# JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

**Department of Electrical and Electronic Engineering (EEE)**

**BSc. Electrical and Electronic Engineering (EEE)**

**Light Current**

**Power Electronics II**

**EEE 2404**

| **<u>Reg. No.</u>** | **<u>Name</u>** |
|---|---|
| **ENE211-0235/2016** | **BERNICE MUKONESI** |
| **ENE211-0239/2016** | **TINEGA CHRISPINE** |


**DC Chopper Design and Analysis Report**

**Topology #9:**

**Boost DC Convertor**

**Input Voltage,** $V_s$: $30\ V < V_s < 42\ V$

**Output Voltage,** $V_o$: $90\ V$

**Load Current,** $I_o$: $0.5\ A < I_o < 1\ A$

**Voltage Ripple,** $\Delta V_o$: $< \pm 5\%$

**Current Ripple,** $\Delta I_L$: $CCCM$

**Frequency,** $f_{sw}$: $20\ kHz$

# ABSTRACT

This report presents the design and analysis of a DC-DC Boost Convertor in the Continuous Current Conduction Mode (CCCM). The DC-DC Boost convertor is designed using a IGBT as switch, an inductor, capacitor, diode and resistor. The mode of operation is discussed using equivalent circuits and analyzed. The expected current and voltage waveforms for each component are determined and drawn for both light and heavy loads. The effect of non-idealities in the diode and transistor are determined analytically and expressions of efficiency derived and calculated. The simulation of the design is done in MATLAB/Simulink for both light and heavy load conditions and the current and voltage waveforms for each component plotted. Simulation of the design considering non-idealities is also done and efficiency measured. The output of the simulation is validated to confirm if the simulation results match the calculated results.

## SECTION ONE

### 1. DC-DC Boost Convertor diagram, mode of operation and analysis

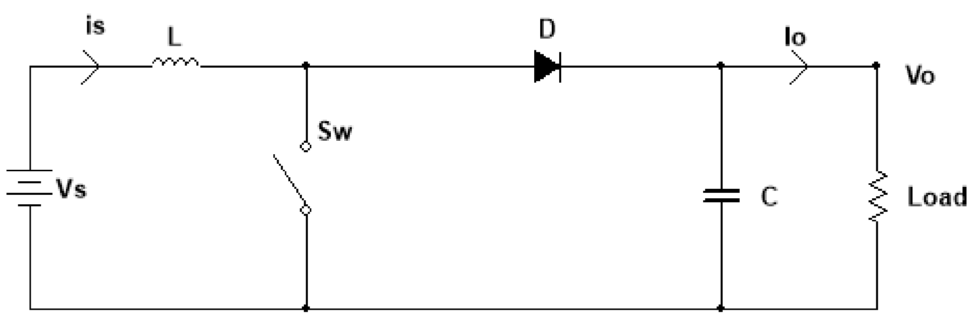



*Figure 1: DC_DC Boost Converter*

**Mode of operation**

The Boost converter increases the input DC voltage to a specified DC output voltage.
The input voltage source $V_s$ is connected to an inductor. The switch is connected across the source. The diode is connected to the capacitor, and the load – which are in parallel to each other as shown in figure 1 above.
The inductor connected to the source leads to a constant input current. The load can be seen as a constant voltage source. The switch is controlled using Pulse Width Modulation (PWM).
If the switch is ON for a time $T_{ON}$ and OFF for a time $T_{OFF}$, the period time, $T$ is defined as $T = T_{ON} + T_{OFF}$ and the switching frequency, $f_{sw} = 1/T$. The duty cycle, $D = T_{ON}/T$.
The Boost converter has two modes of operation:

**Mode 1: Switch ON** $(\mathbf{0 \leq t \leq T_{ON}})$

When the switch is ON, it provides a zero-resistance path to the flow of current – diode is OFF.

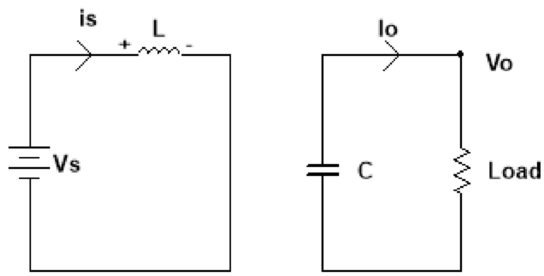



*Figure 2: Mode 1 operation*

By KVL;

$$V_s = V_L = L\frac{di_s}{dt}$$
$$\frac{di_s}{dt} = \frac{V_s}{L} = \frac{\Delta i_s}{DT}$$

Since the switch is closed for $T_{ON} = DT$, $\Delta t = DT$.

Therefore;

$$(\Delta is\,)_{closed} = \left(\frac{V_s}{L}\right)DT$$

**Mode 2: Switch OFF** $(\mathbf{0 \leq t \leq T_{OFF}})$

In this mode, the inductor is reversed. The diode is ON. The energy store in the inductor is released and dissipated in the load resistance. This maintains the flow of current in the same direction through the load and also step-up the output voltage.

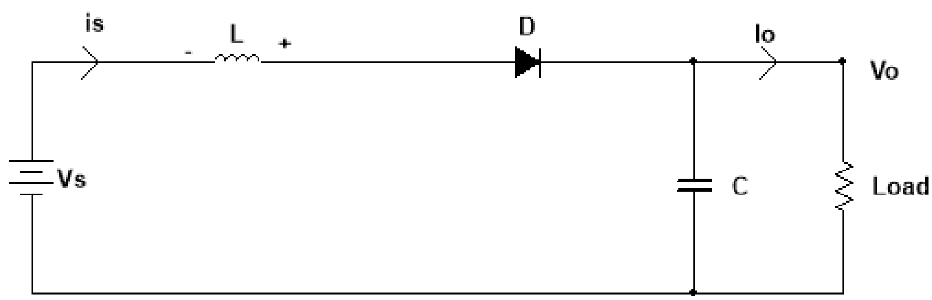



*Figure 3: Mode 2 Operation*

By KVL;

$$V_s = V_L + V_o$$

$$V_L = L\frac{di_s}{dt} = V_s - V_o$$

$$\frac{di_s}{dt} = \frac{\Delta i_s}{\Delta t} = \frac{\Delta i_s}{(1-D)T} = \frac{V_s - V_o}{L}$$

