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Comparison & Analysis of Bridge Rectifier Fed & Bridgeless Buck-Boost Topologies for Sensorless BLDC Motor Drives

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Abstract : *This paper deals with the comparison of a sensorless brushless DC (BLDC) motor drive fed by a buck-boost converter with Diode Bridge Rectifier (DBR) and a bridgeless (BL) buck-boost converter as a cost-effective solution for low power applications. The single phase supply is fed to uncontrolled bridge rectifier, which is followed by a buck-boost converter used to control the voltage of DC link capacitor that feds the Voltage Source Inverter (VSI) of circuit with DBR whereas direct ACDC conversion is done in BL topology, reducing the conduction losses associated with DBR. Voltage of the DC link capacitor of the converter is controlled to achieve the speed control of BLDC motor. Electronic commutation of the VSI is done by detecting the zero crossing points of the back EMF voltage eliminating the need for rotor position sensors. Both converters are designed to operate so as to provide an inherent Power Factor Correction (PFC) at ac mains. A mathematical model of the drive system is simulated with MATLAB/SIMULINK.*

Keywords – *Buck-boost converter, Brushless DC motor, Continuous Conduction Mode (CCM), Discontinuous Conduction Mode(DCM), back EMF, power quality, Sensorless control*

I. INTRODUCTION

In recent years BLDC motors are widely used because of their high torque to weight ratio, high efficiency , high flux density per unit volume, increased reliability, reduced noise, low electromagnetic interference problems, high ruggedness, wide range of speed control, faster dynamic response and lower susceptibility to mechanical wear [2]. Due to these advantages ,they find applications in numerous areas such as household applications-CD/DVD players, small cooling fans; transportation- electric vehicles, hybrid vehicles, radio controlled cars; aerospace that focus on the design of electric drive for flight control actuation system; heating, ventilation and air conditioning; motion control systems like robotics, etc.

Brushless dc motor is a kind of permanent magnet synchronous motor, having permanent magnets on its rotor with trapezoidal back EMF. With the help of power devices BLDC motors energizes its stator phase windings. In motors incorporating position sensors, the switching sequences are determined from the same. The phase current of BLDC motor is synchronized with the back EMF to produce constant torque at a constant speed. In BLDC, mechanical commutator of the brush dc motor is replaced by electronic switches [9].

These brushless dc motors are generally controlled using a three-phase inverter which require a rotor position sensor for starting and providing the proper commutation sequence to control the inverter. These position sensors can be Hall sensors or absolute position sensors [10]. Those sensors will increase the cost and the size of the motor and thus a special mechanical arrangement needs to be made for mounting the sensors. These sensors, particularly Hall sensors, are temperature sensitive, and limits the operation of the motor to below about 75 degree Celsius [11]. Because of the components and wiring they could reduce the system reliability. In many cases , it even may not be possible to mount any position sensor on the motor. Therefore, BLDC motor with sensorless control has been receiving great interest in recent years.

This paper provides a sensorless method for controlling BLDC motor drives. As the conventional control has been improved with sensorless control, the performance and reliability of BLDC motor drivers have been improved. The zero crossing of the back EMF has been used to implement the sensorless control technique [12].

II. BUCK-BOOST CONVERTER FED SENSORLESS BLDC MOTOR DRIVE

Fig.1. shows the circuit diagram of a sensorless BLDC motor drive fed by a conventional Buck-Boost converter. In this, the single phase supply is fed to a DBR which is followed by a Buck-Boost converter. The input filter consists of an inductor L_f and a capacitor C_f that performs the function of a DC filter. A high frequency metal-oxide-semiconductor field-effect transistor (MOSFET) is used in the Buck-Boost converter whose switching is done with PWM technique to achieve PFC at AC mains. For the proper working of a BLDC motor, the stator windings are energized from a VSI through its electronic commutation. Insulated gate bipolar

transistors (IGBTs) are used in the VSI for its low frequency (fundamental frequency) operation. A voltage follower approch is used to provide the closed loop speed control of the BLDC motor drive system.

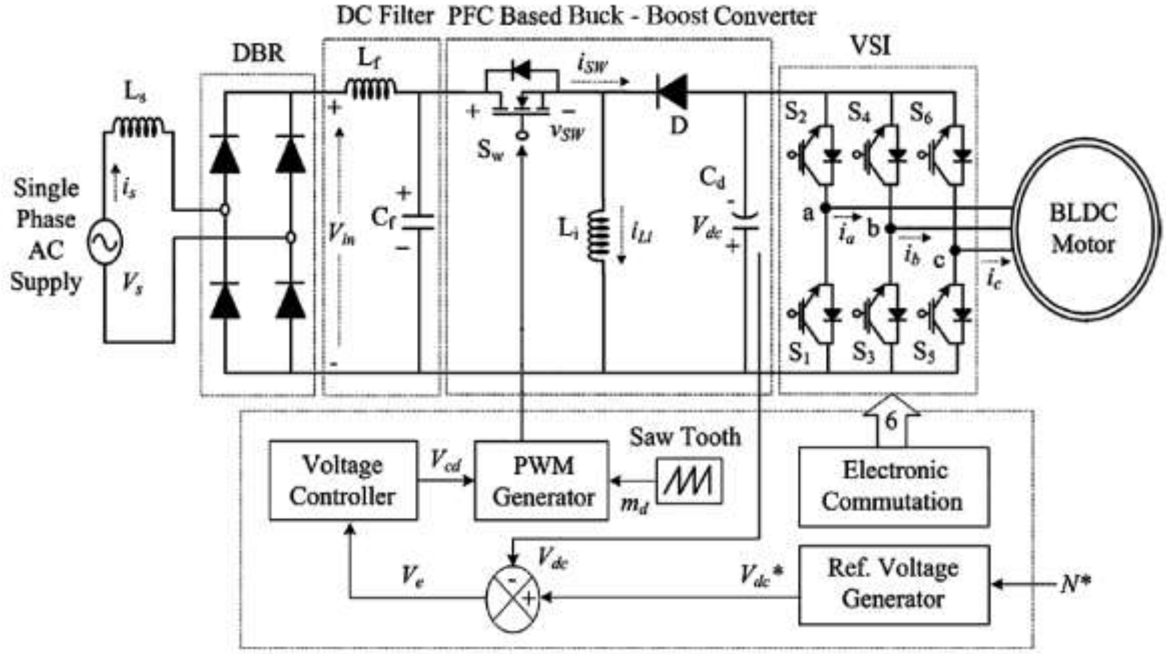


Fig.1. Buck-Boost converter fed sensorless BLDC motor drive with DBR at the front-end

2.1 WORKING OF PFC BUCK-BOOST CONVERTER

Fig.2 (a) shows the circuit diagram of buck-boost converter with the switch in its closed state. When the switch is turned 'ÓN', the inductor current increases while the diode 'D' remains in the reverse biased condition. During this interval, the energy stored in the capacitor feeds the load.

