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Speed control of PMBLDCM drive using Power Factor Correction (PFC) Convertor

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***Abstract:** This paper aims at an improve speed quality employing buck half-bridge DC-DC converter is used as a single-stage power factor correction (PFC) converter for feeding a voltage source inverter (VSI) based permanent magnet brushless DC motor (PMBLDCM) driven air condition. This PFC converter is front end diode bridge rectifier (DBR) fed from single-phase AC mains and connected to a three phase voltage source (VSI) feeding the permanent magnet brushless DC motor (PMBLDCM). The PMBLDCM is used to drive a compressor load of an air conditioner through a three-phase VSI fed from a controlled DC link voltage. The speed of the compressor is controlled to achieve energy conservation using a concept of the voltage control at DC link proportional to the desired speed of the PMBLDCM. Therefore the VSI is operated only as an electronic commutator of the PMBLDCM. The stator current of the PMBLDCM during step change of reference speed is controlled by a rate limiter for the reference voltage at DC link. The proposed PMBLDCM drive with voltage control based PFC converter is designed, modeled and its performance is simulated in Matlab- Simulink environment for an air conditioner compressor driven PMBLDC motor.*

***Index Terms:** PFC, PMBLDCM, Air Conditioner, Buck Half Bridge Converter, Voltage Control, VSI.*

I. INTRODUCTION

Permanent Magnet Brushless Direct Current (PMBLDC) are preferred motors for a compressor of an air conditioning (Air-Con) system due to its features becoming prominent as the demand for efficiency, precise speed and torque control, reliability and ruggedness increases. Air conditioning systems are typically the largest consumers of electrical energy in homes and office buildings. The most common type of air conditioning that we see is technically referred to as direct expansion, mechanical, vapor-compression refrigeration system. As the PMBLDC machine has nonlinear model, the linear PI may no longer be suitable. This has resulted in the increased demand for modern nonlinear control structures like self-tuning controllers, state-feedback controllers, model reference adaptive systems and use of multi-variable control structure. Air conditioning systems are typically the largest consumers of electrical energy in homes and office buildings. In a fixed speed air conditioning system the compressor is cycled on and off to keep the temperature within a set band. For heavy load conditions the compressor operates at a high duty cycle and system efficiency is at its highest. However when the load is lighter, the compressor operates with a lower duty cycle with lower system efficiency.

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II. PROPOSED SPEED CONTROL OF PMBLDC MOTOR FOR AIR CONDITIONER USING PFC CONVERT CONVERTER

Figure 1 shows details diagram of the proposed speed control reference voltage at DC link as an equivalent reference speed, there by replaces the conventional control of the motor speed and a stator current involving various sensors for voltage and current signals. It has two control loops namely speed control loop and voltage control loop. Moreover, the rotor position signals are used to generate the switching sequence for the voltage source inverter as an electronic commutator (switching sequence generator) of the Permanent Magnet Brushless Direct Current (PMBLDC) motor. Therefore, rotor-position information is required only at the commutation points, e.g., every 60°electrical in the three phase [1-4]. The speed control loops begins with comparison of reference speed with speed signal derived from signals of Hall Effect position sensors mounted on the PMBLDCM. The DC link voltage is controlled by a half-bridge buck converter based on the duty ratio (D) of the converter. The PFC control scheme uses a current control loop inside the speed control loop with current multiplier approach which operates in continuous conduction mode (CCM) with average current control. The control loop begins with the comparison of sensed DC link voltage with a voltage equivalent to the reference speed. The resultant voltage error is passed through PFC converter such as a buck type were controlled so that its average per-cycle inductor current were controlled by a scaled input voltage , the resulting current would follow the voltage and the converter input would appear resistive. In other words, from a current loop driven by the input sine wave. Because the loop would require a bipolar range to accommodate a sinusoid, introduce a bridge rectifier at the input. Power factor corrections are given basis advantages of decreased power losses, reduced CO2 emissions and active climate protection.

