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# Comparative Analysis of Voltage and Current Responses in a DC-DC Buck Converter for Different Duty Cycles

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**Abstract**

DC-DC buck converters are widely employed in power electronic systems to provide efficient voltage regulation for various applications. However, the converter performance is significantly influenced by the duty cycle, which determines the output voltage and current characteristics. This study presents a comparative analysis of the voltage and current responses of a DC-DC buck converter operating at duty cycles of 0.5 and 0.25 using MATLAB/Simulink. The objective is to evaluate the effect of duty cycle variation on the converter's dynamic and steady-state performance. A simulation model was developed and tested under identical operating conditions, and the resulting output waveforms were analyzed. The results indicate that increasing the duty cycle enhances both the average output voltage and load current, while a lower duty cycle reduces the output magnitude. The simulated responses closely agree with the theoretical principles of buck converter operation, demonstrating the effectiveness of MATLAB/Simulink for performance evaluation and design optimization.

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## A. Introduction

The increasing demand for efficient power conversion systems in renewable energy applications, electric vehicles, portable electronic devices, and industrial equipment has intensified the importance of DC-DC converters in modern power electronics [1], [2], [6]. Among the various converter topologies, the buck converter is widely employed for step-down voltage conversion due to its simple structure, high efficiency, and reliable performance [2], [5]. According to power electronics theory, the output voltage of a buck converter is directly proportional to the duty cycle, making duty cycle control a critical factor in determining converter performance. Previous studies have investigated the design, modeling, and control of buck converters and demonstrated that variations in duty cycle significantly affect output voltage regulation, current characteristics, and overall system stability [1], [3], [4], [5]. However, a clear comparative analysis of voltage and current responses under different duty cycle conditions remains essential for understanding converter behavior and validating theoretical predictions through simulation. Therefore, this study investigates the voltage and current responses of a DC-DC buck converter operating at duty cycles of 0.5 and 0.25 using MATLAB/Simulink. The objective is to analyze the influence of duty cycle variation on converter performance and to verify the theoretical relationship between duty cycle and output characteristics. The results of this study are expected to provide useful insights for the design, analysis, and optimization of DC-DC power conversion systems in practical engineering applications.

## B. Step-Down or Buck Converter

The buck or step-down converter, shown converts its dc input voltage to another dc voltage which is lower than the dc input voltage value. The buck converter can operate in any of the three following modes:

**Mode I (Inductor and capacitor charging):** This mode starts when a turn-on pulse is applied to the gate of switch S which turns on and connects the input dc source across the output filter and diode D. Therefore, during this mode the diode D is reverse biased. Moreover, during this mode the output inductor and capacitor are charged. This mode ends when switch S is turned off.

**Mode II (Inductor discharging):** This mode starts right after the switch S is turned off and the conduction of diode D starts. During this mode the inductor discharges through diode D and this is why this diode is called freewheeling diode. This mode ends when the switch S is turned on again or when the inductor current becomes zero.

**Mode III (Discontinuous operation):** During this mode none of the two semiconductor switches are conducting and, consequently, there is no energy transfer to the output of the converter. This mode of operation exists in buck converters that operate under discontinuous inductor current. During this mode the capacitor supplies power to the load.[7]

### Buck Converter Analysis When the Inductor Current Is Continuous

For continuous current converter operation the output average voltage is given by:

$$v_o = v_D = \frac{1}{T_s}\int_0^{T_s} v_o(t)\,dt = \frac{1}{T_s}\left[\int_0^{t_{on}} v_{in}dt + \int_{t_{on}}^{T_s} 0 \times dt\right] = v_{in}\frac{t_{on}}{T_s} = v_{in}D \quad (1)$$

where D = switch duty cycle = $t_{on}$ /$T_s$ ; $V_{in}$ = dc input voltage; $t_{on}$ = switch conduction time; $t_{off}$ = switch non-conduction time; $T_s$ = switching period = $t_{on}$ + $t_{off}$; $f_s$ = 1/ $T_s$ = switching or chopping frequency.

