Power Quality Improvement Using Isolated CUK Converter for PMBLDCM Drive

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Abstract: *This paper deals with Power Quality improvement (PQI) at single phase AC mains supply for a PMBLDCM Drive using isolated CUK converter fed through a Diode Bridge Rectifier (DBR). The controller uses current multiplier approach for achieving Power Quality as per IEC-standards. The proposed drive is designed and modeled for a PMBLDC motor rated as 1.3 KW, 2300 rpm, 350 volts and 5.2 Nm. Its performance is simulated in MATLAB Simulink environment and obtained results are presented to demonstrate improved power quality at AC mains for varying speed and input voltage conditions.*

Keywords: *PFC; PMBLDCM; Power Quality (PQ); CUK converter; voltage source inverter (VSI)*

I. INTRODUCTION

Permanent magnet brush-less DC motor (PMBLDCM) Drives have high efficiency and requires low maintenance as compared to single phase induction/ DC motor. Due to this, these motors are more suitable for use in industries as well as in home appliances. Recent advancement in power electronics facilitated these drive applications in the field of Electric-vehicles (EVs) and Hybrid electric-vehicles (HEVs), tread-mills, robotics, hard disc drives of computer, air conditioner compressors, fans, freezers etc. [1-2].

The Permanent magnet brushless (PMBL) motors come under the category of three-phase synchronous motor family and categorized as permanent magnet synchronous motor (PMSM) and PMBLDCM. The PMSM drive system has to have position information continuously to construct the sinusoidal current commands. The resolution of the current command determines the resolution of the position sensor whereas PMBLDCM which have back EMF in trapezoidal shape required position information of rotor after every 60^0 of electrical angle in the three phases. Usually, in practice, it amounts to 8, 10, and 12 bits position per revolution with the effect that the cost of the position sensor is high for PMSMs as against very low cost for PMBLDC motors [3].

In a conventional PMBLDCM drive, a Voltage Source Inverter (VSI) is fed from AC mains through a diode bridge rectifier (DBR) using a capacitive DC-link voltage as shown in Fig.1. Due to uncontrolled charging and discharging of DC link capacitor, DBR draws a peaky pulse shaped current resulting in poor power quality (PQ) at AC mains as shown in Fig.2. The peaky shaped current has total harmonic distortion (THD_i) 84.73%, power factor (PF) 0.7247, crest factor(CF) 2.1347, and displacement power factor (DPF) 0.953 which are power quality indicators at AC mains [3]. The PQ problem become more severe when many such drives are employed simultaneously. Therefore, these drives, when operated from utility supply, they should conform to international PQ standards. There are various international standards for electrical power quality out of which IEC-61000-3-2 presents the limits of current harmonics for low power drives [5].

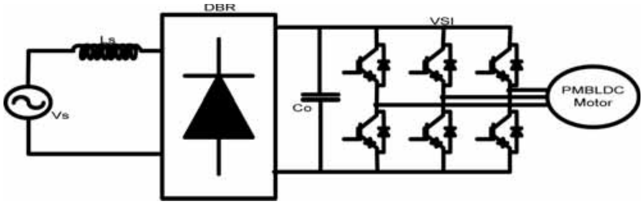

Fig. 1: Without PFC controller single phase DBR fed VSI based PMBLDC Motor.

To meet these international standards PMBLDC motor drives fed through DC-DC converter with Power Factor Correction (PFC) control scheme which results in reduction of input current harmonics, improvement in PF, CF etc. CUK converter is such a DC-DC converter used to feed desired DC link voltage to the PMBLDC motor and to control the power quality at AC mains. It has advantages over Buck-Boost and SEPIC converters like continuous input and output currents,

