Bridgeless Cuk Converter Fed BLDC Motor with Power Factor Correction for Air Conditioning System

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***Abstract*—This paper deals with bridgeless cuk converter operating in discontinuous inductor current mode (DICM) for single-stage power factor correction converter for a permanent magnet brushless dc motor (PMBLDCM).A three-phase voltage-source inverter is used as an electronic commutator to operate the PMBLDCM driving an air-conditioning system. The speed control of PMBLDC motor achieved by controlling the voltage at DC bus using single voltage sensor. The bridgeless cuk converter topology is used for obtaining low switching losses and low size heat sink is used for switches.**

Keywords—Bridgeless cuk converter Permanent magnet brushless DC motor (PMBLDCM),Discontinous inductor current mode(DICM),Power factor correction(PFC),Voltage source inverter(VSI).

I. INTRODUCTION

The use of a permanent-magnet brushless dc motor (PMBLDCM) is used in low and medium power applications because of their high efficiency, wide speed range, high energy density ,high torque/inertia ratio, low maintenance and wide range of speed control. The BLDC motor has three phase distributed winding on stator and permanent magnet on the rotor. There is no brushes used for commutation. It is an electronically commutated motor. The hall sensors are used for rotor position sensing and it is used for commutation state of voltage source inverter switches. The problems associated with mechanical commutator such as sparking, electro-magnetic interference, wear and tear and noise problems in brush and commutator assembly are eliminated.BLDC motors are used household equipments like air conditioners, washing machines,refrigerators,fans etc and it is also used in medical equipments, industrial tools, heating ,ventilation and motion control systems.

A BLDC motor has the developed torque proportional to its phase current and its back electromotive force (EMF), which is proportional to the speed [1]–[4]. A constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDCM under variable speed operation. A speed control scheme uses a reference voltage at dc link proportional to the desired speed of the permanent-magnet brushless direct current (PMBLDC) motor.

The BLDC motor fed by a diode bridge rectifier (DBR) with a high value of DC-link capacitor results in highly distorted supply current and a poor factor [9]. Hence, a power factor corrected (PFC) converter is required for obtaining the improved PQ at the AC mains for a VSI-fed BLDC motor drive. Two stage PFC converters have been in normal practice in which one converter is used for the PFC operation which is typically a boost converter and other converter is used for the voltage control, selection of which depends upon the type of application [10]. This has more losses because of higher number of components and two switches. A single stage PFC converter has gained popularity because of single stage operation which has reduced number of components. A PFC and DC-link voltage control can be achieved in a single stage operation[11, 12].

Two basic modes of operation of a PFC converter, continuous conduction mode (CCM) and dis-continuous conduction mode (DCM) [11,12]. In CCM or DCM, the inductor's current or the voltage across intermediate capacitor in a PFC converter remains continuous or discontinuous in a switching period. The PFC converter operate in CCM, requires three sensors (two voltage, one current) while in DCM operation can be achieved by using a single voltage sensor [12]. The stresses on PFC converter switch operating in DCM are comparatively higher as compared with its operation in CCM.

A PFC boost half-bridge-fed BLDC motor drive using a four switch VSI has been proposed by Madani et al. [13] which uses a constant DC-link voltage with PWM switching of VSI and have high switching losses. Ozturk et al. [14] have proposed a PFC boost converter feeding a direct torque controlled (DTC)-based BLDC motor drive which requires higher number of sensors for DTC operation, have higher switching losses in PWM-VSI and increased complexity of the control unit. A similar configuration using a front-end cascaded buck–boost converter-fed BLDC motor drive has been proposed by Wu and Tzou [15], which also confronts same difficulties. Gopalarathnam and Toliyat [16] have proposed an active PFC using a single ended primary inductance converter (SEPIC) for feeding a BLDC motor drive which again utilized a PWM-based VSI for speed control of BLDC motor which have switching losses corresponding to the switching frequency of PWM pulses.

A PFC Cuk converter operating in CCM for feeding a BLDC motor drive has been proposed by Singh and Singh [17], but it requires three sensors for DC-link voltage control and PFC operation and hence this topology is suited for high-power applications. This main objective of this paper is the development of cost effective motor drive which requires minimum sensors and has reduced switching losses in the VSI. Moreover, the proposed drive operates for improved PQ operation at AC mains over a wide range of speed control.

II. Proposed Bridgeless Cuk Converter-Fed BLCD Motor Drive

Fig. 1 shows the bridgeless Cuk converter-fed BLDC motor driving an air conditioning compressor. The bridgeless Cuk converter is used to control the DC-link voltage (Vdc) of the VSI and to achieve a unity power factor at AC mains. To eliminate a DBR in the front end, a bridgeless converter topology is used which has an advantage of low conduction losses and thermal stress on the devices. A new approach of speed control by controlling the voltage at the DC link is used which utilizes a fundamental frequency switching of VSI (i.e. electronic commutation of BLDC motor) hence offers reduced switching losses. A voltage follower approach is used for the control of bridgeless Cuk converter operating in discontinuous inductor current mode (DICM) in which a single voltage sensor is required for the sensing of DC-link voltage (Vdc). The proposed drive is designed to operate over a wide range of speed control with improved PQ at AC mains.

III. Operation Of Bridgeless Cuk Converter

To eliminate the requirement of a DBR such that its conduction losses are reduced, a bridgeless converter topology is used [18–20]. The converter is designed to operate in DICM, in which the current in output inductor Lo1 and Lo2 remains discontinuous while the current in input inductors (Li1 and Li2) and voltage across the intermediate capacitors (VC1 and VC2) remain continuous to achieve a PFC at the AC mains. Figs. 2a and b show the operation of the converter for a positive and negative half cycles of the AC supply, respectively. As shown in Fig. 2a, for the positive half cycle of the supply voltage, switch Sw1 is in conduction through Li1 and Dp. The energy is transferred through the energy transferring capacitor C1 through Lo1 and D1. Similarly, for negative half cycle of supply voltage, switch Sw2 is conducting through Li2 and Dn as shown in Fig. 2b. A common DC-link capacitor Cd is used for both the positive and negative half cycle of operation. The voltage across this DC-link capacitor Cd is controlled to achieve the speed control of the BLDC motor.

