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IMPROVEMENT OF POWER QUALITY AND SPEED REGULATION OF A BLDC MOTOR DRIVE USING AN INTERLEAVED CONVERTER

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***Abstract*—Interleaved boost converters are preferred for applications which require high efficiency, faster dynamics, less inductor current ripple and high power density. In this paper, an interleaved boost converter is in order to enhance the power quality (PQ). This converter drives a Permanent Magnet Brushless Direct Current (PMBLDC) Motor. The Converter is supplied power through a single phase AC mains supply rectified by a Diode bridge rectifier. The converter supplies DC link voltage to the three phase Voltage Source Inverter (VSI). The inverter goes about as an electronic commutator for the Brushless Direct Current motor driving the Air conditioner compressor. Power Factor correction is done using PI controllers. Speed of the Brushless Direct Current motor is regulated by adjusting the output voltage of the converter. The BLDC motor drive presented is designed and the performance analysis of the drive is done using MATLAB-SIMULINK software.**

Keywords*—*MATLAB-SIMULINK, Permanent Magnet Brushless DC Motor (PMBLDCM), power quality (PQ), Voltage Source Inverter (VSI).

I. INTRODUCTION

Permanent magnet Brushless Direct Current (PMBLDC) motors are classified as one of the types of synchronous motors [1,2]. Ragu S. in “Simulation of Speed Control of Brushless DC Motor for four Quadrant Operation” describes the basic structure of a BLDC motor. The armature windings i.e. the stator windings present in the slots are cut around the poles of the stator (2014) [3]. The armature also has stacked steel laminations [3,4]. The rotor consists of permanent magnets with north and south poles alternatively mounted [3]. This motor has the field which is given by permanent magnets. Hence, this Permanent magnet AC (PMAC) motor has higher efficiency compared to other motors. Brushless Direct Current motors are considered to be one of the promising electrical motors due to increased efficiency, compact size, higher reliability, noiseless operation and lower maintenance [1,2,3,4]. Additionally, in recent times permanent magnets are also less expensive. Arunkumar et al in “A Review Paper on Torque Ripple Reduction and Power Quality Improvement in Brushless DC Motor Drives” emphasizes about how BLDC motors are better compared to others motors for applications in home appliances, medical consumer electronics, automotive sector, aerospace and industries due to their advantages (2014)[4]. This motor is powered by a three phase inverter and it is controlled by the position of the rotor [1,2,3,4]. There are many sensors which are used to find the position of the rotor shaft [1,2]. Shivani Mishra et al in “Speed Control of PMBLDC Motor With the help of PI controller” tells about different position sensors used in detecting the rotor shaft position i.e.Optical encoders, resolvers and Hall sensors are utilized in detecting the angle of rotor shaft w.r.t. a reference axis (2015)[5]. Based on the position of the permanent magnet acting like a rotor, the three Hall sensors give a particular signal. These signals are used to trigger the power electronic switches of the inverter. Hence quasi rectangular current signals with a phase shift of 120º are generated. These signals power the BLDC motor. Hence, this is a motor which is rotated by electronic means [6,7,8,9]. The starting characteristics of a BLDC motor are similar to that of the DC series motors [6]. The speed-regulation characteristics are identical with that of the DC shunt motors [6].

The Air-Conditioning system with BLDC motor has several merits such as has long life, low running cost, lesser maintenance and noiseless operation compared to other motors. [7]. When air-conditioner compressor is loaded to BLDC motor, it helps in the increase of the efficiency of the system [7,8]. The speed of the BLDC motor is controlled to rotate with a speed which is equal to the reference speed [7,8]. Hence, the control of the temperature is done at the zone of the Air-Conditioning system.

Conventional DC machines have mechanical brushes and commutator assembly and hence have problems like wear and tear of the brushes [9]. This problem does not exist in BLDC motor due to the absence of brushes. Therefore, mechanical commutation is not used for BLDC motors and are powered electronically [9].

