Voltage Controlled PFC Forward Converter Fed PMBLDCM Drive for Air-Conditioner

Sanjeev Singh and Bhim Singh

Abstract— **In this paper, a permanent magnet brushless DC motor (PMBLDCM) fed through a three-phase voltage source inverter (VSI) is used to drive a compressor load of an air conditioner. The PMBLDCM drive is fed through a diode bridge rectifier (DBR) from single-phase AC mains using a buck forward DC-DC converter as a single-stage power factor correction (PFC) converter. The speed of the compressor is controlled using a concept of the voltage control at DC link proportional to the desired speed of the PMBLDCM. Therefore the VSI performs only as an electronic commutator for the PMBLDCM. The stator current of the PMBLDCM during step change of the reference speed is 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 simulated in Matlab-Simulink environment for an air conditioner driven through a PMBLDC motor. The obtained results of the proposed speed control scheme are presented to demonstrate an improved efficiency of the PMBLDCM drive system with PFC feature in wide range of the speed and the input AC voltage.**

Index Terms— **PFC, PMBLDCM, Air conditioner, Forward buck converter, Voltage control, VSI.**

I. INTRODUCTION

PERMANENT magnet brushless DC motors (PMBLDCMs) are most preferred motors in many applications due to advantages of high efficiency, wide speed range and low maintenance requirements [1-4]. It is a kind of three-phase synchronous motor with permanent magnets (PMs) on the rotor and trapezoidal back EMF waveform. It operates on electronic commutation accomplished by solid state switches of a three-phase voltage source inverter (VSI). Its application to air-conditioning (Air-Con) compressor 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 compressor exerts constant torque (i.e. rated torque) on the PMBLDCM while operated in speed control mode. Therefore the Air-Con system with PMBLDCM has low running cost, long life and reduced mechanical and electrical stresses on it which is inevitable in case of a single-phase induction motor based air conditioners operating in 'on/off' control mode.

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To maintain constant torque in a PMBLDCM under variable speed operation, a constant current in its stator windings with variable voltage across its terminals are required, because, the back-emf of the PMBLDCM is proportional to the motor speed and the developed torque is proportional to its phase current [1-4]. Keeping above fact in view, a speed control scheme is proposed in this paper 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 the single-phase AC mains through a diode bridge rectifier (DBR) with a capacitor at DC link, draws a pulsed current 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 many power quality (PQ) problems such as poor power factor (PF), increased total harmonic distortion (THD) of AC mains current and its high crest factor (CF). Moreover, the PQ standards for low power equipments such as IEC 61000-3-2 [5], emphasize on low harmonic contents and near unity power factor current to be drawn from AC mains by these motors. Therefore, the use of a power factor correction (PFC) converter amongst various available converter topologies [6-8] is almost inevitable for a PMBLDCM drive.

Presently, a two-stage PFC drives are mostly used which consist of a boost converter for PFC at front-end followed by a flyback or forward converter for low power applications, however, a full-bridge converter is used in second stage of voltage regulation for higher power applications [7-9]. A combination of boost PFC and a forward converter has been used in SMPS [9]. However, these two stage PFC converters have high cost and complexity in implementing two separate switch-mode converters, therefore a single stage PFC converter is more in demand which combines the PFC and voltage regulation. There are many variants of the forward converter [9-15] including two-switch, interleaved and with zero voltage switching / zero current switching (ZVS/ZCS). Its popular applications are in SMPS [9, 12, 15] and in battery charging [10, 14] in the range of 100W-1 kW. The single-stage PFC converter requires a design to operate over a much wider range of operating conditions i.e. input AC voltage and DC link voltage when applied to PMBLDCM.