Figs. 2c–e show the operation of bridgeless Cuk converter for a complete switching cycle during the positive half cycle of supply voltages. Different modes of operation are described below.

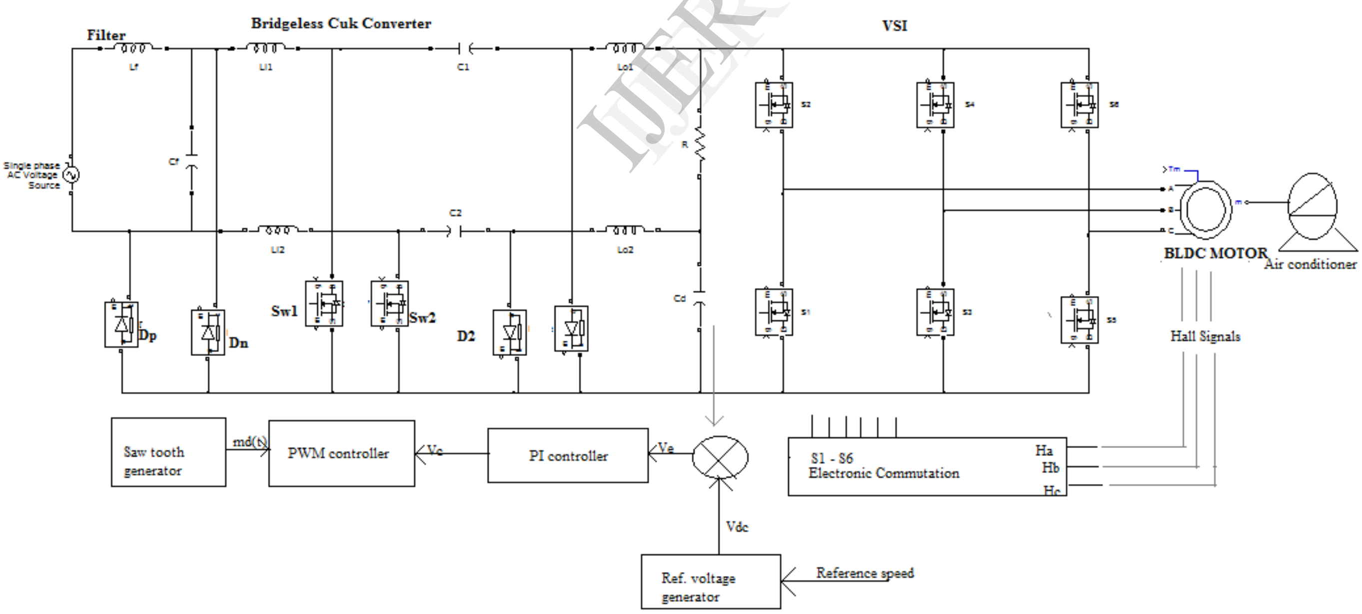
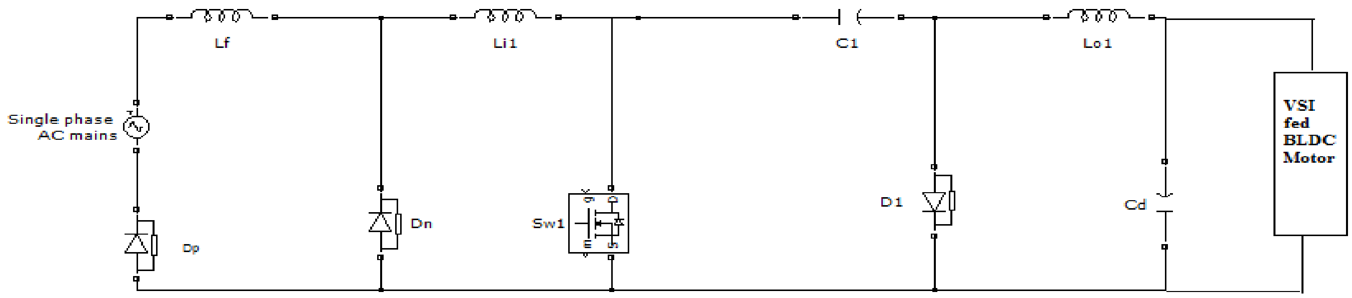


Fig. 1 Bridgeless Cuk converter-fed BLDC motor drive

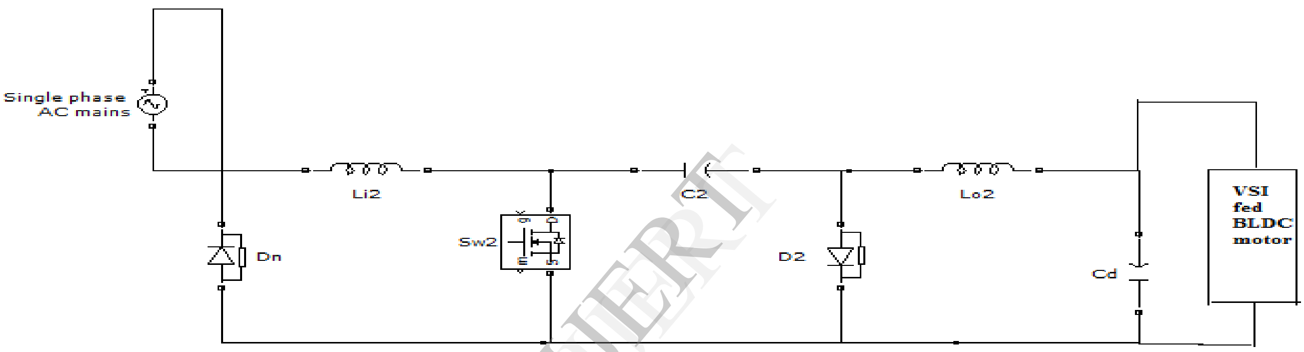
Mode I: When switch Sw1 is turned on, an energy is stored in the input inductor L_{i1} via diode D_p, hence the inductor current i_{Li1} increases as shown in Fig. 2c. Moreover the energy stored in intermediate capacitor C_1 is discharged to the DC-link capacitor C_d and the output inductor L_{o1}. Therefore the current i_{L01} and DC-link voltage V_{dc} are increased and the voltage across the intermediate capacitor V_{c1} reduces in this mode of operation.

