Single-Phase SEPIC Based PFC Converter for PMBLDCM Drive in Air-Conditioning System

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Abstract – In this paper, a permanent magnet brushless DC motor (PMBLDCM) is employed in air-conditioning systems and operated at rated torque and variable speed to achieve energy conservation. A single-phase single-switch power factor correction (PFC) based single ended primary inductor converter (SEPIC) is used to regulate DC bus voltage of voltage source inverter (VSI) to feed PMBLDCM. The analysis, design and performance evaluation of the proposed PFC converter is carried out for a 1.2 kW, 1200 rpm, 164 V PMBLDCM used in air-conditioning system. The proposed PFC converter is modeled and its performance is simulated in Matlab-Simulink environment. An exhaustive evaluation of its performance is carried out to demonstrate improved power factor in wide range of speed of the drive and AC input voltage.

Keywords – PFC converter, SEPIC, PMBLDC motor, air-conditioning, power quality (PQ)

I. Introduction

Air-conditioners (Air-Cons) constitute a considerable amount of load in AC distribution system [1]. However, most of the existing air-conditioners are not energy efficient and thereby, provide a scope for energy conservation. Air-Cons in domestic sector are usually driven by a single-phase induction motor running at constant rated torque with on-off control [1]. A permanent magnet brushless DC motor (PMBLDCM) is a good drive for Air-Cons due to its high efficiency, silent operation, compact size, high reliability, ease of control and low maintenance requirements.

A PMBLDCM is a kind of three-phase synchronous motor having permanent magnets on the rotor [2-7]. Usually these PMBLDCMs in small Air-Cons are powered from single-phase AC mains through a diode bridge rectifier (DBR) with smoothening DC capacitor and a three-phase voltage source inverter (VSI) [3-4, 6-7]. Because of uncontrolled charging of DC link capacitor, the AC mains current waveform is a pulsed waveform featuring a peak value higher than the amplitude of the fundamental input current as shown in Fig. 1. The power factor (PF) is 0.741 and crest factor (CF) of AC mains current is 2.2 with 67% efficiency of the drive. Therefore, many power quality (PQ) problems arise at input AC mains including poor power factor, increased total harmonic distortion (THD) and high crest factor (CF) of AC mains current etc. These PQ problems as addressed in IEC 61000-3-2 [8] especially in low power appliances become severe for the utility when many such drives are employed simultaneously at nearby locations.

Therefore, PMBLDCM drives having inherent power factor correction (PFC) become the preferred choice for the Air-Cons. The PFC converter draws sinusoidal current from AC mains in phase with its voltage. In this PFC converter a DC-DC converter topology is mostly used amongst several available topologies [9-16] e.g. boost, buck-boost, Cuk, SEPIC, zeta converters with variations of capacitive/inductive energy transfer. It results in an improved performance, such as reduction of AC mains current harmonics, acoustic noise, electromagnetic interference (EMI) and number of components; improved efficiency, wide input voltage range utilization etc.

Some attempts [11,13,16] have been made to introduce PFC feature in PMBLDCM drives using uni-polar excitation [13] and bipolar excitation [11,16] of PMBLDCMs. For automotive air-conditioning a low voltage PMBLDCM drive has been reported [15] with compact size of the complete system. PMBLDCM with boost PFC converter [11] and PMSM with improved power quality converter [12] have been reported for domestic Air-Cons. However, a PMBLDCM is best suited for air-conditioning system due to simple control and its high average torque.

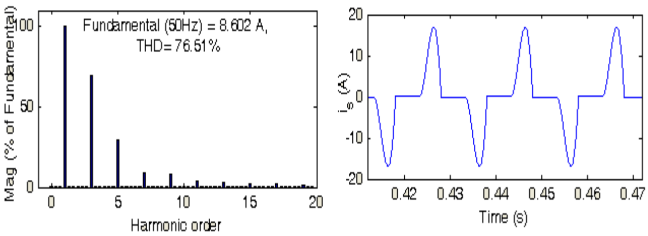

Fig. 1: Supply current and harmonic spectrum (at 220 V_{AC}) of a DBR fed PMBLDCM drive at rated load.

