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Improved Power Quality Cuk Converter for Variable Speed BLDC Motor Drive

Sanatan Kumar and Madhu Singh
National Institutes of Technology Jamshedpur,
P.O. NIT Jamshedpur, 831014 Jharkhand, India

Abstract: This study presents an improved power quality cuk converter fed Brushless DC (BLDC) motor drive used for variable speed operation. In this scheme variable speed of BLDC motor is accomplished by adjusting magnitude of DC link voltage rather than varying switching frequency of Voltage Source Inverter (VSI). The electronic commutation of BLDC motor is achieved at fundamental switching frequency of VSI which minimises the switching losses and thus improves the efficiency of the motor drive system. A cuk converter is connected between diode bridge rectifier and VSI which regulates DC link voltage and improves the power quality at AC mains simultaneously. The performance of the conventional scheme of BLDC motor is included in this study and also the performance is tested with the speed feedback. The proposed drive scheme is simulated in MATLAB/Simulink environment and its performance comparison is evaluated in terms of Power Quality (PQ) over a ample assortment of speed control.

Key words: BLDC motor, power quality, PFC, cuk converter, DICM, performance comparison

INTRODUCTION

The development of an efficient and low cost BLDC motor drive is required which focuses on low and medium power application due to its wide speed range operation, high starting torque, better reliability, low noise level, ease of much control and reduced Electro Magnetic Interference (EMI) problems. Due to these advantages, it finds application in household equipments, industrial tools, automobile sector, robotics and renewable energy application, etc. (Naidu *et al*., 2005; Mohan *et al*., 1995; Acarnley and Watson, 2006).

A BLDC has three phase concentric winding on the stator and permanent magnet on the rotor. Due to concentric winding, the shape of induced Electro Motive-Force (EMF) is trapezoidal in nature. The BLDC motor is also known as ECM (Electronically Commutated Motor), since an electronic commutation through VSI is used with switching sequence of VSI's switch depending upon the rotor position as sensed by hall effect sensors. It does not have mechanical brushes and commutator assembly which has disadvantage like wear and tear of brushes, sparking issue as in case of conventional DC machine are eliminated in BLDC motor with less EMI problems (Miller, 1989; Kenjo and Nagamori, 1985).

A single phase supply feeding DBR with DC link capacitor followed by a VSI based drives are common schemes of BLDCM drive. Such schemes draw peaky supply current which have high amount of harmonics. This leads to a high value of THD in source current, high crest factor and low power factor at AC mains (Singh *et al*., 2003; Singh and Bist, 2013a, b; Singh *et al*., 2011). These problems are due to uncontrolled charging of the DC link capacitor, DC capacitor is charged only when the output voltage of DBR is greater than DC link voltage. Its give pulsed current waveform having a peak value superior than the amplitude of the fundamental input current at AC mains. International Power Quality (PQ) standards such as IEC 61000-3-2, IEEE 519 do not recommend such PQ indices at supply system. Therefore, suitable measures for mitigation of PQ problems are necessary (Ozturk *et al*., 2007; Nikam *et al*., 2012).

A DC-DC converter is introduced between DBR and VSI as a PFC converter while PMBLDCM is being fed from the single phase AC mains. Various configuration of DC-DC converter are available including buck, boost and buck-boost with variation of isolated and non isolated topologies and a number of switches (single, two or four switches) (Singh and Bist, 2013a). The choice of mode of operation of a PFC converter is a critical issue as it directly affects the cost of overall system. The cost of these converters is firstly determined by the sensing requirement which depends upon the mode of operation of the PFC converter. There are two modes of operation in

Corresponding Author: Sanatan Kumar, National Institutes of Technology Jamshedpur, P.O. NIT Jamshedpur, 831014 Jharkhand, India

which a PFC converter is designed to operate. One of them is Continuous Conduction Mode (CCM) another is Discontinuous Conduction Mode (DCM). In the case, PFC converter operating in CCM, the current in the inductor or the voltage across intermediate capacitor remains continuous but it requires sensing of supply voltage, DC link voltage and supply current which is not cost effective but offers low stress on PFC converter switches. However, PFC converter operating in DCM requires a single voltage sensor for DC link voltage control and inherent PFC is achieved at the AC mains but at the cost of higher stresses on PFC converter switches. Therefore, DCM mode of operation is limited to low power applications. Thus, the selection of operating mode of DC-DC converter is a substitution between the allowed stresses on PFC switch, power rating and overall cost of the system. PFC converter operates in discontinuous conduction mode voltage follower control technique is used for any configuration of circuit (Gopalarathnam and Toliyat, 2003; Bist and Singh, 2014; Vlatkovic *et al*., 1996).

Conventional PFC scheme of BLDC motor drive utilize an approach of constant DC link voltage of the PWM-VSI (Pulse Width Modulation-Voltage Source Inverter) and control the speed by controlling the duty ratio of high frequency pulse width modulation signals. This configuration offers higher switching losses in VSI because switching loss depends upon the square of switching frequency ($p_{sw\_loss}\ \alpha\ f_s^2$). Ozturk *et al*. (2007) have explored a various technique for PFC boost converter feed by a Direct Torque Controlled (DTC) based BLDC motor drive which requires large amount of sensors and Digital Signal Processor (DSP) for DTC operation have higher switching losses in PWM-VSI and increased complexity of the control unit. Thus, this scheme is not suited for low cost applications. A buck converter operates as a front-end converter for feeding a BLDC motor drive has been proposed by Singh *et al*. (2003). In this configuration output filter and energy storage elements is used for improvement of the Power Quality (PQ) but it cannot handle up large deviation of voltage between output to input stage for that reason its application is restricted for the ratio of output and input voltages of PFC converter. Wu and Tzou (2009) have propose a BLDC motor drive fed by a cascade buck-boost converter utilize two separate switches for PFC operation because of two switches offer high switching losses and reduces the efficiency of overall system, not suitable for low power applications.