(a) (b)

Fig.2. Buck-Boost converter circuit (a) when the switch is ON, (b) when the switch is OFF

Fig.2 (b) shows the circuit diagram of buck-boost converter with the switch in its open state. When the switch is turned 'OFF', the diode 'D' provides a path for the inductor current. During this interval, the energy stored in the inductor feeds the load through diode. The polarity of the diode results in its current being drawn from the output.

2.2 DESIGN EQUATIONS FOR PFC BUCK-BOOST CONVERTER

The duty ratio is related to voltage by the relation:

$$\frac{V_o}{V} = \frac{D}{(1-D)} \qquad (1)$$

where,
D is the duty ratio
V is the converter input voltage (V)
Vo is the converter output voltage (V)

The inductor value is given by :

$$L = \frac{V_o(1-D)}{\Delta i_L \times f_s} \tag{2}$$

where,
f_s is the switching frequency(Hz)
Δi_L is inductor current ripple.

The capacitor value is given by:

$$C = \frac{I_o D}{\Delta V_o \times f_s} \tag{3}$$

where,
I_o is the load current (A)
ΔVo is the capacitor voltage ripple.

2.3 CLOSED-LOOP CONTROL OF PFC BUCK BOOST CONVERTER

In this approach, a reference voltage V_{dc} corresponding to the particular reference speed N^* is as:

$$V_{dc}^* = k_b \times N^* \tag{4}$$

where,
k_b represents the voltage constant of the BLDC motor
N^* is the reference speed.

This reference voltage is compared to the sensed dc-link voltage V_{dc} to generate a voltage error V_e. The voltage error V_e at any instant "k" is given by:

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \tag{5}$$

This voltage error is given to the voltage PI controller to generate a controlled output as:

$$V_{cd}(k) = V_{cd}(k-1) + k_{pv}\big(V_e(k) - V_e(k-1)\big) + k_{iv}V_e(k) \tag{6}$$

Where k_{pv} and k_{iv} are the proportional and integral gain of the voltage PI controller. Finally, the controller output V_{cd} is compared with the high frequency saw-tooth waveform to generate the PWM signal to be given to PFC converter switch as

$$m_d(t) < V_{cc}(t)$$

then $S_w = 1$, else $S_w = 0$
where S_w denotes the switching signals as 1 and 0 for MOSFET to switch ON and OFF, respectively.

III. BRIDGELESS BUCK-BOOST CONVERTER FED SENSORLESS BLDC MOTOR DRIVE

Fig.4. shows the BLDC motor drive fed by a BL buck-boost converter based VSI. In order to achieve inherent PFC at AC mains, the BL buck-boost converter is designed to operate in discontinuous inductor current mode (DICM). The speed control of BLDC motor is achieved by the dc link voltage control of VSI using a voltage follower approach . Electronic commutation of the VSI is done at the fundamental frequency to avoid switching losses in IGBTs. MOSFETS are used in BL buck-boost converter, whereas IGBTs are used in the VSI for its low frequency operation.

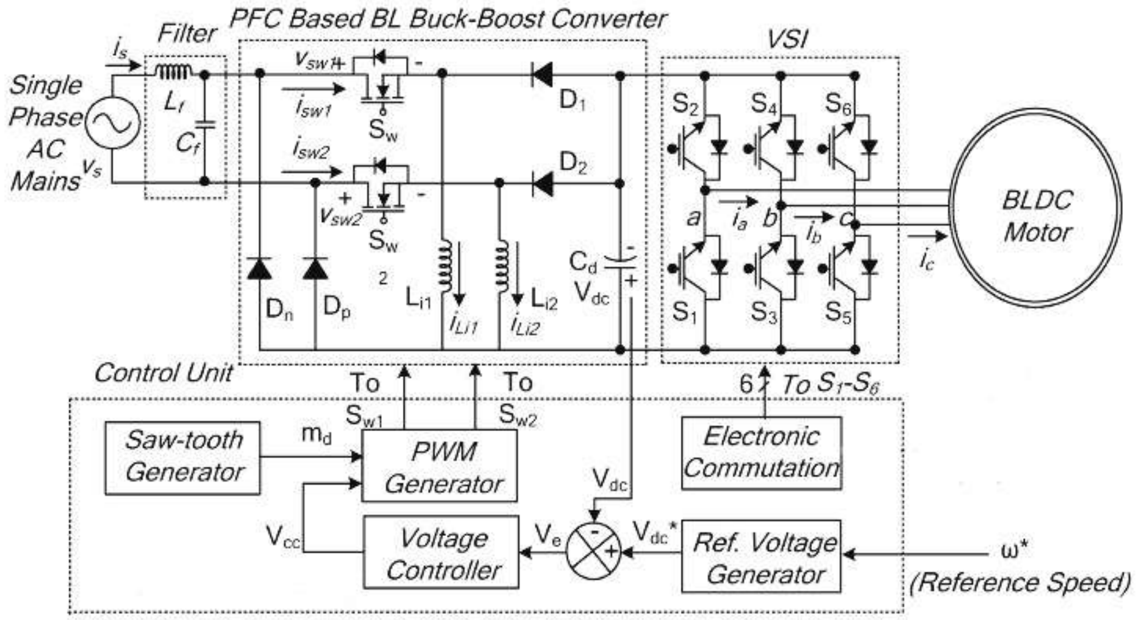


Fig.3. Bridgeless Buck-Boost converter fed sensorless BLDC motor drive

3.1 WORKING OF PFC BL BUCK-BOOST CONVERTER

The working of the PFC BL buck–boost converter is classified into two parts:

3.1.1 DURING POSITIVE AND NEGATIVE HALF CYCLES OF SUPPLY VOLTAGE

In the BL buck–boost converter, switches S_{w1} and S_{w2} operate for the positive and negative half cycles of the supply voltage, respectively. During the positive half cycle of the supply voltage, energy transfer to the DC link capacitor C_d ocuurs through switch S_{w1}, inductor L_{i1},diodes D_1 and D_p as shown in Fig.4-6. Similarly, during the negative half cycle of the supply voltage, energy transfer to the DC link capacitor C_d ocuurs through switch S_{w2}, inductor L_{i2},diodes D_2 and D_n as shown in Fig.7-9.In the DICM operation of the BL buck–boost converter, the inductor current i_{L1} becomes discontinuous for a certain duration in a switching period.

