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### Power Quality Improvement in PMBLDCM Drive using PFC SEPIC Converter for Air Conditioner

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#### Abstract

In this paper, an improved power quality converter employing Single Ended Primary Inductor (SEPIC) converter topology is used to feed a permanent magnet brushless DC motor (PMBLDCM) drive. Normally, the PMBLDCM drive has a three-phase voltage source inverter (VSI) and a PMBLDCM which is fed from single-phase AC mains through a diode bridge rectifier (DBR). In this proposed system a SEPIC DC-DC converter is used after the DBR and it performs power factor correction (PFC) at input AC mains and voltage control at DC link, in a single-stage. The proposed PMBLDCM drive is designed, modeled and its performance is evaluated in Matlab-Simulink environment for an air conditioner (Air-Con) load. The speed of the compressor is controlled for efficient operation of the Air-Con which results in controlling the temperature in the conditioned area at the set point, effectively. Obtained results are presented to demonstrate an improved power quality of PFC converter based PMBLDCM drive in wide range of the speed and input AC voltage besides improved efficiency of an Air-Con system.

**Keywords:** PFC, PMBLDCM, Air conditioner, Speed control, Voltage control, SEPIC Converter

#### Introduction

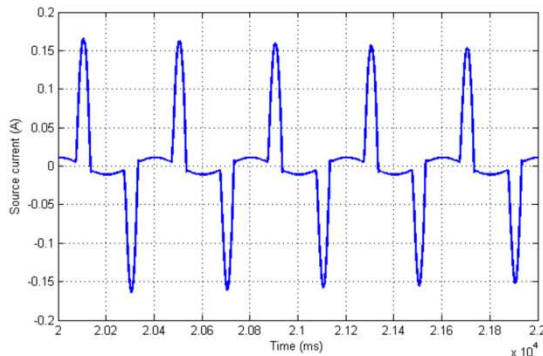
An air-conditioner (Air-Con) is considered as an energy intensive application which consumes around 60% of total energy demand in domestic and commercial sector. The compressor of an Air-Con is the main part of it driven by a single phase induction motor having efficiency in the range of 75-80% at rated load. The single phase induction motor is operated in 'On-Off' mode for temperature control of the conditioned area in a hysteresis band. Moreover, the frequent start-stop of the motor leads to noisy operation, more wear and tear of the motor. Therefore, there is a need of energy efficient motor for Air-Con compressor to cope up rising energy demand and its cost.

A permanent magnet brushless DC motor (PMBLDCM) possesses many advantages such as high efficiency, silent operation, 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 requires a three-phase voltage source inverter (VSI) to be operated as an electronic commutator based on the rotor position signals of the PMBLDCM obtained using Hall effect Sensors. It is employed for Air-Con compressor and operated under speed control, resulting in an improved efficiency of the system. Therefore the Air-

Con system with PMBLDCM has low running cost, long life and reduced mechanical and electrical stresses. The three-phase VSI of the PMBLDCM drive is fed from single-phase AC mains through a diode bridge rectifier (DBR) followed by a smoothing DC capacitor. It draws an uncontrolled charging current for the DC capacitor resulting in a pulsed current as shown in Fig.1. So, many power quality (PQ) problems arise such as poor power factor (PF), increased total harmonic distortion (THD) of AC mains current and its high crest factor (CF).

Moreover, there are many international PQ standards such as IEC 61000-3-2 [5], IEEE 519 etc. which emphasize on low harmonic contents and near unity PF current to be drawn from AC mains by various loads. Therefore, an improved PQ converter based drive is almost essential for the PMBLDCM. There has been some efforts [7-9] for use of power factor correction (PFC) converters for the PQ improvement, however it uses, a two-stage PFC drives which consist of a boost converter for PFC at front-end followed by another DC – DC converter in second stage for voltage regulation. At second stage usually a flyback or a forward converter has been used for low power application and a full-bridge converter for higher power applications [7-9]. However,

the high cost and complexity in implementing two separate switch-mode converters are the constraints of the two stage PFC converters which encourage use of a single stage PFC converter in many applications.

