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Performance analysis of Buck-Boost and Cuk converter-fed brushless DC motor drives

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Abstract

This paper presents a detailed analysis on the performances of Buck-boost and Cuk power factor converter-fed sensor-less Brushless DC (BLDC) motor drives. BLDC motors are widely preferred for low-power applications due to their high efficiency, faster dynamic response, high ruggedness, high power density, long operating life, noiseless operation, high torque-to-weight ratio and higher speed ranges. Speed of the drive is controlled by varying the DC-link voltage of the Voltage Source Inverter (VSI) feeding the motor. Switching losses in the Voltage Source Inverter are reduced by electronic commutation of the BLDC motor, thereby switching the solid state switches of the VSI at line frequency. The converters are operated in Discontinuous Conduction Mode (DCM) to achieve inherent power factor correction (PFC) at AC mains. Voltage mode control is used adjust the duty ratio of the PFC converter switch. Direct Back-EMF Zero Crossing Detection method is used for the sensor-less control of the BLDC motor. The performance of the drive is evaluated using the selected converters over a wide range of speeds. A unity power factor is achieved with power quality indices acceptable within the recommended limits of IEEE 519 standard..

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Keywords: Back-EMF Zero Crossing Detection; Brushless DC Motor; Discontinuous Conduction Mode; Power Factor Correction; Sensor-less Control

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Nomenclature

S_w	switch
L_i	input inductor
L_o	output inductor
C_d	dc-link capacitor
D	diode
V_{dc}^*	reference dc-link voltage
N^*	reference speed
k_v	back-EMF constant
V_{dc}	actual dc-link voltage
V_e	error voltage
V_{cd}	controlled output voltage
k_{pv}	proportional gain constant
k_{iv}	integral gain constant
m_d	high-frequency saw tooth carrier signal
ω_m	rotor speed
T_e	electromagnetic torque
i_a	stator current
E_b	back-EMF
V_{sw}	switch voltage stress
I_{sw}	switch current stress

1. Introduction

The Brushless DC motor is a special type of Permanent Magnet Synchronous motor with trapezoidal back EMF and quasi-rectangular current waveforms. This motor has a three-phase concentrated winding on the stator and permanent magnets on the rotor [2, 3]. BLDC motor drives are widely used in a variety of consumer products and industrial applications due to their innumerable advantages like high efficiency, faster dynamic response, high ruggedness, high power density, long operating life, noiseless operation, high torque-to-weight ratio, higher speed ranges [2,3]. Due to the absence of brushes in this motor, current commutation in the windings is implemented electronically based on rotor position feedback [6, 7, 14-18]. Hence, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position, which increase the cost and size of the motor and reduce its sturdiness [6,7,14-18].Cost reduction of variable-speed drives is accomplished by two approaches. One is the topological approach and the other is control approach [4, 5, 12]. In the first approach, minimum numbers of switches are used to compose the power conversion circuit; whereas in the second approach, control algorithms are designed and implemented so as to produce the desired dynamics [4, 5, 12]. As a result, various sensor-less control techniques have been proposed to enhance the performance of the BLDC motor drives like Back-EMF zero crossing detection, Varying inductance approach, Flux-linkage variation, MRAS control, Extended Kalman filter method etc. [6,7, 9-13].

In conventional BLDC motor drives, a diode bridge rectifier with a DC link capacitor feeds the BLDC motor. This combination however draws a large peaky distorted supply current from the AC mains. Such current has high amount of harmonics and results in high Total Harmonic Distortion(THD) of supply current of the order of 60-80 % which results in power factor as low as 0.65 and crest factor (CF) as high as 3-5 [2,3,8]. These power quality indices are not acceptable under the limits specified by IEEE 519 and IEC 61000-3-2 standards. This necessitates the need for the use of single-phase Power Factor Correction converters for achieving unity power factor at the AC mains [4,5,19].

