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Performance and Analysis of PMBLDCM Drive using A Single-Stage PFC Half-Bridge Converter

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Abstract - Because of their excellent torque-to-weight ratio, small size, and great efficiency, Permanent Magnet Brushless DC Motors are widely used in a variety of applications. A buck half-bridge DC-DC converter acts as a single-stage PFC for a VSI-driven PMBLDCM powering an air conditioner's compressor. The PFC converter is fed from a single-phase AC main via a diode bridge rectifier. The VSI controls the PMBLDCM speed by adjusting the DC link voltage proportionally. The VSI functions solely as a commutator for the PMBLDCM, with stator current controlled by a rate limiter for speed changes. The PMBLDCM drive, incorporating a voltage-controlled PFC converter, is constructed, modeled, and simulated using the MATLAB-Simulink platform for an air conditioner compressor application. The system utilizes a 1.5 kW, 1500 rpm PMBLDC motor. Evaluation outcomes of the speed control strategy exhibit enhanced efficiency across a broad speed spectrum, showcasing the benefits of the drive system's integrated PFC functionality.

Key Words: permanent magnet brushless DC motor, power factor correction converter, electrical drives.

1. INTRODUCTION

Efforts to regulate the speed of Permanent Magnet Brushless DC Motors (PMBLDCM) have spurred exploration into advanced technologies like the Single-Stage Power Factor Correction (PFC) Half-Bridge Converter. This converter, a notable advancement in power electronics, offers a more streamlined method for controlling speed in PMBLDCM drives. Integration of the Single-Stage PFC Half-Bridge Converter into PMBLDCM systems is geared toward enhancing performance and ensuring efficient energy usage. This introduction marks the outset of an extensive examination into the complexities of speed control mechanisms within PMBLDCM drives. Throughout this inquiry, we delve into the operational principles of PMBLDCMs, exploring their inherent benefits and applications across diverse industries [1 – 2]. The Single-Stage PFC Half-Bridge Converter emerges as a key element, enabling not only speed regulation but also improving power factor correction within the system. Through a combination of theoretical understandings and practical applications, this study aims to clarify the nuances of speed control in PMBLDCM drives, highlighting the transformative potential of the Single-Stage PFC Half-Bridge Converter in contemporary motor drive systems.

The PMBLDCM drive, powered by single-phase AC mains via a diode bridge rectifier and a DC link capacitor, encounters power quality (PQ) issues such as inadequate power factor (PF) and elevated total harmonic distortion (THD) of current in the input AC mains. This arises primarily from the unregulated charging of the DC link capacitor, leading to a pulsed current waveform with a peak value surpassing the amplitude of the fundamental input current from the AC mains. The input current's total harmonic distortion measures 20.91%, with a fundamental current of 8.791 A and a power factor of 0.9. Meeting PQ standards for low-power equipment, such as IEC 61000-3-2, underscores the importance of minimal harmonic content and close-to-unity power factor current draw from AC mains for these motors. Consequently, employing a power factor correction (PFC) topology becomes almost necessary for a PMBLDCM drive, given the array of available options. A half-bridge buck DC-DC converter is chosen for the proposed voltage-controlled drive due to its higher power handling capacity than single switch converters. Because only one switch is ever in use, it also has switching losses that are comparable to single switch converters. In addition to adjusting the voltage at the DC link to match the required speed of the Air-Con compressor, it can function as a single-stage power factor corrected (PFC) converter when connected between the VSI and the DBR fed from single-phase AC mains.

2. Modeling of PMBLDC Motor

Modeling a Permanent Magnet Brushless DC (PMBLDC) motor entails developing mathematical equations or simulations that depict its electrical, magnetic, and mechanical characteristics. Below is a basic overview of this procedure [3 - 4] .

$$V_{an} = V_{ao} - V_{no} \quad (1)$$
$$V_{an} = Ri_a + p\lambda_a + e_{an} \quad (2)$$
$$V_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (3)$$
$$V_{cn} = Ri_c + p\lambda_c + e_{cn} \quad (4)$$

where: p denotes differential operator, i_a, i_b, i_c represents three-phase currents, λ_a, λ_b, λ_c represents flux linkages and phase to neutral back emf`s of PMBLDCM are represented as e_{an}, e_{bn}, e_{cn}, resistance of motor windings/phase is represented as R. The flux linkages are represented as,

$$\lambda_a = L_{ia} - M\,(i_b + i_c) \quad (5)$$
$$\lambda_b = L_{ib} - M\,(i_a + i_c) \quad (6)$$
$$\lambda_c = L_{ic} - M\,(i_b + i_a) \quad (7)$$

