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Title: Minimizing Torque Ripple By Using HCC With PFC Based Cuk Converter-Fed BLDC Motor Drive

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Minimizing Torque Ripple by using HCC with PFC Based Cuk Converter-Fed BLDC Motor Drive

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Abstract- The use of brushless dc motor (BLDC) in low-power appliances is increasing because of its features of high efficiency, wide speed range, and low maintenance. This paper deals with a power factor correction (PFC) based Cuk converter fed brushless DC motor (BLDC) drive as a cost effective solution for low power applications. The speed of the BLDC motor is controlled by varying the DC bus voltage of voltage source inverter (VSI) which uses a low frequency switching of VSI (electronic commutation of BLDC motor) for low switching losses. The switching losses in the VSI have been reduced by the use of fundamental frequency switching by electronically commutating the BLDC motor. Two control strategies for BLDC motor drive have been implemented, one of the control strategies is based on PFC-CUK converter fed BLDCM drive and another one is Hysteresis current controller converter fed BLDC motor drive. Comparison has been made between the two control strategies is PI and HCC in terms of minimize Torque ripple, Power factor for different operating speeds. The proposed work has been implemented under MATLAB/Simulink environment.

Index Terms—Brushless dc (BLDC) motor, continuous conduction mode (CCM), Cuk converter, discontinuous conduction mode (DCM), power factor correction (PFC), power quality (PQ).

I. INTRODUCTION

BLDC motor is three phase AC motor with electronic commutation and rotor position feedback. In general BLDC motor is implemented by using six switches, three phase inverter. The Hall Effect sensors are used to provide the information related to rotor position. The wide usage of BLDC motor due its inherent advantages like high efficiency, high flux density, optimal cost etc. this achieved by reduction in the number of switches and sensors [1]. A new topology called Six Switches, Three Phase Inverter (SSTPI) is being considered for BLDC drive system [2, 3]. This topology reduces decreases the requirement of power electronic switches, thereby reducing the overall losses and cost [4, 5]. The Minimization of conducting currents is difficult to asymmetric voltage PWM. The existing PWM schemes cannot be used for SSTPI. Therefore, a new converter topology for three phase BLDC motor drive is to be

developed. The Back EMF wave form of BLDC motor is trapezoidal in shape. And the stator current wave form is rectangular in shape. Hysteresis current control is employ to maintain the actual motor currents close to rectangular reference values [6, 7]. All through steady state analysis SSTPI fed BLDC motor is studied, the modeling, simulation and practical realization is to be explored. PI control is method of speed control of BLDC motor which reduces the steady state error to zero [8], PI controller does not respond to quick variation of speed and reaches the set point slowly. The PI controller can be easily implemented because simplicity and most common usage since long time [9].

In this paper, two control strategies for BLDC motor drive have been implemented. One of the control strategies is based on PFC-CUK converter fed BLDCM drive and another one is Hysteresis current controller converter fed BLDC motor drive and comparison is made between this two control strategies for different operating speeds. The performance of the BLDC motor with CUK converter for four switch VSI fed BLDCM motor is found to be quite effective due to improve power quality, less torque ripple and smooth control of speed of BLDC motor[10-12].

The CUK converter for six switches VSI fed BLDC motor drive system. The control scheme employs hysteresis current control. For each phase of 3-hysteresis current controller, six power electronic switches are used and hence low cost and less switching losses and also reductions in torque ripple, as well as voltage stress and improved dynamic response. The variable DC output of bridge rectifier is fed to CUK converter. The output of the CUK converter is fed three leg VSI inverter which drives BLDC motor [13-14]. The power factor correction control scheme is based on the principle of current multiplier approach. This involves the presence of current loop inside speed control loop, in case of continuous conduction of the converter. The control loop starts with processing of speed obtained by comparing the actual, speed with the desired reference speed. The error is fed to the PI controller to obtain the reference torque and compared with actual torque of BLDC motor. The resultant torque error is multiplied with suitable constant

and amplified is order to provide input to reference current block. The reference current is compared with phase a current which is gives to hysteresis current control. The hysteresis current controller generates pluses for operation of three leg inverter and a rate limiter is introduced, which limits the current within specified limits [15].

II. SYSTEM CONFIGURATION

Figs.1 and .2 shows the PFC Cuk converter based VSI fed BLDC motor drive using a current multiplier and a voltage follower approach respectively.