The PFC converters generally have two modes of operation: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) [2-5, 19]. CCM offers continuous inductor current, reduced stress on the switch of the PFC converter at the cost of higher number of sensors. This mode is generally used for high power applications. DCM offers discontinuous inductor current and requires only a single sensor for sensing the DC-link voltage. This mode is limited to low power applications due to higher stress on the converter switch [2-5, 19]. Commonly used configuration is a BLDC motor fed by a PFC Boost converter. The dc-link voltage is held constant and the speed of the motor is controlled by varying the duty ratio of the PWM pulses supplied to the switches of the VSI, using a current controller. This results in high switching losses in the solid-state switches of the VSI. By electronically commutating the BLDC motor, the switches of the VSI operate at low frequency, thus reducing the switching losses in the VSI. The speed of the BLDC motor can be controlled by varying the dc-link voltage using a suitable control strategy [2, 3]. This paper presents a performance evaluation of two different PFC converter fed BLDC motor drives. Buck-boost and Cuk converters have been selected for this comparison due to dc-link voltage control over a wide range at varying supply voltages.

2. BLDC Motor Drive System Configuration

The drive consists of a single-phase converter and a three-phase BLDC motor [2,3]. (Fig.1) & (Fig.2) show the drive system schematic of Buck-Boost PFC converter fed Sensor-less BLDC motor drive and Cuk PFC converter fed Sensor-less BLDC motor drive respectively. In Fig.1 and Fig.2, a Buck-Boost PFC converter and a Cuk PFC converter, respectively are connected to the output of a bridge rectifier to obtain a regulated dc output voltage. A low-pass filter in the output of the diode bridge rectifier eliminates the ripples and EMI issues [2,3].

Voltage Mode Control is implemented to control the dc-link voltage of the PFC converter. The PFC converters are operated in Discontinuous Conduction Mode (DCM) to reduce the cost and complexity of the drive control system [2,3]. Sensor-less Back-EMF Zero-Crossing detection method is used for the electronic commutation of the BLDC motor drive [6, 14-18]. Here, the Back-EMFs of the three phases of the BLDC motor are used to generate the switching pulses for the solid-state switches of the VSI. This control scheme does not require any position sensor to detect the rotor position every 60 electrical degrees & thus helps in cost-reduction of the drive system[6,14-18].

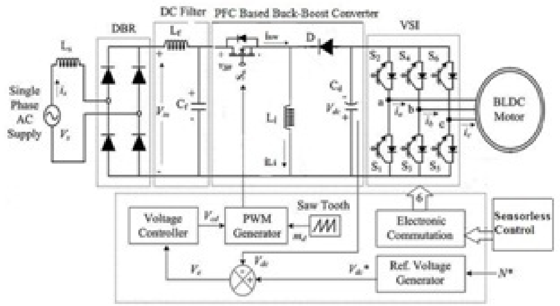

Fig. 1.Buck-Boost PFC converter fed sensor-less BLDC motor drive

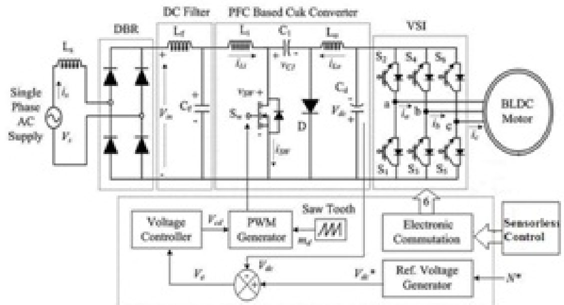

Fig. 2.Cuk PFC converter fed sensor-less BLDC motor drive

3. Modes of Operation of PFC converters

The DCM operation of the two selected PFC converters namely, Buck-Boost PFC Converter and Cuk PFC converters is explained in this section.

3.1. Buck-Boost Power Factor Correction Converter

Figs. 3(a-c) show the three operating modes of proposed PFC converter during a switching period and Fig. 3(d) shows the associated waveforms [1].

Mode I: When the switch S_w is turned ON, the inductor L_i starts charging through the switch. However the dc-link capacitor C_d discharges through the load as shown in Fig. 3(a).

