International Journal of Advanced Computer Research (ISSN (print): 2249-7277 ISSN (online): 2277-7970)
Volume-3 Number-1 Issue-8 March-2013

SEPIC Based PFC Converter for PMBLDCM Drive in Air Conditioning System

Amit Kumar Sinha[1], Gandhi. R[2]
PG Scholar (Power Electronic and Drive) Gnanamani College of Engineering, Namakkal

Abstract

In this paper, A power factor correction (PFC) based single ended primary inductor converter (SEPIC) is used to regulate DC bus voltage of voltage source inverter (VSI) to run PMBLDC motor . Permanent magnet brushless DC motor (PMBLDCM) is used in air-conditioning systems and runs at rated torque and variable speed to achieve energy conservation. The analysis, design and performance of the proposed PFC converter is carried out for a 1.2 kW, 1200 rpm, 164 V PMBLDCM used in air-conditioning system. The PFC converter is modeled and its performance is simulated in Matlab-Simulink environment. The improved power factor of the drive is evaluated in wide range.

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. 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. 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. 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). Because of uncontrolled charging of DC link capacitor, the AC mains current waveform is a pulse 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 65% 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.

So, 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 e.g. boost, buck-boost, Cuk, SEPIC, zeta converters with variations of capacitive/inductive energy transfer. The reduction of AC mains current harmonics, electromagnetic interference (EMI), acoustic noise, and number of components, improved efficiency leads to enhance performances etc.

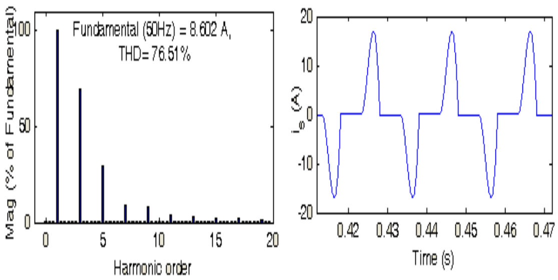


Fig.1: Supply current and harmonic spectrum (at 220 V_{AC}) of a DBR fed PMBLDCM drive at rated load.

Some attempts have been made to introduce PFC feature in PMBLDCM drives using uni-polar excitation and bipolar excitation of PMBLDCMs. For automotive air-conditioning a low voltage PMBLDCM drive has been reported with compact size of the complete system. PMBLDCM with boost PFC converter and PMSM with improved power quality converter 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.

A single ended primary inductor converter (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. 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 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.

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. 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 magnetic, size of filter components and switching losses. Current in the intermediate inductor (L_o) as it operates on the principle of an inductive energy transfer. The boost inductor (L_i), and capacitors (C_1, C_o) are designed according to maximum allowable current and voltage ripple 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.

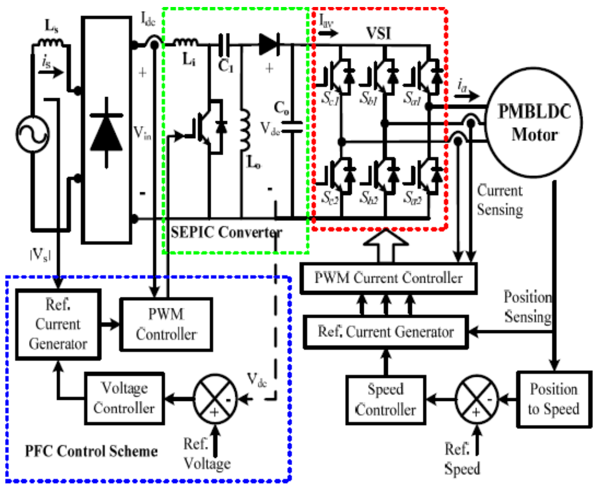


Fig. 2: Control Schematic of PFC based SEPIC Converter fed PMBLDCM Drive

III. Working of Proposed 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 main part of PFC converter. A proportional integral (PI) controller is used to control the DC link voltage.

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

2. Reference Current Generator

The reference inductor current of the SEPIC converter is denoted by i_{dc}^* and given as

$I_{dc}^* = I_c (k) u_V.$ (7)

Where u_V is the unit of the voltage at input AC mains, calculated as,

$u_{VS} = v_d/V_m; \; v_d = |v_s|; \; v_s = V_m \sin \omega t$ (8)

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 $S = 1$ (9)

If $k_{dc} \Delta i_{dc} <= m_d (t)$ then $S = 0$ (10)

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

$\omega_e (k) = \omega^*_r (k) - \omega_r (k)$ (11)

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

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

$I^* = T(k)/(2K_b)$ (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.