A single ended primary inductor converter (SEPIC), as a 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.

II. Operation and Control of SEPIC Converter Fed PMBLDCM

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 signal converted 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.

The paper first received 17 June 2009 and in revised form 10 March 2010.
Digital Ref: A170601230

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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.

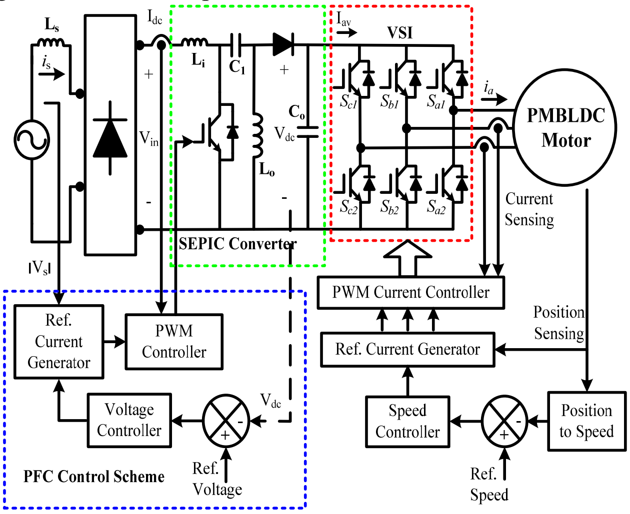


Fig. 2: Control Schematic of PFC based SEPIC Converter fed PMBLDCM Drive

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 (f_s) is decided by the switching device used, power range and switching losses of the device. In this work, insulated gate bipolar transistors (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 components and switching 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 continuous conduction mode (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.

III. Design of SEPIC PFC Converter for PMBLDCM

Fig. 2 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_o) as it operates on the principle of an inductive energy transfer [17]. The boost inductor (L_i), and capacitors (C_1, C_o) 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.

Output voltage	$V_{dc}=D\,V_{in}/(1-D)$	(1)
Boost inductor	$L_i= D\,V_{in}/\{f_s\,(\Delta I_{Li})\}$	(2)
Intermediate capacitor	$C_1= D / \{(Rf_s)\,(\Delta V_{C1}/ V_o)\}$	(3)
Output filter inductor	$L_o= (1-D)V_{dc}/\{f_s(\Delta I_{Lo})$	(4)
Output filter capacitor	$C_o=I_{av}/(2\omega\Delta V_{dc})$	(5)

The PFC converter is designed for a constant DC link voltage V_{dc} = 400V at V_{in} = 198V for V_s = 220V. Other design data are f_s = 40kHz, I_{av} = 5A, R= 80Ω, ΔI_{Li}= 0.75A, ΔI_{Lo}= 0.75 A (15% of I_{av}), ΔV_{dc}= 5V (1.25% of V_{dc}), ΔV_{C1}= 15V (3.75% of V_{dc}). The design parameters calculated are L_i=4.5mH, C_1=5μF, L_o=4.5mH, C_o=1600μF.

IV. Modeling 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. PFC Converter

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 back-bone 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,

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \qquad (6)$$

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 as derived in appendix A is given as,

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

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,

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

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

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

where ω is frequency in rad/sec at input AC mains.

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) saw-tooth carrier waveform $m_d(t)$ to get the switching signals for the IGBT of the PFC converter as,

If $k_{dc}\,\Delta i_{dc} > m_d(t)$ then $S = 1$ (10)

If $k_{dc}\,\Delta i_{dc} <= m_d(t)$ then $S = 0$ (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. PMBLDCM Drive

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 get 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

$$T(k) = T(k-1) + K_{p\omega}\{\omega_e(k) - \omega_e(k-1)\} + K_{i\omega}\,\omega_e(k) \quad (13)$$

where $K_{p\omega}$ and $K_{i\omega}$ are the proportional and integral gains of the speed PI controller.