3.1.2 DURING COMPLETE SWITCHING CYCLE

There are three modes of operation in the positive half cycle.

MODE I: In this mode, the inductor current i_{L1} increases as the switch S_{w1} conducts to charge the inductor L_{i1} as shown in Fig.4. Diode D_p completes the input side circuitry and the DC link capacitor C_d is discharged by the VSI-fed BLDC motor as shown in Fig.10.

MODE II: In this mode of operation, switch S_{w1} is turned off. Now the stored energy in inductor L_{i1} is transferred to dc link capacitor C_d until the inductor is completely discharged. The current in inductor L_{i1} reduces and reaches zero as shown in Fig. 10.

MODE III: In this mode, no energy is left in the inductor and the inductor L_{i1} enters discontinuous conduction making the current i_{Li1} zero for the rest of the switching period. During this period, none of the switch or diode will be conducting as shown in Fig.6. The DC link voltage V_{dc} decreases as capacitor C_d supplies energy to the load.

For the negative half cycle, switch S_{w2}, inductor L_{i2}, diode D_n and diode D_2 operate to produce similar modes mentioned in the positive half cycle operation.

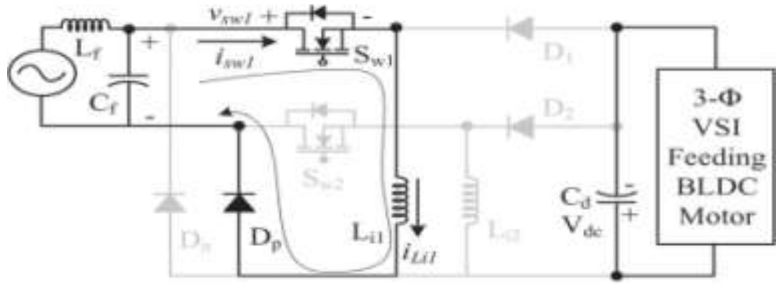


Fig.4. Operation of the BL buck-boost converter for a positive half cycle of supply voltage in MODE I

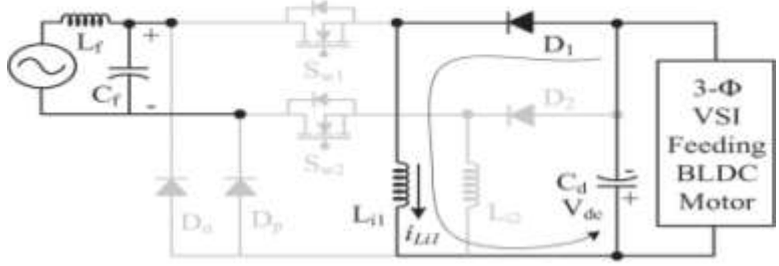


Fig.5. Operation of the BL buck-boost converter for a positive half cycle of supply voltage in MODE II

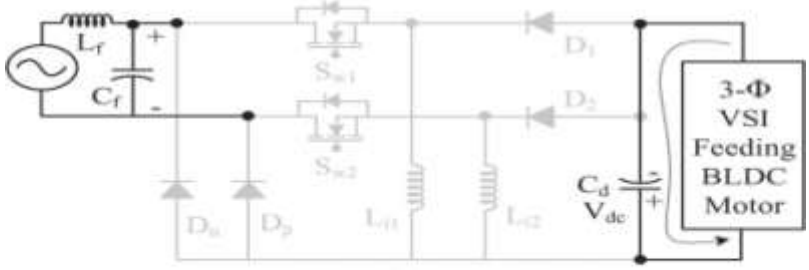


Fig.6. Operation of the BL buck-boost converter for a positive half cycle of supply voltage in MODE III

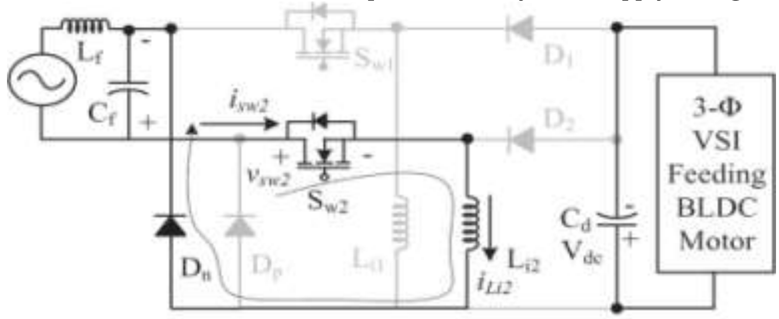


Fig.7. Operation of the BL buck-boost converter for a negative half cycle of supply voltage in MODE I

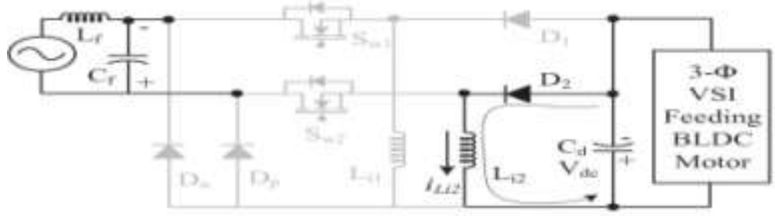


Fig.8. Operation of the BL buck-boost converter for a negative half cycle of supply voltage in MODE II

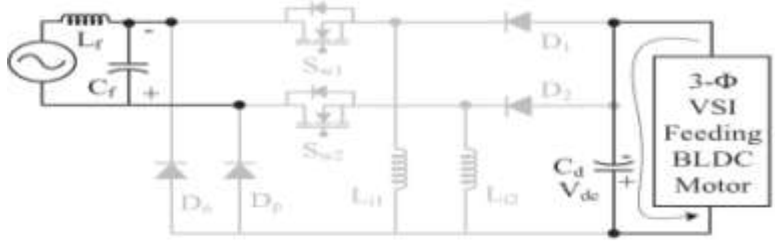


Fig.9.Operation of the BL buck-boost converter for a negative half cycle of supply voltage in MODE III

