Cuk Converter Fed BLDC Motor

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Abstract— Cuk converter-fed brushless dc motor (BLDC) drive as a cost-effective solution for low-power applications is presented. The speed of the BLDC motor is controlled by varying the dc-bus voltage of a voltage source inverter (VSI) which uses a low frequency switching of VSI (electronic commutation of the BLDC motor) for low switching losses. A diode bridge rectifier followed by a Cuk converter working in a discontinuous conduction mode (DCM) and continuous conduction mode (CCM) is used for control of dc-link voltage with unity power factor at ac mains. Performance of the PFC Cuk converter is evaluated under four different operating conditions of discontinuous and continuous conduction modes and a comparison is made to select a best suited mode of operation. The performance of the proposed system is simulated in a MATLAB/Simulink environment. The simulation of sensorless operation of permanent magnet brushless direct current (BLDC) motor. The position sensorless BLDC drive simulated and is based on detection of zero crossing from the terminal voltages differences. This method relies on a difference of line voltages measured at the terminals of the motor. This difference of line voltages provides an amplified version of an appropriate back EMF at its zero crossings. The commutation signals are obtained without the motor neutral voltage. The effectiveness of this method is demonstrated through simulation.

Keywords— Brushless dc (BLDC) motor, continuous conduction mode (CCM), Cuk converter, discontinuous conduction mode (DCM), sensorless operation, zero crossing.

INTRODUCTION

Brushless dc (BLDC) motors are recommended for many low and medium power drive applications because of their high efficiency, high flux density per unit volume, low maintenance requirement, low electromagnetic interference (EMI) problems, high ruggedness, and a wide range of speed control [1], [2]. Due to these advantages, they has applications in numerous areas such as household application [3], transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning [4], motion control and robotics, renew- able energy applications etc. The BLDC motor is a three-phase synchronous motor consisting of a stator having a three-phase concentrated windings and a rotor having permanent magnets. It does not have mechanical brushes and commutator assembly; hence, wear and tear of the brushes and sparking issues as in case of conventional dc machines are eliminated in BLDC motor and thus it has low EMI problems. This motor is also referred as an electronically commutated motor since an electronic commutation based on the Hall-effect rotor position signals is used rather than a mechanical commutation.

The conventional scheme of a BLDC motor fed by a diode bridge rectifier (DBR) and a high value of dc-link capacitor draws a non-sinusoidal current, from ac mains which is rich in harmonics such that the THD of supply current is as high as 0 .65, which results in PF as low as 0.8 [5]. These types of PQ indices cannot comply with the international PQ standards such as IEC 61000-3-2 [6]. Hence, single-phase power factor correction (PFC) converters are used to attain a unity PF at ac mains [7], [8]. These converters have gained attention due to single-stage requirement for dc-link voltage control with unity PF at ac mains. It also has low component count as compared to a multistage converter and therefore offers reduced losses.

Selection of operating mode of the front-end converter is a trade off between the allowed stresses on PFC switch and cost of the overall system. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two different modes of Depending on design parameters, either approach may force the converter to operate in the DCM or CCM. In this study, a BLDC motor drive fed by a PFC Cuk converter operates in four modes.

An electronic commutation [11] of the BLDC motor includes the proper switching of VSI in such a way that a symmetrical dc current is drawn from the dc link capacitor for 120 degree and placed symmetrically at the center of each phase. A Hall-effect position sensor is used to sense the rotor position on a span of 60 degree, which is required for the electronic commutation of the BLDC motor.