The proposed drive is fed through AC mains supply. It is rectified using bridge rectifier which gives a Pulsating DC voltage. Athiyaman S. et al in “Power quality improvement in PMBLDC drive using PFC Sepic Converter for Air Conditioner" talks about the addition of a filter capacitor in order to remove the pulsations in the voltage at the output of the bridge rectifier (2013)[10]. Inclusion of a capacitor as a filter results in pulsed current of a very high amplitude due to the charging of the capacitor which can't be controlled. This leads to reduction of power factor which degrades the power quality at AC mains and there will be increase in the Total Harmonic Distortion (THD) of the supply current [7,8,10]. Hence, there is a need to enhance the power factor so that good quality of power at can be maintained at AC mains [7,8]. The power quality should be such that its parameters should be accepted by international standards of PQ i.e. IEC 61000-3-2 [7, 8, 10, 11]. Stephy Mathew et al in "Review of DC-DC converters for PFC in SMPS" explains about various topologies of Switched Mode Power Converters which are used in improving the Power Factor (2017)[12]. Buck converter does not have the source of the power electronic switch connected to ground. Hence, design of gate driver is difficult. While Boos t converter has more inductor current and output voltage ripple. Converters like Buck-Boost and Cuk face the drawback of reverse polarity of capacitor voltage [13]. Zeta converter has disadvantages of higher Electromagnetic Interference (EMI) because of power electronic switch in series to supply[13]. These result in difficulties in designing a proper gate driver circuit. An Interleaved boost converter provides a solution for the above problems with lesser inductor current ripple and comparatively simple gate driver design.

In the present work, an Interleaved boost converter is utilized for the proposed drive circuit. The converter operates in Continuous Conduction mode (CCM). Thiyagarajan et al in "Analysis and comparison on conventional and Interleaved DC-DC boost converter" emphasizes on the advantages of interleaved boost converters i.e. continuous input current, reduced ripple of input inductor, lesser ripple of output capacitor voltage and component size reduction when compared to the conventional converters (2014)[14]. The BLDC motor's speed is controlled by controlling the output voltage of the converter [15,16,17]. This acts as the DC link voltage for the Three Phase Inverter to obtain the desired speed [15,16,17]. The design of the BLDC drive and its performance assessment is presented in this paper for the compressor application used in air-conditioning systems.

II. PROPOSED VOLTAGE CONTROLLED PFC SYSTEM

Fig.1 shows the proposed voltage controlled drive for enhancement of power quality. The mains supply of 220V is stepped down to 110V using a stepdown transformer. This voltage is rectified by the usage of a bridge rectifier consisting of 4 diodes which results in a pulsating wave having average voltage of 99V. The output of the bridge rectifier provides the input to the interleaved boost converter. The converter boosts the input voltage of 99V to a 300V. The voltage across the output capacitor acts as the DC link voltage which excites the Three Phase Inverter. The inverter is operated in 120º conduction mode which produces quasi rectangular currents to excite the BLDC motor. This motor works on the feedback principle where Hall sensors finds out the position of rotor. The switching sequence of the Voltage Source Inverter is determined by these sensors and the corresponding windings of the motor are excited based on the output of the Hall sensors.

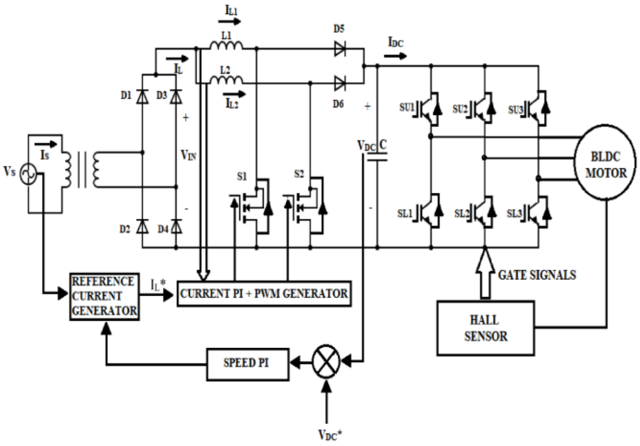

Fig. 1 – Schematic Diagram of the Voltage controlled power quality improvement system