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,

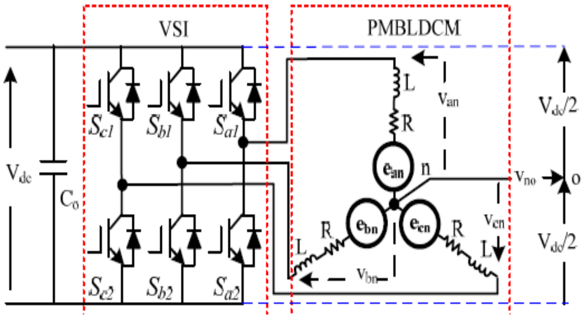


Fig. 3: Equivalent Circuit of a VSI fed PMBLDCM Drive

5. PMBLDC Motor

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

$$v_{xn} = Ri_x + p\lambda_x + e_{xn},$$
$$\lambda_a = Li_a - M(i_b + i_c);$$
$$\lambda_b = Li_b - M(i_a + i_c);$$
$$\lambda_c = Li_c - M(i_b + i_a)$$
$$i_a + i_b + i_c = 0;$$
$$v_{an} = v_{ao} - v_{no}$$
$$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3$$
$$\lambda_a = (L+M)\, i_a,\ \lambda_b = (L+M)\, i_b,\ \lambda_c = (L+M)\, i_c,$$
$$pi_x = (v_{xn} - i_x R - e_{xn})/(L+M)$$

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 $\omega = p\theta$ 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.

IV. 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.

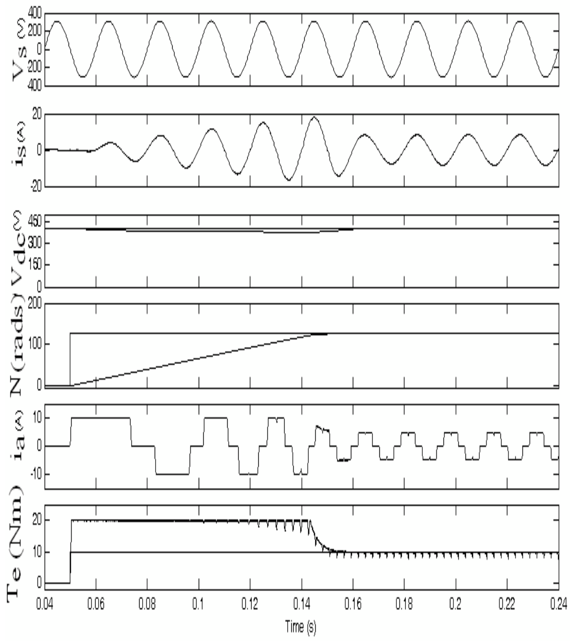
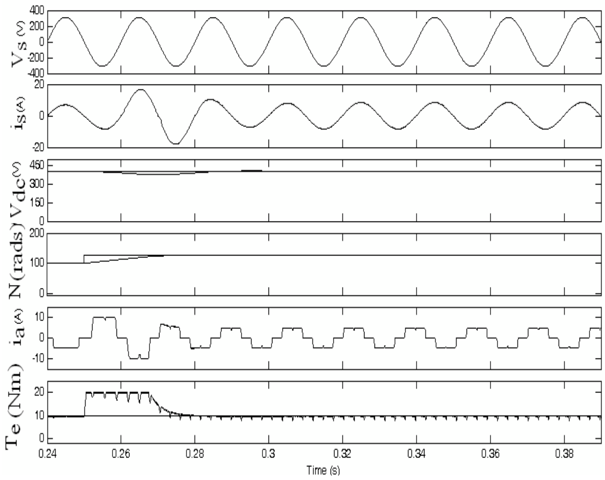
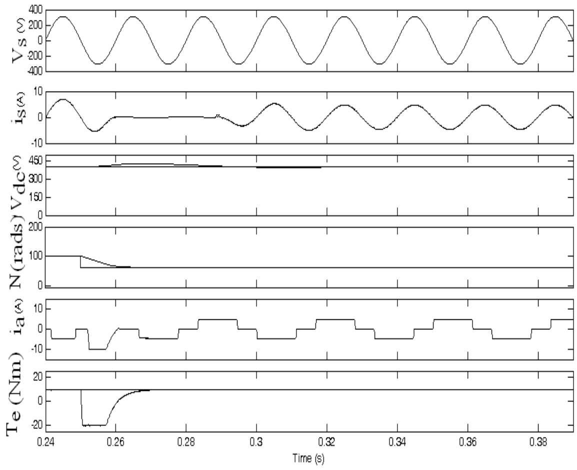