For the proposed voltage controlled drive, a forward buck DC-DC converter is selected as a single-stage PFC converter because of its simplicity and low cost among other single switch converters. Moreover, it has minimum cost, switching losses and voltage drop in the secondary of the high frequency transformer which facilitates improved efficiency of the PFC converter. With improved PF at single-phase AC mains, it controls the voltage at DC link for the desired speed of the Air-Con compressor. A detailed modeling, design and performance evaluation of the proposed drive are presented for an air conditioner compressor driven by a 750 W, 1500 rpm rating PMBLDC motor.

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

The proposed speed control scheme (as shown in Fig. 1) controls reference voltage at DC link as an equivalent reference speed, thereby eliminates the conventional speed control loop and various sensors (voltage and current) in this loop. However, the rotor position signals are used in an electronic commutator, only to generate the switching sequence for the VSI feeding the PMBLDC motor. Therefore, rotor-position is sensed using Hall effect sensors only at the commutation points, i.e. every 60°electrical in the three-phases [1-4].

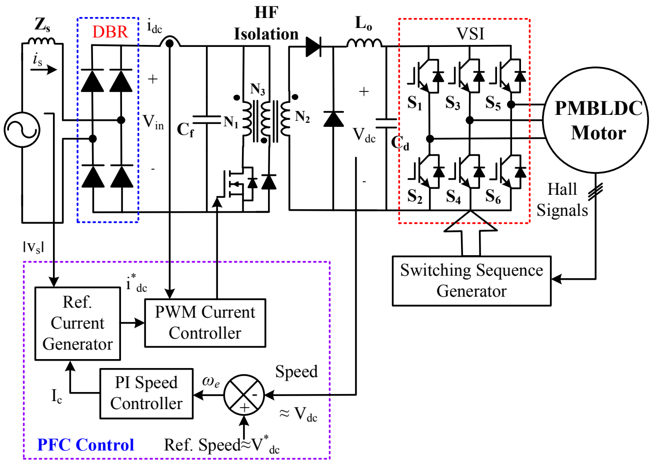

Fig. 1 Proposed forward-buck PFC converter fed VSI based PMBLDCM drive with control scheme

The forward buck DC-DC converter controls the DC link voltage by its duty ratio (D) at a switching frequency (f_s). For a fast and effective control with reduced size of magnetics and filters, a high switching frequency is used; however, its value depends on various factors such as the switching device, switching losses and operating power level. Metal oxide field effect transistor (MOSFET) is used as the switching device for high switching frequency in the proposed PFC converter. However, insulated gate bipolar transistors (IGBTs) are used in VSI bridge feeding PMBLDCM, to reduce the switching stress, because of its operation at lower frequency compared to PFC converter switch.

The PFC control scheme uses a current control loop inside the speed control loop with current multiplier approach operating in the continuous conduction mode (CCM) with an average current control. The control loop begins with the comparison of sensed DC link voltage and a voltage equivalent to the reference speed. The resultant voltage error is passed through a proportional-integral (PI) controller to give the modulating current signal. This signal is multiplied with a unit template of input AC voltage and compared with DC current sensed after the DBR. The resultant current error is amplified and compared with saw-tooth carrier wave of fixed frequency (f_s) to generate the PWM pulse for the forward buck converter. For the current control of the PMBLDCM during step change of the reference voltage due to the change in the reference speed, a rate limiter of 800 V/s is introduced for the change in DC link voltage, which ensures the stator current of the PMBLDCM within the specified limits (i.e. double the rated current).

III. DESIGN OF PFC BUCK FORWARD CONVERTER BASED PMBLDCM DRIVE

The proposed PFC buck forward converter is designed for a PMBLDCM drive with main considerations on PQ constraints at AC mains and allowable ripple in DC link voltage. The DC link voltage of the PFC converter is given as,

$$V_{dc} = (N_2/N_1)\, V_{in}\, D \text{ with } D(1+N_3)/\, N_1<1 \qquad (1)$$

where N_1, N_2, N_3 are number of turns in primary, secondary and tertiary windings of the high frequency (HF) isolation transformer, respectively. The tertiary winding is used to return stored energy back to DC source, during turnoff time, for resetting the flux in the high frequency transformer core.