Since the switch is open for time $T_{OFF} = T - T_{ON} = T - DT = (1-D)T$

**Analysis for expressions of transfer function $\boldsymbol{M}(\propto) = \frac{\boldsymbol{V_o}}{\boldsymbol{V_s}}$**

The net change of inductor current over one complete cycle is zero;

$$\therefore (\Delta i_s)_{closed} + (\Delta i_s)_{open} = 0$$

$$\left(\frac{V_s - V_o}{L}\right)(1-D)T + \left(-\frac{V_o}{L}\right)DT = 0$$

$$\frac{V_0}{V_s} = \frac{1}{1-D}$$

Therefore;

$$\boldsymbol{M}(\propto) = \frac{V_o}{V_s} = \frac{\mathbf{1}}{\mathbf{1-D}}$$

**Analysis for expressions of inductor current $\boldsymbol{I_L}$**

Power supplied by the source is equal to the power absorbed by the load.

$$P_o = \frac{V_O^2}{R} = V_O I_O$$

Input power, $P_{in} = V_s I_s = V_S I_L$

$$V_s I_L = \frac{V_O^2}{R} = \frac{\left[\frac{V_S}{1-D}\right\}^2}{R} = \frac{V_S^2}{(1-D)^2} R$$

Solving:

$$\boldsymbol{I_L} = \frac{V_S}{(1-D)^2 R} = \frac{V_o^2}{V_S R} = \frac{\boldsymbol{V_O I_O}}{\boldsymbol{V_S}}$$

2. **Design of inductor, L and capacitor, C for ripple requirement**

Load resistance, $R_L = \frac{V_o}{I_o}$

$$R_{L_{min}} = \frac{90V}{1A} = 90\ \Omega$$

$$R_{L_{max}} = \frac{90V}{0.5A} = 180\ \Omega$$

Duty cycle, $D = 1 - \frac{V_s}{V_o}$

$$D_{max} = 1 - \frac{30}{90} = 0.6667$$

$$D_{min} = 1 - \frac{42}{90} = 0.5333$$

Critical inductance, $L_c = \frac{D(1-D)^2 R_L}{2f}$

$$L_c = \frac{D_{max}(1 - D_{min})^2 R_{L_{max}}}{2f}$$

$$L_c = \frac{0.6667(1 - 0.5333)^2 \times 180}{2 \times 20k} = 0.653\ mH$$

Verifying maximum inductance value;

$$L_c = \frac{D_{max}(1 - D_{max})^2 R_{L_{max}}}{2f} = 0.3mH$$

$$L_c = \frac{D_{max}(1 - D_{min})^2 R_{L_{min}}}{2f} = 0.3mH$$

$$L_c = \frac{D_{min}(1 - D_{min})^2 R_{L_{max}}}{2f} = 0.5mH$$

$$L_c = \frac{D_{min}(1 - D_{min})^2 R_{L_{min}}}{2f} = 0.26mH$$

$$L_c = \frac{D_{min}(1 - D_{max})^2 R_{L_{max}}}{2f} = 0.3mH$$

$$L_c = \frac{D_{max}(1 - D_{max})^2 R_{L_{min}}}{2f} -= 0.17mH$$

Inductance value to ensure CCCM, $L = L_c \times 10 = \mathbf{6.53\ mH}$

Capacitance $C$:

$$\Delta V_c = \frac{I_o \alpha}{Cf} \Rightarrow\ C = \frac{I_o \propto}{\Delta V_c f}$$

$$\Delta V_o = \pm 5\%\ \times 90 = \pm\ 4.5\ V$$

$$C = \frac{1A \times 0.6667}{4.5\ V \times 20k} = 7.4\ \mu F$$

Therefore, Capacitance, $C$ that will give $< \pm 5\%\ ripple = \mathbf{7.4\ \mu F}$

## 3. Rated values for components, manufacturer's part numbers and data sheets

**Inductor specifications:**
Choke, Common Mode, $10\ mH$, $2A$, MCT18 Series
Part No.: **MCT18X10X10C-103NU**

The selected inductor with inductance of $10\ mH$ with a $2\ A$ current rating was suitable for the design requirement of $6.53\ mH$ and a maximum inductor current of 1.5 A.

**Capacitor specifications:**
$12\ \mu F$,$100V$ Aluminum Electrolytic Capacitor
Part No.: **UPM2A120MED1TD**

A capacitor of $12\ \mu F$ was chosen, against the calculated $7.4\ \mu F$, with a peak voltage rating of $100\ V_{DC}$. This voltage rating is higher than the maximum output voltage of the circuit $V_o = 90\ V$ hence the capacitor was suitable for this application with safe operation.

**Diode specifications:**
3 A, 100V, Schottky Barrier Rectifiers
Part No.: **MBR3100G**

The diode selected had a reverse breakdown voltage, $V_R = 100V$. This rating is higher than the voltage it is subjected to of around $-90\ V$ when it is not conducting hence it can tolerate the operation of the circuit.
Forward current rating of $3A$, which is above the forward current through the diode $I_D = 2.5A$ as per the design hence the diode can withstand the system's ratings.

**IGBT specifications:**
**600V, 40A Field Stop IGBT**
Part No.: **FGH40N60SF**

The maximum stress on the switch during off state is $V_{sw(max)} = 39V$. From the datasheet, the maximum collector to emitter voltage $V_{CES} = 600\ V$ - greater than $V_s$ hence it is suitable to operate in the circuit without damage.
The maximum current through the switch during ON state $I_{SW(max)} = 1.7A$. From the datasheet, the maximum collector current, $I_C = 40A$ hence the IGBT can accommodate the drain current without thermal damage.

4. **Expected current and voltage waveforms for each component in both light and heavy load conditions**.

[Waveforms attached]

**Load Current**

Light load current is expected to be 0.5 A and heavy load current 1 A.

Then the switch is turned ON, the load current increases exponentially until the maximum current is reached.

When the switch is turned OFF, the capacitor discharges current to the load then later charges when the switch is turned ON again. This cycle continues thus a continuous supply of current to the load.

**Diode Current**

When the switch is turned OFF, the low resistance path to current is removed and the inductor's polarity changes. The diode is forward biased and current flows. When the switch is turned ON, the diode is reverse biased and no current flows.

**Capacitor Current**

When the switch is ON, the capacitor supplies current to the load decreasing exponentially with time controlled by a time constant $\tau = RC$. When the switch is OFF, part of the supply current goes through the capacitor which increases exponentially as it charges.