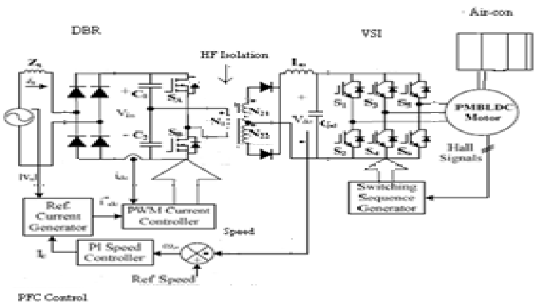

Figure 1: The Proposed Speed Control of PMBLDCM using PFC

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High switching frequency is used in a fast control of DC link voltage and effective PFC action along with additional advantages of reduced size magnetic and filters. The switching frequency is decided by such as the switching device, switching losses and operating power level. A metal oxide field effect transistor (MOSFET) is used as the switching device for the proposed PFC converter.

III. DESIGN OF PFC CONVERTER BASED PMBLDCM DRIVE

The proposed Single Stage PFC 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,

$$V_{dc} = 2\,(N_y/N_x)\,V_{in}\,D \qquad (1)$$

and

$$N_y = N_{yx} = N_{yy}$$

where N_x, N_{yx}, N_{yy} are number of turns in primary, secondary upper and lower windings of the high frequency (HF) isolation transformer, respectively. V_{in} is the average output of the DBR for a given AC input voltage (Vs) related as,

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

Switch mode DC-DC converters inherently produce ripple at the switching system and its harmonics. This unwanted signals , which appears at the both the input and the output, is undesirable for electromagnetic compatibilty. Filtering must generally be employed to reduce it to an acceptable level. A ripple filter is designed to reduce the ripples introduced in the output voltage due to high switching frequency for constant of the buck half-bridge converter. The inductance (Lo) of the ripple filter restricts the inductor peak to peak ripple current (ΔI_{Lo}) within specified value for the given switching frequency

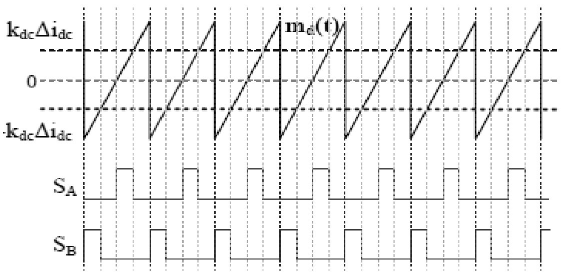

Figure 2: PWM control of the buck converter

(f_s), whereas, the capacitance (Cd) is calculated for a specified ripple in the output voltage (ΔV_{Cd}) [7-8]. The output filter inductor and capacitor are given as,

$$Lo = (0.5-D)V_{dc}/\{f_s(\Delta I_{Lo})\} \qquad (3)$$

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

The PFC converter is designed for a base DC link voltage of V_{dc} = 400 V at V_{in} = 198 V from Vs = 220 V_{rms}. The turns ratio of the high frequency transformer (N2/N1) is taken as 6:1 to maintain the desired DC link voltage at low input AC voltages typically at 170V. Other design data are f_s = 40 kHz, I_o = 4 A, ΔV_{Cd} = 4 V (1% of V_{dc}), ΔI_{Lo}= 0.8 A (20% of I_o). The design parameters are calculated as L_o=2.0 mH, C_d=1600 µF.

IV. MODELING OF THE PROPOSE PMBLDCM DRIVE

The main components of the proposed Speed Control of PMBLDCM drive are the PFC buck converter and voltage source inverter based PMBLDCM drive, which are modeled by mathematical equations and the complete drive is represented as a combination of these models.

a) PFC Buck Bridge 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 of the system. 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 Ve(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 controller output Ic(k) at kth instant is given as,

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

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

2) ***Reference Current Generator :*** The reference input current of the PFC 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 AC mains.

3) ***PWM Controller:*** The reference input current of the buck converter (i^*_{dc}) is compared with its sensed dc current (i_{dc}) to generate the current error Δi_{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 md(t) (as shown in Figure 2) in uni-polar switching mode [7] to get the switching signals for the MOSFETs of the PFC buck half-bridge converter as,

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

$$\text{If } k_{dc}\,\Delta i_{dc} > md\,(t) \text{ then SD} = 1 \text{ else SD} = 0 \qquad (10)$$

where SC, SD are upper and lower switches of the half-bridge converter as shown in Figure 1 and their values ‘1’ and ‘0’ represent ‘on’ and ‘off’ position of the respective MOSFET of the PFC converter.

b) PMBLDCM Drive

The PMBLDCM drive consists of an electronic commutator, a Voltage source inverter and a Permanent Magnet Brushless Direct Current (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. Although Hall sensing is quite common, many industrial applications use electronic commutation schemes with resolver.

