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Power Quality Improvement in A PMBLDCM Drive by Using PFC CUK Converter

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Abstract

The techniques to improve the efficiency of motor drive by power factor correction play an important role in the energy saving during energy conversion. Permanent magnet brushless DC motor (PMBLDCM) drives are being employed in many variable speed applications due to their high efficiency, silent operation, high reliability, ease of control, and low maintenance requirements. These drives have power quality problems and poor power factor at input AC mains as they are mostly fed through diode bridge rectifier. To overcome such problems a single-phase single-switch power factor correction AC-DC converter topology based on a Cuk converter is proposed. It focuses on the analysis, design and performance evaluation of the proposed PFC converter topology for PMBLDCM drive used for an air-conditioning system. The proposed PFC converter topology is modeled and its performance is simulated in Matlab-Simulink environment and results show an improved power quality and good power factor in wide speed range of the drive. Also compared THD of the Input AC current with both PI controller and Fuzzy logic controller in Mat lab-Simulink environment.

Index Terms — Air-conditioner, Cuk converter, power factor (PF) correction (PFC), permanent-magnet (PM) brushless dc motor (PMBLDCM),voltage-source inverter.

I. INTRODUCTION

A permanent magnet brushless DC motor (PMBLDCM) is a kind of three-phase synchronous motor regarded as a rugged and efficient machine for variety of applications. Usually, the PMBLDCMs 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). Due to the uncontrolled charging of DC link capacitor, the AC mains current waveform is a pulsed waveform featuring a peak value higher than the peak of the fundamental input current.

This is due to the fact that, the DBR does not draw any current from the AC mains when the AC voltage is less than the DC link voltage, as the diodes are reverse biased during that period; however, it draws a large current when the AC voltage is higher than the DC link voltage. 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 become more severe for the utility when many such drives are employed simultaneously at various places.

Therefore, the drive system having inherent power factor correction (PFC) are more in demand and PFC converters have become preferred feature of new drives. Since the PMBLDCM drives have to be operated from the utility supply, therefore they should conform to the international PQ standards. To comply with the PQ standards in the low power range, the power factor correction (PFC) converter topology using active wave shaping techniques is a popular and preferred solution in domestic applications. The PFC converter forces the drive to draw sinusoidal AC mains current in phase with its voltage. Moreover, for PFC converter fed PMBLDCM drives, the additional cost and complexity of the PFC converter are not justified, therefore, converter topologies with inherent feature of PFC are preferred in these drives. Therefore, a DC-DC converter topology is mostly preferred amongst several available topologies [5-6].

This paper deals with a Cuk converter as PFC AC-DC converter to feed PMBLDCM driven air-conditioner. Because, the Cuk converter with PFC inherits advantages like low current and voltage ripple in output, near unity power factor with simple control and reduced size magnetics [8-10]. A detailed design and performance evaluation of the proposed PFC converter for feeding PMBLDCM drive are presented for air-conditioning system.

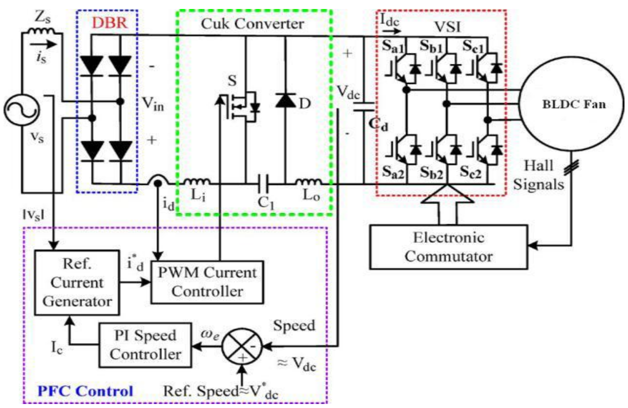


Figure 1. The proposed Cuk PFC converter-fed VSI-based PMBLDCMD control scheme.

