International Journal of Research
Available at https://edupediapublications.org/journals
p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03Issue 10
June2016

Fuzzy Logic Controlled based PFC Cuk Converter Fed BLDC Motor Drive

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Abstract—a bridgeless single phase ac-dc rectifier basedCuk derived converter topology fed BLDC motor isproposed to improvepower factor at the AC mains near tothe unity with low THD for PFC applications. It utilizes onecontrol signal over the whole line cycle.The most effective method of power quality improvement is also simulated using MATLAB/Simulink.It utilizes one control signal over the whole line cycle. In addition, the proposed converter exhibits low inrush current and low magnetic emissions as classical Cuk topology. The partial elimination of diodes in DBR in the bridgeless topology results in lower conduction losses as compared with conventional Cuk converter.The proposed method issimulatedin MATLAB/Simulink with PI and fuzzy logiccontroller for precise speed control. A diode bridge rectifier (DBR) followed by a Cuk converter working in discontinuous conduction mode(DCM)is used for control DC link voltage with unity power factor at AC mains. The fuzzy based controller system is used for general purpose industrial applications.

Index Terms— CCM, Cuk converter, DCM, PFC, BLDC Motor, Power Quality, Fuzzy Logic Control.

I.INTRODUCTION

Efficiency and cost are the major concerns in thedevelopment of low-power motor drives targeting householdapplications such as fans, water pumps, blowers, mixers, etc. The use of the brushless direct current (BLDC)motor in these applications is becoming very common due tofeatures of high efficiency, high flux density per unit volume,low maintenance requirements, and low electromagneticinterferenceproblems[1]. These BLDC motors are notlimited to household applications, but these are suitable forother applications such as medical equipment, transportation,HVAC, motion control, and many industrial tools [2]–[4]. ABLDC motor has three phase windings on the stator andpermanent magnets on the rotor [5], [6]. The BLDC motor isalso known as an electronically commutated motor becausean electronic commutation based on rotor position is usedrather than a mechanical commutation which hasdisadvantages like sparking and wear and tear of brushes andcommentator assembly [7]. Power quality problems have become important issues to

Be considered due to therecommended limits of harmonics in supply current byvarious international power quality standards such as theInternational Electro technical Commission (IEC) 61000-3-2[8]. For class-a equipment (< 600 W, 16 A per phase) whichincludes household equipment, IEC 61000-3-2 restricts theharmonic current of different order such that the totalharmonic distortion (THD) of the supply current should bebelow 19% [9].
Low power motor drives such as fans, water pumps, blowers, mixers, HVAC transmission, motioncontrol etc. use BLDC motor for their efficient operation. Since BLDC offers high efficiency, lowelectromagnetic interference, low maintenance and high flux density per unit volume, we use BLDC for lowpower applications. BLDC motors are very popular in a wide variety of applications. Compared with a DCmotor, the BLDC motor uses an electric commutator rather than a mechanical commutator, so it is morereliable than the DC motor. In a BLDC motor, rotor magnets generate the rotor's magnetic flux, so BLDCmotors achieve higher efficiency. Therefore, BLDC motors may be used in high-end white goods(refrigerators, washing machines, dishwashers, etc.), high-end pumps, and fans and in other appliances whichrequire high reliability and efficiency.In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which themagnet rotates while the conductors remain stationary. In the DC commutator motor, the current polarity isaltered by the commutator and brushes [10-13].

In recent years, the number and variety of applicationsof Fuzzy Logic (FL) haveincreased significantly. Tounderstand why use of Fuzzy Logic has grown, it mustbe first understood as what is meant by Fuzzy Logic.Fuzzy Logic has two different meanings. In a narrowsense, Fuzzy Logic is a logical system, which is anextension of multivalve logic. However, in a widersense Fuzzy Logic is almost synonymous with thetheory of Fuzzy sets, a theory which relates to classes ofobjects with un sharp boundaries in which membershipis a matter of degree. In this perspective, Fuzzy logic inits narrow sense is a branch of Fuzzy Logic. Even in itsmore narrow definition, Fuzzy logic differs both inconcept and substance from traditional multivalvelogical systems.

II. SYSTEM CONFIGURATION

Figs.1-2 show the PFC Cuk converter based VSI fed BLDC motor drive using a current multiplier and a voltage follower approach respectively. 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. 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 Lo), and the voltage across the intermediate capacitor (C1) 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 (Liand 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 a continuous conduction mode of operation and its performance is evaluated for a wide voltage control with unity power factor at AC mains.