In this study, the researchers consider DCM mode for PFC converter operation. In which DICM mode is selected to reduce the cost of the system and has application in low-power household appliances. To the best of researcher's knowledge, the work covered in this study is not addressed in the literature yet.

MATERIALS AND METHODS

Proposed PFC-cuk converter fed BLDC motor drive: Figure 1 shows the proposed BLDC motor drive in which PFC-based cuk converter is introduced between diode bridge rectifier and voltage source inverter using a voltage follower approach. A single-phase AC main supplied followed by DBR and DC filter power to a PFC-based cuk converter feeding BLDC motor via. a three-phase VSI.

A high frequency MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is use as switching element for the proposed cuk converter designed for PFC (power factor correction) and voltage control while IGBT (insulated gate bipolar transistor's) are used in the VSI for sinking switching stress for the reason that it operates at lower frequency. Cuk converter is considered to operate in DICM (Discontinuous Inductor Current Mode) to perform as a natural power factor pre-regulator (Singh and Bist, 2013b). The PFC cuk converter operating in DCM with a voltage follower approach is shown above in Fig. 1, that is to say that current flowing in any of the input inductor (L_i), output inductor (L_o) or the voltage across the intermediate capacitor (C_1) become discontinuous in a switching period. A single sensor of DC bus voltage is required for voltage control and power quality improvement at AC mains, once DICM is used for its operation. The projected design and its performance are simulated in MATLAB/Simulink environment for achieving an improved power quality at AC mains in terms of power factor, THD, crest factor, etc., for wide range of speed control and supply voltage variations.

Operation of PFC-cuk converter in DICM mode: The PFC-cuk converter is considered as a natural power-factor correction for AC supply when its work in DICM. In DICM operation of PFC converter, the current flowing in output inductor (i_{Lo}) becomes discontinuous when switch is off whereas the current in input inductor (i_{Li}) and voltage across intermediate capacitor (v_{C1}) still continuous during a complete switching period. Three dissimilar modes of operations of Cuk converter for complete switching period are shown in Fig. 2a-d show the allied waveforms for a complete switching period.

Mode 1: In this mode, when switch S_W is turned on, input inductor L_i and output inductor L_o stores energy in the

