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Torque Ripple Minimization and PFC of BLDC Motor Drive Using Bridge Less LUO-Converter

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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 BL LUO 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 converters 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 BL-LUO converter fed BLDCM drive. Comparison has been made between the two control convertersis PI in terms of minimize Torque ripple, Power factor, of BLDC Motor drive. The proposed work has been implemented under MATLAB/Simulink environment.

Index Terms: Brushless dc (BLDC) , continuous conduction mode (CCM), Bridge less LUO(BL-LUO), discontinuous conduction mode (DCM), power factor correction (PFC), Diode Bridge Rectifier(DBR), Voltage Source Inverter(VSI),Discontinuous Inductor Current Mode(DICM), 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 archived 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. 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 converters 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 PFC BL-Luo converter fed BLDC motor drive and comparison is made between this two control converter strategies for BLDC motor drive.

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The CUK converter for six switches VSI fed BLDC motor drive system. 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 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 PFC-based bridgeless Luo (BL-Luo) converter-fed BLDC motor drive. A single-phase supply followed by a filter and a BL-Luo converter is used tofeed a VSI driving a BLDC motor. The BL-Luo converter is designed to operate in DICM to act as an inherent power factor preregulator. The speed of the BLDC motor is controlled by adjusting the dc-link voltage of VSI using a single voltage sensor. This allows VSI to operate at fundamental frequency switching (i.e., electronic commutation of the BLDC motor) and hence has low switching losses in it, which are considerably high in a PWM-based VSI feeding a BLDC motor. The proposed scheme is designed, and its performance is simulated for achieving an improved power quality at ac mains for a wide range of speed control and supply voltage variations.

II. SYSTEM CONFIGURATION OF PFC CUK FED BLDC MOTOR DRIVE

Figs.1shows the PFC Cuk converter based VSI fed BLDC motor drive using a voltage follower approach.

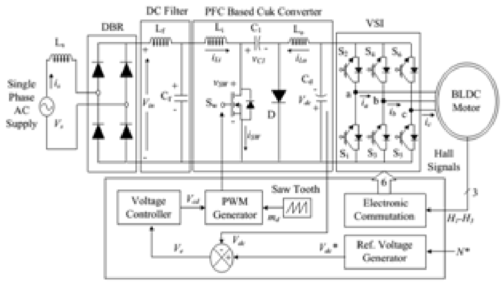

Fig.1. A BLDC motor drive fed by a PFC Cuk converter using a voltage follower approach.

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]. Fig.1 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 (Li and Lo) or the voltage across the intermediate capacitor (C1) 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 this 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 (Li and Lo) and voltage across intermediate capacitor C1 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 Lior Lo becomes discontinuous in their respective modes of operation. While in DCVM operation, the voltage appearing across the intermediate capacitor C1becomes discontinuous in a switching period.The DCM mode of operation is discussed as follows.

A. DICM (Li) Operation:

The operation of Cuk converter in DICM (Li) is described as follows. Figs.2(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.2 (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.2 (a). Input inductor current iLi increases while the voltage across the capacitor C1 decreases as shown in Fig.2 (d).

Interval II:
When switch Sw is 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.

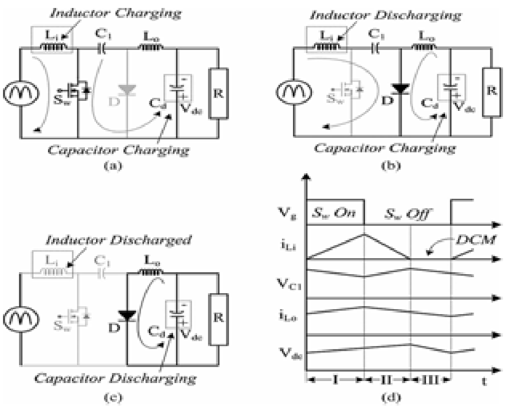

Fig.2. Operation of Cuk converter in DICM (Li) during (a-c) different intervals of switching period and (d) the associated waveforms.

B. DICM (Lo) Operation:
The operation of Cuk converter in DICM (Lo) is described as follows. Figs.3(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.3(d) shows the associated waveforms in a switching period.

Interval I:
As shown in Fig.3(a), when switch Sw is turned on, inductor L stores energy while capacitor C1discharges through switch Sw to transfer its energy to the DC link capacitor Cd.

