TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 12, December 2014, pp. 8060 ~ 8068
DOI: 10.11591/telkomnika.v12i12.6514

Analysis of Variable Speed Chopper Fed Brushless Direct Current Motor

Jeya Selvan Renius, Vinoth Kumar K*, Raja Guru, Arnold Fredderics
Department of EEE, School of Electrical Sciences, Karunya University,
Coimbatore – 641114, Tamilnadu, India
*Corresponding author, e-mail id: kvinoth_kumar84@yahoo.in

Abstract

This paper provides the detailed analysis of the DC-DC chopper fed Brushless DC motor drive used for low-power applications. The various methods used to improve the power quality at the ac mains with lesser number of components are discussed. The most effective method of power quality improvement is also simulated using MATLAB Simulink. Improved method of speed control by controlling the dc link voltage of Voltage Source Inverter is also discussed with reduced switching losses. The continuous and discontinuous modes of operation of the converters are also discussed based on the improvement in power quality. The performance of the most effective solution is simulated in MATLAB Simulink environment and the obtained results are presented.

Keywords*: bridgeless power factor correction (PFC), common-mode noise, continuous-conduction mode (CCM), discontinuous - conduction mode (DCM)/CCM boundary, power factor corrected (PFC), power quality*

1. Introduction

Low power motor drives such as fans, water pumps, blowers, mixers, HVAC transmission, motion control etc. use BLDC motor for their efficient operation. Since BLDC offers high efficiency, low electromagnetic interference, low maintenance and high flux density per unit volume, we use BLDC for low power applications. BLDC motors are very popular in a wide variety of applications. Compared with a DC motor, the BLDC motor uses an electric commutator rather than a mechanical commutator, so it is more reliable than the DC motor. In a BLDC motor, rotor magnets generate the rotor's magnetic flux, so BLDC motors achieve higher efficiency. Therefore, BLDC motors may be used in high-end white goods (refrigerators, washing machines, dishwashers, etc.), high-end pumps, and fans and in other appliances which require high reliability and efficiency.

In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. In the DC commutator motor, the current polarity is altered by the commutator and brushes.

However, in the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position, or the position can be detected without sensors.

The choice of mode of operation of a PFC converter is a critical issue because it directly affects the cost and rating of the components used in the PFC converter. The continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two modes of operation in which a PFC converter is designed to operate. In CCM, the current in the inductor or the voltage across the intermediate capacitor remains continuous, but it requires the sensing of two voltages (dc link voltage and supply voltage) and input side current for PFC operation, which is not cost-effective. On the other hand, DCM requires a single voltage sensor for dc link voltage control, and inherent PFC is achieved at the ac mains, but at the cost of higher stresses on the PFC converter switch; hence, DCM is preferred for low-power applications.

Received July 22, 2014; Revised October 6, 2014; Accepted November 2, 2014

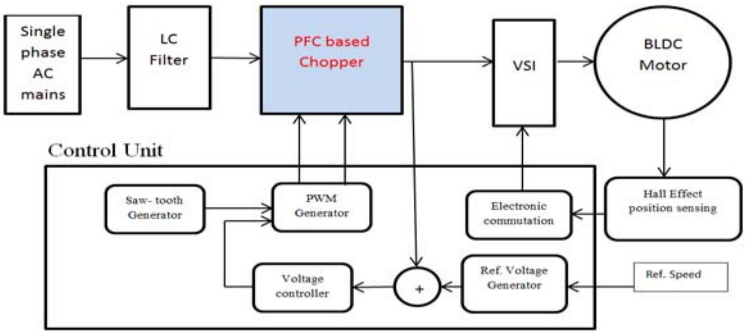


Figure 1. Block diagram of PFC chopper-fed BLDC motor drive

BLDC with diode bridge rectifier with a high value DC link capacitor has a THD (Total Harmonic Distortion) of 65% and power factor as low as 0.8. So the power factor is corrected using the PFC converters. Both continuous and discontinuous modes of the converters are discussed and the discontinuous mode of conduction is best suited for the low power applications. Since the discontinuous conduction requires only a single voltage sensor for DC link voltage control. But conventional PFC uses more number of components that increases the cost of the control circuit. Also the conventional PFC used PWM-VSI for speed control with constant DC link voltage which produces higher switching losses.