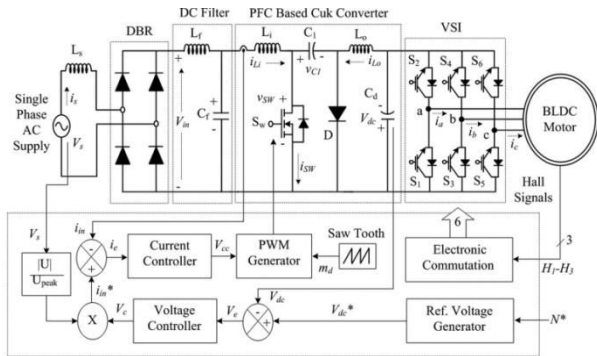


Fig. 1. BLDC motor drive fed by a PFC Cuk converter using a current multiplier approach

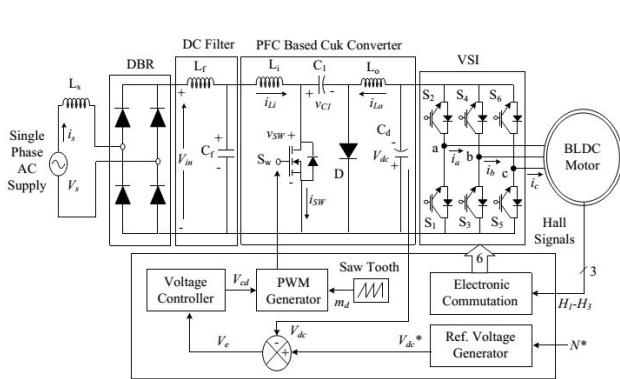


Fig 2. A BLDC motor drive fed by a PFC Cuk converter using a voltage follower approach.

A high frequency metal oxide semiconductor field effect transistor (MOSFET) is used in Cuk converter for PFC and voltage control whereas insulated gate bipolar transistor's (IGBT) are used in the VSI for its low frequency operation .BLDC motor is commutated electronically to operate the IGBT's of VSI in fundamental frequency switching mode to reduce its switching losses [13-14]. The PFC Cuk converter operating in CCM using a current multiplier approach is shown in Fig.1 i.e. the current flowing in the input and output inductors (L_i L_o), and the voltage across the intermediate capacitor (C_1) remains continuous in a switching period. Whereas, Fig.2 shows a Cuk converter

fed BLDC motor drive operating in DCM using a voltage follower Approach. The current flowing in either of the input or output inductor (L_i and L_o) or the voltage across the intermediate capacitor (C_1) become discontinuous in a switching period for a PFC Cuk converter operating in DCM. A Cuk converter is designed to operate in all three discontinuous conduction modes and a continuous conduction mode of operation and its performance is evaluated for a wide voltage control with unity power factor at AC mains [15].

III.OPERATION OF CUK CONVERTER IN DIFFERENT MODES

The operation of Cuk converter is studied in four different modes of CCM and DCM. In CCM, the current in inductors (L_i and L_o) and voltage across intermediate capacitor C_1 remain continuous in a switching period. Moreover, the DCM operation is further classified into two broad categories of discontinuous inductor current mode (DICM) and discontinuous capacitor voltage mode (DCVM). In DICM, the current flowing in inductor L_{ior} L_o becomes discontinuous in their respective modes of operation. While in DCVM operation, the voltage appearing across the intermediate capacitor C_1 becomes discontinuous in a switching period. Different modes for operation of CCM and DCM are discussed as follows.

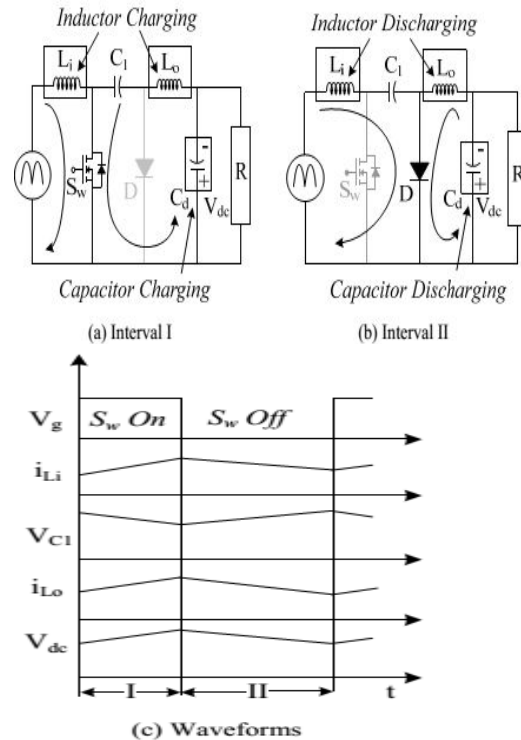


Fig.3. Operation of Cuk converter in CCM during (a-b) different intervals of switching period and (c) the associated waveforms