2) ***Voltage Source Inverter:*** Voltage source inverters are used to regulate the speed of three-phase squirrel cage motors by changes the frequency and the voltage and consists of input rectifier, DC link and output converter. They are available for low voltage range and medium voltage range. Fig. 3 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,

$$V_{ao} = (V_{dc}/2) \text{ for S1} = 1 \qquad (11)$$

TABLE I

VSI switching sequence based on the Hall Effect Sensor signals

Ha	Hb	Hc	Ea	Eb	Ec	S1	S2	S3	S4	S5	S6
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

$$V_{ao} = (-V_{dc}/2) \text{ for S2} = 1 \qquad (12)$$

$$V_{ao} = 0 \text{ for S1} = 0, \text{ and S2} = 0 \qquad (13)$$

$$V_{an} = V_{ao} - V_{no} \qquad (14)$$

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 Figure 3. 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. S= 1 and 0 represent ‘on’ and ‘off’ position of respective IGBTs of the VSI and considered in a similar way for other IGBTs of the VSI i.e. S3- S6. Using similar logic V_{bo}, V_{co}, V_{bn}, V_{cn} are generated for other two phases of the VSI feeding PMBLDC motor.

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

$$V_{an} = R_{ia} + P\lambda_a + E_{an} \qquad (15)$$

$$V_{bn} = R_{ib} + P\lambda_b + E_{bn} \qquad (16)$$

$$V_{cn} = R_{ic} + P\lambda_c + E_{cn} \qquad (17)$$

where P is a differential operator (d/dt), i_a, i_b, i_c are three-phase currents, λ_a, λ_b, λ_c are flux linkages and E_{an}, E_{bn}, Ecn are phase to neutral back emfs of PMBLDCM, in respective phases, R is resistance of motor windings/phase.

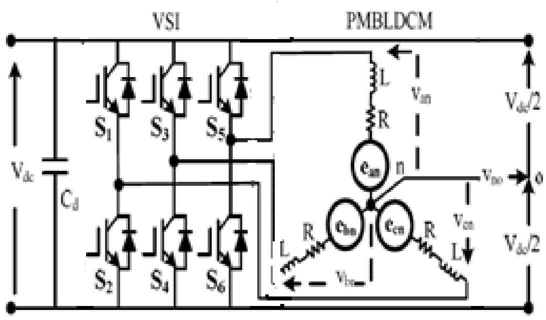

Figure 3: Equivalent Circuit of a VSI fed PMBLDCM Drive

The flux linkages are represented as,

$$\lambda_a = L_{ia} - M\,(i_b + i_c) \qquad (18)$$

$$\lambda_b = L_{ib} - M\,(i_a + i_c) \qquad (19)$$

$$\lambda_c = L_{ic} - M\,(i_b + i_a) \qquad (20)$$

where L is self-inductance/phase, M is mutual inductance of motor winding/phase. Since the PMBLDCM has no neutral connection, therefore,

$$i_a + i_b + ic = 0 \qquad (21)$$

From Eqs. (14-21) the voltage between neutral terminal (n) and mid-point of the DC link (o) is given as:

$$V_{no} = \{V_{ao} + V_{bo} + V_{co} - (E_{an} + E_{bn} + E_{cn})\}/3 \qquad (22)$$

From Eqs. (18-21), the flux linkages are given as:

$$\lambda_a = (L+M)\,i_a,\ \lambda_b = (L+M)\,i_b,\ \lambda_c = (L+M)\,i_c \qquad (23)$$

From Eqs. (15-17 and 23), the current derivative in generalized state space form is given as,

$$Pi_x = (V_{xn} - i_x R - E_{xn})/(L+M) \qquad (24)$$

where x represents phase a, b or c. The developed electromagnetic torque Te in the PMBLDCM is given as:

$$T_e = (E_{an}\,i_a + E_{bn}\,i_b + E_{cn}\,i_c)/\,\omega \qquad (25)$$

where ω is motor speed in rad/sec.The back emfs may be expressed as a function of rotor position (θ) as:

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$$E_{xn}= K_b\, fx(\theta)\, \omega \quad (26)$$