**Inductor Current**

The current through the inductor increases gradually until the maximum value when the switch is turned ON but decreases exponentially once the switch is turned OFF to minimum value.

**Switch Current**

Current only flows through the switch when it is turned ON. Current through is the same as that of the inductor during the period.

**Load Voltage**

When the switch is ON, the voltage across the capacitor is reflected on the load. When the switch is OFF, the source is connected to the load hence the capacitor charges. The load's voltage rises as the capacitor charges.

**Diode Voltage**

The diode is forward biased and only conducts when the switch is OFF. When the switch is ON, the diode is reverse biased as the polarity on the inductor. Hence the voltage that appears across the diode is that of the load.

**Capacitor Voltage**

When the switch is OFF, the capacitor is connected to the source voltage and the charged inductor and charges. Voltage therefore increases gradually until fully charged according to Lenz's law. When the switch is ON, the capacitor is disconnected from the supply. However, the capacitor is still in a closed circuit with the load. The voltage across it decreases exponentially as it supplies the load with its stored energy.

**Inductor Voltage**

When the switch is ON, the source voltage appears across the inductor and will try to pass current (I=V/R) abruptly through the inductor. But according to Lenz's law, the inductor will oppose this change in current. The current will gradually increase until it reaches its final value. At the same time, voltage across the inductor will decrease gradually until it reaches zero. When the switch is OFF, the polarity of the inductor changes. The current continues to flow in the same direction, but now through the diode and the load.

**Switch Voltage**

When the switch is ON, the voltage across the switch is 0V for an ideal one. If non-idealities are considered, voltage drop across the switch is given by: $V_{sw} = R_{ON} \times i_L$.

5. **Effect of non-idealities and derivation of expressions for efficiency**

Non-idealities cause a significance voltage drop across the inductor, transistor, switch and diode, which consequently causes a reduction in the overall efficiency of the circuit.

**Diode**

During $T_{ON}$;

$$V_L = V_S$$

During $T_{OFF}$;

$$V_L = V_S - V_{DON} - V_O$$

Applying Volt-Second Rule;

$$\int_0^{T_{ON}} (V_S)dt + \int_0^{T_{OFF}} (V_S - V_{DON} - V_0)dt = 0$$

$$DV_S + (1 - D)(V_S - V_{DON} - V_O) = 0$$

$$V_S - V_{DON} + DV_{DON} = V_O(1 - D)$$

$$V_O = \frac{V_S - V_{DON} + DV_O}{1 - D}$$

From the analysis, it can be noted that $V_{DON}$ decreases the output voltage by $\frac{V_{DON}}{1-D}$

**Switch**

During $T_{ON}$;

$$V_L = V_S - V_{TON}$$

During $T_{OFF}$;

$$V_L = V_S - V_O$$

Applying Volt-Second Rule;

$$\int_0^{T_{ON}} (V_S - V_{TON})dt + \int_0^{T_{OFF}} (V_S - V_0)dt = 0$$

$$D(V_S - V_O) + (1 - D)(V_S - V_O) = 0$$

$$V_S - DV_{TON} + DV_O = V_O(1 - D)$$

$$V_O = \frac{V_S - DV_{TON} + DV_O}{1 - D}$$

From the analysis, it can be noted that $V_{TON}$ decreases the output voltage by $\frac{DV_{TON}}{1-D}$.

Combining both the effects of $V_{DON}$ and $V_{TON}$:

$$V_O = \frac{V_S - V_{DON} - DV_{TON} + DV_O}{1 - D}$$

The expression for efficiency can therefore be calculated:

Percentage efficiency, $\%\,\eta = \frac{V_O - losses}{V_O} \times 100$

$$\%\,\eta = \frac{\frac{V_S - V_{DON} - DV_{TON} + DV_O}{1 - D}}{\frac{V_S + DV_O}{1 - D}} \times 100 = \frac{V_S - V_{DON} - DV_{TON} + DV_O}{V_S + DV_O} \times 100$$

Therefore;

$$\%\,\eta = \frac{V_S - V_{DON} - DV_{TON} + DV_O}{V_S + DV_O} \times 100$$

6. **Efficiency of the circuit taking values of $V_{DON} = 0.5\ V$ and $V_{TON} = 0.9\ V$ in both light and heavy load conditions.**

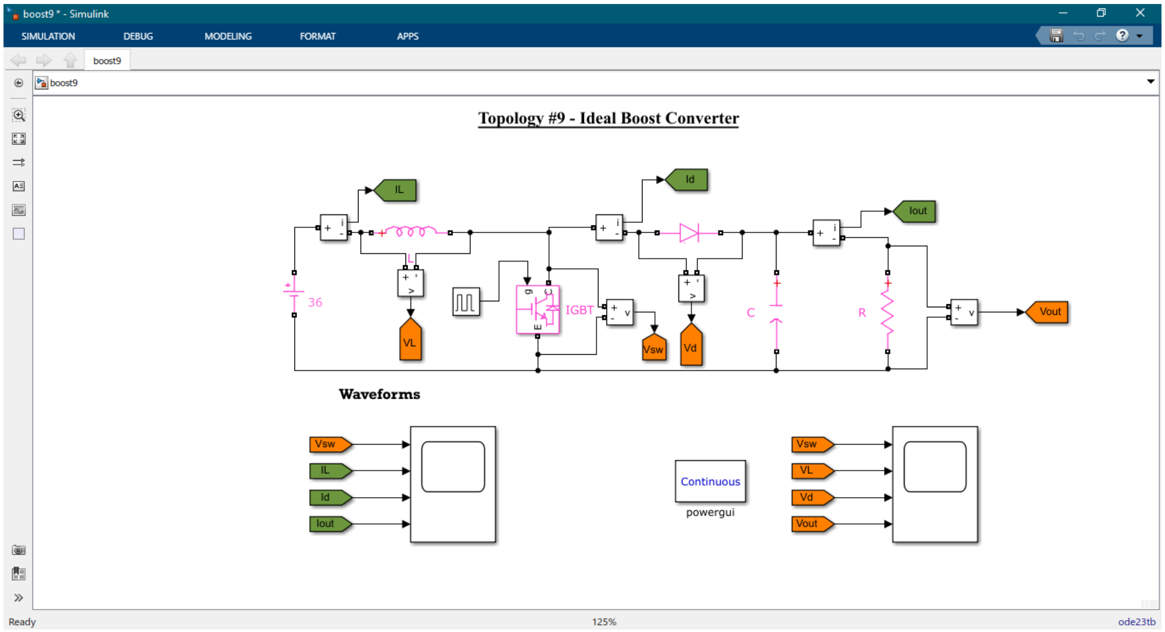
   Substituting the values of $V_{DON}$, $V_{TON}$, $V_S$, $V_O$ and $D$ in the expression for $\%\,\eta$:

$$\%\,\eta = \frac{V_S - V_{DON} - DV_{TON} + DV_O}{V_S + DV_O} \times 100$$

$$= \frac{36 - 0.5 - 0.6667(0.9) + 0.6667(90)}{36 + 0.6667(90)} \times 100 = \mathbf{98.85}\ \%$$