Mode II: When the switch S_w is turned OFF, the diode D starts conducting. The inductor L_i starts discharging through the diode D and the dc-link capacitor C_d. And the dc-link capacitor C_d starts charging as shown in Fig. 3(b).

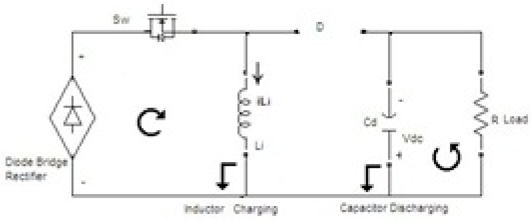

Fig. 3(a).Mode I

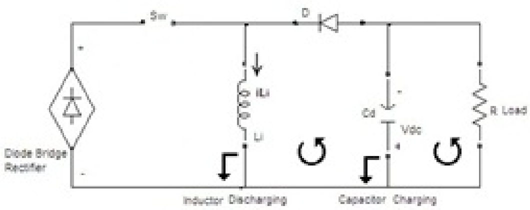

Fig. 3(b).Mode II

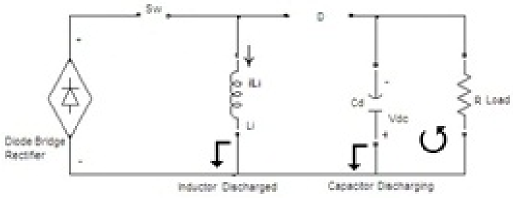

Fig. 3(c).Mode III

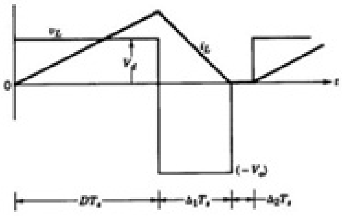

Fig. 3(d).Waveforms of Buck-Boost PFC Converter in DCM

Mode III: In this mode, the inductor L_i is completely discharged and enters the DCM mode as shown in Fig. 3(c) and, the dc-link capacitor C_d supplies the required energy and continues to discharge in this mode as in Fig. 3(d).

3.2. Cuk Power Factor Correction Converter

Figs. 4(a-c) show the three operating modes of proposed PFC converter during a switching period.

Mode I: When the switch S_w is turned ON, the inductor L_i starts charging through the switch. However the dc-link capacitor C_d discharges through the load as shown in Fig. 4(a).

Mode II: When the switch S_w is turned OFF, the diode D starts conducting. The inductor L_i starts discharging through the diode D and the dc-link capacitor C_d. And the dc-link capacitor C_d starts charging as shown in Fig. 4(b).

Mode III: In this mode, the inductor L_i is completely discharged and enters the DCM mode as shown in Fig. 4(c) the dc-link capacitor C_d supplies the required energy and continues to discharge in this mode.

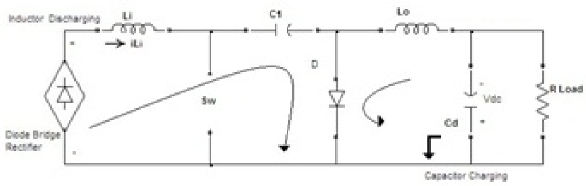

Fig. 4(a).Mode I

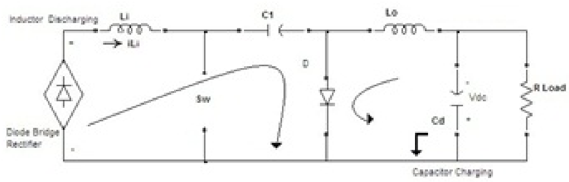

Fig. 4 (b).Mode II

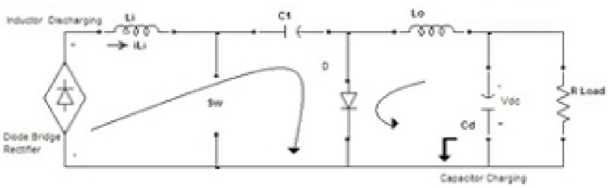

Fig.4(c). Mode III

4. Control of the drive system

Control of the drive system can be sub-divided into two sub-sections as control of the PFC converter for adjusting the DC bus voltage with PFC operation and control of the BLDC motor to achieve an electronic commutation [2, 3].