Thus the analysis is made for different methods that improve the power quality at the ac mains. For further improvement in efficiency, bridgeless (BL) converters are used which allow the elimination of DBR in the front end. A buck–boost converter configuration is best suited among various BL converter topologies for applications requiring a wide range of dc link voltage control (i.e., bucking and boosting mode). These can provide the voltage buck or voltage boost which limits the operating range of dc link voltage control. A new family of BL SEPIC and Cuk converters has been reported but requires a large number of components and has losses associated with it.

This paper presents a detailed analysis of chopper-fed BLDC motor drive with variable dc link voltage of VSI for improved power quality at ac mains with reduced components.

2. Exsisting Topologies

The conventional PFC uses Pulse Width Modulated Voltage Source Inverter (PWM-VSI) for speed control with constant DC link voltage. This causes higher switching losses. The switching losses in this conventional approach increases as a square function of switching frequency.

T. Gopalarathnam and H.A. Toliyat [1] in 2003 proposed a Single Ended Primary Inductance Converter (SEPIC) based BLDC which also has higher losses in the VSI due to conventional PWM switching and large number of current and voltage sensors are used that additionally adds to the cost of the converter.

S. Singh and B. Singh [2] in 2011 proposed a paper about Buck-Boost converter based on constant DC link voltage and also use PWM-VSI for speed control which again increases the switching losses.

S. Singh and B. Singh [3] again in 2012 proposed a cuk converter fed BLDC motor with a variable DC link voltage that reduces the switching losses since it uses only the fundamental switching frequency. Speed control is performed by controlling the voltage at the DC bus of VSI. In this paper, Continuous Conduction Mode (CCM) is used. But the major disadvantage is that it requires three sensors. So it is not encouraged for low-cost and low-power rating applications.

Since only the bridge converters are used in all the above used topologies, it also contributed for the switching losses. Thus the bridgeless topologies are preferred. The different bridgeless topologies are analysed based on the power quality of the ac mains.

3. Bridgeless Converter Topologies

The bridgeless converters eliminate the use of diode rectifiers. The diode rectifiers cause more switching stresses. This is not good for the proper functioning of the converter.

3.1. Boost Converters

Y. Jang and M.M. Jovanovic [4] in the year 2011 proposed a concept based on boost converter fed BLDC motor drive. The basic topology of the bridgeless PFC boost rectifier is shown in Figure 2. Compared to conventional PFC boost rectifier one diode is eliminated from the line-current path, so that the line current simultaneously flows through only two semiconductors, resulting in reduced conduction losses. However, the bridgeless PFC boost rectifier in Figure 2 has significantly larger common-mode noise than the conventional PFC boost rectifier. In fact, in the conventional PFC boost rectifier, the output ground is always connected to the ac source through the full-bridge rectifier whereas, in the bridgeless PFC boost rectifier in Figure 2, the output ground is connected to the ac source only during a positive half-line cycle, through the body diode of switch, while during a negative half-line cycle the output ground is pulsating relative to the ac source with a high frequency (HF) and with an amplitude equal to the output voltage. This HF pulsating voltage source charges and discharges the equivalent parasitic capacitance between the output ground and the ac line ground, resulting in a significantly increased common-mode noise.

