A POWER FACTOR CORRECTION PFC BASED CUK CONVERTER FED BRRUSHLESS DC MOTOR DRIVE AS A COST EFFECTIVE SOLUTION FOR LOW POWER APPLICATIONS

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ABSTRACT

The main aim of this project is an application of a PFC converter for the speed control of a PMBLDCMD. For the proposed voltage controlled drive, a Boost dc–dc converter is used as a PFC converter because of its continuous input and output currents, small output filter, and wide output voltage range as compared to other single switch converters. The brushless dc (BLDC) servomotor drives have been widely used in aeronautics, electric vehicles, robotics, and food and chemical industries. The use of a permanent-magnet (PM) brushless dc motor (PMBLDCM) in low-power appliances is increasing because of its features of high efficiency, wide speed range, and low maintenance. Brushless DC Motors are driven by DC voltage but current commutation is controlled by solid state switches. The commutation instants are determined by the rotor position. The rotor shaft position is sensed by a Hall Effect sensor, which provides signals to the respective switches. Hall Effect sensors are used to ascertain the rotor position and from the Hall sensor outputs, it is determined whether the machine has reversed its direction. This is the ideal moment for energizing the stator phase so that the machine can start motoring in the counter clockwise direction.

KEYWORDS; *PFC Converter, PMBLDCMD, DC-DC Converter, Hall Effect sensor*

I. INTRODUCTION

Electrical motors are an integral part of industrial plants with no less than 5 billion motors built worldwide every year. Residential and commercial applications mostly use conventional motor drive technologies. Typically, machines found in these appliances are single-phase induction motors or brushed dc machines which are characterized by low efficiency and high maintenance. Single-phase induction motors are less efficient because of the ohmic loss in the rotor and due to the phase angle displacement between the stator current and back electromotive force (EMF). In the case of dc machines, they require more maintenance due to the presence of brushes. Replacing these inefficient motors with more efficient brushless dc (BLDC) motors will result in substantial energy savings. Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor.

The motor part of a brushless motor is often a permanent magnet synchronous motor, but can also be a switched reluctance motor, or induction motor. Brushless motors may also be described as stepper motors; however, the term stepper motor tends to be used for motors that are designed specifically to be operated in a mode where they are frequently stopped with the rotor in a defined angular position. This page describes more general brushless motor principles, though there is overlap.

The Brushless DC motor has a rotor with permanent magnets and a stator with windings. It is essentially a DC motor turned inside out. The brushes and commutator have been eliminated and the windings are connected to the control electronics. The control electronics replace the function of the commutator and energize the proper winding. The motor has less inertia, therefore easier to start and stop. BLDC motors are potentially cleaner, faster, more efficient, less noisy and more reliable. The Brushless DC motor is driven by rectangular or trapezoidal voltage strokes coupled with the given rotor position. The voltage strokes must be properly aligned between the phases, so that the angle between the stator flux and the rotor flux is kept close to 90° to get the maximum developed torque. BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position or its position can also be detected without sensors. BLDC motors are used in Automotive, Aerospace, Consumer, Medical, Industrial Automation equipment's and instrumentation.

The brushless dc (BLDC) motors have such good features as simple construction, high reliability, light electromagnetic pollution, and high power density; they are used extensively in servo systems and low-power drive systems. The performance of such motors has been significantly improved due to great development of power electronics, microelectronics, and magnetic performance of magnets and motion control technology in recent years. Nowadays, many studies have been focused on how to reduce the cost of the BLDC motor and its control system without performance degradation.

Brushless DC motor has the characteristic of simple structure, large torque, don't need to change phase based on the brush, and has long use time, good speed regulation. For the advantages mentioned above now electric vehicles and micro electric motor cars in the market mostly adopt BLDCM. The traditional BLDC controlling system requires hall sensor signals to drive the motor. When disturbance on the hall sensor exists, the wrong actions on the main circuit prompts the BLDCM action unsteady, the reliability of the whole controlling system is greatly reduced, also the cost of controller is increased. In recent years, some of these developments like Proportional-Integral (PI) controllers have been implemented for the speed control of B LDC motors. Different advanced control theories like the optimal and adaptive strategies have been used.

