PFC CUK CONVERTER FOR PMBLDCM DRIVE

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Abstract: *This paper deals with a Cuk dc-dc converter as a single stage power factor correction (PFC) converter for a permanent magnet brushless DC motor (PMBLDCM) fed through a diode rectifier (DBR) from a single phase AC mains. This converter is used due to single stage requirement for dc link voltage control with unity PF at ac mains. A three phase voltage source inverter is used as an electronic commutator to operate the PMBLDCM drive. A proportional plus integral (PI) controller is used in loop control algorithm to control speed.. Voltage proportional to speed is compared with the rms value of supply voltage to generate the reference current which is used to compare with the actual current of the dc –dc converter. Analysis are done for varying conditions of torque and speed. As a modification fuzzy based PFC for BLDC drive is implement.The model is designed with necessary controls and modeled in MATLAB Simulink and simulated results are presented.*

***Keywords**:* Cuk converter, Power factor correction (PFC), Cuk converter, permanent magnet brushless DC motor (PMBLDCM).

1 INTRODUCTION

The applications of PMBLDC motors are increasing in the day to day life because of its features like low maintenance, high efficiency, and wide speed range. Brushless DC electric motor (BLDC motors) also known as electronically commutated motors , they 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. In this context, AC, alternating current, does not imply a sinusoidal waveform, but rather a bi-directional current with no restriction on waveform. Additional sensors and electronics control the inverter output amplitude and waveform (and therefore percent of DC bus usage/efficiency) and frequency (i.e. rotor speed).

The use of PMBLDCM in low power appliances are increasing because of its features of high efficiency, wide speed range and low maintenance [1-4]. The PMBLDCM are used in various applications like air conditioning system, electric traction etc. A PMBLDCM has torque directly proportional to phase current and its back EMF, which is proportional to the speed. So, it has a constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDCM under variable speed operation [1-4]. However, the control of VSI is done by electronic commutation based on the rotor position signals of the PMBLDC motor. The motor drive is fed from a single-phase ac supply via a diode bridge rectifier (DBR) followed by a capacitor at dc link. The dc link capacitor draws current in short pulses. This will generate harmonics and yield poor PF, resulting in poor power quality which lower the efficiency. Therefore various PFC converter topologies are available in order to meet the required IEC 61000-3-2 standard [7].

Drive is supplied via diode bridge rectifier and a capacitor. But the capacitor draws pulsating currents which results in harmonics due to an uncontrolled charging of the dc link capacitor. So PFC converters are implemented in front of the dc link capacitor for PFC correction. A PF correction (PFC) converter among various available converter topologies [3] is applicable for a PMBLDCM drive . Among these topologies most of them use boost topology at their front end. Here switching losses are high due to the presence of the diode bridge. This affects the performance of the whole drive system.

2. PROPOSED SPEED CONTROL SCHEME OF PMBLDC MOTOR

The proposed speed control scheme which is based on the control of the DC link voltage reference as an equivalent to the reference speed is shown in fig 1.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, therefore, rotor-position is required only at the commutation points [1-4].

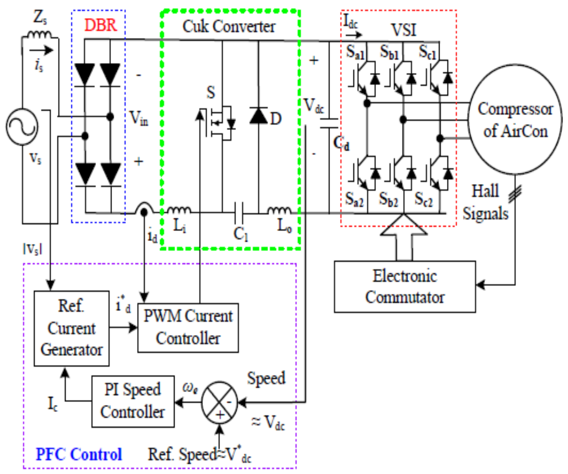


Fig 1. Control scheme of pm bldc Motor

The Cuk DC-DC converter controls the DC link voltage using capacitive energy transfer which results in non pulsating input and output currents [8]. The proposed PFC converter is operated at a high switching frequency for fast and effective control .