The flux linkages are given as:

$$\lambda_a = (L+M)\, i_a \quad (8)$$
$$\lambda_b = (L+M)\, i_b \quad (9)$$
$$\lambda_c = (L+M)\, i_c \quad (10)$$

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

$$T_e = (e_{an} i_a + e_b n_{ib} + e_c n_{ic})/\omega \quad (11)$$

where: L is self-inductance/phase, M is mutual inductance of motor winding/phase.

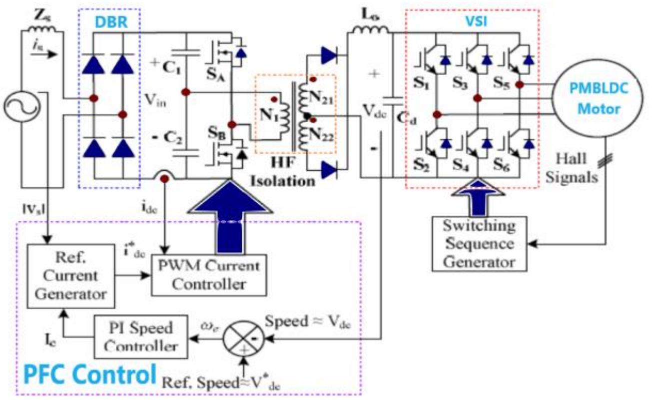

Fig -1: The control schematic for the proposed PMBLDCM drive-fed Bridge-buck PFC converter

Table - 1: 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

The suggested speed control technique, seen in Fig. 1, substitutes the traditional method of controlling the motor speed and stator current, which involved a number of sensors for voltage and current signals. Instead, reference voltage at the DC link is controlled as an equivalent reference speed. Additionally, the VSI, which functions as the PMBLDC motor's electronic commutator, generates its switching sequence using the rotor position signals. As a result, only at the commutation points—that is, every 60°electrical in the three-phase—is rotor position information needed [1-4]. As indicated in Table 1, the rotor position of the PMBLDCM is detected by Hall Effect position sensors, which are then used to create the switching sequence for the VSI.

3. Simulation Performance of PMBLDC Motor

Through an isolation transformer, the voltage source inverter receives the output of the buck converter. Because they run at a lower frequency than PFC switches, insulated gate bipolar transistors (IGBTs) are employed in VSI Bridge feeding PMBLDCM to lessen switching stress. The high frequency and low frequency sides are separated by a high frequency isolation transformer. With a current multiplier method, the PFC control scheme [5 - 8] employs a current control loop inside the speed control loop that runs in continuous conduction mode (CCM) with average current control. The measured DC link voltage is compared to a voltage equal to the reference speed to initiate the control loop. The modulating current signal is obtained by passing the voltage error that results via a proportional-integral (PI) controller. This signal is multiplied by the input AC voltage unit template and compared to the DC current detected following the DBR.

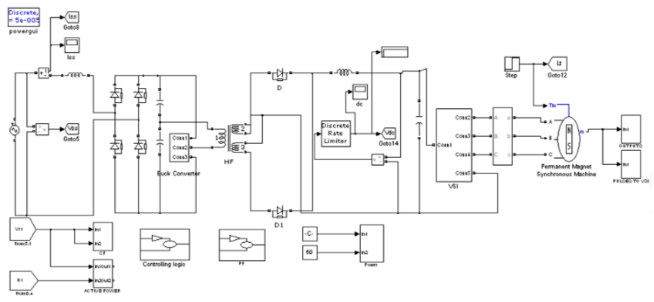

Fig -2: Model of the Bridge-buck PFC converter fed PMBLDCM drive

Figs. 5.7 to 5.12 illustrate the performance of the proposed PMBLDCM drive fed by 220 V AC mains while beginning at rated torque, or 9.55 N-m and 900 rpm speed. Figures 5.7 to 5.12 display the supply voltage (Vin), supply current (Is), rotor speed (N), armature current in phase "a" (Ia), and output power (Po) waveforms as a function of time. To control the starting current of the motor and the DC link capacitor's charging current, a rate limiter of 800 V/s is added to the reference voltage.