II. CONSTRUCTION AND FOUR QUADRANT CONTROL AND OPERATION OF THE BLDC DRIVE

The BLDC motor is sometimes referred to as an inside out dc motor because its armature is in the stator and the magnets are on the rotor and its operating characteristics resemble those of a dc motor. Instead of using a mechanical commutator as in the conventional dc motor, the BLDC motor employs electronic commutation which makes it a virtually maintenance free motor.There are two main types of BLDC motors: trapezoidal type and sinusoidal type. In the trapezoidal motor the back-emf induced in the stator windings has a trapezoidal shape and its phases must be supplied with quasi-square currents for ripple free operation. The sinusoidal motor on the other hand has a sinusoidally shaped back – emf and requires sinusoidal phase currents for ripple free torque operation. The shape of the back – emf is determined by the shape of rotor magnets and the stator winding distribution.

The sinusoidal motor needs high resolution position sensors because the rotor position must be known at every time instant for optimal operation. It also requires more complex software and hardware. The trapezoidal motor is a more attractive alternative for most applications due to simplicity, lower price and higher efficiency.

BLDC motors exist in many different configurations but the three phase motor is most common type due to efficiency and low torque ripple. This type of motor also offers a good compromise between precise control and number of power electronic devices needed to control stator currents. Fig.5.1 shows a transverse section of a BLDC motor. Position detection is usually implemented using three Hall - an effect sensor that detects the presence of small magnets that are attached to the motor shaft.

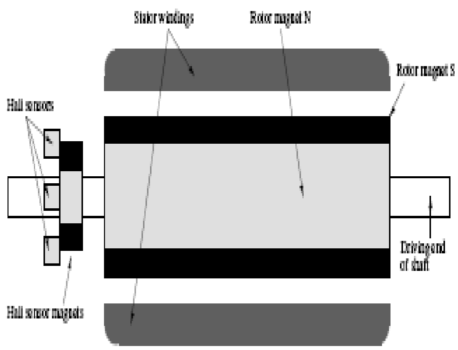


Fig. 1 BLDC motor transverse section.

Typically, a Brushless dc motor is driven by a three-phase inverter with, what is called, six-step commutation. The conducting interval for each phase is 120^{o} by electrical angle. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting strategies called one step. Therefore, only two phases conduct current at any time, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60^{o} so that current is in phase with the back EMF. The commutation timing is determined by the rotor position, which can be detected by Hall sensors as shown in the figure (H1, H2, H3). The figure also shows ideal currents and back emf waveforms.

Figure shows a cross section of a three phase star connected motor along with its phase energizing sequence. Each interval starts with the rotor and stator field lines 120^{0} apart and ends when they are 60^{0} apart. Maximum torque is reached when the field lines are perpendicular. Current commutation is done by inverter as shown in a simplified from in figure. The switches are shown as bipolar junction transistors but MOSFET switches are more common. Table 3.1 shows the switching sequence, the current direction and the position sensor signals.

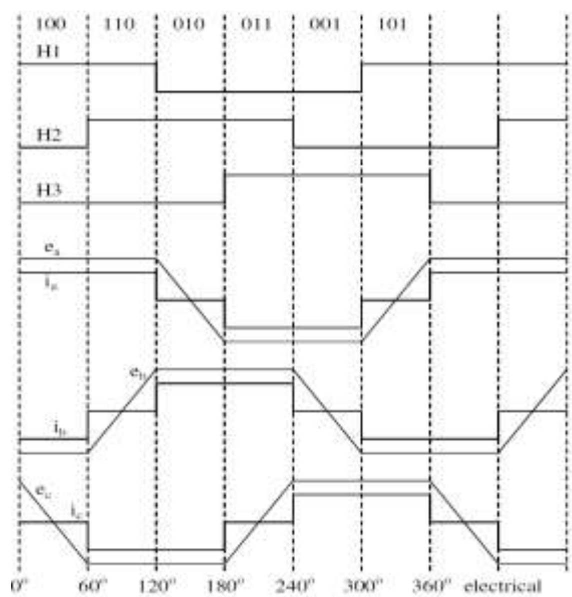


Fig.2 Ideal back-emf's phase currents, and position sensor signals.