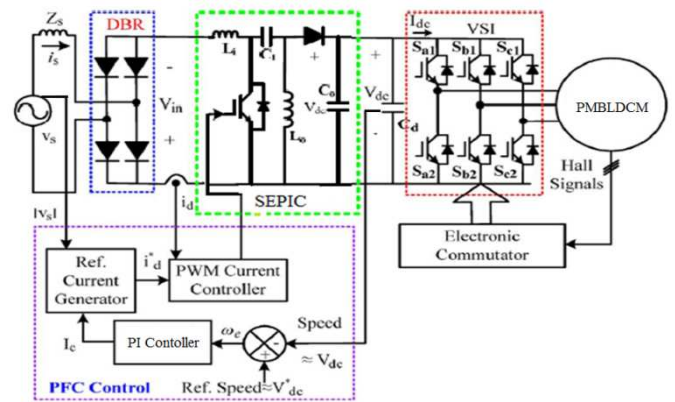


**Fig.1 Current waveform at ac mains for the PMBLDCM drive without PFC.**

A single ended primary inductor converter (SEPIC), as a single stage PFC converter, inherits merits of continuous input current, ripple current reduction [16-17]. Therefore, a SEPIC converter is proposed for PFC in a PMBLDCM drive used to drive Air-Cons. This paper, deals with detailed design and exhaustive performance evaluation of the SEPIC converter as a PFC converter, for PMBLDCM driven air conditioner system.

**Proposed Control Scheme for PFC Converter**

A SEPIC as a PFC converter, inherits merits of continuous input current, ripple current reduction. Therefore, a SEPIC converter is proposed for PFC in a PMBLDCM drive used to drive Air-Cons. Fig.2 shows the proposed SEPIC based PFC converter fed PMBLDCM drive for the speed control as well as PFC in wide range of input AC voltage. A proportional integral (PI) controller [4] is used for the speed control of the PMBLDCM driving constant torque compressor of Air-Con. The speed signals obtained from the rotor position of PMBLDCM (sensed using Hall effect sensors) are compared with the reference speed. The resultant speed error is fed to a speed controller to give the torque which is converted to current signal. This signal is multiplied with a rectangular unit template in phase with top flat portion of motor's back EMF to get reference currents of the motor. These reference motor currents are compared with sensed motor currents to give current error. These current errors are amplified and compared with triangular carrier wave to generate the PWM pulses for VSI switches.



**Fig.2 Control scheme of the proposed SEPIC PFC converter-fed PMBLDCM**

The SEPIC based PFC converter has a conventional DBR fed from single-phase AC mains followed by the SEPIC DC-DC converter, an output ripple filter and a three-phase VSI to feed the PMBLDC motor. The DC-DC converter provides a controlled DC voltage from uncontrolled DC output of DBR, with PFC action through high frequency switching. The duty ratio (D) of the DC-DC converter is controlled by the DC voltages at its input and output. The switching frequency (fs) is decided by the switching device used, power range and switching losses of the device. In this work, IGBTs are used as the switching devices in the PFC switch as well as in VSI bridge, because IGBTs can operate in wide switching frequency range to make optimum balance between magnetics, size of filter elements and switch losses.

The PFC controller has outer voltage control loop and inner current control loop. An average current control scheme with current multiplier approach is used in this topology and a CCM operation of SEPIC is considered for PMBLDCM drive. The voltage control loop starts with sensing of DC link voltage which is compared with the reference DC link voltage. The error DC voltage is passed through a voltage PI controller to give the modulating current signal. This signal is multiplied with a unit template of input AC voltage and the resultant signal is compared with DC current sensed after the DBR to give current error. This current error is amplified and amplified signal is then compared with saw-tooth carrier wave to generate the PWM switching pulses for the DC-DC converter switch

**Design of SEPIC PFC converter for PMBLDCM Drive**

The Figure:1 shows the proposed SEPIC converter fed PMBLDCM drive. The SEPIC converter achieves high power density and fast transient response when operated at high switching frequency [16]. It is

designed for constant current in the intermediate inductor ( $L_i$ ) as it operates on the principle of an inductive energy transfer [17]. The boost inductor ( $L_f$ ), and capacitors ( $C_1, C_2$ ) are designed according to maximum allowable current and voltage ripple during transient conditions of the PMBLDCM drive. The design equations governing the duty ratio and other component values are as follows.

$$\text{Output voltage } V_{dc} = DV_{in} / (1 - D) \quad (1)$$

$$\text{Boost inductor } L_f = DV_{in} / \{f_s (\Delta I_{L_f})\} \quad (2)$$

$$\text{Intermediate capacitor } C_1 = D / \{(R_f f_s) (\Delta V_{C1} / V_o)\} \quad (3)$$

$$\text{Output filter inductor } L_o = (1 - D)V_{dc} / f_s \{(\Delta I_{L_o})\} \quad (4)$$

$$\text{Output filter capacitor } C_o = I_{av} / (2\omega \Delta V_{dc}) \quad (5)$$