Mode II: When switch Sw1 is turned off, the inductor L_{i1} discharges through intermediate capacitor C_1 via diode D_1 and D_p. Moreover, inductor L_{o1} also transfers its stored energy to DC-link capacitor C_d as shown in Fig. 2d. Hence, in this mode of operation, the current in inductors i_{Li1} and i_{Lo1} continues to decrease while the voltage across DC-link capacitor C_d and intermediate capacitor C_1 increases.

Mode III: Fig. 2e shows the DCM of operation. In this mode, none of the energy is left in the output inductor L_{o1}, that is, i_{Lo1}= 0. The voltage across intermediate capacitor C_1 and current in input inductor i_{Li1} increases, while the DC-link capacitor C_d supplies the required energy to the load, hence V_{dc} reduces in this mode of operation . This operation continues till the switch Sw1 is again turned 'on'.



a



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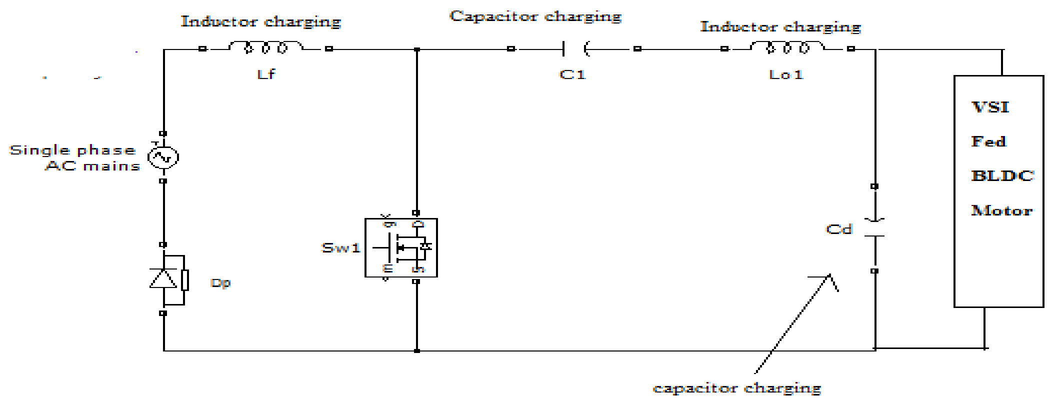

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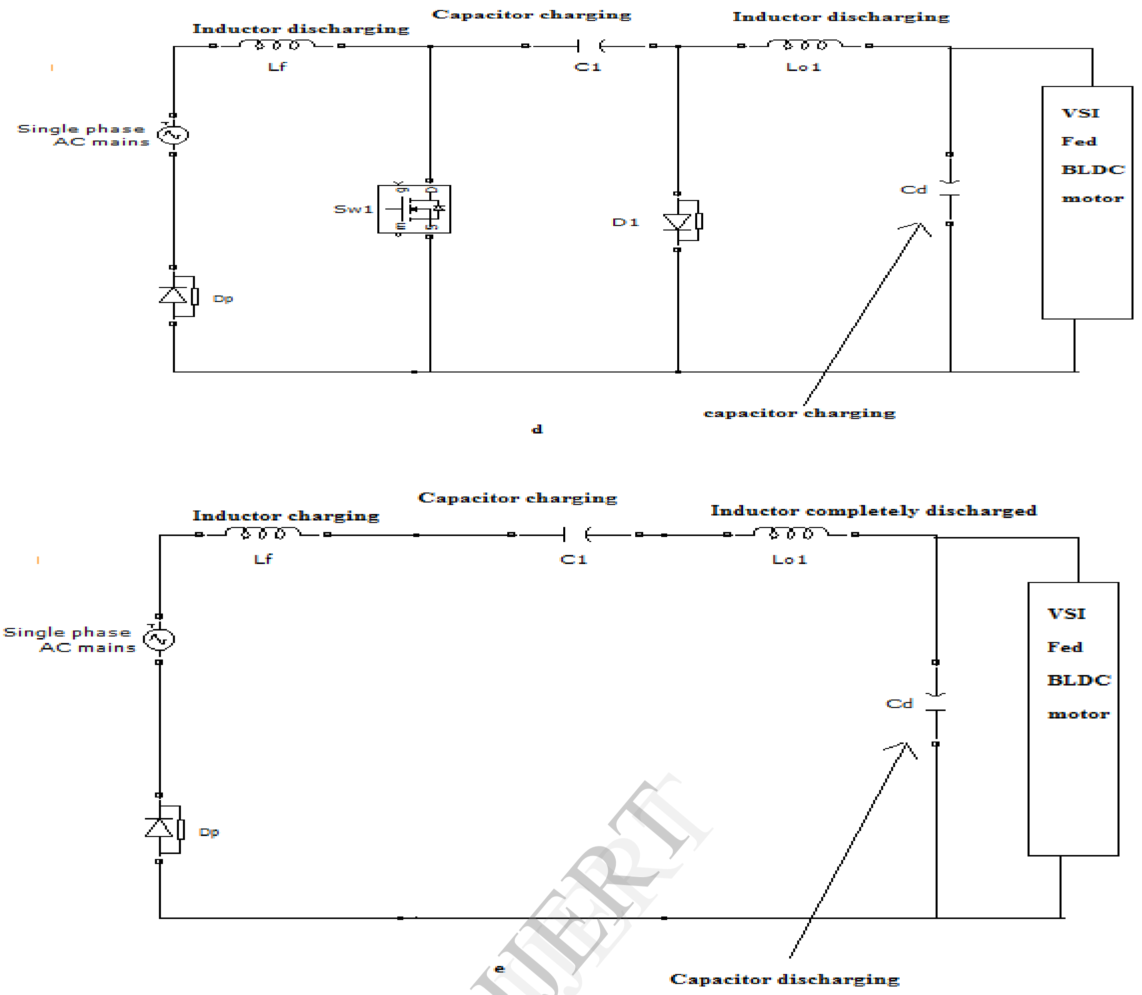


