A Voltage Controlled PFC Cuk Converter Based PMBLDCM Drive for Air-Conditioners

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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 bridge rectifier (DBR) from a single-phase AC mains. A three-phase voltage source inverter is used as an electronic commutator to operate the PMBLDCM driving an air conditioner compressor. The speed of the compressor is controlled to achieve optimum air-conditioning using a concept of the voltage control at DC link proportional to the desired speed of the PMBLDCM. The stator currents of the PMBLDCM during step change in the reference speed are controlled within the specified limits by an addition of a rate limiter in the reference DC link voltage. The proposed PMBLDCM drive with the voltage control is designed, modeled and its performance is evaluated in Matlab-Simulink environment. The obtained results are presented to demonstrate an improved power quality (PQ) at AC mains of the PMBLDCM drive system in wide range of the speed and the input AC voltage.**

Index Terms-- **Air conditioner, Cuk converter, PFC, PMBLDCM, Voltage control, VSI.**

I. INTRODUCTION

The use of permanent magnet brushless DC motor (PMBLDCM) in low power appliances are increasing because of its features of high efficiency, wide speed range and low maintenance [1-4]. It is a rugged three-phase synchronous motor due to use of permanent magnets (PMs) on the rotor. The commutation in a PMBLDCM is accomplished by solid state switches of a three-phase voltage source inverter (VSI). Its application to the compressor of an air-conditioning (Air-Con) system results in an improved efficiency of the system if operated under speed control while maintaining the temperature in the air-conditioned zone at the set reference consistently. The Air-Con exerts constant torque (i.e. rated torque) on the PMBLDCM while operated in speed control mode. The Air-Con system with PMBLDCM has low running cost, long life and reduced mechanical and electrical stresses compared to a single-phase induction motor based Air-Con system operating in 'on/off' control mode.

A PMBLDCM has the developed torque proportional to its phase current and its back-emf is proportional to the speed [1-4]. Therefore, a constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDCM under variable speed operation. A speed control scheme is proposed which uses a reference voltage at DC link proportional to the desired speed of the PMBLDC motor. However, the control of VSI is only for electronic commutation based on the rotor position signals of the PMBLDC motor.

The PMBLDCM drive is fed from a single-phase AC supply through a diode bridge rectifier (DBR) followed by a capacitor at DC link. It draws a pulsed current as shown in Fig.1, with a peak higher than the amplitude of the fundamental input current at AC mains due to an uncontrolled charging of the DC link capacitor. This results in poor power quality (PQ) at AC mains in terms of poor power factor (PF) of the order of 0.728, high total harmonic distortion (THD) of AC mains current at the value of 81.54% and high crest factor (CF) of the order of 2.28. Therefore, the use of a power factor correction (PFC) converter amongst various available converter topologies [5-6] is almost inevitable for a PMBLDCM drive. Moreover, the PQ standards for low power equipments such as IEC 61000-3-2 [7], emphasize on low harmonic contents and near unity power factor current to be drawn from AC mains by these drives.

There are very few publications regarding PFC in PMBLDCM drives despite many PFC topologies for SMPS and battery charging applications. This paper deals with an application of a PFC converter for the speed control of a PMBLDCM drive. For the proposed voltage controlled drive, a Cuk 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 [8-10]. Moreover, apart from PQ improvement at AC mains, it controls the voltage at DC link for the desired speed of the Air-Con. The detailed modeling, design and performance evaluation of the proposed drive are presented for an air conditioner driven by a 0.816 kW, 1500 rpm PMBLDC motor.

II. PROPOSED SPEED CONTROL SCHEME OF PMBLDC MOTOR FOR AIR CONDITIONER

Fig. 2 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

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VSI feeding the PMBLDC motor, therefore, rotor-position is required only at the commutation points [1-4].

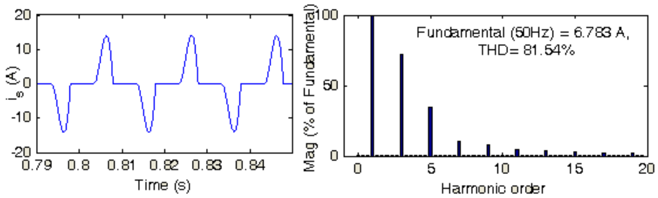

Fig. 1. Current waveform at AC mains and its harmonic spectra for the PMBLDCM drive without PFC

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 with additional advantage of a small size filter. 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, 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_d^*) and compared with DC current (I_d) 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 within the specified value which is considered as double the rated current in this work.