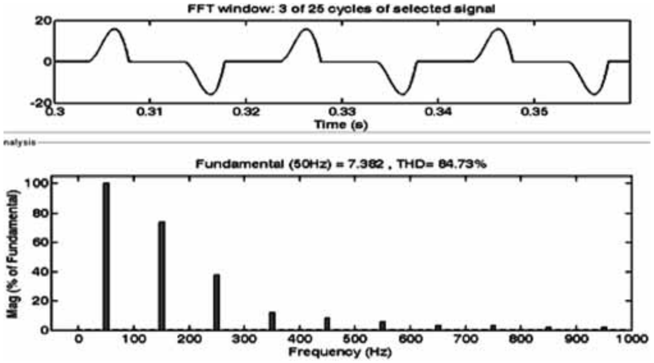

Fig. 2: Input Current waveform and its Harmonic order at ac mains for PMBLDCM drive without PFC.

small output filter and better efficiency [6-7]. CUK converter requires smaller size core due to that it has lower core and copper losses. Moreover, improvement of PQ at AC mains, it also controls the voltage at DC link capacitor for achieving desired speed of PMBLDCM drive.

There are basically two important approaches for DCDC converters for controlling the DC link voltage and PQ through duty cycle of switch for improvement in PQ and efficiency. These approaches are voltage follower approach and current multiplier approach. This paper deals with current multiplier approach to achieve the power factor correction (PFC) in continuous conduction mode (CCM) operation of DC-DC converters. The discontinuous conduction mode (DCM) control requires voltage follower approach to be used.

This paper proposes design of isolated CUK converter fed PMBLDCM drive using current multiplier approach for variable speed control under rated torque and rated supply voltage.

II. DESIGN OF ISOLATED CUK CONVERTER

Fig. 3 shows the block diagram of non-isolated and isolated CUK converters fed from AC mains through DBR. The CUK converter is one type of buck –boost converter but output of CUK converter is inverted in polarity with input supply. Isolated CUK converter can be designed by splitting intermediate capacitor of non isolated converter in two parts and introducing transformer between them [8].

Some advantages of isolated CUK converter over non isolated CUK converter are:

(a) The voltage and current stress of MOSFET transistor and diodes are minimized by proper selection of the transformer turns ratio.

(b) The transformer allows large step-up and step-down ratio.

(c) By adding multiple secondary windings and converter secondary-side circuits multiple DC outputs can also be obtained.

Nomenclatures

C_o	Capacitor of the output ripple filter, μF
C_{ia}	Intermediate capacitor in primary side, μF
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D	Duty cycle ratio
e_x	Back emf of phase x of PMBLDCM
f_s	Switching frequency, kHz
H_a, H_b, H_c	Hall effect position sensors
I_{av}	Average motor current from DC link, A
I^*_{dc}	Reference inductor current, A
I_s	Input AC Current (in RMS), A
J	Inertia of PMBLDC motor, kgm^2
K_b	Back EMF constant of the PMBLDCM
K_{pv}, K_{iv}	Proportional and integral gains of the voltage PI controller
K_{pw}, K_{iw}	Proportional and integral gains of the speed PI controller
k_{dc}	Gain
L_i	Boost inductor, mH
L_o	Inductance of output ripple filter, mH
L_s	Self-inductance of the PMBLDCM/phase, mH
M	Mutual inductance of the PMBLDCM
m_d	Carrier waveform
N_1, N_2	Turns of primary and secondary side
P	Number of poles in the PMBLDCM
R	Equivalent Output Resistance at DC Link, Ω
R_a	Resistance of motor winding/phase, Ω
S_i	Ith switch of VSI
T_e	Electromagnetic torque of PMBLDCM
T_l	Load torque on the PMBLDC motor
u_{vi}	Unit template of the input AC
V^*_{dc}	Reference DC link voltage, V
V_{dc}	Output voltage, V
V_{dc}	Sensed DC link voltage, V
V_e	Voltage error at DC Link, V
V_{in}	Output voltage of DBR, V
V_s	Input AC Voltage (in RMS), V
Greek Symbols	
ΔI_{Li}	Peak to peak current ripple in boost inductor, A
ΔI_{Lo}	Inductor peak to peak current ripple, A
ΔV_{Co}	Peak to peak ripple in output voltage, V
ΔV_{Cia}	Peak to peak voltage ripple of intermediate capacitor 1, V
ΔV_{Cib}	Peak to peak voltage ripple of intermediate capacitor 2, V
θ	Rotor position
ω	Frequency at input AC mains, rad/s
ω^*_r	Reference speed of PMBLDCM, rad/s
ω_r	Speed of PMBLDCM, rad/s
ω_e	Speed error, rad/s