Fig 2.Operation of bridgeless cuk converter for positive (fig. 2a) and negative (fig. 2b) half cycle of supply voltage

Different modes of operation of bridgeless Cuk converter in a complete switching cycle (Figs. 2c–e) for a positive half cycle of supply voltage
a Operation for positive half cycle of supply voltage
b Operation for negative half cycle of supply voltage
c Mode I
d Mode II
e Mode III

IV. Design Of Bridgeless Cuk Converter

A bridgeless Cuk converter is designed for its operation in discontinuous inductor current mode (DICM) to act as a power factor (PF) pre-regulator with a wide voltage conversion ratio. In this mode, the input inductors (Li1 and Li2) and intermediate capacitors (C1 andC2) are designed to operate in continuous conduction whereas; the current in output inductors (Lo1 and Lo2) becomes discontinuous in a complete switching period. A PFC converter of 500W is designed for a 0.5 hp BLDC motor . For the supply voltage (Vs) of 220 V, the input average voltage V_{inav} is given as

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2}\times 220}{\pi} \cong 198\text{V} \qquad (1)$$

The PFC bridgeless Cuk converter is designed for the DC-link voltage control from 70 V (V_{dcmin}) to 310V(V_{dcmax}) with a nominal value DC-link voltage as 190 V (V_{dcdes}) .The duty ratio D, for a Cuk converter which is a buck–boost converter topology is given as

$$D = \frac{V_{dc}}{V_{dc} + V_{in}} \qquad (2)$$

Hence the duty ratio for designed (d_{des}) maximum (d_{max}) and minimum ($d_{min,}$) corresponding to V_{dcdes}, V_{dcmax} and V_{dcmin} are calculated using (2) as 0.4897, 0.6103 and 0.2612, respectively.

Now the nominal duty ratio (d_{nom}) is taken less than d_{des} (designed duty ratio) for an efficient control in DICM, hence d_{nom} is taken as 0.2. If the amount of permitted ripple current is Δi_{Li} (30% of I_{in}, where I_{in}= 2P/V_{in} =3.215A) in both inductors L_{i1} and L_{i2}, then the value of L_{i1} and L_{i2} is given as

$$L_{i1} = L_{i2} = \frac{V_m d_{nom} T_s}{\Delta i_{Li}} = \frac{311 \times 0.2 \times (1/20000)}{0.3 \times 3.215} = 3.22mH \quad (3)$$

Where Vm is the peak of supply voltage (i.e. 220√2 V), T_s is the switching period (i.e 1/fs, where f_s is the switching frequency = 20 kHz). Hence, a value of 3 mH is selected for inductor L_{i1} and L_{i2}. The critical conduction parameter K_{acrit} is given as

$$K_{acrit} = \frac{1}{2(M+n)^2} = \frac{1}{2[\left(\frac{V_{dcdes}}{V_m}\right)+n]^2} = \frac{1}{2[\left(\frac{190}{311}\right)+1]^2} = 0.1927 \quad (4)$$

Where M = V_{dc}/V_m and n is the turns ratio for isolated converter, (here n = 1 for non-isolated converter). Now, the conduction parameter K_a for operation in DICM is to be taken a

$$K_a < K_{a\,(critical)} \quad (5)$$

The value of K_a is taken around two-thirds of $K_{a(critical)}$ for an efficient control in [DICM]. Hence K_a is taken as 00.13.Now, the equivalent inductance Leq is calculated as

$$L_{eq} = \frac{R_o T_s K_a}{2} = \frac{\left(\frac{V_{dcdes}^2}{P}\right)(1/f_s)K_a}{2} = \frac{\left(\frac{190^2}{500}\right)\left(\frac{1}{20000}\right)\times 0.13}{2} = 234.65\mu H \quad (6)$$

where R_o is the equivalent load resistance. Now the value of output side inductor (L_{o1} and L_{o2}) is given as

$$L_{o1} = L_{o2} = \frac{L_i L_{eq}}{L_i - L_{eq}} = \frac{3000 \times 234.65}{3000 - 234.65} = 254.56\mu H \quad (7)$$

Hence a value of 100 µH is selected to ensure a deep DICM condition (i.e. discontinuous conduction at very low duty ratio) to maintain a high PF even at very low value of DC link voltage. The capacitance of the energy transferring capacitors C_1 and C_2 is given as

$$C_1 = C_2 = \frac{1}{\omega_r^2 (L_i + L_o)} = \frac{1}{(2\pi \times 5000)^2 (3000+100) \times 10^{-6}} = 0.327\mu F \quad (8)$$

where $\omega_r = 2\pi f_r$,' f_r ' is resonant frequency of intermediate capacitor (C_1 and C_2) and $f_s > f_r > f_L$ where f_L is the line frequency. Hence for the line frequency and switching frequency of 50 and 20000 Hz, a resonant frequency of 5000 Hz is selected. Hence the value of capacitors C_1 and C_2 is selected as0.33 µH. The value of DC-link capacitor is given as

$$C_d = \frac{I_d}{2\omega_L \Delta V_{dc}} = \frac{\left(\frac{500}{190}\right)}{2 \times 314 \times 0.01 \times 190} \cong 2205\ \mu F \quad (9)$$

where I_d is the DC-link current, ω is the line frequency in rad/s and ΔV_{dc} is the permitted ripple voltage of DC-link capacitor which is taken as 1% of DC-link voltage.