4.1. Control of the PFC Converter: Voltage Follower Approach

In this approach of DC-Link voltage control, a reference voltage, V_{dc}* corresponding to a reference speed, N* is:

$$V_{dc}^{*} = k_v N^{*} \tag{1}$$

Where, k_v represents back-EMF constant and N* denotes the reference speed of the motor. This reference speed is compared with the actual DC-link voltage to generate an error voltage, V_e. The error voltage at any instant 'k' is given by:

$$V_e(k) = V_{dc}^{*}(k) - V_{dc}(k) \tag{2}$$

This error voltage is given to the voltage Proportional-Integral controller to generate a controlled output voltage as:

$$V_{cd}(k) = V_e(k-1) + k_{pv}\{V_e(k) - V_e(k-1)\} + k_{iv} V_e(k) \tag{3}$$

Where, k_{pv} and k_{iv} represent the proportional and integral gain constants respectively.Finally, the controller output V_{cd} is compared with the high frequency saw-tooth waveform to generate the Pulse Width Modulated signal [1,2] to be given to the converter switch as:

$$m_d(t) < V_{cd}(t), then\, S_w = 1; else\, S_w = 0 \tag{4}$$

S_w denotes the switching signals as 1 and 0 for converter switch to turn ON and OFF respectively.

4.2. Sensor-less Control of BLDC motor

Sensored control of BLDC motor requires Hall-effect position sensors to detect the rotor position during every 60º electrical so as to perform the current commutation of each phase efficiently. Hall-effect position sensors add to the size and cost of the overall drive system. Here, a position sensor-less control strategy of BLDC motor is used which reduces the overall size and cost of the drive system. It is based on detecting the instant (switching point) when the back-EMF in the unexcited phase crosses zero [6, 7, 14-18]. This zero crossing is then used to obtain the switching pattern. Each phase remains unexcited during 60° electrical. During this period, the back-EMF can be measured, and it crosses zero. At this zero crossing point, the corresponding phase voltage is equal to the neutral voltage. In order to use this zero crossing point to derive the switching sequence, this point must be phase-shifted by 30°electrical [6].

5. Simulation Results and Discussions

Buck-boost & Cuk PFC converter-fed BLDC motor drive is simulated in MATLAB/Simulink. The performance evaluation of the drive is carried for different speeds, supply voltages and loadings on the BLDC motor. Motor parameters such as rotor speed (ω_m), electromagnetic torque (T_e), stator current (i_a), back-EMF (E_b) are analyzed to evaluate the performance of the drive system. The parameters of both PFC converters like DC-Link voltage, inductor currents, and intermediate capacitor voltages are studied to demonstrate the performance of the front-end converter. Power quality indices such as Power Factor (PF) and Total Harmonic Distortion (THD) of the supply current at AC mains are assessed. Peak voltage stress and peak current stress on the PFC converter switch are also measured to decide the switch ratings.

5.1. Steady State Performance of the drive

Fig.5 and Fig.6 illustrate the performance characteristics of the PFC Buck-Boost converter-fed & PFC Cuk converter-fed BLDC motor drives respectively, at rated conditions during steady state operation. The supply current in-phase with the supply voltage confirms a unity power factor operation. The discontinuity in the inductor currents and capacitor voltages demonstrates the DCM operation of the Buck-Boost & Cuk PFC converters.

Table I shows the voltage and current stresses in the switches of the two PFC converters. These are found to be within the acceptable range. THD of the supply current in both Buck-Boost and Cuk PFC converter-fed BLDC motor drives is below 5% and is found to be within the acceptable limits of IEC 61000-3-2.