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

$$V_{in} = 2\sqrt{2}V_s/\pi \qquad (2)$$

The high frequency AC voltage from the transformer is rectified using half-wave rectifier that provides improved efficiency due to voltage drop of only one diode in the forward converter.

A ripple filter is designed to reduce the ripples introduced in the output voltage due to high switching frequency of the buck forward 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 a specified ripple in the output voltage (ΔV_{Cd}) [7-8]. The output filter inductor and capacitor are given as,

$$L_o= (1-D)V_{dc}/\{f_s(\Delta I_{Lo})\} \qquad (3)$$

$$C_d=I_o/(2\omega\Delta V_{Cd}) \qquad (4)$$

The PFC converter is designed for a base DC link voltage of V_{dc} = 400 V at V_{in} = 198 V from V_s = 220 Vrms. The turns ratio of the high frequency transformer (N_3:N_2/N_1) is taken as 1:6:1 to maintain the desired DC link voltage under input AC voltage variation typically at lower range of 170V. Other design data are f_s = 40 kHz, I_o = 2.5 A, ΔV_{Cd}= 4 V (1% of V_{dc}), ΔI_{Lo}= 1.5 A. The design parameters are calculated as L_o=4.5 mH, C_d=1000 μF.

IV. Modeling of the Proposed PFC Converter Based PMBLDCM Drive

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

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, the prime component of this control scheme, is a proportional-integral (PI) controller which closely tracks the reference speed as an equivalent reference voltage.

If at k^{th} instant of time, $V^*_{dc}(k)$ is reference DC link voltage, $V_{dc}(k)$ is sensed DC link voltage then the voltage error $V_e(k)$ is calculated as,

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \qquad (5)$$

The PI controller gives desired control signal after processing this voltage error. The output of the controller $I_c(k)$ at k^{th} instant is given as,

$$I_c(k) = I_c(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \qquad (6)$$

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 buck forward converter is denoted by i_{dc}^* and given as,

$$i_{dc}^* = I_c(k)\, u_{Vs} \qquad (7)$$

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

$$u_{Vs} = v_d/V_{sm};\ v_d = |v_s|;\ v_s = V_{sm} \sin \omega t \qquad (8)$$

where V_{sm} is the amplitude of the voltage and ω is frequency in rad/sec at input AC mains.

3) PWM Controller: The reference input current of the buck forward converter (i_{dc}^*) is compared with its sensed current (i_{dc}) to generate the current error $\Delta i_{dc} = (i_{dc}^* - i_{dc})$. This current error is amplified by gain k_{dc} and compared with fixed frequency (f_s) saw-tooth carrier waveform $m_d(t)$ [7] to get the switching signal for the MOSFET of the PFC forward buck converter as,

$$\text{If } k_{dc}\,\Delta i_{dc} > m_d(t) \quad \text{then } S = 1 \ \text{else } S = 0 \qquad (9)$$

where S denotes MOSFET of the forward buck converter as shown in Fig.1 and its values '1' and '0' represent 'on' and 'off' condition. The maximum duty cycle of the forward converter is limited to 0.5.

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 voltage source inverter based on the logic given in Table I.

2) Voltage Source Inverter: Fig. 2 shows an equivalent circuit of a VSI fed PMBLDCM. The output of VSI to be fed to phase 'a' of the PMBLDC motor is given as,

$$v_{ao} = (V_{dc}/2) \quad \text{for } S_1 = 1 \qquad (10)$$

$$v_{ao} = (-V_{dc}/2) \quad \text{for } S_2 = 1 \qquad (11)$$

$$v_{ao} = 0 \quad \text{for } S_1 = 0, \text{ and } S_2 = 0 \qquad (12)$$

$$v_{an} = v_{ao} - v_{no} \qquad (13)$$

where v_{ao}, v_{bo}, v_{co}, and v_{no} are voltages of the three-phases 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 point (n) and V_{dc} is the DC link voltage. The values 1 and 0 for S_1 or S_2 represent 'on' and 'off' condition of respective IGBTs of the VSI. Similarly, the switching of other IGBTs of the VSI i.e. S_3- S_6 is considered.