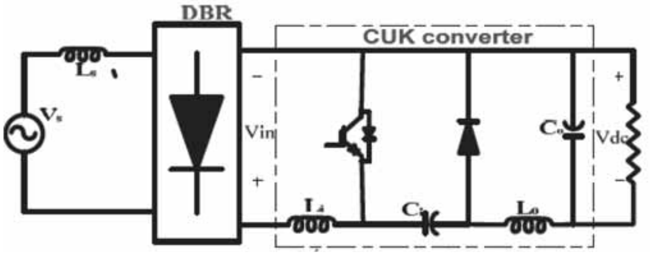

Fig. 3(a). Non isolated CUK convener diagram

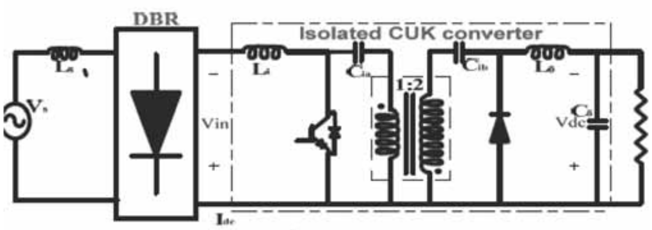

Fig. 3(b): Isolated CUK converter diagram

Fig. 3: Non-isolated and isolated CUK converter with resistive load

(d) By using transformer in opposite polarity positive output from CUK converter is also possible. Disadvantage of using isolated CUK converter with transformer is that transformer's leakage inductance leads to switching loss.

Parameters of CUK converter are calculated using following equations [4]:

Output Voltage $$V_{dc} = \frac{D(N_2/N_1)\,V_{in}}{(1\text{-}D)} \quad (1)$$

Input Boost Inductor $$L_i = \frac{DV_{in}}{f_s \Delta I_{Li}} \quad (2)$$

Intermediate Capacitor 1 $$C_{ia} = \frac{V_{in}\,(N_2/N_1)^2 D^2}{Rfs\Delta V_{cia}\,(1\text{-}D)} \quad (3a)$$

Intermediate Capacitor 2 $$C_{ib} = \frac{D}{Rfs\Delta V_{cib}\,(V_o)} \quad (3b)$$

Output Inductor $$L_o = \frac{(1\text{-}D)\,V_o}{fs\Delta I_{Lo}} \quad (4)$$

Output Capacitor $$C_o = \frac{V_o\,(1\text{-}D)}{8L^2_0 \Delta V_{Co} f^2_s} \quad (5)$$

Using above equations for Vdc (=Vo) = 350 V, Vin = 210 V, Vac = 120 Vrms, fs = 30kHz, Iav = 4A, R = 87.5 Ω, ΔILi= 1.5 A, ILo = 2.0 A, ΔVo = 4.0 V (1.143% of Vo), ΔVC1= 14.0 V (4% of Vo). The design parameters value of CUK converter comes as Li = 1.582mH, Cia = 10.53μF, Cib = 5.27μF, Lo = 2.374mH and Co = 877.62μF.

It is also considered that the PQ constrains such as THDi ≤ 5%, PF ≥ 0.999 and variation in output voltage ≤ 4% etc. are remains in limit for above calculated values.

III. MODELING OF PCF CONTROL SCHEMES AND ELECTRONIC COMMUTATION FOR PMBLD CM DRIVE

The main design parts of PFC controlled CUK converter fed PMBLDCM drive are PFC control and electronic commutation as shown in Fig.4. Mathematical equation for modeling of these parts are shown in the below box [8]. Switching sequence for VSI are generate using signals from Hall Effect positions sensors as shown in Table-I.