### Modelling of Proposed PFC Converter Based PMBLDCM Drive

The modeling of proposed PFC converter fed PMBLDCM drive involves modeling of a PFC converter and PMBLDCM drive. The PFC converter consists of a DBR at front end and a SEPIC converter with output ripple filter. Various components of PMBLDCM drive are a speed controller, a reference current generator, a PWM current controller, VSI and a PMBLDC motor. All these components of a PMBLDCM drive are modeled by mathematical equations and the complete drive is represented by combination of these models.

#### A. Modeling Of PFC Converter

The PFC converter consists of a DBR at front end and a SEPIC converter with output ripple filter. The modeling of a PFC converter involves the modeling of a voltage controller, a reference current generator and a PWM controller as given below.

**1) Voltage controller:** The voltage controller is backbone of PFC converter; therefore it affects the performance of complete drive. A proportional integral (PI) controller is used to control the DC link 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,

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \quad (6)$$

The voltage (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,

$$I_c(k) = I_c(k-1) + K_{pv}\{V_e(k) - V_e(k-1)\} + K_{iv}V_e(k) \quad (7)$$

Where  $K_{pv}$  and  $K_{iv}$  are the proportional and integral gains of the voltage controller.

**2) Reference current generator:** The reference inductor current of the SEPIC converter is denoted by  $I_{dc}^*$  and given as,

$$I_{dc}^* = I_c(k) u_{vs} \quad (8)$$

Where  $u_{vs}$  is the unit template of the voltage at input AC mains and is calculated as

$$u_{vs} = v_d / V_{im}; v_d = |v_s|; v_s = V_{im} \sin \omega t \quad (9)$$

Where  $\omega$  is frequency in rad/sec at input AC mains.

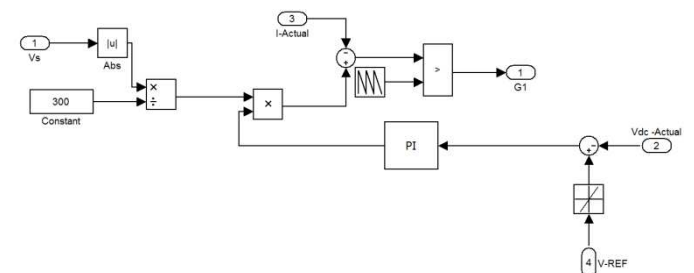


Fig.3 Simulation Diagram of the PFC Circuit

**3) PWM controller:** The reference inductor current of the SEPIC 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 ( $f_s$ ) sawtooth carrier waveform  $m_d(t)$  to get the switching signals for the IGBT of the PFC converter as,

$$\text{If } k_{dc} \Delta I_{dc} > m_d(t) \text{ then } S = 1 \quad (10)$$

$$\text{If } k_{dc} \Delta I_{dc} \leq m_d(t) \text{ then } S = 0 \quad (11)$$

Where S is the switching function representing 'on' position of IGBT of PFC converter with S=1 and its 'off' position with S=0.

#### B. Modeling Of PMBLDCM Drive

Various components of PMBLDCM drive are a speed controller, a reference current generator, a PWM current controller, VSI and a PMBLDC motor. All these components of a PMBLDCM drive are modeled by mathematical equations and the complete drive is represented by combination of these models. The modeling of a speed controller is quite important as the performance of the drive depends on this controller. If at  $k^{th}$  instant of time,  $\omega_r^*(k)$  is reference speed,  $\omega_r(k)$  is rotor speed then the speed error  $\omega_e(k)$  can be calculated as

$$\omega_e(k) = \omega_r^*(k) - \omega_r(k) \quad (12)$$

This speed error is processed through a speed controller to induce desired control signal.

**1) Speed controller:** The speed controller used in this work is a PI controller due to its simplicity. Its output at  $k^{th}$  instant is given as

$$T(k) = T(k-1) + K_{pv}\{\omega_e(k) - \omega_e(k-1)\} + K_{iv}\omega_e(k) \quad (13)$$

Where  $K_{PI}$  and  $K_{IW}$  are the proportional and integral gains of the speed PI controller.

