Q = C.(\Delta V)$$

$$\tfrac{1}{8} T_S . \Delta I \ = \ C.(\Delta V)$$

$$\Delta V = \frac{(1-D)\, V_{out}}{8LC f_s^2}$$

$$\frac{\Delta V}{V_{out}} = \frac{(1-D)}{8LC f_s^2}$$

Consider the voltage ripple corresponding to 5% of the DC output voltage.

$$0.05 = \frac{(1-D)}{8LC f_s^2}$$

$$C = \frac{(1-D)}{0.4L f_s^2}$$

$$C = 4\mu F$$

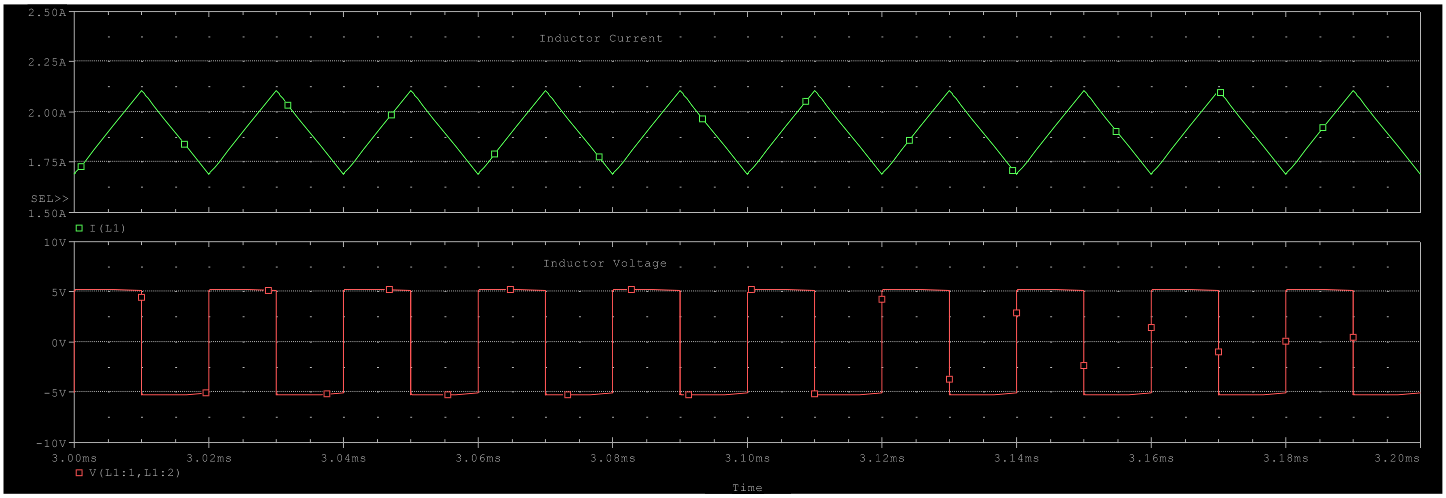
- ## Equivalent Resistance Value of Output Load(R)