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

$$fa(\theta) = 1 \text{ for } 0 < \theta < 2\pi/3 \quad (27)$$

$$fa(\theta) = \{(6/ \pi)(\pi- \theta)\}-1 \text{ for } 2\pi/3 < \theta < \pi \quad (28)$$

$$fa(\theta) = -1 \text{ for } \pi < \theta < 5\pi/3 \quad (29)$$

$$fa(\theta) = \{(6/\pi)(\theta -2\pi)\}+1 \text{ for } 5\pi/3 < \theta < 2\pi \quad (30)$$

The functions $fb(\theta)$ and $fc(\theta)$ are similar to $fa(\theta)$ with a phase difference of 120º and 240º respectively. Therefore, the electromagnetic torque is expressed as,

$$T_e = K_b\{fa(\theta)\, i_a + fb(\theta)\, i_b+ fc(\theta)\, i_c\} \quad (31)$$

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

$$P\omega= (p/2)\, (T_e-T_L-B\omega)/(J) \quad (32)$$

The derivative of the rotor position angle is given as:

$$P\, \theta = \omega \quad (33)$$

where p is no. 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 (15-33) represent the dynamic model of the PMBLDC motor.

V.PERFORMANCE EVALUATION OF PROPOSED PFC DRIVE

The proposed Speed Control of PMBLDCM drive is modeled in Matlab-Simulink environment and evaluated for an air conditioning compressor load. The compressor load is considered as a constant torque load equal to rated torque with the speed control required by air conditioning system. A 1.5 kW rating PMBLDCM is used to drive the air conditioner compressor, 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 Speed control of PMBLDCM using PFC drive is evaluated on the basis of various parameters such as total harmonic distortion (THDi) and the Crest Factor (CF) of the current at input AC mains, Displacement Power Factor (DPF), Power Factor (PF) and efficiency of the drive system (η_{driv}) at different speeds of the motor. The results are shown in Figures 4 and 5 to demonstrate the effectiveness of the proposed PMBLDCM drive in a wide range of speed and input AC voltage. The PFC half-bridge buck converter maintains good power factor during the starting period by keeping the input AC mains current waveform in phase with the supply voltage.

a) Performance during Starting

To evaluate the performance of the proposed PMBLDCM drive fed to 220 V AC mains during starting at rated torque and 900 rpm speed as shown in Figure 4a. 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 (i_s) waveform at input AC mains is in phase with the supply voltage (v_s) demonstrating nearly unity power factor during the starting.

b) Performance under Speed Control

Figure 4 and 5 shows the performance of the proposed PMBLDCM drive under the speed control at constant rated torque (9.55 Nm) and 220 V AC mains supply voltage. These results are categorized as performance during transient and steady state conditions.

1) ***Transient Condition:*** In the proposed PMBLDCM drive, the speed control of the compressor is shown in Figure 4b and 4c. The 1979 reference speed is changed from 900 rpm to 1500 rpm for the rated load performance of the compressor; from 900 rpm to 300 rpm for performance of the compressor at light load. It is observed that the speed control is fast and smooth in either direction i.e. acceleration or retardation with power factor maintained at nearly unity value.

2) ***Steady State Condition:*** The speed control of the PMBLDCM driven compressor under steady state condition is carried out for different speeds and the results are shown in Figure 5 and 6. Table-II demonstrates the effectiveness of the proposed drive in wide speed range. Figure5a to 5c shows 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), and shaft power output (P_o) at 300 rpm, 900 rpm and 1500 rpm speeds.

c) Power Quality Performance

The performance of the proposed PMBLDCM drive in terms of various PQ parameters such as THDi, CF, DPF, PF. Nearly unity power factor (PF) and reduced THD of AC mains current are observed 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 as well as load.

d) ***Performance under Variable Input AC Voltage***

Performance evaluation of the proposed PMBLDCM drive is carried out under varying input AC voltage at rated load (i.e. rated torque and rated speed) to demonstrate the operation of proposed PMBLDCM drive for air conditioning system in various practical situations as summarized. The THD of current at AC mains is within specified limits of international norms [5] along with nearly unity power factor in wide range of AC input voltage.