2. Reference Winding Currents

The amplitude of stator winding current is calculated as

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

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

$i_a^* = I^*$, $i_b^* = -I^*$, $i_c^* = 0$ for $0^o \le \theta \le 60^o$ (15)

$i_a^* = I^*$, $i_b^* = 0$, $i_c^* = -I^*$ for $60^o \le \theta \le 120^o$ (16)

$i_a^* = 0$, $i_b^* = I^*$, $i_c^* = -I^*$ for $120^o \le \theta \le 180^o$ (17)

$i_a^* = -I^*$, $i_b^* = I^*$, $i_c^* = 0$ for $180^o \le \theta \le 240^o$ (18)

$i_a^* = -I^*$, $i_b^* = 0$, $i_c^* = I^*$ for $240^o \le \theta \le 300^o$ (19)

$i_a^* = 0$, $i_b^* = -I^*$, $i_c^* = I^*$ for $120^o \le \theta \le 180^o$ (20)

where θ 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 Δi_a, Δi_b, Δi_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,

If $k_1\,\Delta i_a > m(t)$ then $S_a = 1$ (21)

If $k_1\,\Delta i_a <= m(t)$ then $S_a = 0$ (22)

The switching 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

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,

$v_{ao} = (V_{dc}/2)$ for $S_{a1} = 1, S_{a2} = 0$ (23)

$v_{ao} = (-V_{dc}/2)$ for $S_{a1} = 0, S_{a2} = 1$ (24)

$v_{ao} = 0$ for $I_a^* = 0$ (25)

$v_{an} = v_{ao} - v_{no}$ (26)

Using similar logic v_{bo}, v_{co}, v_{bn}, v_{cn} are generated for other two phases of the VSI feeding PMBLDC motor, where v_{ao}, v_{bo}, v_{co}, and v_{no} are voltages of three-phases and neutral with respect to virtual mid-point of the capacitor shown as 'o' in Fig. 3. The voltages v_{an}, v_{bn}, v_{cn} are voltages of three-phases with respect to neutral and V_{dc} is the DC link voltage.

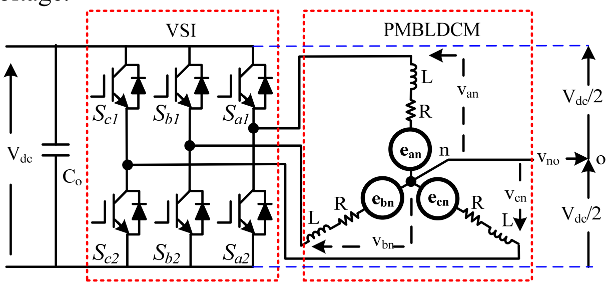


Fig. 3: Equivalent Circuit of a VSI fed PMBLDCM Drive

5. PMBLDC Motor

The PMBLDCM is modeled in the form of a set of differential equations given in Table 1.

Table 1: Modeling Equations of PMBLDC Motor

$v_{xn} = Ri_x + p\lambda_x + e_{xn},$	
$\lambda_a = Li_a - M(i_b + i_c);$	
$\lambda_b = Li_b - M(i_a + i_c);$	
$\lambda_c = Li_c - M(i_b + i_a)$	
$i_a + i_b + i_c = 0;$	
$v_{an} = v_{ao} - v_{no}$	
$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3$	
$\lambda_a = (L+M)\,i_a,\ \lambda_b = (L+M)\,i_b,\ \lambda_c = (L+M)\,i_c,$	
$pi_x = (v_{xn} - i_x R - e_{xn})/(L+M)$	
$T_e = (e_{an}\,i_a + e_{bn}\,i_b + e_{cn}\,i_c)/\,\omega$ and	
$e_{xn} = K_b\,f_x(\theta)\,\omega$	
$f_a(\theta) = 1$	for $0 < \theta < 2\pi/3$
$f_a(\theta) = \{(6/\pi)(\pi - \theta)\}-1$	for $2\pi/3 < \theta < \pi$
$f_a(\theta) = -1$	for $\pi < \theta < 5\pi/3$
$f_a(\theta) = \{(6/\pi)(\theta - 2\pi)\}+1$	for $5\pi/3 < \theta < 2\pi$
$T_e = K_b\{f_a(\theta)\,i_a + f_b(\theta)\,i_b + f_c(\theta)\,i_c\}$	
$p\omega = (P/2)\,(T_e - T_L - B\omega)/(J)$	