To avoid the reflection of high-order harmonics in s supply system, a low-pass LC filter is designed. For a line frequency of 50 Hz, the cut-off frequency of filter is selected as 200 Hz. The maximum value of filter capacitance, C_{fmax} is g given and calculated as

$$Cf_{max} = \frac{I_{peak}}{\omega_L V_{peak}} \tan(\theta)$$

$$= \frac{(500\sqrt{2}/220)}{314 \times 220\sqrt{2}} \tan(1^0)$$

$$\cong 574 \text{ nF} \qquad (10)$$

Hence a value of filter capacitor of 330 nF is selected. Finally, the value of filter inductor L_f is calculated using the expression given as

$$L_f = \frac{1}{4\pi^2 f_c^2 C_f}$$

$$= \frac{1}{4\pi^2 \times 200^2 \times 330 \times 10^{-9}}$$

$$= 1.918 \text{mH} \qquad (11)$$

Hence a LC filter with inductance L_f and capacitance C_f is selected as 2 mH and 330 nF, respectively.

V. Control Of Proposed Drive System

The control algorithm of the proposed drive is divided into following different sections.

A. Reference voltage generator

A reference DC voltage V_{dc}^* is generated by a reference voltage generator which is equivalent to the particular reference speed of the BLDC motor. This voltage is compared with the sensed DC-link voltage to produce a voltage error signal to be fed in the speed controller. The reference voltage is generated by multiplying the voltage constant (K_v) of the BLDC motor with the reference speed.

B. Speed controller

A voltage error signal is given to the speed controller which is a proportional integral controller for generating a controlled output for the PWM generation stage. At any time instant k, the voltage error signal Ve(k) and controller output Vc(k) is given as

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \qquad (12)$$

$$V_c(k) = V_c(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \qquad (13)$$

where Kp and K_i represent the proportional and integral gain constants, respectively.

C. PWM generator

A fixed frequency, varying duty ratio PWM is generated by a PWM generator by comparing the controlled output of the speed controller with a high frequency saw-tooth generator

$$\text{If } m_d(t) < V_c(k) \text{ then } S_{w1}=S_{w2}=1 \text{ else } S_{w1}=S_{w2}=0 \qquad (14)$$

where S_{w1} and S_{w2} denote the switching signals as 1 and 0 for MOSFET S_{w1} and S_{w2} to switch on and off, respectively.

VI. Modeling Of Proposed Drive System

The modeling of a BLDC motor drive consists of a modeling of a BLDC motor, a VSI and an electronic commutation.

A. BLDC motor

The dynamic modeling of the BLDC motor is governed by following equations [7, 17]. Per phase voltage (V_{xn}, where x represents a, b or c and n represents neutral) are given as [7]

$$V_{xn} = R_s i_s + p\lambda_x + e_{xn} \qquad (15)$$

$$V_{xn} = V_{xo} - V_{no} \qquad (16)$$

where p is the time differential operator, R_s represents resistance per phase, i_x is the phase current, e_{xn} represents back emf, λ_x represents flux linkages, V_{xo} and V_{no} is potential difference of a particular phase 'x' and neutral 'n' with the zero reference potential 'o' which at the mid-point of DC-link respectively as shown in Fig. 3.

The flux linkages are represented as [7]

$$\lambda_x = L_s i_s - M(i_y + i_z) \qquad (17)$$

where L_s is the self-inductance per phase and M is the mutual inductance of the windings. If 'x' represents phase 'a', then 'y' and 'z' represent the phases 'b' and 'c', respectively, and vice versa.

Moreover for star connected three phase windings of the stator of BLDC motor

$$\sum i_x = 0 \qquad (18)$$

Hence by substituting (18) in (17) the flux linkages are obtained as

$$\lambda_x = (L_s + M)i_x \qquad (19)$$

Hence, the phase current derivative by using (15) and (19) are obtained as

$$pi_x = \frac{V_{xn} - i_x R_x - e_{xn}}{(L_s + M)} \qquad (20)$$

The developed electromagnetic torque of the BLDC motor is given as [7]

$$Te = \sum \frac{e_{xn}\ i_x}{\omega_r} \quad (21)$$

where ω_r is the rotor speed electrical rad/s.