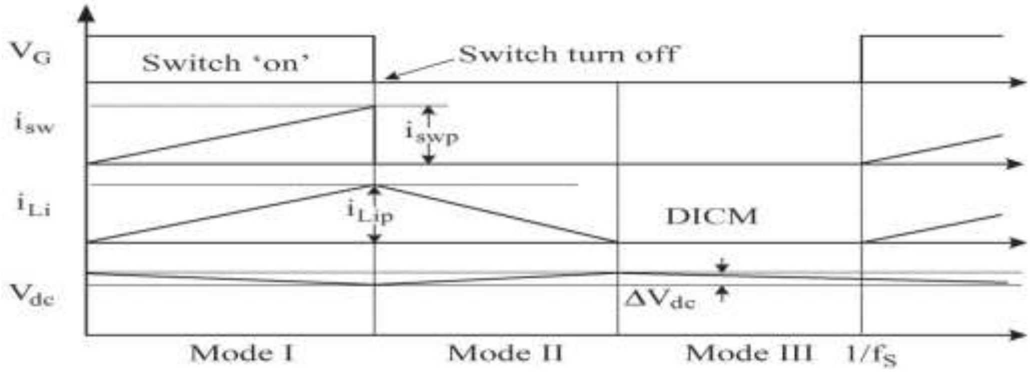


Fig.10. Waveforms during complete switching cycle

3.2 DESIGN EQUATIONS FOR PFC BL BUCK-BOOST CONVERTER

The inductor value at the critical condition given by the equation:

$$L_{ic} = \frac{R(1-D)^2}{2f_s} \tag{7}$$

where,
R is the load resistance value (Ω)
f_s is the switching frequency (Hz)
D is the duty ratio
The values of inductors L_{i1} and L_{i2} are selected as $1/10^{th}$ of the critical inductor value to assure DICM mode of operation of the BL buck-boost converter.

The dc link capacitor value is given by the equation:

$$C_d = \frac{I_o}{2\omega\Delta V_{dc}} \tag{8}$$

where,
Io is the output current (A)
ΔV_{dc} is the dc link voltage ripple.
$\omega = 2\pi f_s$

3.3 CLOSED LOOP CONTROL

The control of the front-end PFC BL buck-boost converter is done using a voltage follower approach. To achieve PFC at AC mains, PWM pulses are generated for switches S_{w1} and S_{w2}. This controls the DC link voltage V_{dc} of the PFC BL buck-boost converter operating in DICM is given by:

$$V_{dc}^* = k_v \times \omega^* \tag{9}$$

where,
k_v is the volatge constant of the motor
V_{dc} is the reference DC link voltage
ω * is the reference speed

This reference voltage is compared to the sensed dc-link voltage V_{dc} to generate a voltage error V_e. The voltage error V_e at any instant "k" is given by:

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \tag{10}$$

This voltage error is given to the voltage PI controller to generate a controlled output as:

$$V_{cc}(k) = V_{cc}(k-1) + k_{pv}\left(V_e(k) - V_e(k-1)\right) + k_{iv}V_e(k) \tag{11}$$

Where k_{pv} and k_{iv} are the proportional and integral gain of the voltage PI controller.
Finally, the controller output V_{cc} is compared with the high frequency saw-tooth waveform to generate the PWM signals to be given to PFC converter switches as:

$$\begin{gathered}\text{For } v_s > 0;\\ \text{if } m_d < V_{cc} \text{ then } S_{w1} = \text{ON}\\ \text{if } m_d \geq V_{cc} \text{ then } S_{w1} = \text{OFF}\\ \text{For } v_s < 0;\\ \text{if } m_d < V_{cc} \text{ then } S_{w2} = \text{ON}\\ \text{if } m_d \geq V_{cc} \text{ then } S_{w2} = \text{OFF}\end{gathered}$$

IV. SIMULATION RESULTS

The proposed systems are modeled and simulated in MATLAB R2014a and the waveforms are plotted using Simplot. Both BLDC motor drives with and without DBR are simulated separately to have a comparative study of the same. To determine the satisfactory operation of the BLDC motor drives, at its rated load condition, its speed, electromagnetic toque, stator current and back EMF waveforms are used.

Table.4.1 Specification of BLDC motor

PARAMETERS	VALUES
No. of poles (P)	8
Rated power	350 W
Rated DC link voltage (V_{rated})	200 V
Rated Torque (T_{rated})	2 Nm
Rated Speed (N)	1000 rpm
Back EMF constant (k_b)	146.6077 V/krpm
Torque constant (K_t)	1.333 Nm/A
Phase resistance (R_{ph})	2.28750 Ω
Phase inductance (L_{ph})	8.5 mH
Moment of inertia (J)	0.8×10^{-3} kgm^2

4.1 MATLAB SIMULATIONS OF BUCK-BOOST CONVERTER FED SENSORLESS BLDC MOTOR DRIVE SYSTEM

For a supply voltage of 220 V(rms) , the input side voltage V_{in} is given by:

$$V = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2} \times 220}{\pi} = 198\text{V}$$

$$\text{Duty Ratio } D = \frac{V_0}{V_0 + V}$$

With the motor specifications given in Table 4.1, the value of inductance is obtained using equation (2) at a switching frequency f_s= 20kHz. Taking the output voltage as 200 V with a output current ripple of 5% the inductor value is calculated. From equation (3), the value of DC link capacitor is obtained by taking DC link voltage ripple of 3% .

Table 4.2 Design parameters for DBR buck- boost converter

Inductor L	22.8 mH
Capacitor C	5.8 µF
Switching Frequency f_s	20 kHz
Filter Inductor L_f	1.57 mH
Filter Capacitor C_f	330 nF