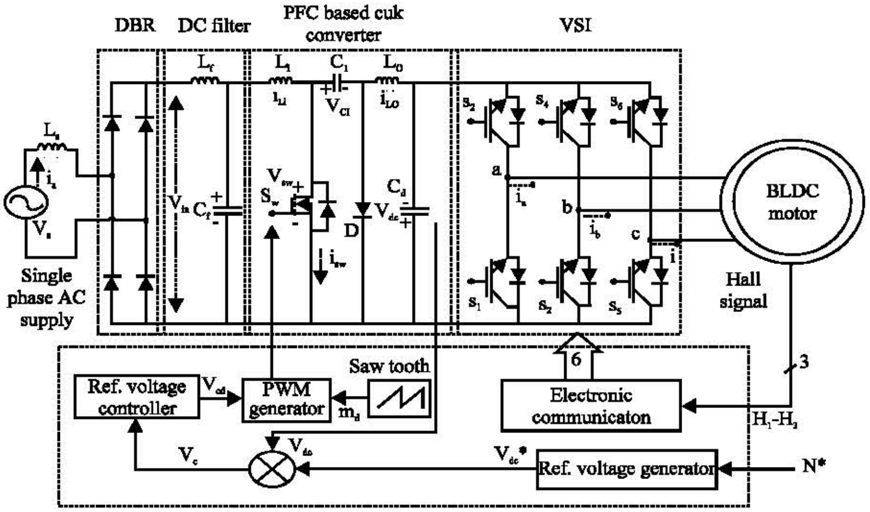

Fig. 1: Proposed BLDC motor drive fed by a PFC-cuk converter

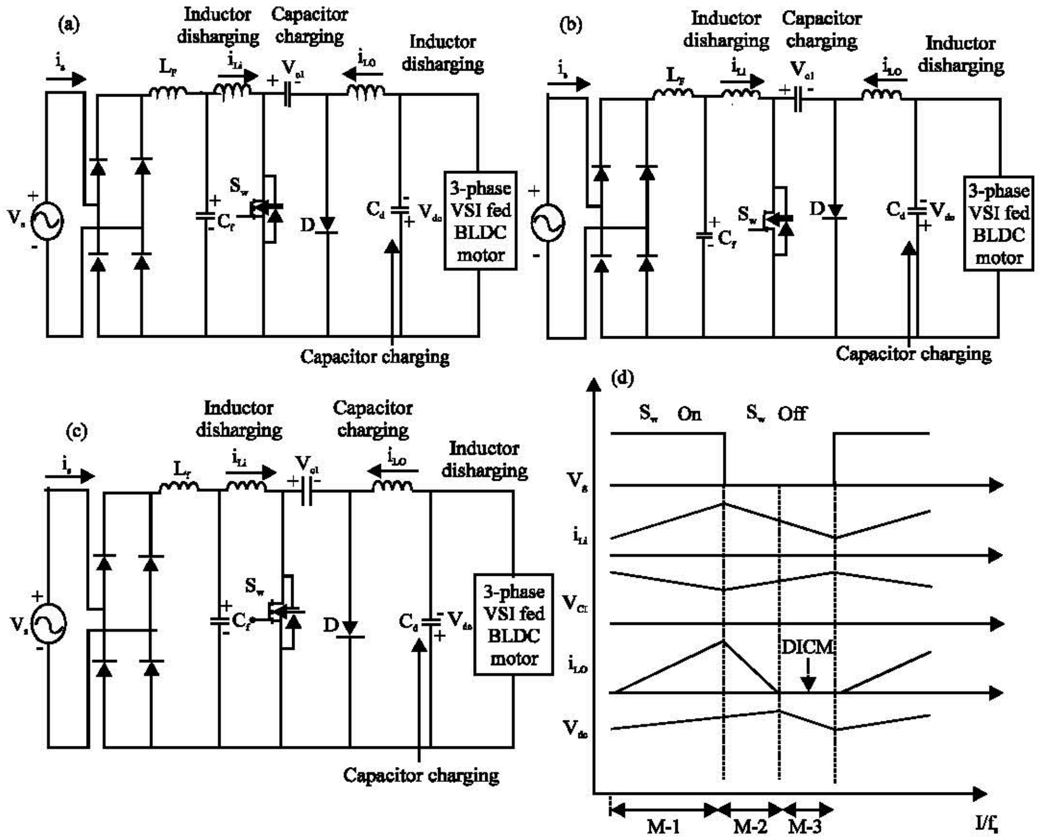

Fig. 2: Operation of cuk converter in DICM (L_O) during: a-c) Different operating modes for a complete switching period and d) The associated Waveforms of different parameters

form of magnetic field at the same time capacitor C_1 discharge through switch S_W to transmit its energy to the DC-link capacitor C_d as shown in Fig. 2a.

Mode 2: When switch S_W is turned off, then the magnetic energy stored in input as well as output inductor L_i and L_o is transferred in electrical energy for charging the intermediate capacitor C_1 and DC link capacitor C_d.

Mode 3: In this mode of operation switch S_W is still off the output inductor current i_{Lo} is fully discharge and the input inductor current i_{Li} continue to discharge as shown in Fig. 2c. An input inductor L_i operates in continuous conduction to transmit its magnetic energy to the electrical energy for intermediate capacitor C_1 via. diode D.

Design of PFC cuk converter: A PFC cuk converter fed BLDC motor drive is designed for a broad variation of speed with power quality improvement at the supply side, by means of controlling DC link voltage. The cuk converter is considered to work for a lowest DC-link voltage of 40 V (V_{dclow}) to a highest DC-link voltage of 200 V (V_{dchigh}). The maximum rating of PFC converter is 350 W (P_{max}) is designed for the preferred BLDC motor of 250 W (P_m) along with the switching frequency (f_s) is taken as 20 kHz. Applied input voltage V_s to the DBR is given as:

$$V_s = V_m \text{Sin}\omega = 220\sqrt{2}\text{Sin}(314t)\,\text{V} \tag{1}$$

Where:

V_m = Maximum input Voltage (i.e., V_s)

ω = The angular frequency that is 314 r/sec

At this time, the instantaneous value of output voltage come out at the output of DC filter is given as:

$$V_{in} = \left|V_m \text{Sin}(\omega t)\right| = \left|220\sqrt{2}\text{Sin}(314t)\right|\text{V} \tag{2}$$

While, || represent the modulus function. A cuk converter belongs to buck-boost converter category that's why the output DC bus voltage, V_{dc} is expressed as function of duty ratio (D) (Singh *et al*., 2011):

$$V_{dc} = \left(\frac{D}{1\text{-}D}\right)V_{in}(t) \tag{3}$$

Thus, the instantaneous value of duty ratio D depends on the input Voltage (V_{in}) and the required DC-link Voltage (V_{dc}). Duty ratio D at any instant is obtained by substituting Eq. 2 into Eq. 3 and rearranging it as:

$$D(t) = \frac{V_{dc}}{V_{in(t)}+V_{dc}} = \frac{V_{dc}}{\left|V_m \text{Sin}(2\pi f_L t)\right|+V_{dc}} \tag{4}$$

Since, by varying the DC bus voltage of VSI the speed of BLDC motor is controlled, therefore the instantaneous power, P_i at various value of DC bus voltage (V_{dc}) is expressed as a linear function of V_{dc} as:

$$P_i = \left(\frac{P_{max}}{V_{dchigh}}\right)V_{dc} \tag{5}$$

Where:

V_{dchigh} = Higher value of DC-link voltage

P_{max} = The maximum rated power of PFC converter

Using Eq. 5, the minimum power (P_{min}) corresponding to the lower value of DC bus voltage of 40 V (V_{dclow}) is calculated as 70 W (P_{min}).

