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Improvement of Power Quality in A PMBLDC Motor Drive Using a Forward Buck Converter

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Abstract: ***Solid-state switch-mode rectification converters have reached a matured level for improving power quality in terms of power-factor correction (PFC), reduced total harmonic distortion at input ac mains and precisely regulated dc output in buck, boost, buck–boost and multilevel modes with unidirectional and bidirectional power flow. In this paper, an improved power quality converter employing conventional PI based & intelligence controlled (FLC) forward buck converter topology is used to feed a permanent magnet brushless DC motor (PMBLDCM) drive. Normally, the PMBLDCM drive consists of 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 conventional pi and fuzzy logic controlled based forward buck 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 control.***

Keywords: Air conditioner, Forward Buck Converter, Speed Control, PFC, PMBLDCM, VSI, Fuzzy Logic Controller (FLC).

1. Introduction

Electric Power quality is a term which has captured increasing attention in power engineering in the recent years, The measure of power quality depends upon the needs of the equipment that is being supplied. What is good power quality for an electric motor may not be good enough for a personal computer. Usually the term power quality refers to maintaining a sinusoidal waveform of bus voltages at rated voltage and frequency [1]. The waveform of electric power at generation stage is purely sinusoidal and free from any distortion. Many of the Power conversion and consumption equipment are also designed to function under pure sinusoidal voltage waveforms. However, there are many devices that distort the waveform. These distortions may propagate all over the electrical system. In recent years, there has been an increased use of non-linear loads which has resulted in an increased fraction of non-sinusoidal currents and voltages in Electric Network. Classification of power quality areas may be made according to the source of the problem such as converters, magnetic circuit non linearity, arc furnace or by the wave shape of the signal such as harmonics, flicker or by the frequency spectrum (radio frequency interference). The wave shape phenomena associated with power quality may be characterized into synchronous and non synchronous phenomena. Synchronous phenomena refer to those in synchronism with A.C waveform at power frequency [2],[3].

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 fly back or a forward converter has been used for low power application and a full-bridge converter for higher power applications.. 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.

A forward buck DC-DC converter is employed as a single-stage PFC converter for power quality improvement in the PMBLDCM driven Air-Con due to its simplicity and low cost among other single switch converters. Moreover, it has minimum cost, switching losses and voltage drop in the secondary winding of the high frequency transformer which results in improved efficiency of the PFC converter. The proposed single-stage PFC converter based drive needs a careful design to operate over a wide range of operating conditions for a PMBLDCM driven Air-Con i.e. variable input AC voltage and speed of the motor.

Conventionally, PI, PD and PID controller are most popular controllers and widely used in most power electronic closed loop appliances however recently there are many researchers reported successfully adopted Fuzzy Logic Controller (FLC) to become one of intelligent controllers to their appliances [3]. With respect to their successful methodology implementation, control closed loop forward buck converter. This kind of methodology implemented in this paper is using fuzzy logic controller with feed back by introduction of voltage output respectively. The introduction of voltage output in the circuit will be fed to fuzzy controller to give appropriate measure on steady state signal. The fuzzy logic controller serves as intelligent controller for this propose. This paper deals with the detailed modeling, design and performance evaluation of the proposed drive with conventional PI controller and intelligence controller (FLC)

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and simulation work is carried out in MATLAB/SIMULINK platform.

2. Literature Survey

2.1 Control Scheme for PFC Converter

The proposed control scheme for improved PQ converter i.e. the forward buck converter or PFC converter is shown in Fig. 1 which uses average current control with current multiplier approach. The forward buck converter controls the DC link voltage as well as performs PFC action by its duty ratio (D) at a constant switching frequency (fs). The proposed PFC control scheme employs a current control loop inside the voltage control loop in the continuous conduction mode (CCM) operation of the PFC converter.