These equations (Table 1) represent the dynamic model of the PMBLDC motor. Various symbols used in these equations are the reference currents of the PMBLDCM for phases a, b, c are i_a^*, i_b^*, i_c^*, current error of phase "a" is Δi_a, error gain k_1 and carrier waveform for the PWM current controller m(t). Voltages of the three-phases and neutral point (n) with respect to virtual mid-point of the DC link voltage ‘o’, v_{ao}, v_{bo}, $v_{co,}$ and v_{no}, voltages of three-phases with respect to neutral point (n) v_{an}, v_{bn}, v_{cn} and the DC link voltage V_{dc} as shown in Fig. 2. R is resistance of motor/phase, L is self-inductance/phase, M is mutual inductance of motor winding/phase and x represents any of the phases a, b or c, p is a differential operator (d/dt), i_a, i_b, i_c are line currents, e_{an}, e_{bn}, e_{cn} are phase to neutral back emfs, θ is rotor position and ω=pθ is speed of PMBLDCM in rad/sec, 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.

V. PERFORMANCE EVALUATION

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 of Air-Con, while running at variable speed as per requirement of air-conditioning system. The PMBLDCM of 1.2 kW, 164 V, 5 A rating, with 1200 rpm rated speed and 9.61 Nm rated torque is used to drive such load. The detailed data of the PMBLDC motor [6] are given in Appendix B. The performance of the drive is simulated for constant rated torque (9.61 Nm) at rated speed. The DC link voltage is kept constant at 400 V with an input AC rms voltage of 220 V. 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 in Section III. The controller gains are tuned to get the desired PQ parameters and the values of controller gains are given in Appendix. The performance evaluation is made on the basis of various PQ parameters i.e. total harmonic distortion of current (THD_i) at input AC mains, displacement power factor (DPF), power factor (PF), crest factor (CF), rms value of input AC current (I_s) and efficiency (η_{drive}) of the drive.

A. Performance during Starting

Fig 4 shows that the starting of the drive is smooth with rated torque (9.61 Nm) and PFC is achieved during the starting of the drive. The motor is started from 220 V_{rms} AC input at rated torque with reference speed set at rated speed i.e. 125.7 rad/s (1200 rpm). The maximum allowable torque and the stator current during transient condition are limited to double the rated value. The motor speed reaches the reference speed within 0.1 sec. and resumes the rated value of stator current and motor torque within a cycle of AC mains frequency.

B. Performance at Variable Speeds

Figs. 5a-c show the performance of the drive during speed control of Air-Cons. The speed is increased and decreased at rated torque for detailed evaluation of the drive. The motor speed is increased to rated speed i.e. 125.7 rad/s (1200 rpm) and decreased to half the rated speed i.e. 62.85 rad/s (600 rpm) from 80% of the rated speed i.e. 100.53 rad/s (960 rpm) as shown in Figs. 5a and 5b, respectively. The motor reaches the reference speed within couple of cycles of AC mains frequency during these changes. Moreover, the motor speed is reduced to 20% of its rated value i.e. 25.13 rad/s (240 rpm) from 62.85 rad/s (600 rpm) within 0.01 sec. while achieving the PFC at input AC mains (as shown in Fig. 5c). These results validate fast control of speed, current and torque in an Air-Con with the proposed PMBLDCM drive.