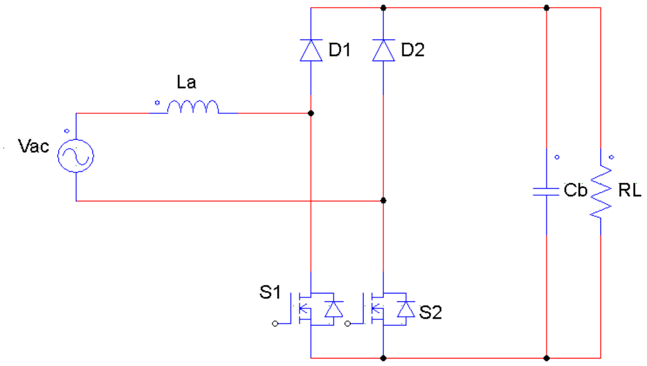


Figure 2. Bridgeless PFC Boost converter

The bridgeless boost converter provides only voltage boost which limits the operating range of DC link voltage control. Thus we move for another topology.

3.2. Cuk Converters

L. Huber, Y. Jang and M.M. Jovanovic [5] in the year 2008 proposed a paper based on cuk converter based BLDC. In this section, the topology derivation of the proposed converter is presented. Figure 3 shows a modified Cuk converter also known as a “Self-lift Cuk” converter. Referring to Figure 3, the converter can be manipulated to produce a positive output voltage from a negative input voltage. Similarly, for a converter it is possible to produce a negative output voltage from a negative input voltage. Note that the converters have similar output characteristics and they are identical except for their input voltage polarity and switch drain-to source connection. Therefore, it is possible to combine the two converters into a single bridgeless ac-dc PFC converter containing a bi-directional switch and an alternating input voltage source. Likewise, the converter can be combined into a single bridgeless ac-dc PFC converter which offers an inverted output voltage polarity. Unlike the conventional bridgeless PFC converters, all components in the proposed converter are fully utilized as there are no idle components during both the positive and negative ac-line cycle. Also, no additional diodes or capacitors are added to the topology to filter out common mode noise since the output is not floating.

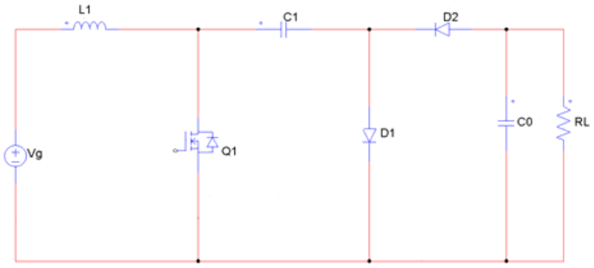


Figure 3. Modified Cuk converter with Negative output polarity

This converter also has a serious disadvantage of switching losses. So this topology is also not used now.

3.3. Buck-boost Converter

W. Lei, L. Hongpeng, J. Shigong and X. Dianguo [6] in the year 2008 proposed a scheme with buck-boost converter fed BLDC [. According to the above analysis, Switches S_1 and S_3 should have a symmetrical blocking voltage characteristic. So, the RB-IGBT (Reverse Blocking IGBT) is used. It can block both forward and reverse voltage during its off state. Comparing IGBT with a series connected diode, elimination of the series diode helps to reduce losses by decreasing the on-state voltage across the switching element. Comparing with bridge buck boost PFC converter bridgeless buck-boost PFC converter has one more switch and capacitor, two less slow diodes. However, comparing the conduction path of these two circuits, at every moment, three semiconductor devices are only conducting for bridgeless buck-boost PFC converter, but four semiconductors are conducting for bridge buck-boost PFC converter. Therefore, conduction loss can be reduced, especially in low line voltage.

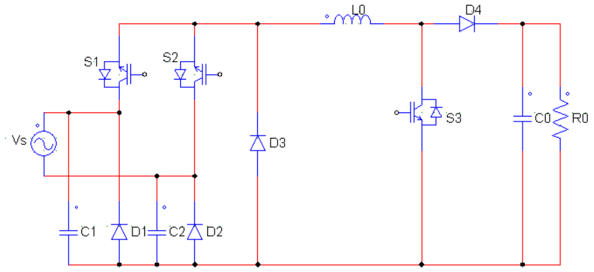


Figure 3. Bridgeless PFC Buck-Boost converter

The above PFC buck-boost converter uses three switches which is cost effective and also increases the switching losses. Thus this method of power quality improvement also has some limitations. So we go for some other topology for better power quality.

