

# Design and Simulation of DC-DC Buck-Boost Converter with Voltage Source Inverter Using MATLAB/Simulink for BLDC Motor Drives

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**Abstract**—The brushless DC (BLDC) motor is frequently employed in various applications, as it has excellent features compared with those of the conventional brushed DC motor. Furthermore, the BLDC motor is electrically commuted by power switches, resulting in higher reliability, more significant dynamic response, and longer operating life. A three-phase voltage source inverter (VSI) is fed to the BLDC motor to operate, as it has better performance at low speeds. The inverter operates in 120° and 180° conduction modes. In this paper, a DC-DC buck-boost converter was implemented to act as the step-up or step-down transformer for the system, as it offers high efficiency across extensive input and output voltage ranges. A simulation using MATLAB/Simulink software was carried out with different duty cycles, and the result was analyzed. Based on the results obtained, the overshoot percentage was 5.22% with a settling time of 0.042s.

**Keywords**—BLDC motor, voltage source inverter

## I. INTRODUCTION

Due to the growing awareness of global environmental protection and the depletion of petroleum resources, there is a concern for energy efficiency, and the operation of mechanical parts in industries is being substituted with electronic methods. In the drive system, DC motors and brushless DC (BLDC) motors are frequently employed. In recent years, BLDC motors have rapidly gained popularity, as they have several benefits compared with the conventional brushed DC motor due to their excellent features. The BLDC motor is a permanent-magnet synchronous electric motor driven by direct current (DC), and it is electrically commutated by power switches instead of brushes [1]. Compared with the brushed DC motor, the BLDC motor offers several advantages: higher efficiency and reliability, excellent dynamic response, excellent power factor, better heat removal, better speed versus torque characteristics, higher speed range, and low maintenance cost.

Besides that, the BLDC motor can reduce audible noise and radio-frequency interference (RFI) problems, as it does not have a brush and commutator [2]. BLDC motors are not only used in low- and medium-power applications but are also commonly used in industries, especially in appliance production, medicine, aeronautics, industrial automation, and many more.

Commutation is a process that converts input direct current (DC) into alternating current (AC), evenly transmitting to each

winding in the armature. The DC-AC converter, known as the voltage source inverter (VSI), is commonly used to drive AC motors, especially in the three-phase system. It provides high motion-control quality and energy efficiency and offers clean current waveform and regenerative operation in AC-DC power converter applications [3].

The three-phase inverter can be operated in 120° or 180° conduction modes. For a three-phase inverter with the 180° conduction mode, the switching is complementary, and each phase is connected as either positive or negative, and the phase currents are always continuous. The three-phase inverter with the 120° mode is almost similar to that with the 180° mode. The difference is the switch's closing time, which is reduced to 120° instead of 180°. The speed of the BLDC motor is directly proportional to its terminal voltages, which can be altered by varying the average voltage across the winding [4].

One of the standard methods to control the motor's speed is the pulse-width modulation (PWM) switching technique. PWM is used to generate gate signals for power converter switches [5]–[7]. PWM has excellent features, such as easy to apply and command and is suitable for modern digital controllers. Analog and digital are two techniques in PWM. The duty cycle of the PWM input at a set frequency controls the output of the buck-boost converter [8]. The analog method has a significant disadvantage, as it is relatively easy to be affected by noise and can change with applied voltage and temperature.

This paper will outline the design and simulation of a DC-DC buck-boost converter with the VSI. The buck-boost converter was connected to a DC link. The speed of the BLDC motor can be adjusted by varying the duty cycle of the buck-boost converter. The DC-link capacitor's value was chosen to be large enough to ensure that the DC voltage remained constant. All critical parameter values, such as the inductance and the capacitance in the buck-boost converter, were calculated to ensure that the converter operated in the continuous conduction mode (CCM).