II. OPERATION AND CONTROL OF CUK CONVERTER FED PMBLDCM

Fig.1 shows the proposed speed control scheme which is based on the control of the dc link voltage reference as an equivalent to the reference speed. However, the rotor position signals acquired by Hall-effect sensors are used by an electronic commutator to generate switching sequence for the VSI feeding the PMBLDC motor, and therefore, rotor position is required only at the commutation points [1]–[4].

The Cuk dc–dc converter controls the dc link voltage using capacitive energy transfer which results in no pulsating input and output currents [8]. The proposed PFC converter is operated at a high switching frequency for fast and effective control with additional advantage of a small size filter. For high-frequency operation, a metal–oxide–semiconductor field-effect transistor (MOSFET) is used in the proposed PFC converter, whereas insulated gate bipolar transistors (IGBTs) are used in the VSI bridge feeding the PMBLDCM because of its operation at lower frequency compared to the PFC converter.

The PFC control scheme uses a current multiplier approach with a current control loop inside the speed control loop for continuous-conduction-mode operation of the converter. The control loop begins with the processing of voltage error (Ve), obtained after the comparison of sensed dc link voltage (Vdc) and a voltage (V*dc) equivalent to the reference speed, through a proportional–integral (PI) controller to give the modulating control signal (I_c). This signal (I_c) is multiplied with a unit template of input ac voltage to get the reference dc current (I*d) and compared with the dc current (Id) sensed after the DBR. The resultant current error (I_e) is amplified and compared with a saw tooth carrier wave of fixed frequency (f_s) to generate the pulse width modulation (PWM) pulse for the Cuk converter. Its duty ratio (D) at a switching frequency (f_s) controls the dc link voltage at the desired value. For the control of current to PMBLDCM through VSI during the step change of the reference voltage due to the change in the reference speed, a rate limiter is introduced, which limits the stator current of the PMBLDCM within the specified value which is considered as double the rated current in this work.

III. PFC CUK CONVERTER DESIGN FOR PMBLDCMD

The proposed PFC Cuk converter is designed for a PMBLDCMD with main considerations on the speed control of the Air-Con and PQ improvement at ac mains. The dc link voltage of the PFC converter is given as

$$V_{dc} = V_{in}D/\ (1 - D) \quad (1)$$

Where V_{in} is the average output of the DBR for a given ac input voltage (V_s) related as

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

The Cuk converter uses a boost inductor (L_i) and a capacitor (C_1) for energy transfer. Their values are given as

$$L_i = DV_{in}\ /\ \{f_s\ (\Delta I_{Li})\} \quad (3)$$

$$C_1 = DI_{dc}\ /\ \{f_s \Delta V_{C1}\} \quad (4)$$

where ΔI_{Li} is a specified inductor current ripple, ΔV_{C1} is a specified voltage ripple in the intermediate capacitor (C_1), and I_{dc} is the current drawn by the PMBLDCM from the dc link.

A ripple filter is designed for ripple-free voltage at the dc link of the Cuk converter. The inductance (L_o) of the ripple filter restricts the inductor peak-to-peak ripple current (ΔI_{Lo}) within a specified value for the given switching frequency (f_s), whereas the capacitance (C_d) is calculated for the allowed ripple in the dc link voltage

(ΔV_{Cd}) [7], [8]. The values of the ripple filter inductor and capacitor are given as

$$L_o = (1 - D)\, V_{dc} / \{f_s\, (\Delta I_{Lo})\} \quad (5)$$

$$C_d = I_{dc} / (2\omega \Delta V_{Cd}) \quad (6)$$

The PFC converter is designed for a base dc link voltage of Vdc = 298 V at Vs = 220 V for fs = 40 kHz, Is = 4.5 A, ΔILi = 0.45 A (10% of Idc), Idc = 3.5 A, ΔILo = 3.5 A (≈ Idc), ΔVCd = 4 V (1% of Vo), and ΔVC1 = 220 V (≈ Vs). The design values are obtained as Li = 6.61 mH, C1 = 0.3 μF, Lo = 0.82 mH, and Cd=1590μF.

IV. MODELING OF PFC CONVERTER-BASED PMBLDCMD

The PFC converter and PMBLDCMD are the main components of the proposed drive, which are modeled by mathematical equations, and a combination of these models represents the complete model of the drive.