Interval II:
When switch Sw is turned off, then the energy stored in inductor Li and Lo is transferred to intermediate capacitor C1and DC link capacitor Cd respectively.

Interval III:
In this mode of operation, the output inductor Lo is completely discharged hence its current iLo becomes zero. An inductor Li operates in continuous conduction to transfer its energy to the intermediate capacitor C 1 via diode D.

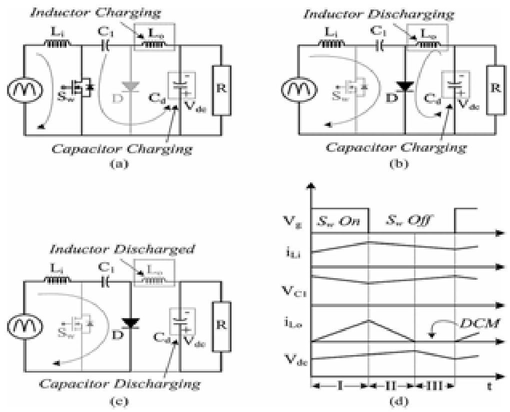

Fig.3.Operation of Cuk converter in DICM (Lo) during (a-c) different intervals of switching period and (d) the associated waveforms.

C.Design of a PFCCuk 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,

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

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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,

$$V_{in}(t)=|V_m \text{Sin}(wt)|=|220\sqrt{2}\ \text{Sin}(314t)|V \qquad (2)$$

Where | | represents the modulus function. The output voltage, Vdc of Cuk converter is given as

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

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,

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

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, at 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: DESIGN PARAMETERS IN DIFFERENT MODES OF OPERATION OF CUK CONVERTER

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
DICM(Li)	100µ H	4.3m H	0.66 µF	220µ F
DICM(Lo)	2.5m H	70µ H	0.66 µF	220µ F

IV. SYSTEM CONFIGURATION OF PFC BL-LUO CONVERTER FED BLDC MOTOR DRIVE

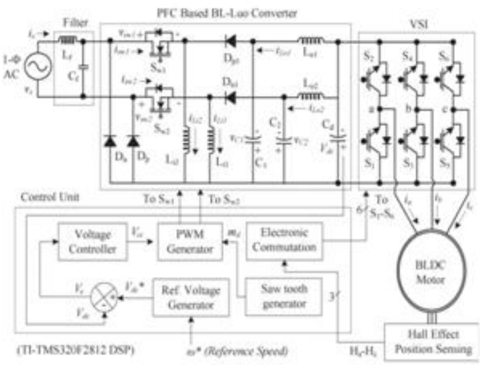

Fig. 4.A BLDC motor drive fed by a PFC BL-Luoconverter using a voltage follower approach.

The operation of the proposed PFC BL-Luo converter is classified into two parts which include the operation during the positive and negative half cycles of supply during the complete switchingcycle. The bridgeless converter is designed such that two different switches operate for positive and negative half cycles of supply voltages. As shown in Fig4, switch Sw1, inductors Li1 and Lo1, and diodes Dpand Dp1 conduct during the positive half cycle of supply voltage. In a similar manner, switch Sw2, inductors Li2 and Lo2, and diodes Dnand Dn1 conduct during the negative half cycle of supply voltage as shown in Fig.4. Fig.7 shows the associated waveforms demonstrating the variation of different parameters such as supply voltage (vs), discontinuous input inductor currents (iLi1 and iLi2), output inductor current (iLo1 and iLo2), and the intermediate capacitor's voltage (VC1 and VC2) during the complete cycle of supply voltage.

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A. Operation of BL-Luo converter in DICM:
The operation of the proposed PFC BL-Luo converter is classified into two parts.They are during the positive and negative half cycles of supply voltage during the complete switching cycle.

Mode P-I:
As shown in Fig. 5(a), when switch Sw1 is turned on, the input side inductor (Li1) stores energy, depending upon the current (iLi) flowing through it and the inductor value (Li1).Moreover, the energy stored in the intermediate capacitor (C1) is transferred to the dc-link capacitor (Cd) and the output side inductor (Lio). Hence, the voltage across the intermediate capacitor (VC1) decreases, whereas the current in the output inductor (iLo1) and the dc-link voltage (Vdc) are increased.