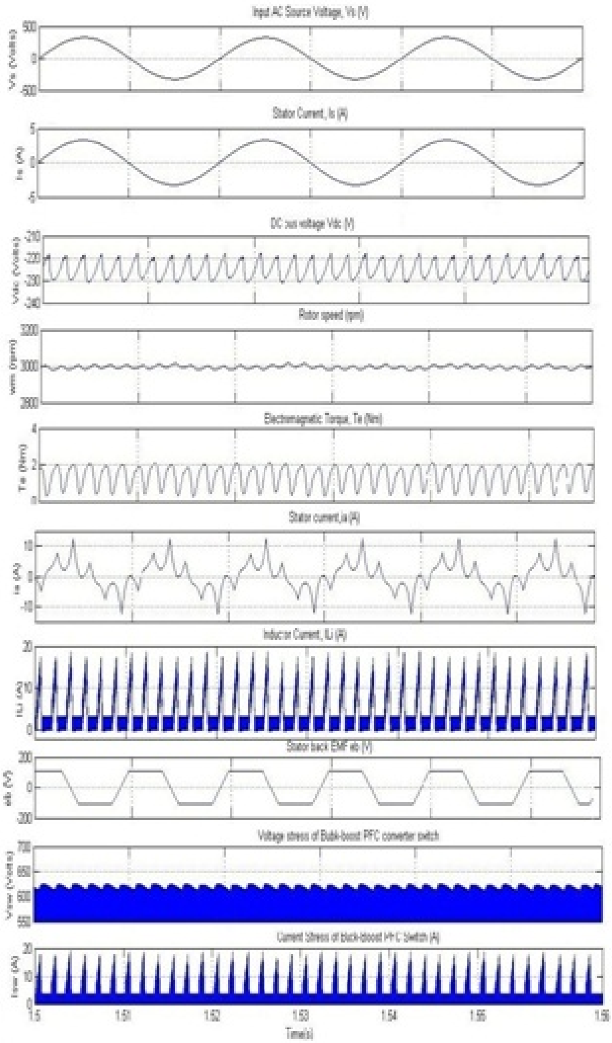

Fig. 5. Steady state performance characteristics of Buck-Boost PFC converter-fed BLDC motor drive

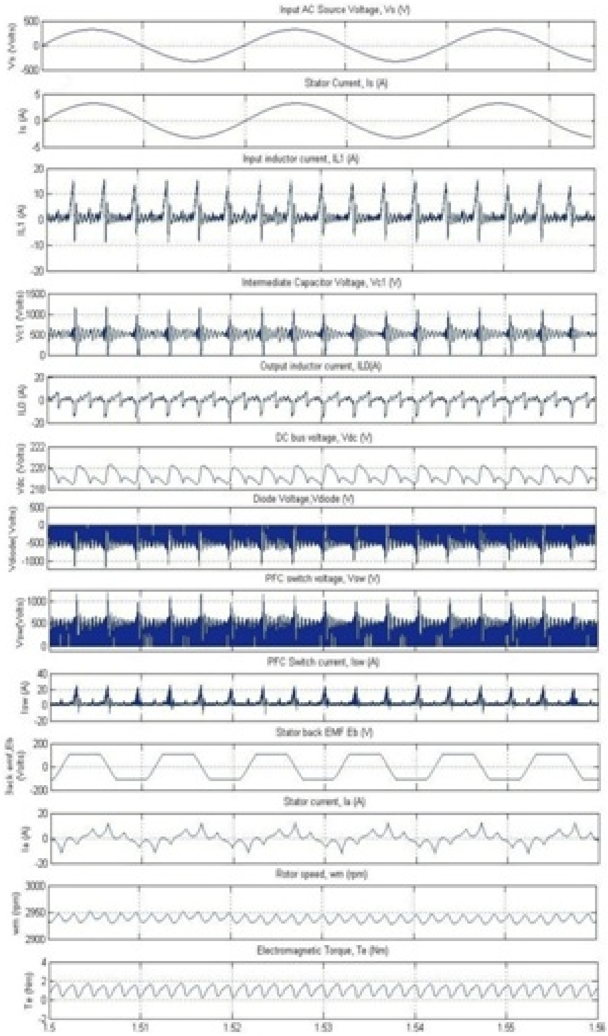

Fig. 6. Steady state performance characteristics of Cuk PFC converter fed BLDC motor drive