Considering the power output of the load,

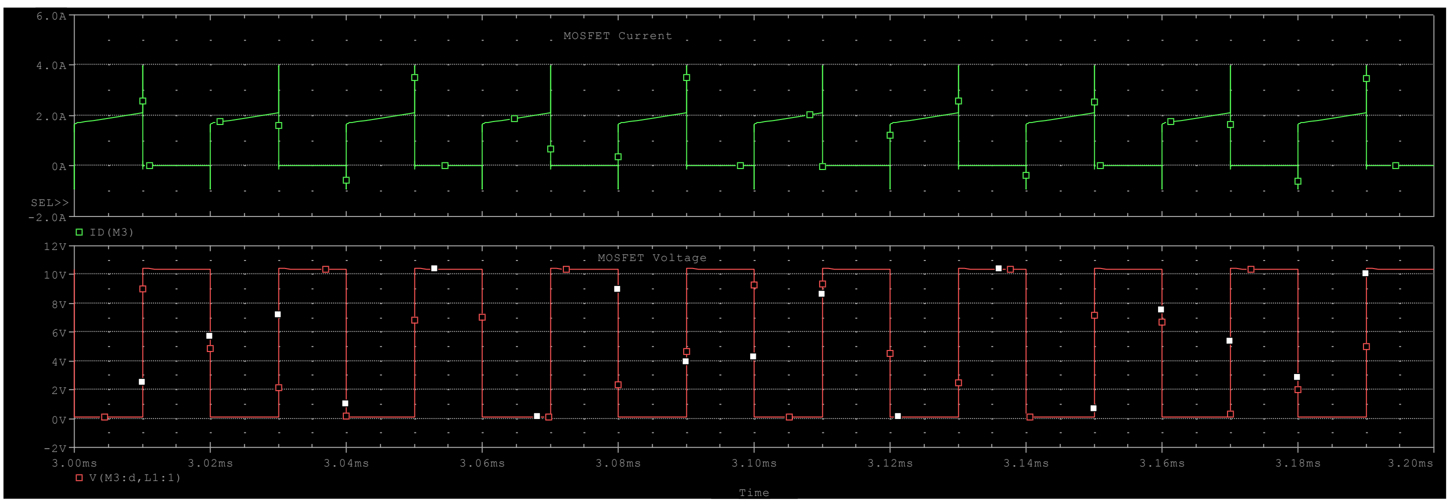
$$P = \frac{V_{DC}^2}{R}$$

$$R = \frac{V_{DC}^2}{P} = 2.5\Omega$$

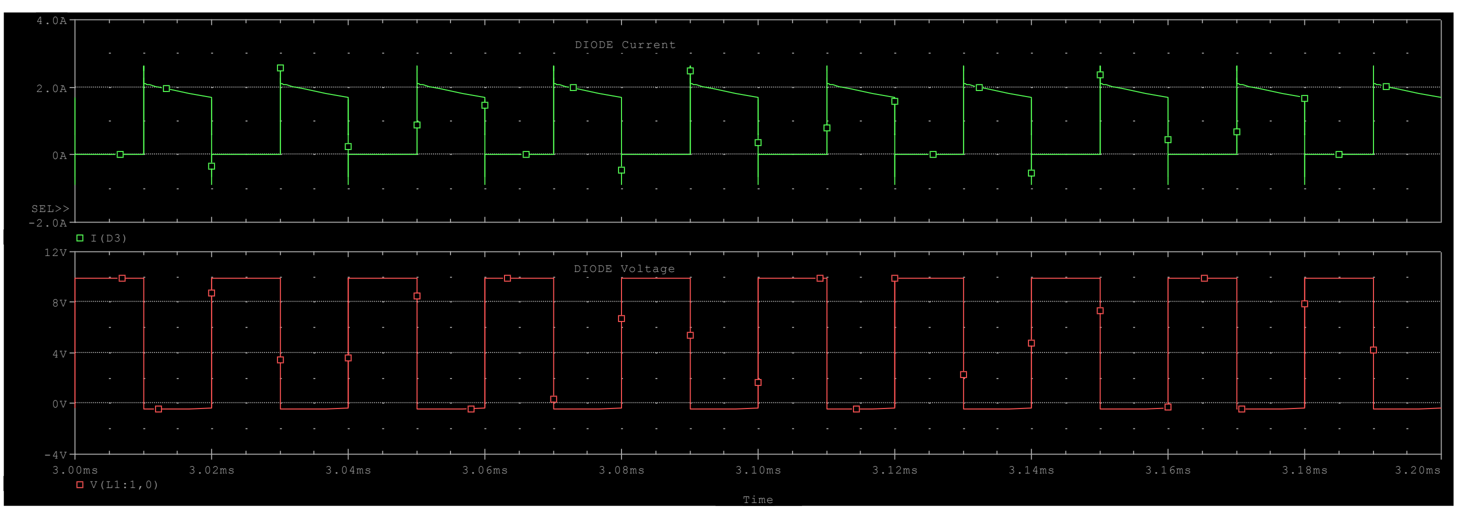
iv. Simulations



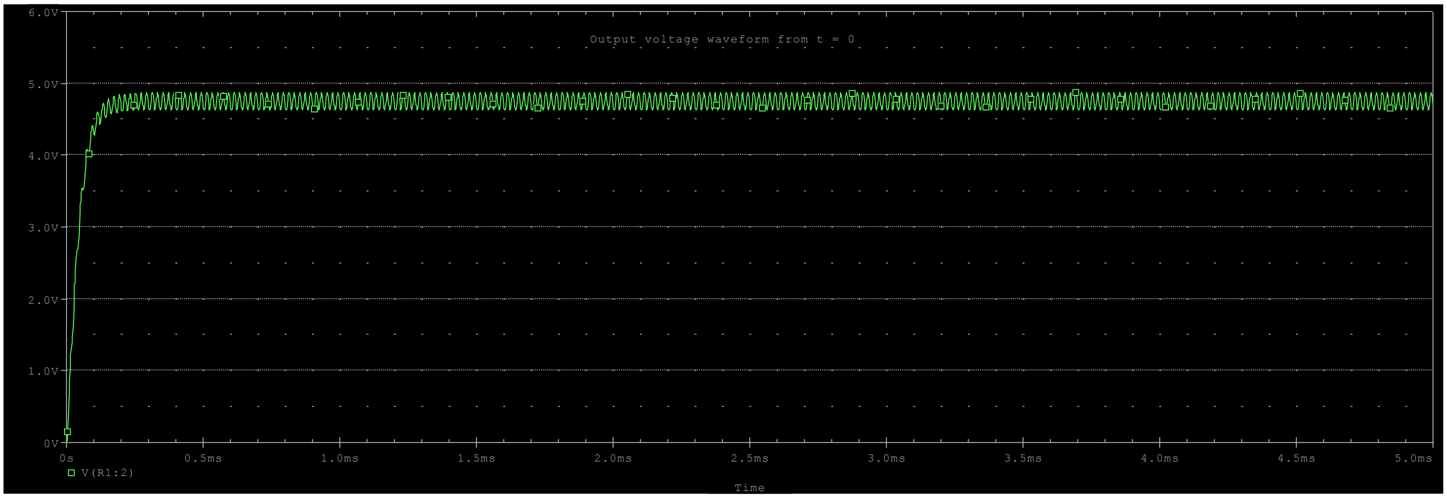
1(a) Inductor voltage and current at the steady-state



1(b) MOSFET voltage and current at the steady-state



1(c) Diode voltage and current at the steady-state



1(d) Output voltage waveform from t = 0

v. Discussion

• Output Voltage Analysis

By analyzing the Output voltage simulation at Steady State,

$$\begin{aligned} &DC\ output\ voltage &&= 4.748\ V \\ &Maximum\ output\ voltage &&= 4.867\ V \\ &Minimum\ output\ voltage &&= 4.629\ V \\ &Voltage\ ripple\ factor &&= 5.01\ \% \end{aligned}$$

According to the simulation Ripple Factor obtained is 5.01 % which is slightly deviated from the ripple factor 5% which was used in theoretical analysis.

• Output Current Analysis

By analyzing the Inductor Current simulation at Steady State,

$$\begin{aligned} &DC\ output\ Current &&= 1.899 A \\ &Maximum\ inductor\ current &&= 2.107 A \\ &Minimum\ inductor\ current &&= 1.691\ A \\ &Current\ ripple\ factor &&= 21.91\ \% \end{aligned}$$

According to the simulation Ripple Factor obtained is 21.91 % which is slightly deviated from the ripple factor 20% which was used in theoretical analysis.

• Switch Analysis