## II. CIRCUIT CONFIGURATION

The buck-boost converter with the VSI for the BLDC motor drive consisted of the buck-boost converter as the step-up or step-down transformer in the system, while the VSI was used to convert the DC input to AC output. Fig. 1 shows the

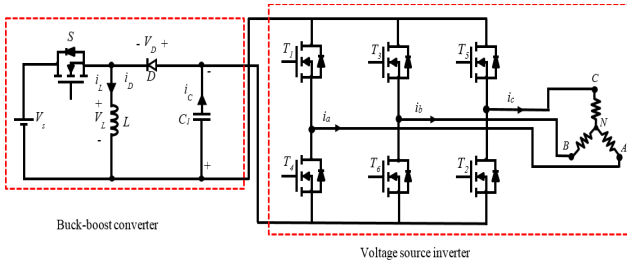


Fig. 1. Circuit configuration of DC-DC buck-boost converter with VSI.

proposed design of the DC-DC buck-boost converter with the VSI circuit configuration.

### A. DC-DC Buck-Boost Converter

Buck-boost converter is derived from the buck and boost converters connected in a cascade. The general configuration of the DC-DC buck-boost converter is shown in Fig. 2. The output voltage can be greater or lower than the input voltage, depending on the duty cycle of the switch. The operation of the converter can be divided into two modes, which are open-switch and closed-switch modes.

During the closed-switch mode, switch  $S$  is turned on and inductor  $L$  is charging, while diode  $D$  is open. In this mode, the input is disconnected from the output, where there is no energy flowing from the input to the output, and the output gets its energy from the capacitor. Fig. 3 shows the buck-boost converter's circuit in the closed-switch mode.

The inductor will initially keep the current low by dropping most of the voltage provided by the source. The current is obtained through the inductor when the switch is closed, as stated in (1).

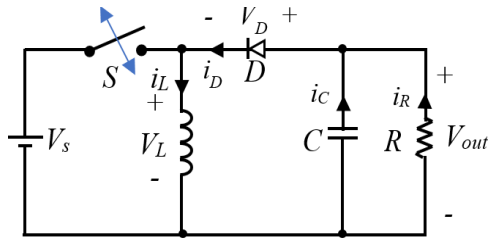


Fig. 2. Buck-boost converter circuit configuration.

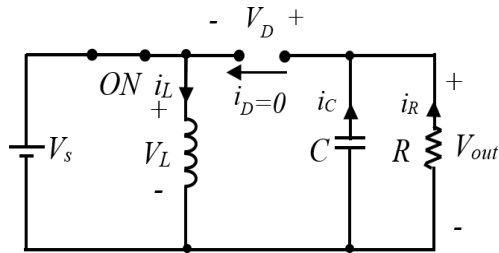


Fig. 3. Closed-switch mode circuit configuration.

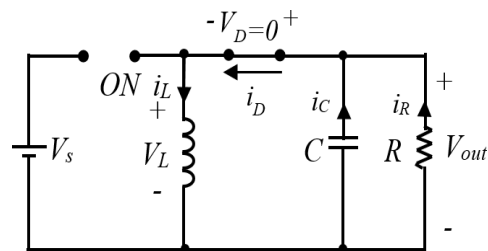


Fig. 4. Open-switch mode circuit configuration.

$$\Delta i_{L(closed)} = \frac{V_S}{L} DT \quad (1)$$

During the open-switch mode, switch  $S$  is turned off and inductor  $L$  is discharging, forcing diode  $D$  to be forward-biased. In this mode, the input is also disconnected from the output. The energy stored in inductor  $L$  is transferred to the load, and inductor current  $i_L$  falls until switch  $S$  is turned on again in the next cycle. Fig. 4 shows the buck-boost converter's circuit in the open-switch mode.

The inductor current when the switch is open depends on the duty cycle as in (2).

$$\Delta i_{L(opened)} = \frac{V_O}{L} (1 - D)T \quad (2)$$

In the steady-state operation, the average inductor voltage is zero over one switching period. Thus, the output voltage can be computed as (3).

$$V_O = -V_S \left( \frac{D}{1-D} \right) \quad (3)$$

### B. Three-Phase VSI

The basic construction of the VSI consists of three single-phase inverter switches, where each of the switches can be linked to one of the three load terminals. There are two possible conduction modes for gating the switching devices, which are the  $120^\circ$  and  $180^\circ$  modes [9].