The voltages for other two phases of the VSI feeding PMBLDC motor i.e v_{bo}, v_{co}, v_{bn}, v_{cn} are generated using similar logic.

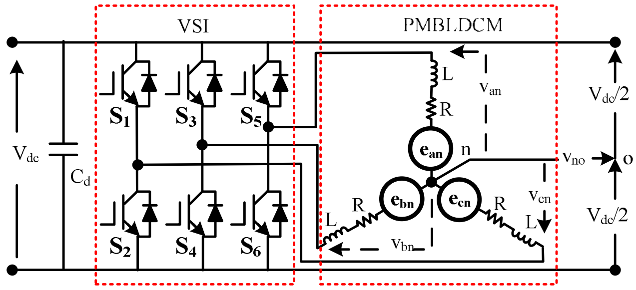

Fig. 2 Equivalent circuit of a VSI fed PMBLDCM drive

TABLE-I
VSI Switching Sequence Based on the Hall Effect Sensor Signals

H_a	H_b	H_c	E_a	E_b	E_c	S_1	S_2	S_3	S_4	S_5	S_6
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
0	1	1	-1	0	+1	0	1	0	0	1	0
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0
1	1	0	0	+1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

3) PMBLDC Motor: The PMBLDCM is modeled in the form of a set of differential equations [16] given as,

$$v_{an} = Ri_a + p\lambda_a + e_{an} \qquad (14)$$

$$v_{bn} = Ri_b + p\lambda_b + e_{bn} \qquad (15)$$

$$v_{cn} = Ri_c + p\lambda_c + e_{cn} \qquad (16)$$

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. Moreover, the flux linkages can be represented as,

$$\lambda_a = L_s i_a - M(i_b + i_c) \qquad (17)$$

$$\lambda_b = L_s i_b - M(i_a + i_c) \qquad (18)$$

$$\lambda_c = L_s i_c - M(i_b + i_a) \qquad (19)$$

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,

$T_e = (e_{an}\, i_a + e_{bn}\, i_b + e_{cn}\, i_c)/\, \omega_r$ (20)

where ω_r is motor speed in rad/sec.

Since the PMBLDCM has no neutral connection, therefore,

$i_a + i_b + i_c = 0$ (21)

From Eqs. (13-19, 21) the voltage (v_{no}) between neutral point (n) and mid-point of the DC link (o) is given as,

$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3$ (22)

From Eqs. (17-19, 21), the flux linkages are given as,

$\lambda_a = (L_s+M)\, i_a,\ \lambda_b = (L_s+M)\, i_b,\quad \lambda_c = (L_s+M)\, i_c,$ (23)

From Eqs. (14-16 and 23), the current derivatives in generalized state space form are given as,

$pi_x = (v_{xn} - i_x R - e_{xn})/(L_s+M)$ (24)

where x represents phase a, b or c.

The back emfs may be expressed as a function of rotor position (θ) as,

$e_{xn} = K_b f_x(\theta)\, \omega_r$ (25)

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,

$f_a(\theta) = 1$ for $0 < \theta < 2\pi/3$ (26)

$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} - 1$ for $2\pi/3 < \theta < \pi$ (27)

$f_a(\theta) = -1$ for $\pi < \theta < 5\pi/3$ (28)

$f_a(\theta) = \{(6/\pi)(\theta - 2\pi)\} + 1$ for $5\pi/3 < \theta < 2\pi$ (29)

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,

$T_e = K_b\{f_a(\theta)\, i_a + f_b(\theta)\, i_b + f_c(\theta)\, i_c\}$ (30)

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

$p\omega_r = (P/2)\,(T_e - T_l - B\omega_r)/(J)$ (31)

The derivative of rotor position is given as,

$p\theta = \omega_r$ (32)

where 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.