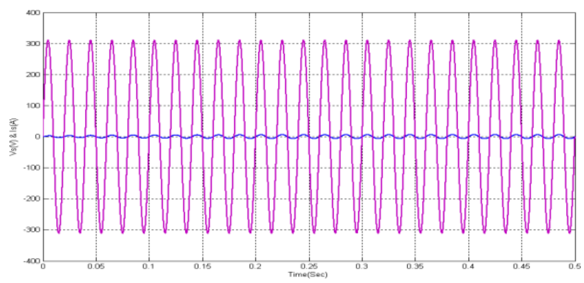

Fig -3: Waveform of input voltage and input current when the motor runs at 900 rpm speed and rated torque

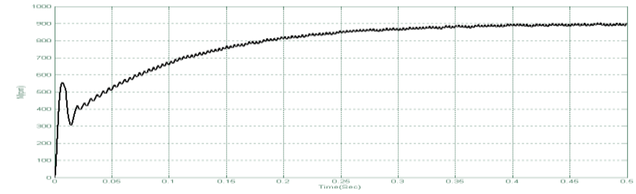

Fig -4: Waveform of rotor speed when the motor runs at 900 rpm speed and rated torque

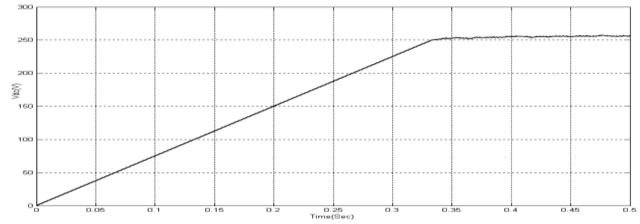

Fig -5: Waveform of DC link voltage when the motor runs at 900 rpm speed and rated torque

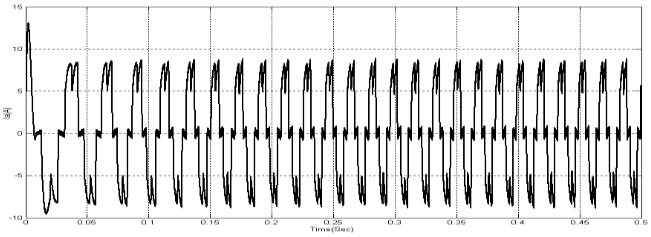

Fig -6: Waveform of armature current when the motor runs at 900 rpm speed and rated torque

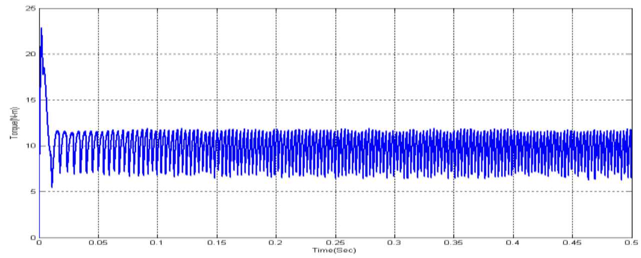

Fig -7: Waveform of electromagnetic torque when the motor runs at 900 rpm speed and rated torque

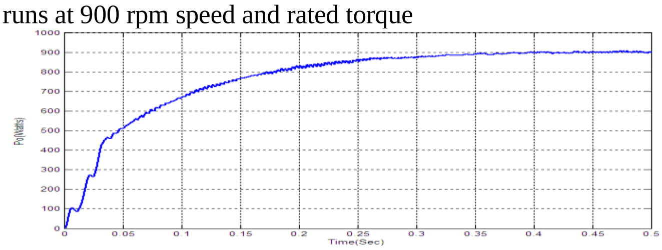

Fig -8: Waveform of output power when the motor runs at 900 rpm speed and rated torque

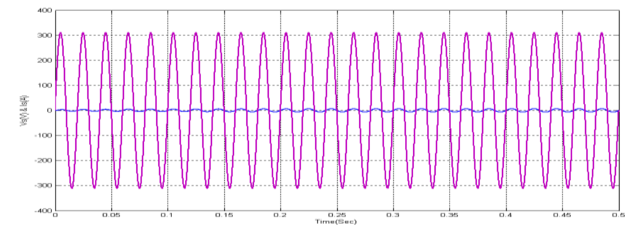

Fig -9: Waveform of input voltage and input current when the reference speed is changed from 900 rpm to 1500 rpm