For the  $180^\circ$  conduction mode, each of the MOSFETs is conducting for  $180^\circ$  of a cycle. For the time interval of  $180^\circ$ , the MOSFET pair in each arm, i.e.,  $(T_1, T_4)$ ,  $(T_3, T_6)$ , and  $(T_5, T_2)$ , are turned on. This means that  $T_1$  will remain on for  $180^\circ$  of a cycle. The MOSFET in the upper arm is conducting at an interval of  $120^\circ$  as shown in Fig. 5. It can be concluded that only three MOSFETs are conducting in every  $60^\circ$  interval: one from the upper arm and two from the lower arm, and vice versa.

For the  $120^\circ$  conduction mode, each of the MOSFETs is conducting for  $120^\circ$ . The  $120^\circ$  mode is similar to the  $180^\circ$  mode, as it requires six steps—each for  $60^\circ$  intervals—to complete one cycle of the output AC voltage. As shown in Fig. 6 the MOSFETs are conducting for the  $120^\circ$  duration only and remain off for the next  $60^\circ$ . Two MOSFETs are conducted

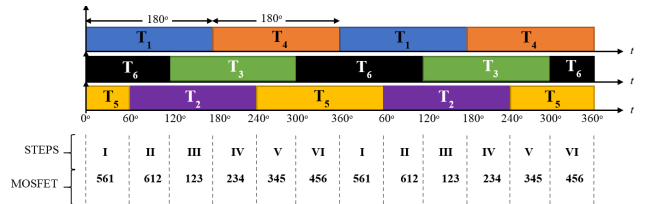


Fig. 5.  $180^\circ$  conduction mode firing sequence.

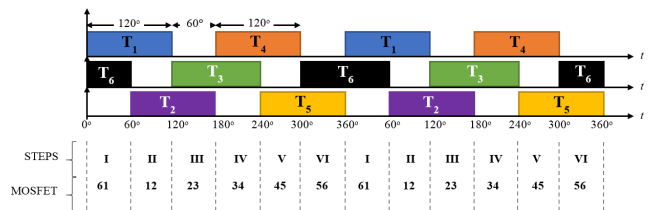


Fig. 6.  $120^\circ$  conduction mode firing sequence.

during each step: one from the upper arm and one from the lower arm.

### C. Design of DC-DC Buck-Boost Converter with VSI

The DC-DC buck-boost converter with the VSI was proposed to improve the performance of the BLDC motor. The buck-boost converter was connected to the VSI through the DC-link capacitor. The buck-boost converter was used in the system, as this converter offers a more efficient solution with fewer and smaller external components. The PWM technique was used to reduce power loss and generate gating signals quickly [10]. The switching devices used in the converter were the MOSFETs. A MOSFET is a semiconductor device that is commonly used in both analog and digital circuits. The buck-boost converter acted as the step-up or step-down transformer to supply voltage to the VSI through the DC-link capacitor in the system.

## III. CIRCUIT SIMULATIONS

Simulations using MATLAB/Simulink were performed to verify that the proposed circuit design of the buck-boost converter with the VSI can work appropriately for the BLDC motor drive.

### A. Simulation of DC-DC Buck-Boost Converter

Before simulating the buck-boost converter, the initial value of the parameters for the buck-boost converter needed to be set first. TABLE I shows the initial value of the parameters set for the buck-boost converter.

The simulation was conducted with different duty cycles ranging from 0.1 to 0.9 to observe the output voltage's characteristics. The average inductor current,  $I_L$ , is determined as (4):

$$I_L = \frac{V_s D}{R(1-D)^2} \quad (4)$$

The average source current is related to the average inductor current:

$$I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} - \frac{V_s D T}{2L} \quad (5)$$

For the continuous conduction mode (CCM), the current must remain positive. The  $I_{min}$  equation is set to zero to determine the boundary between the continuous and discontinuous modes as in (6);

$$L_{min} = \frac{(1-D)^2 R}{2f} \quad (6)$$

The required duty ratio can be expressed as in (7);

$$D = \frac{|V_o|}{V_s + |V_o|} \quad (7)$$

The simulation of the three-phase VSI in MATLAB/Simulink software was performed to corroborate the theoretical waveform with the simulated waveform. Six MOSFET switching devices with a switching frequency of 10 kHz were used in this circuit. The Y-connected three-phase series R load was connected to the three-phase VSI. The 120° and 180° conduction modes were used to simulate the voltage output waveform of the three-phase VSI. For the 180°