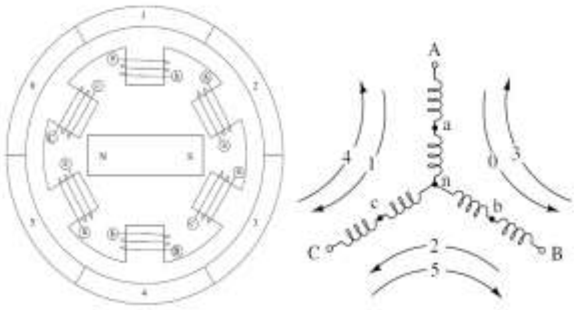


Fig.3: BLDC motor cross section and phase energizing sequence

III. PROPOSED SYSTEM

Fig. 4 shows the proposed speed control scheme which is based on the control of the dc link voltage reference as an equivalent to the reference speed.

However, the rotor position signals acquired by Hall-effect sensors are used by an electronic commutator to generate switching sequence for the VSI feeding the PMBLDC motor, and therefore, rotor position is required only at the commutation points [1]–[4].

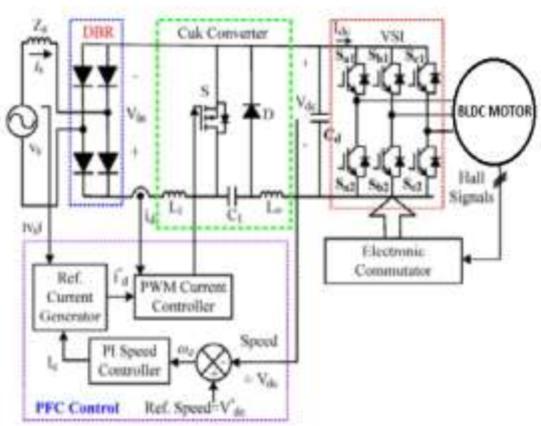


Fig. 4. Control scheme of the proposed Cuk PFC converter-fed VSI-based PMBLDCMD.

The Cuk dc–dc converter controls the dc link voltage using capacitive energy transfer which results in non-pulsating input and output currents [7]. The proposed PFC converter is operated at a high switching frequency for fast and effective control with additional advantage of a small size filter. For high-frequency operation, a metal–oxide–semiconductor field-effect transistor (MOSFET) is used in the proposed PFC converter, whereas insulated gate bipolar transistors (IGBTs) are used in the VSI bridge feeding the PMBLDCM because of its operation at lower frequency compared to the PFC converter. The PFC control scheme uses a current multiplier approach with a current control loop inside the speed control loop for continuous-conduction-mode operation of the converter. The control loop begins with the processing of voltage error (Ve), obtained after the comparison of sensed dc link voltage (Vdc) and a voltage (V^*dc) equivalent to the reference speed, through a proportional–integral (PI) controller to give the modulating control signal (Ic). This signal (Ic) is multiplied with a unit template of input ac voltage to get the reference dc current (I∗d) and compared with the dc current (Id) sensed after the DBR. The resultant current error (Ie) is amplified and compared with a sawtooth carrier wave of fixed frequency (fs) to generate the pulse width modulation (PWM) pulse for the Cuk converter. Its duty ratio (D) at a switching frequency (fs) controls the dc link voltage at the desired value. For the control of current to PMBLDCM through VSI during the step change of the reference voltage due to the change in the reference speed, a rate limiter is introduced, which limits the stator current of the PMBLDCM withinthe specified value which is considered as double the rated current in this work.