This expression for the torque confronts computational difficulty at zero speed as induced emfs are zero. Hence, it is reformulated by expressing back-emf as a function of rotor position angle θ, which can be written as [17]

$$e_{xn} = k_b f_x(\theta)\omega_r \quad (22)$$

where k_b is the back emf constant and $f_x(\theta)$ are functions of rotor position having the trapezoidal shape as that of back-emf obtained in BLDC motor with a maximum magnitude of + or –1.The function $f_a(\theta)$ corresponding to phase 'a' is represented as [17]

$$f_a(\theta) = 1\ ;\ \text{for } 0^0 < \theta < 120^0 \quad (23)$$

$$f_a(\theta) = \left\{\left(\tfrac{6}{\pi}\right)(\pi - \theta)\right\} - 1;\ \text{for } 120^0 < \theta < 180^0 \quad (24)$$

$$f_a(\theta) = -1\ ;\ \text{for } 180^0 < \theta < 300^0 \quad (25)$$

$$f_a(\theta) = \left\{\left(\tfrac{6}{\pi}\right)(\theta - 2\pi)\right\} + 1;\ \text{for } 300^0 < \theta < 360^0 \quad (26)$$

Similarly the function $f_b(\theta)$ and $f_c(\theta)$ for phase 'b' and 'c' can be obtained by using a phase difference of 120° and 240°, respectively. Now, substituting (22) into (21), the torque expression becomes

$$T_e = k_b \sum f_x(\theta) i_x \quad (27)$$

The torque balance equation is given as [7]

$$T_e = T_L + B\omega_r + J\left(\frac{2}{P}\right)p\omega_r \quad (28)$$

where T_e is developed electromagnetic torque, T_L is the load torque, B is the friction coefficient in N ms/rad, J is moment of inertia in kg m2 and P is the number of poles. Now (28) is used with (27) to obtain the time derivative of torque as

$$p\omega_r = \frac{T_e - T_L - B\omega_r}{J(2/P)} \quad (29)$$

The potential of neutral terminal with respect to zero potential (V_{no}) is required to be considered in order to avoid unbalance in applied voltage. Substituting (16) in (15) and taking the sum for three phases, it results in

$$\sum V_{xo} = R\sum i_x + (L_s + M)p\sum i_x + \sum e_{xn} \quad (30)$$

Substituting (18) in (30) one obtains

$$\sum V_{xo} - 3V_{no} = \sum e_{xn} \quad (31)$$

Thus

$$V_{no} = \frac{\sum V_{no} - \sum e_{xn}}{3} \quad (32)$$

Moreover, the rotor position derivative of the BLDC motor is given as [7]

$$p(\theta) = \omega_r \quad (33)$$

Hence, (20), (29) and (33) represent the time derivative of current, speed and rotor position and hence govern the dynamic model of a BLDC motor.

B. *Voltage Source Inverter*

The output of the VSI for phase 'a' is given as [17]

$$V_{ao} = (V_{dc}/2),\quad \text{for } S_1 = 1 \quad (34)$$

$$V_{ao} = -(V_{dc}/2),\quad \text{for } S_2 = 1 \quad (35)$$

$$V_{ao} = 0,\ \text{for } S_1 = 0,\ \ S_2 = 0 \quad (36)$$

where V_{dc} represents the DC-link voltage and the on and off conditions for the IGBT's S_1 and S_2 are represented as 1 and 0, respectively.

6.3 Electronic Commutation

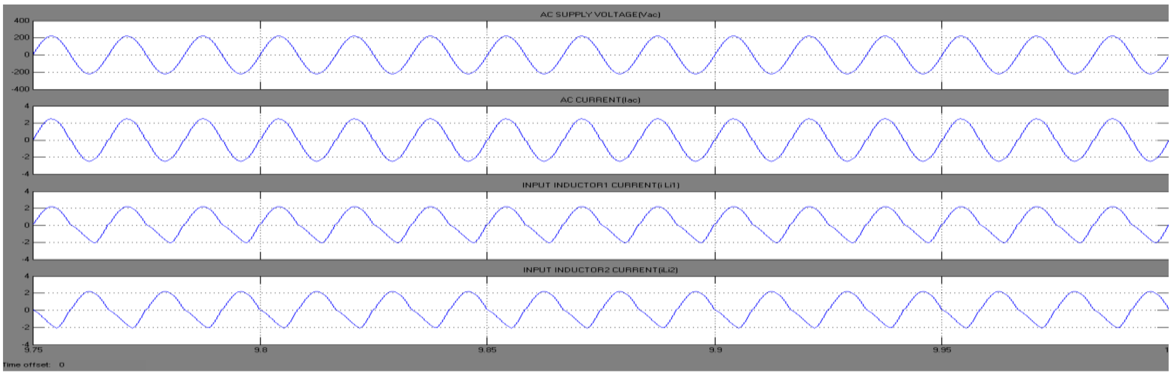
The switching sequence of the VSI is the state of switches for a particular rotor position of the BLDC motor as sensed by the Hall effect sensor. The turn on and turn off condition of the IGBT's is represented as '1' or '0', respectively. The switching sequence of VSI for different positions of the rotor are shown in Table 1.

Table 1 Switching states based on Hall effect position sensor signal

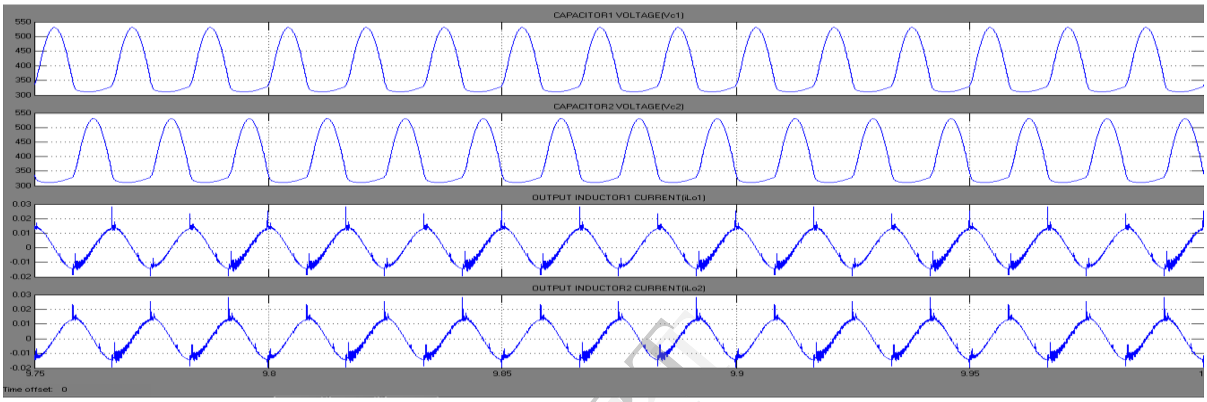
Hall signals			Switching signals					
H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
0	0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	0	1
0	1	0	0	1	1	0	0	0
0	1	1	0	0	1	0	0	1
1	0	0	0	0	0	1	1	0
1	0	1	1	0	0	1	0	0
1	1	0	0	1	0	0	1	0
1	1	1	0	0	0	0	0	0