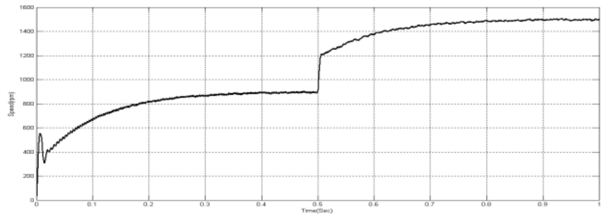

Fig -10: Waveform of rotor speed when the reference speed is changed from 900 rpm to 1500 rpm

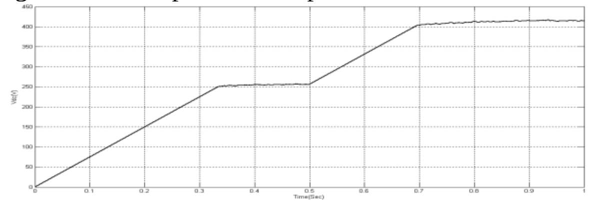

Fig -11: Waveform of DC link voltage when the reference speed is changed from 900 rpm to 1500 rpm

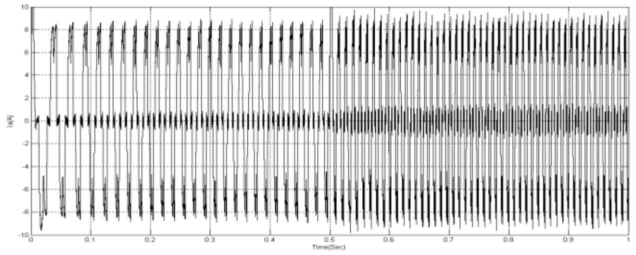

Fig -12: Waveform of armature current when the reference speed is changed from 900 rpm to 1500 rpm

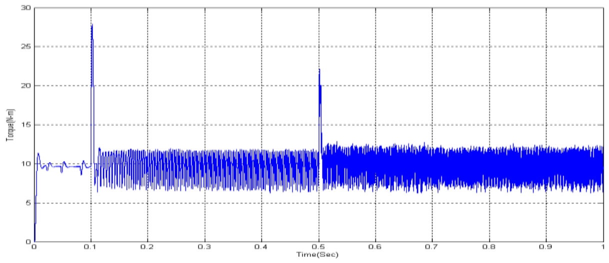

Fig -13: Waveform of electromagnetic torque of rotor when the reference speed is changed from 900 rpm to 1500 rpm

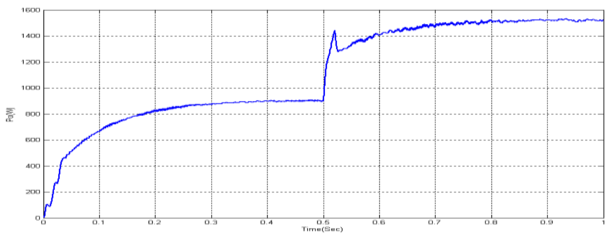

Fig -14: Waveform of output power when the reference speed is changed from 900 rpm to 1500 rpm

It is noted that the power factor is kept at almost unity while the speed control is quick and seamless in both directions, i.e., acceleration or retardation. Furthermore, because a rate limiter was added to the reference voltage, the stator current of the PMBLDCM is now twice the rated current, within the permitted limit.

Steady State Condition:

The speed control of the PMBLDCM driven compressor under steady state condition is carried out for different speeds at rated voltage 230 Vrms, at 9.55 N-m rated torque and the results are shown as a function of time 't' from Fig. 5.25 to Fig. 5.42. These figures show waveforms input voltage (Vin), input current (Is), DC link voltage, speed of the motor (N), and the stator current of the PMBLDC motor for phase 'a' (Ia), output power (Po).

The reference speed is set at 900 rpm. The motor is run for steady state. The waveforms of DC link voltage (Vdc), speed of the motor (N), and the stator current of the PMBLDC motor for phase 'a' (Ia), is shown in Fig. 5.25 to Fig. 5.30. The waveforms are taken after reaching steady state i.e., after 1 sec.