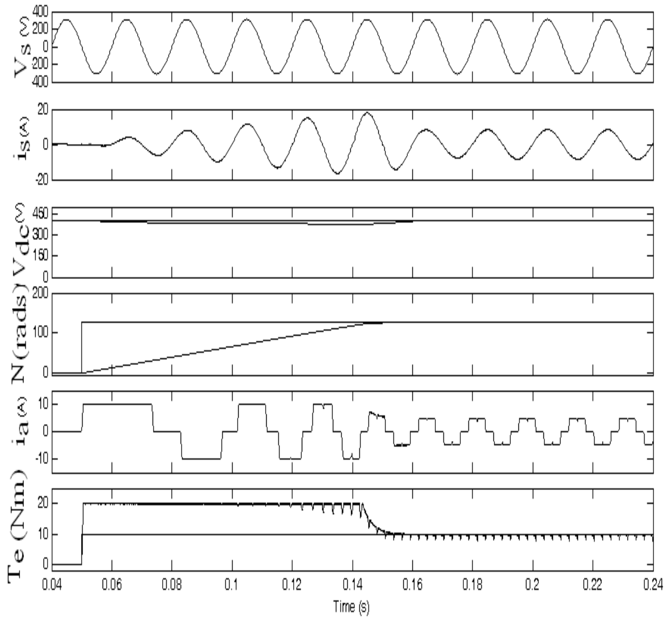
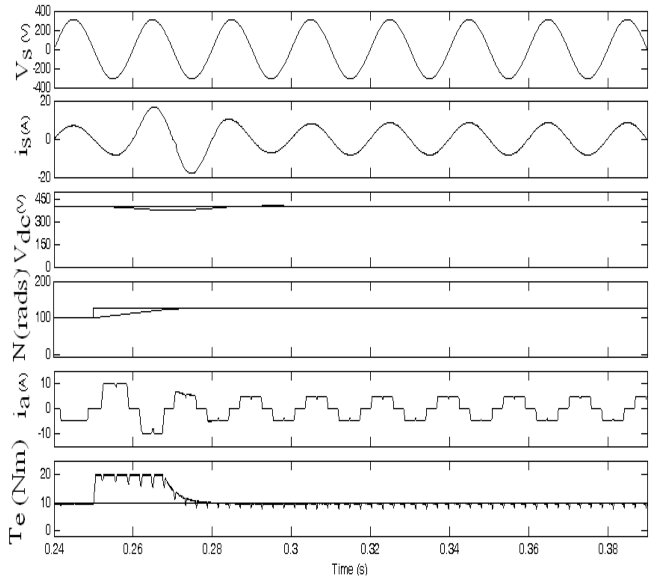
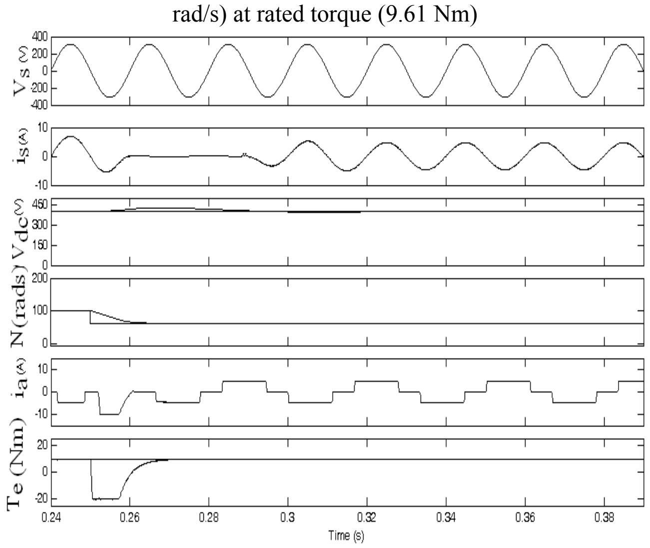


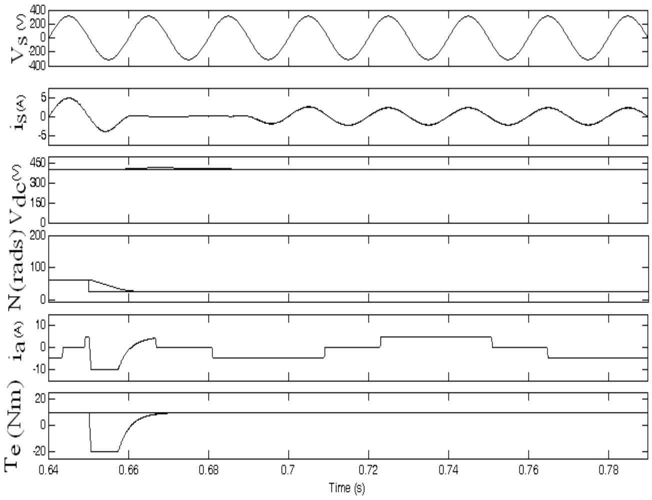
Fig. 4: Performance of a SEPIC converter fed PMBLDCM drive during Starting at rated speed i.e. 1200 rpm (125.7 rad/s) and rated torque (9.61 Nm) with 220 V_{AC} input supply