Design of input inductor for its operation in continuous conduction: The input side inductor (L_i) of PFC cuk converter is calculated for an allowable ripple current (η) is given as Singh *et al.* (2011):

$$L_{iccm} = \frac{V_{in}(t)D(t)}{\eta I_{in}(t)f_s} = \frac{R_{in}D(t)}{\eta f_s} = \left(\frac{V_s^2}{P_i}\right)\frac{D(t)}{\eta f_s} = \frac{1}{\eta f_s}\left(\frac{V_s^2}{P_i}\right)\left(\frac{V_{dc}}{V_{in(t)}+V_{dc}}\right) \tag{6}$$

Where:

R_{in} = The input resistance

f_s = The switching frequency

P_i = The instantaneous power

$I_{in}(t)$ = The input current for PFC converter

For a minimum value of supply voltage (V_{smin} = 85 V), most of the ripple in inductor current is obtained at the rated operating conditions that is V_{dc} = 200 V. That's why; the input side inductor of PFC converter is designed for the crest value of minimum supply voltage with permitted current ripple as 25% of I_{in} using (Eq. 6) as:

$$L_{iccm} = \frac{1}{\eta f_s}\left(\frac{V_{s\,min}^2}{P_{max}}\right)\left(\frac{V_{dc}}{\sqrt{2}V_{s\,min}+V_{dc}}\right) = \frac{1}{0.25\times 20000}\left(\frac{85^2}{350}\right)\left(\frac{200}{85\sqrt{2}+200}\right) = 2.57\text{ mH} \tag{7}$$

Therefore, the magnitude of input inductor (L_i) for PFC cuk converter is chosen as 2.57 mH to bind the ripple in input inductor current lower than 25% limit for its operation in continuous conduction mode.

Design of output inductor for it operation in discontinuous conduction: The influential output side inductor (L_{oc}) of PFC cuk converter to operate at the edge of continuous and discontinuous conduction mode is deliberate as Singh *et al.* (2011):

$$L_{OC} = \frac{V_{dc}(1\text{-}D)(t)}{2I_{Lo}(t)f_s} = \frac{V_{dc}D(t)}{2I_{in}(t)f_s} = \frac{R_{in}V_{dc}D(t)}{2V_{in}(t)f_s} = \left(\frac{V_s^2}{P_i}\right)\left(\frac{V_{dc}}{V_{in(t)}+V_{dc}}\right) \tag{8}$$

The ripples in an inductor occur high for the maximum power and for minimum cost of supply voltage. For this reason, the critical value of output inductor is considered for the crest value of supply voltage used for higher and lower value of DC-link voltage L_{oc200} and L_{oc50}:

$$L_{OC200} = \left(\frac{V_{s\,min}^2}{P_{max}}\right)\left(\frac{V_{dchigh}}{2\sqrt{2}V_{s\,min}+f_s}\right)\left(\frac{V_{dchigh}}{\sqrt{2}V_{s\,min}+V_{dchigh}}\right) = \left(\frac{85^2}{350}\right)\left(\frac{200}{2\sqrt{2}\times 85\times 20000}\right)\left(\frac{20000}{85\sqrt{2}+200}\right) = 536\ \mu H \tag{9}$$

$$L_{OC40} = \left(\frac{V_{s\,min}^2}{P_{min}}\right)\left(\frac{V_{dclow}}{2\sqrt{2}V_{s\,min}+f_s}\right)\left(\frac{V_{dclow}}{\sqrt{2}V_{s\,min}+V_{dclow}}\right) = \left(\frac{85^2}{70}\right)\left(\frac{40}{2\sqrt{2}\times 85\times 20000}\right)\left(\frac{40}{85\sqrt{2}+40}\right) = 214.4\ \mu H \tag{10}$$

Therefore, the significant magnitude of output inductor (L_o) for PFC cuk converter is preferred a smaller amount of the minimum value of critical (i.e., L_{oc40}). That's why these are calculated as the order of $L_{oc}/3$ like 70 μH.

Design of intermediate capacitor for it operation in continuous conduction: The intermediate capacitor of PFC Cuk converter operate in CCM with a allowable ripple voltage is designed as Singh *et al*. (2011):

$$C_{1ccm} = \frac{V_{dc}D(t)}{kV_{c1}(t)f_sR_1} = \frac{V_{dc}}{k\{V_{dc}+V_{in}\}(t)f_s\left(\frac{V_{dc}^2}{P_i}\right)} \left(\frac{V_{dc}}{V_{in}(t)+V_{dc}}\right) = \frac{P_i}{kf_s\left(V_{in}(t)+V_{dc}\right)^2} \tag{11}$$

Thus, the amount of intermediate capacitor is designed for maximum ripple voltage which occurs on maximum supply voltage of 200 V and higher DC-link voltage is given as:

$$C_1 = \frac{P_{max}}{kf_s\left(\sqrt{2}V_{Smax}+V_{dchigh}\right)^2} = \frac{350}{0.1\times 20000\left(270\sqrt{2}+200\right)^2} = 0.516\ \mu F \tag{12}$$

Hence, the nearby feasible value of intermediate capacitor (C_1) is selected as 0.66 μF for the application in continuous conduction mode.

Design of DC-link capacitor: DC link capacitor of PFC cuk converter play a vital role for BLDC drive, magnitude of capacitor is calculated by Singh *et al*. (2011):

$$C_d = \frac{I_{dc}}{2\omega\Delta V_{dc}} = \frac{\frac{P_i}{V_{dc}}}{2\omega\delta V_{dc}} = \frac{P_i}{2\omega\delta V_{dc}^2} \tag{13}$$

where, δ represent the allowable ripple for the DC-link voltage that is taken as lower than 4% of V_{dc} for this value of we calculate maximum and minimum value of the DC-link capacitor for higher and lower value of DC-link voltage is presented as:

$$C_{d200} = \frac{P_{max}}{2\omega\delta V_{dchigh}^2} = \frac{350}{2\times 314\times 0.4\times 200^2} = 348.33\ \mu F \tag{14}$$

$$C_{d40} = \frac{P_{min}}{2\omega\delta V_{dclow}^2} = \frac{70}{2\times 314\times 0.4\times 40^2} = 1741.6\ \mu F \tag{15}$$

From now, we choose a maximum value of DC link capacitor for the operation of PFC converter in both continuous and discontinuous conduction to make sure a ripple of DC link voltage is <4% still for lower values of DC link voltages. For this reason the DC link capacitor is selected higher than C_{d40} of the order of 2200 μF.