If the dc input voltage and the switching frequency are kept constant, the average output voltage of the buck converter can be varied by varying the conduction time $t_{on}$ of the switch S. Moreover, when $t_{on}$ = 0 the output voltage average value is zero and when $t_{on}$ = $T_s$ (maximum conduction time) then the output voltage average value is equal to the dc input voltage $V_{in}$ .[7,8,9] Also, the output average current is given by:

$$I_o = I_L = \frac{V_o}{R} \quad (2)$$

When the switch is on,

$$v_L(t) = v_{in} - v_o \quad (3)$$

When the diode is conducting,

$$v_L(t) = -v_o$$
$$\frac{dv_o}{dt} = \frac{i_C}{C}$$
$$v_L(t) = L\frac{di_L(t)}{dt} \quad (4)$$

The duty cycle is,

$$D = \frac{V_o}{V_{in}} \quad (5)$$

The maximum and minimum values of the inductor current of the buck converter are given by

$$I_{L,max} = \frac{V_{in}D}{R} + \frac{V_{in}D(1-D)T_s}{2L} \quad (6)$$

$$I_{L,min} = \frac{V_{in}D}{R} - \frac{V_{in}D(1-D)T_s}{2L} \quad (7)$$

When the buck converter switch S is on, the rate of change of the inductor current,

$$\Delta I_L = \frac{V_{in}-V_o}{L}t_{on} = \frac{\frac{V_o}{D}-V_o}{L}DT_s = \frac{V_o(1-D)}{Lf_s} \quad (8)$$

The value of the output voltage peak-to-peak ripple,

$$\Delta v_o = \frac{(1-D)v_o T_s^2}{8LC} = \frac{(1-D)v_o}{8LC f_s^2} \quad (9)$$

**Buck Converter Analysis When the Inductor Current Is Discontinuous**

The average voltage across the inductor is equal to zero and,the following equation is derived:[7,8]

$$(v_{in} - v_o)D_1 T_s - v_o D_2 T_s = 0 \quad (10)$$

Therefore, the average output voltage is given by:

$$v_o = \frac{V_{in} D_1}{D_1 + D_2} \quad (11)$$

Where, $D_1 = \frac{t_{on}}{T_s}; D_2 = \frac{t_1 - t_{on}}{T_s}$

Moreover, the peak-to-peak inductor current ripple is given by:

$$\Delta I_L = \frac{V_{in} - v_o}{2L} D_1 T_s \quad (12)$$

## C. Results and Discussions

A DC-DC buck converter was designed and simulated to step down the input voltage.Table 1 shows the parameters of step-down chopper.

**Table 1.** Parameter of buck converter [7]

| No | Parameter | *Value* | *Unit* |
|---|---|---|---|
| 1 | Input voltage | 100 | V |
| 2 | Sampling frequency | 5 | kHz |
| 3 | Capacitor | 100 | uF |
| 4 | Resistor | 5 | Ω |
| 5 | Inductor | 1 (for CCM),<br>0.1 (for DCM) | mH |

Figure 1 presents the MATLAB/Simulink model employed for monitoring the input voltage ($v_{in}$), inductor voltage ($v_L$), and output voltage ($v_{out}$) as functions of time. The simulation was performed to investigate the voltage characteristics and transient response of the buck converter operating at the selected duty cycle and switching frequency.