A. PFC Control Scheme Design

I. Voltage Controller

Voltage Error $$V_e(k) = V^*_{dc}(K) - V_{dc}(k) \quad (6)$$

PI controller output at K^th instant

$$I_c(k) = Ic(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \quad (7)$$

II. Reference current generator

$$I^*_d = I_c(k)uv_s$$

Unit template $$uv_s = \frac{V_d}{V_{sm}}\ ;\ V_d + |V_s|; V_s = V_{sm}\sin\omega t \quad (9)$$

III. PWM Controller $$\Delta i_d = i^*d - i_d \quad (10)$$

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

$$k_d \Delta i_d > m_d(t) \text{ else } S = 0 \quad (12)$$

B PMBLDCM drive equations

I. Speed controller

Speed error $$\omega e(k) = \omega^*_r(k) - \omega_r(k) \quad (13)$$

Speed controller output at k^th instant

$$T(k) = T(k-1) + K_{p\omega}\{\omega_e(k) - \omega_e(k-1)\} + ki\omega_{\omega} e() \quad (14)$$

II. Reference winding currents

$$I^* \quad \frac{T(k)}{2\,kb}\ ; \tag{15}$$

$$i^*a = 1,\ I^*b = -I, \text{ and } i^*_c = 0 \tag{16}$$

Current errors given by

$$\Delta i_a = (i^*_a - i_a),\ \Delta i_b = (i^*_b - i_b), \text{ and } \Delta i_c = (i^*_c - i_c) \tag{17}$$

III. PWM Current Controller

If $k_i \Delta ia > m(t)$ then $S_a = 1$ (18)

If $k_i \Delta ia \le m(t)$ else $S_a = 0$ (19)

IV. PMBLDC motor equations

$$p i_x = \frac{p_x - i_x R_a - e_x}{Ls + M} \tag{20}$$

$$p\omega_r = \frac{\left(\frac{P}{2}\right)(T_e - T_1)}{1} \tag{21}$$

$$p\theta = \omega_r \tag{22}$$

$$e_x = K_b f_x(\theta)\,\omega_r \tag{23}$$

$$f_a(\theta) = 1 \quad \text{for } 0 < \theta < 2\pi/3 \tag{24}$$

$$f_a(\theta) = \left(\frac{6}{\pi}\right)(\pi - \theta) - 1 \text{ for } 2\pi/3 < \theta < \pi \tag{25}$$

$$f_a(\theta) = 1 \quad \text{for } \pi < \theta < 5\pi/4 \tag{26}$$

$$f_a(\theta) = \left(\frac{6}{\pi}\right)(\theta - 2\pi) + 1 \text{ for } 5\pi/3 < \theta < 2\pi \tag{27}$$

Electromagnetic torque of motor expressed as

$$T_e = K_b\,[\,f_a(\theta)\,i_a + f_b(\theta)\,i_a + f_b(\theta) i_b + f_c(\theta)\,i_c] \tag{29}$$