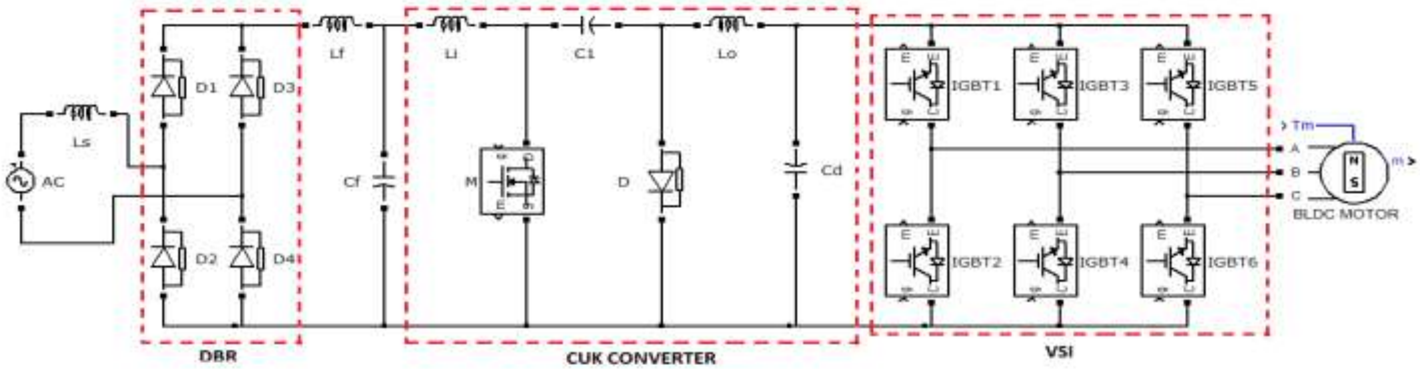

Fig. 1 Cuk converter fed BLDC motor

CUK CONVERTER

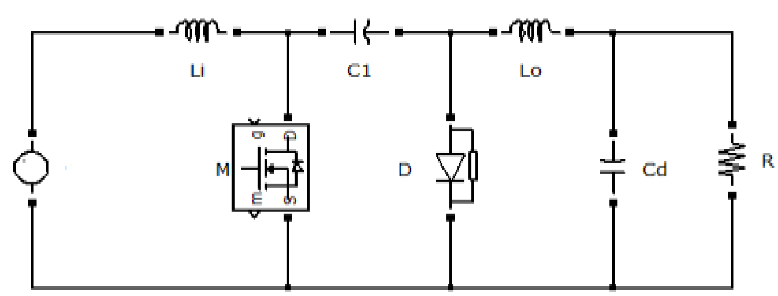

Fig. 2 Cuk converter

The operation of the Cuk converter is studied in four different modes of CCM and DCM [9], [10]. In CCM, the current in inductors (Li and Lo) and voltage across intermediate capacitor C1 remain continuous in a switching period. Moreover, the DCM operation is further classified into two broad categories of a discontinuous inductor current mode (DICM) and a discontinuous capacitor voltage mode (DCVM). In the DICM, the current owing in inductor Li or Lo becomes discontinuous in their respective modes of operation. While in DCVM operation, the voltage appearing across the intermediate capacitor C1 becomes discontinuous in a switching period. Different modes for operation of the CCM and DCM are discussed as follows.

a) CCM Operation

The operation of the Cuk converter in the CCM is described as follows. Fig. 3 shows the operation of the Cuk converter in two different intervals.

1) Interval 1: When switch in turned ON, inductor Li stores energy while capacitor C_1 discharges and transfers its energy to dc-link capacitor C_d. Input inductor current i_{Li} increases while the voltage across the intermediate capacitor V_{C1} decreases.
2) Interval 2: When switch is turned OFF, the energy stored in inductor Lo is transferred to dc-link capacitor C_d, and inductor Li transfers its stored energy to the intermediate capacitor C_1. The designed values of Li, Lo, and C_1 are large enough such that a finite amount of energy is always stored in these components in a switching period.

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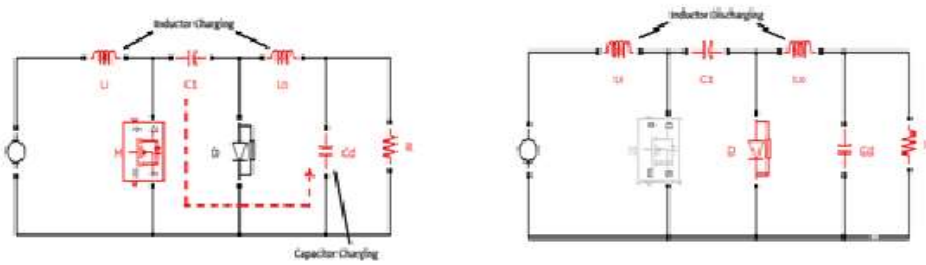

Fig. 3 Interval 1 and interval 2 operation

b) DICM(L_i) Operation

The operation of the Cuk converter in the DICM (Li) is described as follows. Fig. 4 shows the operation of the Cuk converter in three different intervals.