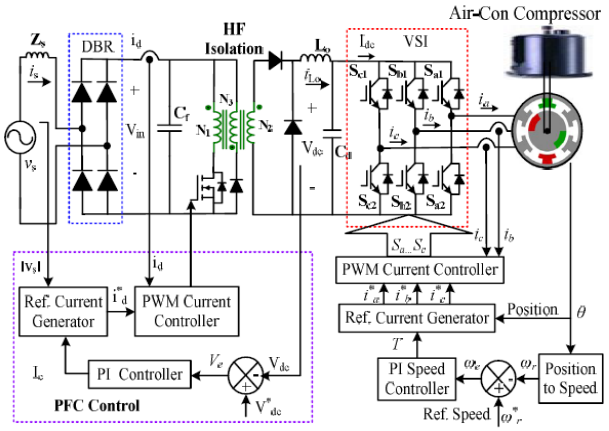

Fig. 2: Schematic diagram of the proposed forward-buck PFC converter fed PMBLDCM drive

A proportional-integral (PI) controller forms an integral part of this controller which processes the voltage error resulting from the comparison of set voltage reference and sensed voltage at DC link. The resultant control signal of PI controller is multiplied with a unit template of input AC voltage and compared with DC current sensed after the DBR. The resultant current error is amplified and compared with a saw-tooth carrier wave of fixed frequency (fs) for generating the PWM pulses for controlling switch of PFC converter. Use of a high switching frequency results in a fast control of DC link voltage and effective PFC action along with additional advantage of reduced size magnetics and filters. The optimum switching frequency is decided by various factors such as the switching device, switching losses and operating power level. A metal oxide field effect transistor (MOSFET) is used as the switching device for the proposed PFC converter.

2.2 Design of PFC Forward Buck Converter

The proposed PFC forward buck converter is designed for a PMBLDCM drive with an objective of PQ improvement at AC mains. It consists of a DBR, a forward buck converter and an output ripple filter. The DBR has average output voltage (V_{in}) for a given AC input voltage (Vs) related as

$$V_{in} = 2\sqrt{2}V_s/\pi \quad (1)$$

The forward buck converter controls the DC link voltage at a set reference value given as,

$$V_{dc} = (N_2/N_1)\, V_{in}\, D \text{ with } D(1+N_3)/N_1<1 \quad (2)$$

where N1, N2, N3 are number of turns in primary, secondary and tertiary windings of the high frequency (HF) isolation transformer, respectively. The tertiary winding is used for resetting the flux in the transformer core during turnoff time, which returns stored energy back to DC source. The high frequency AC voltage is rectified using half wave rectifier. A ripple filter is designed for constant output voltage with inductance (Lo) and capacitance (C_d) so that the peak to peak ripple of inductor current (ΔI_{Lo}) and capacitor voltage (ΔV_{Cd}) is maintained within specified value for the given switching frequency (fs). The values of output filter inductor and capacitor are calculated as,

$$L_o = (1-D)V_{dc}/\{f_s(\Delta I_{Lo}) \quad (3)$$

$$C_d = I_{dc}/(2\omega\Delta V_{Cd}) \quad (4)$$

3. Methods/Approach

3.1 Modelling of PFC Converter Based PMBLDCM Drive

The modeling of PMBLDCM drive involves modeling of the PFC converter and PMBLDCM drive in the form of mathematical equations. The combination of these individual models represents a complete model of proposed PFC drive.

The modeling of PFC converter consists of the modeling of a DC link voltage controller, a reference current generator and a PWM controller.

1) DC Link Voltage Controller:

The DC link voltage controller is a PI controller which outputs a control signal (I_c) to minimize the input voltage error. 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,

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \quad (5)$$

The controller output $I_c(k)$ at k_{th} instant is given as,

$$I_c(k) = I_c(k-1) + K_{pv}\{V_e(k) - V_e(k-1)\} + K_{iv}V_e(k) \quad (6)$$

where K_{pv} and K_{iv} are the gains of the voltage PI controller

2) Reference Converter Current:

The reference input current of the PFC converter (i^*_d) is given as,

$$i^*_d = I_c(k)\, u_{vs} \quad (7)$$

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

$$u_{vs} = v_d/V_{sm};\ v_d = |v_s|;\ v_s = V_{sm} \sin \omega t \quad (8)$$

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

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3) PWM Controller:

The reference input current of the PFC converter (i^*_d) is compared with its sensed current (i_d) to generate the current error $\Delta i_d = (i^*_d - i_d)$. This current error is amplified by gain k_d and compared with fixed frequency (f_s) saw-tooth carrier waveform $m_d(t)$ to get the switching signals for the MOSFET of the PFC converter as,

$$\text{If } k_d \Delta i_d > m_d(t) \text{ then } S = 1 \quad (9)$$
$$\text{If } k_d \Delta i_d <= m_d(t) \text{ then } S = 0 \quad (10)$$

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

The PMBLDCM drive has a speed controller, a reference winding current generator, a PWM current controller, a VSI and a PMBLDC motor as the main components.