A. PFC Converter

The modeling of the PFC converter consists of the modeling of a speed controller, a reference current generator, and a PWM controller as given hereinafter.

1) Speed Controller: The speed controller is a PI controller which tracks the reference speed as an equivalent reference voltage. If, at the kth instant of time, V ∗ dc(k) is the reference dc link voltage and Vdc(k) is the voltage sensed at the dc link, then the voltage error Ve(k) is given as

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k). \quad (7)$$

The PI controller output $I_c(k)$ at the kth instant after processing the voltage error $V_e(k)$ is given as

$$I_c(k) = I_c(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \quad (8)$$

where K_p and K_i are the proportional and integral gains of the PI controller.

2) Reference Current Generator: The reference current at the input of the Cuk converter (i^*d) is

$$i^*d = I_c(k) uV_s \quad (9)$$

where uV_s is the unit template of the ac mains voltage, calculated as

$$uV_s = v_d/V_{sm};\ v_d = |v_s|;\ v_s = V_{sm} \sin \omega t \quad (10)$$

where V_{sm} and ω are the amplitude (in volts) and frequency (in radians per second) of the ac mains voltage.

3) PWM Controller: The reference input current of the Cuk converter (i^*_d) is compared with its current (i_d) sensed after DBR 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 $m_d(t)$ [6] to get the switching signal for the MOSFET of the PFC Cuk converter as

$$\text{If } k_d \Delta i_d > m_d(t) \text{ then } S = 1 \text{ else } S = 0 \quad (11)$$

where S denotes the switching of the MOSFET of the Cuk converter as shown in Fig. 1 and its values "1" and "0" represent "on" and "off" conditions, respectively.

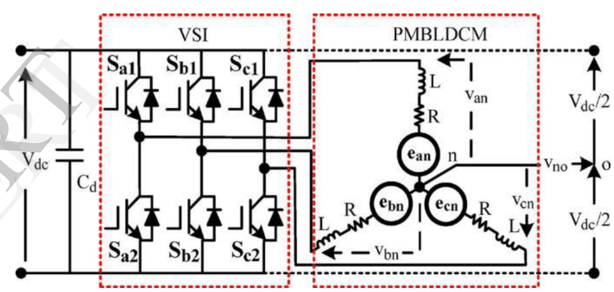


Figure 2. Equivalent circuit of a VSI-fed PMBLDCMD

B. PMBLDCMD

The PMBLDC motor can be modeled in the form of a set of differential equations given as,

$$p i_x = (v_x - i_x R_a - e_x) / (L_s + M) \quad (12)$$

$$p\omega_r = (P/2)\,(T_e - T_l) / J \quad (13)$$

$$p\theta = \omega_r \quad (14)$$

The back emfs may be expressed as a function of position (θ) as,

$$e_x = K_b\, f_x(\theta)\, \omega_r \quad (15)$$

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,

$$f_a(\theta) = 1 \text{ for } 0 < \theta < 2\pi/3 \quad (16)$$

$$f_a(\theta) = (6/\pi)(\pi - \theta) - 1 \text{ for } 2\pi/3 < \theta < \pi \quad (17)$$

$$f_a(\theta) = -1 \text{ for } \pi < \theta < 5\pi/3 \quad (18)$$

$$f_a(\theta) = (6/\pi)(\theta - 2\pi) + 1 \text{ for } 5\pi/3 < \theta < 2\pi \quad (19)$$

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,

$$T_e = K_b[f_a(\theta)\, i_a + f_b(\theta)\, i_b + f_c(\theta)\, i_c] \quad (20)$$

Equations (12-20) represent the model of the PMBLDC motor.

V.INTRODUCTION TO 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 CUK converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behaviour. Matlab/Simulink simulation model is built to study the dynamic behaviour of CUK 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 Figure 3.