By analyzing the MOSFEFT simulation at Steady State

$$\begin{aligned} &MOSFET\ Maximum\ Current &&= 3.692\ A \\ &MOSFET\ DC\ Current &&= 1.385\ A \\ \\ &MOSFET\ Maximum\ Voltage &&= 10.433 V \\ &MOSFET\ DC\ Voltage &&= 7.2318\ V \end{aligned}$$

IRF044 - REPETITIVE AVALANCHE AND Dv/Dt RATED IRF044 HEXFET TRANSISTORS is used as the MOSFET for the Buck Converter Active Switch. It was selected due to its DC-DC converter specific design. It has very low on-state resistance combined with high transconductance; superior reverse energy and diode recovery dv/dt capability.

Its significant parameters are 20V drain to source breakdown voltage and $44A$ continuous drain current I_D.Specially this has 0.028Ω resistance at V_{GS} is 10V. Also this have very low rise time, turn of delay, turn of delay and a fall time.

By analyzing the MOSFEFT simulation at Steady State

$$\begin{aligned} &Diode\ Maximum\ Current &&= 2.645\ A \\ &Diode\ DC\ Current &&= 1.312\ A \\ \\ &Diode\ Maximum\ Voltag &&= 9.906\ V \\ &Diode\ DC\ Voltage &&= 7.205\ V \end{aligned}$$

1N5820 Schottky Barrier Plastic Rectifier is used as the Schottky Diode for the buck converter passive switch. It is selected due to its special design features such as guarding for overvoltage protection, very small conduction losses, extremely fast switching and low forward voltage drop. Also this diode is recommended to use in DC-DC converters.