The Interleaved boost converter which acts as a PFC converter has MOSFET as the power electronic device used for switching. The Inverter which excites the BLDC motor has Insulated Bipolar Gate Transistor (IGBT) as the switching device. Current multiplier approach is used for enhancing the power quality. It consists of Cascade loops i.e. speed control loop that acts as the outer loop and the current control loop which is a fast acting inner loop. The voltage across the capacitor of the Interleaved Boost converter is equivalent to the motor speed. This converter output voltage is fed back and is given to a comparator with a DC voltage reference (V_{DC}*). The error obtained is given to a Speed PI controller that results in a current control signal(I_C). This signal I_C is multiplied by an absolute value of sine wave with unit value. This gives the Inductor current reference I_L*. The reference current obtained is given to a comparator with fed back inductor currents I_{L1} and I_{L2} of the converter. The error obtained is given to two Current PI controllers which give the modulating signals m_{d1} and m_{d2}. These signals are then compared with a unit amplitude carrier of saw tooth shape wave having a constant frequency. One carrier wave has a phase delay of zero degree and another has a phase delay of 180º. This generates the Gating signals G1 and G2 for the converter switches. When the voltage reference V_{DC}* is changed, the converter output voltage tracks the voltage reference. This DC link voltage is an equivalent of the motor speed. Hence by changing the reference to different voltage levels, the converter output voltage is adjusted thereby regulating the speed of the motor.

III. MODELLING OF VOLTAGE CONTROLLER BASED POWER QUALITY ENHANCER DRIVE

The drive presented comprises of the following divisions- A) PQ enhancer Block B) Inverter block
C) Controller Block.

A. PFC Converter

The proposed Converter used for improving the quality of power has the same calculations as it is for the boost converter. The voltage across output capacitor is calculated by -

$$V_{O} = V_{DC} = V_{IN} / (1-D) \qquad (1)$$

Where, D is the duty ratio of the switches and V_{IN} is the average voltage of the bridge rectifier output. This acts as the supply to the interleaved converter. It is related to the stepped down input voltage V_{ST} as –

$$V_{IN} = 2\sqrt{2}V_{ST}/\pi \qquad (2)$$

The value of the boost inductors of the converter is calculated by-

$$L_1 = DV_{IN} / \{f_S (\Delta I_{L1})\} \qquad (3)$$

$$L_2 = DV_{IN} / \{f_S (\Delta I_{L1})\} \qquad (4)$$

Where, f_s is the frequency at which the switching of the individual switches occur. ΔI_{L1} and ΔI_{L2} are the inductor current ripples in the boost inductors L_1 and L_2 respectively. The inductor current is divided in the two branches. Hence the current across each inductor will be exactly half of the total inductor current.

The output capacitor value is calculated as –

$$C = DI_{DC}/f_S(\Delta V_O) \qquad (5)$$

Where, ΔV_O is the output voltage ripple and I_{DC} is the DC link current which is the input current to the Three Phase Inverter.

The converter is designed for a DC link voltage V_O=V_{DC}=300V for an input voltage of 99V. The switching frequency of each switch is chosen as 10kHz. The input inductor values and capacitor value obtained after calculation are 13.26mH and 0.724mF respectively.

B. BLDC Motor Drive

The BLDC Motor Drive consists of-

i) Hall sensor ii)An Inverter iii) BLDC motor

i) Hall Sensor

Motors like induction motor, synchronous motor etc., are mechanically commutated. But BLDC motor is electronically commutated by 3 position sensors called as Hall sensors. Table I illustrates the commutation sequence of the Hall sensors [1,7,18]. Depending on the output signal of the Hall sensors, the sequence of switching the Voltage source Inverter switches will be decided. Thereby the corresponding stator windings will be excited.

Table I - Commutation Sequence depending on Hall Sensor Output [1,7]

Output of the sensor			Sequence of switching					
H_a	H_b	H_c	S_{U1}	S_{L1}	S_{U2}	S_{L2}	S_{U3}	S_{L3}
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0

ii) Three Phase Voltage Source Inverter(VSI)

Fig.2 shows the Voltage source Inverter to which the armature windings of the Brushless Direct Current motor are connected. It is operated in 120 degree conduction mode to excite the motor.