2) **Reference winding currents:** The amplitude of stator winding current is calculated as

$$I^* = T(k) / (2 K_b) \quad (14)$$

Where  $K_b$  is the back emf constant of the PMBLDCM. The reference three-phase currents of the motor windings are denoted by  $i_a^*, i_b^*, i_c^*$  for phases a, b, c respectively and given as

$$i_a^* = I^*, i_b^* = -I^*, i_c^* = 0 \text{ for } 0^\circ \leq \theta \leq 60^\circ \quad (15)$$

$$i_a^* = I^*, i_b^* = 0, i_c^* = -I^* \text{ for } 60^\circ \leq \theta \leq 120^\circ \quad (16)$$

$$i_a^* = 0, i_b^* = I^*, i_c^* = -I^* \text{ for } 120^\circ \leq \theta \leq 180^\circ \quad (17)$$

$$i_a^* = -I^*, i_b^* = I^*, i_c^* = 0 \text{ for } 180^\circ \leq \theta \leq 240^\circ \quad (18)$$

$$i_a^* = -I^*, i_b^* = 0, i_c^* = I^* \text{ for } 240^\circ \leq \theta \leq 300^\circ \quad (19)$$

$$i_a^* = 0, i_b^* = I^*, i_c^* = I^* \text{ for } 120^\circ \leq \theta \leq 180^\circ \quad (20)$$

Where  $\theta$  is rotor position angle in electrical radian/sec. These reference currents are compared with sensed phase currents to generate the current errors  $\Delta i_a = (i_a^* - i_a)$ ,  $\Delta i_b = (i_b^* - i_b)$ ,  $\Delta i_c = (i_c^* - i_c)$  for three phases of the motor. These current errors  $\Delta i_a, \Delta i_b, \Delta i_c$  are amplified by gain  $K_1$  before feeding through the PWM current controller.

3) **PWM current controller:** The PWM current controller compares these amplified current errors of each phase with carrier waveform  $m(t)$  of a fixed frequency and generates the switching sequence for the voltage source inverter based on the logic given for phase "a" as,

$$\text{If } k_1 \Delta i_a > m(t) \text{ then } S_a = 1 \quad (21)$$

$$\text{If } k_1 \Delta i_a \leq m(t) \text{ then } S_a = 0 \quad (22)$$

The switch sequences  $S_b$  and  $S_c$  are generated using similar logic for other two phases of the VSI feeding PMBLDC motor.

4) **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

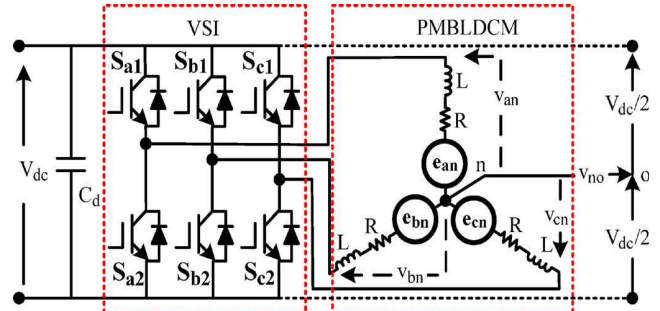


Fig.4 Equivalent circuit of VSI fed PMBLDCM

$$V_{ao} = (V_{dc} / 2) \text{ for } S_{a1} = 1 \quad (23)$$

$$V_{ao} = (-V_{dc} / 2) \text{ for } S_{a2} = 1 \quad (24)$$

$$V_{ao} = 0 \text{ for } S_{a1} = 0, \text{ and } S_{a2} = 0 \quad (25)$$

$$V_{an} = V_{ao} - V_{no} \quad (26)$$

Where  $V_{ao}, V_{bo}, V_{co}$ , and  $V_{no}$  are the voltages the three phases (a, b, and c) and neutral point (n) with respect to the virtual midpoint of the dc link voltage. The voltage  $V_{an}, V_{bn}$ , and  $V_{cn}$  are the voltages of the three phases with respect to the 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 the "on" and "off" conditions of respective Insulated Gate Bipolar junction Transistors (IGBTs) of the VSI. The voltages for the other two phases of the VSI feeding the PMBLDC motor, i.e.,  $V_{bo}, V_{co}, V_{bn}$ , and  $V_{cn}$ , and the switching pattern of the other IGBTs of the VSI (i.e.,  $S_{b1}, S_{b2}, S_{c1}$ , and  $S_{c2}$ ) are generated in a similar way.