3.4. Sepic PFC Rectifier

A.A. Fardoun, E.H. Ismail, A.J. Sabzali and M.A. Al-Saffar [7] in the year 2012 proposed a method of SEPIC PFC rectifier for BLDC. Figure 4 shows the power stage of a bridgeless SEPIC PFC rectifier. In this circuit, the SEPIC converter is combined with the input rectifier and operates like a conventional SEPIC PFC converter. The operation of this converter is symmetrical in two half-line cycles of input voltage. Therefore, the converter operation is explained during one switching period in the positive half-line cycle of the input voltage. It is assumed that the converter operates in DCM. It means that the output diode turns off before the main switch is turned on. In order to simplify the analysis, it is supposed that the converter is operating at a steady state, and all circuit elements are ideal. In addition, the output capacitance is assumed sufficiently large to be considered as an ideal dc voltage source (V_0). Also, the input voltage is assumed constant and equal to Vac (t_0) in a switching cycle. Based on the aforementioned assumptions, the circuit operation in a switching cycle can be divided into three modes.

The circuit diagram gives the Single Ended Primary Inductance Converter (SEPIC) converter fed BLDC motor for the improvement in the power quality.

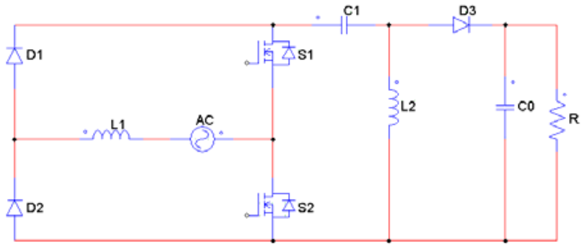


Figure 4. Bridgeless SEPIC PFC converter

Thus the SEPIC converter is efficient but it requires large number of components. So it is not cost effective.

These are some of the bridgeless PFC converter techniques for the improvement of power quality in the ac mains. But all these techniques have some limitations. They also cannot be used for low power applications. So the proposed technique below is designed in such a way that is best suited for low power applications.

4. Proposed Topology

Figure 5 shows the proposed BL buck–boost converter-based VSI-fed BLDC motor drives. The parameters of the BL buck–boost converter are designed such that it operates in discontinuous inductor current mode (DICM) to achieve an inherent power factor correction at ac mains. The speed control of BLDC motor is achieved by the dc link voltage control of VSI using a BL buck–boost converter. This reduces the switching losses in VSI due to the low frequency operation of VSI for the electronic commutation of the BLDC motor. The performance of the proposed drive is evaluated for a wide range of speed control with improved power quality at ac mains. Moreover, the effect of supply voltage variation at universal ac mains is also studied to demonstrate the performance of the drive in practical supply conditions. Voltage and current stresses on the PFC converter switch are also evaluated for determining the switch rating and heat sink design.

Finally, a software implementation of the proposed BLDC motor drive is carried out to demonstrate the feasibility of the proposed drive over a wide range of speed control with improved power quality at ac mains.

The proposed circuit diagram of the Buck-boost converter fed BLDC motor is shown in the Figure 5.

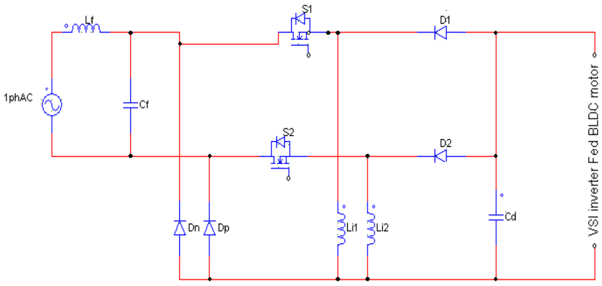


Figure 5. Proposed Circuit diagram of the Buck-boost converter fed BLDC

The above circuit is perfectly suitable for the low power applications.

5. Operating Principle of the Proposed PFCBL Buck– Boost Converter

The operation of the PFC BL buck–boost converter is classified into two parts which include the operation during the positive and negative half cycles of supply voltage and during the complete switching cycle.