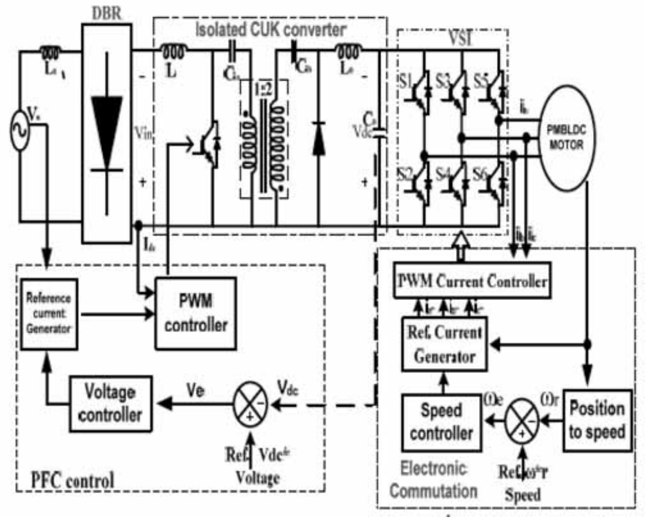

Fig. 4: Block diagram of PFC controlled CUK converter fed PMBLDC motor drive

IV. RESULT AND PERFORMANCE EVALUATION OF PMBLDCM DRIVE

The proposed design of PMBLDCM drive is modeled in Matlab-Simulink for 1.3 kW PMBLDCM having rated torque 5.2 Nm and speed 2300 rpm. Simulink model of the proposed drive is shown in Fig.5. *Appendix 1* contains the parametric data value of PMBLDC motor. The performance of the drive is simulated for constant rated torque (5.2 Nm) at reference speed of 1800 rpm. The input ac voltage taken as 120 Vrms with constant DC link voltage at 350 V. The parameters value of isolated CUK converter are calculated using equations such a way that PQ constraint remain in limit as discussed in section 2.

The performance of the drive is evaluated on the basis of various PQ parameters i.e. power factor (PF), crest factor (CF), total harmonic distortion (THDi) at input AC mains current of drive.

The starting performance of the drive is shown in Fig.6(a) with rated torque (5.2 Nm) and AC input voltage