4) Speed controller

The speed controller is a PI controller which closely tracks the reference speed. If at kth instant of time, $\omega^*_r(k)$ is the reference speed, $\omega_r(k)$ is the rotor speed then the speed error $\omega_e(k)$ can be calculated as,

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

This speed error is fed to a speed controller to get a control signal. The controller's output at k_{th} instant T(k) is given as,

$$T(k) = T(k-1) + K_{p\omega}\{\omega_e(k) - \omega_e(k-1)\} + K_{i\omega}\,\omega_e(k) \quad (12)$$

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

5) Reference Winding Current Generator:

The amplitude of stator winding current is calculated as,

$$I^* = T(k) / (2K_b) \quad (13)$$

where, K_b is the back emf constant of the PMBLDCM. The reference phase currents of the PMBLDCM are denoted by i_a^*, i_b^*, i_c^* for phases a, b, c respectively. For duration of 0-60º the reference currents are given as,

$$i_a^* = I^*,\ i_b^* = -I^* \text{ and } i_c^* = 0 \quad (14)$$

Similarly, the reference winding currents during other 60º duration are generated in rectangular 120º block form in phase with trapezoidal voltage of respective phases.

6) PWM Current Controller:

Reference winding currents are compared with sensed currents (i_a, i_b, i_c) in a PWM current controller to get 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 and compared with a fixed frequency carrier waveform m(t) to generate the switching sequence for the VSI as shown for phase "a",

$$\text{If } k_1 \Delta i_a > m(t) \text{ then } S_a = 1 \text{ (IGBT 'On')} \quad (15)$$
$$\text{If } k_1 \Delta i_a \leq m(t) \text{ then } S_a = 0 \text{ (IGBT 'Off')} \quad (16)$$

The switching sequences S_b and S_c are generated using similar logic for other two phases of the motor

7) Voltage Source Inverter

The VSI bridge feeding PMBLDCM uses insulated gate bipolar transistors (IGBTs) to reduce the switching stress, because of its operation at lower frequency compared to PFC converter. Fig. 2 shows an equivalent circuit of a VSI fed PMBLDCM. The output of VSI for phase 'a' is given as,

$$v_{ao} = (V_{dc}/2) \text{ for } S_{a1} = 1, \text{ and } S_{a2} = 0 \quad (17)$$
$$v_{ao} = (-V_{dc}/2) \text{ for } S_{a2} = 1, \text{ and } S_{a1} = 0 \quad (18)$$
$$v_{ao} = 0 \text{ for } S_{a1} = 0, \text{ and } S_{a2} = 0 \quad (19)$$

The voltages (v_{bo}, v_{co}, v_{bn}, v_{cn}) for other phases of the VSI fed PMBLDCM are generated using similar logic

$$v_{an} = v_{ao} - v_{no} \quad (20)$$

where v_{ao}, v_{bo}, v_{co}, and v_{no} are voltages of 3-phases and neutral point (n) with respect to virtual mid-point of the DC link voltage shown as 'o' in Fig. 3. The voltages v_{an}, v_{bn}, v_{cn} are voltages of 3-phases with respect to neutral point (n). The values 1 and 0 for S_{a1} or S_{a2} represent 'on' and 'off' condition of respective IGBTs of the VSI. The switching of other IGBTs of the VSI i.e. S_b and S_c are obtained in a similar way.