For high frequency operation, a metal oxide field effect transistor (MOSFET) is used in the proposed PFC converter, whereas, insulated gate bipolar transistors (IGBTs) are used in VSI bridge feeding PMBLDCM as switches , because of its operation at lower frequency compared to 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 (CCM) operation of the converter. The control loop begins with the processing of voltage error (V_e), obtained after comparison of sensed DC link voltage (V_{dc}) and a voltage (V_{dc} *) equivalent to the reference speed, through a proportional-integral (PI) controller to give the modulating control signal (I_c). This signal (I_c) is multiplied with a unit template of input AC voltage to get reference DC current (I_{dc}*) and compared with DC current (I_c) sensed after the DBR. The resultant current error (I_e) is amplified and compared with saw-tooth carrier wave of fixed frequency (f_s) to generate the PWM pulse for the Cuk converter. Its duty ratio (D) at a switching frequency (f_s) controls the DC link voltage at the desired value. For the control of current to PMBLDCM through VSI during 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.

3.DESIGN OF PFC CUK CONVERTER BASED PMBLDCM

The proposed PFC Cuk converter is designed for a PMBLDCM with main consideration on the speed control .The dc link voltage of the PFC converter is given as

$$V_{dc} = V_{in}(D/(1-D)) \quad (1)$$

Where V_{in} is the average output of the diode bridge rectifier for a given ac input voltage V_s related as

$$V_{in} = \frac{2\sqrt{2}\, V_s}{\pi} \quad (2)$$

The cuk converter uses a boost inductor (L_i) and a capacitor (C_i) for energy transfer and their values are given as

$$L_i = \frac{D\, V_{in}}{\{f_s\,(\Delta\, I_{Li})\}} \quad (3)$$

$$C_i = \frac{D\, I_{dc}}{\{f_s\,(\Delta\, I_{Li})\}} \quad (4)$$

Where $\Delta\, I_{Li}$ is a specified inductor current ripple , $\Delta\, V_{Ci}$ is a specified voltage ripple in the intermediate capacitor C_i , and I_{dc} 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 (L_o) of the ripple filter restricts the inductor peak to peak ripple current ($\Delta\, I_{Lo}$) within specified value for the given switching frequency (f_s), where as, the capacitance (C_d) is calculated for the allowed ripple in the DC link voltage ($\Delta\, V_{Cd}$) [7-8]. The values of the ripple filter inductor and capacitor are given as,

$$L_o = \frac{(1-D)\, V_{dc}}{\{f_s(\Delta\, I_{Lo})\}} \quad (5)$$

$$C_d = \frac{I_{dc}}{(2\,\omega\,\Delta\, V_{Cd})} \quad (6)$$

The PFC converter is designed for a base dc link voltage of V_{dc} = 298 V at V_s = 220 V for f_s = 40 kHz , I_s= 4.5 A , $\Delta\, I_{Li}$= 0.45 A (10% of I_{dc}) , I_{dc} = 3.5 A , $\Delta\, I_{Lo}$= 3.5 A(≈ I_{dc}) , ΔV_{Cd}= 4V (1% of V_o),and ΔV_{Ci} =220 V (≈ V_s) .The design values are obtained as L_i =6.61 mH , C_i = 0.3 μF , L_o = .82 mH , and C_d = 1590 μF.

4.CONTROL OF PFC CUK CONVERTER FED BLDC MOTOR DRIVE

The control of the proposed drive system is divided into two categories of control of the PFC converter for dc link voltage control and control of three phase VSI for achieving the electronic commutation of the BLDC motor as follows .

A. Control of PFC converter

The modeling of the PFC converter consists of the modeling of speed controller ,reference current generator and PWM controller as given .