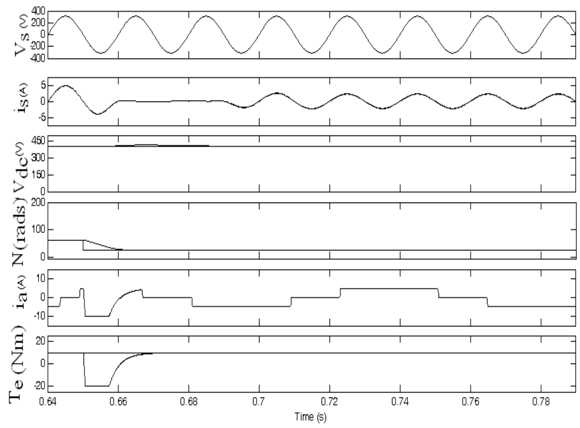
Fig. 4: Performance of a SEPIC converter fed PMBLDCM drive during Starting at rated speed i.e. 1200 rpm (125.7 rad/s) and rated torque (9.61 Nm) with 220 V_{AC} input supply



5(a): Speed change from 960 rpm (100.5 rad/s) to 1200rpm (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

B. Working Performance at Various Variable Speeds

Figs. 5a-c shows 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.

C. Working Performance under Various 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) .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.

Table 1: 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

V. Conclusion

The PFC converter has ensured reasonable high power factor close to unity in wide range of the speed as well as input AC voltage. A PFC based SEPIC converter for a PMBLDCM drive has been designed for a compressor load of an air-conditioner. 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. 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 $I_c(k-1)$ 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

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

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

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

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

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

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

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

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: 0.03pu, 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

References

[1] A. M.Jungreisand A.W. Kelley, "Adjustable speed drive for residential applications", IEEE Trans. Ind. Appl., Vol.31, No.6, Nov.-Dec. 1995, pp.1315 – 1322.

[2] T. Kenjo and S. Nagamori, Permanent Magnet Brushless DC Motors, Clarendon Press, oxford, 1985.

[3] T. J. Sokira and W. Jaffe, Brushless DC Motors: Electronic Commutation and Control, Tab Books USA, 1989.

[4] J. R. Hendershort Jr and T. J. E. Miller, Design of Brushless Permanent-Magnet Motors, Clarendon Press, Oxford, 1994.

[5] J.F. Gieras and M. Wing, Permanent Magnet Motor Technology – Design and Application, Marcel Dekker Inc. New York, 2002.

[6] N. Matsui, "Sensor less PM brushless DC motor drives", IEEE Trans. Ind. Electron., Vol.43, No.2, April 1996, pp.300 – 308.

[7] P. Pillay and R. Krishnan, "Modeling, simulation and analysis of a permanent magnet brushless dc motor drives, part II: the brushless dc motor drive", IEEE Trans. Ind. Appl., Vol. 25, No.2, Mar. Apr 1989, pp 274-279.

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

Amit Kumar Sinha was born in Jamshedpur, India, in 1991. He received B.E (Electrical and Electronics)degree from Meenakshi Academy of Higher Education and Research, Chennai, India in 2012. He is doing M.E (Power Electroics and Drives) from Gnanamani College of Engineering, Anna University, Chennai, India .His area of intrest includes Power electronics, Electrical Machines and Power Quality. He is a student member of Institute of Electrical and Electronics Engineers (IEEE).

Gandhi.R was born in Namakkal, India, in 1979. He received B.E (Electrical and Electronics) degree from Madras University, Chennai, India in 2001. He had done M.E in (Power Electronics and Drives) from Sona College of Technology, Anna University, Chennai, India in 2008. He is doing Ph.d (part time) from Anna University, Chennai, India. His area of intrest includes Power electronics and Electrical Machines.