III. Design of PFC Cuk Converter based PMBLDCM Drive

The proposed PFC Cuk converter is designed for a PMBLDCM drive with main considerations on the speed control of the Air-Con and PQ improvement at AC mains. The DC link voltage of the PFC converter is given as,

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

where V_{in} is the average output of the DBR for a given AC input voltage (V_s) related as

$$V_{in} = 2\sqrt{2}V_s/\pi \tag{2}$$

The Cuk converter uses a boost inductor (L_i) and a capacitor (C_1) for energy transfer. Their values are given as,

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

$$C_1 = DI_{dc} / \{f_s \Delta\, V_{C1}\} \tag{4}$$

where ΔI_{Li} is specified inductor current ripple, ΔV_{C1} is a specified voltage ripple in the intermediate capacitor (C_1) and I_{dc} is the current drawn by the PMBLDCM from 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 (ΔI_{Lo}) within specified value for the given switching frequency (f_s), whereas, the capacitance (C_d) is calculated for the allowed ripple in the DC link voltage (ΔV_{Cd}) [7-8]. The values of the ripple filter inductor and capacitor are given as,

$$L_o = (1-D)V_{dc}/\{f_s(\Delta I_{Lo})\} \tag{5}$$

$$C_d = I_{dc}/(2\omega\Delta V_{Cd}) \tag{6}$$

The PFC converter is designed for a base DC link voltage of V_{dc}=298V at V_s=220V for f_s=40kHz, I_s=4.5A, ΔI_{Li}=0.45A (10% of I_{dc}), I_{dc}=3.5A, ΔI_{Lo}=3.5A (≈I_{dc}), ΔV_{Cd}=4V (1% of V_o), ΔV_{C1}=220V (≈V_s). The design values are obtained as L_i=6.61 mH, C_1=0.3μF, L_o=0.82 mH, C_d=1590 μF.

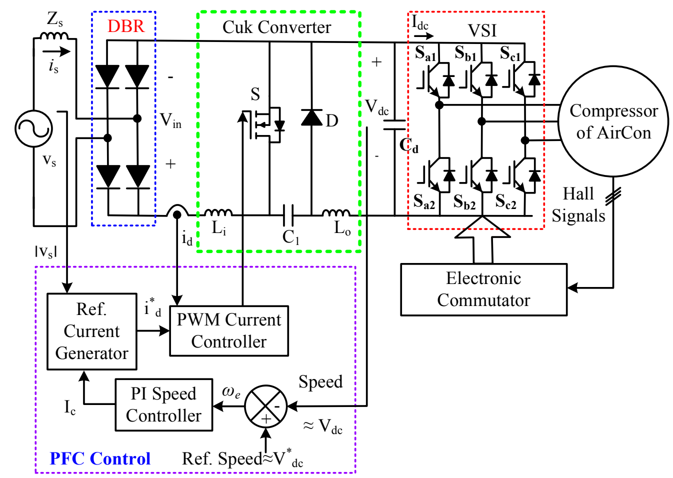

Fig. 2. Control scheme of the proposed Cuk PFC converter fed VSI based PMBLDCM drive

IV. Modeling of PFC Converter Based PMBLDCM Drive

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

A. PFC Converter

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

1) Speed Controller

The speed controller is a PI controller which tracks the reference speed as an equivalent reference voltage. If at k^{th} instant of time, $V^*_{dc}(k)$ is the reference DC link voltage, $V_{dc}(k)$ is the voltage sensed at DC link then the voltage error $V_e(k)$ is given as,