1) Interval 1: When switch in turned ON, inductor Li stores energy while capacitor C_1 discharges through Switch to transfer its energy to the dc-link capacitor Cd. Input inductor current i_{Li} increases while the voltage across the capacitor C_1 decreases.
2) Interval 2: When switch is turned OFF, the energy stored in inductor Li is transferred to intermediate capacitor C_1 via diode D, till it is completely discharged to enter DCM operation.
3) Interval 3: During this interval, no energy is left in input inductor Li; hence, current i_{Li} becomes zero. Moreover, inductor Lo operates in continuous conduction to transfer its energy to dc-link capacitor C_d.

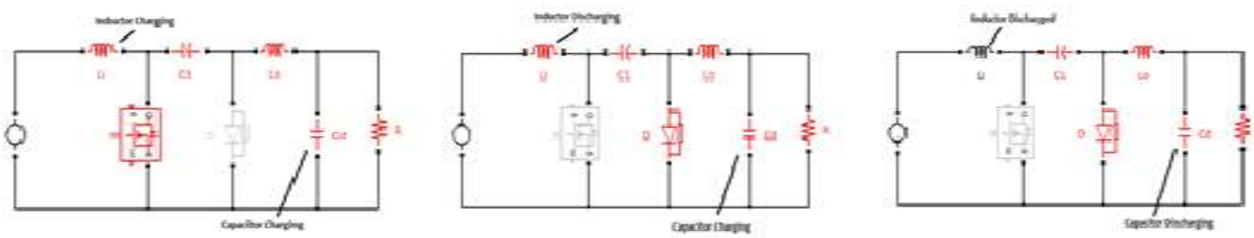

Fig. 4 Interval 1 , interval 2 and interval 3 operation

C) DICM(Lo) Operation

The operation of the Cuk converter in the DICM (Lo) is described as follows. Fig. 5 shows the operation of the Cuk converter in three different intervals.

1) Interval 1: When switch is turned ON, inductor Li stores energy while capacitor C_1 discharges through switch to transfer its energy to the dc-link capacitor C_d.
2) Interval 2: When switch is turned OFF, the energy stored in inductor Li and Lo is transferred to intermediate capacitor C_1 and dc-link capacitor C_d, respectively.
3) Interval 3: In this mode of operation, the output inductor Lo is completely discharged; hence, its current i_{Lo} becomes zero. An inductor Li operates in continuous conduction to transfer its energy to the intermediate capacitor C_1 via diode D.

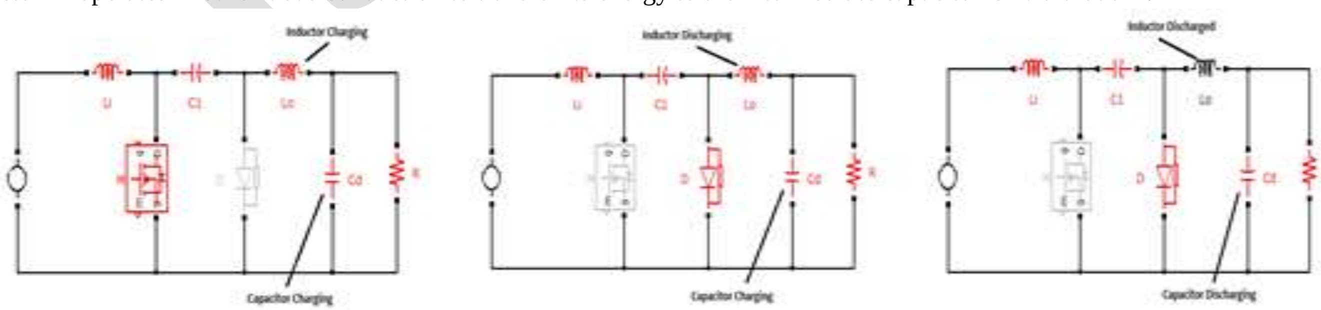

Fig. 5 Interval 1 , interval 2 and interval 3 operation

c) DCVM(C_1) Operation

The operation of the Cuk converter in the DCVM (C_1) is described as follows. Fig. 6 shows the operation of the Cuk converter in three different intervals of a switching period.