(a): Speed change from 960 rpm (100.5 rad/s) to 1200 rpm (125.7 rad/s) at rated torque (9.61 Nm)



(b): Speed change from 960 rpm (100.5 rad/s) to 600 rpm (62.83 rad/s) at rated torque (9.61 Nm)



(c) Speed change from 600 rpm (62.83 rad/s) to 240 rpm (25.13 rad/s) at rated torque (9.61 Nm)

Fig. 5: Performance of a SEPIC converter fed PMBLDCM drive during speed variation at 220 V_{AC} input supply

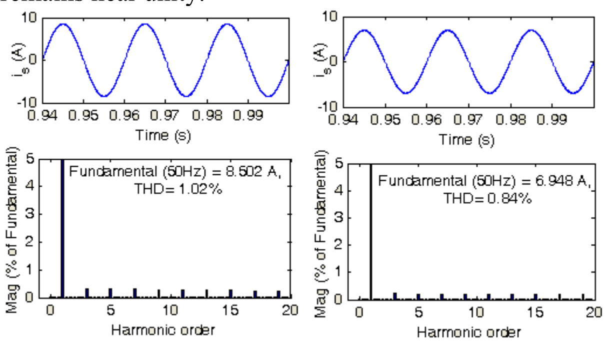
C. Performance under Steady State Condition

The current waveform at input AC mains and its harmonic spectrum during steady state at 1200 rpm (125.7 rad/s), 960 rpm (100.53 rad/s), 600 rpm (62.85 rad/s) and 240 rpm (25.13 rad/s) are shown in Figs. 6a-d. The variation of PQ parameters and drive efficiency with load (variable speed at rated torque) is shown in Table 2. The current THD at AC mains remains less than 5% with near unity power factor in the wide range of speed control of PMBLDCM drive. Moreover, an improved performance of the drive is observed in terms of reduced ripples in torque, current and speed during steady state conditions.

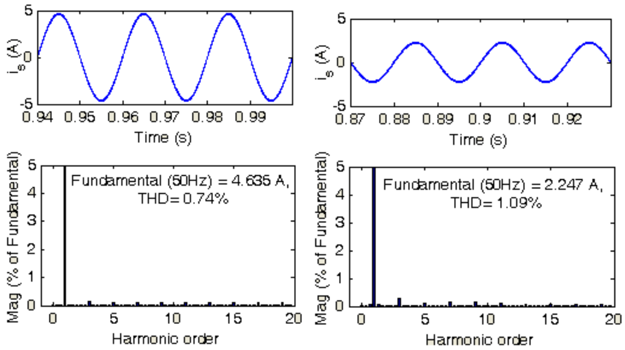
D. Performance under Input Voltage Variation

Table 3 shows the PQ parameters for variable input AC voltages (170 V-270 V) at constant DC link voltage (400 V) to the drive running at rated speed i.e. 125.7 rad/s (1200 rpm) and rated torque (9.61 Nm). These results show reduced THD of AC mains current (less than 5%) and near unity PF in wide range of input AC voltage. The efficiency of the drive remains more than 91% in the complete voltage range.

The transient and steady state performances, current waveforms and its harmonic spectra and PQ parameter variation with speed and input voltage are shown in Figs. 4-6 and Tables 2-3 to provide an exhaustive evaluation of the proposed drive system. The current THD at input AC mains in steady state conditions always remains within the standards of IEC 61000-3-2 [8] and the power factor remains near unity.



(a) at 1200 rpm speed (b) at 960 rpm speed



(c) at 600 rpm speed (d) at 240 rpm speed

Fig.6 Supply current and harmonic spectra (at 220 V_{AC}) of a SEPIC converter fed PMBLDCM drive during steady-state condition at rated torque (9.61 Nm).