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

The PI controller output $V_c(k)$ at k^{th} instant after processing the voltage error $V_e(k)$ is given as,

$$V_c(k) = V_c(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \quad (8)$$

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

2) *Reference Current Generator*

The reference current at input of Cuk converter (i_d^*) is as,

$$i_d^* = I_c(k)\, u_{Vs} \quad (9)$$

where u_{Vs} is the unit template of the AC mains voltage, calculated as,

$$u_{Vs} = v_d/V_{sm};\ v_d = |v_s|;\ v_s = V_{sm}\sin\omega t \quad (10)$$

where V_{sm} and ω are the amplitude (Volts) and frequency (rad/sec) 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 $\Delta i_d = (i_d^* - i_d)$. This current error is amplified by gain k_d and compared with fixed frequency (f_s) saw-tooth carrier waveform $m_d(t)$ [6] to get the switching signal for the MOSFET of the PFC Cuk converter as,

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

where S denotes switching of the MOSFET of the Cuk converter as shown in Fig.2 and its values '1' and '0' represent 'on' and 'off' condition.

B. *PMBLDCM Drive*

The PMBLDCM drive consists of an electronic commutator, a VSI and a PMBLDC motor.

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.

2) *Voltage Source Inverter*

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,

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

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

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

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

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. 3. 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_{bo}, v_{co}, v_{bn}, v_{cn} 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,

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

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

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

In these equations, p represents 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.

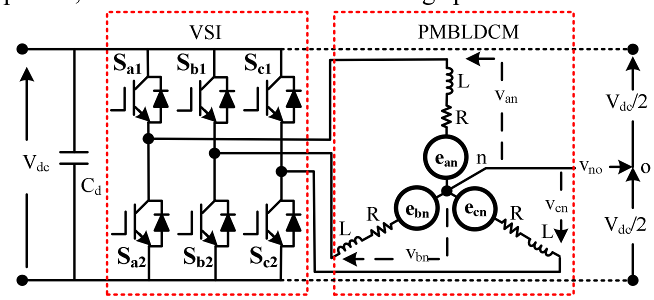

Fig. 3. Equivalent circuit of a VSI fed PMBLDCM drive

Moreover, the flux linkages can be represented as,

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

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

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

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,

$$T_e = (e_{an}\, i_a + e_{bn}\, i_b + e_{cn}\, i_c)/\,\omega_r \quad (22)$$

where ω_r is motor speed in rad/sec,

Since PMBLDCM has no neutral connection, so,

$$i_a + i_b + i_c = 0 \quad (23)$$

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

$$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3 \quad (24)$$

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

$$\lambda_a = (L_s+M)\, i_a, \quad \lambda_b = (L_s+M)\, i_b, \quad \lambda_c = (L_s+M)\, i_c \quad (25)$$

From (16)-(18) and (25), the current derivatives in generalized state space form are given as,

$$pi_x = (v_{xn} - i_x R - e_{xn})/(L_s+M) \quad (26)$$

where x represents phase a, b or c.

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

$$e_{xn} = K_b f_x(\theta)\, \omega_r \quad (27)$$

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,

$$f_a(\theta) = 1 \quad \text{for } 0 < \theta < 2\pi/3 \quad (28)$$

$$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} - 1 \quad \text{for } 2\pi/3 < \theta < \pi \quad (29)$$

$$f_a(\theta) = -1 \quad \text{for } \pi < \theta < 5\pi/3 \quad (30)$$

$$f_a(\theta) = \{(6/\pi)(\theta - 2\pi)\} + 1 \quad \text{for } 5\pi/3 < \theta < 2\pi \quad (31)$$

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

Therefore, the electromagnetic torque expressed as,

$$T_e = K_b\{f_a(\theta)\, i_a + f_b(\theta)\, i_b + f_c(\theta)\, i_c\} \quad (32)$$

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

$$p\omega_r = (P/2)\,(T_e\text{-}T_l\text{-}B\omega_r)/(J) \qquad (33)$$

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 kg-m^2 and B is friction coefficient in Nms/Rad.

The derivative of rotor position is given as,

$$p\theta=\omega_r \qquad (34)$$

Equations (16)-(34) represent the dynamic model of the PMBLDC motor.