1) Interval 1: When switch in turned ON as shown, inductor Li stores energy while capacitor C_1 discharges through switch to transfer its energy to the dc-link capacitor C_d as shown.
2) Interval 2: The switch is in conduction state but intermediate capacitor C_1 is completely discharged. Hence ,the voltage across it becomes zero. Output inductor Lo continues to supply energy to the dc-link capacitor.
3) Interval 3: As the switch is turned OFF, input inductor Li starts charging the intermediate capacitor, while the output inductor Lo continues to operate in continuous conduction and supplies energy to the dc-link capacitor.

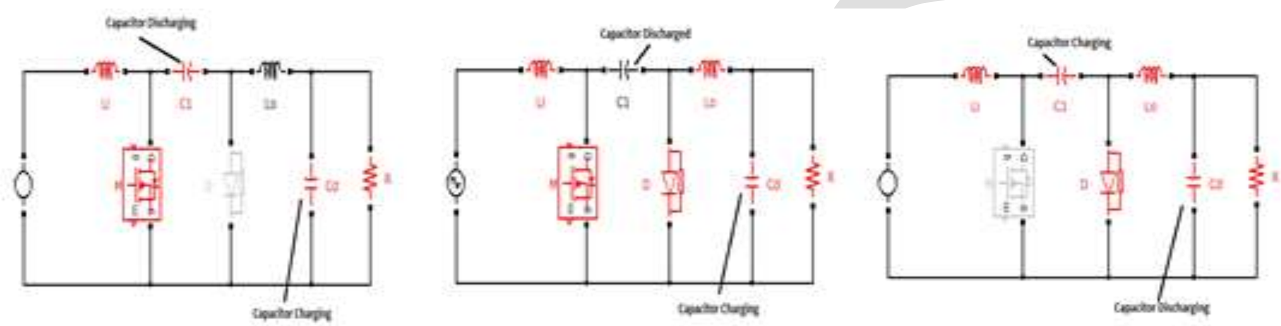

Fig. 6 Interval 1 , interval 2 and interval 3 operation

DESIGN OF COMPONENTS

The Cuk converter [9] is designed to operate from a minimum dc voltage of 40 V (V_{dcmin}) to a maximum dc-link voltage of 200 V (V_{dcmax}). The PFC converter of maximum power rating of 350 W (P_{max}) and the switching frequency is taken as 20 kHz. For a minimum value of dc-link voltage as 40 V, the minimum power is calculated as 70 W.

a) CCM.

The value of input inductor to operate in the CCM is decided by the amount of permitted ripple current, where the permitted amount of ripple current (η) is selected as 25% of the input current. The maximum inductor ripple current is obtained under the rated condition, i.e., V_{dc} = 200 V for a minimum supply voltage (V_{smin} = 85 V). Hence, the input side inductor is designed at the peak value of minimum supply voltage and got the value as 2.57mH.

$$L_{iccm} = \frac{1}{\eta f_s}\left(\frac{Vs2}{P_{max}}\right)\frac{V_{dc}}{V_{in}+V_{dc}} \qquad (1)$$

The value of output inductor to operate in the CCM is decided by the amount of permitted ripple current, where the permitted amount of ripple current (λ) is selected as 25% of the input current. The maximum current occurs at maximum dc-link voltage (i.e., P_{max}) and the minimum supply voltage of 85 V (i.e., V_{smin}). Got the value as 4.29mH.

$$L_{occm} = \frac{Vs^2}{P_{max}}\,\frac{V_{dc}}{V_{in}+V_{dc}}\,\frac{V_{dc}}{V_{in} f_s \lambda} \qquad (2)$$

The value of intermediate capacitance to operate in the CCM with a permitted ripple voltage, selected as 10% of the maximum voltage appearing across the intermediate capacitor. The value of intermediate capacitor is calculated at maximum ripple voltage in C_1 which occurs at maximum value of supply voltage (i.e., V_{smax} = 270 V) and maximum dc-link voltage and got the value as 0.6μF.