5.1. Operation during Positive and Negative Half Cycles of Supply Voltage

In the proposed scheme of the BL buck–boost converter, switches S_1 and S_2operate for the positive and negative half cycles of the supply voltage, respectively. During the positive half cycle of the supply voltage, switch S_1, inductor L_{i1}, and diodes D_1 and D_p are operated to transfer energy to dc link capacitor C_d as shown in Figure 6(a)-(c).

Similarly, for the negative half cycle of the supply voltage, switch S_2, inductor L_{i2}, and diodes D_2 andD_n conduct as shown in Figure 7(a)-(c). In the discontinuous mode of operation of the BL buck–boost converter, the current in inductor L_i becomes discontinuous for certain duration in a switching period.

5.2. Operation During Complete Switching Cycle

Three modes of operation during a complete switching cycle are discussed for the positive half cycle of supply voltage as shown hereinafter.

Mode I:

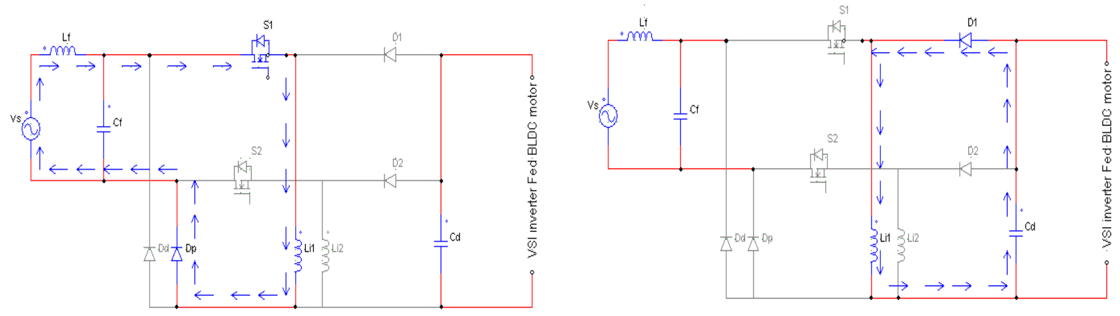
In this mode, switch S_1conducts to charge the inductor L_{i1}; hence, an inductor current i_{Li1} increases in this mode as shown in Fig. 6(a). Diode D_p completes the input side circuitry, whereas the dc link capacitor C_d is discharged by the VSI-fed BLDC motor.

Mode II:

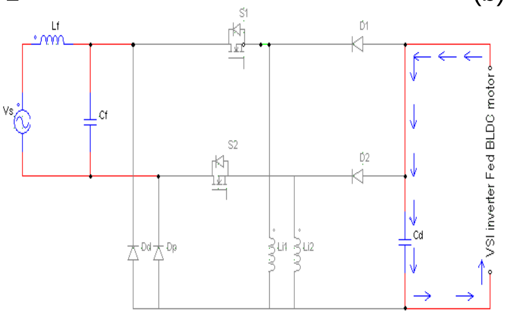
As shown in Figure 6(b), in this mode of operation, switch $S_1$is turned off, and the stored energy in inductor $L_{i1}$is transferred to dc link capacitor $C_d$until the inductor is completely discharged. The current in inductor L_{i1} reduces and reaches zero.

Mode III:

In this mode, inductor L_{i1} enters discontinuous conduction, i.e., no energy is left in the inductor; hence, current i_{Li1} becomes zero for the rest of the switching period. As shown in Fig. 6(c), none of the switch or diode is conducting in this mode, and dc link capacitor $C_d$supplies energy to the load; hence, voltage V_{dc} across dc link capacitor C_d starts decreasing. The operation is repeated when switch $S_1$is turned on again after a complete switching cycle.