V. PERFORMANCE EVALUATION OF PMBLDCM DRIVE

The proposed PMBLDCM drive is modeled in Matlab-Simulink environment and its performance is evaluated for an Air-Con compressor load. The compressor load is considered as a constant torque load equal to rated torque (5.2 Nm) with variable speed as required by air conditioning system. A 0.816 kW rating PMBLDCM is used to drive the air conditioner, the speed of which is controlled effectively by controlling the DC link voltage. The detailed data of the motor are given in Appendix. The performance evaluation of the proposed PFC drive is evaluated on the basis of various parameters such as total harmonic distortion (THD_i) and the crest factor (CF) of the AC mains current, displacement factor (DPF) and PF at different speeds of the motor as well as variable input AC voltage. For the performance evaluation of the proposed drive under input AC voltage variation the DC link voltage is kept constant at 298 V which is equivalent to 1500 rpm speed of the PMBLDCM. Figs. 4-8 and Tables II-III show the obtained results which demonstrate effectiveness of the proposed PMBLDCM drive in a wide range of the speed and the input AC voltage.

A. Performance of the PMBLDCM Drive during Starting

The performance of PMBLDCM drive during starting is evaluated while feeding it from 220 V AC mains with the reference speed set at 1000 rpm and rated torque. Fig. 4a shows starting performance of the drive depicting voltage (v_s) and current (i_s) at AC mains, voltage at DC link (V_{dc}), speed of motor (N), electromagnetic torque (T_e) and stator current of phase 'a' (i_a). A rate limiter is introduced in the reference voltage to limit the starting current of the motor as well as the charging current of the DC link capacitor. The PI controller tracks the reference speed so that the motor attains reference speed smoothly within 0.35 sec while keeping the stator current within the desired limits i.e. double the rated value. The current waveform at input AC mains is in phase with the supply voltage demonstrating nearly unity PF during starting.

B. Performance of PMBLDCM Drive under Speed Control

Figs. 4-6 show the performance of PMBLDCM drive for speed control at constant rated torque (5.2 Nm) and 220 V AC mains voltage, which is categorized as performance during transient and steady state conditions of the PMBLDCM.

1) Transient Condition

The performance of the drive during the speed transients is evaluated for acceleration and retardation of the compressor and shown in Figs. 4b-c. The reference speed is changed from 1000 rpm to 1500 rpm and from 1000 rpm to 500 rpm for the performance evaluation of the compressor at rated load under speed control. It is observed that the speed control is fast and smooth in either direction i.e. acceleration or retardation, with PF maintained at nearly unity value. Moreover, the stator current of PMBLDCM is less than twice the rated current due to the rate limiter introduced in the reference voltage.