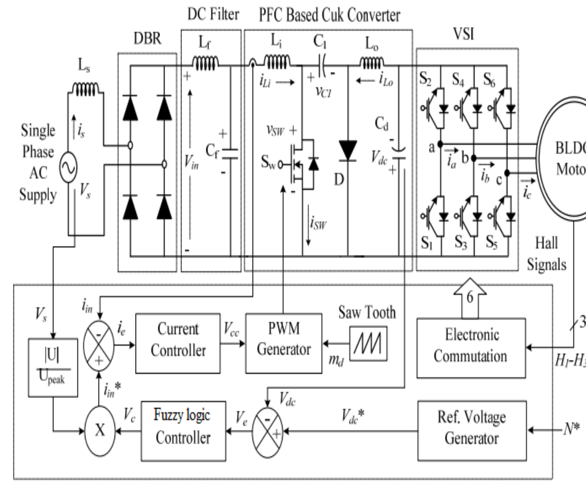

Fig.1. A BLDC Motor Drive Fed by aPFC Cuk Converter Using A Current Multiplier Approach With Fuzzy Logic Controller.

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 (Liand 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. Different modes for operation of CCM and DCM are discussed as follows.

A. CCM Operation

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

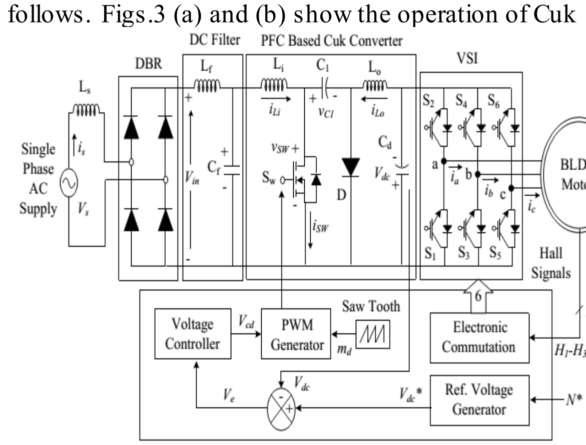

Fig.2. ABLDC Motor Drive Fed by aPFC Cuk Converter Using a Voltage Follower Approach.

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

International Journal of Research
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e-ISSN: 2348-795X
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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 Fig.3(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 Swto 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.

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 Swim turned on, inductor L stores energy while capacitor C1discharges through switch Swto transfer its energy to the DC link capacitor Cd. Interval II: When switch Swiss turned off, then the energy stored in inductor Li and Lo is transferred to intermediate capacitor C1and DC link capacitor Cdrespectively. Interval III: In this mode of operation, the output inductor Lo is completely discharged hence its current iLobecomes zero. An inductor Li 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 Swim turned on as shown in Fig.6 inductor L Is tares energy while capacitor C1discharges through switch Sw to transfer its energy to the DC link capacitor Cd as shown in Fig.6 (d). Interval II: The switch is in conduction state but intermediate capacitor C1is completely discharged, hence the voltage across it becomes zero. Output inductor Lo continues to supply energy to the DC link capacitor. Interval III: As the switch Sw is turned off, input inductor L I starts charging the intermediate capacitor, while the output inductor Lo continues to operate in continuous conduction and supplies energy to the DC link capacitor.