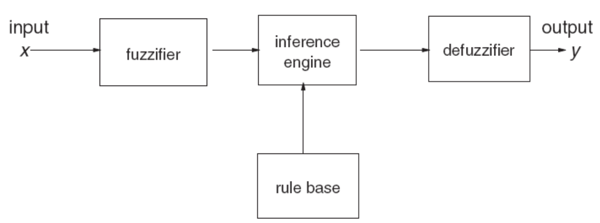
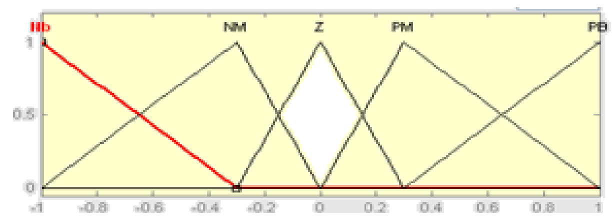


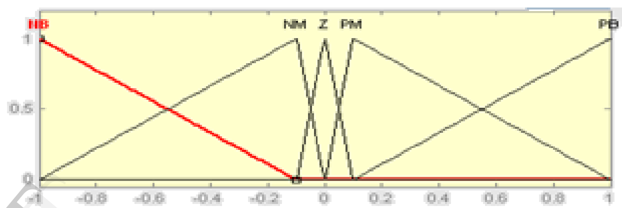
Figure 3: Block diagram Fuzzy logic system

A. Fuzzy Logic Membership Functions

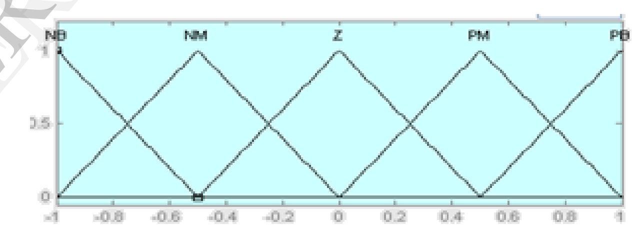
Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style 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.



(a) Error (e)



(b) Change in Error (de)



(c)Output variable (u)

Figure 4: 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 cuk 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 . These fuzzy control rules for error and change of error can be referred in the table 1 is shown below:

Table 1: Rules of membership functions

(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

VI. MATLAB/SIMULINK MODELING AND SIMULATION RESULTS

Here the simulation is carried out by two cases

1. A Proposed cuk converter using Conventional PI controller.
2. A Proposed cuk converter using fuzzy logic Controller.

Case 1: A Proposed cuk converter using Conventional PI controller.

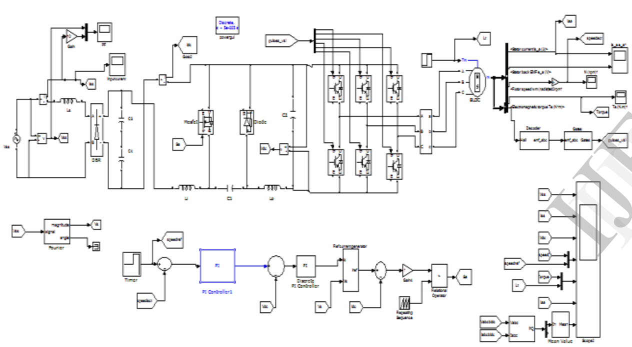


Figure 5: Matlab/Simulink model of proposed cuk converter using conventional PI controller.