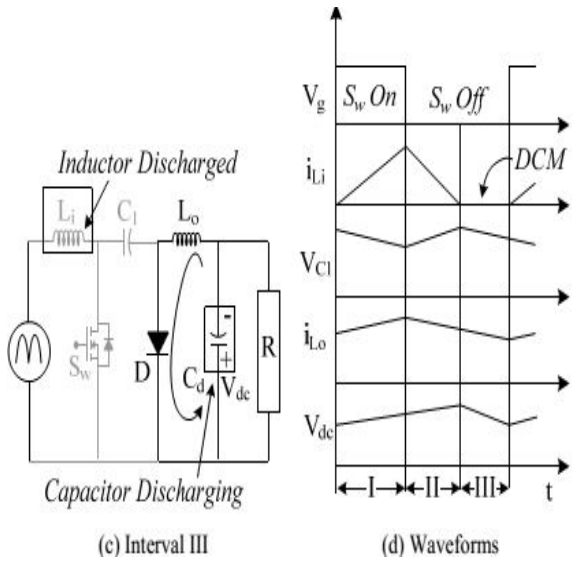


Fig.4. Operation of Cuk converter in DICM (L_i) during (a-c) different Intervals of switching period and (d) the associated waveforms

A. CCM Operation

The operation of Cuk converter in CCM is described as follows. Figs.3(a) and (b) show the operation of Cuk

Converter in two different intervals of a switching period and Fig.3(c) shows the associated waveforms in a complete switching period.

Interval I: When switch S_{w1} turned on, inductor L_i stores energy while capacitor C_1 discharges and transfers its energy to DC link capacitor C_d as shown in Fig.3(a). Input inductor current i_{L_i} increases while the voltage across the intermediate capacitor V_{C_1} decreases as shown in Fig.3(c).

Interval II: When switch S_{w2} turned off, then the energy stored in inductor L_o is transferred to DC link capacitor C_d , and inductor L_i transfers its stored energy to the intermediate capacitor C_1 as shown in Fig.3(b). The designed values of L_i , L_o and C_1 are large enough such that a finite amount of energy is always stored in these components in a switching period.

B. DICM (L_i) Operation:

The operation of Cuk converter in DICM (L_i) is described as follows. Figs.4(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.4 (d) shows the associated waveforms in a switching period.

Interval I: When switch S_{w1} turned on, inductor L_i stores energy while capacitor C_1 discharges through Switch S_w to transfers its energy to the DC link capacitor C_d as shown in Fig.4 (a). Input inductor current i_{L_i} increases while the voltage across the capacitor C_1 decreases as shown in Fig.4 (d).

Interval II: When switch S_{w2} turned off, then the energy stored in inductor L_i is transferred to intermediate

capacitor C_1 via diode D , till it is completely discharged to enter DCM operation.

Interval III: During this interval, no energy is left in input inductor L_i , hence current I_{L_i} becomes zero. Moreover, inductor cooperates in continuous conduction to transfer its energy to DC link capacitor C_d .

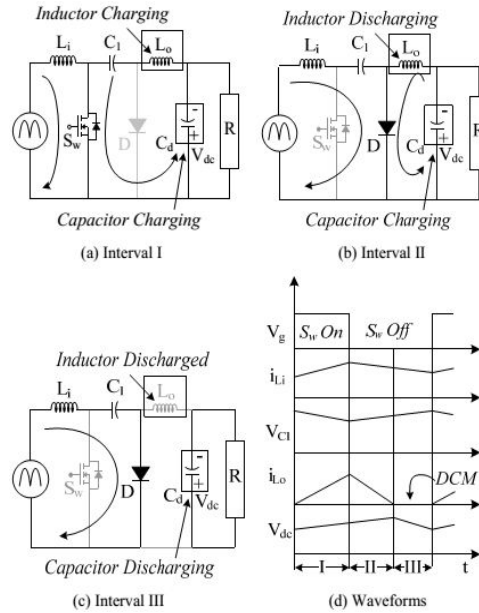


Fig.5. Operation of Cuk converter in DICM (L_o) during (a-c) different intervals of switching period and (d) the associated waveforms.