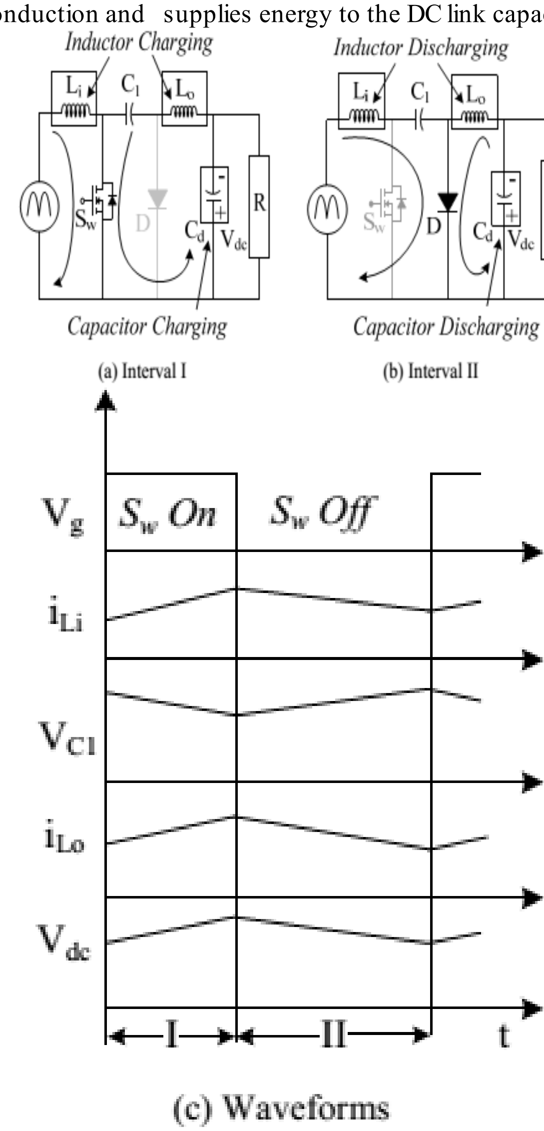

Fig.3. Operation Of Cuk Converter In CCM During (A-B) Different Intervals Of Switching Period And (C) The Associated Waveforms.

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

p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03Issue 10
June2016

designed for a CCM and three different DCMs. In DCM, any one of the energy storing elements Li, Loor 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,

$$V_s(t)=V_m \sin(2\pi f_L t)=220\sqrt{2}\sin(314t)v \qquad (1)$$

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,

$$V_{in}(t)=|vm\sin(t)|=|220\sqrt{2}\sin(314t)|V \qquad (2)$$

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.

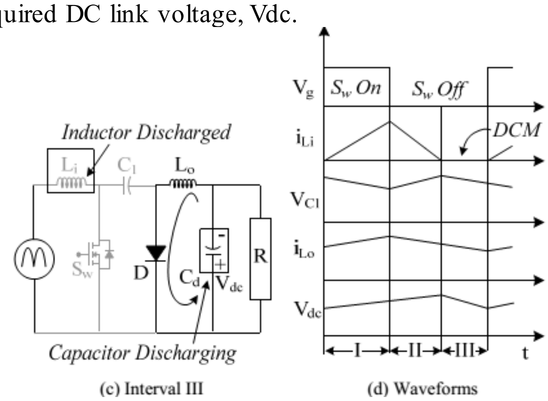

Fig. 4. Operation of Cuk converter in DICM (Li) during (a-c) different Intervals of switching period and (d) the associated waveforms.

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

$$D(t)=\frac{Vdc}{Vin(t)+Vdc}=\frac{Vdc}{|Vm\sin(\omega t)|+Vdc} \qquad (4)$$

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, 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.

A. Design of Li

For Continuous or Discontinuous Current Conduction the critical value of input inductor Lice is expressed as

$$Lic=\frac{Vin(t)D(t)}{2Iin(t)fs}=\frac{Rin\,D(t)}{2fs}=\left(\frac{Vs2}{Pi}\right)\frac{D(t)}{2fs}$$

$$=\frac{1}{2fs}\left(\frac{Vs2}{Pi}\right)\frac{Vdc}{Vin(t)+Vdc} \qquad (5)$$

(3)

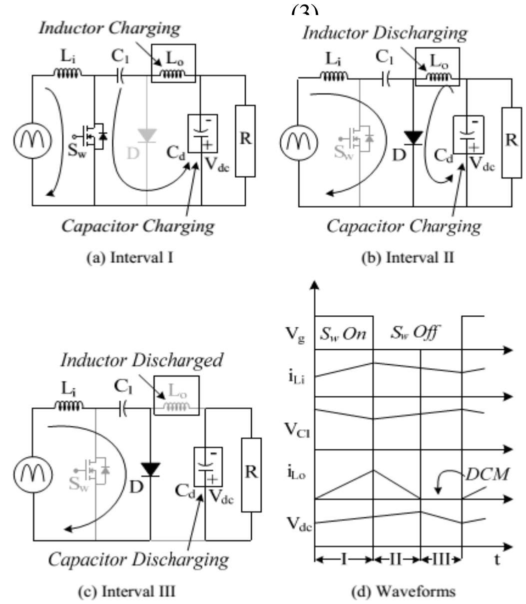

Fig.5. Operation of Cuk converter in DICM (Lo) during (a-c) different intervals of switching period and (d) the associated waveforms.