These equations (14-32) represent the dynamic model of the PMBLDC motor.

V. Performance Evaluation of Proposed PMBLDCMD

The proposed PMBLDCM drive is modeled in Matlab-Simulink environment and evaluated for an Air-Con compressor load. The compressor load is considered as a constant torque load equal to rated torque (4.77 Nm) with the speed control required by air conditioning system. A 0.75 kW rating PMBLDCM is used to drive the air conditioner compressor, the speed of which is controlled effectively by controlling the DC link voltage. The detailed data of the motor and simulation parameters are given in Appendix. The performance 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 power factor (DPF), PF and efficiency of the drive system (η_{drive}) at different speeds of the motor.

Moreover, these parameters are also evaluated for variation in input AC voltage with DC link voltage kept constant at 408 V which is equivalent to 1500 rpm speed of the PMBLDCM. Figs. 3-8 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 during Starting of the PMBLDCM Drive

To evaluate the performance of the proposed PMBLDCM drive fed from 220 V AC mains during starting the reference speed is set at 900 rpm with rated torque. The starting performance of the drive is shown in Fig. 3a 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), stator current (i_a) and shaft power (P_o). A rate limiter of 800 V/s 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 closely 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 power factor during the starting.

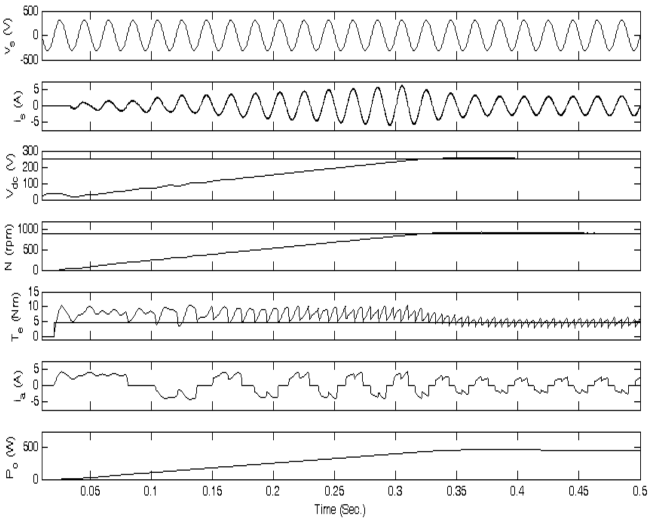

Fig. 3a Starting performance of the proposed drive at 900 rpm.

B. Performance under Speed Control of the PMBLDCMD

Figs. 3-5 show the performance of the proposed PMBLDCM drive under the speed control at constant rated torque (4.77 Nm) and 220 V AC mains voltage. These results are showing voltage (v_s) and current (i_s) waveforms at AC mains, DC link voltage (V_{dc}), speed of the motor (N), developed electromagnetic torque of the motor (T_e), the stator current of the PMBLDC motor for phase 'a' (i_a), shaft power output (P_o) and 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 obtained for acceleration and retardation of the compressor as shown in Figs. 3b-c. The reference speed is changed from 900 rpm to 1500 rpm and 300 rpm for the

performance of the compressor at rated load and at light load, respectively. 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 within the allowed limit (twice the rated current) due to the introduction of a rate limiter in the reference voltage.