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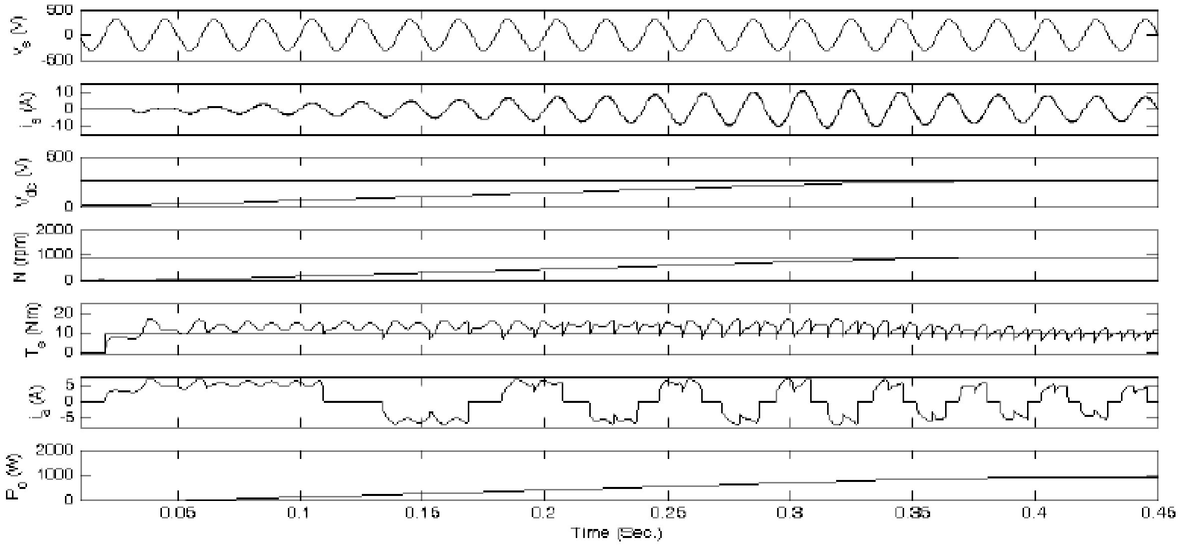
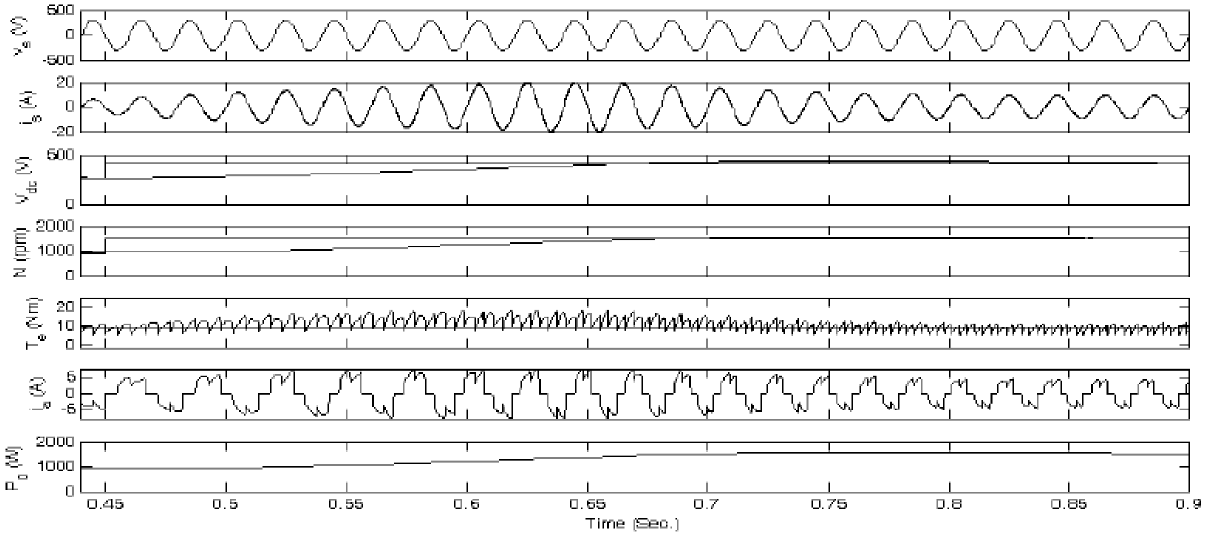