IV. DESIGN OF PFC CUK CONVERTER-BASED PMBLDCM

The proposed PFC Cuk converter is designed for a PMBLDCMD and PQ improvement at ac mains. The dc link voltage of the PFC converter is given as

$$Vdc = VinD/(1 - D) \qquad (1)$$

where Vin is the average output of the DBR for a given ac input voltage (Vs) related as

$$Vin = 2\sqrt{2}Vs/\pi. \quad (2)$$

The Cuk converter uses a boost inductor (Li) and a capacitor (C1) for energy transfer. Their values are given as

$$Li = DVin/\{fs(\Delta ILi)\} \quad (3)$$

$$C1 = DIdc/\{fs\Delta VC1\} \quad (4)$$

where ΔILi is a specified inductor current ripple, ΔVC1 is a specified voltage ripple in the intermediate capacitor (C1), and Idc is the current drawn by the PMBLDCM from the dc link. A ripple filter is designed for ripple-free voltage at the dc link of the Cuk converter. The inductance (Lo) of the ripple filter restricts the inductor peak-to-peak ripple current (ΔILo) within a specified value for the given switching frequency (fs), whereas the capacitance (Cd) is calculated for the allowed ripple in the dc link voltage (ΔVCd) [7]. The values of theripple filter inductor and capacitor are given as

$$Lo = (1 - D)Vdc/\{fs(\Delta ILo)\} \quad (5)$$

$$Cd = Idc/(2\omega\Delta VCd). \quad (6)$$

The Cuk regulator is based on the capacitor energy transfer. As a result, the input current is continuous. The circuit has low switching losses and has high efficiency. When transistor Q_1 is turned ON, it has to carry the currents of inductors L_1 and L_2. As a result a high peak current flows through transistor Q_1. Because the capacitor provides the energy transfer, the ripple current of the capacitor C_1 is also high.

V. MODELING OF PFCCONVERTER-BASED PMBLDCMD

The PFC converter and PMBLDCMD are the main components of the proposed drive, which are modelled by mathematical equations, and a combination of these models represents the complete model of the drive.

A. PFC Converter:

The modellingof the PFC converter consists of the modelling of a speed controller, a reference current generator, and a PWM controller as given hereinafter.

1).Speed Controller: The speed controller is a PI controller which tracks the reference speed as an equivalent reference voltage. If, at the kth instant of time, $V^*_{dc}(k)$ is the reference.

The dc link voltage and $V_{dc}(k)$ is the voltage sensed at the dc link, then the voltage error $V_e(k)$ is given as

$$V_e(k)=V^*_{dc}(k) - V_{dc}(k) \quad (7)$$

The PI controller output Ic(k) at the kth instant after processing the voltage error Ve(k) is given as

$$I_c(k)=I_c(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_iV_e(k) \quad (8)$$

where $K_p$and $K_i$are the proportional and integral gains of the PI controller.

TABLE I
ELECTRONIC COMMUTATOR OUTPUT BASED ON THE
HALL-EFFECT SENSOR SIGNALS [6], [11]

Hall Signals			Switching Signals					
H_a	H_b	H_c	S_{a1}	S_{a2}	S_{b1}	S_{b2}	S_{c1}	S_{c2}
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0

2) Reference Current Generator:

The reference current at the input of the Cuk converter (i^*_d) is

$$i^*_d = I_c(k)^{\mu}{}_{Vs} \qquad (9)$$

where $^{\mu}v_s$ is the unit template of the ac mains voltage, calculated as

$$^{u}V_s = \upsilon_d/V_{sm};\ \upsilon_d = |\upsilon_s|;\ \upsilon_s = V_{sm}\sin\omega t \qquad (10)$$

where V_{sm} and ω are the amplitude (in volts) and frequency (in radians per second) of the ac mains voltage.

3) PWM Controller: The reference input current of the Cuk converter (i^*_d) is compared with its current (i_d) sensed after DBR to generate the current error $\Delta id = (i^*_d - i_d)$. This current error is amplified by gain k_d and compared with fixed frequency (f_s) sawtooth carrier waveform $m_d(t)$ [6] to get the switching signal for the MOSFET of the PFC Cuk converter as

$$\text{If } k_d\Delta i_d > md(t) \text{ then } S = 1 \text{ else } S = 0 \qquad (11)$$

where S denotes the switching of the MOSFET of the Cuk converter as shown in Fig. 3 and its values "1" and "0" represent "on" and "off" conditions, respectively.