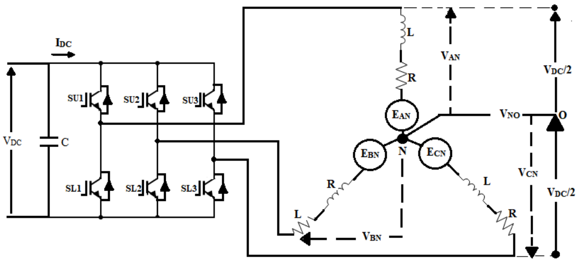

Fig 2. - Three Phase Voltage source Inverter

The phase voltages of a, b and c phases are given by-

$$V_{PHASE} = V_{DC}/2 \text{ for } S_U = 1 \qquad (6)$$

$$V_{PHASE} = -V_{DC}/2 \text{ for } S_L = 1 \qquad (7)$$

$$V_{PHASE} = 0 \text{ for } S_L = 0 \text{ and } S_U = 0 \qquad (8)$$

Where, S_U represents the Upper leg switches. S_L represents the Lower leg switches of the Inverter. V_{DC} is the DC link voltage[13].

The values 1&0 depict the states “ON” and “OFF” of the Inverter IGBT switches.

iii) BLDC Motor

The Brushless Direct Current motor modelling is done using differential equations [10, 18] -

$$V_X = I_X R_X + dI_X/dt(L_X+M) + E_X \qquad (9)$$

Where, “x” represents phases a, b and c.
V_X represents the phase voltage in volts.
I_X represents the phase current in amperes.

R_X represents the phase resistance in ohms.
E_X represents the back emf generated in volts.
(L_X+M) represents the self-inductance and mutual inductance in Henry.

$$T_E = T_L + J\, d\omega/dt + B\omega \qquad (10)$$

Where, T_E is the motor torque in Nm.
T_L represents compressor load torque in Nm.[18]
J depicts moment of Intertia in kgm^2.
B represents the viscous damping in Nms/(rad)
ω is the speed of the motor in rad/s.

$$\omega = d\theta /dt \qquad (11)$$

$$\omega_r = (P/2)*\omega \qquad (12)$$

Where, θ is the rotor position in degrees
The emf produced at stator can be implicated by a function of the rotor angle (θ) [7] as,

$$E_X = K_B\, f_X(\theta)\, \omega_r \ [18] \qquad (13)$$

Where, K_B represents the constant of stator emf in volts/(rad/s).[7] $f_X(\theta)$ implicates the rotor angle function. It has an upper and lower bound of ±1. The value of this function at different positions of rotor at phase 'a' is given by [9]-

$f_A(\theta) = 1$ for $0 < \theta < 120^o$ [10] (14)
$f_A(\theta) = [(180^o - \theta) -1]/30^o$ for $120^o < \theta < 180^o$ [10] (15)
$f_A(\theta) = -1$ for $180^o < \theta < 300^o$ [10] (16)
$f_A(\theta) = [(180^o - \theta) -1]/30^o$ for $180^o < \theta < 360^o$ [10] (17)

$fb(\theta)$ and $fc(\theta)$ are identical to $fa(\theta)$ having 120^o and 240^o phase difference respectively [18].
The electromagnetic torque i.e. motor torque is expressed as,

$$T_E = K_B[f_A(\theta)\, I_A + f_B(\theta)\, I_B + f_C(\theta)\, I_C] \ [18,19] \qquad (18)$$

Equations (9)-(18) depict the overall dynamic BLDC motor model.

Table II displays the specifications of the motor.

Table II – BLDC motor specifications [12]

Rated power	375W
Rated speed	3000rpm
Rated Torque	1.2Nm
Rated voltage	300V
K_E	78V/krpm
K_T	0.744Nm/A
Poles	4
R_s	14.56Ω
L_s	25.71mH
Inertia(J)	$0.03kgm^2$

C. PFC CONTROLLER

The PFC controller consists of three main components

a). a speed controller b) a current controller c) a PWM generator.

a) Speed Controller

PI controller is used as speed controller. It tracks the voltage reference and speed is equivalent of it. If $V_{DC}*(n)$ is the DC voltage reference [7]. $V_{DC}(n)$ is the DC link voltage at the nth time. The difference of the two voltages is given by –

$$V_E(n) = V_{DC}*(n) - V_{DC}(n) \ [10] \qquad (19)$$

The PI controller output $I_C(n)$ at the nth instant is -

$$I_C(n)=I_C(n-1)+ K_P\{V_E(n) - V_E(n-1)\} + K_I V_E(n) \ [17] \qquad (20)$$

Where, K_P is the gain of proportional term. K_I is the gain of the integral term of the speed PI controller. The tuned gain parameters K_P and K_I for the speed controller in this model are 0.2 and 0.04 respectively.
The input inductor current reference I_L* is created by performing multiplication with sine wave of unit amplitude to obtain the signal I_C.