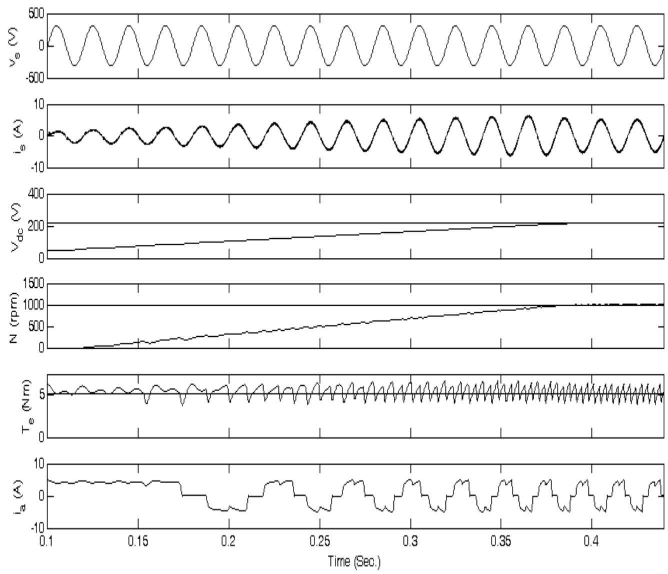

Fig. 4a. Starting performance of the proposed drive at 1000 rpm

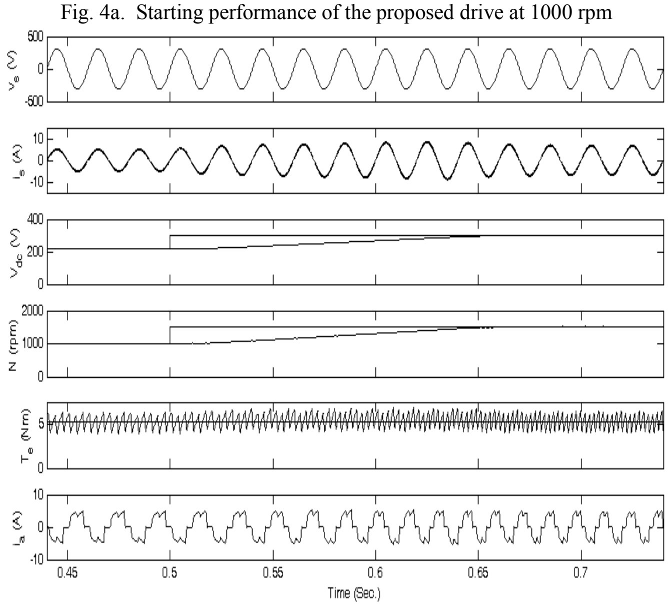

Fig. 4b. Proposed drive under speed control from 1000 rpm to 1500 rpm

2) Steady State Condition

The performance of drive under steady state speed condition is obtained at different speeds as summarized in Table-II which demonstrates the effectiveness of the proposed drive in wide speed range. Fig.5 shows linear relation between motor speed and DC link voltage. Since the reference speed is decided by the reference voltage at DC link, it is observed that the control of the reference DC link voltage controls the speed of the motor.

C. Power Quality Performance of the PMBLDCM Drive

The performance of PMBLDCM drive in terms of PQ indices i.e. THD_i, CF, DPF, PF is obtained for different speeds as well as loads. These results are shown in Figs. 6-7 and Table-II. Figs. 6a-b show nearly unity power factor (PF) and reduced THD of AC mains current in wide speed range of the PMBLDCM. The THD_i and harmonic spectra of AC mains current drawn by the proposed drive at 500 and 1500 rpm speeds are shown in Figs. 7a-b demonstrating less than 5% THD_i in wide range of speed.

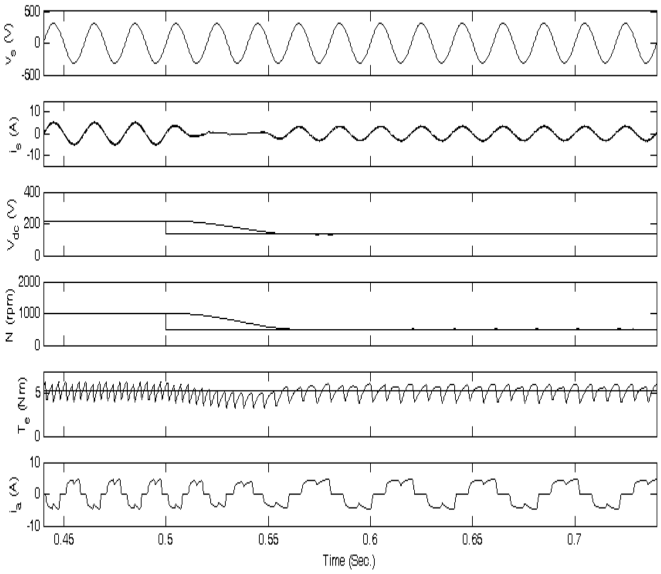

Fig. 4c. Proposed drive under speed control from 1000 rpm to 500 rpm

Fig. 4. Performance of the proposed PFC drive under speed control at 220 VAC input

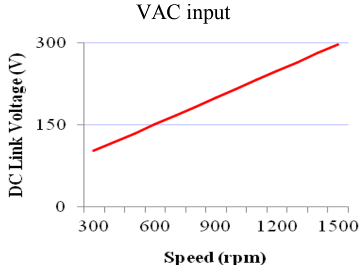

Fig. 5. Variation of DC link voltage with speed for proposed PFC drive at rated torque and 220 V AC input

D. Performance of the PMBLDCM Drive under Varying Input AC Voltage

Performance of the proposed PMBLDCM drive is evaluated under varying input AC voltage at rated load (i.e. rated torque and rated speed) to demonstrate the effectiveness of the proposed drive for Air-Con system in various practical situations as summarized in Table-III.