VII. Simulated Performance Of The Proposed Bridgeless Cuk Converter-Fed BLDC Motor Drive

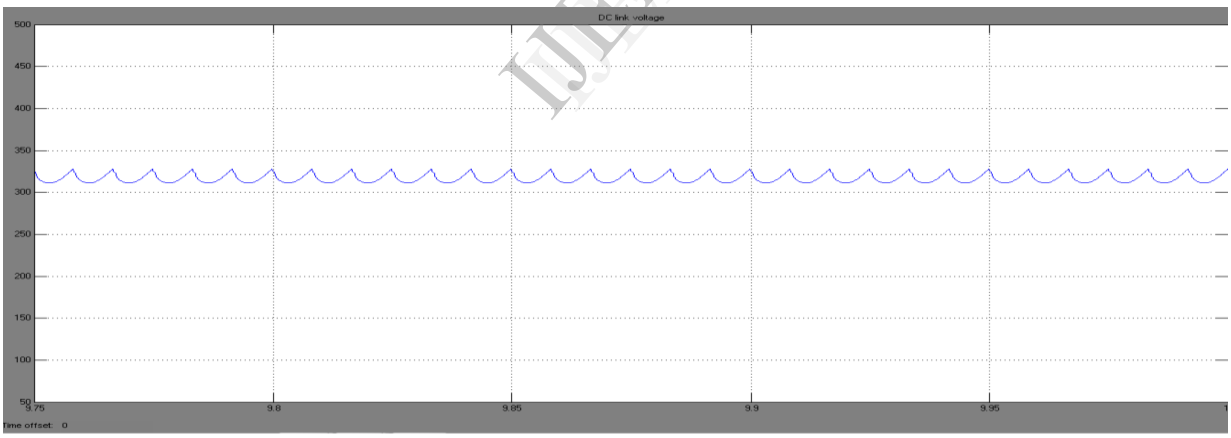
The performance of the proposed bridgeless Cuk converter-fed BLDC motor drive is evaluated on the basis of performance indices such as supply voltage (Vs), supply current (i_s), DC-link voltage (V_{dc}), speed (ω),electromagnetic torque (Te), input inductor current(i_{Li1}, i_{Li2}), output inductor current (i_{Lo1}, i_{lo2}) and intermediate capacitor's voltage (V_{c1}, V_{c2}).


AC SUPPLY VOLTAGE(Vac)
AC CURRENT(Iac)
INPUT INDUCTOR1 CURRENT(iLi1)
INPUT INDUCTOR2 CURRENT(iLi2)
Time offset: 0

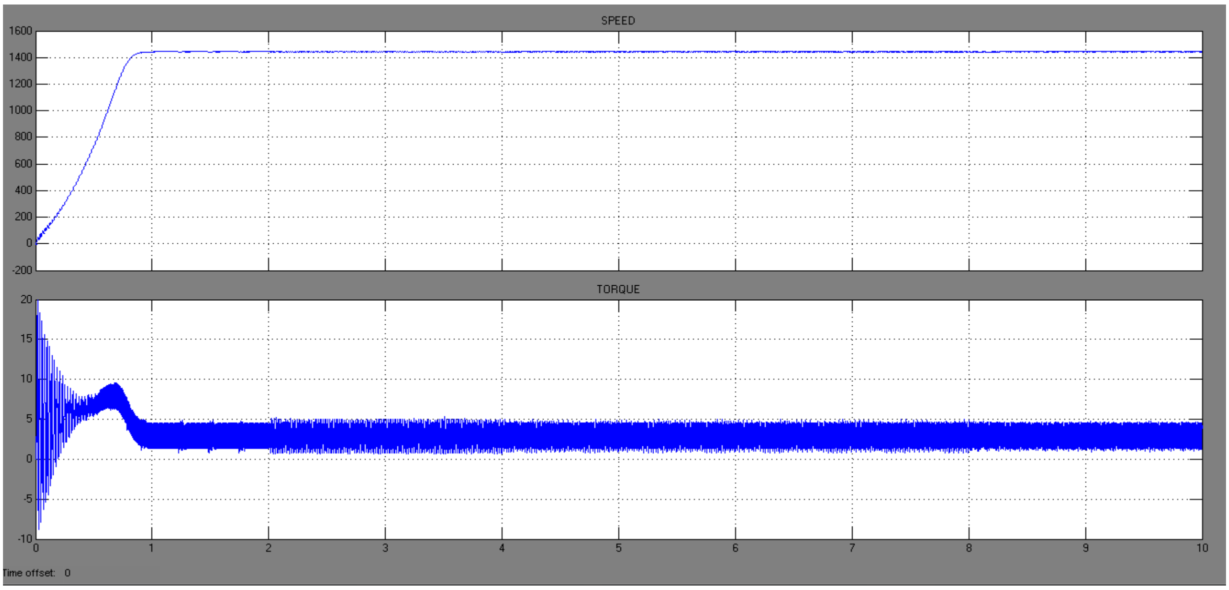
a


CAPACITOR1 VOLTAGE(Vc1)
CAPACITOR2 VOLTAGE(Vc2)
OUTPUT INDUCTOR1 CURRENT(iLo1)
OUTPUT INDUCTOR2 CURRENT(iLo2)
Time offset: 0

b


DC link voltage
Time offset: 0

c



d

Fig 3 Steady state performance of the bridgeless cuk converter fed BLDC motor drive.

