International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Torque Ripple Reduction using HCC with Power Factor Correction Based Cuk Converter Fed to BLDC Motor Drive Electric Vehicles

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A B S T R A C T

The use of brushless dc motor (BLDC) in electric vehicles 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) driven EV which is a cost effective solution for electric vehicle segment. 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 losses of switching in the VSI are minimized by using fundamental frequency switching by electronically commutating the BLDC used in EVs. Apart from this the speed of the BLDC motor is controlled by controlling the dc link voltage of the VSI. The bridgeless configuration of the Cuk converter offers low conduction losses due to partial elimination of diode bridge rectifier at the front end. 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. The two control strategies are PI and HCC in terms of minimize Torque ripple, Power factor for different operating speeds. The work is implemented under MATLAB/Simulink tools.

Keywords: Brushless dc (BLDC) motor, continuous conduction mode (CCM), Cuk converter, discontinuous conduction mode (DCM), power factor correction (PFC), power quality (PQ), Four Switches, Three Phase Inverter(FSTPI).

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 archived by reduction in the number of switches and sensors [1]. A new topology called Four Switches, Three Phase Inverter (FSTPI) 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 FSTPI.

. 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 FSTPI 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 based on CUK converter for Four Switch VSI Fed BLDCM Drive and CUK converter for four Switches VSI fed BLDCM Drive has been developed and comparison is made between this two control strategies for different operating speeds. The performance of the BLDC motor with CUKconverter 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].

TheCUK converter for four switches VSI fed BLDC motor drive system. The control scheme employs hysteresis current control. For each phase of 3-hystersis current controller, four 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 two 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 speedcontrol 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 two leg inverter and a rate limiter is introduced, which limits the current within specified limits [15].

SYSTEM CONFIGURATION

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

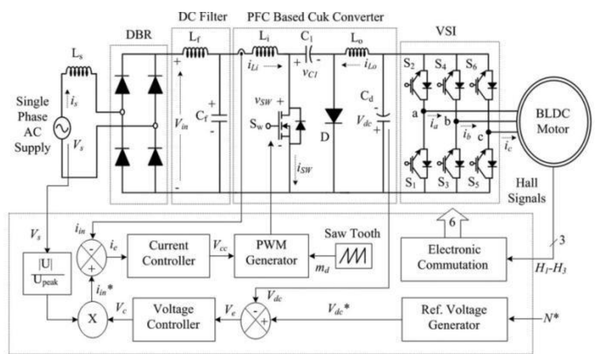


Fig. 1. BLDC motor drive fed by a PFC Cuk converter using a current multiplier approach

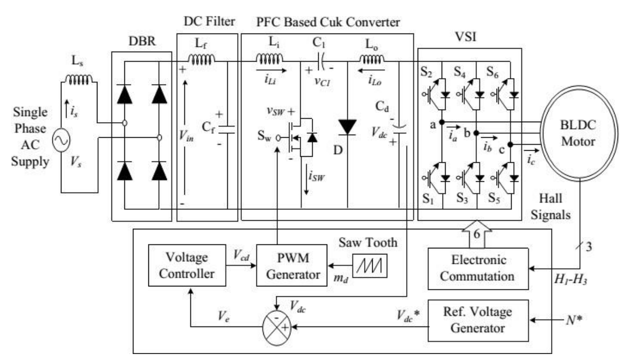


Fig 2. A BLDC motor drive fed by a PFC Cuk converter using a voltage follower approach.