Table 2: PQ parameters at variable speed and rated torque (9.61 Nm) at 220 V_{AC} input at 400 V DC link voltage

Load (%)	THD_i (%)	DPF	PF	CF	I_s (A)	η_{drive} (%)
10	1.8	0.9999	0.9999	1.41	1.02	53.5
20	1.09	1.0000	0.9999	1.41	1.59	69.1
30	0.90	1.0000	1.0000	1.41	2.15	76.5
40	0.70	1.0000	1.0000	1.41	2.72	80.7
50	0.74	1.0000	1.0000	1.41	3.28	83.8
60	0.74	1.0000	1.0000	1.41	3.83	86.1
70	0.77	1.0000	1.0000	1.41	4.37	88.0
80	0.84	1.0000	1.0000	1.41	4.91	89.4
90	0.93	1.0000	1.0000	1.41	5.47	90.4
100	1.02	1.0000	0.9999	1.41	6.02	91.3

Table 3: PQ parameters at variable input AC voltage (V_{AC}) at rated speed (1200 rpm) and rated torque (9.61Nm) at 400 V DC link voltage

V_s (V)	THD_i (%)	DPF	PF	CF	I_s (A)	η_{drive} (%)
170	2.07	0.9999	0.9997	1.43	7.79	91.3
180	1.77	1.0000	0.9998	1.41	7.35	91.3
190	1.53	1.0000	0.9999	1.41	6.97	91.3
200	1.33	1.0000	0.9999	1.41	6.62	91.3
210	1.16	1.0000	0.9999	1.41	6.30	91.3
220	1.02	1.0000	0.9999	1.41	6.02	91.3
230	0.93	1.0000	1.0000	1.41	5.76	91.3
240	0.85	1.0000	1.0000	1.41	5.52	91.4
250	0.79	1.0000	1.0000	1.41	5.30	91.4
260	0.72	1.0000	1.0000	1.41	5.09	91.4
270	0.68	1.0000	1.0000	1.41	4.90	91.4

VI. 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 the speed as well as input AC voltage. Moreover, performance parameters show an improved power quality with less torque ripple, smooth speed control of the PMBLDCM drive. The THD of AC mains current is observed well below 5% in most of the cases and satisfies the international standards [8]. 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.

APPENDIX A

The output of the voltage PI controller $I_c(k-1)$ [4] having K_{pv} and K_{iv} as proportional and integral gains and V_e as voltage error, is calculated at $(k-1)^{th}$ instant, as

$$I_c(k\text{-}1)=K_{pv}V_e(k\text{-}1)+K_{iv}\sum_{i=1}^{k-1}V_e(i) \quad (A1)$$

The output of the PI controller $I_c(k)$ at k^{th} instant, is

$$I_c(k)=K_{pv}V_e(k)+K_{iv}\sum_{i=1}^{k}V_e(i) \quad (A2)$$

Subtracting eqn. (a1) from eqn. (a2), the relation becomes as,

$$I_c(k)-I_c(k\text{-}1)=K_{pv}\{V_e(k)-V_e(k\text{-}1)\}+K_{iv}V_e(k) \quad (A3)$$

Therefore, the output of the PI controller $I_c(k)$ at k^{th} instant is given as

$$I_c(k)=I_c(k\text{-}1)+K_{pv}\{V_e(k)-V_e(k\text{-}1)\}+K_{iv}V_e(k) \quad (A4)$$

APPENDIX B

Rated Power: 1.2 kW, Rated Voltage: 164 V, Rated Speed: 1200 rpm, Rated Current: 5.0 A, Rated torque: 9.61 Nm, No of poles: 6, Resistance R: 1.91 Ω/ph., Inductance (L+M): 9.55 mH/ph., Torque constant K_T : 0.332 Nm/A, Inertia J= 0.00776 Kg-m^2. The Circuit Parameters used for simulations: Source impedance: 0.03 pu, Switching frequency of PFC switch = 40 kHz. The gains of voltage and speed PI controllers: K_{pv}=0.485, K_{iv}=6.85, $K_{p\omega}$=0.11, $K_{i\omega}$=1.2.

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