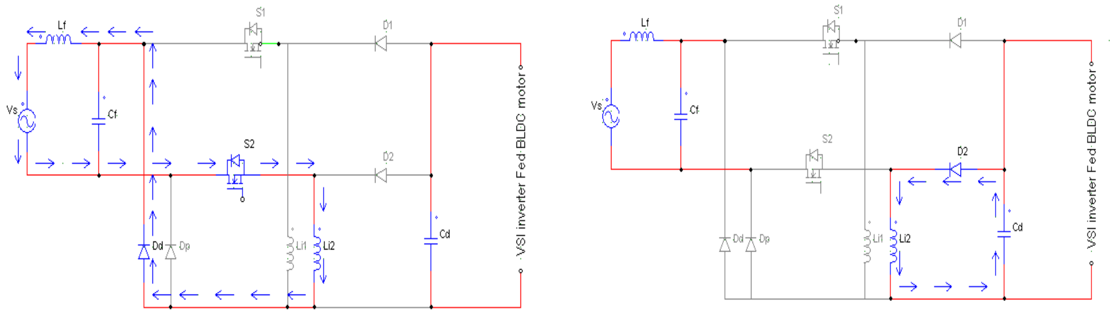


(a) Mode 1 (b) Mode 2

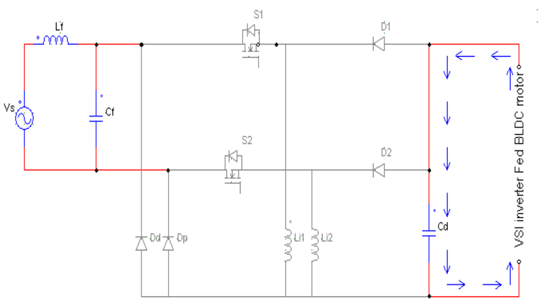


(c) Mode 3

Figure 6. Operation of the proposed converter in different modes (a)-(c) for a positive half cycle of the supply voltage



(a) Mode 1 (b) Mode 2



(c) Mode 3

Figure 7. Operation of the proposed converter in different modes (a)-(c) for a negative half cycle of the supply voltage

6. Simulation Circuit

The proposed bridgeless buck-boost converter fed BLDC with variable DC link voltage of VSI to improve the power quality at ac mains with reduced components is simulated in MATLAB and the results are shown below.

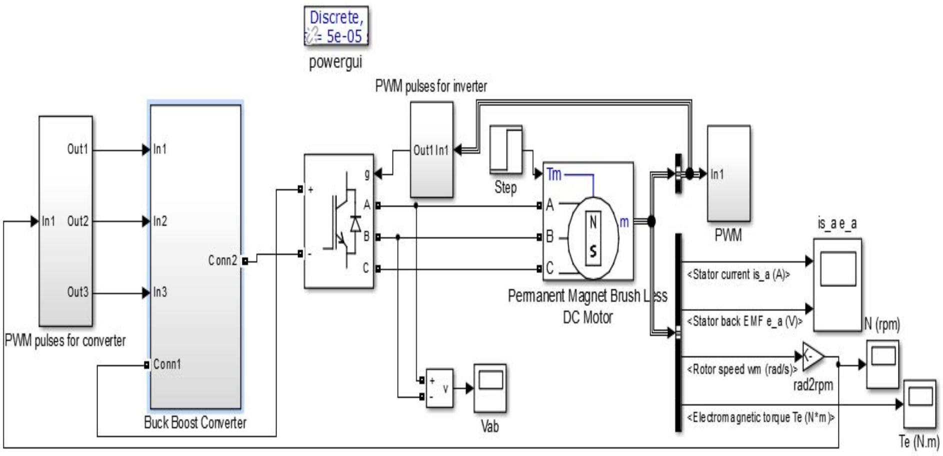


Figure 8. Simulation circuit of Buck-boost converter fed BLDC in MATLAB Simulink

The above circuit consists of the main blocks which are used for the BLDC control. The sub-blocks are presented below. The main sub-block is the buck-boost converter block.