Mode P-II:
As shown in Fig. 5(b), when switch Sw1 isturned off, the input side inductor (Li1) transfers its energyto the intermediate capacitor (C1) via diode Dp1. Hence,thecurrent iLi1 decreases until it reaches zero, whereas the voltageacross the intermediate capacitor (VC1) increases. The dc-link capacitor (Cd) provides the required energy to the load; hence, the dc-link voltage Vdcreduces in this mode of operation.

Mode P-III:
As shown in Fig. 5(c), no energy is left in the input inductor (Li1), i.e., current iLi1 becomes zero and enters the discontinuous conduction mode of operation. The intermediate capacitor (C1) and output inductor (Lo1) are discharged; hence, current iLo1 and voltage VC1 are reduced, and dc-link voltage Vdcincreases.

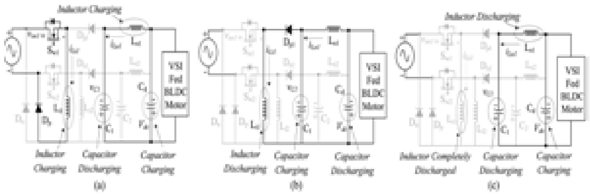

Fig.5. Operation of BL Luo converter in DICM during positive (a-c)

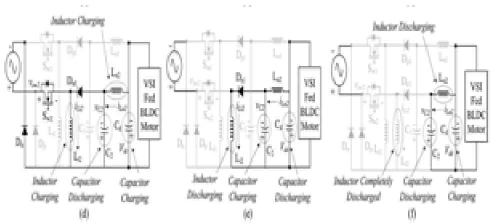

Fig.6. Operation of BL Luo converter in DICM during negative (d-f) .

In a similar way, for a negative half cycle of supply voltage, the inductor's Li2 and Lo2, diode Dn1, and intermediate capacitor C2 conduct to achieve a desired operation. Is shown in Fig. 6(d-f),

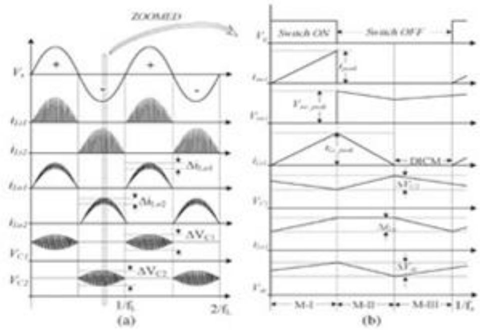

Fig.7. Waveforms of BL Luo converter during its operation(a)complete line cycle (b)complete switching cycle.

B. Design of a PFCBL-Luo Converter:
The PFC BL-Luo converter is designed for its operation in DICM to act as a power factor preregulator. The current in the input inductors (iLi1 and iLi2) becomes discontinuous in a switching period, whereas the output inductor currents (iLo1 and iLo2) and intermediate capacitor's voltages (VC1 and VC2) remain continuous. A 400-W (Pmax) PFC converter is designed to control the dc-link voltage from 50 V (Vdc min) to 200 V (Vdcmax). Since the speed is directly proportional to the dc-link voltage; hence, output power is taken as a linear function of the dc-link voltage. Therefore, the output power corresponding to the minimum dc-link voltage is taken as 50 W (Pmin). The average voltage (Vin) appearing at the input of filter is given as
Vin $=2\sqrt{2}V_s/\pi=(2\sqrt{2}\times 220)/\pi\approx 198$ V.(1)

The relation between the input and output voltages for a
BL-Luo converter is given as

$d = \frac{Vdc}{Vin + VdC}$.(2)

Now, using (2), the minimum (dmin) and maximum (dmax)duty ratios corresponding to Vdcminand Vdcmaxare calculatedas 0.2016 and 0.5025, respectively.

The critical value of the input inductor operating in DICM for a worst duty ratio of dminis given as

$Lic = \frac{dmin\ (1-dmin\ )Vin}{2IofS} = \frac{0.2016\ X(1-0.2016)X\ 198}{2\ X\ 2\ X\ 20000}$(3)

Where fs is the switching frequency which is taken as 20 kHz and Io is the load current.

Now, the value of the input inductor is to be selected much less than this critical value [16] to achieve a deep discontinuous conduction over a wide range; hence, the selected value of the inductors (Li1 and Li2) is taken as 40μH.