(4a) Starting performance of the PMBLDCM drive at 900 rpm



(4b) PMBLDCM drive under speed variation from 900 rpm to 1500 rpm

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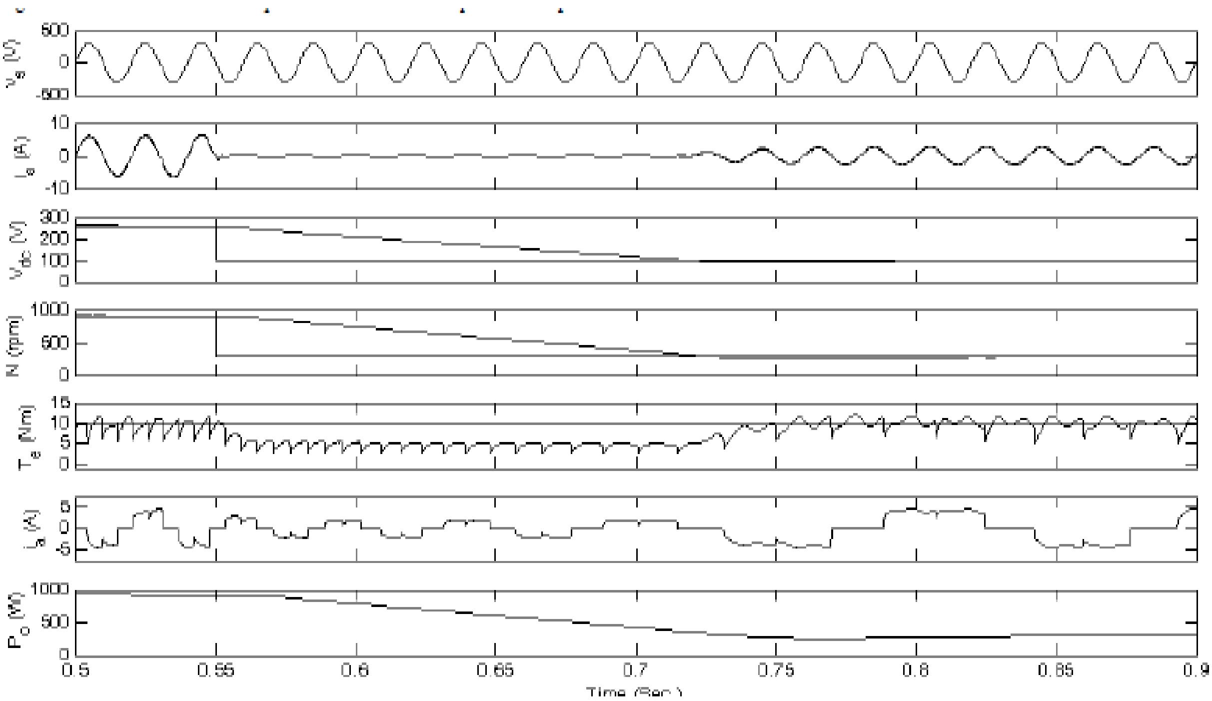
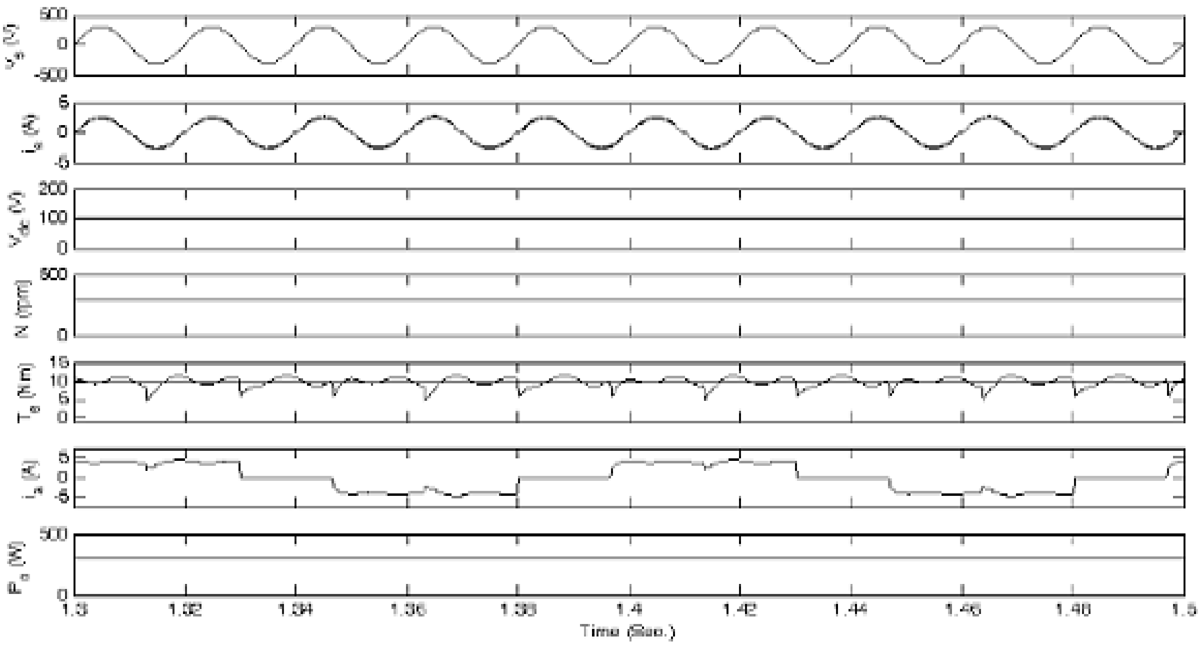