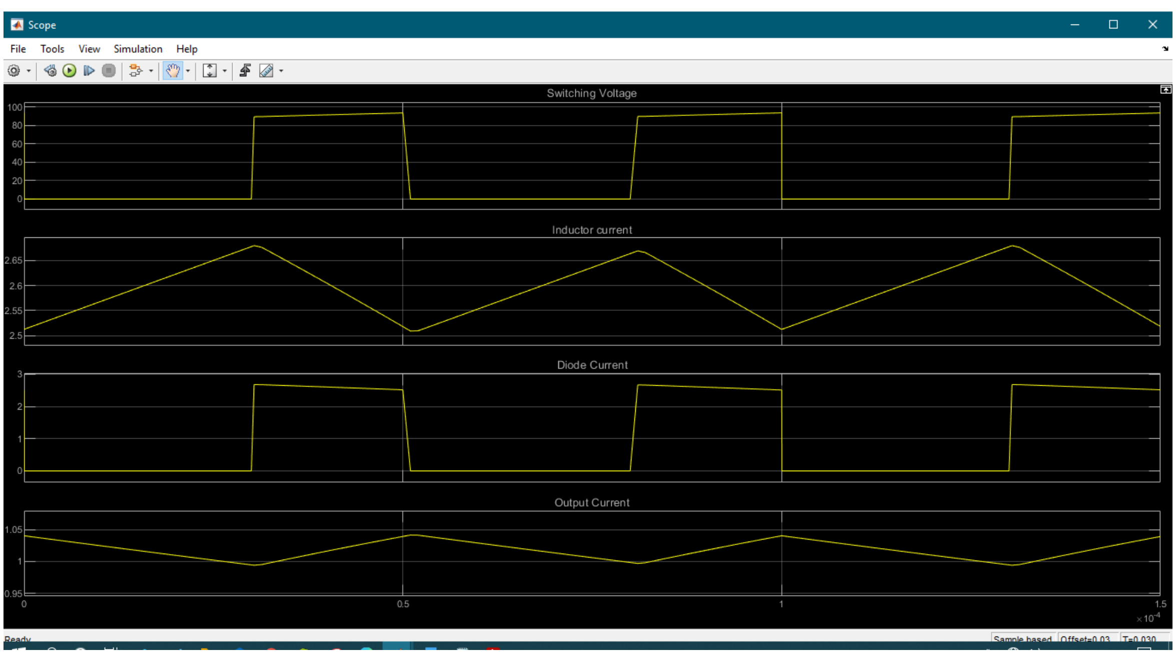
# SECTION TWO

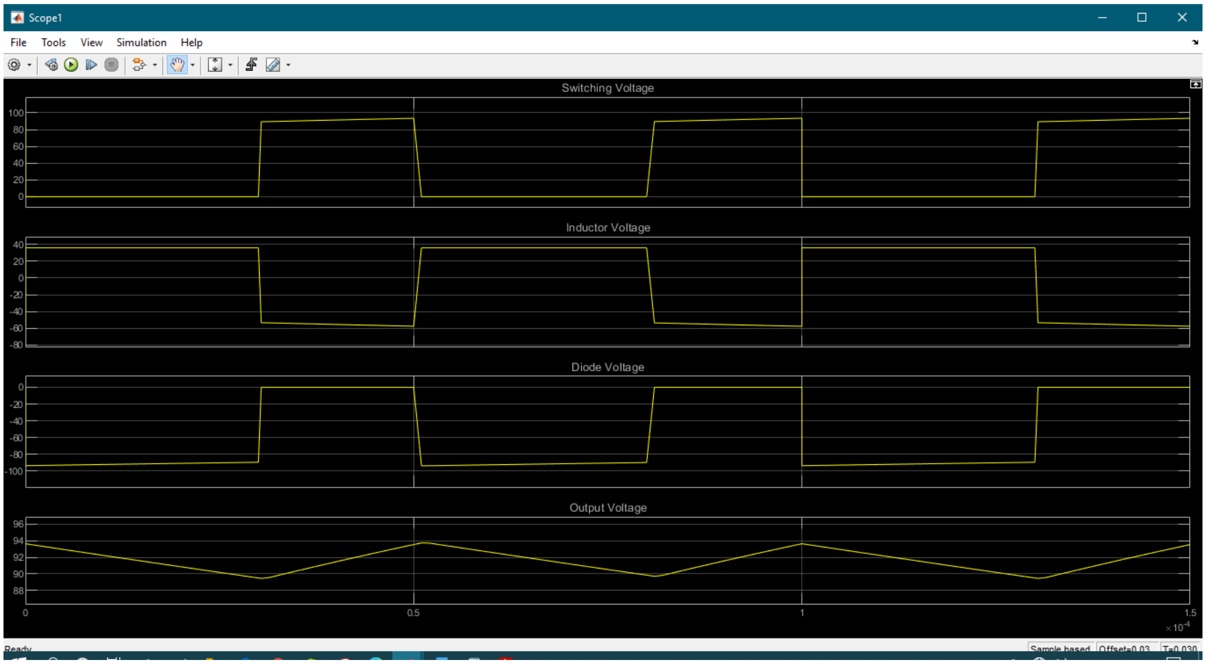
1. **MATLAB/SIMULINK simulation of ideal circuit under both light and heavy load conditions**




## Ideal Circuit waveforms under light load condition

The light load resistance was taken as $R_{L_{min}} = 90\ \Omega$






From the simulation of the ideal circuit under light load condition;