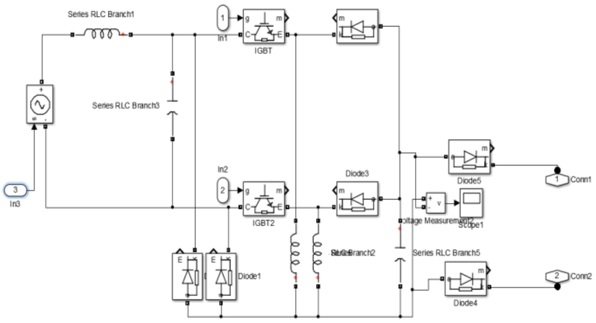
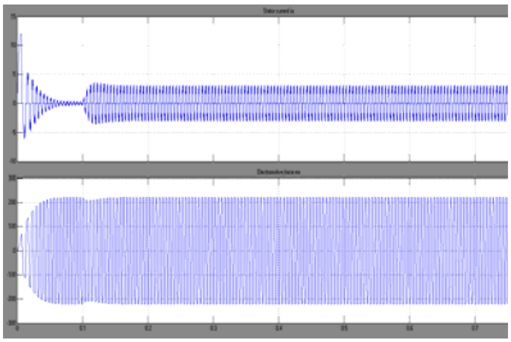


Figure 9. Simulation sub-block of buck-boost converter

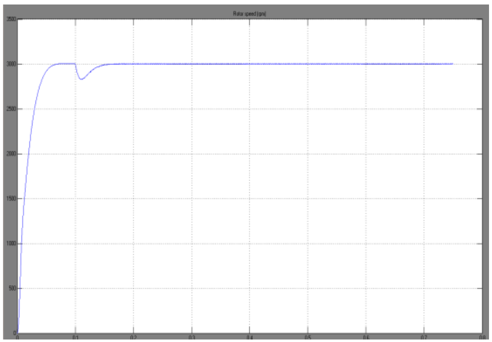
The proposed method is simulated in MATLAB as given above and the results are evaluated.

7. Simulated Results

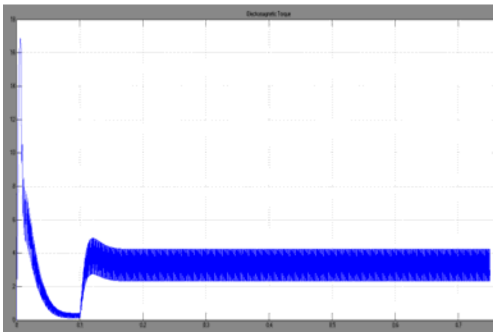
The simulated results for various parts of the proposed circuit are shown below. The performance of the proposed BLDC motor drive is simulated in MATLAB/Simulink environment using the Sim-Power System toolbox. The performance evaluation of the proposed drive is categorized in terms of the performance of the BLDC motor and BL buck–boost converter and the achieved power quality indices obtained at ac mains. The parameters associated with the BLDC motor such as speed (N), electromagnetic torque (T_e), and stator current (i_a) are analysed for the proper functioning of the BLDC motor. Parameters such as supply voltage (V_s), supply current (i_s), dc link voltage (V_{dc}), inductor's currents (i_{li1}, i_{li2},), switch voltages (V_{sw1},, V_{sw2}), and switch currents(i_{sw1}, i_{sw2}) of the PFC BL buck–boost converter are evaluated to demonstrate its proper functioning.



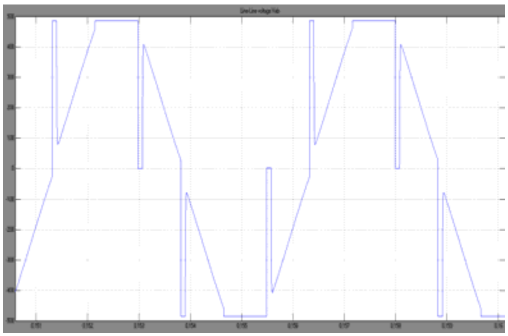
(a) Stator current and electromotive force output waveform