1) Speed controller : The speed controller is a PI controller which tracks the reference speed as an equivalent reference voltage .The reference voltage (V^*_{dc}) is obtained by multiplying the reference speed (ω^*) with motor's voltage constant (k_v) as

$$V^*_{dc} = k_v \omega^* \qquad (7)$$

For kth instant of time , $V^*_{dc}(k)$ is the reference dc link voltage and $V_{dc}(k)$ is the voltage sensed at the dc link then the error voltage $V_e(k)$ is given by

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \qquad (8)$$

The PI controller output after processing the voltage error at the kth instant is given as

$$I_c(k) = I_c(k-1) + k_p\{ V_e(k) - V_e(k-1) + k_i V_e(k) \qquad (9)$$

Where k_p and k_i are the proportional and integral gains of the PI controller.

2) Reference current generator : The reference current at the input of the cuk converter (I^*_d) is given as

$$I^*_d = I_c(k) uv_s \qquad (10)$$

Where uv_s is the unit template of the ac mains voltage ,calculated as

$$uv_s = \frac{V_d}{V_{sm}} \;;\; V_d = |v_s| \;;\; v_s = V_{sm} \sin \omega t \qquad (11)$$

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 is compared with its current sensed after DBR to generate the current error . This current error is amplified by gain and compared with fixed frequency sawtooth carrier waveform [6] to get the switching signal for the MOSFET of the PFC Cuk converter as

$$k_d \Delta i_d > m_d(t) \text{ then } S=1 \text{ else } S=0 \qquad (12)$$

Where S denotes the switching of the MOSFET of the cuk converter as shown in fig 1.

B) PMBLDCMD

The PMBLDCMD consists of two sections

1) Electronic commutator: The electronic commutator uses signal from hall-effect sensor to generate the switching sequence for the VSI as shown in table I[6],[11]
2) VSI: The output of VSI fed to pahse "a" of the PMBLDC motor is calculated from the equivalent circuitof a VSI-fed PMBLDCM shown in fig 2 as

$$v_{ao} = \frac{V_{dc}}{2} \quad \text{for } S_{a1} = 1 \qquad (13)$$

$$v_{ao} = \frac{-V_{dc}}{2} \quad \text{for } S_{a2} = 1 \qquad (14)$$

$$v_{ao}=0 \text{ for} S_{a1} = 0 \text{, and } S_{a2} = 0 \qquad (15)$$

$$v_{an} = v_{ao} - v_{no} \qquad (16)$$

Table-1: Electronic Output Based On The Hall Effect Signal

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

Where v_{ao} , v_{bo} , v_{co} and v_{no} are the voltages the three phases (a,b,c) and neutral point (n) with respect to virtual mid-point of the DC link voltage shown as 'o' in Fig. 2. The voltages v_{an}, v_{bn}, v_{cn} are voltages of three-phases with respect to 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 'on' and 'off' condition of respective IGBTs of the VSI.

The voltages for other two phases of the VSI feeding PMBLDC motor i.e v_{ao} , v_{bo} , v_{co} and the switching pattern of other IGBTs of the VSI (i.e. S_{b1}, S_{b2} , S_{c1} , S_{c2}) is generated in a similar way.

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

$$v_{an} = Ri_a + p\lambda_a + e_{an} \quad (17)$$

$$v_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (18)$$

$$v_{cn} = Ri_c + p\lambda_c + e_{cn} \quad (19)$$

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

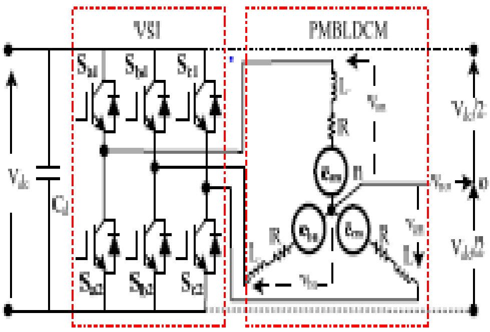


Fig 2. Equivalent circuit of a VSI fed PMBLDCM drive

Moreover, the flux linkages can be represented as,

$$\lambda_a = L_s i_a - M(i_b + i_c) \quad (20)$$

$$\lambda_b = L_s i_b - M(i_a + i_c) \quad (21)$$

$$\lambda_c = L_s i_c - M(i_b + i_a) \quad (22)$$

where L_s is self-inductance/phase, M is mutual inductance of PMBLDCM winding/phase.