B. PMBLDCMD:

The PMBLDCMD consists of an electronic commutator, a VSI, and a PMBLDCM.

1) Electronic Commutator: The electronic commutator uses signals from Hall-effect position sensors to generate the switching sequence for the VSI as shown in Table I [6], [7].

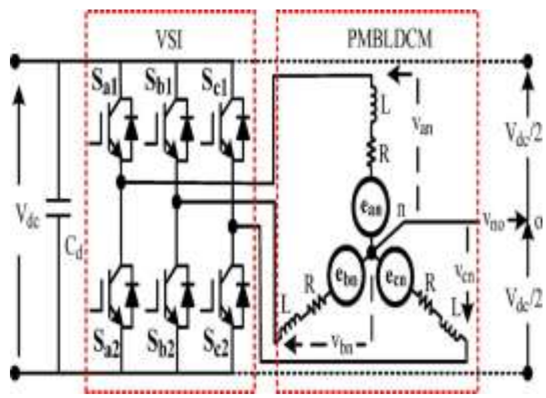


Fig. 5. Equivalent circuit of a VSI-fed PMBLDCMD.

2) VSI: The output of VSI to be fed to phase "a" of the PMBLDC motor is calculated from the

equivalent circuit of a VSI-fed PMBLDCM shown in Fig. 3 as

$$v_{ao} = (V_{dc}/2) \text{ for } S_{a1} = 1 \quad (12)$$

$$v_{ao} = (-V_{dc}/2) \text{ for } S_{a2} = 1 \quad (13)$$

$$v_{ao} = 0 \text{ for } S_{a1} = 0, \text{ and } S_{a2} = 0 \quad (14)$$

$$v_{an} = v_{ao} - v_{no} \qquad (15)$$

where v_{ao}, v_{bo}, v_{co}, and v_{no} are the voltages the three phases (a, b, and c) and neutral point (n) with respect to the virtual midpoint of the dc link voltage shown as "o" in Fig. 4. The voltages v_{an},

v_{bn}, and v_{cn} are the voltages of the three phases with respect to the neutral terminal of the motor (n), and V_{dc} is the dc link voltage. The values 1 and 0 for S_{a1} or S_{a2} represent the "on" and "off" conditions of respective IGBTs of the VSI. The voltages for the other two phases of the VSI feeding the PMBLDC motor, i.e., v_{bo}, v_{co}, v_{bn}, and v_{cn}, and the switching pattern of the other IGBTs of the VSI (i.e., S_{b1}, S_{b2}, S_{c1}, and S_{c2}) are generated in a similar way.

3) PMBLDC Motor: The PMBLDCM is modelled in the form of a set of differential equations [11] given as

$$v_{an} = Ri_a + p\lambda_a + e_{an} \quad (16)$$

$$v_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (17)$$

$$v_{cn} = Ri_c + p\lambda_c + e_{cn}. \quad (18)$$

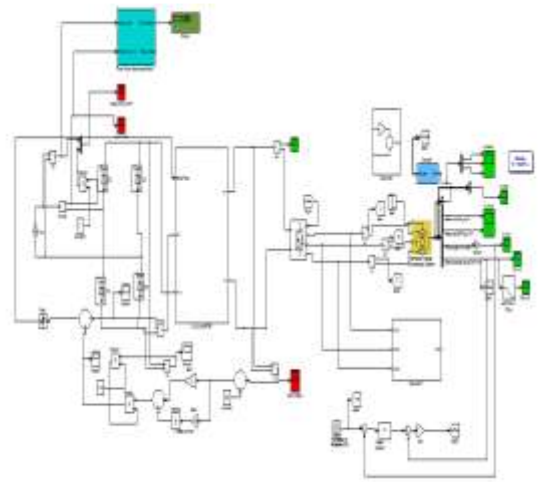
In these equations, p represents the differential operator (d/dt), i_a, i_b, and i_c are currents, λ_a, λ_b, and λ_c are flux linkages, and e_{an}, e_{bn}, and e_{cn} are phase-to-neutral back EMFs of PMBLDCM, in respective phases; R is the resistance of motor windings/phase. Moreover, the flux linkages can be represented as

$$\lambda_a = L_s i_a - M(i_b + i_c) \quad (19)$$

VI.SIMULATION RESULTS

The Simulink model of the BLDC motor [13]. The closed loop controller for a three phase brushless DC motor is modelled using MATLAB/Simulink [14] and [15] is shown in Fig. 6. Permanent Magnet Synchronous motor with trapezoidal back EMF is modelled as a Brushless DC Motor.