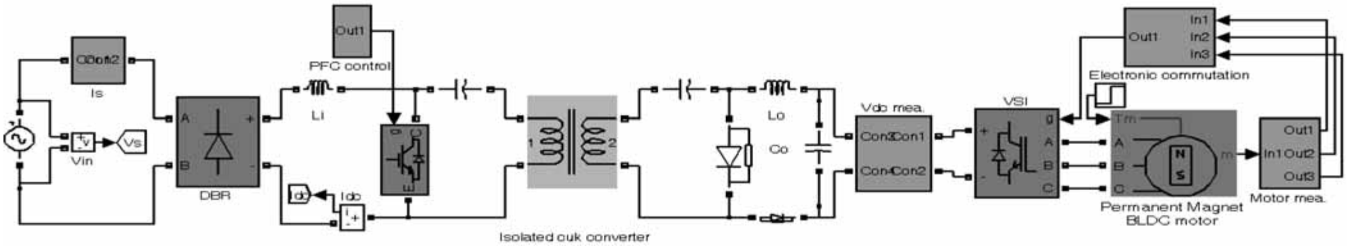

Fig. 5 MATLAB-Simulink-model of the proposed Drive

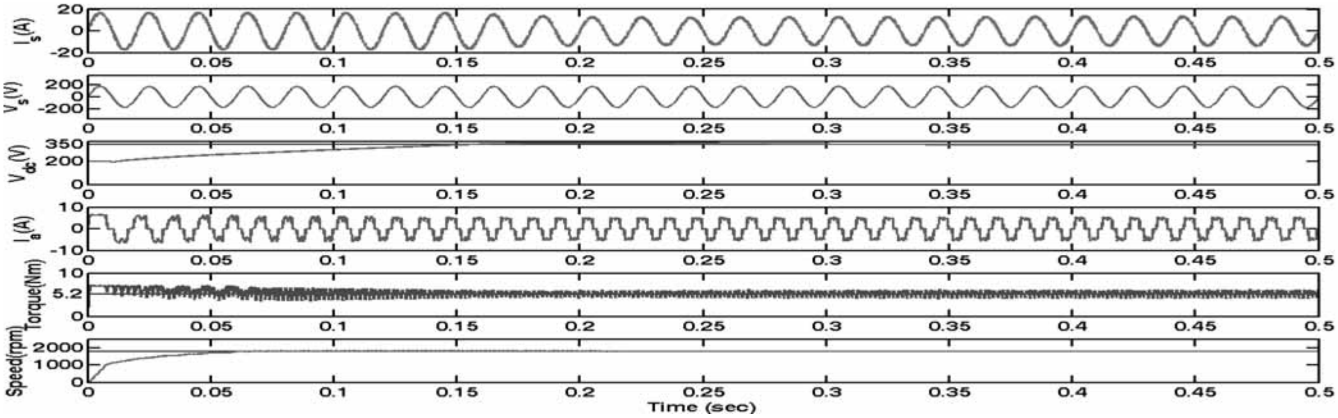

Fig. 6(a): Starting performance of PMDLDCM Drive with 1800 rpm reference speed

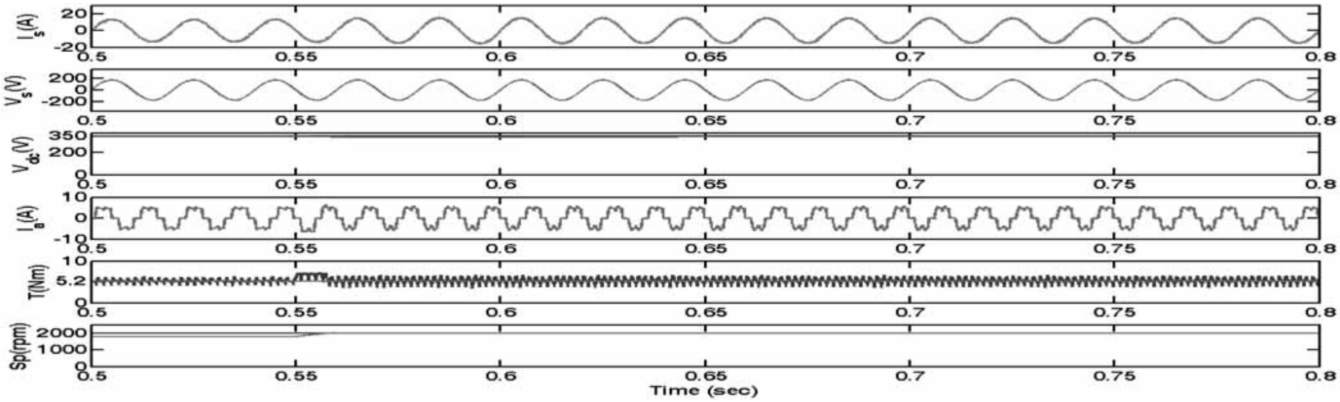

Fig. 6 (b): Performance of Drive for speed change from 1800 rpm to 2000 rpm

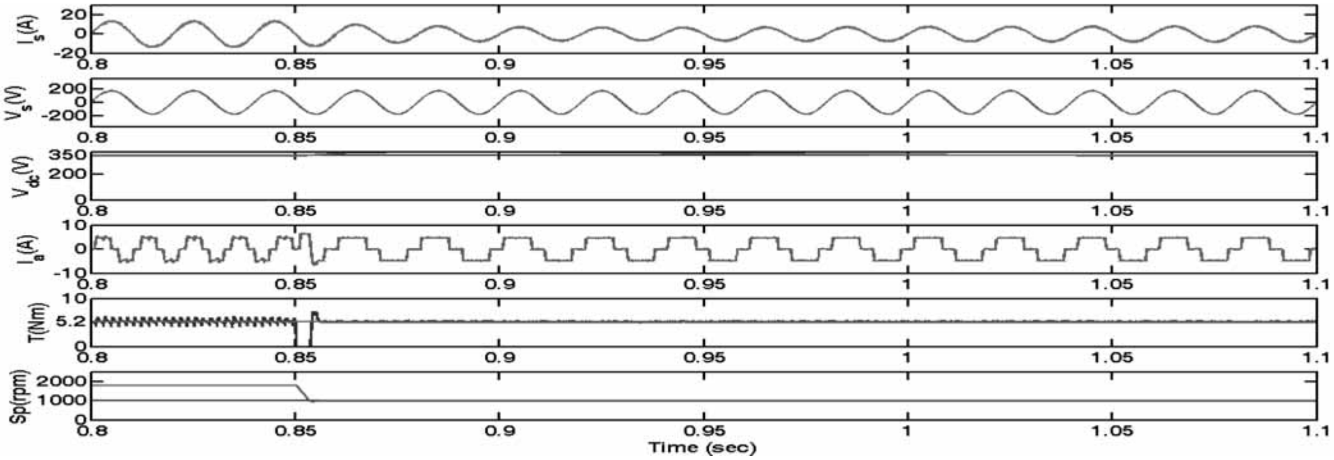

Fig. 6 (c): Performance of Drive for speed change from 1800 rpm to 1000 rpm

at mains side 120Vrms. Reference speed 1800 rpm is achieved within 0.06s, Vdc voltage settles within specified limit in 0.16s, Torque remain in limit within 0.17s. PFC of drive is achieved during starting within 0.02s as shown in Fig.6(a).