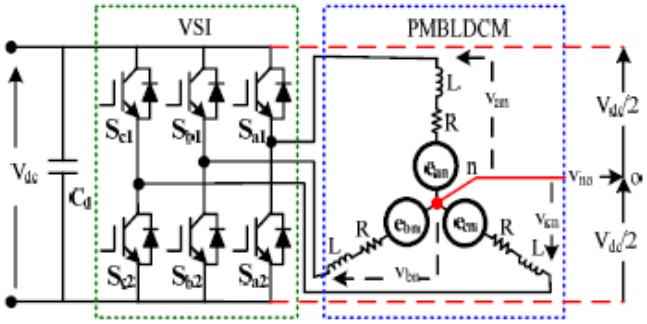

Figure 2: Equivalent circuit of a VSI fed PMBLDCM drive

8) PMBLDC Motor

The PMBLDCM is modeled in the form of a set of differential equations given as,

$$v_{an} = Ri_a + p\lambda_a + e_{an} \quad (21)$$
$$v_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (22)$$
$$v_{cn} = Ri_c + p\lambda_c + e_{cn} \quad (23)$$

In these equations, p represents differential operator (d/dt), i_a, i_b, i_c are currents, λ_a, λ_b, λ_c are flux linkages and e_{an}, e_{bn}, e_{cn} are phase to neutral back emfs of PMBLDCM, in respective phases, R is resistance of motor windings/phase. Moreover, the flux linkages can be represented as,

$$\lambda_a = L_s i_a - M(i_b + i_c) \quad (24)$$
$$\lambda_b = L_s i_b - M(i_a + i_c) \quad (25)$$
$$\lambda_c = L_s i_c - M(i_b + i_a) \quad (26)$$

The developed torque T_e in the PMBLDCM is given as,

$$T_e = (e_{an} i_a + e_{bn} i_b + e_{cn} i_c)/\Delta_r \quad (27)$$

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where Δ_r is motor speed in rad/sec, Since the PMBLDCM has no neutral connection, therefore,

$$i_a + i_b + i_c = 0 \quad (28)$$

From Eqs. (20-26, 28) the voltage (v_{no}) between neutral point (n) and mid-point of the DC link (o) is given as,

$$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3 \quad (29)$$

From Eqs. (24-26, 28), the flux linkages are given as,

$$\lambda_a = (L_s+M)\, i_a, \lambda_b = (L_s+M)\, i_b, \lambda_c = (L_s+M)\, i_c, \quad (30)$$

generalized state space form are given as,

$$pi_x = (v_{xn} - i_x R - e_{xn})/(L_s+M) \quad (31)$$

where x represents phase a, b or c. The back emfs may be expressed as a function of rotor position (θ) as,

$$e_{xn} = K_b f_x(\theta)\, \theta_r \quad (32)$$

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

$$f_a(\theta) = 1 \text{ for } 0 < \theta < 2\pi/3 \quad (33)$$

$$f_a(\theta) = \{(6/\pi)(\pi - \theta)\} - 1 \text{ for } 2\pi/3 < \theta < \pi \quad (34)$$

$$f_a(\theta) = -1 \text{ for } \pi < \theta < 5\pi/3 \quad (35)$$

$$f_a(\theta) = \{(6/\pi)(\theta - 2\pi)\} + 1 \text{ for } 5\pi/3 < \theta < 2\pi \quad (36)$$

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

$$T_e = K_b\{f_a(\theta)\, i_a + f_b(\theta)\, i_b + f_c(\theta)\, i_c\} \quad (37)$$

The speed derivative is given as,

$$p\omega_r = (P/2)\,(T_e - T_l - B\omega_r)/(J) \quad (38)$$

The derivative of rotor position is given as,

$$p\theta = \omega_r \quad (39)$$

where P is number of poles, T_l is load torque, J is moment of inertia (kg-m2) and B is friction coefficient (Nms/Rad). These equations (21-39) represent the dynamic model of the PMBLDC motor.

3.2 Fuzzy Logic Controller

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and Some time even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to forward buck converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of forward buck converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of converters. The basic scheme of a fuzzy logic controller is shown in Fig 3 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [1111].