(4c) PMBLDCM drive under speed variation from 900 rpm to 300 rpm

Figure 4: Performance of the Proposed PMBLDCM drive under speed variation at 220 VAC input



(5a) Performance of PMBLDCM drive at 300rpm

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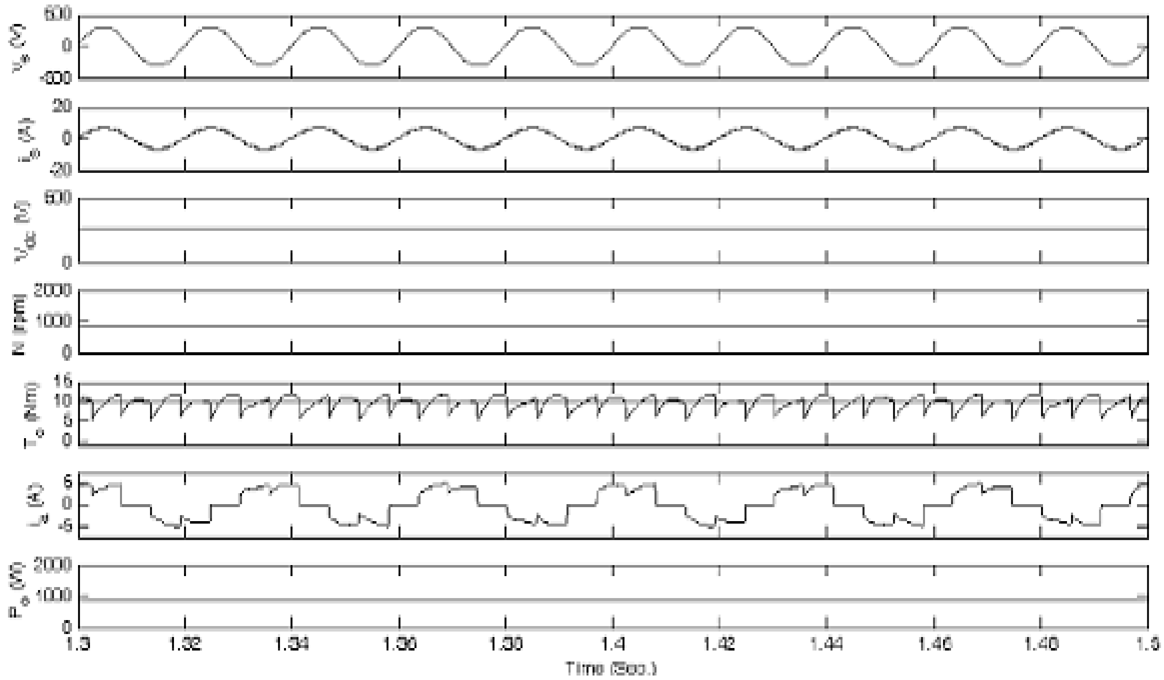
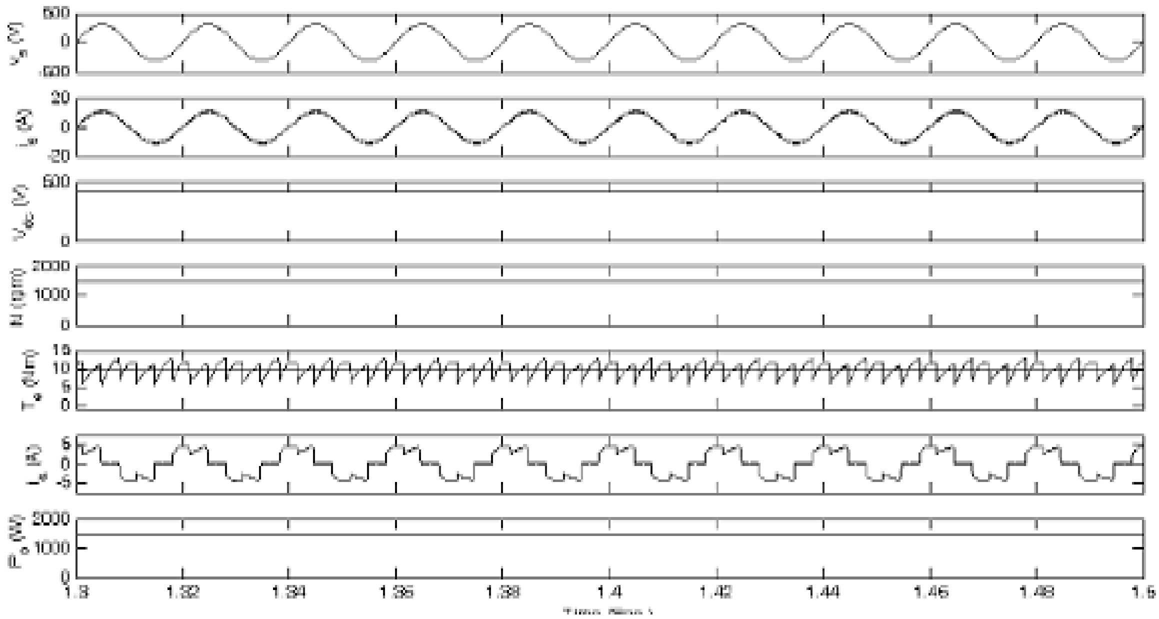