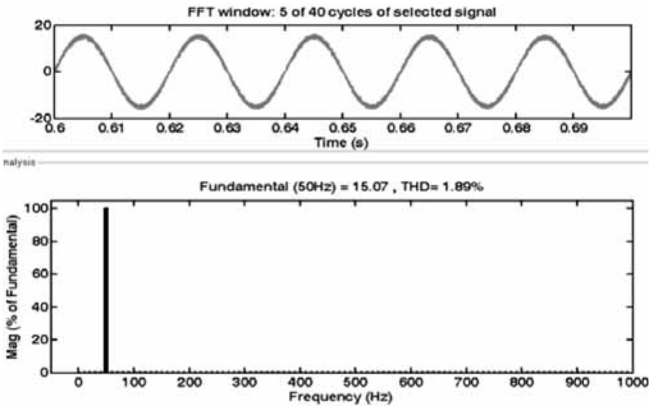

Fig.7(a): I_s and its THD at 2000 rpm

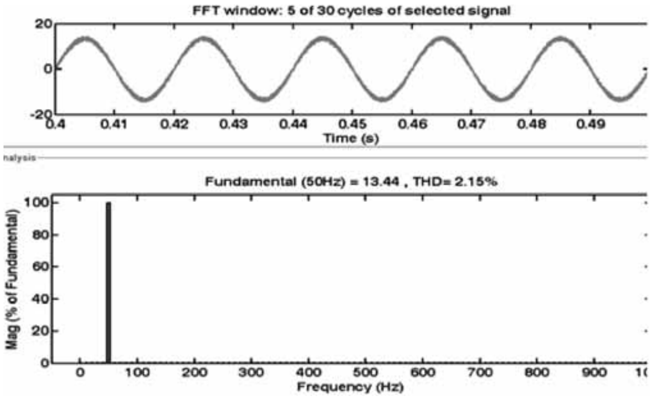

Fig. 7(b): I_s and its THD at 1800 rpm

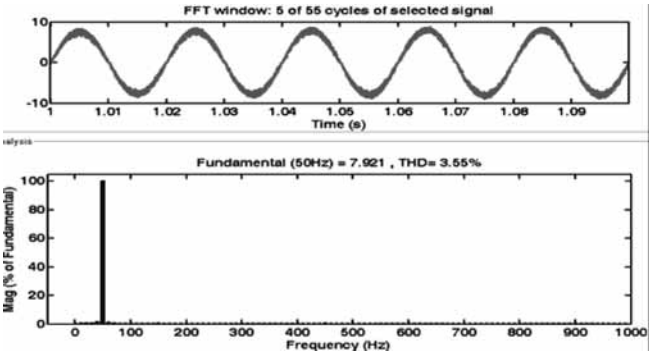

Fig. 7(c): I_s and its THD at 1000 rpm

Fig.7: Supply current (I_s) and its harmonic spectra (for 120 V_{rms} AC main) for different speed.

The speed of the drive is controlled at rated torque (5.2 Nm). The performance of the motor drive for speed increasing from 1800 rpm to 2000 rpm and for decreasing speed from 1800 rpm to 1000 rpm is shown in Fig.6 (b)-(c). The motor drive attains the change speed within few cycles.