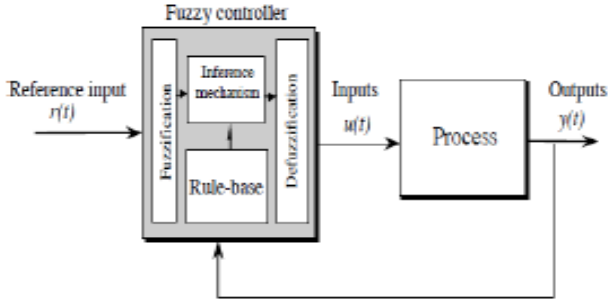

Figure 3: General structure of the fuzzy logic controller on closed-loop system

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [101111]. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

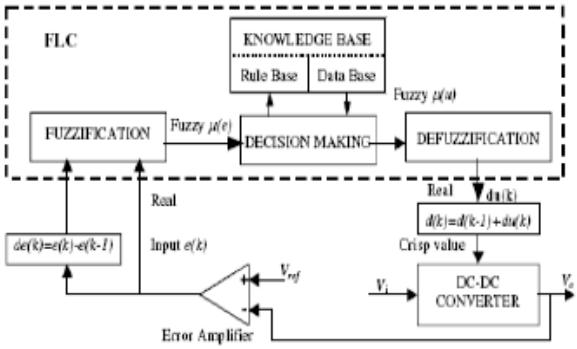

Figure 4: Block diagram of the Fuzzy Logic Controller (FLC) for forward buck converter

A. Fuzzy Logic Membership Functions

Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty gain signal of the converter.

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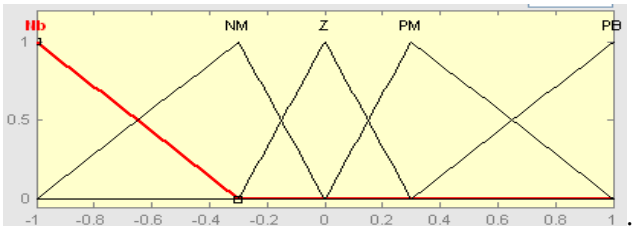
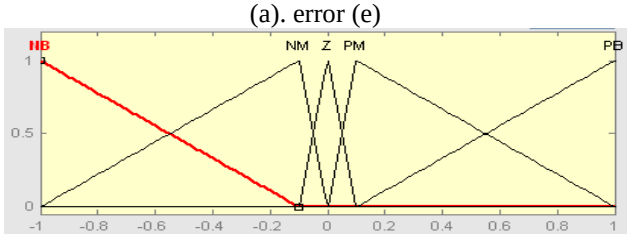
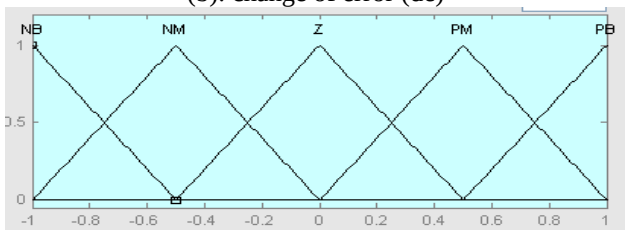


(a). error (e)



(b). change of error (de)



(c) output variable (u)

Figure 5: The Membership functions for error(e), change in error(de), output(u)

B. Fuzzy Logic Rules:

The objective of this dissertation is to control the output voltage of the forward buck converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Medium, ZO: Zero Area and PM: Positive Medium, PB: Positive Big and its parameter [10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Fig.6 as per below:

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

Figure 6: Rules for membership functions

4. Results

4.1 Matlab/Simulink Modelling And Simulation Results

Here the simulation is carried out by two cases

1) A Proposed forward buck converter using conventional pi controller
2) A Proposed forward buck converter using fuzzy logic controller.