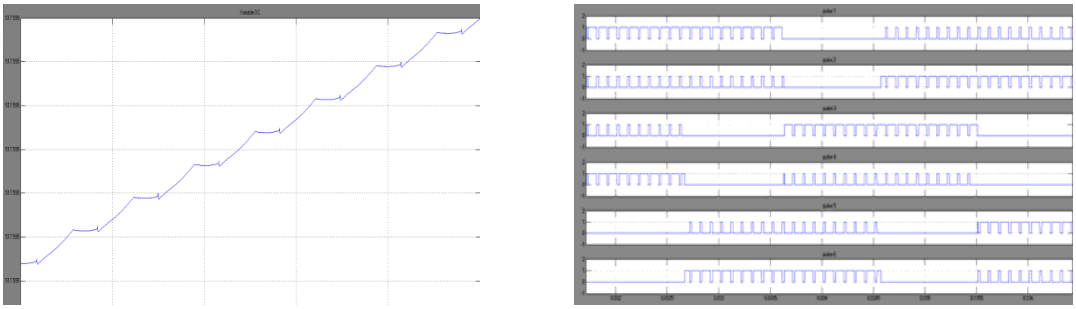
(b) Rotor Speed output waveform



(c) Electromagnetic Torque output waveform

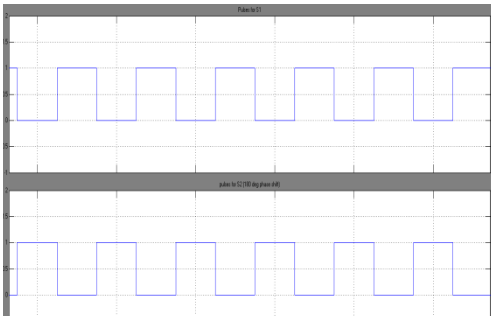


(d) Line to line voltage output waveform



(e) Variable DC voltage output waveform

(f) Pulse waveform for VSI



(g) Pulses for buck-boost converter

7. Conclusion

A PFC BL buck–boost converter-based VSI-fed BLDC motor drive has been proposed targeting low power applications. A new method of speed control has been utilized by controlling the voltage at dc bus and operating the VSI at fundamental frequency for the electronic commutation of the BLDC motor for reducing the switching losses in VSI. The front-end BL buck boost converter has been operated in DICM for achieving an inherent power factor correction at ac mains. A satisfactory performance has been achieved for speed control and supply voltage variation with power quality indices. Moreover, voltage and current stresses on the PFC switch have been evaluated for determining the practical application of the proposed scheme. The proposed scheme has shown satisfactory performance, and it is a recommended solution applicable to low-power BLDC motor drives.

References

[1] T Gopalarathnam, HA Toliyat. A new topology for unipolar brushless dc motor drive with high power factor. *IEEE Trans. Power Electron.,* 2003; 18(6): 1397–1404.

[2] S Singh, B Singh*. Power quality improved PMBLDCM drive for adjustable speed application with reduced sensor buck-boost PFC converter*. Proc. 4th ICETET. 2011; 180–184.

[3] S Singh, B Singh. A voltage-controlled PFC Cuk converter based PMBLDCM drive for air conditioners. *IEEE Trans. Ind. Appl.,* 2012; 48(2): 832–838.

[4] Y Jang, MM Jovanovi´c. Bridgeless high-power-factor buck converter. *IEEE Trans. Power Electron.,* 2011; 26(2): 602–611.

[5] L Huber, Y Jang, MM Jovanovi´c. Performance evaluation of bridgeless PFC boost rectifiers. *IEEE Trans. Power Electron.*, 2008; 23(3): 1381–1390.

[6] W Wei, L Hongpeng, J Shigong, X Dianguo. *A novel bridgeless buck-boost PFC converter.* IEEE PESC/IEEE Power Electron. Spec. Conf., 2008; 1304–1308.

[7] AA Fardoun, EH Ismail, AJ Sabzali, MA Al-Saffar. New efficient bridgeless Cuk rectifiers for PFC applications. *IEEE Trans. Power Electron.,* 2012; 27(7): 3292–3301.