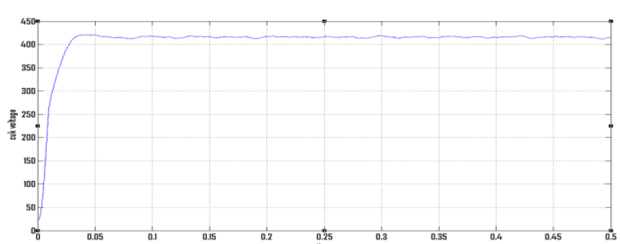


Figure 6: Output voltage of the cuk converter

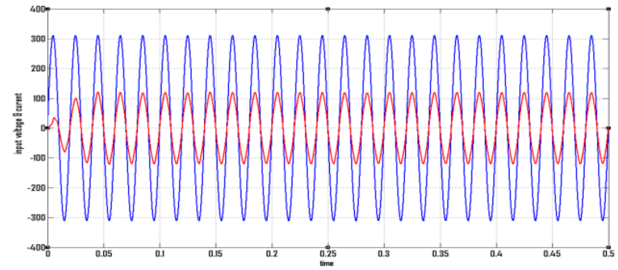


Figure7: Power factor

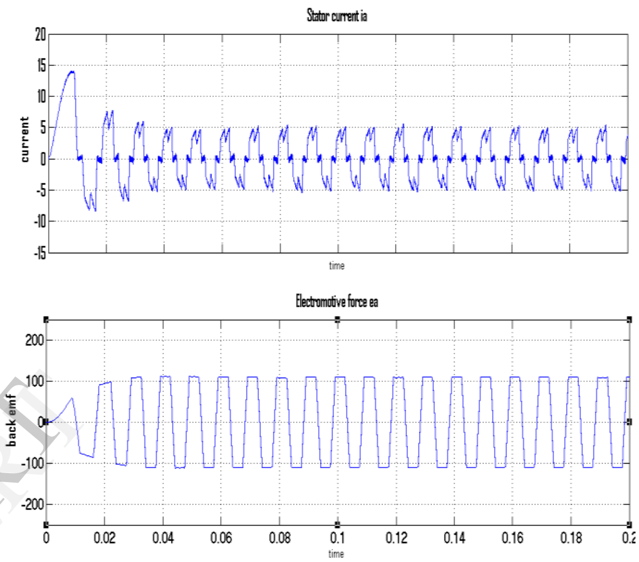


Figure 8: Stator current and Back emf of the BLDC motor drive.

BLDC Motor speed

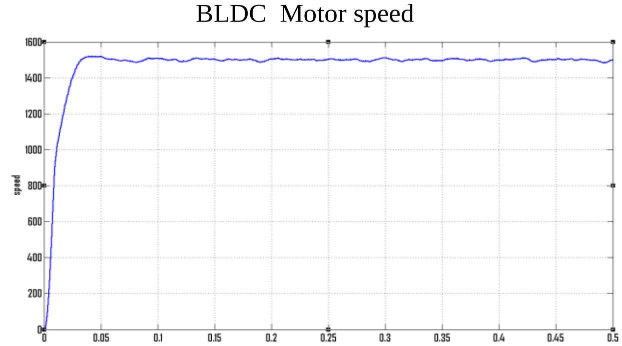


Figure 9: Speed of the BLDC motor drive.

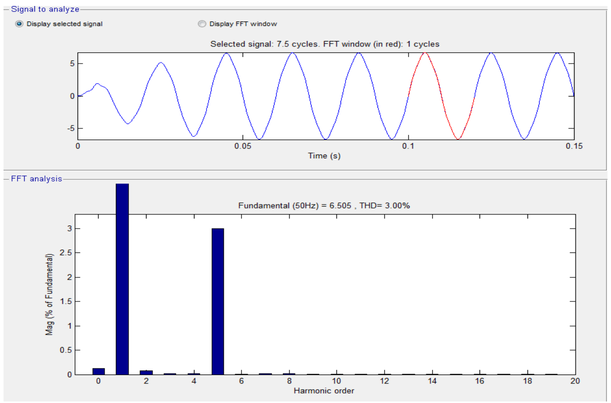


Figure 10: Input current THD for PI controller at a speed of 1500 RPM

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

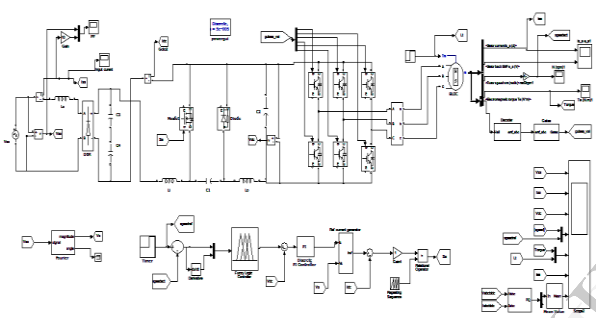


Figure 11: Matlab/Simulink Model of Proposed cuk converter using fuzzy logic controller