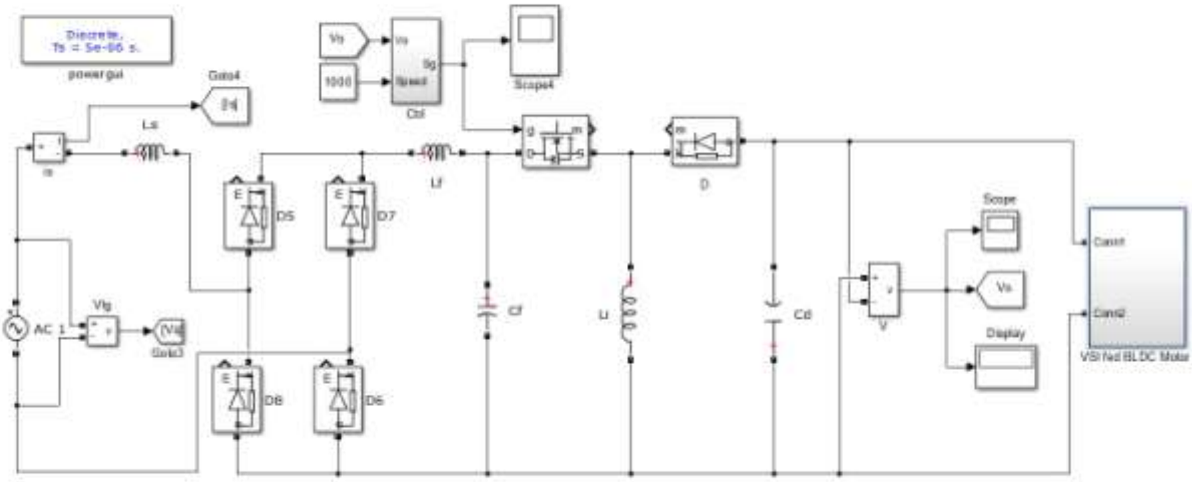


Fig.11. Simulation diagram of buck-boost converter fed sensorless BLDC motor drive with DBR

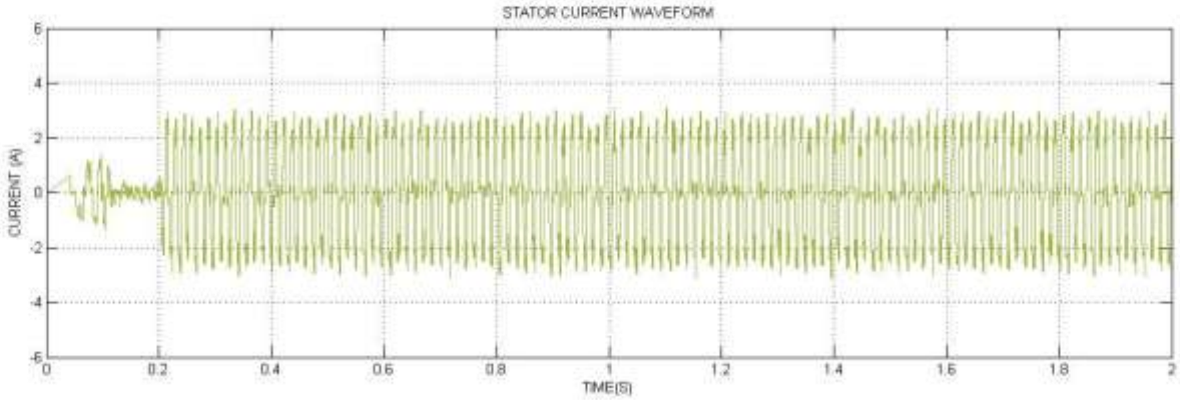


Fig.12. Stator current waveform of buck-boost converter fed sensorless BLDC motor drive with DBR

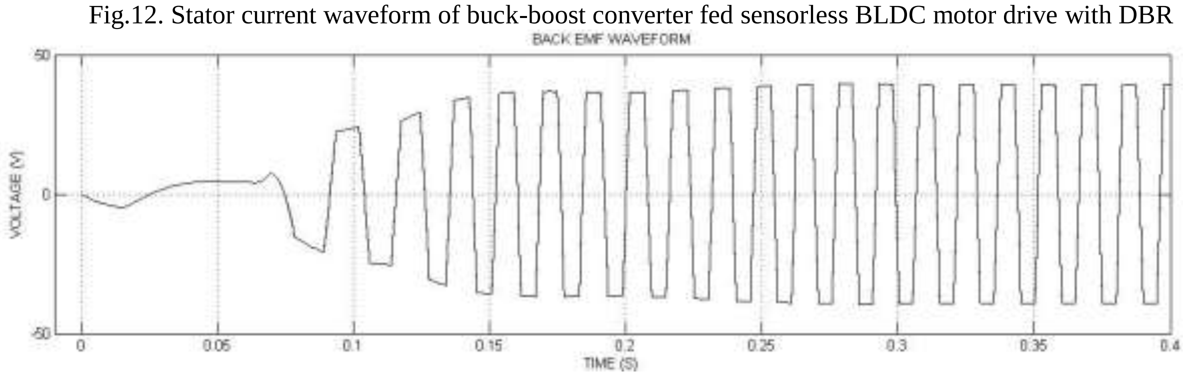


Fig.13. Back EMF waveform of buck-boost converter fed sensorless BLDC motor drive with DBR

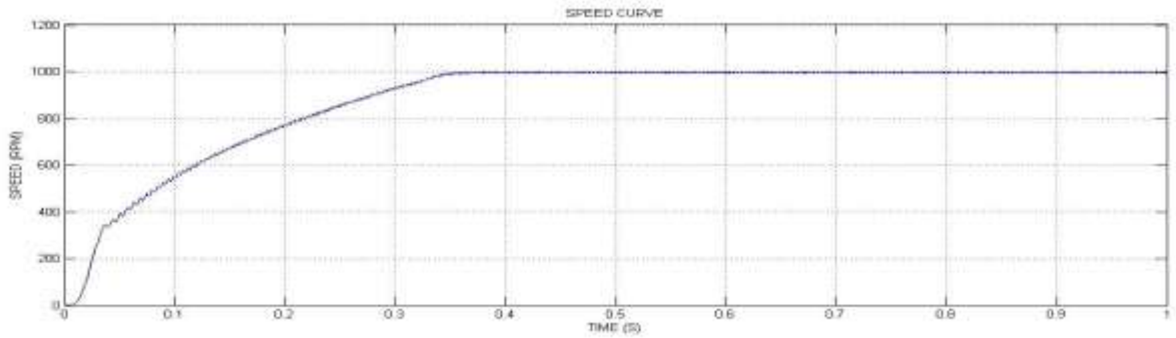


Fig.14. Speed curve of buck-boost converter fed sensorless BLDC motor drive with DBR