(5b) Performance of PMBLDCM drive at 900rpm



(5c) Performance of PMBLDCM drive at rated speed (1500rpm)

Figure 5: Performance of the PMBLDCM drive under steady state condition at 220 V AC input.

VI. CONCLUSION

A PFC half-bridge buck converter based new speed control strategy of a PMBLDCM drive is validated for a compressor load of an air conditioner which uses the reference speed as an equivalent reference voltage at DC link. The speed control is directly proportional to the voltage control at DC link. 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 additional PFC feature to the proposed drive ensures nearly unity PF in wide range of speed, decreased power losses, reduced CO2 emissions, active climate protection and input AC voltage.

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The proposed drive has good speed control with energy efficient operation of the drive system in the wide range of speed and input AC voltage. The proposed drive has been found as a promising candidate for a PMBLDCM driving Air-Con load in 1-2 kW power range.

APPENDIX

Rated Power: 1.5 kW, rated speed: 1500 rpm, rated current: 4.0 A, rated torque: 9.55 Nm, number of poles: 4, stator resistance (R): 2.8 Ω/ph., inductance (L+M): 5.21 mH/ph., back EMF constant (K_b): 0.615 Vsec/rad, inertia (J): 0.013 Kg-m2. Source impedance (Z_s): 0.03 pu, switching frequency of PFC switch (f_s) = 40 kHz, capacitors (C1= C2): 15nF, PI speed controller gains (K_p): 0.145, (K_i): 1.45.

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BIOGRAPHIES

Padmini Sahu was born in Rajim, India, in 1986. She received the B.E. (Electronics & Telecommunication) degree from P.T.R.S. University, Raipur, India, in 2008 and pursuing M.E. from CSVTU, Bhilai, India.
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Anurag Singh Tomer received the B.E. and M.E. in Electrical Engineering and pursuing his Phd. He is working in the Department of Electrical Engineering, Rungta College of Engineering & Technology Bhilai, as an Associate Professor. He has presented 6 papers in different fields, attended 20 workshops/seminars/conferences and published 1 international journal.

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