Its significant parameters are maximum rms voltage $= 20V$, maximum rms current $= 3A$, maximum dc blocking voltage $= 20A$, very low resistance and very small leakage current.

- ## Power Analysis

Component	Power dissipation	Percentage
SOURCE	$9.891\ W$	–
LOAD	$9.015W$	91.14%
MOSFET	$139.624\ mW$	1.14%
DIODE	$365.662\ mW$	3.70%

Through simulations, were able to get power up to only $9.015W$ which is slightly less than expected outcome. When efficiency is considered there is an efficiency of 9114% which is a reasonable for a boost converter. It is not possible to achieve ideal power output through components due to the presence of impedance values that are not considered in calculations. (Since components are considered ideal)

3. Boost Converter

i. Introduction

This is a step-up converter. Boost converters are mainly used in regulated DC Power supplies and the regenerative braking of DC Motors. Output voltage of buck converter is always greater than input voltage.(step-up)

Output voltage of the boost converter is controlled by varying the duty ratio and, average output voltage ratio varies linearly with control voltage. When boost converter component values are determined, Continuous Conduction Mode is taken as the operating mode of buck converter.

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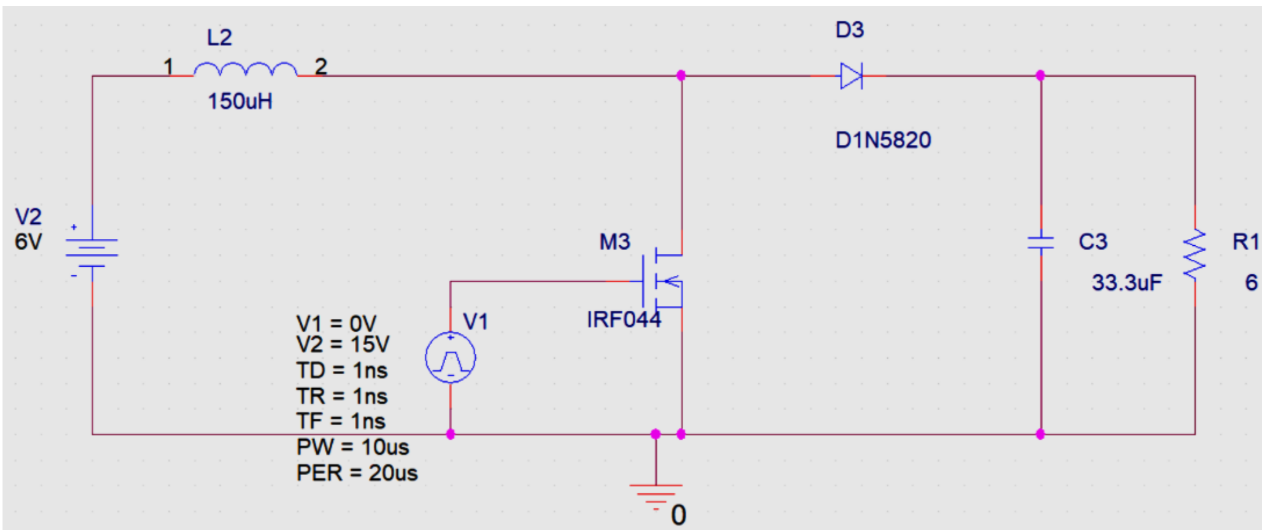
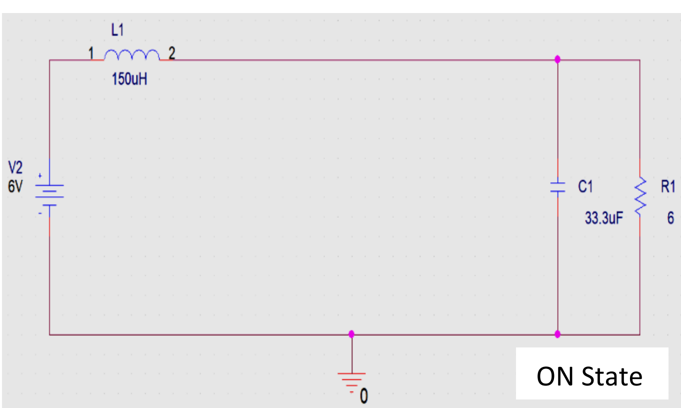
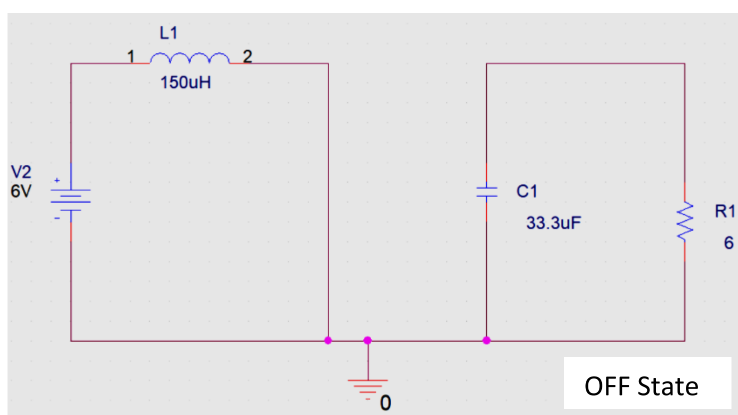