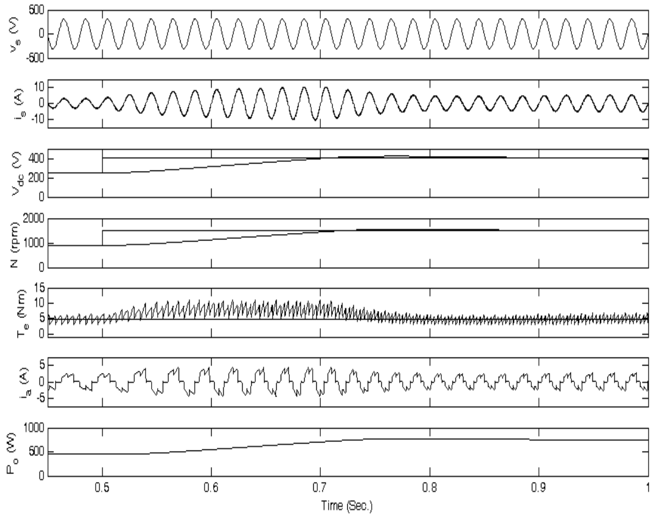

Fig. 3b Performance of the proposed drive under speed variation from 900 rpm to 1500 rpm.

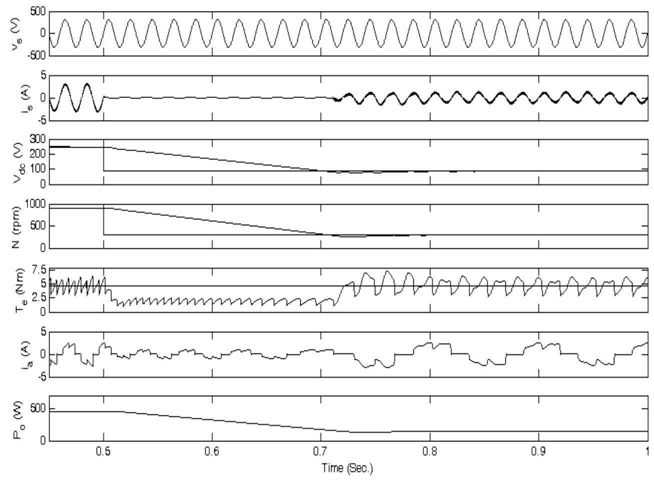

Fig. 3c Performance of the proposed drive under speed variation from 900 rpm to 300 rpm.

Fig. 3 Performance of the proposed drive under speed variation at 220 VAC input.

2) Steady State Condition: The performance of drive under steady state speed condition is obtained at different speeds as shown in Figs. 4-5 to demonstrate the effectiveness of the proposed drive in wide speed range. Figs.4a-b show different performance parameters at 300 rpm and 1500 rpm speeds. Fig. 5a 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 instantaneously. Fig. 5b shows the efficiency of the drive system (η_{drive}) which is above 85% in wide range of speed.

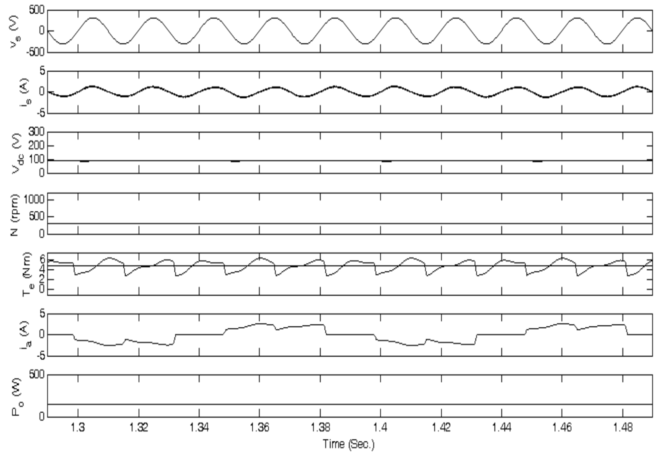

Fig. 4a Performance of the proposed drive at 300 rpm.