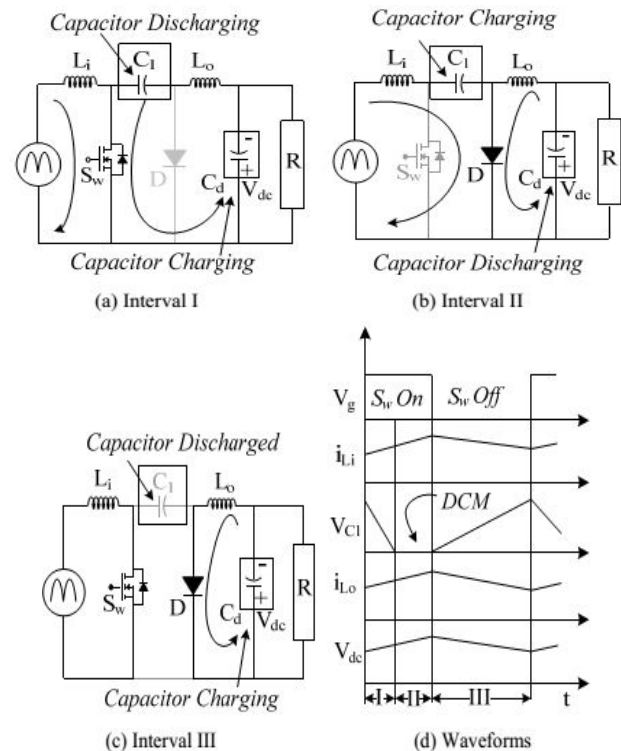


Fig.6. Operation of Cuk converter in DCVM (C_1) during (a-c) different intervals of switching period and (d) the associated waveform.

C. DICM (Lo) Operation:

The operation of Cuk converter in DICM (Lo) is described as follows. Figs.5(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.5(d) shows the associated waveforms in a switching period.

Interval I: As shown in Fig.5(a), when switch S_{wm} turned on, inductor L stores energy while capacitor C_1 discharges through switch S_w to transfer its energy to the DC link capacitor C_d .

Interval II: When switch S_{wm} turned off, then the energy stored in inductor L_i and L_o is transferred to intermediate capacitor C_1 and DC link capacitor C_d respectively.

Interval III: In this mode of operation, the output inductor L_o is completely discharged hence its current i_{L_o} becomes zero. An inductor L_i operates in continuous conduction to transfer its energy to the intermediate capacitor C_1 via diode D .

D. DCVM (C1) Operation:

The operation of Cuk converter in DCVM (C1) is described as follows. Figs.6(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig. 6(d) shows the associated waveforms in a switching period.

Interval I: When switch S_{wm} turned on as shown in Fig.6 inductor L stores energy while capacitor C_1 discharges through switch S_w to transfer its energy to the DC link capacitor C_d as shown in Fig.6 (d).

Interval II: The switch is in conduction state but intermediate capacitor C_1 is completely discharged, hence the voltage across it becomes zero. Output inductor L_o continues to supply energy to the DC link capacitor.

Interval III: As the switch S_w is turned off, input inductor L_i starts charging the intermediate capacitor, while the output inductor L_o continues to operate in continuous conduction and supplies energy to the DC link capacitor.

IV. DESIGN OF A PFC CUK CONVERTER

A PFC based Cuk converter fed BLDC motor drive is designed for DC link voltage control of VSI with power factor correction at the AC mains. The Cuk converter is designed for a CCM and three different DCMs. In DCM, any one of the energy storing elements L_i , L_o or C_1 are allowed to operate in discontinuous mode whereas in CCM, all these three parameters operate in continuous conduction. The design and selection criterion of these three parameters is discussed in the following section. The input voltage V_s applied to the DBR is given as,

$$V_s(t) = |V_m \sin(2\pi f_L t)| = |220\sqrt{2} \sin(314t)| \text{ V} \quad (1)$$

Where V_m is the peak input voltage (i.e. $\sqrt{2}V_s$, V_s is the rms value of supply voltage), f_L is the line frequency i.e. 50 Hz. The instantaneous voltage appearing after the DBR is as,

$$V_{in}(t) = |V_m \sin(\omega t)| = |220\sqrt{2} \sin(314t)| \text{ V} \quad (2)$$

Where $||$ represents the modulus function. The output voltage, V_{dc} of Cuk converter is given as

$$V_{dc} = \frac{D}{(1-D)} V_{in}(t) \quad (3)$$

Where D represents the duty ratio. The instantaneous value of duty ratio, $D(t)$ depends on the Input voltage appearing after DBR, $V_{in}(t)$ and the required DC link voltage, V_{dc} .