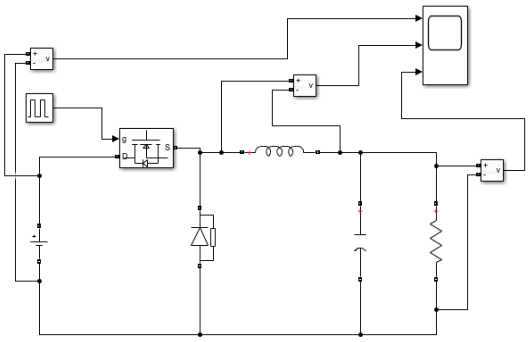
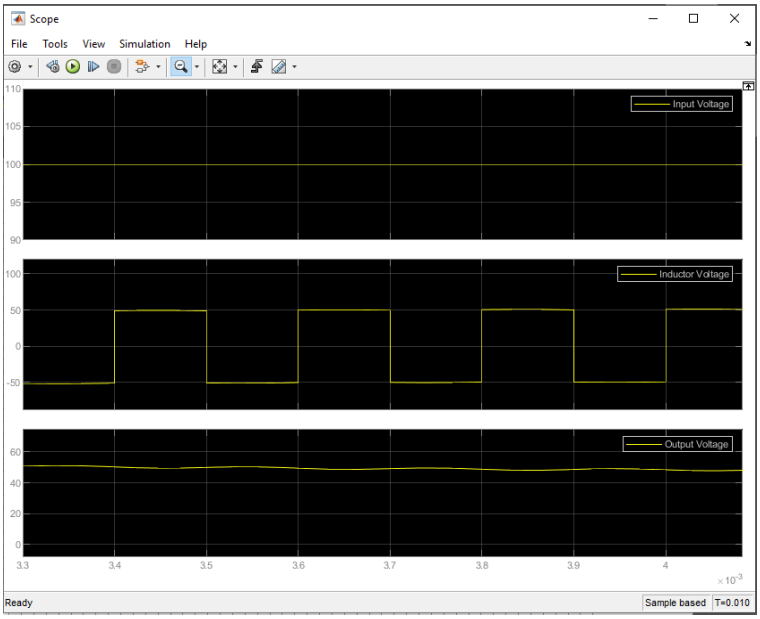
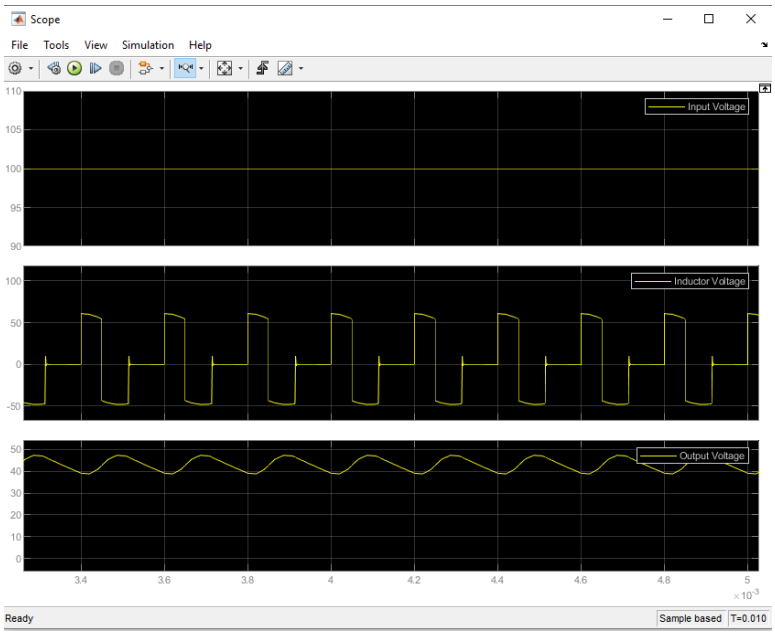


**Figure 1.** Simulink block diagram of time versus $v_{in}$, $v_L$ and $v_{out}$




(a)




(b)

**Figure 2**. Waveforms of $v_{in}$, $v_L$ and $v_{out}$ for (a) D = 0.5 (b) D = 0.25

Figure 2 describes the simulated voltage waveforms of the buck converter for duty cycle (D) value 0.5 and 0.25. The input voltage remains constant at 100 V throughout the simulation. The inductor voltage alternates between +50 V and −50 V as the power switch changes state, indicating normal energy storage and release by the inductor. The output voltage is regulated around 50 V at a duty cycle of 0.5 and around 40 V with a small ripple component at a duty cycle of 0.25.