conduction mode, the voltages of the load are given as in (8) and (9);

$$V_{AN} = V_{CN} = \frac{V}{3} \quad (8)$$

$$V_{BN} = -\frac{2V}{3} \quad (9)$$

The line voltages are given as (10), (11) and (12);

$$V_{AB} = V_{AN} - V_{BN} = V \quad (10)$$

$$V_{BC} = V_{BN} - V_{CN} = -V \quad (11)$$

$$V_{CA} = V_{CN} - V_{AN} = 0 \quad (12)$$

For the 120° conduction mode, the phase voltages are equal to the line voltages are as (13) and (14);

$$V_{AB} = V_{in} \quad (13)$$

$$V_{BC} = V_{CA} = -\frac{V}{2} \quad (14)$$

The DC input voltage, switching frequency, inductor, and capacitor were set with the parameter values shown in Table I. Fig. 7 shows the block model of the buck-boost converter with the VSI constructed in MATLAB/Simulink software. The duty cycles used for the simulation of the buck-boost converter with the VSI ranged from 0.1 to 0.9. The outputs to be observed were from the DC-link capacitor and the load at the VSI.

## IV. RESULTS AND ANALYSIS

The proposed design of the buck-boost converter with the VSI for the BLDC motor drive was successfully developed using MATLAB/Simulink software, as shown in Fig. 7. The circuits were simulated separately to analyze the performance of the circuit. The results obtained are shown in following sections.

### A. DC-DC Buck-Boost Converter

The simulation of the buck-boost converter in MATLAB/Simulink software was conducted to observe the output voltage of the converter with different duty cycles. Fig. 8 shows the output waveform of the switching signal, inductor current, inductor voltage, and capacitor current of the buck-boost converter respectively.

TABLE I. INITIAL VALUE OF PARAMETERS

Parameter	Value
Input voltage, $V_{in}$	24 V
Switching frequency, $f_s$	10 kHz
Capacitor, $CI$	1000 $\mu$ F
Inductor, $LI$	470 $\mu$ H
Resistor, $R$	10 $\Omega$

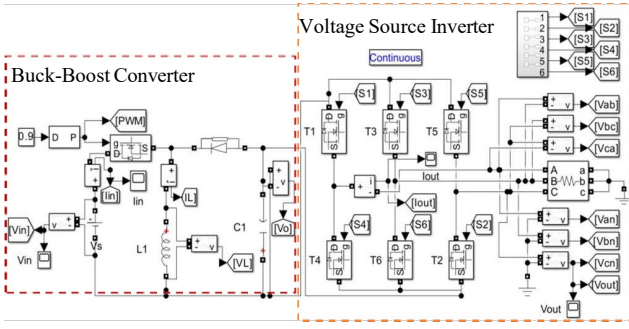


Fig. 7. Block model of the buck-boost converter with VSI in MATLAB/Simulink software.

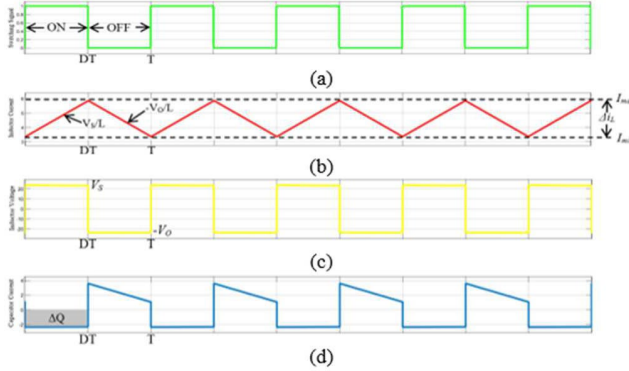


Fig. 8. Output waveform of PWM switching signal, (b) inductor current, (c) inductor voltage and (d) capacitor current.

Table II shows the output voltage of the buck-boost converter with different duty cycles. It can be concluded that the output voltage's magnitude of the buck-boost converter can be lower or greater than the input voltage, depending on the duty ratio of the switch. The converter operated in boost mode when  $D > 0.5$ , where it stepped up the input voltage. In contrast, the converter operated in buck mode when  $D < 0.5$ , where it stepped down the input voltage.