TABLE I. Voltage and Current stresses in PFC converter switch

Type of PFC Converter	**Voltage Stress, V_{sw} (Volts)**	**Current Stress, I_{sw} (Amperes)**
Buck-Boost	620	17
Cuk	625	22

5.2. Performance during Supply Voltage Fluctuation

Fig.7 and Fig.8 illustrate the dynamic performance of the BLDC motor drive fed from Buck-Boost and Cuk PF Pre-regulators respectively, during a supply voltage fluctuation from 270V to 180 V.

5.3. Dynamic Performance of the drive

Three conditions have been studied so as to understand the dynamic behaviour of the BLDC motor drive fed by Buck-boost and Cuk PF Pre-regulators. These include (i) Starting of the BLDC motor drive during step change in dc-voltage from 0V to 75V with a limited inrush in stator current and ac mains current (ii) Dynamic behaviour during speed control with a step-change in dc-link voltage from 100V to 150V (iii) Dynamic behaviour of the drive during a step-change in load from 0.4Nm to 0.8 Nm. Performance of the BLDC motor drive during a fluctuation in the supply voltage from 270V to 180V is also observed.

Fig.9 and Fig.10 illustrate the dynamic behaviour during starting with a step-change in the dc-link voltage from 0V to 75V; Fig.11 and Fig.12 demonstrate the dynamic performance during speed control with a step change in the dc-link voltage from 100V to 150V; Fig.13 and Fig.14 illustrate the dynamic characteristics during a step-change in load torque from 0.4Nm to 0.8Nm of the BLDC motor drive fed by Buck-boost and Cuk converters respectively. As the dc-link voltage, Vdc is controlled smoothly over the complete operating range; a satisfactory performance is achieved in both Buck-boost and Cuk converter-fed BLDC motor drives.

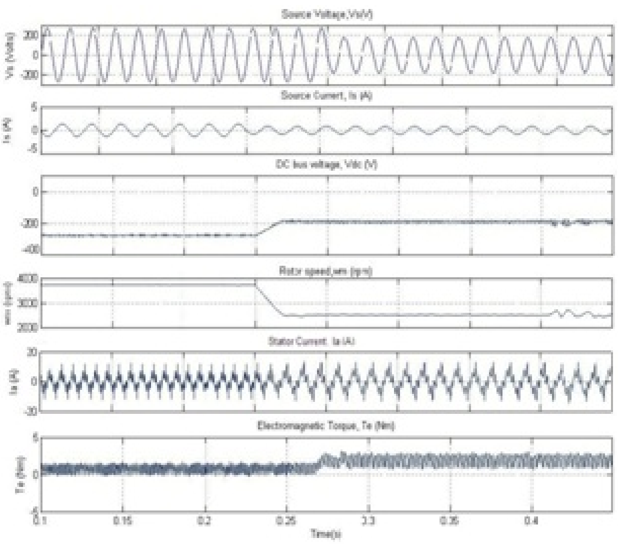

Fig.7. Dynamic characteristics of Buck-Boost PFC converter-fed motor drive during step change in supply voltage from Vs=270V to 180V

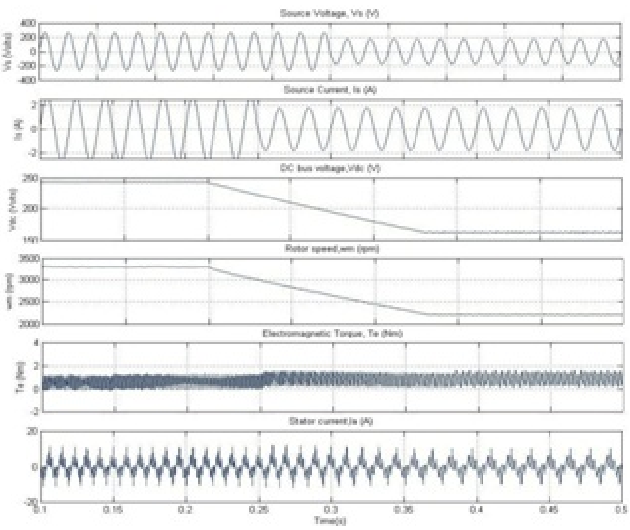

Fig.8. Dynamic characteristics of Cuk PFC converter-fed BLDC fed BLDC motor drive during step change in supply voltage from Vs=270V to 180V