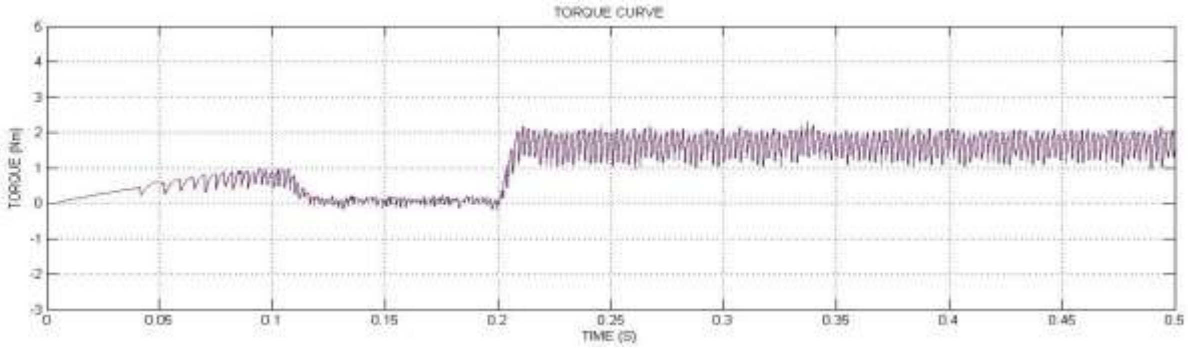


Fig.15. Torque curve of buck-boost converter fed sensorless BLDC motor drive with DBR

4.1 MATLAB SIMULATIONS OF BRIDGELESS BUCK-BOOST CONVERTER FED SENSORLESS BLDC MOTOR DRIVE SYSTEM

For a supply voltage of 220 V(rms) , the input side voltage V_{in} is given by:

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2} \times 220}{\pi} = 198V$$

$$Duty\ Ratio\ D = \frac{V_{dc}}{V_{dc} + V_{in}}$$

By taking $V_{dc} = 200\ V$, D is be obtained as 0.2016.

With the motor specifications given in Table 4.1, the value of critical inductance is obtained using equation (7) at a switching frequency f_s= 20kHz. Hence the value of inductors L_{i1} and L_{i2} are selected as $1/10^{th}$ of the L_{ic} value.

From equation (8), the value of DC link capacitor is obtained by taking DC link voltage ripple as 3%.

Table 4.2 Design parameters for BL buck- boost converter

PARAMETERS	VALUES
Inductor L_{i1}	35 µH
Inductor L_{i2}	35 µH
Capacitor C_d	2200 µF

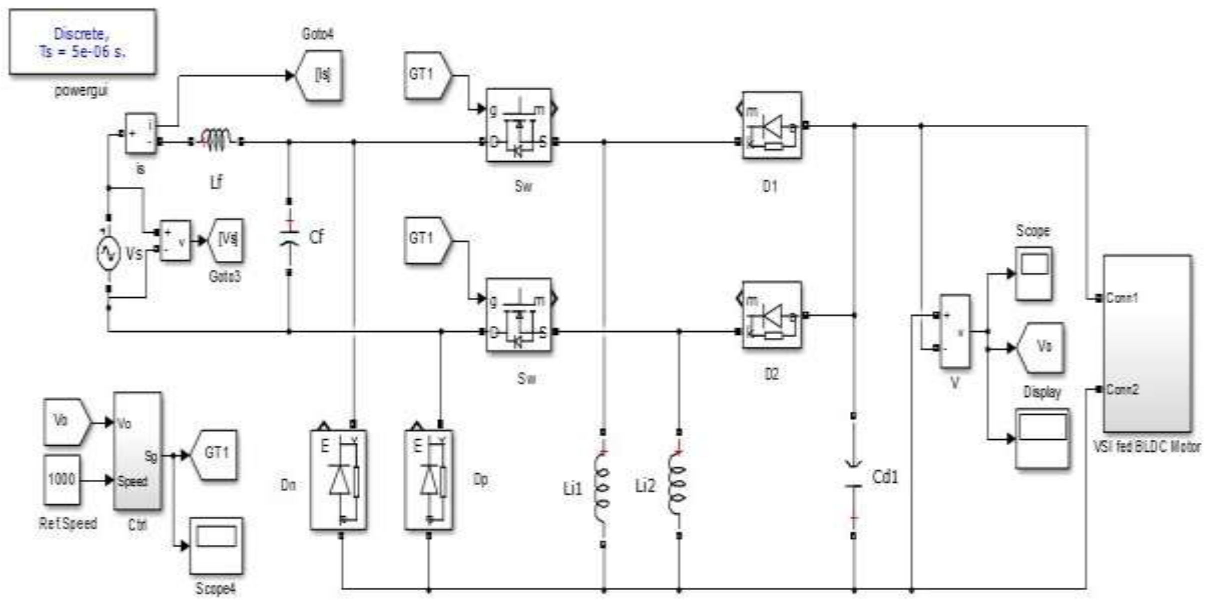


Fig.16. Simulation diagram of BL buck-boost converter fed sensorless BLDC motor drive

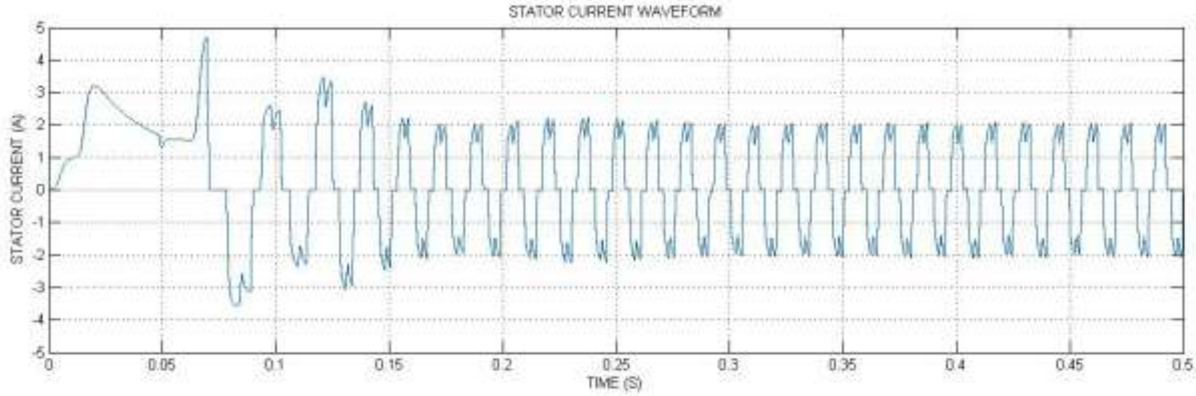


Fig.17. Stator current waveform of BL buck-boost converter fed sensorless BLDC motor drive