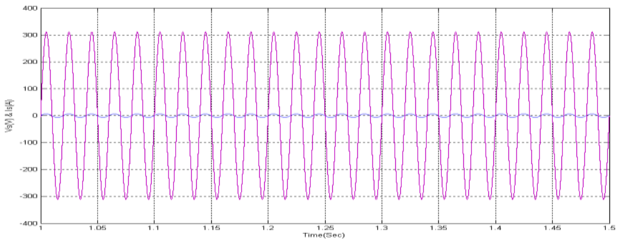

Fig -15: Steady state waveform of input voltage and input current when the reference speed is set at 900 rpm

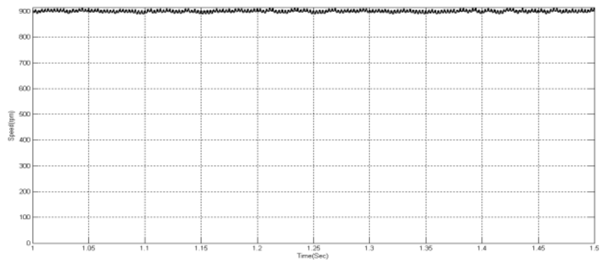

Fig -16: Steady state waveform of rotor speed when the reference speed is set at 900 rpm

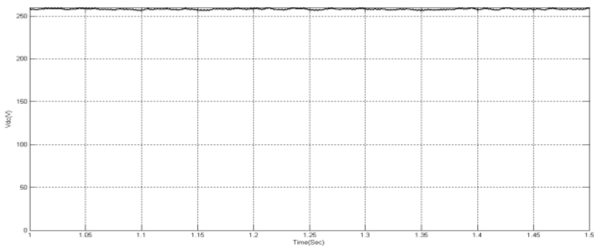

Fig -17: Steady state waveform of DC link voltage when the reference speed is set at 900 rpm

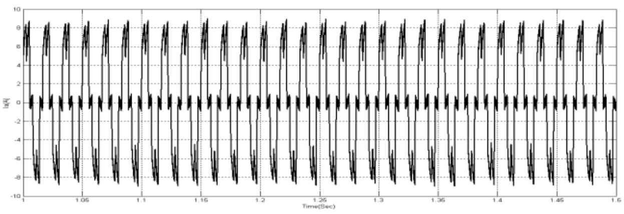

Fig -18: Steady state waveform of armature current when the reference speed is set at 900 rpm

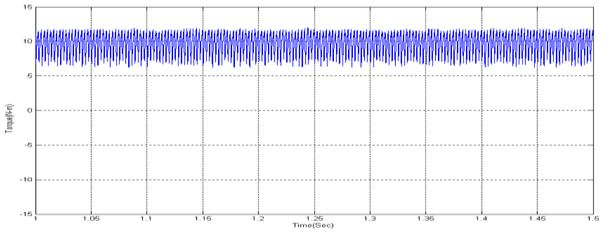

Fig -19: Steady state waveform of electromagnetic torque of rotor when the reference speed is set at 900 rpm

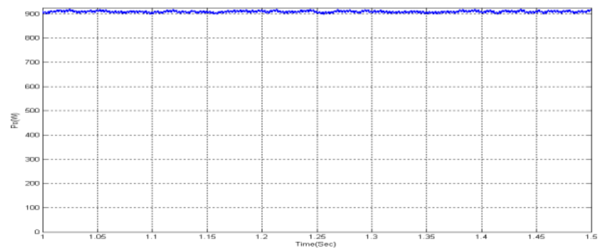

Fig -20: Steady state waveform of output power when the reference speed is set at 900 rpm

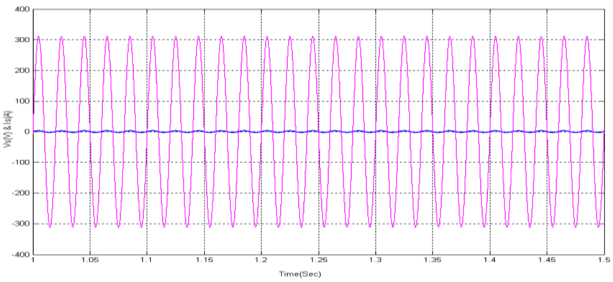

Fig -21: Steady state waveform of input voltage and input current when the reference speed is set at 300 rpm