ii. Circuit behaviors





iii. Calculations

• Duty Ratio(D)

For Steady State operation; waveform must repeat from one time period to another and integral of inductor voltage over one time period must be zero.(Inductor Voltage Balance)

$$\int_{T_s} V_L dt = \int_{T_{ON}} V_L dt + \int_{T_{OFF}} V_L dt = 0$$

$$(V_{in})T_{ON} + (V_{in} - V_{out})T_{OFF} = 0$$

$$(V_{in})DT_s + (V_{in} - V_{out})(1 - D)T_s = 0$$

$$V_{in} + (-V_{out})(1 - D) = 0$$

$$\boldsymbol{V_{out} = \frac{1}{1 - D}.V_{in}}$$

According to Buck Converter Requirements.

$$V_{out} = \frac{1}{1 - D}.V_{in}$$

$$D = 1 - \frac{V_{out}}{V_{in}} = 0.5$$

Where D is the duty cycle,

$$D = \frac{T_{ON}}{T_s}$$

• Inductor Value(L)

Considering the power output of the load,

$$P = V_{DC}.I_{DC}$$

$$I_{DC} = \frac{P}{V_{DC}} = 2A$$

Finding the current ripple corresponding to 20% of I_{DC},

$$\frac{\Delta I}{I_{DC}} = 20\% \rightarrow \Delta I = 0.2I_{DC} = 0.4A$$

Consider voltage across inductor,

$$L\frac{di}{dt} = V_L$$

$$L\frac{\Delta I}{\Delta t} = V_L$$

Considering the ON state

$$L\frac{\Delta I}{D.T_s} = V_{in}$$

$$L = \frac{D.V_{in}}{\Delta I \,.\, f_s} = 150\mu H$$

Where f_s is the switching frequency of the converter is $50kHz$,

$$f_s = \frac{1}{T_s}$$

- ## Equivalent Resistance Value of Output Load(R)

Considering the power output of the load,

$$P = \frac{V_{DC}^2}{R}$$

$$R = \frac{V_{DC}^2}{P} = 6\Omega$$

- ## Capacitor Value(C)

From Charge Balance of the Capacitor within a period,

$$\int_{T_s}^{\cdot} i\, dt = 0$$

Assume that the ripple component of the inductor current flow completely through the capacitor and its average value flows through the load resistor,