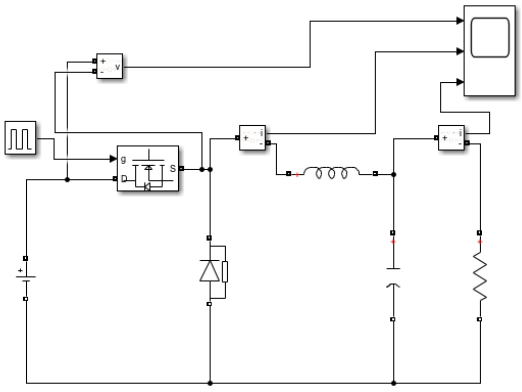
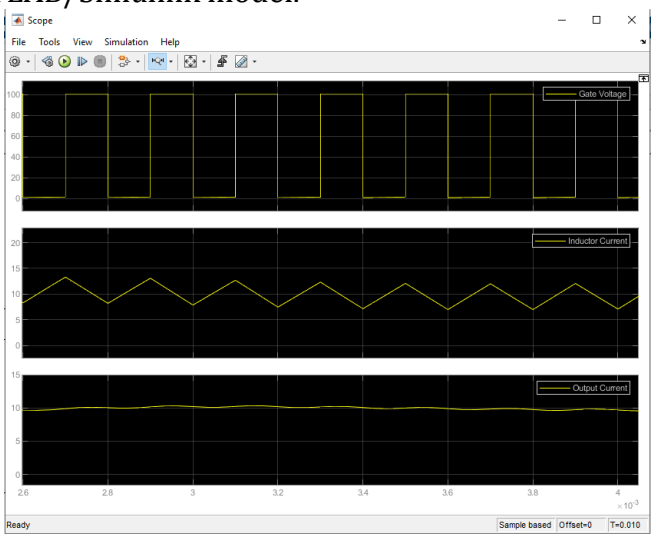
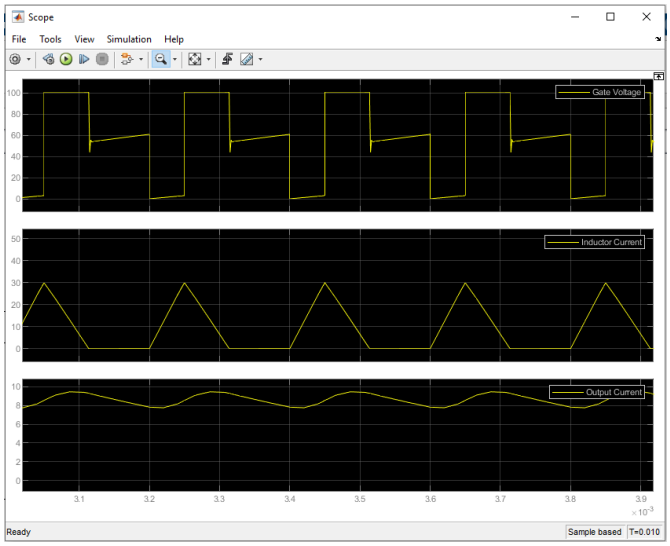


**Figure 3.** Simulink block diagram of time versus $v_{gate}$, $i_L$ and $i_{out}$

Figure 3 shows the gate voltage ($v_{gate}$), inductor voltage ($v_L$), and output current ($i_{out}$) MATLAB/Simulink model.




(a)




(b)

**Figure 4.** Waveforms of $v_{gate}$, $i_L$ and $i_{out}$ for (a) D = 0.5 (b) D = 0.25

Figure 4 presents the simulated voltage and current waveforms of the buck converter for duty cycles of 0.5 and 0.25. At D = 0.5, the converter operates in continuous conduction mode (CCM), with the inductor current varying between 7.5 A and 12.5 A. At D = 0.25, the converter operates in discontinuous conduction mode (DCM), where the inductor current rises to 30 A and falls to 0 A during each switching cycle. The output current is approximately 10 A for D = 0.5 and about 8 A with a small ripple for D = 0.25. The gate voltage reaches 100 V during the switch ON state, confirming proper switching action.

Simulink block diagram of gate voltage, capacitor current and input current is shown in Figure 5.