$$C_{1ccm} = \frac{P_{max}}{k f_s (V_{in}+V_{dc})^2} \qquad (3)$$

b) DCM

The worst case design of Li occurs for the minimum value of supply voltage (i.e., V_{smin} = 85 V). Now, the critical value of input inductor at the maximum dc-link voltages of 200 V at the peak value of supply voltage and the critical value of the input inductor at the minimum value of dc-link voltages of 40 V at the peak value of supply voltage is calculated.

$$L_{ic} = \frac{1}{2f_s}\left(\frac{Vs^2}{P_i}\right)\frac{V_{dc}}{V_{in}+V_{dc}} \tag{4}$$

We got the values as L_{ic200}= 322.3μH and L_{ic40}= 644.25μH. Hence, the value of critical input inductance is obtained lower at maximum dc-link voltage. Therefore, the critical value of input inductor is selected lower than L_{ic200}.

The maximum current ripple in an inductor occurs at the maximum power and for minimum value of supply voltage (i.e., V_{smin} = 85 V). Hence, the output inductor is calculated at the peak of supply voltage. The critical value of the inductor corresponding to maximum dc-link voltage of 200V. Moreover, the critical value of output side inductor at peak of V_{smin} and minimum dc-link voltage of 40 V is calculated.

$$L_{oc} = \frac{Vs^2}{P_i}\frac{V_{dc}}{V_{in}+V_{dc}}\frac{V_{dc}}{2V_{in}f_s} \tag{5}$$

We got the values as L_{oc200}= 536μH and L_{oc40}= 214.25μH. Hence, the value of critical input inductance is obtained lower at maximum dc-link voltage. Therefore, the critical value of input inductor is selected lower than L_{oc40}.

The maximum ripple in the intermediate capacitor occurs at the maximum value of supply voltage (i.e. 270 V). Hence, the critical value of the intermediate capacitance is calculated at maximum dc-link voltage 200V and minimum dc link voltage of 40V.

$$C_{1c} = \frac{P_i}{2f_s(V_{in}+V_{dc})^2} \tag{6}$$

We got the values as C_{1C200}= 25nF and C_{1C40}= 9.8nF. Hence, the value of critical capacitor is obtained lower at minimum dc link voltage. Therefore, the critical value of input inductor is selected lower than C_{1C40}.

MATLAB SIMULINK MODEL AND SIMULATION RESULTS

a) MATLAB Simulink model(with sensor)

The Simulink model of cuk converter fed BLDC motor is given in Fig.7. Single phase input voltage is given. Switching frequency of 20 kHz is selected. First the input is rectified, then filtered and converted to DC using cuk converter. The DC link voltage is given as input to VSI and then to motor. Rated dc link voltage is 200V. For CCM operation, the values of Li, C_1 and Lo are 2.5mH, 0.66μ H and 4.3mH. For DICM(Li) operation the values are 300μ H, 0.66μH and 4.3mH. For DICM(Lo) the values are 2.5mH, 0.66μH and 214μH. For DCVM(C_1) the values are 2.5mH, 9.1nF and 4.3mH.