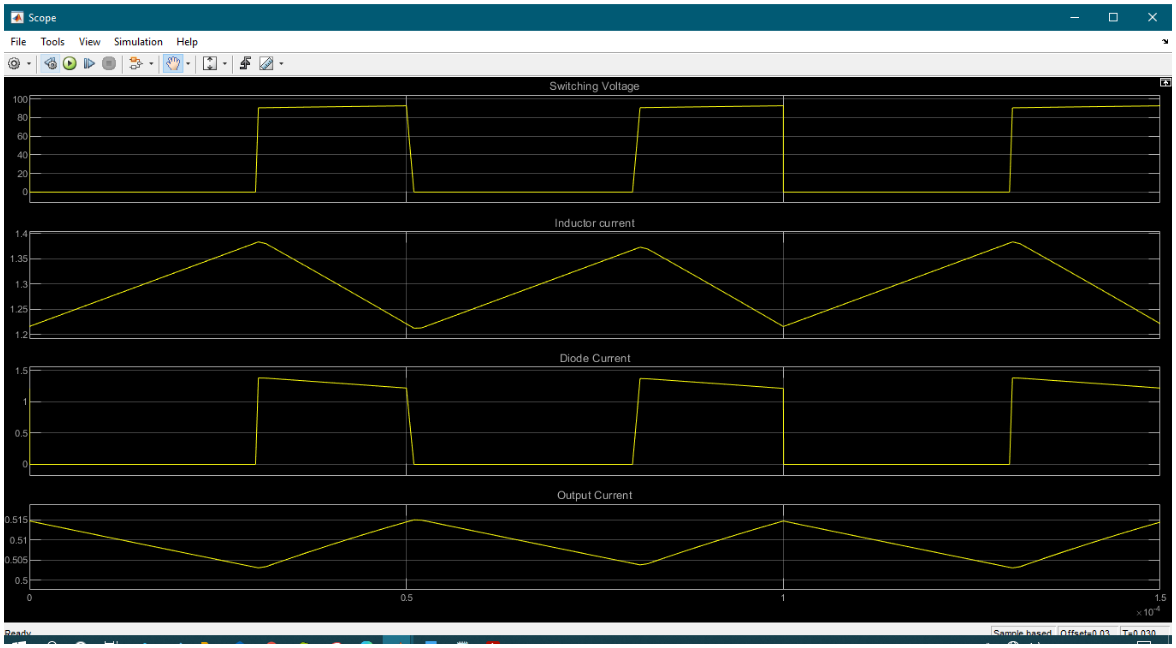
The inductor current varies between 2.5A to 2.7A. The diode current is zero during time $T_{ON}$ and 2.7A during time $T_{OFF}$. The output current varies between 0.9A and 1A.

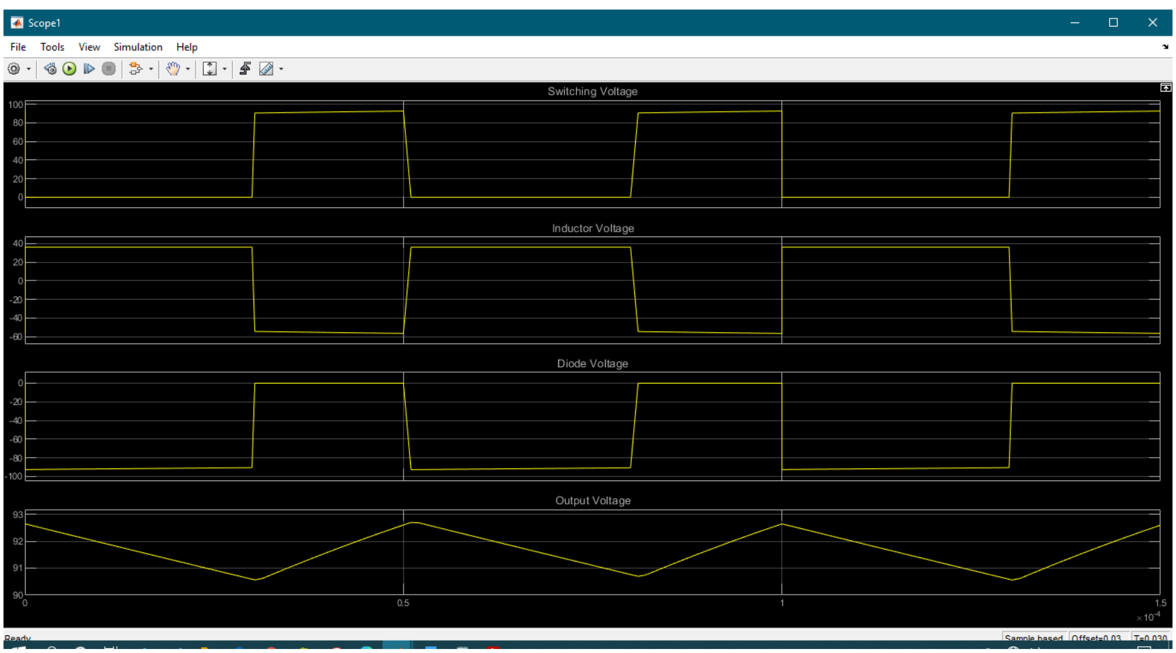
The voltage across the inductor is 38V during $T_{ON}$ and -38V during $T_{OFF}$. The diode voltage is -90V during $T_{ON}$ and 0 during $T_{OFF}$. The output voltage varies between 89V and 93V.

The simulated values matched with the those expected from the calculations and expected waveforms of the ideal circuit under light load conditions.

**Ideal Circuit waveforms under heavy load condition**

Heavy load is taken as $R_{L_{max}} = 180\ \Omega$.