Fig 6: Simulink model of the PFC based



BLDC drive

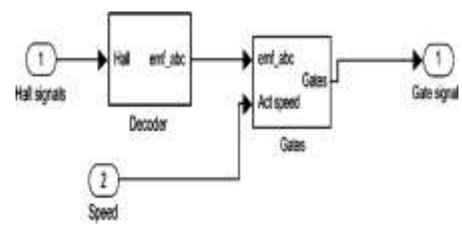


Fig 7 : Modelling of the controller

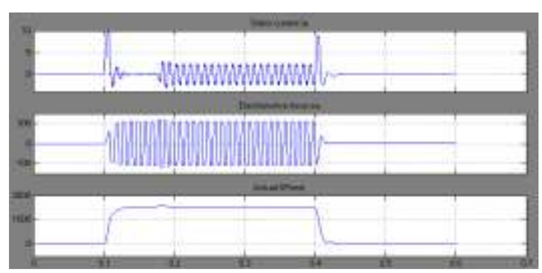


Fig: 8 Output model of the Simulink: stator current,back emf, actual speed.

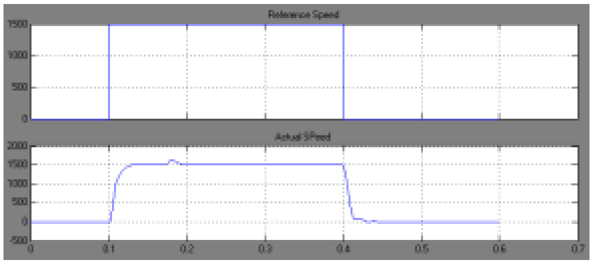


Fig: 9 Reference speed and actual speed in rpm.

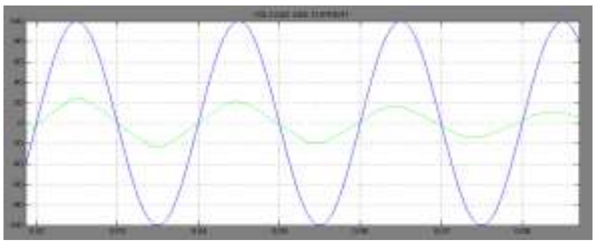


Fig: (a)

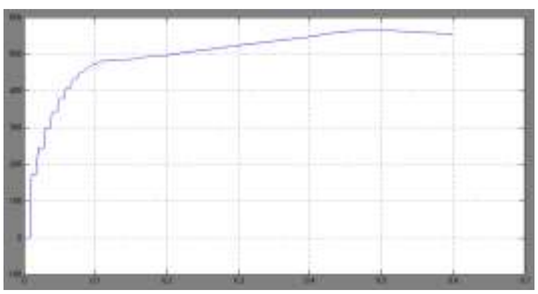


Fig:(b)

Fig:9 after connecting the cuk converter at the rectifier end (a) input voltage and current (b) dc output voltage

CONCLUSION

The digital control concept for BLDC machines has been introduced and experimentally verified. The aim of this paper is to control the four quadrants of the BLDC motor. The problem of the input ac current is also rectified then the power factor goes to nearer to unity. Increase the system life time and efficiency. The PFC Cuk converter has ensured near unity PF in a wide range of the speed and the input ac voltage.

The time taken to achieve this braking is comparatively less. The generated voltage during the regenerative mode can be returned back to the supply mains which will result in considerable saving of power. This concept may well be utilized in the rotation of spindles, embroidery machines and electric vehicles where there is frequent reversal of direction of rotation of the motor. BLDC motors are used in Automotive, Aerospace, Consumer, Medical, Industrial Automation equipment's and instrumentation

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