Hence the instantaneous duty ratio, $D(t)$ is obtained by substituting (2) in (3) and rearranging it as,

$$D(t) = \frac{V_{dc}}{V_{in}(t) + V_{dc}} = \frac{V_{dc}}{|V_m \sin(\omega t)| + V_{dc}} \quad (4)$$

The Cuk converter is designed to operate from a minimum DC voltage of 40V ($V_{dc \text{ min}}$) to a maximum DC link voltage of 200V ($V_{dc \text{ max}}$). The PFC converter of maximum power rating of 350W (P_{max}) is designed for a BLDC motor of 251W (P_m) (full specifications given in Table I) and the switching frequency (f_s) is taken as 20kHz. Since the speed of the BLDC motor is controlled by varying the DC link voltage of the VSI, hence the instantaneous power, P_{inst} any DC link voltage (V_{dc}) can be taken as linear function of V_{dc} . Hence for a minimum value of DC link voltage as 40V, the minimum power is calculated as 70W.

TABLE I

SPECIFICATIONS OF A BLDC MOTOR

S.NO	PARAMETERS	VALUES
1	No. of poles (P)	4 POLES
2	Rated power (P_{RATED})	251.3 W
3	Rated DC link voltage (V_{RATED})	200V
4	Rated torque (T_{RATED})	1.2 N-M
5	Rated speed (N_{RATED})	2000 RPM
6	Back Emf constant (k_b)	78V/KRPM
7	Torque constant (k_t)	0.74N-M/A
8	Phase resistance (R_{PH})	14.56 Ω
9	Phase inductance (L_{PH})	25.71mH
10	Moment of inertia (J)	1.3×10^{-4} N-M/ s^2

TABLE II

ELECTRONIC OUTPUT BASED ON THE HALL EFFECT SIGNAL:

HALL SIGNALS			SWITCHING SIGNALS					
H1	H2	H3	Sa1	Sa2	Sb1	Sb2	Sc1	Sc2
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

TABLE III

DESIGN PARAMETERS IN DIFFERENT MODES OF OPERATION

SPECIFICATIONS	VALUES			
Supply voltage(Vs)	Rated:220v ,(Universal Mains:85-270v)			
DC Link Voltage(Vcd)	Rated:220v,(40v-200v)			
Power (P)	Rated:350w,(70w-350w)			
Switching frequency(fs)	20khz			
OPERATION	Li	Lo	C1	Cd
CCM	2.5MH	4.3mH	0.66µF	220µF
DICM(Li)	100µH	4.3MH	0.66µF	220µF
DICM(Lo)	2.5Mh	70µH	0.66µF	220µF
DCVM(C1)	2.5mH	4.3mH	9.1nF	220µF

V.HYSTERESIS CURRENT CONTROL OF INVERTER

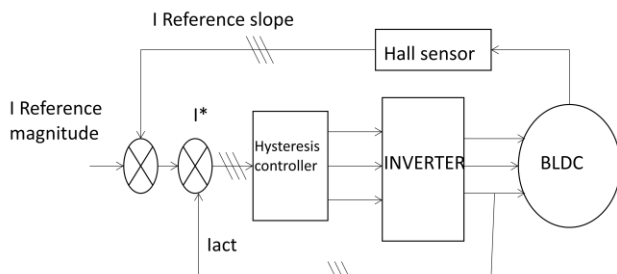


Fig.7.Hysteresis Current controlled Inverter fed BLDC drive.

Fig.7 shows the block diagram of hysteresis current controller which will generate the gating signals for inverter. The input currents, i_a, i_b, i_c are measured and compared with the reference currents, i_a^*, i_b^*, i_c^* . The error is fed to a comparator with a prescribed hysteresis band. Switching of the power semiconductor devices (S1 ON and S2 OFF) occurs when the current attempts to exceed a set value corresponding to the desired current. The reverse switching (S1 OFF and S2 ON) occurs when the current attempts to become less than i_a ref. Hysteresis controller is simple to implement and produces a very good quality of waveform. The drawback of this method is that the switching frequency does not remain constant but varies along different portions of the desired current.

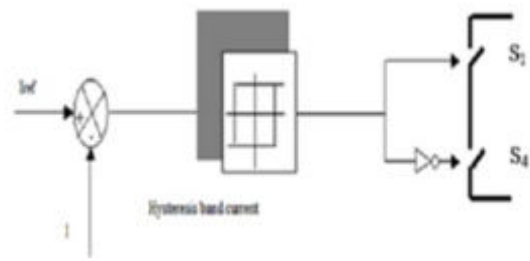


Fig.8. i_{ref} and i_{act} given to Hysteresis current control

The switching pattern is given as:
 If $\Delta i_a > H$, S1 is on and S2 is off.
 If $\Delta i_a < L$, S1 is off and S2 is on.
 If $\Delta i_b > H$, S3 is on and S4 is off.
 If $\Delta i_b < L$, S3 is off and S4 is on.
 If $\Delta i_c > H$, S5 is on and S6 is off.
 If $\Delta i_c < L$, S5 is off and S6 is on.