Case 1: A Proposed forward buck converter using conventional pi controller:

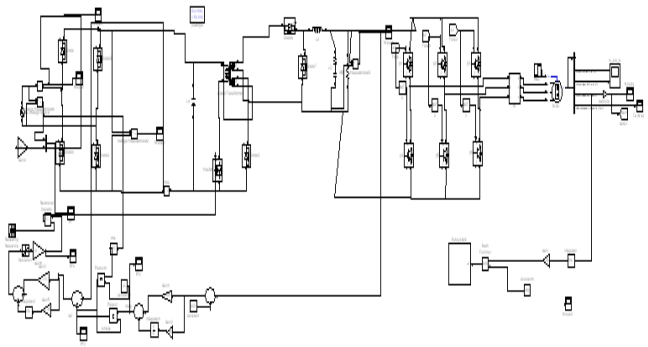


Figure 7: Matlab/Simulink model of proposed forward buck converter using conventional pi controller

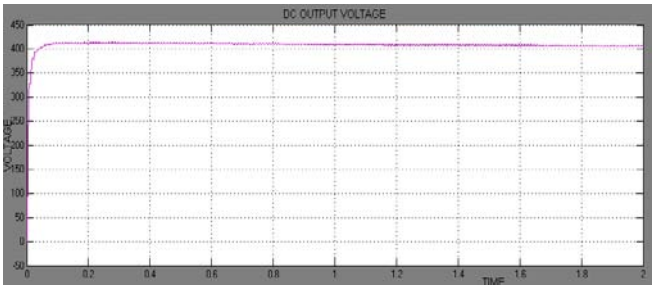


Figure 8: Output voltage of the forward buck converter

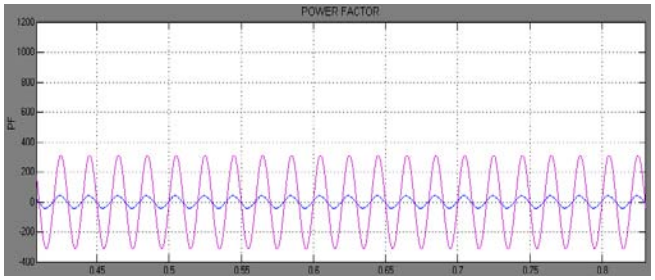


Figure 9: Power factor

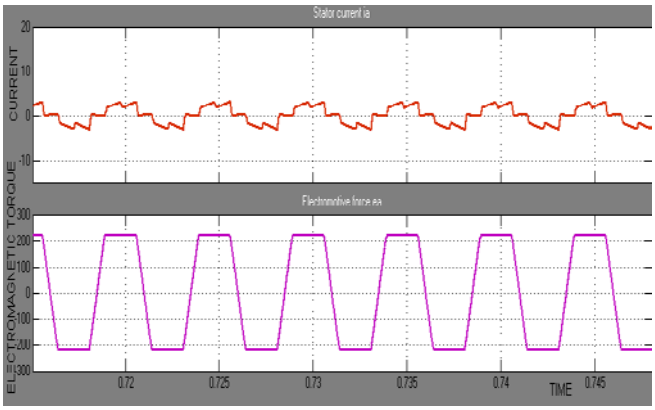


Figure 10: Stator current and electromagnetic torque of the BLDC motor drive

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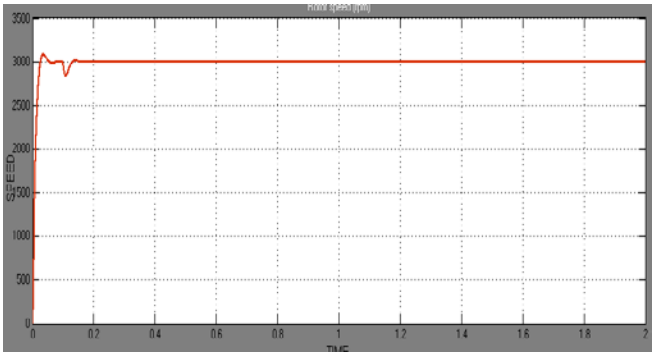

Figure 11: Speed of the BLDC motor drive

Case 2: A Proposed forward buck converter using fuzzy logic controller

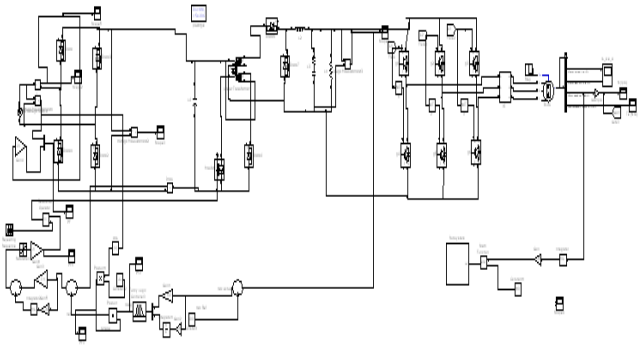

Figure 12: Matlab/Simulink Model of Proposed forward buck converter using fuzzy logic controller