### B. Three-Phase Voltage Source Inverter

For the  $180^\circ$  conduction mode, the output voltage waveforms are shown in Fig. 9 and Fig. 10. In Fig. 9, the red line represents the voltage output for the connection of the red and yellow phases,  $V_{RY}$ . The yellow line represents the voltage output for the connection of the yellow and blue phases,  $V_{YB}$ , and the blue line represents the connection of the blue and red phases,  $V_{BR}$ . In Fig. 10, the voltage output for the red line represents the red phase,  $V_R$ , while the yellow line represents the yellow phase,  $V_Y$ , and the blue line represents the blue phase,  $V_B$ .

Both sets of output voltage waveforms clearly show that six steps were required in each cycle of the output voltage of each phase, and each step had a duration of  $60^\circ$ . Results obtained show that the  $120^\circ$  conduction mode had similar output voltage waveforms to those of the conduction mode of  $180^\circ$ . The only difference is that the MOSFETs were conducted for  $120^\circ$  only and remained off for the next  $60^\circ$  in the  $120^\circ$  conduction mode.

### C. Buck-Boost Converter with VSI

The buck-boost converter was used to supply DC voltage to the three-phase VSI, and the three-phase VSI then converted the DC voltage into AC output. The output voltage observed was at the DC-link capacitor and the VSI output. The

TABLE II. DUTY CYCLE VERSUS OUTPUT VOLTAGE

Duty Cycle, $D$	Output Voltage, $V_o$
0.1	2.07
0.2	5.20
0.3	9.47
0.4	15.12
0.5	22.91
0.6	34.18
0.7	51.66
0.8	80.01
0.9	114.00

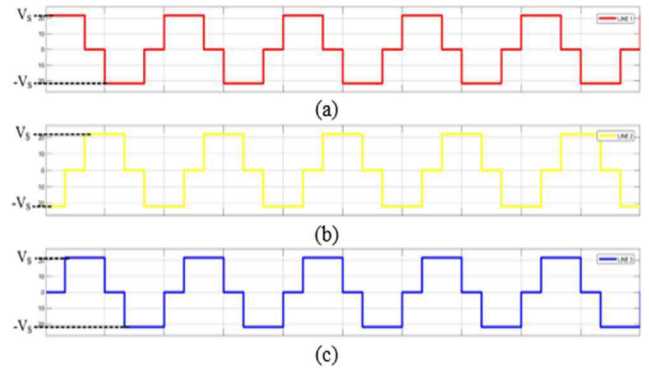


Fig. 9. Phase-to-phase voltage of (a)  $V_R$ , (b)  $V_Y$ , and (c)  $V_B$

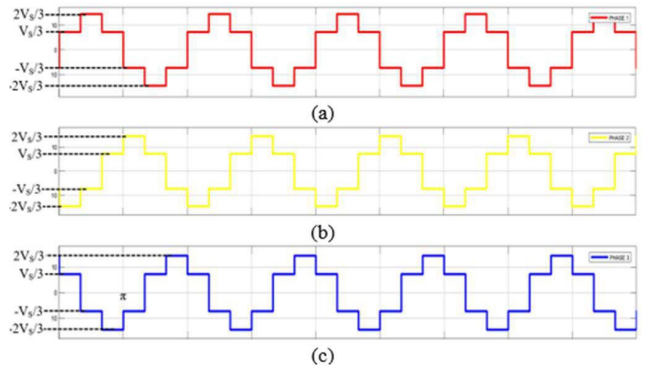


Fig. 10. Phase-to-ground voltage of (a)  $V_{RY}$ , (b)  $V_{YB}$ , and (c)  $V_{BR}$

VSI showed two different outputs, which were line voltage and phase voltage. Table III tabulates the output voltages from the simulation of the buck-boost converter with the three-phase VSI in MATLAB/Simulink software. The circuit was simulated in the  $180^\circ$  conduction mode.