The Cuk converter uses a high frequency metal oxide semiconductor field effect transistor (MOSFET) for PFC and voltage control, whereas the VSI uses insulated gate bipolar transistors (IGBT) for low frequency operation. To reduce switching losses, a BLDC motor is commutated electronically to run the IGBTs of VSI in fundamental frequency switching mode [13-14]. The current flowing in the input and output inductors (L Lo) and the voltage across the intermediate capacitor (C1) stay constant during a switching period in the PFC Cuk converter working in CCM employing a current multiplier technique, as shown in Fig.1. A Cuk converter fed BLDC motor drive working in DCM using a voltage follower approach is shown in Fig.2. In a switching period for a PFC Cuk converter working in DCM, the current flowing in either the input or output inductor (Li and Lo) or the voltage across the intermediate capacitor (C1) becomes discontinuous. A Cuk converter is designed to function in all three discontinuous conduction modes as well as a continuous conduction mode, and its performance is assessed at AC mains for wide voltage control and unity power factor..

OPERATION OF CUK CONVERTER IN DIFFERENT MODES

The operation of the Cuk converter is investigated in four different CCM and DCM modes. During a switching period in CCM, the current in inductors (Li and Lo) and the voltage across intermediate capacitor C1 stay constant. Furthermore, the DCM operation is divided into two categories: discontinuous inductor current mode (DICM) and discontinuous capacitor voltage mode (DICVM) (DCVM). The current passing through the inductor Lior Lo in DICM becomes discontinuous in their respective modes of operation. During a switching period in DCVM operation, the voltage appearing across the intermediate capacitor C1 becomes discontinuous. The following are the many modes of operation for CCM and DCM.

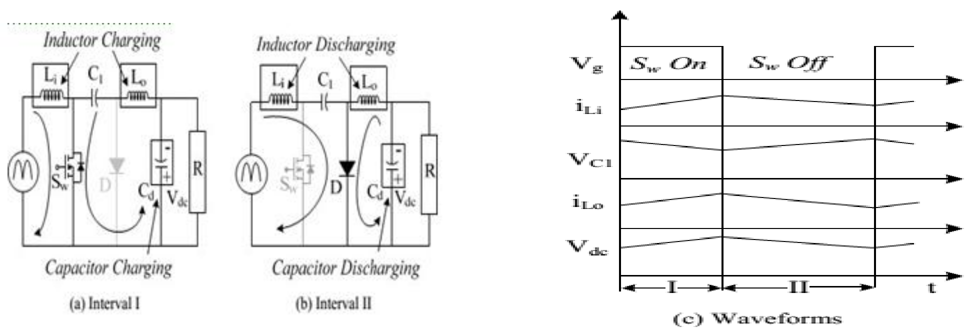
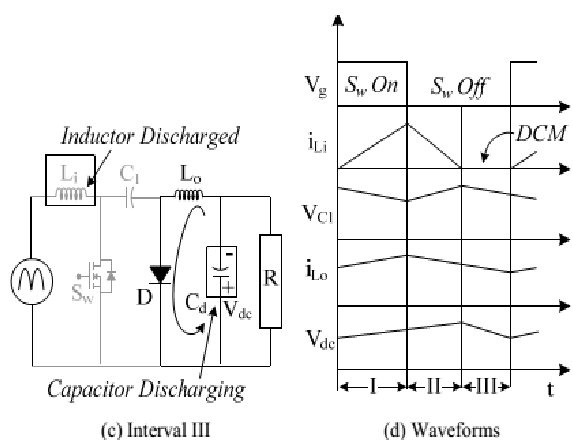


Fig.3. Operation of Cuk converter in CCM during (a-b) different intervals of switching period and (c) the associated waveforms



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 Swim turned on, inductor LI stores energy while capacitor C1discharges and transfers its energy to DC link capacitor C d as shown in Fig.3(a). Input inductor current iLi increases while the voltage across the intermediate capacitor VC1 decreases as shown in Fig3(c).

Interval II: When switch Swiss turned off, then the energy stored in inductor Lo is transferred to DC link capacitor Cd, and inductor Li transfers its stored energy to the intermediate capacitor C1 as shown in Fig.3(b). The designed values of Li, Lo and C1are large enough such that a finite amount of energy is always stored in these components in a switching period.