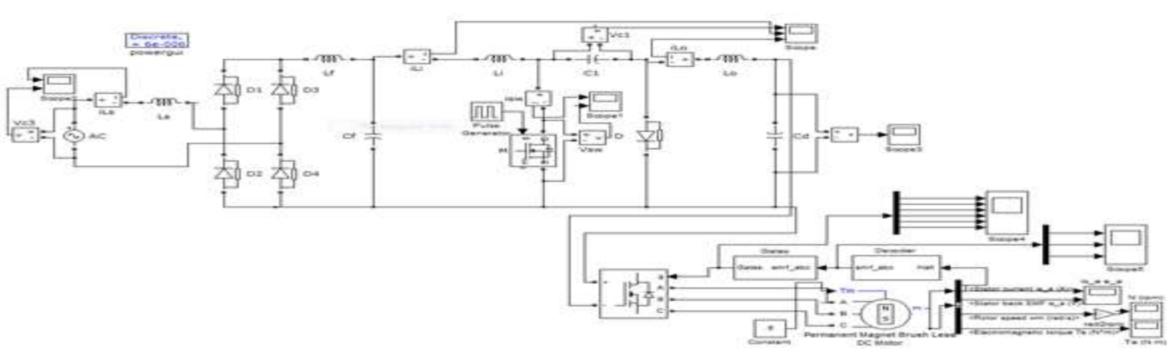

Fig. 7 MATLAB Simulink model of cuk converter fed BLDC motor

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b) Simulation results

Simulation results of cuk converter fed BLDC motor is given below for CCM and different DCM. For every operations the dc link voltage is 200V. The speed is around 1500rpm. Input voltage given is 220V. Pulses given to VSI is same for each modes.

In CCM the switch current is around 9A and the voltage across switch is 520V. Here got a PF of 0.93 and THD of 5%.

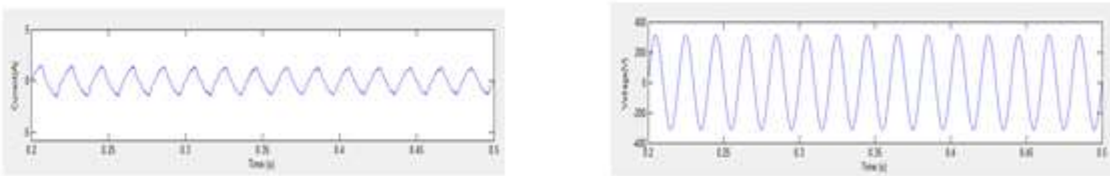

Fig. 8 Input current and input voltage waveform

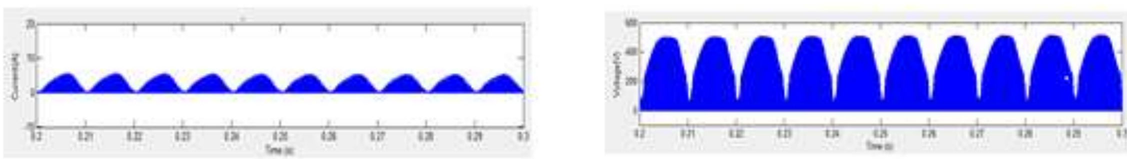

Fig. 9 Switch current and switch voltage waveform

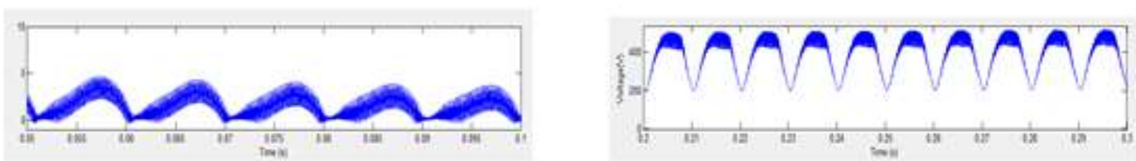

Fig. 10 Inductor Li current and voltage across capacitor C1

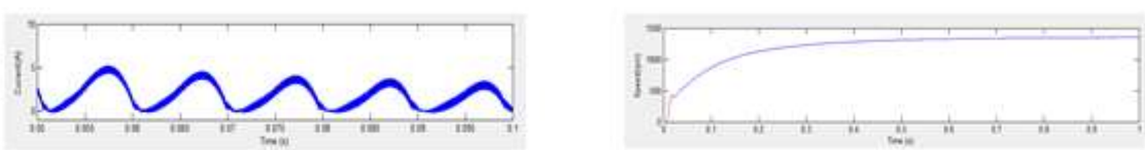

Fig. 11 Inductor Lo current and speed of motor

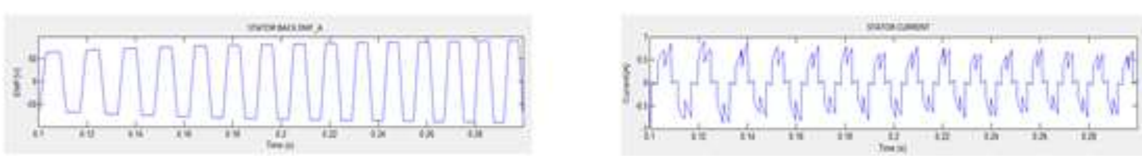

Fig. 12 Stator back enf and stator current

In DICM (Li),the switch current is around 11A and the voltage across switch is 510V. Here got a pf of 0.92 and THD of 8%.