The developed electromagnetic torque T_e in the PMBLDCM is given as,

$$T_e = (e_{an} i_a + e_{bn} i_b + e_{cn} i_c)/\omega_r \quad (23)$$

where ω_r is motor speed in rad/sec,

Since PMBLDCM has no neutral connection, so,

$$i_a + i_b + i_c = 0 \quad (24)$$

From (15)-(21) and (23) the voltage (v_{no}) between neutral point (n) and mid-point of the DC link (o) is given as,

$$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3 \quad (25)$$

From (19)-(21) and (23), the flux linkages are given as,

$$\lambda_a = (L_s + M)i_a, \lambda_a = (L_s + M)i_a, \lambda_a = (L_s + M)i_a \quad (26)$$

From (16)-(18) and (26), the current derivatives in generalized state space form are given as,

$$pi_x = (v_{xn} - i_x R - e_{xn})/(L_s + M) \quad (27)$$

where x represents phase a, b or c.

The back emf is a function of rotor position (θ) as,

$$e_{xn} = K_b f_x(\theta)\omega_r \quad (28)$$

where x can be phase a, b or c and accordingly $f_x(\theta)$ represents function of rotor position with a maximum value ±1, identical to trapezoidal induced emf, given as,

$$f_a(\theta) = 1 \quad for\ 0 < \theta < 2\pi/3 \quad (29)$$

$$f_a(\theta) = 1\{(6/\pi)(\pi - \theta)\} - 1 \ for \ \frac{2\pi}{3} < \theta < \pi \quad (30)$$

$$f_a(\theta) = -1 \quad for\ \pi < \theta < 5\pi/3 \quad (31)$$

$$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} + 1 \ for \ \frac{5\pi}{3} < \theta < 2\pi \quad (32)$$

The functions $f_b(\theta)$ and $f_c(\theta)$ are similar to $f_a(\theta)$ with a phase difference of 120º and 240º respectively.

Therefore, the electromagnetic torque expressed as,

$$T_e = K_b\{f_a(\theta)i_a + f_b + f_c(\theta)i_c\} \quad (33)$$

The mechanical equation of motion in speed derivative form is given as ,

$$p\omega_r = (P/2)(T_e - T_l - B\omega_r)/(J) \quad (34)$$

where ω_r is the derivative of rotor position θ, P is number of poles, T_l is load torque in Nm, J is moment of inertia in kgm^2,and B is friction coefficient in Nms/Rad.

The derivative of rotor position is given as,

$$p\theta = \omega_r \qquad (35)$$

Equations (16)-(35) represent the dynamic model of the PMBLDC motor.

5. PERFORMANCE EVALUATION OF THE PROPOSED DRIVE

The proposed PMBLDCM drive system is evaluated and tested in a MATLAB Simulink environment. The results are then compared with the conventional system which uses PI controller for power factor correction. That is the fuzzy based PFC cuk converter fed PMBLDCM drive is compared with the PI based conventional Cuk PFC converter fed PMBLDCM drive. They are compared in terms of power factor etc. The simulation of the proposed system is given in Fig (3).