B. DICM (Li) Operation

The operation of Cuk converter in DICM (Li) 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 Swim turned on, inductor Li stores energy while capacitor C1discharges through Switch Sw to transfers its energy to the DC link capacitor C d as shown in Fig.4 (a). Input inductor current iLi increases while the voltage across the capacitor C1 decreases as shown in Fig.4 (d).

Interval II: When switch Swiss turned off, then the energy stored in inductor Li is transferred to intermediate capacitor C1 via diode D, till it is completely discharged to enter DCM operation.

Interval III: During this interval, no energy is left in input inductor Li, hence current I Latecomers zero. Moreover,inductor cooperates in continuous conduction to transfer its energy to DC link capacitor Cd.

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 Li, Lo or C1are 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 Vs applied to the DBR is given as,

$$v_s(t) = V_m \mathrm{Sin}(2\pi f_L t) = 220\sqrt{2}\,\mathrm{Sin}(314t)V$$

Where V_m is the peak input voltage (i.e. √2Vs, Vs is the rms value of supply voltage), fL is the line frequency i.e.

50 Hz. The instantaneous voltage appearing after the DBR is as,

$$V_{in}(t) = |V_m \mathrm{Sin}(\omega t)| = |220\sqrt{2}\,\mathrm{Sin}(314t)|\,V$$

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

represents the modulus function. T the output voltage, and the

Vdc of Cuk onverter is given as (3)

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

Where D represents the duty ratio. The instantaneous value of duty ratio, D(t) depends on the Input voltage appearing after DBR, Vin (t) and the required DC link voltage, Vdc.

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

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

The Cuk converter is designed to operate from a minimum DC voltage of 40V (Vdc min) to a maximum DC link voltage of 200V (Vdc max). The PFC converter of maximum power rating of 350W (P max) is designed for a BLDC motor of 251W (Pm) (full specifications given in Table I) and the switching frequency (fS) 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, Piatt any DC link voltage (Vdc) can be taken as linear function of Vdc. 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})	251.32W
3.	Rated DC link Voltage (V_{rated})	200V
4.	Rated Torque (T_{rated})	1.2Nm
5.	Rated Speed (ω_{rated})	2000rpm
6.	Back EMF Constant (K_b)	78V/krpm
7.	Torque Constant (K_t)	0.74Nm/A
8.	Phase Resistance (R_{ph})	14.56Ω,
9.	Phase Inductance (L_{ph})	25.71mH
10.	Moment of Inertia (J)	$1.3\text{x}10^{-4}\text{Nm/s}^2$

TABLE II

DESIGN PARAMETERS IN DIFFERENT MODES OF OPERATION

Specifications ↓	*Values*			
Supply Voltage (V_s)	Rated: 220V, (Universal Mains: 85-270V)			
DC Link Voltage (V_{dc})	Rated: 200V, (40V-200V)			
Power (P)	Rated: 350W, (70W-350W)			
Switching Frequency (f_s)	20kHz			
Operation ↓	L_i	L_o	C_1	C_d
CCM	2.5mH	4.3mH	0.66μF	2200μF
DICM (L_i)	100μH	4.3mH	0.66μF	
DICM (L_o)	2.5mH	70μH	0.66μF	
DCVM (C_1)	2.5mH	4.3mH	9.1nF	