5) **PMBLDC motor:** The PMBLDCM is modeled in the form of a set of differential equations as shown in the Table: 5.1

Table:1 Modeling Equations of PMBLDC Motor

$V_{an} = R i_a + p \lambda_a + e_{an}$
$V_{bn} = R i_b + p \lambda_b + e_{bn}$
$V_{cn} = R i_c + p \lambda_c + e_{cn}$
$\lambda_a = L_s i_a - M (i_b + i_c)$
$\lambda_b = L_s i_b - M (i_a + i_c)$
$\lambda_c = L_s i_c - M (i_a + i_b)$
$T_e = (e_{an} i_a + e_{bn} i_b + e_{cn} i_c) / \omega_r$
$i_a + i_b + i_c = 0$
$V_{no} = \{V_{ao} + V_{bo} + V_{co} - (e_{an} + e_{bn} + e_{cn})\} / 3$
$\lambda_a = (L_s + M) i_a, \lambda_b = (L_s + M) i_b, \lambda_c = (L_s + M) i_c$
$p i_x = (V_{xn} - i_x R - e_{xn}) / (L_s + M)$
$e_{xm} = k_b f_x(\theta) \omega_r$
$f_a(\theta) = 1 \text{ for } 0 < \theta < 2\pi/3$
$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} - 1 \text{ for } 2\pi/3 < \theta < \pi$
$f_a(\theta) = -1 \text{ for } \pi < \theta < 5\pi/3$
$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} + 1 \text{ for } 5\pi/3 < \theta < 2\pi$

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

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

$$p \theta = \omega_r$$

In the above equations shown in Table:1,  $p$  represent the differential operator ( $d/dt$ ),  $i_a$ ,  $i_b$ , and  $i_c$  are currents,  $\lambda_a$ ,  $\lambda_b$ , and  $\lambda_c$  are flux linkages, and  $e_{an}$ ,  $e_{bn}$ , and  $e_{cn}$  are phase-to-neutral back EMFs of PMBLDCM, in respective phases,  $R$  is the resistance of motor windings/phase,  $L_s$  is the self inductance/phase and  $M$  is the mutual inductance/phase,  $T_e$  is the developed torque,  $\omega_r$  is the motor speed in radians per second,  $x$  represents phase a, b, or c,  $f_x(\theta)$  represents a function of rotor position with a maximum value  $\pm 1$ ,  $P$  is the number of poles,  $T_l$  is the load torque in newton meters,  $J$  is the moment of inertia in kilogram square meters, and  $B$  is the friction coefficient in newton meter seconds per radian.

**Simulation Result**

The proposed PMBLDCM drive is modeled in Matlab-Simulink environment and its performance is evaluated for a compressor load of an Air-Con. A constant torque load equal to rated torque mimics the compressor load, while running at variable speed as per requirement of air-conditioning system. The DC link voltage is kept constant at 400 V with an input AC rms voltage of 220V. The components of SEPIC converter are selected on the basis of PQ constraints at AC mains and allowable ripple in DC-link voltage as discussed. The controller gains are tuned to get the desired PQ parameters. The performance evaluation is made on the basis of various PQ parameters i.e. total harmonic distortion of current (THD %) at input AC mains, power factor (PF) and input AC current ( $I_s$ ).

Fig.6 shows the current ( $i_s$ ) waveform at input AC mains is in phase with the supply voltage ( $v_s$ ) representing nearly unity power factor. The waveforms of trapezoidal back EMF of PMBLDCM drive are shown in Figure-8. Performance of the proposed PMBLDCM drive is evaluated under varying input AC voltage to demonstrate the effectiveness of the proposed drive for Air-Con system in various practical situations in Table-2. Figs. 10-13 show variation of current and its THD at AC mains with AC input voltage. The THD of AC mains current is observed well below 5% in most of the cases and satisfies the international standards [8] along with nearly unity PF in wide range of AC input voltage.