Design of EMI filter's capacitor and inductor: Filter is designed for avoiding the reflection of ripple currents of higher order harmonics in supply system. For this reason low pass inductive-capacitive filter is placed between DBR and PFC converter, the magnitude of filter capacitance (C_f) is preferred such that its value is always inferior to the maximum Capacitive value of filter (C_{max}) and is specified as Vlatkovic *et al*. (1996):

$$C_{max} = \frac{I_m}{\omega_l V_m}\tan\theta = \frac{\left(\frac{P_{max}\sqrt{2}}{V_s}\right)}{\omega_l V_m}\tan\theta = \frac{\left(\frac{350\sqrt{2}}{200}\right)}{314\times 220\sqrt{2}}\tan 1^\circ = 401.98\ nF \tag{16}$$

Whereas V_m and I_m are the crest magnitude of supply voltage and supply current correspondingly at the same time displacement angle θ is angle involving between fundamental component of supply voltage and supply current. When θ is taken as small as 1°, then the value of filter Capacitor, C_f is taken as 330 nF.

The significance of filter inductor is calculated by considering the supply impedance (L_S) of 4-5% of the base impedance. Therefore, the amount of inductance for filter when cut-off frequency f_c is selected as $f_s/10$ is given as:

$$L_f = L_{req} + L_s \Rightarrow L_{req} = \frac{1}{4\pi^2 f_c^2 C_f} - 0.04\left(\frac{1}{\omega_1}\right)\left(\frac{V_S^2}{P_O}\right) \tag{17}$$

$$\therefore L_{req} = \frac{1}{4\pi^2 \times (2000)^2 \times 330 \times 10^{-9}} - 0.04 \left(\frac{1}{314}\right)\left(\frac{220^2}{350}\right) = 1.573 \text{ mH} \tag{18}$$

A LC filter of 1.57 mH and 330 nF are elected for limiting the indication of high switching frequency current ripples in the source of the system.

Control of proposed PFC cuk converter fed BLDC motor Drive: The controller for motor and PFC Cuk converter is essential for achieving proper operation of BLDC motor drive. Controller for BLDC motor is required for an electronic commutation at the same time controller for a PFC converter is used for adjusting the DC bus voltage for power factor correction operation.

Control of PFC switch: Production of high frequency PWM signals used in solid-state Switch (S_w) of PFC converter are described in this segment. Voltage follower scheme is used for controlling of PFC converter in which a single voltage control loop is used for the generation of a reference Voltage (V_{dc}^*) consequent to the particular reference speed (N^*) same as current multiplier approach:

$$V_{dc}^* = k_b N^* \tag{19}$$

Where:

K_b = The voltage constant of BLDC motor

N^* = The set reference speed

Voltage error generator (V_e) gives the comparator output by comparing the reference DC-link voltage (V_{dc}^*) and the sensed DC bus voltage of capacitor (V_{dc}) as:

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \tag{20}$$

Where, ‘k’ represent the kth sampling order. This voltage error signal is feed in to a PI controller for the generation of controlled output voltage (V_{cd}) given as:

$$V_{cd}(k) = V_{cd}(k-1) + k_{pv}\{V_e(k) - V_e(k-1)\} + k_{iv} V_e(k) \tag{21}$$

Where, the proportional constant and integral gain of the voltage PI controller is is represented by k_{pv} and k_{iv}, respectively. Comparing the PI controller output voltage (V_{cd}) with high-frequency saw-tooth signal (m_d) for the generation of PWM signal for PFC converter swatches given as:

$$m_d(t) < V_{cd}(t) \text{ then } S_W = 1, \text{ else } S_W = 0 \tag{22}$$

Where, switch S_w shows the switching signals 1 and 0 for MOSFET to switch on and off correspondingly.

Control of BLDC motor: An electronic commutation is same as the mechanical commutation, electronic commutation results into maintenance free. Similar to conventional DC motors, brushless DC motors among electronic commutation can operate from a DC voltage source and speed can be attuned by changing supply voltages for this power semiconductor switches are used for commutation as well as terminal voltage control of the motor via. the PWM (Pulse Width Modulation) technique. Proper implementation of switching for inverter has drawn a control armature current from the DC link capacitor. A typical commutation technique is use for trapezoidal back-emf BLDC motor in which only two stator phases conduct at any well-known instance of time. A rotor position is sensed by Hall Effect position sensors for a period of 60° that is essential for electronic commutation. The conduction state of the two switches is shown in Fig. 3. A line current i_{ab} is drawn from the DC link

Table 1: Switching states for electronic commutation of BLDC motor

		Position sensors				Phase current		
Switching interval	Sequence number	H_1	H_2	H_3	Switch closed	A	B	C
0°-60°	0	1	0	0	Q1, Q4	+	-	Off
60°-120°	1	1	1	0	Q1, Q6	+	Off	-
120°-180°	2	0	1	0	Q3, Q6	Off	+	-
180°-240°	3	0	1	1	Q3, Q2	-	+	Off
240°-300°	4	0	0	1	Q5, Q2	-	Off	+
300°-360°	5	1	0	1	Q5, Q4	Off	-	+