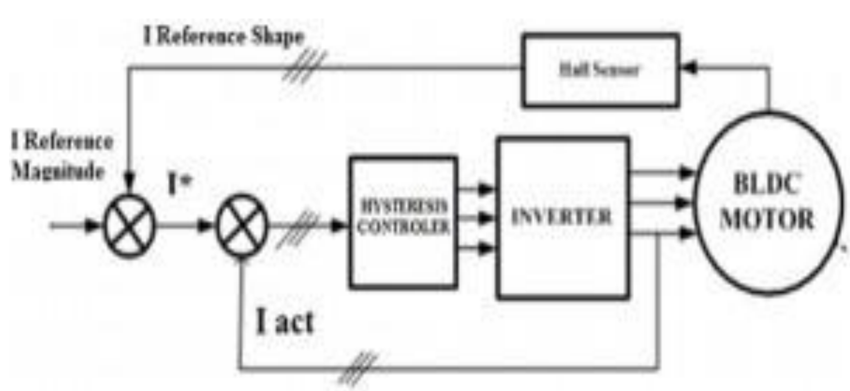


Fig.7.Hysteresis Current controlled Inverter fed BLDC drive

HYSTERESIS CURRENT CONTROL OF INVERTER

Fig.7 shows the block diagram of hysteresis current controller which will generate the gating signals for inverter. The input currents, ia, ib, ic are measured and compared with the reference currents, ia*, Ib*, Ic*. 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 iaref . 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

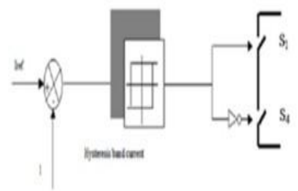
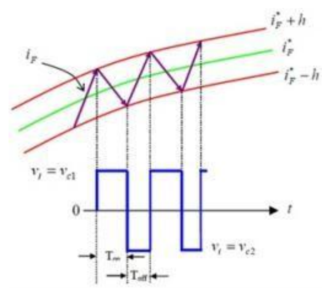


Fig.8.Iref and Iact given to Hysteresis current control The switching pattern is given as:

If ΔIa > H , S1 is on and S2 is off.
If ΔIa < L , S1 is off and S2 is on.
If ΔIb > H , S3 is on and S4 is off.

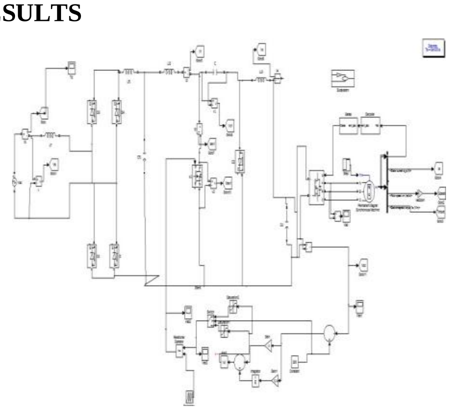


If ΔIb < L , S3 is off and S4 is on.
If ΔIc > H, S5 is on and S6 is off.
If ΔIc < L, S5 is off and S6 is on.

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.

MATLAB/ SIMULATION RESULTS



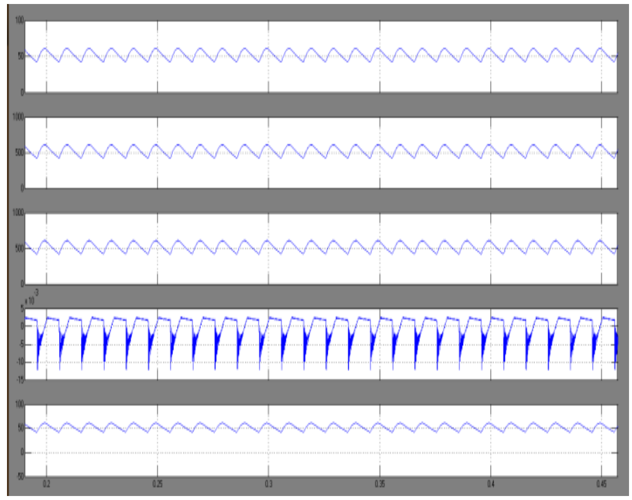


Fig 10 Simulation model of BLDC motor drive fed by a PFC Cuk converter using a multiplier approach