The value of the intermediate capacitors (C1 and C2) is

calculated for the worst duty ratio (dmax) and is given as

$C1,2 = \frac{dmax\ \ Vc}{2f_s R_{l}\frac{(\Delta Vc)}{2}} = \frac{0.5025\ X\ 398}{2\ X\ 20000\ X\ 100\ X\ 119.4}$= 0.419 μF(4)

where RL is the emulated load resistance, i.e., V2dc/Pmax, VCis the voltage appearing across C1 or C2 (i.e., Vin +Vdc),and ΔVC is the permitted voltage ripple which is taken as60% of VC.

Hence, the values of intermediate capacitors (C1 and C2) areselected as 0.44 μF.

The value of the output inductors (Lo1 and Lo2) for thePermitted ripple current in the output inductors (which is taken

$L_{o12} = \frac{dmax\ \ Io}{16\ f_s^2 XC_{in}\ (\Delta Io/2)}$ =1.78 mH.(5)

Hence, the value of Lo1 and Lo2 obtained is 1.78 mH.

The value of the dc-link capacitor (Cd) is obtained for the Worst duty ratio as

$Cd = \frac{Io}{2\omega L \Delta Vdc\ \ min} = \frac{2}{2\ X\ 314\ X\ (0.03\ X\ 50)}$= 2123.14 μF(6)

WhereΔVdcis the permitted ripple voltage in the dc-link Capacitor (taken as 3%) and ωLis the line frequency in radiansper second.

Hence, the dc-link capacitor of 2200 μF is selected.

An input filter (L–C filter) is designed to avoid the reflectionof high current ripple in the supply system. The maximum valueof the filter capacitor (Cmax) is given as

$Cmax = \frac{Ipeak}{\omega LVpeak}\ \tan(\theta) =$ = 459.4 nF(7)

WhereVpeakand Ipeakrepresent the peak value of the supply voltage and supply current, respectively, and θrepresent displacement angle between the supply voltage and supply current

Hence, the selected value of the filter capacitor is 330 nF.

Now, the value of the filter inductor is designed by considering the source impedance (Ls) of 4%–5% of the base impedance. Hence, the additional value of inductance required is given as

$Lf == Lreq\ + Ls\ = Lreq\ + 0.04 \left(\frac{1}{w_L}\right) \left(\frac{v_s^2}{p}\right)$=3.77mH (8)

where fc is the cutoff frequency which is selected such that fL<fc <fS; hence it is taken as fS/10.

Hence, an LC filter of 3.77 mH and 330 nF is selected

TABLE II: SPECIFICATIONS OF A BLDC MOTOR

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S.NO	PARAMETERS	VALUES
1	No. of poles (P)	4 POLES
2	Rated power (P_{RATED})	251.3 W
3	Rated DC link voltage	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

C. Control Of PFC Bl-Luo Converter-Fed BLDC Motor Drive:

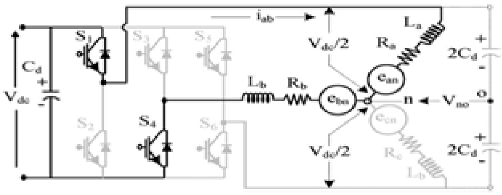

Fig 8.VSI feeding a BLDC motor

An electronic commutation of the BLDC motor includes the proper switching of VSI in such a way that a symmetrical dc current is drawn from the dc-link capacitor for 120◦ and placed symmetrically at the center of each phase. A rotor position on a span of 60◦ is required for electronic commutation, which is sensed by Hall effect position sensors. The conduction states of two switches (S1 and S4) are shown in Fig. 8. A line current iab is drawn from the dc-link capacitor, whose magnitude depends on the applied dc-link voltage (Vdc), back electromotive forces (EMFs) (eanand ebn), resistance (Ra and Rb), and self- and mutual inductances (La, Lb, and M) of the stator windings. Table III shows the governing switching states of theVSI feeding a BLDC motor based on the Hall effect position signals (Ha–Hc).