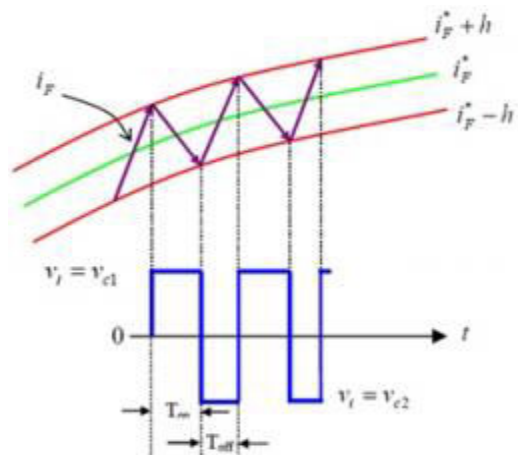


Fig.9.Hysteresis Band switching.

This means that only one of the switching devices can be on at any given time. However, the switching frequency in the HCC method is not constant. HCC technique is based on minimizing the error between

reference and actual current. The technique adaptively adjusts the phase-current waveform to maintain ripple less electromagnetic torque, so that commutation torque ripples, particularly at high rotational speeds, are effectively eliminated. With the implementation of the proposed hysteresis current controller loop with current feedback loop and it is observed that there is a reduction in the current ripple hence torque ripple are minimized. Simulation analysis has been done to shows that current ripple and torque ripple are minimized which enhance the performance of the drive.

VI. MATLAB/SIMULATION RESULTS:

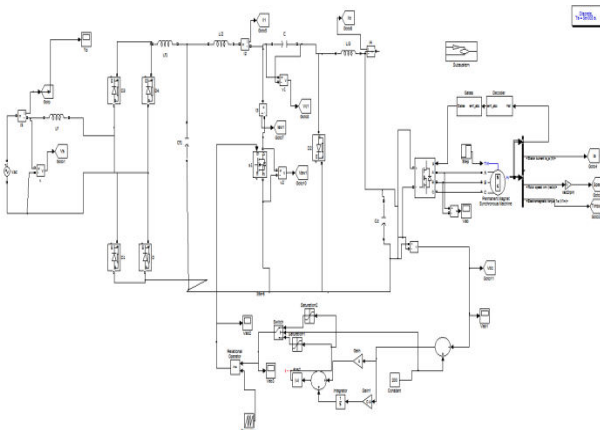


Fig 10 Simulation model of BLDC motor drive fed by a PFC Cuk converter using a multiplier approach

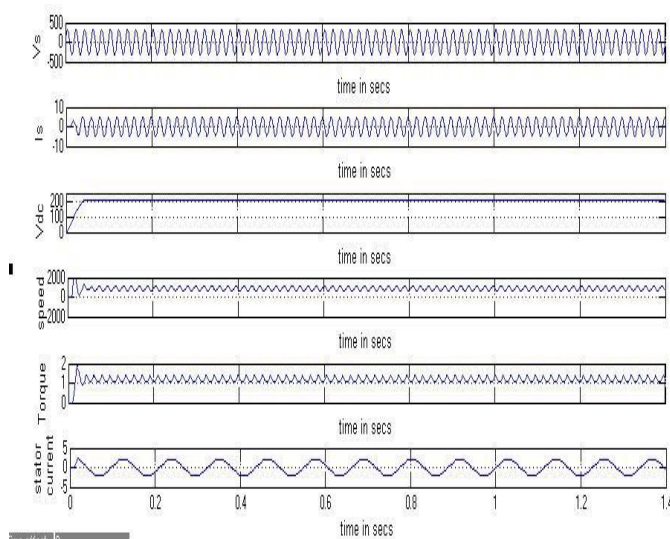


Fig.11.Simulation waveform for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the CCM

Performance of BLDC Motor Fed Cuk Converter Operating in the CCM:

The circuit configuration and control of the PFC Cuk converter operating in the CCM. The parameters selected for this converter to operate in the CCM are as follows: Input inductor $L_i = 2.5$ mH, output inductor $L_o = 4.3$ mH, intermediate capacitor $C_1 = 0.66$ μ F and dc-link capacitor $C_d = 2200$ μ F.

The performance of the proposed BLDC motor drive fed by a PFC Cuk converter operating in the CCM. The input inductor current i_{Li} , output inductor current i_{Lo} , and intermediate capacitor's voltage V_{C1} are continuous in operation while the supply current I_s is sinusoidal and in phase with the supply voltage v_s , which shows a 0.9306 PF at ac mains.