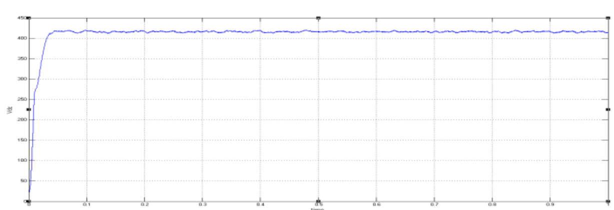


Figure 12: Output voltage of the cuk converter

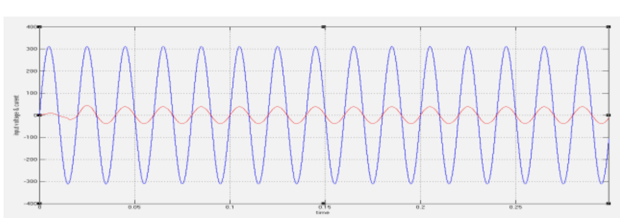


Figure13: Power factor

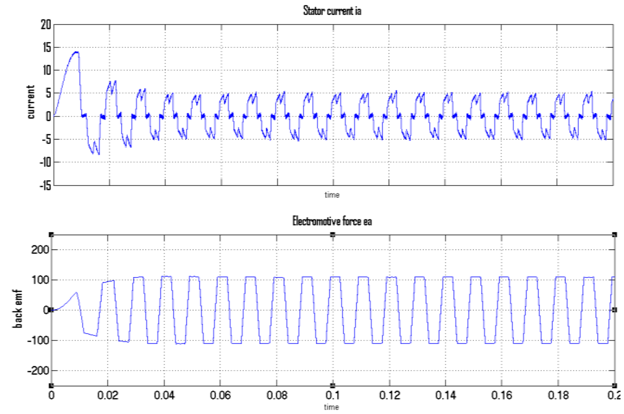


Figure 14. Stator current and Back emf of the BLDC motor drive.

BLDC Motor speed

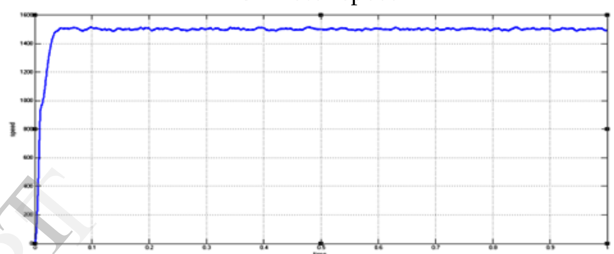


Figure 15: Speed of the BLDC motor drive.

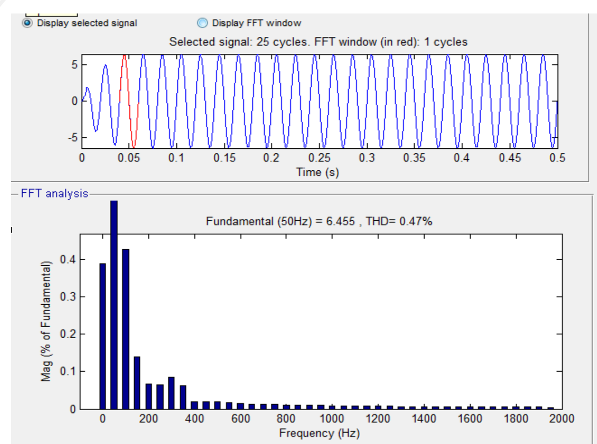


Figure 16: Input current THD for Fuzzy controller at a speed of 1500 RPM.

Here all the above results are obtained at a speed of 1500 rpm for PMBLDCM drive. The comparison between PI & Fuzzy controller for input current THD is shown in Table 2.

Table 2: Comparison between PI & FUZZY controllers

	THD at 500 rpm	THD at 1500 rpm	Power factor
PI controller	3.0%	3.02%	0.9996
Fuzzy controller	0.19%	0.47%	0.9998

VII. CONCLUSION

A single stage PFC control strategy of a VSI fed PMBLDCM drive using CUK 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 CUK converter in continuous conduction mode. The PFC CUK 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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