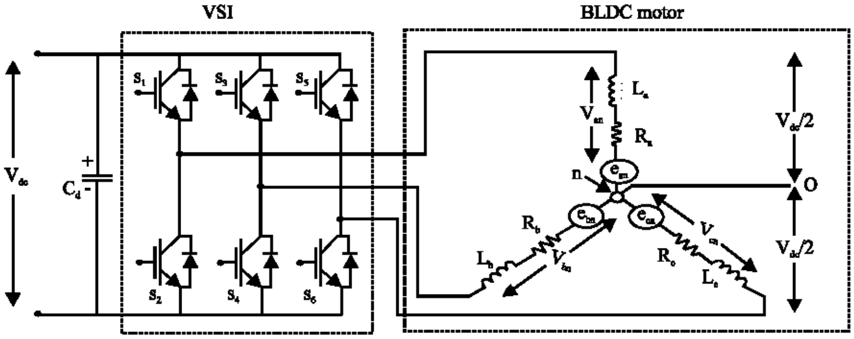

Fig. 3: Simplified equivalent circuit of BLDC drive

capacitor which magnitude depends on the applied DC link voltage (V_{dc}), Table 1 shows the leading switching states of the VSI feeding a BLDC motor based on the Hall Effect position signals (H_a-H_c) (Murphy and Turnbull, 1988).

Modeling of BLDC motor drive: The BLDC motor drive is fundamentally combination of an electronic commutator, a VSI and a PMBLDC motor. The dynamic modelling of each component is given by Gopalarathnam and Toliyat (2003).

Voltage Source Inverter (VSI): Figure 3 shows an equivalent circuit of VSI-fed BLDC motor in which output of VSI is fed to different phase of armature windings. The output voltage across phase 'a' is given as:

$$V_{ao} = \left(\frac{V_{dc}}{2}\right) \text{for } S_1 = 1 \text{ and } S_2 = 0 \tag{23}$$

$$V_{ao} = \left(\frac{-V_{dc}}{2}\right) \text{for } S_1 = 0 \text{ and } S_2 = 1 \tag{24}$$

$$V_{ao} = 0 \text{ for } S_1 = 0 \text{ and } S_2 = 0 \tag{25}$$

$$V_{an} = V_{ao} - V_{n0} \tag{26}$$

Where, 1 and 0 stand for the 'on' and 'off' position of the IGBT switch of the inverter, respectively using above similar logic, V_{bo}, V_{co}, V_{bn} and V_{cn} be generated for other two phases of inverter in favor of BLDC motor. The voltages V_{ao}, V_{bo}, V_{co} and V_{no} are voltages of the three-phases and the neutral point (n) with respect to the virtual mid-point of the DC link voltage shown as 'o' in Fig. 3. Voltage V_{an}, V_{bn} and V_{cn} are phase voltages with respect to the neutral point (n); V_{dc} is the DC link voltage.

Modeling of BLDC motor: The BLDC motor is modeled in the form of set of differential equations given:

$$V_{an} = Ri_a + \frac{d\lambda_a}{dt} + e_{an} \tag{27}$$

$$V_{bn} = Ri_b + \frac{d\lambda_b}{dt} + e_{bn} \tag{28}$$

$$V_{cn} = Ri_c + \frac{d\lambda_c}{dt} + e_{cn} \tag{29}$$

Where:

λ_a, λ_b and λ_c = The current

λ_a, λ_b and λ_c = The flux linkages by each phase

e_{an}, e_{bn} and e_{cn} = The back-emf of BLDC motor for a particular phases

R = The phase resistance of motor winding

Likewise, the flux linkage can be represented as:

$$\lambda_a = L_s i_a - M(i_b + i_c) \tag{30}$$

$$\lambda_b = L_s i_b - M(i_a + i_c) \tag{31}$$

$$\lambda_c = L_s i_c - M(i_b + i_a) \tag{32}$$

where, L_S and M represents the self inductance and mutual inductance of the motor winding for each phase, respectively. BLDC motor does not consist any neutral connection, so, Eq. 26-33 the Voltage (V_{no}) between the neutral point (n) and the mid-point of the DC link (o) is given as:

$$i_a + i_b + i_c = 0 \tag{33}$$

$$V_{no} = \left\{\frac{V_{ao} + V_{bo} + V_{co} - (e_{an} + e_{bn} + e_{cn})}{3}\right\} \tag{34}$$

Since, flux linkages are given from Eq. 30-33:

$$\lambda_a = (L_s + M) i_a \tag{35}$$

$$\lambda_b = (L_s+M)i_b \tag{36}$$

$$\lambda_c = (L_s+M)i_c \tag{37}$$

From Eq. 27-29 and 35-37, the current derivatives in the generalized state space form are given as:

$$pi_x = \frac{(v_{xn}-i_x-e_{xn})}{(L_s+M)} \tag{38}$$

Where:
p = Change in derivative
'x' = Individual phases a, b or c

Electromagnetic Torque T_e developed in the BLDC motor is given as:

$$T_E = \frac{(e_{an}i_a+e_{bn}i_b+e_{cn}i_c)}{\omega_r} \tag{39}$$

Here ω_r is the angular speed of motor in rad/sec and back-emf for any phase may be articulated as a function of rotor position (θ) as:

$$e_{xn} = k_b f_x(\theta)\omega_r \tag{40}$$

$f_x(\theta)$ represents rotor position function for a maximum and minimum value like to the trapezoidal-induced emf given as:

$$f_a(\theta)=1 \text{ for } 0<\theta<\frac{2\pi}{3} \tag{41}$$

$$f_a(\theta) = \left\{\left(\frac{6}{\pi}\right)(\pi-0)\right\}-1 \text{ for } \frac{2\pi}{3}<0<n \tag{42}$$

$$f_a(\theta) = -1 \text{ for } n<\theta<\frac{5\pi}{3} \tag{43}$$

$$f_a(\theta) = \left\{\left(\frac{6}{\pi}\right)(\theta-2\pi)\right\}+1 \text{ for } \frac{5\pi}{3}<\theta<2n \tag{44}$$