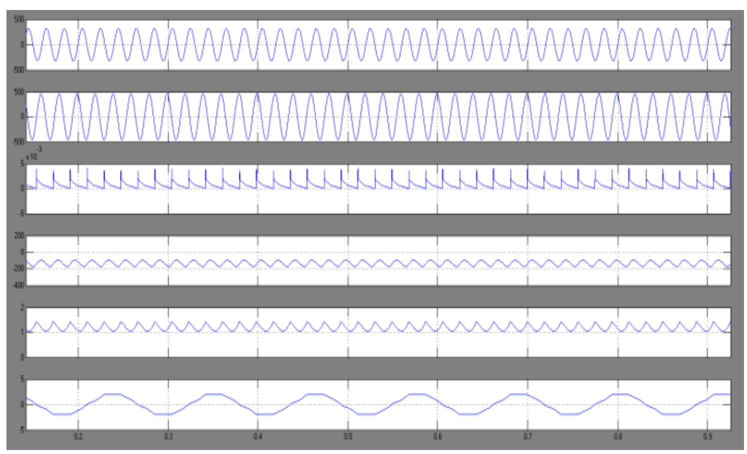


Fig.11.Simulation wave form for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the CCM.

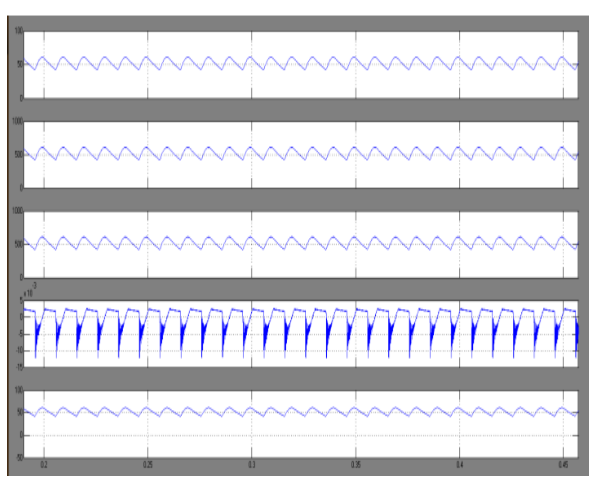


Fig 12 Simulation waveform for the switch voltage and current,Il1, Il2, Ilo of the BLDC motor drive with the Cuk converter operating inCCM.

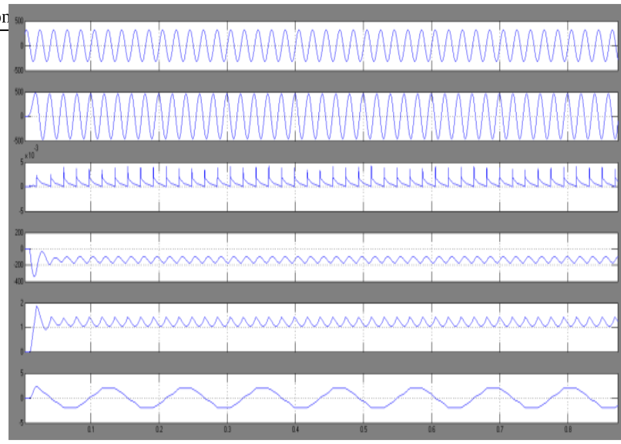


Fig.13.Simulation waveform for source voltage and current,dc voltage, speed, torque and armature current of the BLDC motordri ve with the Cuk converter operating in the DICM (Li).

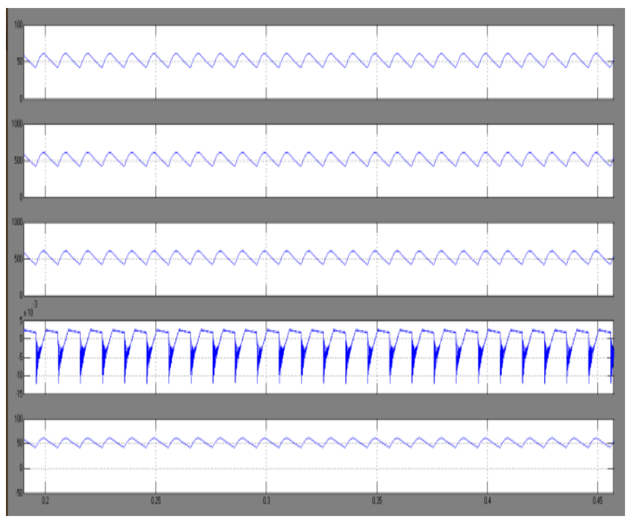


Fig 14 Simulation waveform for switch voltage and current,Il1, Il2, Ilo of the BLDC motor drive with the Cuk converter operat ing in the DICM