$$I_L* = I_C(n)*u \qquad (21)$$

Where, "u" is the unit value of the ac mains voltage, given by-

$$u = V_{AC}/V_A;\ V_A = V_M;\ V_{AC} = |V_M \sin \omega t| \qquad (22)$$

Where, V_M is the maximum amplitude of the mains supply in volts. ω is the mains frequency in radians per second.

b) Current controller

The inductor current reference I_L* is compared with the current through both the inductors. The current errors I_{E1} and I_{E2} are given to current PI controllers which give the modulating signals m_{d1} and m_{d2}.

$$I_{E1}(n) = I_L*(n) - I_{L1}(n) \qquad (23)$$

$$I_{E2}(n) = I_L*(n) - I_{L2}(n) \qquad (24)$$

$$m_{d1}(n) = m_{d1}(n-1)+ K_P\{ I_E- I_{E1}(n-1)\} + K_I I_{E1}(n) \qquad (25)$$

$$m_{d2}(k) = m_{d2}(k-1)+ K_P\{ I_E- I_{E1}(n-1)\} + K_I I_{E2}(n) \qquad (26)$$

The tuned gain parameters K_P and K_I for current controller in this model are 0.9 and 0.8 respectively.

c) PWM generator

The modulating signals m_{d1} and m_{d2} are compared with a saw tooth carrier wave S_C. This carrier wave has unit amplitude and fixed frequency. This generates the Gating signals G_1 and G_2 for the switches of the converter and is given as -

if $m_{dx} > S_C$, then $S_X = 1$ else $S_X = 0$, where m_{dx} represents the modulating signal for switch S_X. "1" and "0" represents the switching states "ON" and "OFF" of the MOSFET switches.

IV. GRAPHICAL ANALYSIS OF THE BLDC DRIVE

Simulation for the BLDC drive is performed in MATLAB-SIMULINK software. The performance assessment of the drive is done for an Air conditioner compressor load having a load Torque of 1 Nm. The rated speed of the motor is considered as 3000 rpm where a rated power of 375W is obtained. By varying the DC voltage reference, the capacitor voltage of converter is tracked and thereby desired speed is obtained.

Fig.3 shows the parameters of AC mains before the improvement of power quality. The current is in the pulsed form with very high amplitude. This could cause damage to the equipment connected to it.

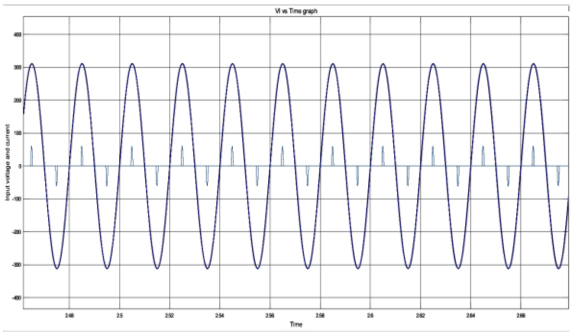

Fig. 3 – AC mains without power factor correction

Fig.4 displays the total schematic diagram of PFC controller system. It has the input block which consists of the AC mains supply, a step down transformer which would reduce the voltage. Diode bridge rectifier converts AC to pulsating DC voltage. The input block is connected to an interleaved boost converter block. This block is the input for inverter feeding the BLDC motor. The Hall sensor inputs are fed back to the inverter through a decoder block. This decides the sequence at which inverter IGBTs will switch. The controller block consists of a speed controller, a current controller and a PWM generator.

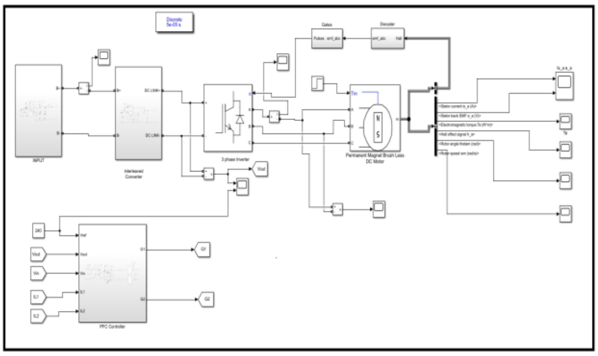

Fig. 4 - Block Diagram of the PFC controller system

Fig.5 implicates the PFC controller block which has speed PI controller, current PI controller and a PWM generator which is used to enhance the quality of power.