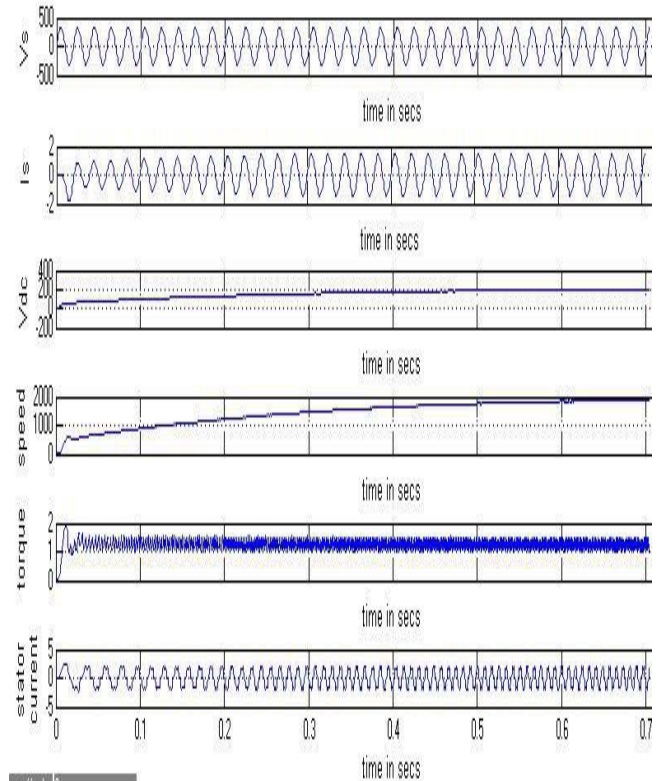


Fig.12.Simulation waveform for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the DICM (L_i).

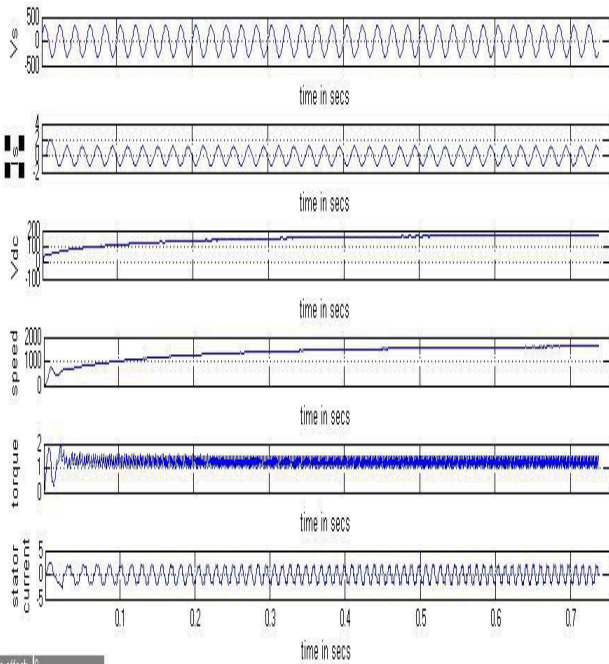


Fig.13.Simulation waveform for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the DICM (Lo).

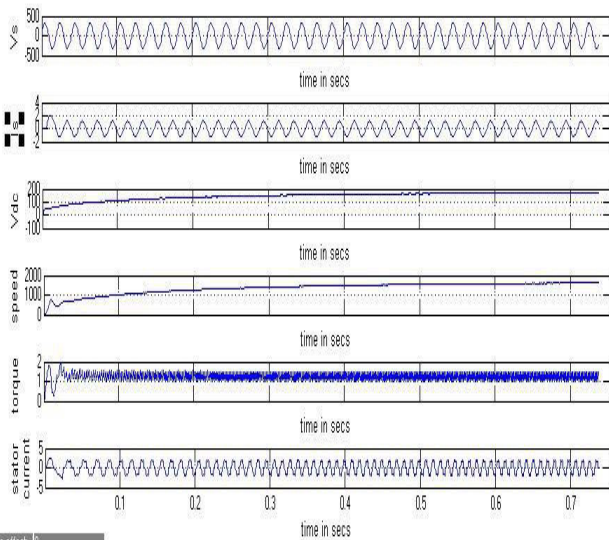


Fig.14.Simulation wave form for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the DCVM.