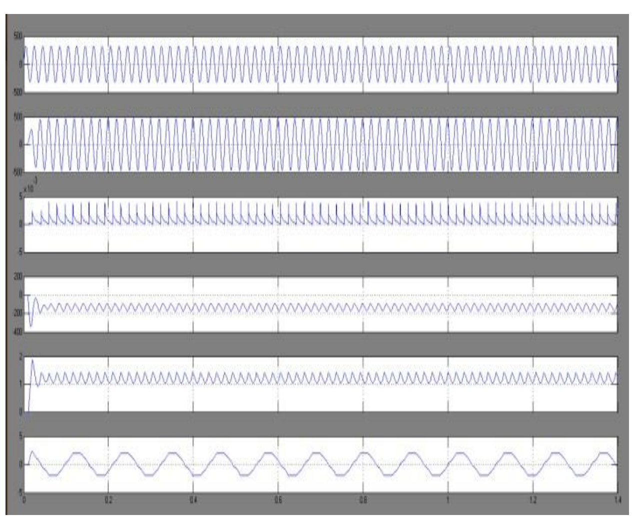


Fig.15.Simulation waveform for source voltage and current, dc vol tage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the DICM (Lo).

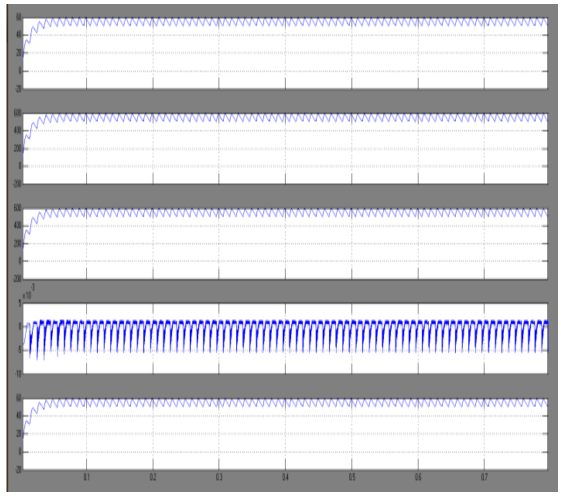


Fig.16.Simulation waveform for switch voltage and current, Il1, Il2, Ilo of the BLDC motor drive with the Cuk converter operating in the DICM (Lo)

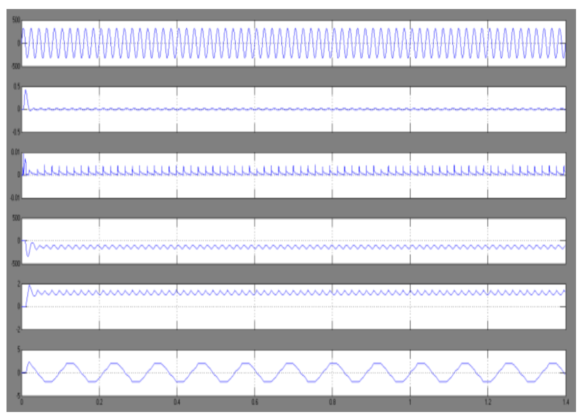


Fig.17.Simulation wave form for source voltage and current, dc voltage, speed, torque and armature current of the BLDC motor drive with the Cuk converter operating in the DCVM.