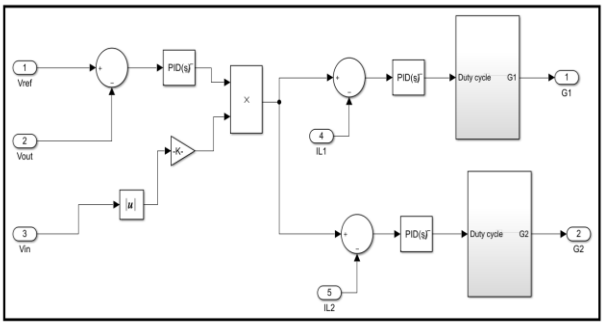

Fig. 5 - PFC controller inner circuitry

The simulation for BLDC motor is initially done for an output capacitor voltage of 300V and a Rated current of 1.62A with a Load torque maintained constant at 1Nm.

Fig.6 shows the graph of back EMF of all 3 phases for rated values. The back EMF is trapezoidal with 120 degree phase shift between each phase.

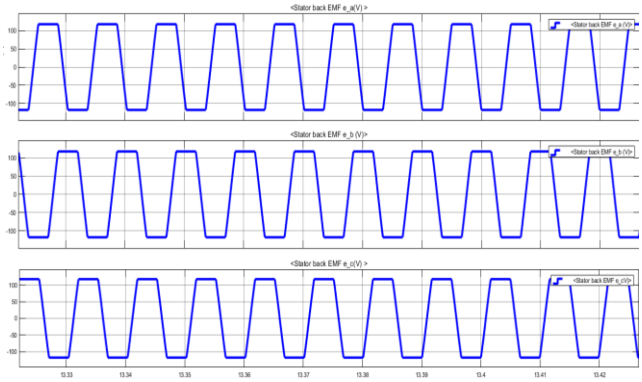

Fig. 6 - Stator emf of all three phases

Fig.7 shows the waveform of stator current of all three phases. The stator current is quasi rectangular in shape with 120 degree phase shift between each phase.

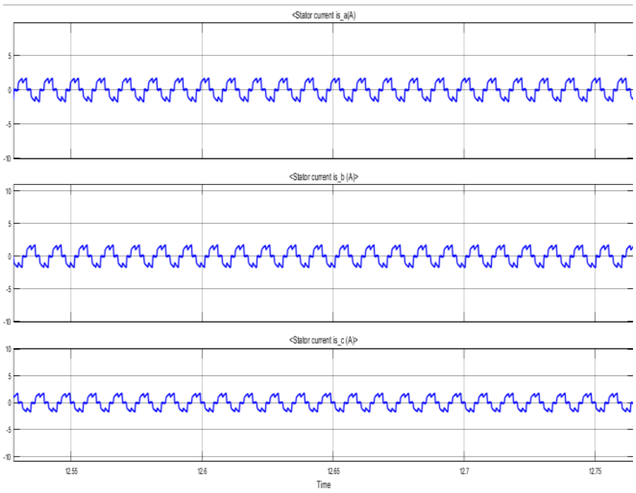

Fig. 7 - Stator current for all three phases

Fig.8 shows the speed and torque waveforms at rated values.

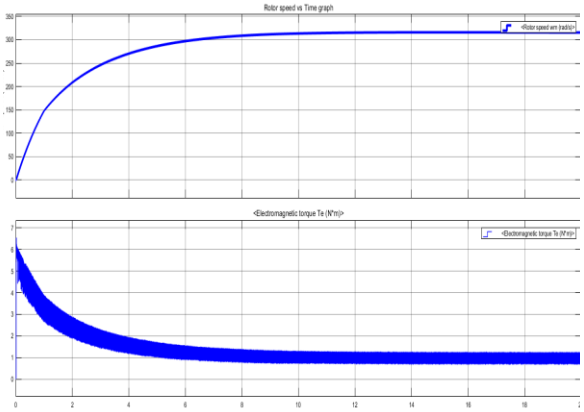

Fig. 8 - Speed and Torque waveforms

Fig.9 displays how the controller tracks the DC voltage reference V_{DC}*.