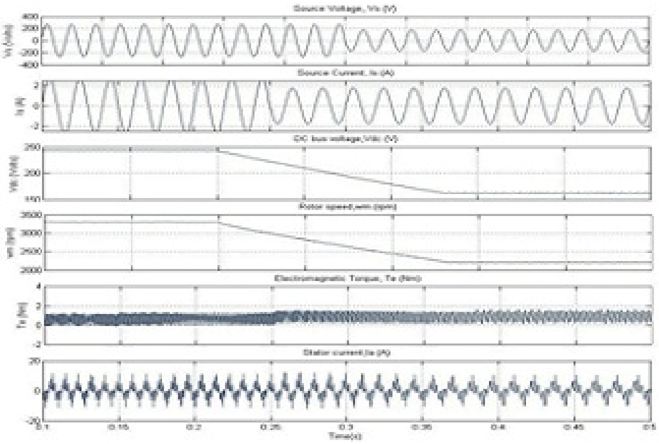

Fig.9. Dynamic characteristics of Buck-Boost PFC converter fed BLDC motor drive during start up from V_{dc} = 0V to 75V

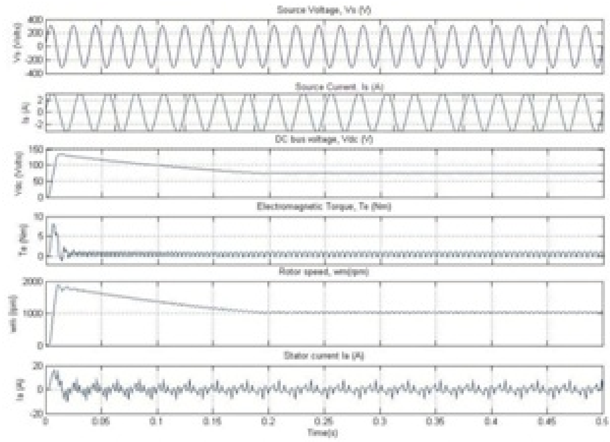

Fig.10. Dynamic characteristics of Cuk PFC converter fed BLDC motor drive during start up from V_{dc} = 0V to 75V

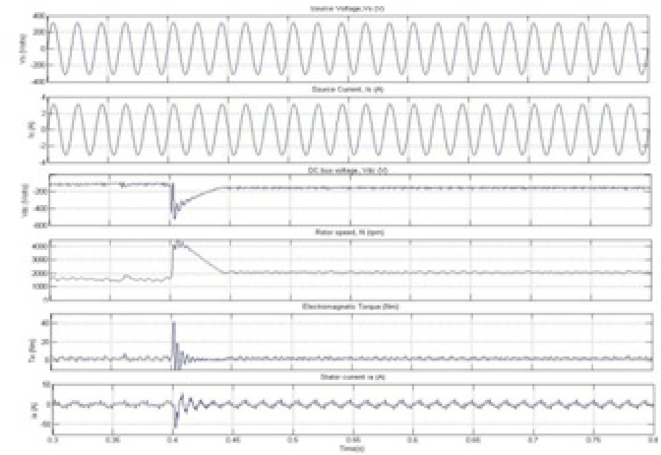

Fig.11. Dynamic characteristics of Buck-Boost PFC converter-fed BLDC Motor drive during step change in dc-link voltage from V_{dc} = 100V to150V