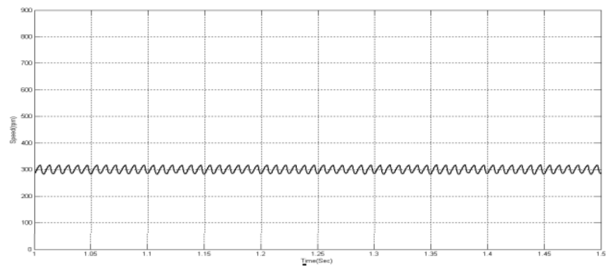

Fig -22: Steady state waveform of rotor speed when the reference speed is set at 300 rpm

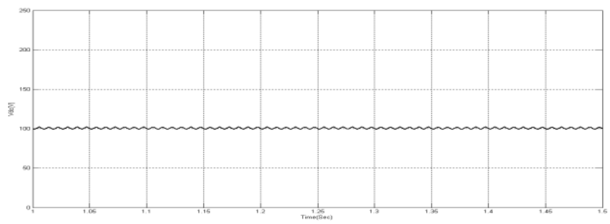

Fig -23: Steady state waveform of DC link voltage when the reference speed is set at 300 rpm

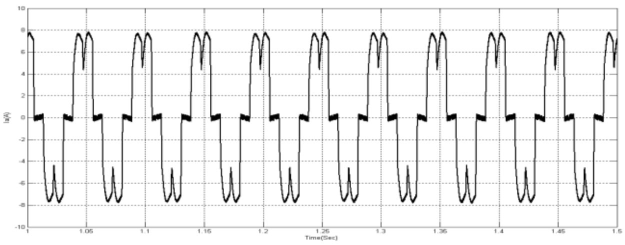

Fig.

Fig -24: Steady state waveform of armature current when the reference speed is set at 30rpm

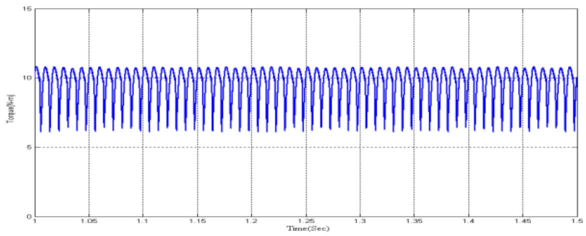

Fig -25: Steady state waveform of electromagnetic torque of rotor when the reference speed is set at 300 rpm

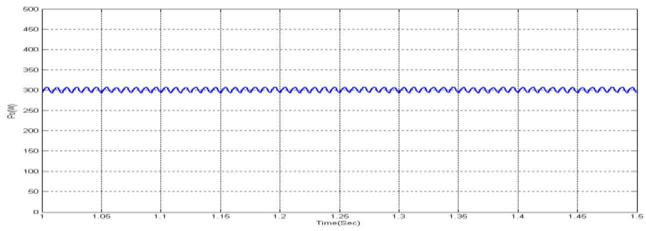

Fig -26: Steady state waveform of output power when the reference speed is set at 300 rpm

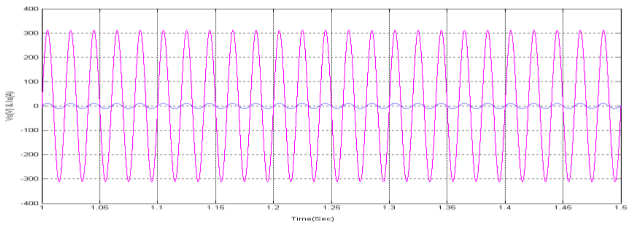

Fig -27: Steady state waveform of input voltage and input current when the reference speed is set at 1500 rpm

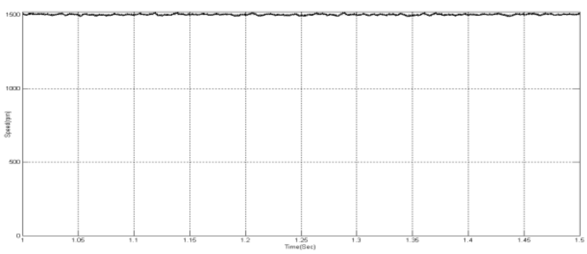

Fig -28: Steady state waveform of rotor speed when the reference speed is set at 1500 rpm