TABLE III: SWITCHING STATES OF VSI TO ACHIEVE ELECTRONICCOMMUTATION OF BLDC MOTOR

θ^0	HALL SIGNALS			SWITCHING SIGNALS					
	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
NA	0	0	0	0	0	0	0	0	0
0-60	0	0	1	0	0	0	1	1	0
60-120	0	1	0	0	1	1	0	0	0
120-180	0	1	1	0	1	0	0	1	0
180-240	1	0	0	1	0	0	0	0	1
240-300	1	0	1	1	0	0	1	0	0
300-360	1	1	0	0	0	1	0	0	1
NA	1	1	1	0	0	0	0	0	0

V.MATLAB/SIMULATION RESULTS

A. Simulation model of CUK-converter fed BLDCM drive:

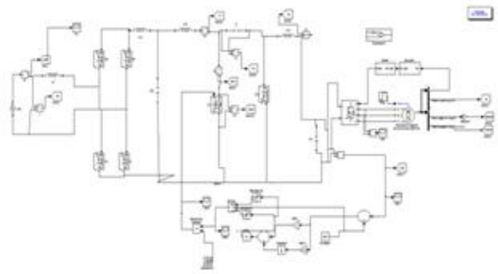

Fig.9. Simulation model of BLDC motor drive fed by a PFC Cuk converter

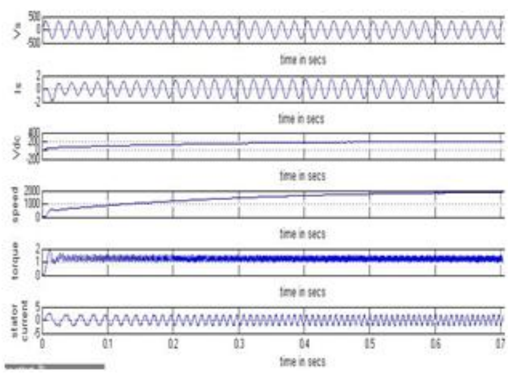

Fig.10. Simulation results for source voltage, current, dc link voltage, and speed, torque, stator current of the BLDC motor drive with the Cuk converter operating in the DICM (Li)

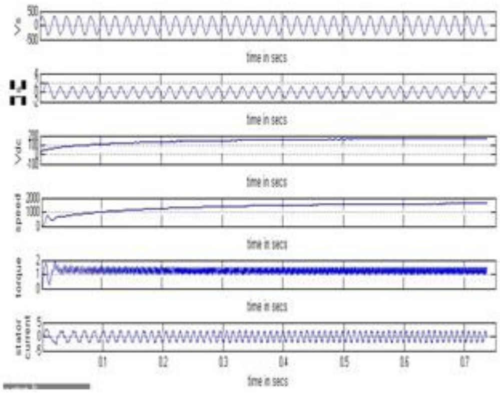

Fig.11. Simulation results for source voltage, current, dc link voltage, and speed, torque, stator current of the BLDC motor drive with the Cuk converter operating in the DICM (Lo)

B. Simulation model of PFC BL-Luo -converter fed BLDCM drive:

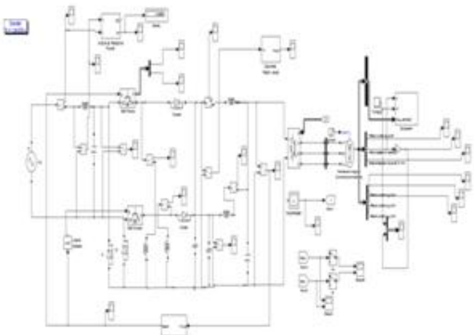

Fig.12. Simulation model of BLDC motor drive fed by a PFC BL-Luo converter

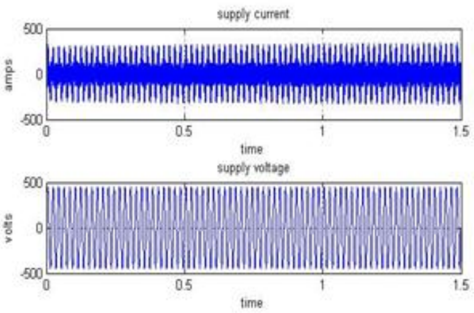

Fig.13. Simulation results for supply voltage, and supply current, of the BLDC motor drive with the BL-Luo converter operating in the DICM

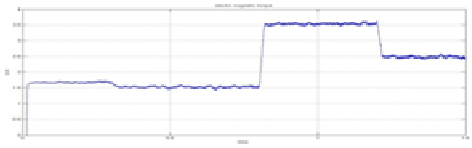

Fig.14. Simulation results BLDC Motor Fed BL-Luo Converter of, rotor speed,electromagnetic torque,