The function $f_b(\theta)$ and $f_c(\theta)$ are same as $f_a(\theta)$ but only difference in the phase displacement of 120 and 240°, respectively. So, the electromagnetic torque is expressed as rotor position function given as:

$$T_e = K_b\{f_a(\theta)i_a+f_b(\theta)i_b+f_c(\theta)i_c\} \tag{45}$$

Here, in the form of speed derivative mechanical equation of motion is presented as:

$$\omega_r = (P/2)(T_e-T_L-B\omega_r)/(J) \tag{46}$$

Rotor position derivative is given as:

$$P\theta = \omega_r \tag{47}$$

where number of poles by P, load torque T_l in Nm, moment of inertia J in kg-m^2, friction coefficient B in Nms/rad. From Eq. 27-47 correspond to the dynamic model of the BLDC motor.

Electronic commutator: Electronic commutator uses switching signals sensed by the Hall-Effect rotor position sensor. Switching sequence generation is based on the logic for the VSI given in Table 1.

RESULTS AND DISCUSSION

Simulated performance of proposed BLDC motor drive: Cuk converter act as a power factor correction converter for BLDC motor drive is designed and simulated in MATLAB/Simulink environment. Overall system configurations shown in Fig. 1 are simulated in MATLAB using Simulink library. The performance of Cuk converter for four different modes of operation is obtained on the base of designing parameter value of converter element. DICM mode of operation for output inductor current is evaluated because it acts as an inherent PF corrector. Power quality indices like power factor, THD, crest factor and displacement factor are estimating for various parameters in the vein of supply Voltage (V_s) and supply current (i_s). The rotor speed, developed electromagnetic torque and the stator current of the BLDC motor is obtained for determining the best action of BLDC motor. While the inductor's current, intermediate capacitor voltage, DC link voltage, switching voltage and switching current are used for the satisfactory performance valuation of the PFC Cuk converter.

The circuit configuration and different modes of operation in DICM through output inductor operating in discontinuous conduction of PFC cuk converter are shown in Fig. 2. The steady state performance of entire system operating in DICM is shown for 3 cycles of line frequency in Fig. 4. Table 2 shows the performance of

Table 2: Power quality indices with DC voltage variation

V_{dc} (V)	Speed (rpm)	THD of I_s (%)	DPF	PF	I_s(A)
40	310	6.42	0.9953	0.9930	0.494
60	520	5.83	0.9964	0.9948	0.632
80	720	4.95	0.9972	0.9956	0.765
100	910	4.66	0.9976	0.9964	0.902
120	1130	4.21	0.9985	0.9975	0.998
140	1340	3.78	0.9992	0.9983	1.171
160	1550	2.92	0.9998	0.9992	1.305
180	1760	2.46	0.9999	0.9995	1.428
200	1960	1.91	0.9999	0.9996	1.537

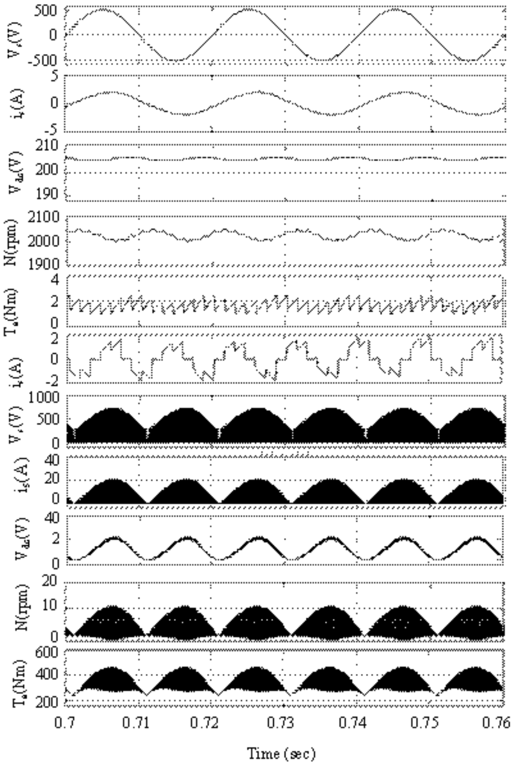

Fig. 4: Simulated performance result of BLDC motor drive with cuk converter operating in DICM mode

BLDC motor drive in terms of power quality indices such as Power Factor (PF), Crest Factor (CF), Displacement Power Factor (DPF) and Total Harmonic Distortion (THD) of supply current over a wide range of DC link voltage, an enhanced power quality operation is achieve for the complete range of speed control.

Performance of the proposed drive during speed control: The simulated results of the proposed BLDC motor drive at rated DC voltage of 200 V are shown in Fig. 4. The voltage across the DC link capacitor (V_{dc}) retain at the desired set reference value and the BLDC motor is operating at variable speeds which are justified by the magnitude and frequency of stator current. As shown in these outcome a supply current (I_s) is sinusoidal and within phase with supply voltage which demonstrate a unity power factor operation. Obtained different power quality index are gratifying IEC 61000-3-2 standard (Anonymous, 2001).