From the output result, when  $D < 0.5$ , the output voltage of the DC-link capacitor was lower than the input voltage of 24 V. This shows that the converter acted as the step-down transformer in the system when the duty cycle was between 0.1 and 0.4. As for  $D = 0.5$ , the output voltage of the DC-link capacitor was approximately equal to the input voltage. When  $D > 0.5$ , the output voltage of the DC-link capacitor was greater than the input voltage of 24 V, showing that the converter acted as the step-up transformer in the system. The line voltage of the VSI obtained from the simulation was the same as the output voltage at the DC-link capacitor. The phase

TABLE III. OUTPUT VOLTAGE FOR BUCK-BOOST CONVERTER WITH VSI

Buck-Boost Converter		Voltage Source Inverter					
D	Vo	Line-to-Line Voltage (V <sub>ll</sub> )					
		0-60°	61°-120°	121°-180°	181°-240°	240°-300°	301°-360°
0.1	2.65	2.65	2.65	0	-2.65	-2.65	0
0.2	5.65	5.65	5.65	0	-5.65	-5.65	0
0.3	9.46	9.46	9.46	0	-9.46	-9.46	0
0.4	15.11	15.11	15.11	0	-15.11	-15.11	0
0.5	22.95	22.95	22.95	0	-22.95	-22.95	0
0.6	34.44	34.44	34.44	0	-34.44	-34.44	0
0.7	52.65	52.65	52.65	0	-52.65	-52.65	0
0.8	84.36	84.36	84.36	0	-84.36	-84.36	0
0.9	135.40	135.40	135.40	0	-135.40	-135.40	0
D	Vo	Phase-to-Ground Voltage (V <sub>rv</sub> )					
		0-60°	61°-120°	121°-180°	181°-240°	240°-300°	301°-360°
0.1	2.65	0.86	1.72	0.86	-0.86	-1.72	-0.86
0.2	5.65	1.83	3.69	1.83	-1.83	-3.69	-1.83
0.3	9.46	3.17	6.24	3.17	-3.17	-6.24	-3.17
0.4	15.11	4.88	9.77	4.88	-4.88	-9.77	-4.88
0.5	22.95	7.44	14.90	7.44	-7.44	-14.90	-7.44
0.6	34.44	11.24	22.47	11.24	-11.24	-22.47	-11.24
0.7	52.65	17.79	34.98	17.79	-17.79	-34.98	-17.79
0.8	84.36	27.74	55.83	27.74	-27.74	-55.83	-27.74
0.9	135.40	43.97	87.62	43.97	-43.97	-87.62	-43.97

voltage output was the same as from (4) and (5). Fig. 11 shows the output voltage response of the DC-link capacitor from the simulation of the buck-boost converter with the VSI in MATLAB/Simulink software.

Based on the results obtained at  $D=0.9$ , the overshoot percentage was 5.22 %, and it takes approximately 0.042s to reach steady state.

### V. CONCLUSION

A buck-boost converter fed with the three-phase VSI is presented in this paper. A simulation was done using MATLAB/Simulink software to verify the performance of the buck-boost converter with the VSI with different duty cycles. A buck-boost converter can be used to both step-up and step-down output voltages. It can be concluded from the simulation that the proposed design allowed the buck-boost converter to supply DC voltage to the three-phase VSI through the DC-link capacitor. Then, the VSI converted the DC voltage into AC output. The buck-boost converter offers high efficiency to the

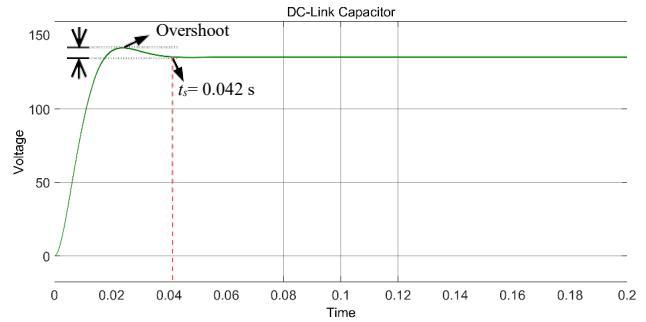


Fig. 11. Output voltage waveform of DC-link capacitor.

system, which is suitable for the performance of the BLDC motor drive.

### ACKNOWLEDGMENT

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