Hence the critical value of input side inductor is directly proportional to the rams value of supply voltage; therefore the worst case design occurs for the minimum value of supply voltage (i.e. Vs=Vs min =85V). Now the critical value of input inductor at the maximum DC link voltages of 200V at the peak value of supply voltage (i.e. √2Vsmin) is calculated as,

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June2016

$$L_{ic200} = \frac{1}{2fs}\left(\frac{Vsmin2}{Pmax}\right).\frac{Vdcmax}{\sqrt{2}Vsmin+Vdcmax}$$

$$=\frac{1}{2\times20000}\left(\frac{85^2}{350}\right)\left(\frac{200}{85\sqrt{2}+200}\right)=322.3\mu H \quad (6)$$

And the critical value of input inductor at the minimum value of DC link voltages of 40V at the peak value of supply voltage is calculated as

$$L_{ic40} =\frac{1}{2fs}\frac{Vsmin2}{Pmin}.\left(\frac{Vdcmin}{\sqrt{2}Vsmin+Vdcmin}\right)$$

$$=\frac{1}{2\times20000}\left(\frac{85^2}{70}\right)\left(\frac{40}{85\sqrt{2}+40}\right)= 644.25\mu H \quad (7)$$

Hence the value of critical input inductance is obtained lower at maximum DC link voltage. Therefore, the critical value of input inductor is selected lower than Lic200. The Performance of the Cuk converter feeding BLDC motor drive is analyzed for different values of input side inductor i.e.

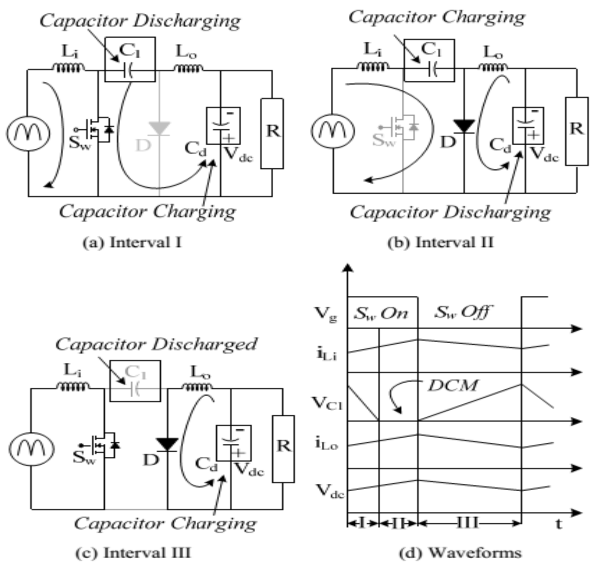

Fig.6. Operation of Cuk converter in DCVM (C1) during (a-c) different intervals of switching period and (d) the associated waveforms.

A high THD of AC mains current is obtained at higher values of input side inductor which doesn't comply with the IEC 61000-3-2 [14]. Hence the input inductor (Li) of the order of 100µH is selected for its operation in discontinuous conduction to achieve a low value of THD of supply current at AC mains. The value of input inductor to operate in CCM is decided by the amount of permitted ripple current (η) and is as,

$$L_{iccm}=\frac{Vin(t)D(t)}{\eta Iin(t)fs}=\frac{Rin\,D(t)}{\eta fs}=\left(\frac{Vs2}{Pi}\right)\frac{D(t)}{\eta fs}$$

$$= \frac{1}{\eta fs}\left(\frac{Vs2}{Pi}\right)\frac{Vdc}{Vin(t)+Vdc} \quad (8)$$

The maximum inductor ripple current is obtained at the rated condition i.e. Vdc=200V for a minimum supply voltage (Vs min =85V). Hence the input side inductor is designed at the peak value of minimum supply voltage (i.e. Vs=√2Vsmin) as,

$$L_{oc} = \frac{Vdc(1-D(t)}{2Ilo(t)fs}=\frac{Vdc\,D(t)}{2Iin(t)fs}=\frac{RinVdc\,D(t)}{2Vin(t)fs}$$

$$=\left(\frac{Vs2}{Pi}\right)\frac{Vdc}{2Vin(t)fs}\left(\frac{Vdc}{Vin(t)+Vdc}\right) \quad (9)$$

Where the permitted amount of ripple current is selected as 25% of the input current. Hence the input side inductor of 2.5mH is selected for its operation in continuous conduction.

V.FUZZY LOGIC CONTROL

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of compensator.