Figs. 8a-b show current and its THD at AC mains, DPF and PF with AC input voltage. The THD of AC mains current is within specified limits of international norms [7] at nearly unity PF in wide range of AC input voltage.

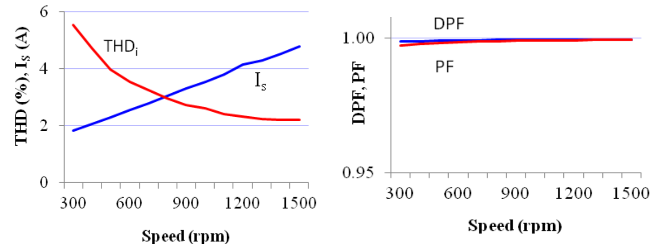

Fig. 6a. Variation of I_s and its THD Fig. 6b. Variation of DPF and PF

Fig. 6. PQ indices of proposed drive under speed control at rated torque and 220 V AC input

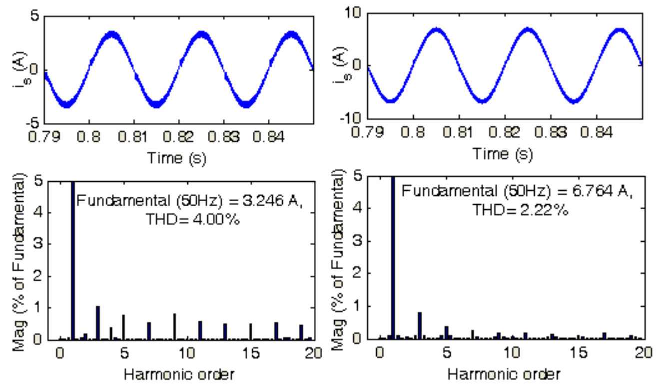

Fig.7a. I_s and THD at 500 rpm Fig.7b. I_s and THD at 1500 rpm

Fig. 7. Current waveform at input AC mains and its harmonic spectra for the proposed drive under steady state condition at rated torque and 220 VAC input.

TABLE I
ELECTRONIC COMMUTATOR OUTPUT BASED ON THE HALL EFFECT SENSOR SIGNALS

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

VI. CONCLUSION

A new speed control strategy for a PMBLDCM drive using the reference speed as an equivalent voltage at DC link has been validated for an air conditioner employing Cuk PFC converter. The speed of PMBLDCM has been found proportional to the DC link voltage, thereby a smooth speed control is observed while controlling the DC link voltage. The introduction of a rate limiter in the reference DC link voltage effectively limits the motor current within the desired value during the transient conditions. The PFC Cuk converter has ensured nearly unity PF in wide range of the speed and the input AC voltage. Moreover, power quality indices of the proposed PFC drive are in conformity to the International standard IEC 61000-3-2 [7]. The proposed PMBLDCM drive has been found as a promising variable speed drive for the Air-Con system.

TABLE II
PERFORMANCE OF THE PROPOSED DRIVE UNDER SPEED CONTROL AT 220 V INPUT AC VOLTAGE (V_S)

V_{DC} (V)	Speed (rpm)	THD_i (%)	DPF	PF	I_s (A)	Load (%)
104.0	300	5.55	0.9990	0.9975	1.82	20.0
119.0	400	4.74	0.9990	0.9979	2.05	26.7
135.5	500	4.00	0.9992	0.9984	2.30	33.3
151.5	600	3.55	0.9993	0.9987	2.55	40.0
167.5	700	3.25	0.9993	0.9988	2.79	46.7
183.5	800	2.97	0.9994	0.999	3.04	53.4
200.0	900	2.75	0.9995	0.9991	3.29	60.0
216.5	1000	2.63	0.9995	0.9992	3.54	66.7
233.0	1100	2.43	0.9996	0.9993	3.79	73.4
249.5	1200	2.33	0.9996	0.9993	4.15	80.0
265.5	1300	2.24	0.9997	0.9994	4.29	86.7
282.0	1400	2.23	0.9996	0.9994	4.53	93.4
298.0	1500	2.22	0.9996	0.9994	4.79	100.0