Performance of PFC based cuk converter: The input inductor current (I_{Li}), intermediate capacitor voltage (V_{C1}) are continuous in nature and output inductor current (I_{Lo}) is discontinuous for a complete switching cycle also waveforms of supply voltage (V_s), supply current (I_s) and DC link voltage (V_{dc}), respectively are shown in Fig. 4 which confirms the DICM operation for output inductor of the PFC converter. The crest value of voltage and current stresses on the PFC converter switch at rated condition is 560 V and 15 A is achieved which are relatively low for the action of PFC converter in DICM.

Table 3: Comparative analysis of proposed drive with conventional drive

	Schemes		
Items	Conventional (No PFC)	Conventional (PFC)	Proposed
Variable DC bus	-	No	Yes
Control (BLDC motor) (complex)	Current controlled commutation	Current controlled on (simple)	Electronic (complex)
Control (PFC)	-	Voltage follower	Voltage follower
Sensor (BLDC motor)	2-current+ 1-hall	2-current+ 1-hall	1-hall
Sensor (PFC)	-	1-voltage	1-voltage
Losses (VSI)	High	High	Low
PFC	-	Yes	Yes
Cost	Medium	High	Low

Performance of the proposed drive at various dynamic conditions: At the time of starting of BLDC motor an ostensible overshoot in stator current as well as supply current is achieved within the utmost current limit of stator windings for DC link voltage of 40 V. When we change a step in DC bus voltage, a stator current frequency and magnitude is increased which tells that motor is gaining speed by changing DC-bus voltage. That's why DC link voltage is controlled very efficiently during the complete working range gives a suitable closed-loop performance of the proposed drive.

Comparative evaluation of proposed pattern with conventional schemes: This segment deals among a comparative study of three pattern of BLDC motor drive. The proposed pattern is compared through the conventional DBR fed BLDC motor drive and a usual single switch PFC converter feeding BLDC motor drive by the use of PWM based switching of VSI (Gopalarathnam and Toliyat, 2003; Bist and Singh, 2014; Vlatkovic *et al*., 1996). The valuation is based on the necessity of sensor, control requirement, system complication and losses in a drive system and in general cost of the system.

The individual losses occur in BLDC motor, VSI and PFC converter are shown in Fig. 5. Total losses occurred in BLDC motor drive is the combination of all losses measured separately in three different segment of the proposed BLDC motor drive. Relative analysis of losses in different parts of proposed and conventional BLDC motor drive is shown above in bar chart.

Relative presentation of the proposed configuration with the conventional scheme of BLDC motor drive is shown in Table 3. The simplicity, low losses in VSI due to

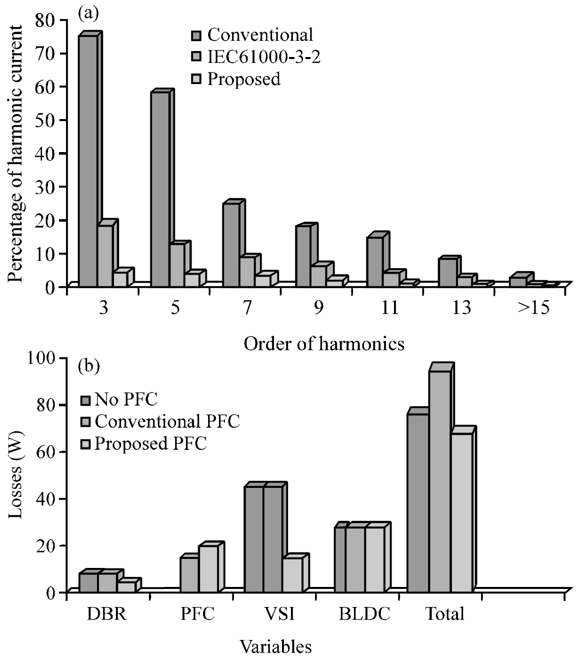

Fig. 5: Comparison analysis of: a) Order of harmonic of supply current and b) Losses of each component of BLDC motor drive

fundamental switching and a much simple move toward the speed control with a power factor correction at AC mains make the proposed drive is good resolution for low power application.

CONCLUSION

A cuk converter designed for VSI fed BLDC motor drive achieving improved power quality operation at different speeds and supply voltages. The PFC converter is operated with voltage follower control to find a reduced sensor controller. By varying the DC link voltage of VSI speed of the BLDC motor drive has been controlled which allow the VSI to operate in fundamental frequency switching mode for condensed switching losses. A natural PFC has been achieved for the reason that PFC converter design in DICM mode for a single voltage sensor that can be utilized for the complete operation of the proposed drive. A reasonable PQ performance has been achieved for a variety of speeds and supply voltage fulfilling the limits of IEC 61000-3-2 standard. The proposed drive system has shown satisfactory result in all aspects and is a recommended solution for low power BLDC motor drives applications.

APPENDIX

- BLDC motor specification: poles: 4
- Rated power (P_{rated}) = 250 W
- Rated DC bus voltage (V_{rated}) = 200 V
- Rated torque (Trated) = 1.3 Nm
- Rated speed (ω_{rateed}) = 2000 rpm
- Motors back-EMF constant (K_v) = 78 V/krpm
- Torque constant (K_t) = 0.74 Nm/A
- Per phase resistance and inductance (R_{ph}, L_{ph}) = 14.56 Ω
- The 25.71 mH and moment of inertia (J) = 1.3×10-4 Nm/sec
- Controller gains: K_p = 0.3 and K_i = 0.001

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