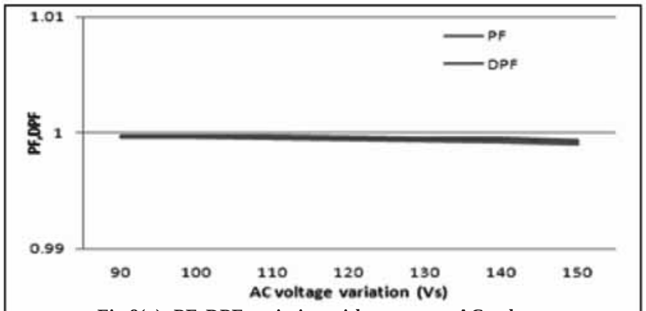

Fig 8(a): PF, DPF variation with respect to AC voltage

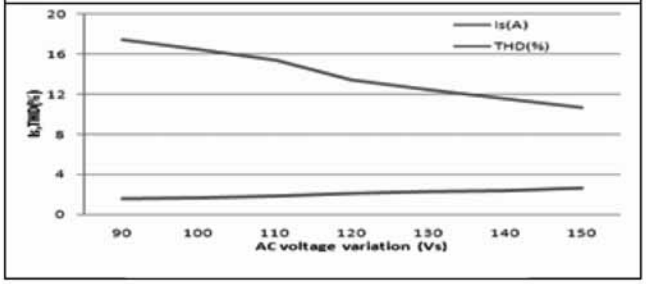

Fig 8: Variation of PQ parameters of Drive with Input supply voltage (Vs) variation.

Table I: Look-up Table for Hall Effect Position Sensor

H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
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	1	1	1	1	1	1

The current waveforms at AC input mains with its total harmonic distortions during steady state at 2000 rpm, 1800 rpm, 1000 rpm are shown in fig. 7(a)-(c). The current THD remains within 5% with near unity power factor for wide range of speed control. The drive shows improved performance in terms of reduced torque ripple, current ripple and speed ripple.

The PQ parameters variation is analyzed for varying input AC voltage of mains supply from 90V to 150V with constant DC link voltage 350V at reference speed of 1800 rpm as shown in fig.8. As transformers turns ratio is 1:2 due to that voltage at secondary side of isolated converter varies from 180V to 300V. For this variation results show that THDi remain within 5% and PF remain more than 0.999 (near to unity) as shown in Table-II.

Table-II: Variation of PQ parameters with Input supply AC voltage (V_s) for isolated CUK converter fed PMBLDCM drive at 1800 rpm speed and rated torque 5.2 Nm with Constant DC link voltage (350 V)

Vs(V)	Is(A)	THD(%)	PF	DPF	CF
90	17.45	1.6	0.9996	0.99973	1.41
100	16.45	1.71	0.9996	0.99975	1.41
110	15.41	1.84	0.9995	0.99967	1.41
120	13.44	2.13	0.9994	0.99963	1.41
130	12.41	2.26	0.9993	0.99956	1.41
140	11.54	2.42	0.9992	0.99949	1.41
150	10.64	2.64	0.9990	0.99935	1.41

V. CONCLUSION

An Isolated CUK converter based PFC scheme for PMBLDCM drive has been designed, modeled and simulated under speed and AC mains voltage variation. The proposed drive has very high power factor value of order 0.999 in wide range of variation for speed as well as for input AC voltage (Vs). The THDi of AC mains current remains well below to 5% for most of the cases and satisfy the international standard. This topology is well suited for applications involving speed control variation for constant torque load.

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Appendix A

Rated power	1.3 kW
Rated torque	5.2 Nm
Rated speed	2300 rpm
Rated voltage	350 V
Poles	6
Resistance R_s	3.43 Ω/phase
Inductance (Ls + M)	10.43mH/phase
Inertia J	0.00068kgm^2
Voltage controller gains value k_{pv}, k_{iv}	0.1699,2.069
Speed controller gains value K_{pw}, K_{iv}	0.095,1.0995

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