VIII. CONCLUSION

The bridgeless PFC cuk converter fed PMBLDC motor drive system has been proposed for an air conditioning system. The attention devoted to the quality of the currents absorbed from the utility line by electronic equipment is increasing due to several reasons. In fact a low power factor reduces the power available from the utility grid while a high harmonic distortion of the line current causes EMI problems and cross-interferences. From this point of view the standard rectifier employing a diode bridge followed by a filter capacitor gives unacceptable performances. Thus the development of bridgeless cuk converters as interface systems improved the power factor of standard electronic loads. The front end PFC bridgeless cuk converters operating in DICM has been used for dual operation of PFC and DC link voltage control. The proposed drive system has maintained high power factor and improved power quality for a wide range of speed control for varying supply voltages. An efficient topology modification of the combined system with DBR to bridgeless cuk converter is presented in this project provide more convenient operation and improve the system efficiency.

9. REFERENCES

1 Kenjo, T., Nagamori, S.: ‘Permanent magnet brushless DC motors’ (Clarendon Press, Oxford, 1985)

2 Gieras, J.F., Wing, M.: ‘Permanent magnet motor technology – design and application’ (Marcel Dekker Inc., New York, 2002)

3 Miller, T.J.E.: ‘Brushless permanent magnet and reluctance motor drive’ (Clarendon Press, Oxford, 1989)

4 Handershot, J.R., Miller, T.J.E.: ‘Design of brushless permanent magnet motors’ (Clarendon Press, Oxford, 2010)

5 Hanselman, D.C.: ‘Brushless permanent magnet motor design’ (McGraw-Hill, New York, 2003)

6 Sokira, T.J., Jaffe, W.: ‘Brushless DC motors: electronic commutation and control’ (Tab Books, USA, 1989)

7 Krishnan, R.: ‘Electric motor drives: modeling, analysis and control’ (Pearson Education, India, 2001)

8 Toliyat, H.A.: ‘Campbell S.: DSP-based electromechanical motion control’ (CRC Press, New York, 2004)

9 Limits for Harmonic Current Emissions (Equipment input current ≤16 A per phase), International Standard IEC 61000-3-2, 2000

10 Mohan, N., Undeland, T.M., Robbins, W.P.: ‘Power electronics: converters, applications and design’ (John Wiley and Sons Inc, USA, 2009)

11 Singh, B., Singh, B.N., Chandra, A., Al-Haddad, K., Pandey, A., Kothari, D.P.: ‘A review of single-phase improved power quality AC–DC converters’, IEEE Trans. Ind. Electron., 2003, 50, (5), pp. 962–981

12 Singh, B., Singh, S., Chandra, A., Al-Haddad, K.: ‘Comprehensive study of single-phase AC–DC power factor corrected converters with high-frequency isolation’, IEEE Trans. Ind. Inf., 2011, 7, (4), pp. 540–556

13 Madani, S.M., Lei, H., Toliyat, H.A.: ‘A low-cost four-switch BLDC motor drive with active power factor correction’. Proc. 28th Annual IEEE Conf. Industrial Electronics Society (IECON), 2002, 5–8 November 2002, vol. 1, pp. 579–584

14 Ozturk, S.B., Yang, Oh., Toliyat, H.A.: ‘Power factor correction of direct torque controlled brushless DC motor drive’. Proc. 42nd IAS Annual Meeting and IEEE Industrial Applications Conf., 23–27 September 2007, pp. 297–304

15 Wu, C.-H., Tzou, Y.-Y.: ‘Digital control strategy for efficiency optimization of a BLDC motor driver with VOPFC’. IEEE Conf. Energy Conversion Congress and Exposition (ECCE), 20–24 September 2009, pp. 2528–2534

16 Gopalarathnam, T., Toliyat, H.A.: ‘A new topology for unipolar brushless DC motor drive with high power factor’, IEEE Trans. Power Electron., 2003, 18, (6), pp. 1397–1404

17 Singh, S., Singh, B.: ‘A voltage-controlled PFC Cuk converter based PMBLDCM drive for air-conditioners’, IEEE Trans. Ind. Appl., 2012, 48, (2), pp. 832–838

18 Sabzali, A.J., Ismail, E.H., Al-Saffar, M.A., Fardoun, A.A.: ‘New bridgeless DCM sepic and Cuk PFC rectifiers with low conduction and switching losses’, IEEE Trans. Ind. Appl., 2011, 47, (2), pp. 873–881

19 Fardoun, A.A., Ismail, E.H., Sabzali, A.J., Al-Saffar, M.A.: ‘A comparison between three proposed bridgeless Cuk rectifiers and conventional topology for power factor correction’. IEEE Int. Conf. Sustainable Energy Technologies (ICSET), 6–9 December 2010, pp. 1–6

20 Fardoun, A.A., Ismail, E.H., Sabzali, A.J., Al-Saffar, M.A.: ‘New efficient bridgeless Cuk rectifiers for PFC applications’, IEEE Trans. Power Electron., 2012, 27, (7), pp. 3292–3301

21 Simonetti, D.S.L., Sebastian, J., Uceda, J.: 'The discontinuous conduction mode Sepic and Cuk power actor preregulators: analysis and design', IEEE Trans. Ind. Electron., 1997, 44, (5), pp. 630–637
22 Vlatkovic, V., Borojevic, D., Lee, F.C.: 'Input filter design for power factor correction circuits', IEEE Trans. Power Electron., 1996, 11, (1),pp. 199–205

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