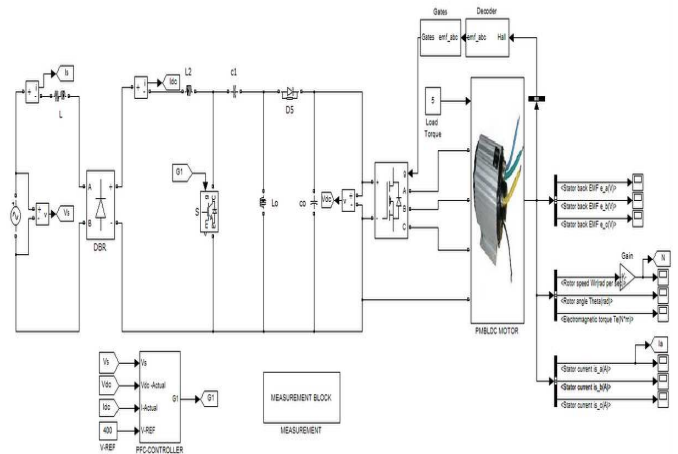
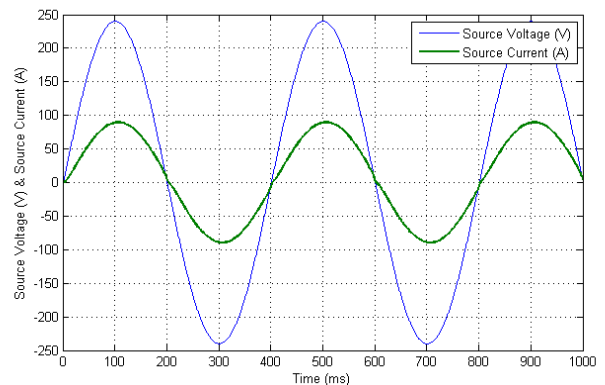


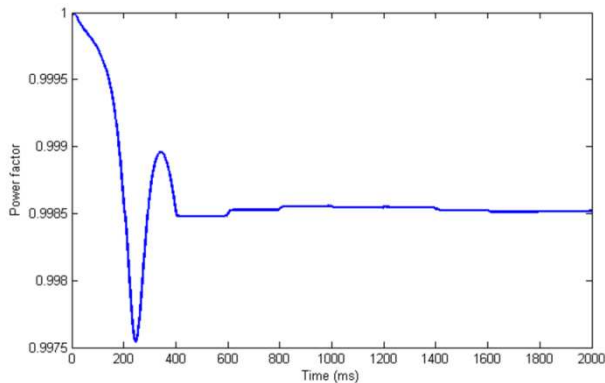
Fig.5 Simulation Diagram of the Proposed Circuit

Table:2 PQ Parameters of a PMBLDCMD at Variable Input AC Voltage

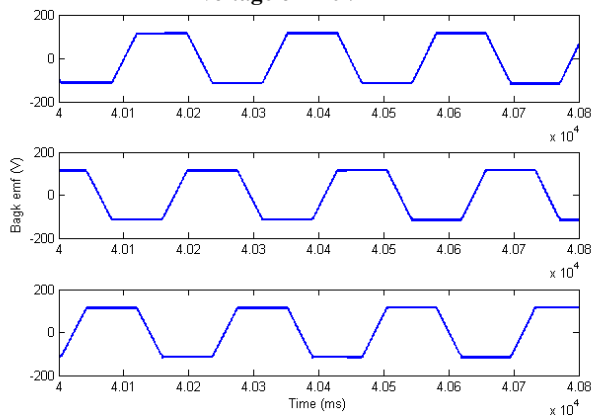
PEAK SOURCE VOLTAGE (Vs) VOLTS	PEAK SOURCE CURRENT (Is) VOLTS	SPEED (N) RPM	TOTAL HARMONIC DISTORTION (THD %) (%)	POWER FACTOR (PF)
300	3.712	1350	1.95	0.9992
270	3.342	1240	1.72	0.9987
240	2.971	1165	1.47	0.9987
210	2.600	1050	1.32	0.9986
180	2.229	910	1.11	0.9985
150	1.857	810	1.03	0.9985
120	1.486	690	0.98	0.9984
90	1.114	560	0.89	0.9985
60	0.724	380	1.25	0.9985
30	0.371	230	0.96	0.9985



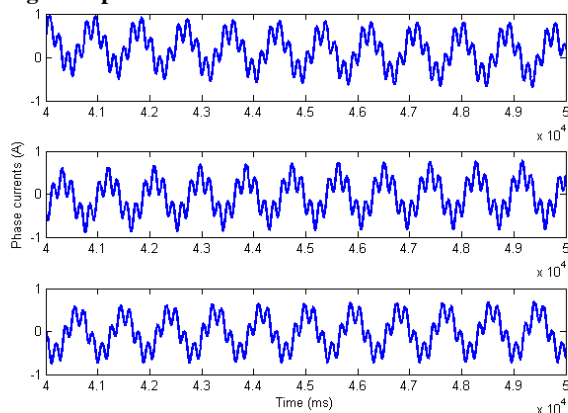
**Fig.6 Source voltage and source current of a PMBLDCM drive representing unity power factor at peak source voltage of 240V**