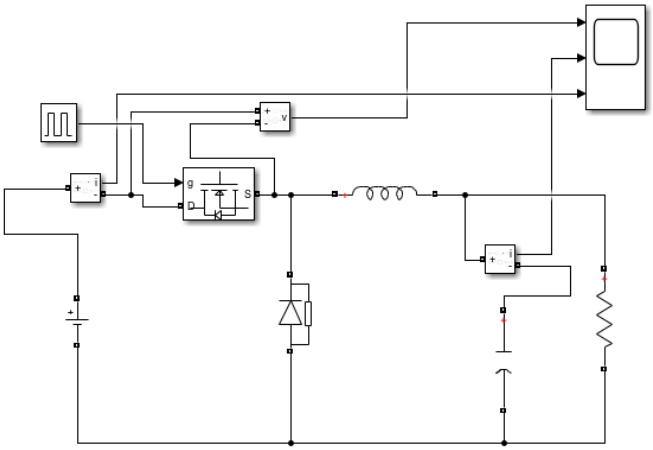
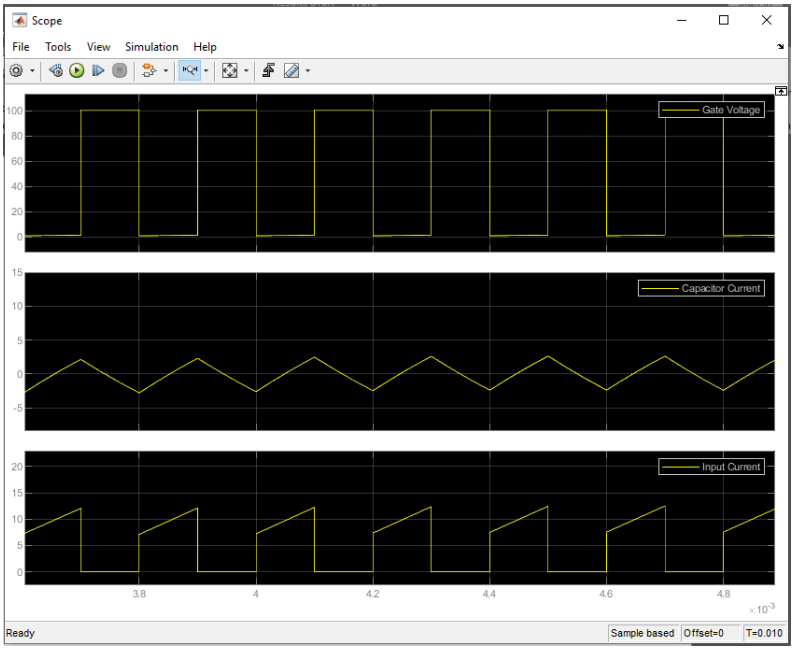
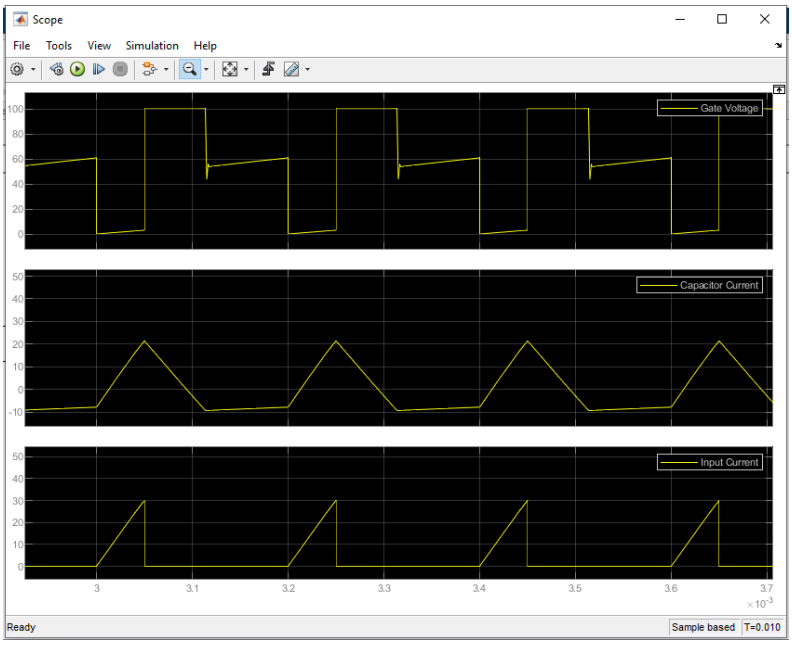


**Figure 5.** Simulink block diagram of time versus $v_{gate}$, $i_C$ and $i_{in}$




(a)




(b)

**Figure 6.** Waveforms of $v_{gate}$, $i_C$ and $i_{in}$ for (a) D = 0.5 (b) D = 0.25

Figure 6 describes the simulated electrical characteristics of the buck converter for duty cycles of 0.5 and 0.25. For D = 0.5, the converter operates in continuous conduction Mode (CCM), with the capacitor current varying between +2.5 A and −2.5 A. Reducing the duty cycle to 0.25 results in Discontinuous Conduction Mode (DCM), where the capacitor current reaches a peak value of approximately 20 A and decays to zero before the subsequent switching period. The input current ranges from 7.5 A to 12.5 A in CCM, while in DCM it increases from 0 A to nearly 30 A. The gate-drive voltage attains 100 V during the switch ON interval, indicating reliable switching operation. The gate voltage, diode voltage and input current waveforms are achieved from Figure 7.