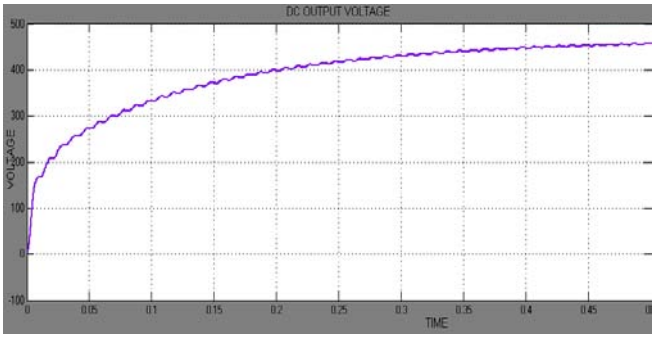

Figure 13: Output voltage of the forward buck converter

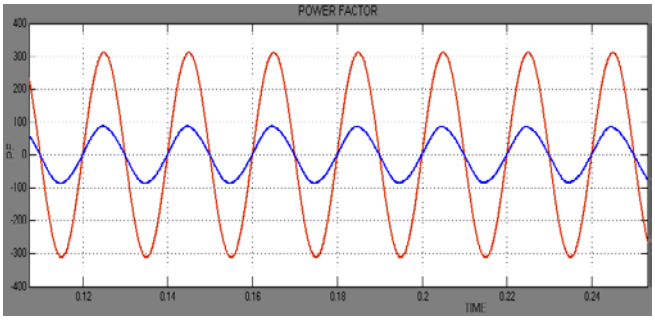

Figure 14: power factor, our voltage and current are in phase

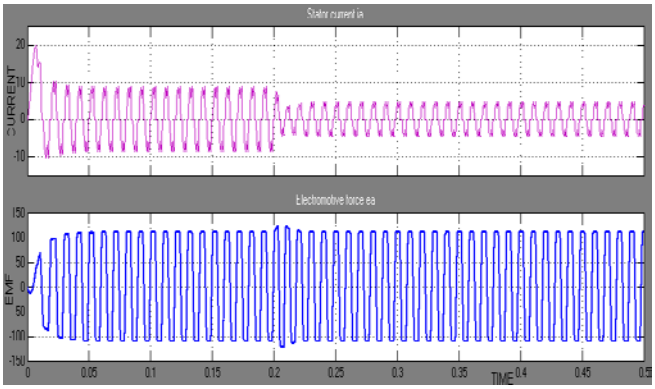

Figure 15: Stator current and electromagnetic torque of the BLDC motor drive

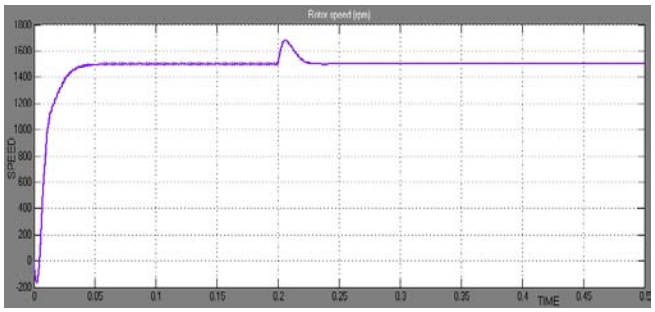

Figure 16: Speed of the BLDC motor drive

5. Conclusion

A single stage PFC control strategy of a VSI fed PMBLDCM drive using forward buck converter using conventional pi controller and fuzzy logic controller has been validated for a compressor load of an air conditioner. The current multiplier approach with average current control has been used for operation of a forward buck converter in continuous conduction mode. The PFC forward buck converter of the proposed drive has ensured nearly unity PF in wide range of the speed and the input AC voltage. Moreover, power quality parameters of the proposed drive are in conformity to the International standard IEC.

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