Simulation model of CUK-converter fed HCC BLDCM drive by using HCC:

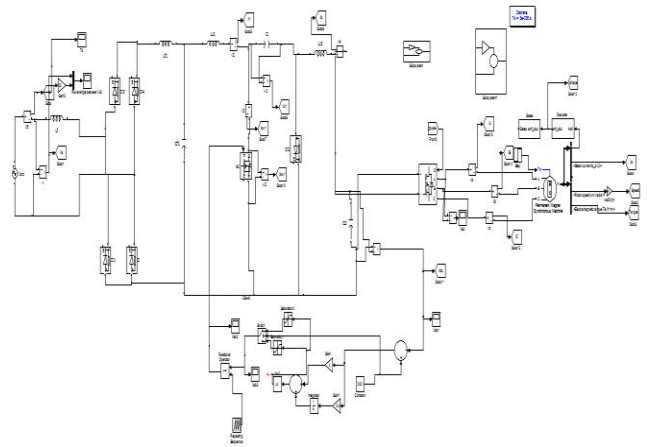


Fig.15. Simulation model of HCC based BLDC motor drive fed by a PFC Cuk converter.

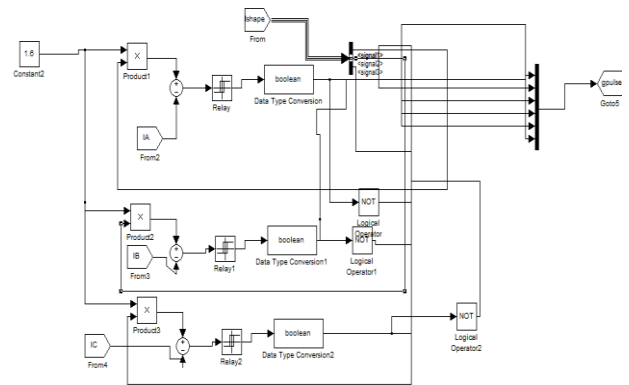


Fig.16.Control strategies for hysteresis current control.

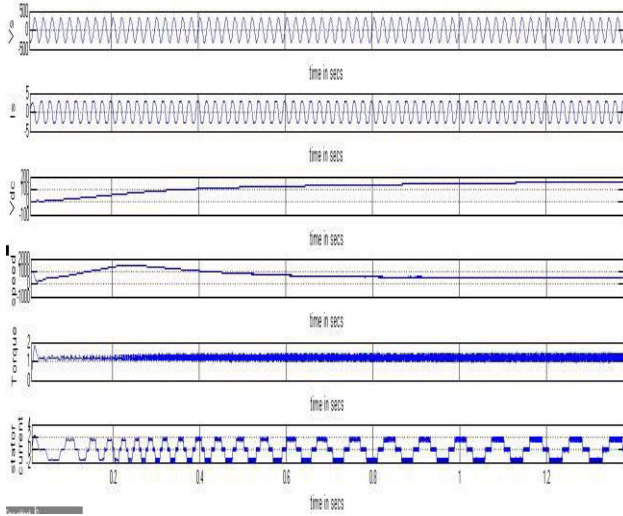


Fig.17.Simulation results for source voltage, current, dc link voltage, and speed, torque, stator current of BLDC motor under hysteresis current control.

Performance of HCC based BLDC Motor Fed Cuk Converter:

Finally, a best suited mode of Cuk converter operating in CCM has been selected for experimental verifications. By using HCC the power factor is improved from 0.9306 to 0.9994. The simulation model which is implemented in a modular manner with HCC under MATLAB environment allows dynamic characteristics such as phase currents, rotor speed, and mechanical torque ripple has been effectively reduced.

Performance details:

S.NO	BLDC MOTOR	POWER FACTOR
1	Fed CUK-converter	0.9306
2	fed CUK-Converter along with HCC	0.9994

VII.CONCLUSION

A Cuk converter for VSI fed BLDC motor drive has been designed for achieving a unity power factor at AC mains for the development of low cost PFC motor for numerous low power equipment's such fans, blowers, water pumps etc. The speed of the BLDC motor drive has been controlled by varying the DC link voltage of VSI; which allows the VSI to operate in fundamental frequency switching mode for reduced switching losses. Four different modes of Cuk converter operating in CCM and DCM have been explored for the development of BLDC motor drive with unity power factor at AC mains. Proposed hysteresis current controller system has a good adaptability and strong robustness whenever the system is disturbed. By using HCC the power factor is improved from 0.9306 to 0.9994. The simulation model which is implemented in a modular manner with HCC under MATLAB environment allows dynamic characteristics such as phase currents, rotor speed, and mechanical torque ripple has been effectively reduced.

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