$$I_o D T_s = \Delta Q \qquad \text{(Assuming constant current output)}$$

For output voltage ripple,

$$\Delta V = \frac{\Delta Q}{C}$$

$$\Delta V = \frac{I_o D T_s}{C}$$

$$\Delta V = \frac{V_{out}}{R} \frac{D T_s}{C}$$

$$\frac{\Delta V}{V_{out}} = \frac{D T_s}{RC}$$

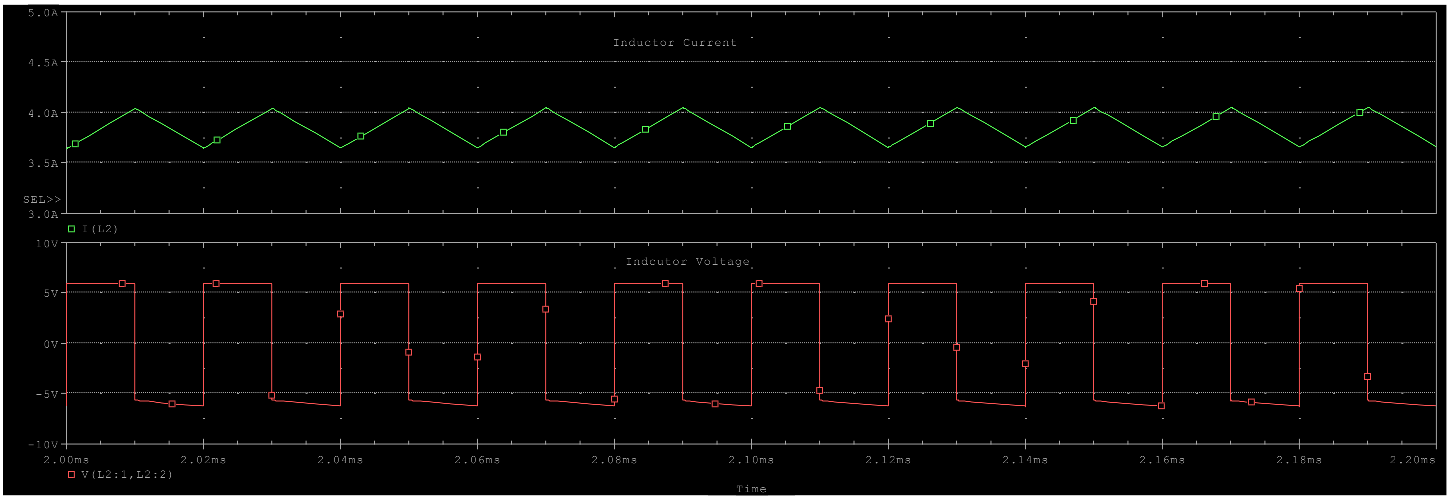
Consider the voltage ripple corresponding to 5% of the DC output voltage.