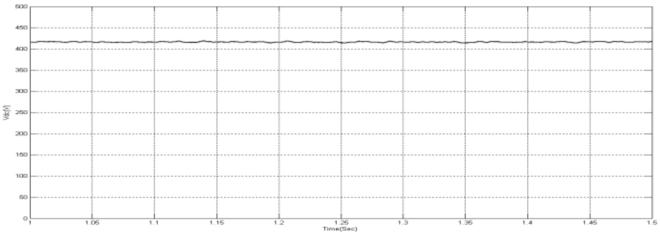

Fig -29: Steady state waveform of DC link voltage when the reference speed is set at 1500 rpm

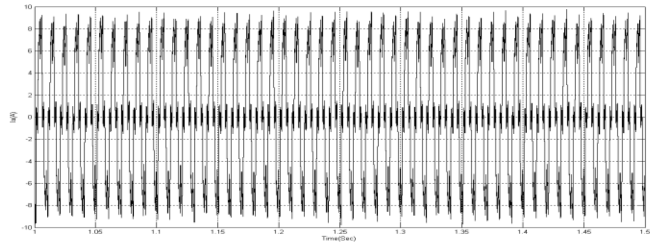

Fig -30: Steady state waveform of armature current when the reference speed is set at 1500 rpm

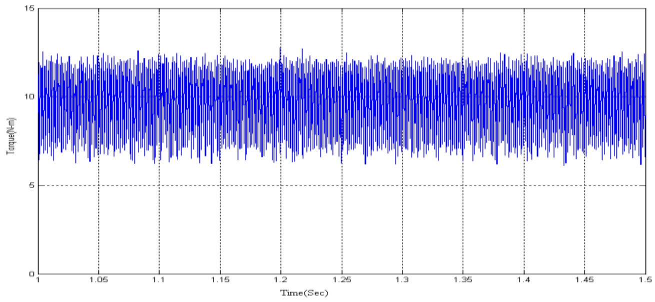

Fig -31: Steady state waveform of electromagnetic torque of rotor when the reference speed is set at 1500 rpm

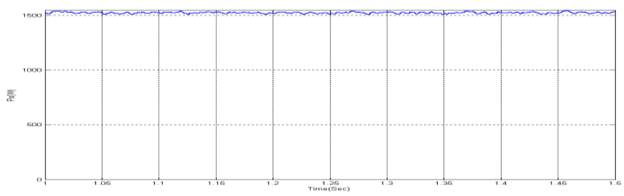

Fig -32: Steady state waveform of output power when the reference speed is set at 1500 rpm

4. Comparison of the drive performance with PFC and without PFC technique

Comparison can be done by calculating the THD and PF at different speeds in the steps of 100 rpm and it is done for BLDC motor with PFC control technique and without PFC control technique. Comparison is shown in the table 5.2. From the table it can be concluded that the THD of input current is decreased about 20% and PF is improved to almost unity when BLDC motor is applied with PFC control technique.

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Table -1: Comparison of the performance of the drive without PFC and with PFC control technique

Speed (rpm)	THD_i% with PFC	THD_i% without PFC	PF with PFC	PF without PFC
300	4.82	26.37	0.9987	0.8377
400	3.96	25.27	0.9994	0.824
500	2.64	24.80	0.9996	0.8716
600	2.89	23.67	0.9997	0.8652
700	2.63	22.73	0.9998	0.8719
800	2.43	22.27	0.9998	0.8839
900	2.24	22.09	0.998	0.8819
1000	2.22	26.93	0.999	0.8841
1100	2.13	21.22	0.9998	0.8911
1200	2.03	20.68	0.9999	0.8947
1300	2.05	21.09	0.9999	0.8967
1400	2.06	20.84	0.9999	0.9024
1500	2.10	20.91	0.9999	0.921

From Table 1 it is found that THD and PF are within the specified limits of international standards [8].

5. CONCLUSIONS

A unique PMBLDCM drive speed control method for the compressor load of an air conditioner is validated by using the reference speed as an equivalent reference voltage at the DC link. The voltage control and speed control are precisely proportional at the DC link. The rate limiter that was added to the reference voltage at the DC connection (starting and speed control) successfully limits the motor current during the transient state within the required value. The additional PFC function of the recommended drive ensures almost unity PF over a wide speed range. Moreover, the power quality requirements of the proposed PMBLDCM drive meet the requirements of the international standard IEC 61000-3-2. It has been demonstrated that the recommended drive's energy-saving drive technology and efficient speed control.

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