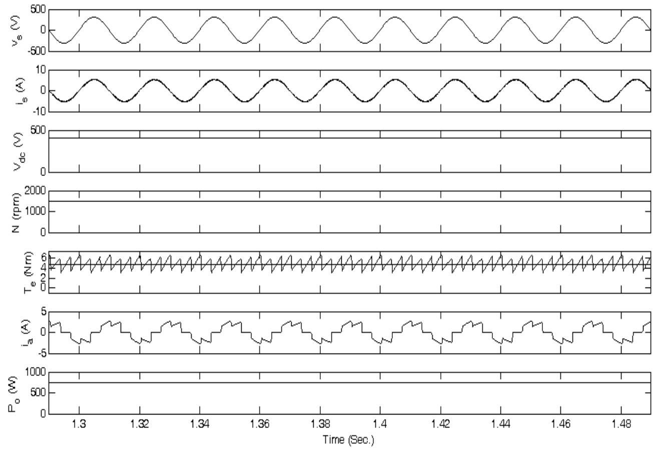

Fig. 4b Performance of the proposed drive at rated speed (1500 rpm).

Fig. 4 Performance of the proposed drive under steady state condition at 220 VAC input.

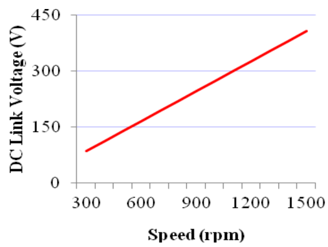

Fig. 5a DC link voltage with speed

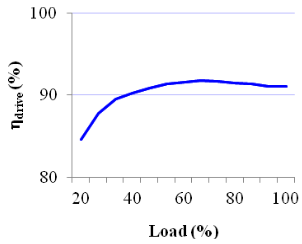

Fig. 5b Efficiency of drive with load

Fig. 5 Proposed drive under speed control at rated torque and 220 V AC input

C. Power Quality Performance of the PMBLDCM Drive

The performance of the proposed 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. 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 of AC mains current remains less than 5% along with nearly unity PF in wide range of speed and load as shown in Figs. 7a-b.

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. Figs. 8a-b show variation of 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 [5] with nearly unity PF in wide range of AC input voltage.

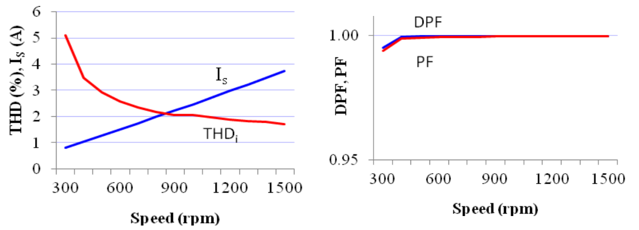

Fig.6a Variation of I_s and its THD Fig. 6b Variation of DPF and PF

Fig. 6 PQ indices of proposed drive under speed control at rated torque

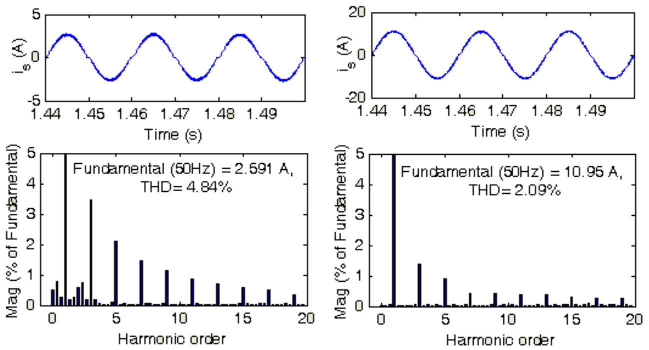

Fig.7a I_s and its THD at 300 rpm Fig. 7b I_s and its THD at 1500 rpm

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

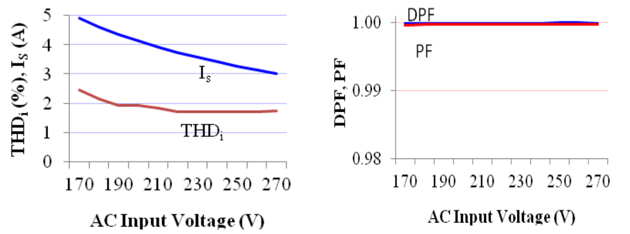

Fig.8a Variation of I_s and its THD Fig. 8b Variation of DPF and PF

Fig. 8 PQ indices with input AC voltage at a DC link voltage of 408 V (equivalent to 1500 rpm)