$$0.05 = \frac{D}{RC f_s}$$

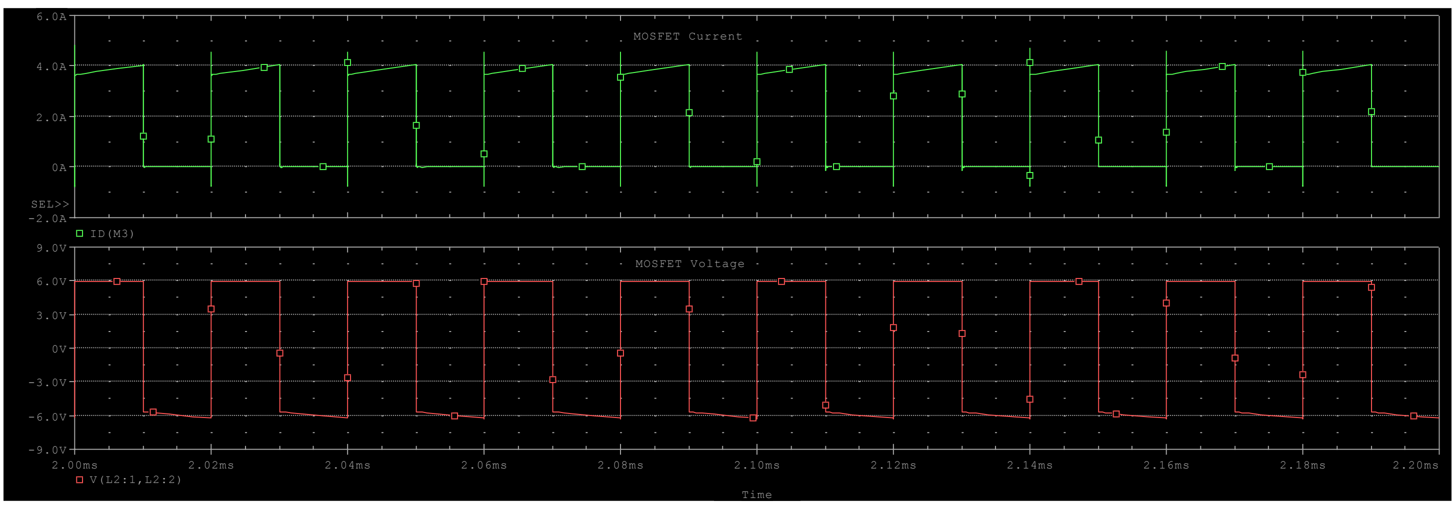
$$C = \frac{D}{0.05 R f_s}$$

$$C = 33.3\mu F$$

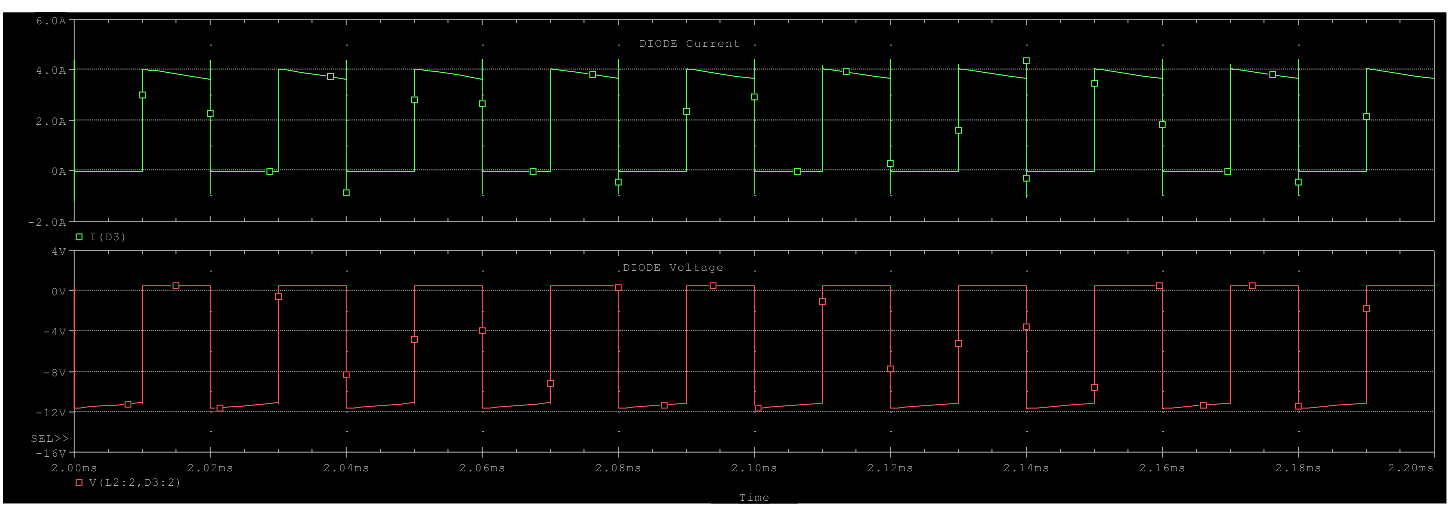
iv. Simulations



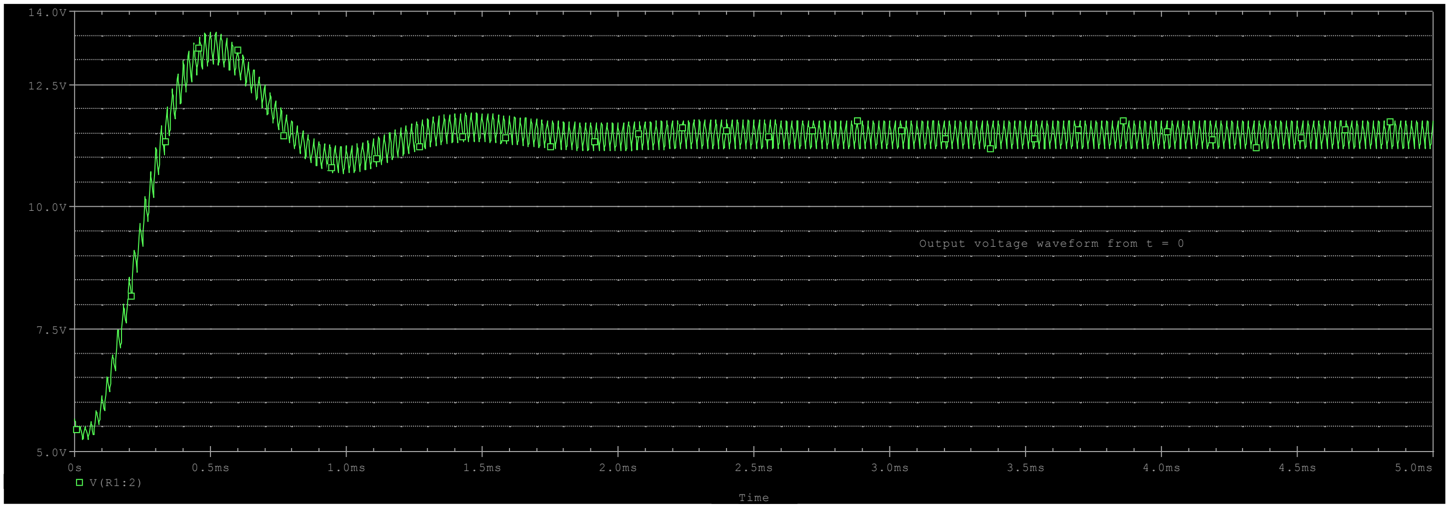
1(a) Inductor voltage and current at the steady-state