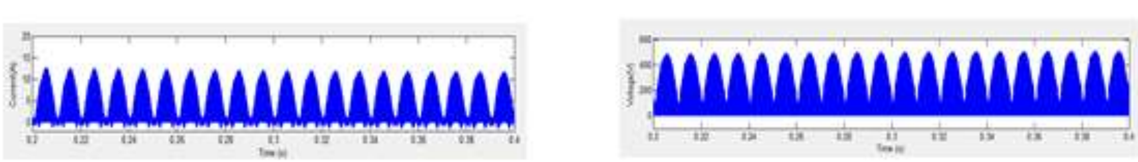

Fig. 13 Switch current and switch voltage waveform

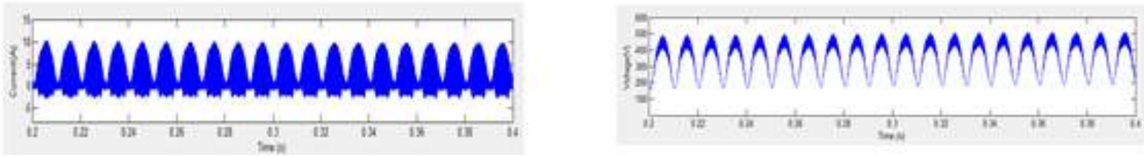

Fig. 14 Inductor Li current and voltage across capacitor C1

In DICM (Lo),the switch current is around 10.5A and the voltage across switch is 400V. Here got a PF of 0.93 and THD of 6%.

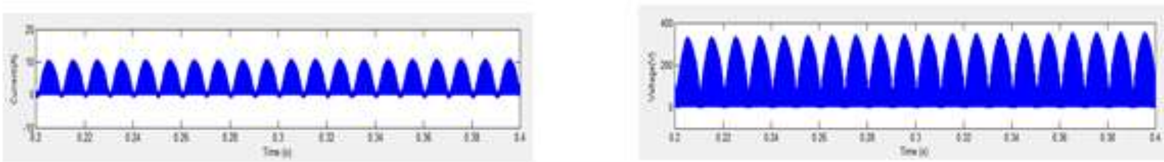

Fig. 15 Switch current and switch voltage waveform

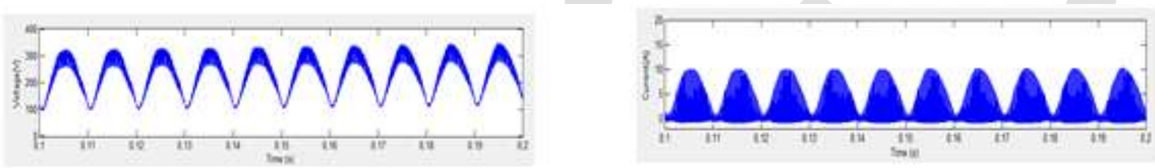

Fig. 16 Voltage across capacitor C1 and inductor Lo current

In DCVM (C_1),the switch current is around 11A and the voltage across switch is 2000V. Here got a PF of 0.92 and THD of 14%.