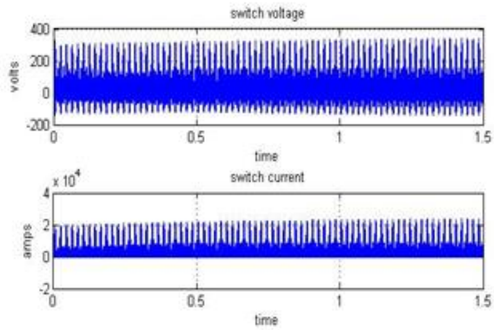

Fig.15.Simulation results for Switch voltage, and Switch current, of the BLDC motor drive with the BL-Luo converter operating in the DICM

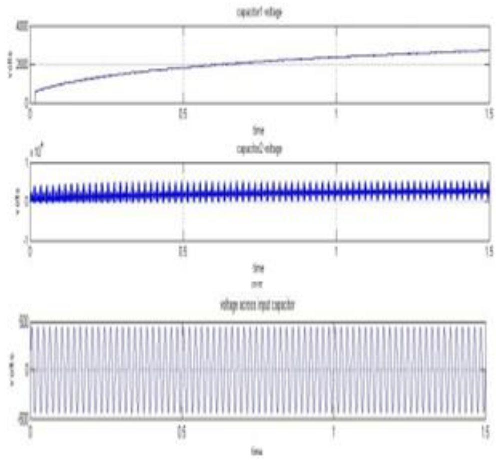

Fig.16.Simulation results for voltage across intermediate capacitors, of the BLDC motor drive with the BL-Luo converter operating in the DICM

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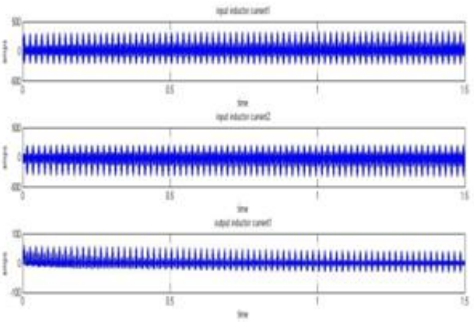

Fig.17.Simulation results for currents in input inductors, of the BLDC motor drive with the BL-Luo converter operating in the DICM

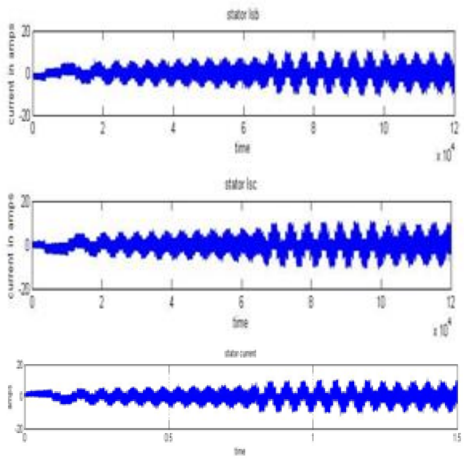

Fig.18. Simulation results for BLDC Motor Fed BL-Luo Converter of stator currents

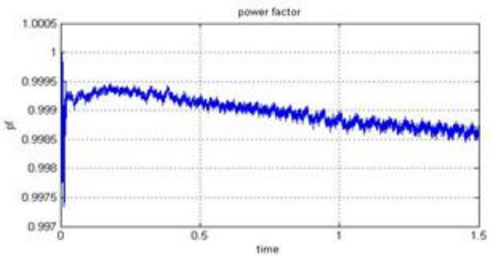

Fig.19. Simulation results for BLDC Motor Fed BL-Luo Converter ofpower factor

PERFORMANCE DETAILS

S.NO	BLDC MOTOR	POWER FACTOR
1	Fed CUK-converter	0.9306
2	fed BL-LUO-Converter	0.9992

VI.CONCLUSION:

In the BL Luo 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 equipments 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. The bridge less Luo converter is operated in DICM have been explored for the development of BLDC motor drive with unity power factor at AC mains. In this project the bridge Cuk converter is being replaced with bridge less Luo converter where the bridge switching losses has been reduced and the overall power factor is improved. Finally, a best suited mode of BL Luo converter with output inductor current operating in DICM has been selected for experimental verifications. By using BL Luo converter the power factor is improved from 0.9306 to 0.9992.The simulation model which is implemented under MATLAB environment allows dynamic characteristics such as phase currents, rotor speed, and mechanical torque ripple has been effectively reduced.

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