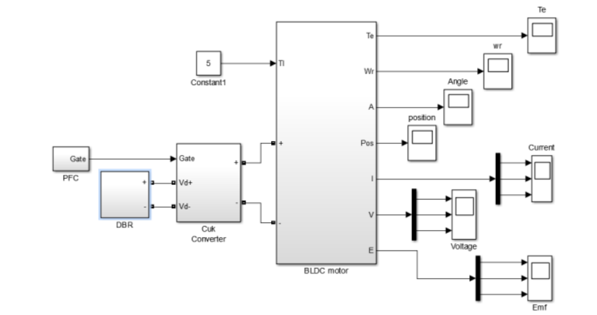
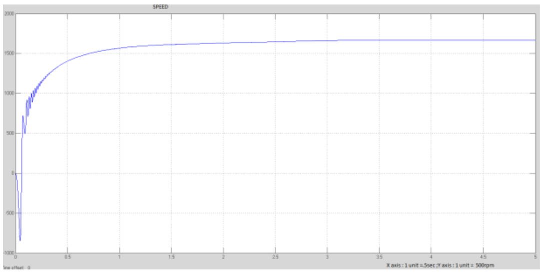


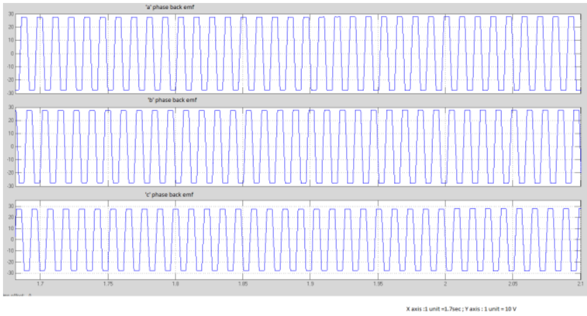
Fig 3: Simulation diagram of the proposed drive

The proposed PMBLDCM drive system‟s speed, input voltage n current current, electromagnetic torque and back EMFs waveforms are as below:

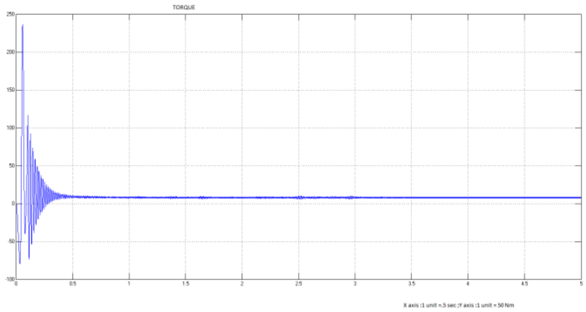


The rotor steady state speed is as in Fig 3(a)

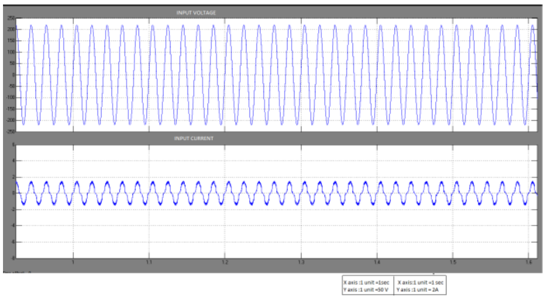
where at starting speed various and by the controller action it is set a steady state speed



The Fig 3(b) shows the quasi trapezoidal waveform.



The electromagnetic torque is shown in Fig 3(c)



The input voltage and current are shown in Fig 3(d)

The proposed drive system is then compared with the conventional Cuk PFC converter based PMBLDCM drive in terms of THD to establish that the proposed drive is efficient over the conventional system. The THD analysis and power correction is shown in table II

Table -2: Performance Details

TYPE	COVENTIONAL SYSTEM	PROS\POSED SYSTEM
THD – INPUT CURRENT (%)	19.53	15.43
POWER FACTOR	.995	.997

IV. CONCLUSION

A fuzzy based PFC Cuk converter for a PMBLDCM drive has been proposed and validated The PFC converter has ensured reasonable high power factor of the order of 0.997 in wide range of the speed as well as input AC voltage. The THD of AC mains current has been observed well below 19 % in most of the cases .The performance of the drive has been found very good in the wide range of input AC This topology has been found suitable for the applications involving speed control at constant torque load.

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