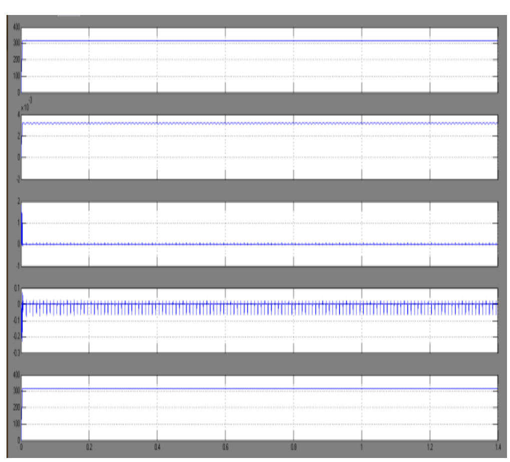


Fig.18.Simulation waveform for the switch voltage and current, Il1, Il2, Ilo of the BLDC motor drive with the Cuk converter operating in the DCVM.

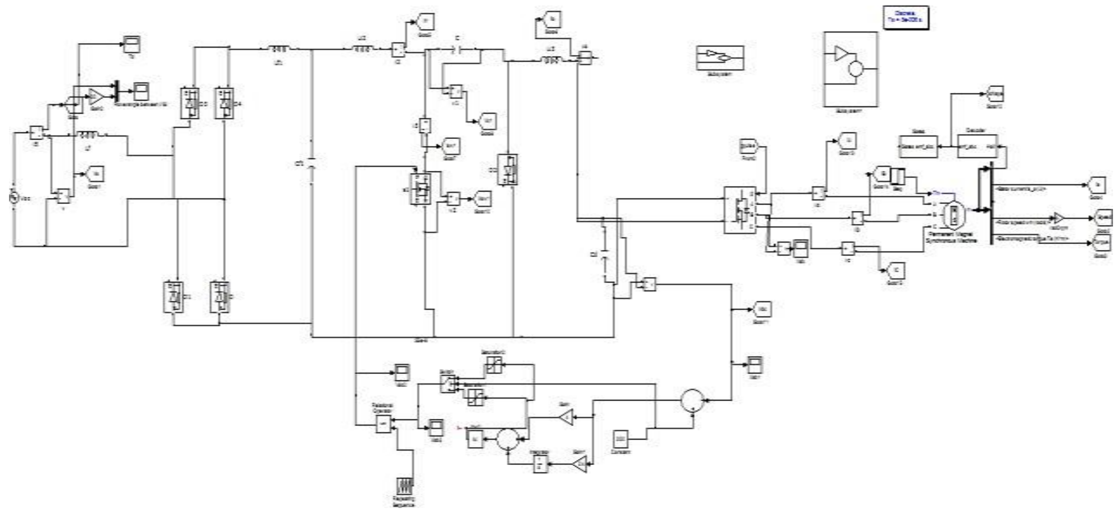


Fig.19. Simulation model of HCC based BLDC motor drive fed by a PFC Cuk converter