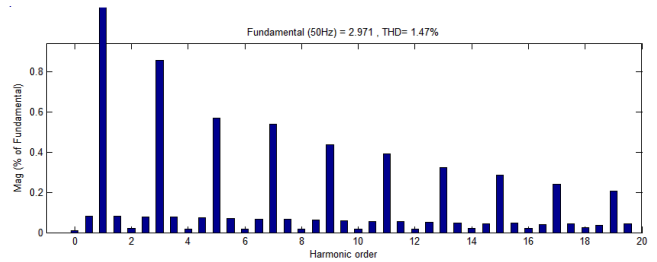
**Fig.7 Power factor of the PMBLDC motor at peak source voltage of 240V**



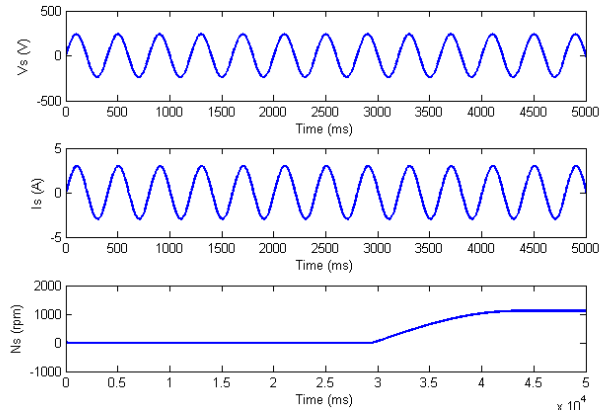
**Fig.8 Trapezoidal back emf of the PMBLDC motor**



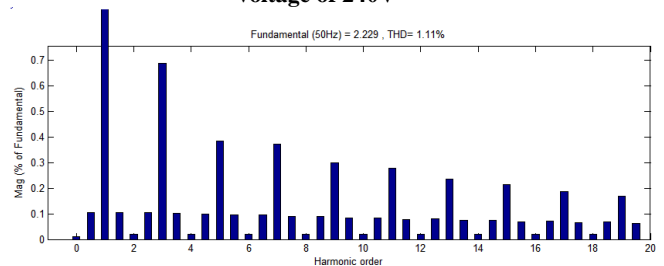
**Fig.9 Phase currents of the PMBLDC motor**



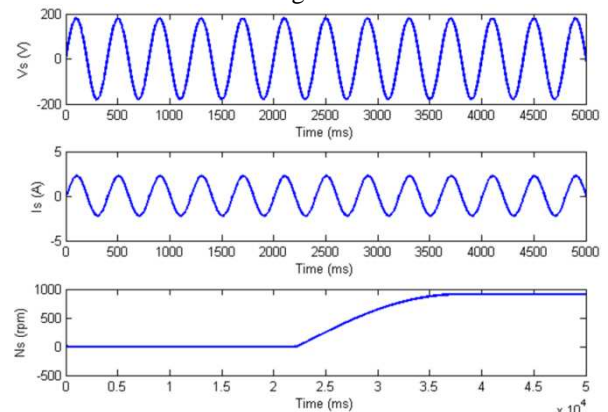
**Fig.10 FFT analysis of a PMBLDCM drive at peak source voltage of 240V**



**Fig.11 Performance of the PMBLDCM drive at peak source voltage of 240V**



**Fig.12 FFT analysis of a PMBLDCM drive at peak source voltage of 180V**



**Fig.13 Performance of the PMBLDCM drive at peak source voltage of 180V**

**I. CONCLUSION**

A PFC based SEPIC converter for a PMBLDCM drive has been designed for a compressor load of an air-conditioner. The PFC converter has ensured reasonable high power factor close to unity in wide range of input voltage. The parameters shown in the fig 6 to fig 13 represents an improved power quality, smooth speed control of the PMBLDCM drive with quasi sinusoidal shaped phase currents and back emf which are displaced by  $120^\circ$ . The THD of AC mains current is within specified limits of international norms. The performance of the drive is very good in the wide range of input AC voltage with desired power quality parameters. This converter has been found suitable for the speed control at constant torque load of air-conditioning systems.

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