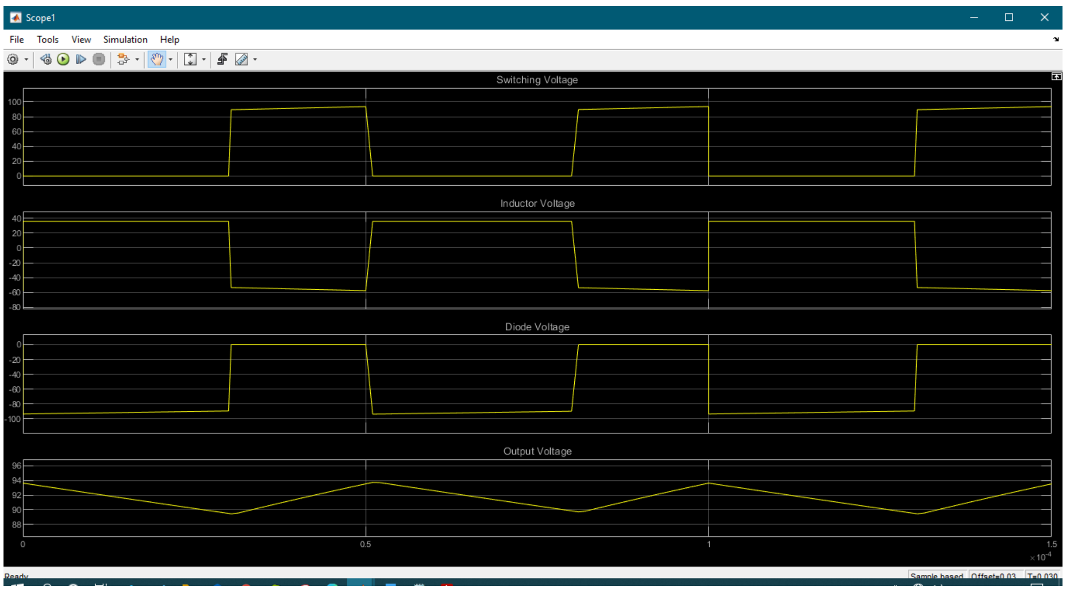



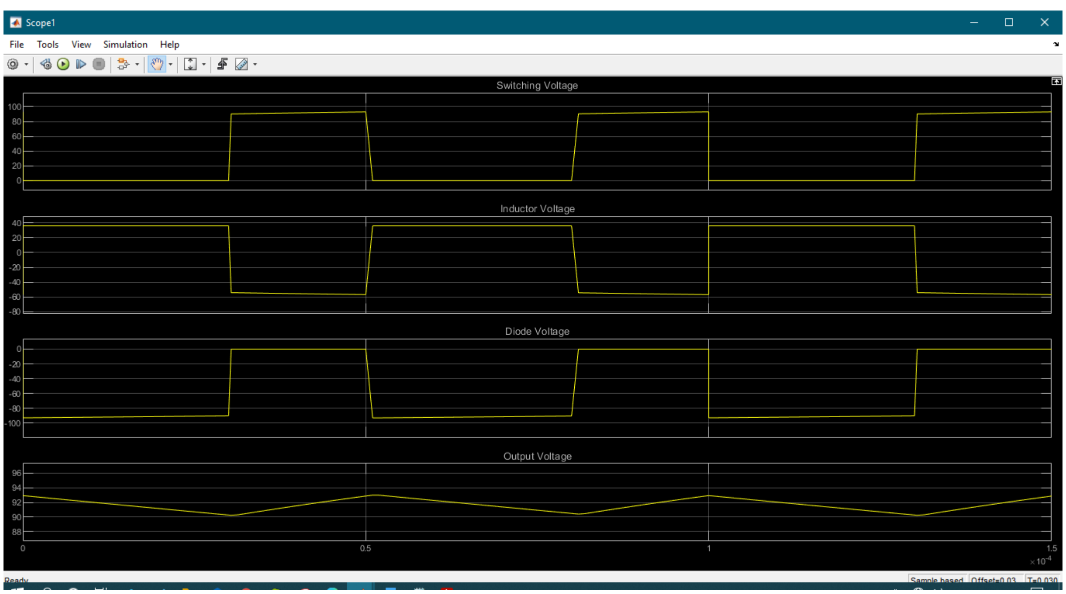

From the simulation of the ideal circuit under heavy load condition;
The inductor current varies between 1.2A to 1.3A. The diode current is zero during time $T_{ON}$ and 1.3A during time $T_{OFF}$. The output current varies between 0.51A and 0.6A. The

voltage across the inductor is 38V during $T_{ON}$ and -38V during $T_{OFF}$. The diode voltage is -90V during $T_{ON}$ and 0 during $T_{OFF}$. The output voltage varies between 90.5V and 92.5V. The simulated circuit under heavy load indicated values of current and voltage within the expected range.

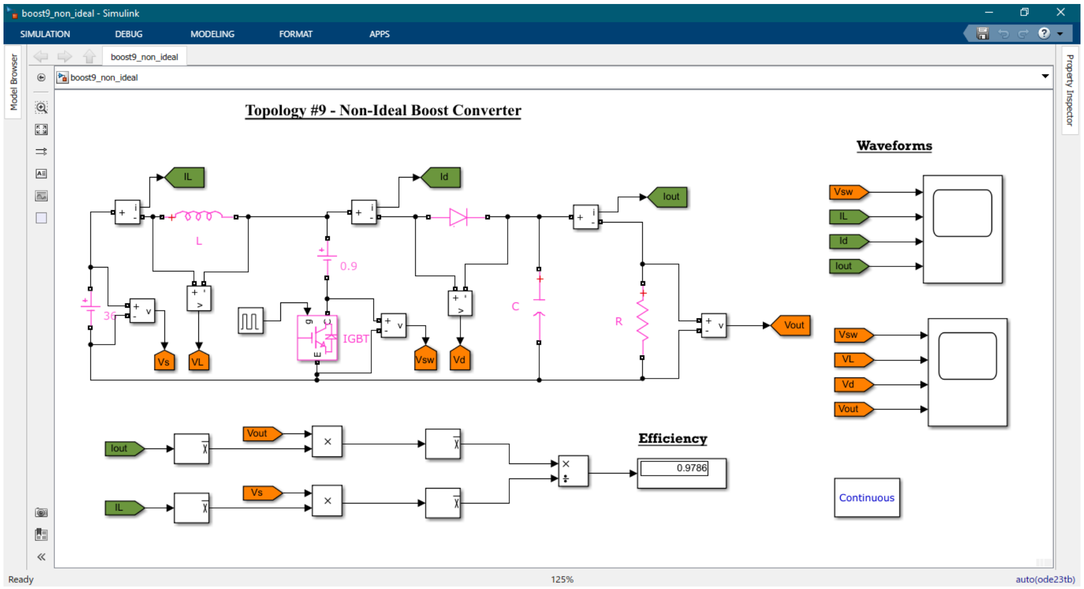
2. **Plots of voltage and current waveforms for each component over 3 switching intervals in steady state**