TABLE III
PQ INDICES WITH INPUT AC VOLTAGE (V_S) VARIATION AT 1500 RPM

V_{AC} (V)	THD_i (%)	DPF	PF	CF	I_s (A)
170	1.51	0.9998	0.9997	1.41	6.19
180	1.55	0.9998	0.9997	1.41	5.85
190	1.73	0.9997	0.9996	1.41	5.54
200	1.87	0.9998	0.9996	1.41	5.26
210	2.06	0.9997	0.9995	1.41	5.01
220	2.22	0.9996	0.9994	1.41	4.79
230	2.39	0.9996	0.9993	1.41	4.58
240	2.47	0.9996	0.9993	1.41	4.39
250	2.49	0.9995	0.9992	1.41	4.22
260	2.77	0.9995	0.9991	1.41	4.05
270	3.04	0.9995	0.999	1.41	3.90

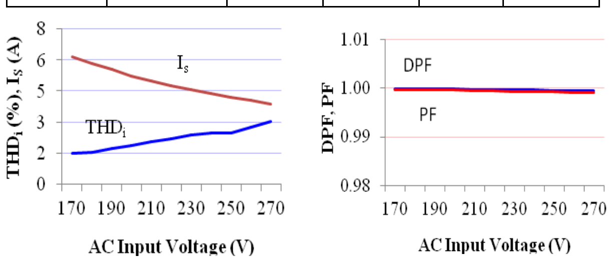

Fig. 8a. Variation of I_s and its THD Fig. 8b. Variation of DPF and PF
Fig. 8. PQ indices with input AC voltage variation at a constant DC link voltage of 298 V (≈1500 rpm)

APPENDIX

Rated power: 0.816 kW, rated speed: 1500 rpm, rated torque: 5.2 Nm, poles: 6, stator resistance (R): 3.57 Ω/ph., inductance (L+M): 9.165 mH/ph., back EMF constant (K_b): 1.3 Vsec/rad, Inertia (J): 0.068 Kg-m^2. Source impedance (Z_s): 0.03 pu, Switching frequency of PFC switch (f_s): 40 kHz, PI speed controller gains (K_p): 0.145, (K_i): 1.85.

REFERENCES

[1] T. Kenjo and S. Nagamori, *Permanent Magnet Brushless DC Motors*, Clarendon Press, Oxford, 1985.
[2] T. J. Sokira and W. Jaffe, *Brushless DC Motors: Electronic Commutation and Control*, Tab Books USA, 1989.
[3] J. R. Hendershort and T. J. E. Miller, *Design of Brushless Permanent-Magnet Motors*, Clarendon Press, Oxford, 1994.
[4] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology – Design and Application*, Marcel Dekker Inc., New York, 2002.
[5] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D. P. Kothari, "A review of single-phase improved power quality AC-DC converters," *IEEE Trans. Industrial Electron*., vol. 50, no. 5, pp. 962 – 981, oct. 2003.
[6] N. Mohan, T. M. Undeland and W. P. Robbins, "*Power Electronics: Converters, Applications and Design*," John Wiley and Sons Inc, USA, 1995.
[7] *Limits for Harmonic Current Emissions (Equipment input current ≤16 A per phase)*, International Standard IEC 61000-3-2, 2000.
[8] S. Cuk and R.D. Middlebrook, "Advances in switched-mode power conversion Part-I," *IEEE Trans. Ind. Electron*., vol. 30, no.1, pp. 10 - 19, Feb 1983.
[9] C. J. Tseng and C. L. Chen, "A novel ZVT PWM Cuk power factor corrector," *IEEE Trans. Ind. Electron*., vol.46, no.4, pp. 780 – 787, Aug. 1999.
[10] B. Singh, and G.D. Chaturvedi, "Analysis, design and development of single switch Cuk AC-DC converter for low power battery charging application," in *Proc. IEEE PEDES '06*, 2006, pp.6.
[11] C. L. Puttaswamy, Bhim Singh and B.P. Singh, "Investigations on dyanamic behavior of permanent magnet brushless DC motor drive," *Electric Power Components and Sys*., vol.23, no.6, pp. 689 - 701, Nov. 1995.