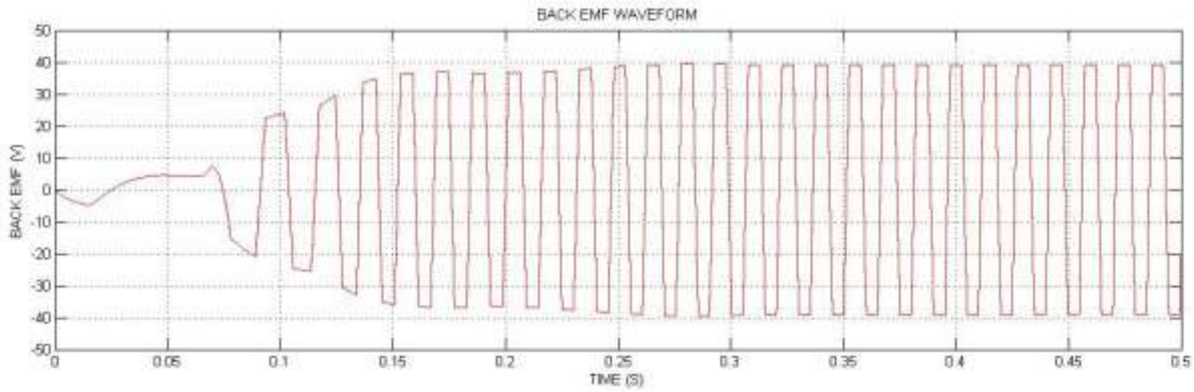


Fig.18. Back EMF waveform of BL buck-boost converter fed sensorless BLDC motor drive

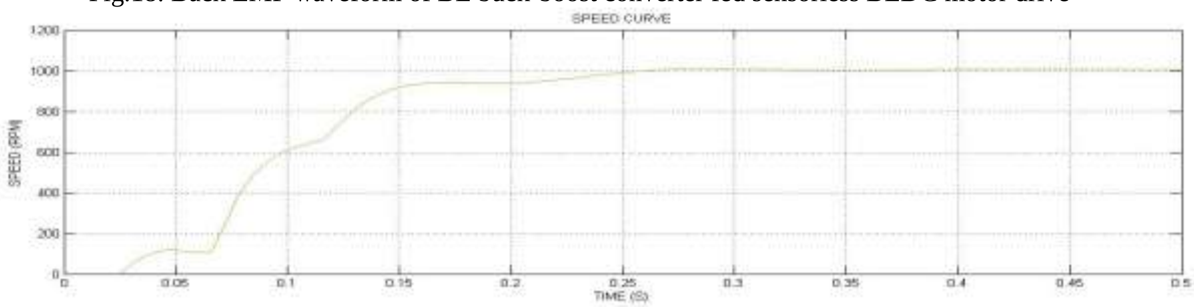


Fig19. Speed curve of BL buck-boost converter fed sensorless BLDC motor drive

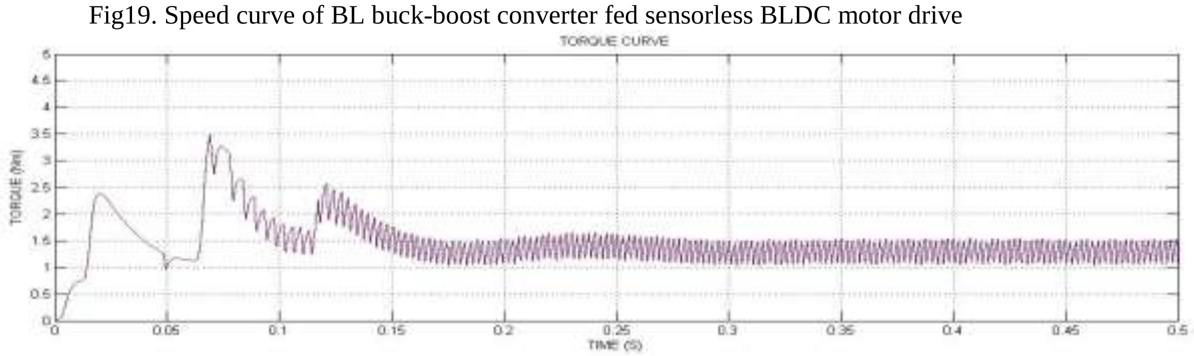


Fig.20. Torque curve of BL buck-boost converter fed sensorless BLDC motor drive

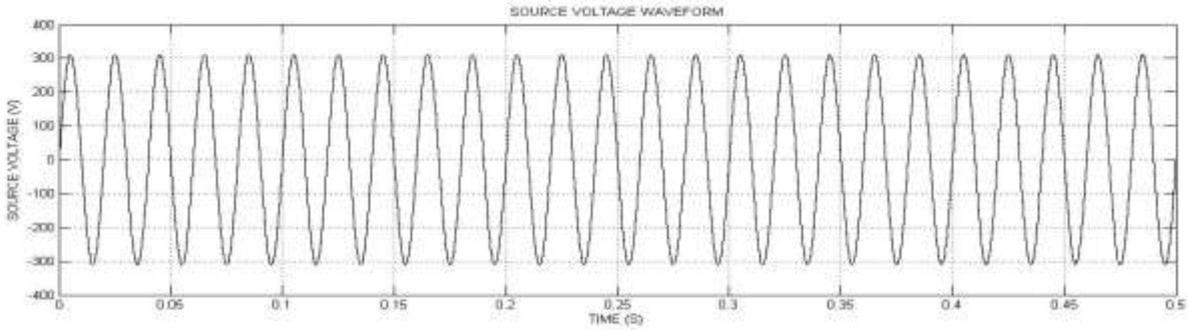


Fig.21. Source voltage waveform of BL buck-boost converter fed sensorless BLDC motor drive