**<u>Waveforms over 3 switching intervals</u>**



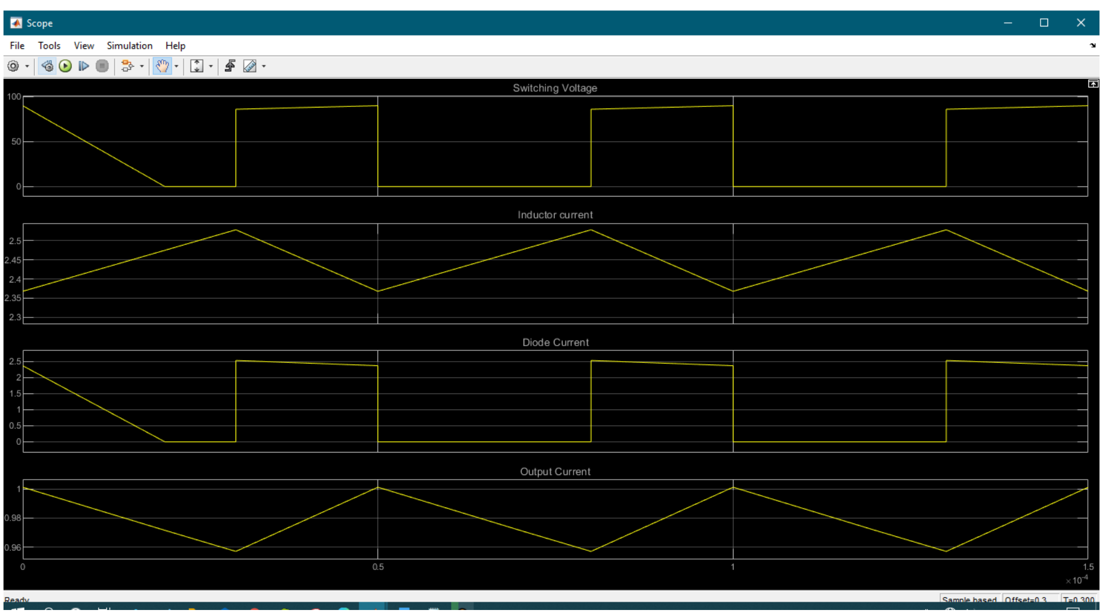
3. **MATLAB/SIMULINK simulation including non-idealities from section one 5) above.**