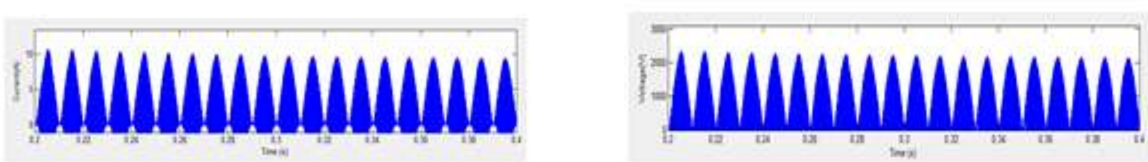

Fig. 17 Switch current and switch voltage waveform

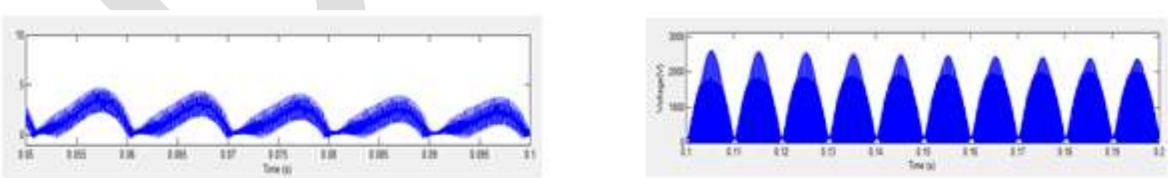

Fig. 18 Inductor Li current and voltage across capacitor C1

CUK CONVERTER FED BLDC MOTOR WITH SENSORLESS CIRCUIT

Consider a BLDC motor having three stator phase windings connected in star [14]. Permanent magnets are mounted on the rotor. The BLDC motor is driven by a three phase inverter in which the devices are triggered with respect to the rotor position.
Consider the interval when phases A and C are conducting and phase B is open . In this interval, phase A winding is connected to the positive terminal of the dc supply, phase C to the negative terminal of the dc supply and phase B is open. Therefore, $i_a = -i_c$ and i_b

= 0. The back EMF in phases A and C are equal and opposite. Therefore, in that interval V_{abbc} may be simplified as

$$V_{abbc} = V_{ab} - V_{bc} = e_{an} - 2e_{bn} + e_{cn} = -2e_{bn}$$

The difference of line voltages waveform is, thus, an inverted representation of the back EMF waveform. The EMF values would be those in a resistance, inductance, [15] EMF (RLE) representation of the phase (not referred to ground). It may also be noted that the subtraction operation provides a gain of two to the EMF waveform thus amplifying it. It is again evident that during this interval the back EMF e_{bn} transits from one polarity to another crossing zero. Therefore, the operation $V_{ab} - V_{bc}$ (V_a) enables detection of the zero crossing of the phase B EMF. Similarly, the difference of line voltages V_{bcca} enables the detection of zero crossing of phase C back EMF when phase B and C back EMFs are equal and opposite. The difference of line voltages V_{caab} waveform gives the zero crossing of phase A back EMF where phases C and B have equal and opposite back EMFs. Therefore, the zero- crossing instants of the back EMF waveforms may be estimated indirectly from measurements of only the three terminal voltages of the motor.

The simulated sensorless method uses this approach to estimate the zero-crossing instants of the back EMF from the terminal voltages of the motor from which the correct commutation instants are estimated. This sensorless method is simulated in MATLAB/SIMULINK software.

SIMULATION RESULTS

Simulation results of cuk converter fed BLDC motor without sensors is given below for CCM. For every operations the dc link voltage is 200V. The speed is around 1500rpm. Input voltage given is 220V. Pulses given to VSI is same as that of sensor method.

Fig. 19 Bach enf waveforms emf_a, emf_b

Fig. 20 Emf_c waveform and speed of motor

CONCLUSION

A Cuk converter for VSI-fed BLDC motor drive has been designed for achieving a unity PF at ac mains for the development of the low-cost PFC motor for numerous low-power equipments such fans, blowers, water pumps, etc. The speed of the BLDC motor drive has been controlled by varying the dc-link voltage of VSI, which allows the VSI to operate in the fundamental frequency switching mode for reduced switching losses. Four different modes of the Cuk converter operating in the CCM and DCM have been explored for the development of the BLDC motor drive with PF near to unity at ac mains. A detailed comparison of all modes of operation has been presented on the basis of feasibility in design and the cost constraint in the development of such drive for low-power applications. Finally, a best suited mode of the Cuk converter with output inductor current operating in the CCM has been selected for experimental verifications. A simple technique to detect back EMF zero crossings for a BLDC motor using the line voltages is simulated using MATLAB/SIMULINK. It is shown that the method provides an amplified version of the back EMF. Only three motor terminal voltages need to be measured thus eliminating the need for motor neutral voltage. Running the machine in sensorless mode is then simulated. Sensor control responds faster and smoother to reference speed changes. But if low cost is the primary concern and motor speed is not an issue, then sensorless control will be the better choice.

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