1(b) MOSFET voltage and current at the steady-state



1(c) Diode voltage and current at the steady-state



1(d) Output voltage waveform from t = 0

v. Discussion

• Output Voltage Analysis

By analyzing the Output voltage simulation at Steady State,

$$\begin{aligned} &DC\ output\ voltage &&= 11.458\,V \\ &Maximum\ output\ voltage &&= 11.760\,V \\ &Minimum\ output\ voltage &&= 11.152V \\ &Voltage\ ripple\ factor &&= 5.31\ \% \end{aligned}$$

According to the simulation Ripple Factor obtained is 5.31 % which is slightly deviated from the ripple factor 5% which was used in theoretical analysis.

• Output Current Analysis

By analyzing the Inductor Current simulation at Steady State,

$$\begin{aligned} &DC\ output\ current &&= 1.906\,A \\ &Maximum\ inductor\ current &&= 4.052A \\ &Minimum\ inductor\ current &&= 3.643\,A \\ &Current\ ripple\ factor &&= 21.4\% \end{aligned}$$

According to the simulation Ripple Factor obtained is 21.4 % which is slightly deviated from the ripple factor 20% which was used in theoretical analysis.

• Switch Analysis

By analyzing the MOSFEFT simulation at Steady State

$$\begin{aligned} &MOSFET\ Maximum\ Current &&= 4.830\,A \\ &MOSFET\ DC\ Current &&= 2.759\,A \\ \\ &MOSFET\ Maximum\ Voltage &&= 5.956\,V \\ &MOSFET\ DC\ Voltage &&= 5.9401\,V \end{aligned}$$

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Its significant parameters are 20V drain to source breakdown voltage and $44A$ continuous drain current I_D. Specially this has 0.028Ω resistance at V_{GS} is 10V. Also this have very low rise time, turn of delay, turn of delay and a fall time.

By analyzing the MOSFEFT simulation at Steady State

$$\begin{aligned}
&Diode\ Maximum\ Current &&= 4.427A \\
&Diode\ DC\ Current &&= 2.595\ A \\
\\
&Diode\ Maximum\ Voltag &&= 11.842\ V \\
&Diode\ DC\ Voltage &&= 11.689\ V
\end{aligned}$$

1N5820 Schottky Barrier Plastic Rectifier is used as the Schottky Diode for the buck converter passive switch. It is selected due to its special design features such as guarding for overvoltage protection, very small conduction losses, extremely fast switching and low forward voltage drop. Also this diode is recommended to use in DC-DC converters.

Its significant parameters are maximum rms voltage $= 20V$, maximum rms current $= 3A$, maximum dc blocking voltage $= 20A$, very low resistance and very small leakage current.

- ## Power Analysis

Component	Power dissipation	Percentage
SOURCE	$23.086W$	-
LOAD	$21.414W$	92.76%
MOSFET	$282.783\ mW$	1.22%
DIODE	$1.3319W$	5.76%

Through simulations, were able to get power up to only $21.414W$ which is slightly less than expected outcome. When efficiency is considered there is an efficiency of 92.76% which is a reasonable for a boost converter. It is not possible to achieve ideal power output through components due to the presence of impedance values that are not considered in calculations.