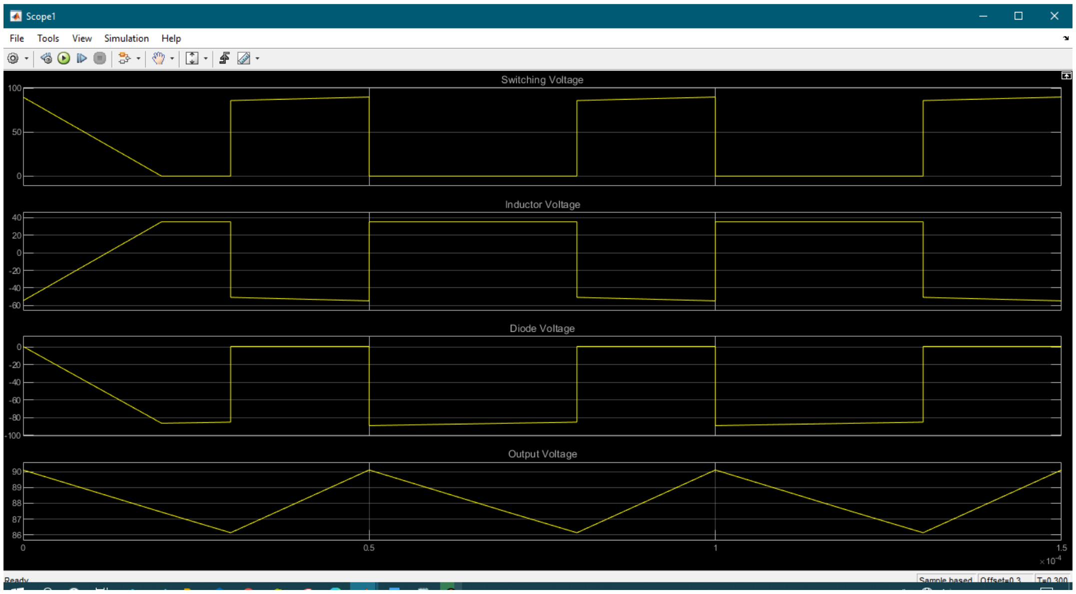




## Non-Ideal Circuit waveforms under light load condition

The light load resistance was taken as $R_{L_{min}} = 90\ \Omega$

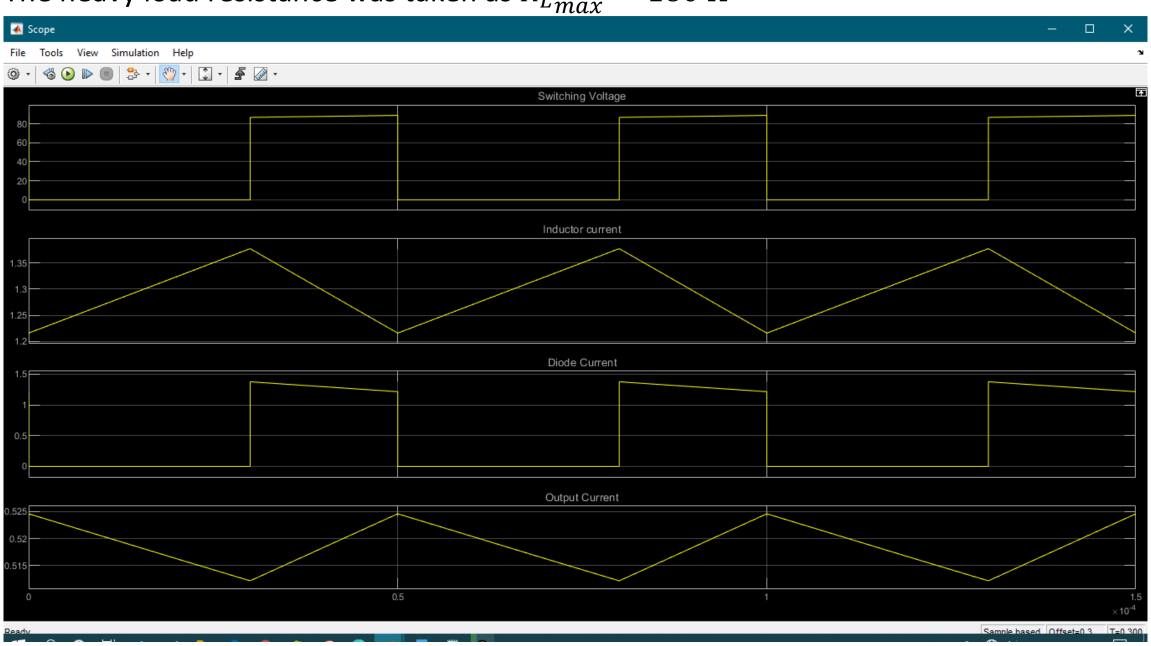


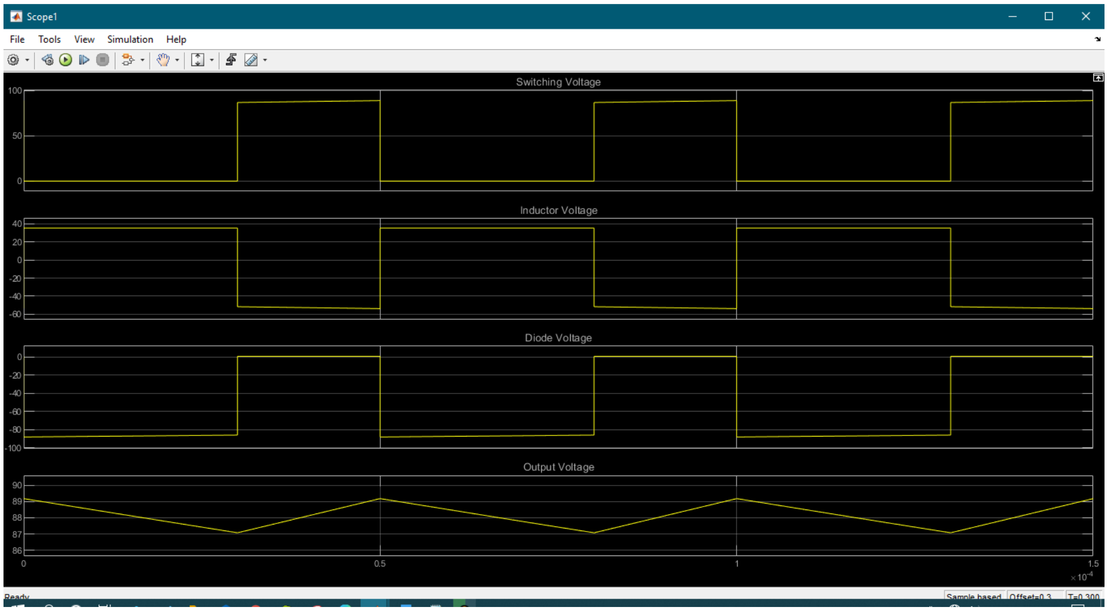



From the simulation of the non-ideal circuit under light load condition;
The inductor current varies between 2.36A to 2.55A. The diode current is zero during time $T_{ON}$ and 2.5A during time $T_{OFF}$. The output current varies between 0.9A and 1A. The voltage across the inductor is 38V during $T_{ON}$ and -50V during $T_{OFF}$. The diode voltage is -90V during $T_{ON}$ and 0 during $T_{OFF}$. The output voltage varies between 86V and 90V.
Non-idealities introduce more voltage drops in the circuit hence a relatively lower voltage than in the ideal case.

**Non-Ideal Circuit waveforms under heavy load condition**

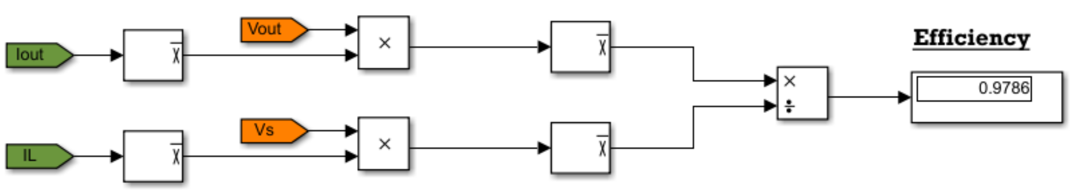
The heavy load resistance was taken as $R_{L_{max}} = 180\ \Omega$






From the simulation of the ideal circuit under heavy load condition;
The inductor current varies between 1.2A to 1.4A. The diode current is zero during time $T_{ON}$ and 1.4A during time $T_{OFF}$. The output current varies between 0.51A and 0.52A. The voltage across the inductor is 38V during $T_{ON}$ and -54V during $T_{OFF}$. The diode voltage is -90V during $T_{ON}$ and 0 during $T_{OFF}$. The output voltage varies between 89V and 89V. Under heavy load, the simulated values concur with what was expected i.e., the output current to be much lower than in the light load condition. The output voltage and current are still within the expected range of ripple.

4. **Measurement of efficiency versus load and comparison with calculated results in section one 6) above.**




Measured efficiency:

$$\eta = 0.9786 \times 100 = 97.86\ \%$$

The measured efficiency was found to be $\mathbf{97.86}$ %. Calculated efficiency was found to be $\mathbf{98.85}$ %. The measured efficiency depicts what was expected.

## CONCLUSION

The boost converter circuit was designed and simulated with MATLAB/Simulink and the output was observed. The boost converter circuit was tested and verified with the calculation obtained. Each of the values obtained from each set is compared to ensure that the design requirements are satisfied.
Theoretically, a boost converter is designed to produce output voltage higher or greater than input voltage and the results from simulation showed that the output voltage is greater than input voltage.

## REFERENCES


[1] Daniel W. Hart, Introduction to Power Electronics, Daniel W. Hart, McGraw Hill International Edition, 2011.

[2] Jintendra, D. (2016). Design and Analysis of DC-DC Converter.

[3] Boost Converter | Step Up Chopper, Electrical4U: https://www.electrical4u.com/boost-converter-step-up-chopper/

[4] Vithayathil, J. (1995). Power Electronics: Principles and Applications. New York: McGraw Hill Series.

[5] D. M. Mitchell, "DC-DC Switching Regulator Analysis", New York: McGraw-Hill, 1988