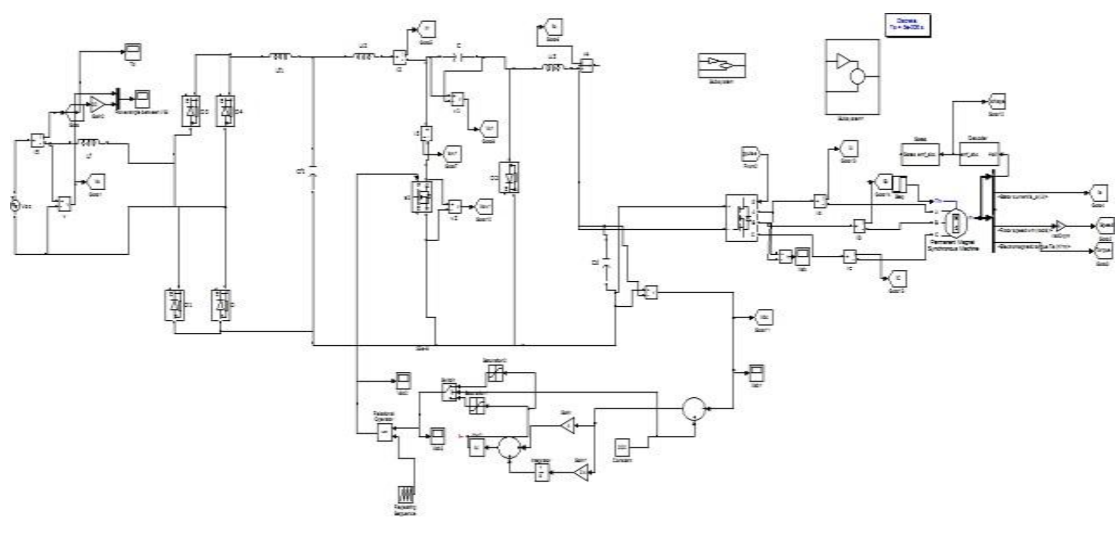


Fig.20.Control strategies for hysteresis current control

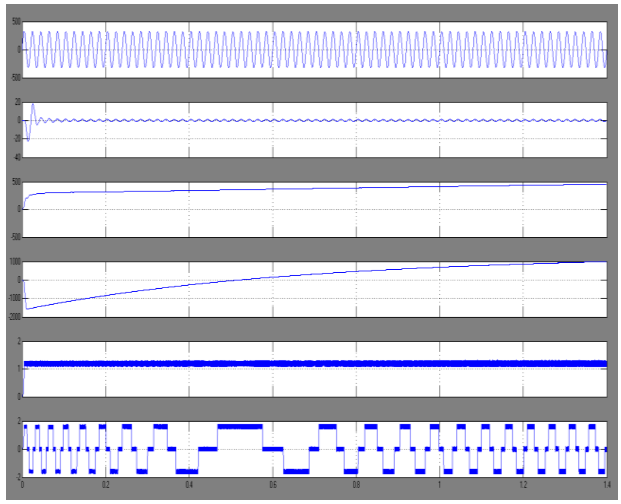


Fig.21.Siumulation results for source voltage, current, dc link voltage, and speed, torque, stator current of BLDC motor under hysteresis current control.

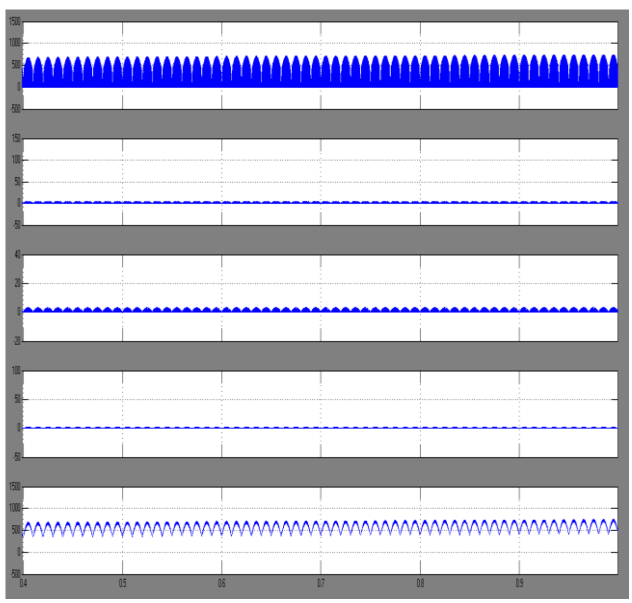


Fig.22.Simulation results for iLi1, iLi2, Vsw1, isw1, Vsw2, isw2 of PFC converter under hysteresis current control

CONCLUSION

A Torque Ripple Reduction using HCC with Power Factor CorrectionBased Cuk Converter Fed to BLDC Motor Drive Electric Vehicles.
has been designed for achieving a unity power factor at AC mains. 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. The project involves hysteresis current controller system has a good adaptability and strong robustness whenever the system is disturbed. 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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