VI. CONCLUSION

A new speed control strategy of a PMBLDCM drive using the reference speed as an equivalent reference voltage at DC link has been validated for a compressor load of an air conditioner employing forward buck PFC converter. The speed of PMBLDCM has been found directly proportional to the voltage at DC link and a smooth speed control is observed with the DC link voltage. The rate limiter introduced in the reference voltage at DC link effectively limits the motor current within the desired value during the transient condition (starting and speed control). The PFC forward buck converter of the proposed drive has ensured nearly unity PF in wide range of the speed and the input AC voltage. Moreover, power quality parameters of the proposed drive are in conformity to the International standard IEC 61000-3-2 [5]. The proposed PMBLDCM drive has been found as a promising candidate for variable speed operation of a compressor load (i.e. constant torque load) in 100W-1 kW power range.

APPENDIX

Rated power: 0.75 kW, rated speed: 1500 rpm, rated current: 2.5 A, rated torque: 4.77 Nm, poles: 4, stator resistance (R): 1.78 Ω/ph., inductance (L+M): 18.59 mH/ph., back EMF constant (K_b): 1.23 Vsec/rad, Inertia (J): 0.0092 Kg-m^2. Source impedance (Z_s): 0.03 pu, Switching frequency of PFC switch (f_s): 40 kHz, input filter capacitor (C_f): 12nF, PI speed controller gains (K_p): 0.145, (K_i): 2.85.

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] *Limits for Harmonic Current Emissions (Equipment input current ≤16 A per phase)*, International Standard IEC 61000-3-2, 2000.

[6] 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.

[7] N. Mohan, T. M. Undeland and W. P. Robbins, "*Power Electronics: Converters, Applications and Design*," John Wiley and Sons Inc, USA, 1995.

[8] A. I. Pressman, *Switching Power Supply Design*, McGraw Hill, New York, 1998.

[9] D. M. Divan, G.Venkataramanan and C. Chen, "A unity power factor forward converter," in *Proc. IEEE IAS Ann. Meet.*, Oct. 1992, vol.1, pp.666 – 672.

[10] Y.W. Lo and R. J. King, "High performance ripple feedback for the buck unity-power-factor rectifier," *IEEE Trans. Power Electron.*, vol. 10, pp. 158-163, March 1995.

[11] A.A. Pereira, J.B. Vieira Jr., and L.C. de Freitas, "A lossless switching forward converter with unity power factor operation," in *Proc. IEEE IECON*, Nov. 1995, vol.1, pp. 329 – 334.

[12] M. Daniele, P. K. Jain and G. Joos, "A single-stage power-factor-corrected AC/DC converter," *IEEE Trans. Power Electron.*, vol. 14, pp. 1046 -1055, Nov 1999.

[13] K. Matsui, I. Yamamoto, S. Hirose, K. Ando and T. Kobayashi, "Utility-interactive photovoltaic power conditioning systems with forward converter for domestic applications," *IEE Proc.-Electric Power Appl.*, vol. 147, no. 3, pp. 199-205, May 2000.

[14] B. Singh, and G.D. Chaturvedi, "Analysis, design and development of single switch forward buck AC-DC converter for low power battery charging application," in *Proc. IEEE PEDES '06*, 2006, pp.6.

[15] F. Chimento, S. Musumeci, A. Raciti, L. Abbatelli, S. Buonomo, and R. Scollo, "A forward converter with a monolithic cascode device: Design and experimental investigation," in *Proc. EPE-PEMC'08*, Sept. 2008, pp.61 – 68.

[16] 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.