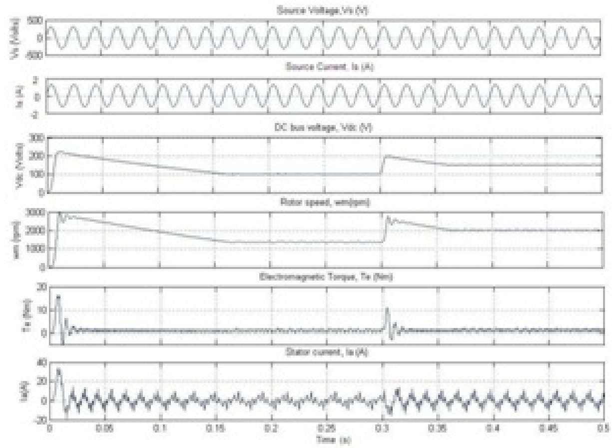

Fig.12. Dynamic characteristics of Cuk PFC converter-fed BLDC motor drive during step change in dc-link voltage from V_{dc} = 100V to150V

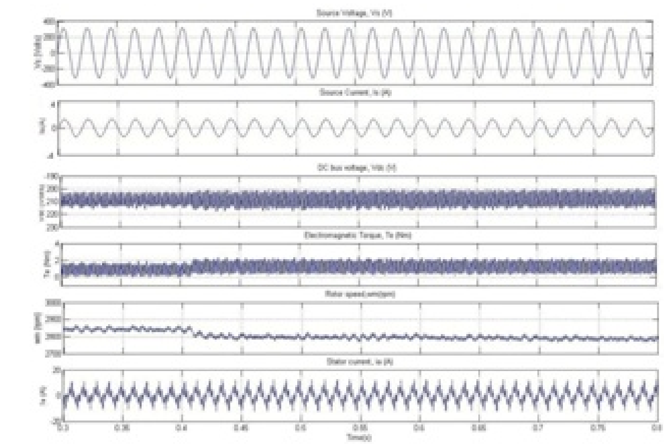

Fig.13. Dynamic characteristics of Buck-Boost PFC converter-fed BLDC motor drive during a step change in load torque from 0.4Nm to 0.8Nm

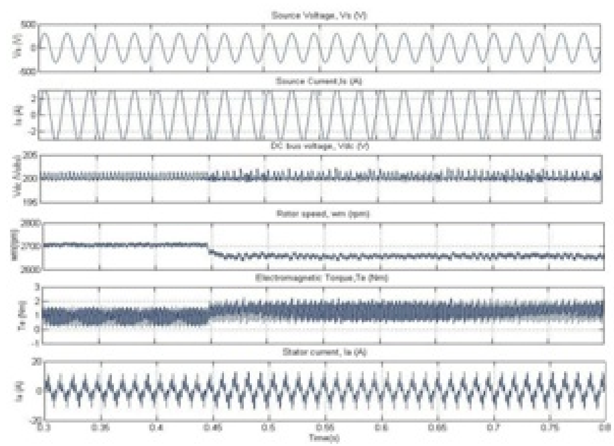

Fig.14. Dynamic characteristics of Cuk PFC converter-fed BLDC motor drive during step change in load torque from 0.4Nm to 0.8Nm

6. Conclusion

Performance analysis of Buck-Boost converter and Cuk-converter-fed BLDC motor drives has been presented in this paper. Variable dc-link voltage method has been used for the speed control of the BLDC motor drive. The six switches of the VSI are operated at the line frequency using electronic commutation of the BLDC motor, thus reducing the switching losses of the solid-state switches of the VSI. Sensor-less Back-EMF Zero-Crossing Detection method is used to generate the switching pulses for the VSI switches. This improves the overall cost and efficiency of the drive, as the requirement of Hall-effect position sensors to detect the rotor position every 60°electrical is eliminated. An inherent power factor correction is achieved as the PFC converters are designed to operate in DCM. The power quality indices obtained are found to be within the recommended limits of IEEE 519 standard. Depending upon the specific requirements, designers can select either of the two Power Factor Correction converters for their application.

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