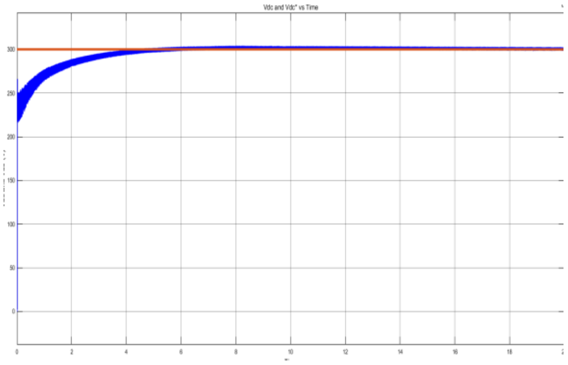

Fig. 9 - Tracking of the reference voltage by PI controller

Fig.10 illustrates the THD which the input supply current has and the harmonics at different frequencies. The THD is expected to be in the acceptable range according international standards of PQ IEC 61000-3-2[7,8,10,15].

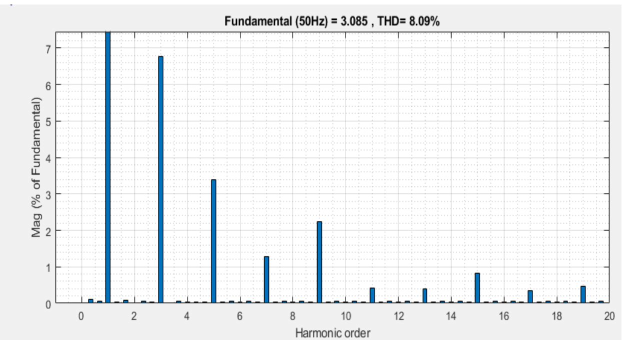

Fig. 10 THD of the input current

Fig.11 shows the waveform of parameters at AC mains after the power quality is improved. The current waveform is in phase with the voltage waveform to make the power factor nearer to 1.

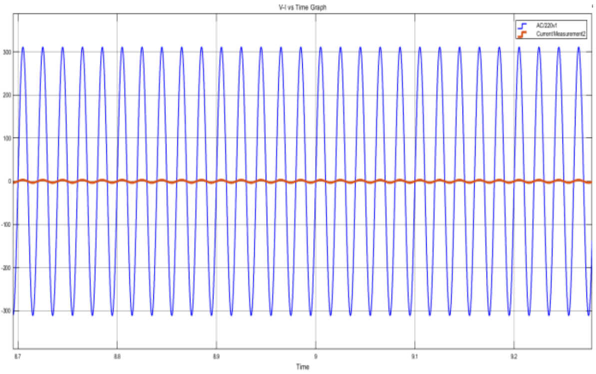

Fig 11 AC mains supply and current after PFC

Table III represents the overall aim of Speed control and Power Factor correction. A power factor of more than 0.99 is maintained for almost all the speeds and the values of the corresponding Back EMF generated is also tabulated.

TABLE III. Power Factor at mains supply for different motor speeds

V_{DC}	Speed(rpm)	EMF(V)	PF	THD
300	3000	117	0.9957	8.09%
285	2845	110	0.9949	8.12%
270	2670	104	0.9934	8.15%
255	2500	97	0.9932	8.21%
240	2330	91	0.9928	8.29%
225	2155	84	0.9919	8.41%
210	2000	77	0.9915	8.56%
195	1810	70	0.9912	8.74%
180	1640	64	0.9903	9.02%
165	1420	55	0.9897	9.47%
150	1290	50	0.9892	9.85%

V. CONCLUSION

Design and simulation of an interleaved converter fed BLDC motor drive has been analyzed using the MATLAB-SIMULINK software. The power factor, close to the desired value is achieved. Also the speed control of the motor is achieved for Air-conditioner compressor load application. The drive presented has exhibited an improvement in the quality of power at the supply end for different values of speed. The resulted PQ parameters are in the same range of that of Standard PQ values. Therefore, desired performance is obtained for the drive at different speeds with an increased quality of power. The results are very satisfactory and is suitable for application in an Air-conditioning system.

VI. ACKNOWLEDGEMENT

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