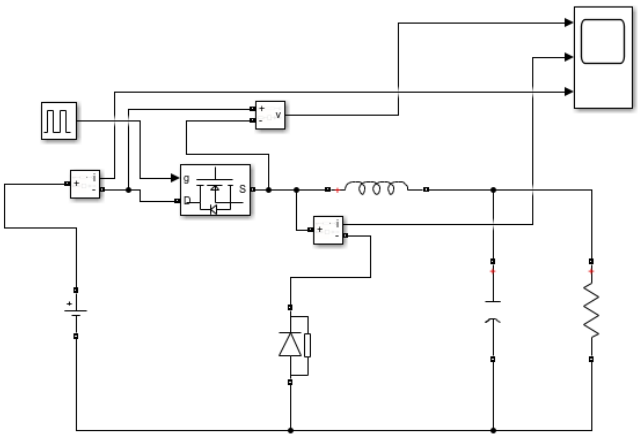
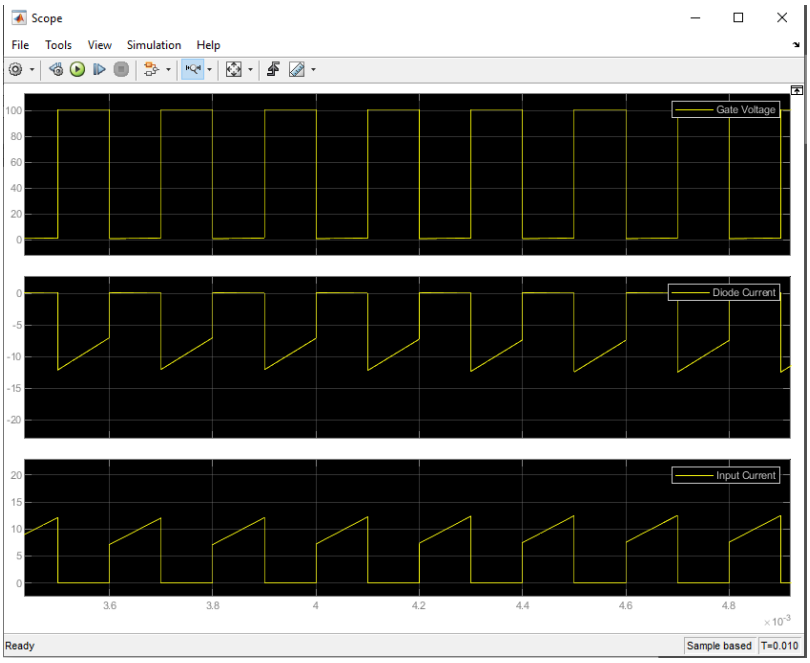
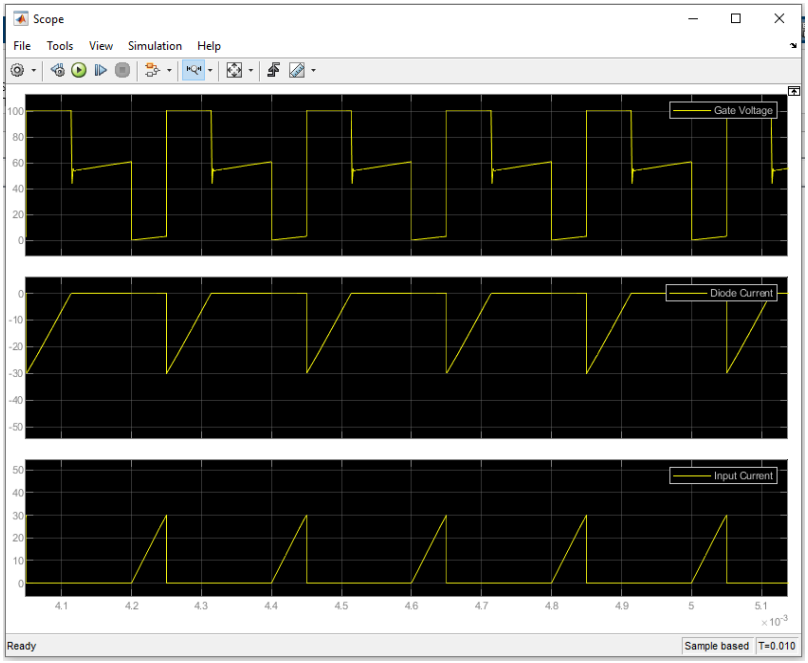


**Figure 7.** Simulink block diagram of time versus $v_{gate}$, $i_D$ and $i_{in}$




(a)




(b)

**Figure 8.** Waveforms of $v_{gate}$, $i_D$ and $i_{in}$ for (a) D = 0.5 (b) D = 0.25

In Figure 8 (a), the diode current operates in continuous conduction mode (D= 0.5), varying from -12.5 A to -7.5 A. At D = 0.25, the converter operates in discontinuous conduction mode, where the diode current discharges -30 A to 0 A during each switching cycle.