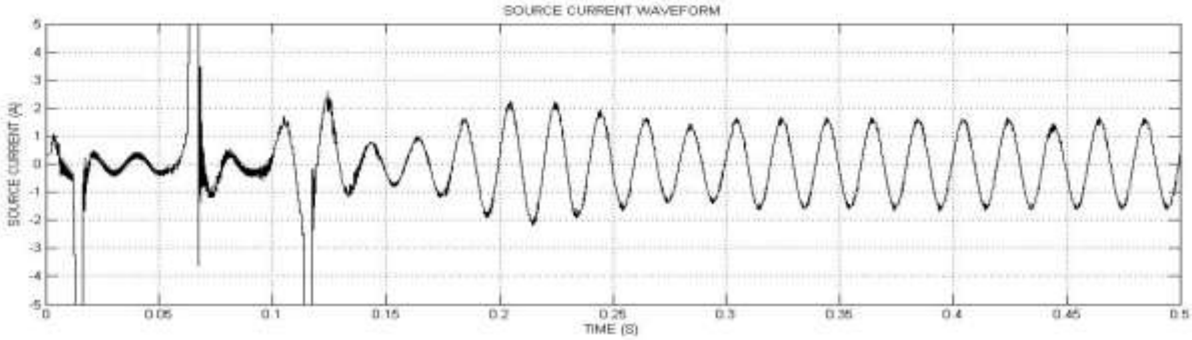
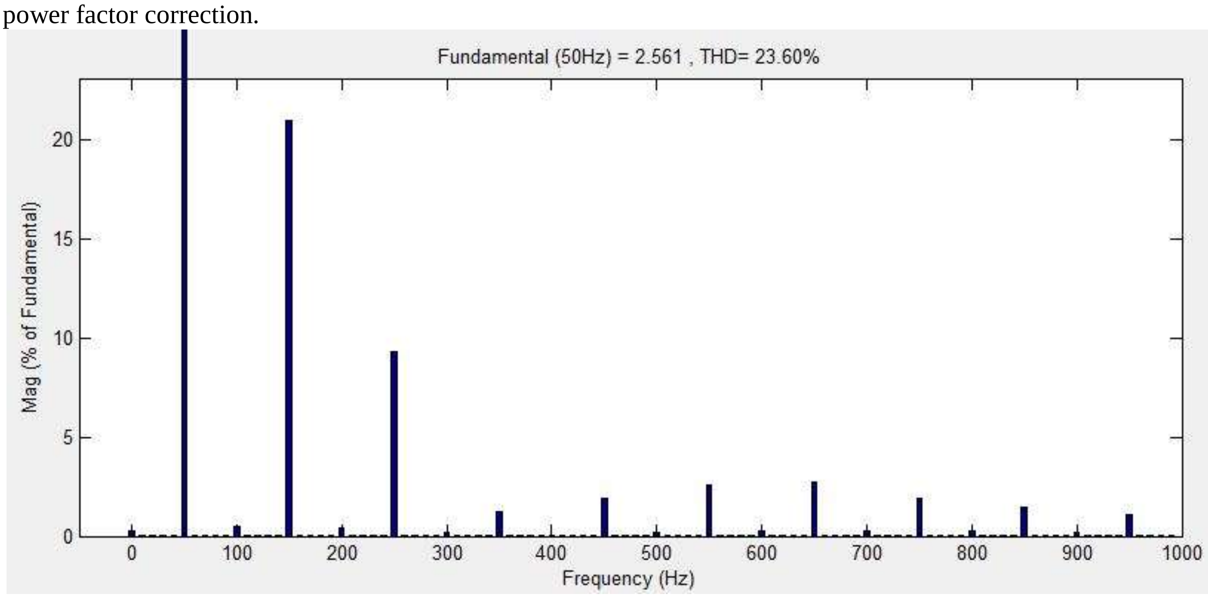
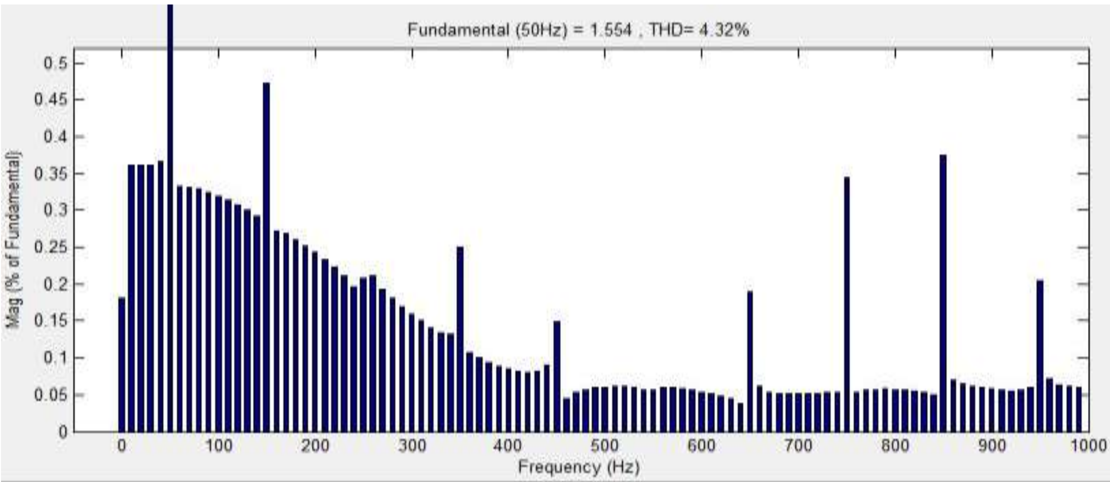


Fig.22. Source current waveform of BL buck-boost converter fed sensorless BLDC motor drive

Fig.21 and Fig.22 shows the source voltage and source current waveforms at AC mains. By observing the zero crossing points of both the waveforms it can be concluded that the power-factor correction is achieved at the source side. Both source voltage and source current are in-phase with same zero crossing instants owing to power factor correction.



Source current THD of buck-boost converter fed sensorless BLDC motor drive with DBR



Source current THD of BL buck-boost converter fed sensorless BLDC motor drive

V. CONCLUSION

A sensorless BLDC motor drive has been designed for numerous low-power applications. To reduce the switching losses,the BLDC motor is commutated electronically to operate the IGBTs of VSI in the fundamental frequency.The speed of the BLDC motor drive has been controlled by varying the dc-link voltage of VSI. In this method the zero crossing points of back EMF are detected and made 30 degree electrical angle lag to get six discrete rotor position signals in each electrical cycle from which the commutation information is obtained by the logical switch circuit , and the the sensorless operation is implemented. It is verified that the proposed BLDC motor drive with sensor and the modified sensorless BLDC motor drive are similar in nature. The stator current, back EMF, speed and torque outputs for both were the same and sensorless BLDC is of low cost compared to a BLDC with sensor. Performance and reliability of BLDC motor drivers have been improved because the conventional control sensing techniques have been improved through sensorless technology.If low cost is a primary concern and low-speed motor operation is not a requirement, and the motor load is not expected to change rapidly, sensorless control is the best choice. Moreover, if the THDs are considered, sensorless BLDC motor drives proved to have a lower THD compared to the one with position sensors. This result is verified using the FFT analysis in MATLAB.

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