**Table 2.** Comparison results for buck converter

| No | Duty cycle | *Theory results* | *Simulation results* |
|---|---|---|---|
| 1 | 0.5 (for CCM) | $V_o$ = 50V,<br>$I_o$ = 10A,<br>$V_L$ = 50V,<br>$I_{L(max)}$ = +12.5 A,<br>$I_{L(min)}$ = +7.5 A,<br>$I_{C(max)}$ = +2.5 A,<br>$I_{C(min)}$ = -2.5 A | $V_o$ ~ 50V<br>(Figure 2(a))<br>$I_o$ ~10A<br>(Figure 4(a))<br>$V_L$ ~ +50V to -50V<br>((Figure 2(a))<br>$I_L$ ~ +7.5 A to +12.5 A (Figure 4(a))<br>$I_C$ ~ -2.5A to +2.5A<br>(Figure 6(a)) |
| 2 | 0.25 (for DCM) | $V_o$ = 25V,<br>$I_o$ = 5A,<br>$V_L$ = 75V,<br>$I_{L(max)}$ = +23.75 A,<br>$I_{L(min)}$ = -13.75 A,<br>$I_{C(max)}$ = +18.75 A,<br>$I_{C(min)}$ = -18.75 A | $V_o$ ~ 40V<br>(Figure 2(b))<br>$I_o$ ~ 8A<br>(Figure 4(b))<br>$V_L$ ~ +50V to -50V<br>((Figure 2(b))<br>$I_L$ ~ +30A to 0 A<br>(Figure 4(b))<br>$I_C$ ~ -10A to +20A<br>(Figure 6(b)) |

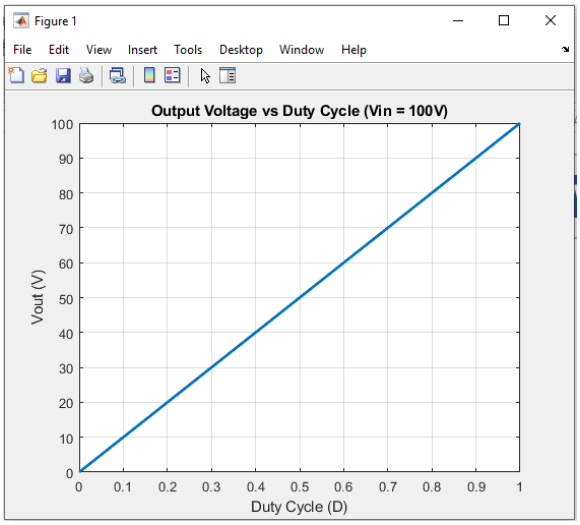



**Figure 9**. Output voltages versus duty cycles

Figure 9 graph exhibits a linear relationship between the duty cycle and the output voltage. As the duty cycle increases, the output voltage ($v_{out}$) rises proportionally from 0V to 100V, confirming the ideal voltage conversion characteristic of the buck converter.

## D. Conclusion

The electrical characteristics analyzed the effects of duty cycle and inductance variation on the performance of a DC–DC buck converter with a 100 V input using MATLAB/Simulink. The results confirmed that the output voltage increases proportionally with the duty cycle, consistent with the theoretical behavior of an ideal buck converter. The converter operated in Continuous Conduction Mode (CCM) at higher duty cycles and transitioned to Discontinuous Conduction Mode (DCM) at lower duty cycles. In addition, increasing the inductance reduced current ripple and improved conduction stability, whereas lower inductance values promoted DCM operation. These findings demonstrate the importance of duty-cycle control and inductor selection in optimizing buck converter performance for the design and optimization of power electronic converters used in renewable energy systems, battery charging applications, and DC power management systems.

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