The basic scheme of a fuzzy logic controller is shown in Fig 7 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

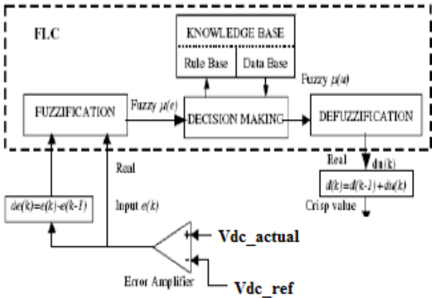

Fig.7 Block diagram of the Fuzzy Logic Controller (FLC) for Proposed Converter.

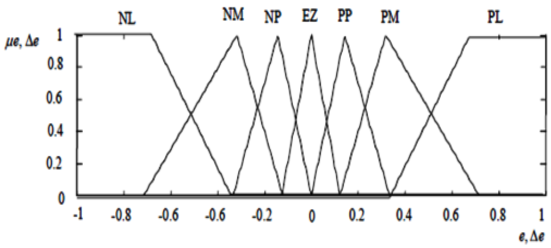

Fig.8 Membership functions for Input, Change in input, Output.

Rule Base:the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table 1, with 'Vdc' and 'Vdc-ref' as inputs.

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

VI.MATLAB/SIMULINK RESULTS

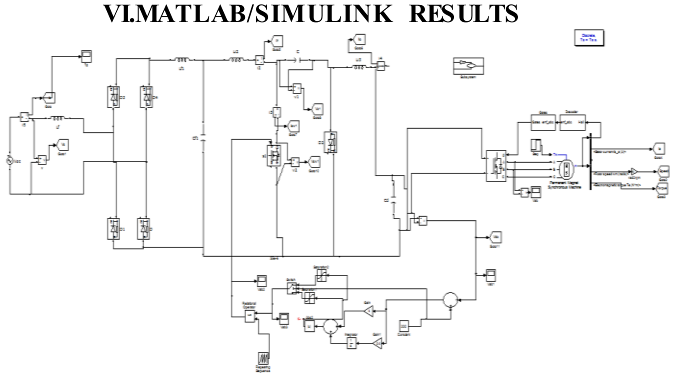

Fig.9.Matlab/Simulink Model of A BLDC Motor Drive Fed by a PFC Cuk Converter with PI Controller.

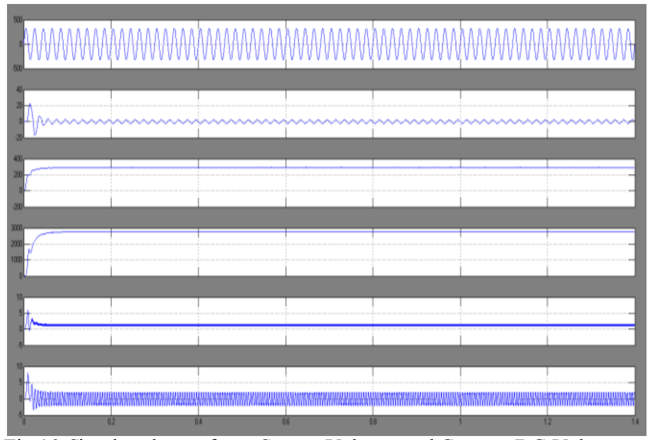

Fig.10.Simulated waveform Source Voltage and Current DC Voltage, Speed, Torque, Armature Current of BLDC motor drive with Cuk converter operating in CCM.

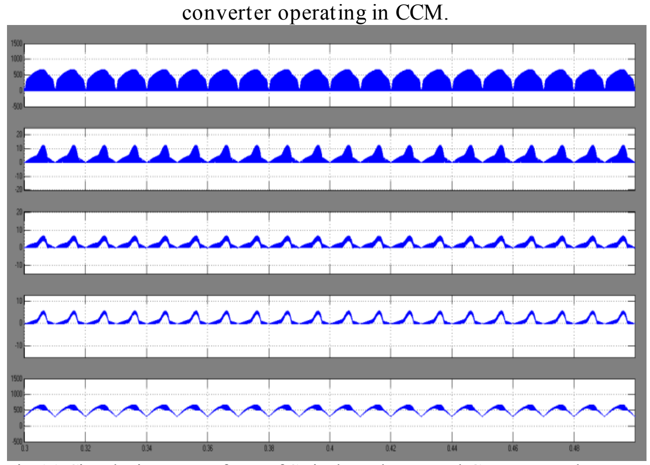

Fig.11.Simulation Waveform of Switch Voltage and Current, Inductor Current, Load Current and Capacitor Voltage of BLDC Motor Drive with Cuk Converter Operating in CCM.

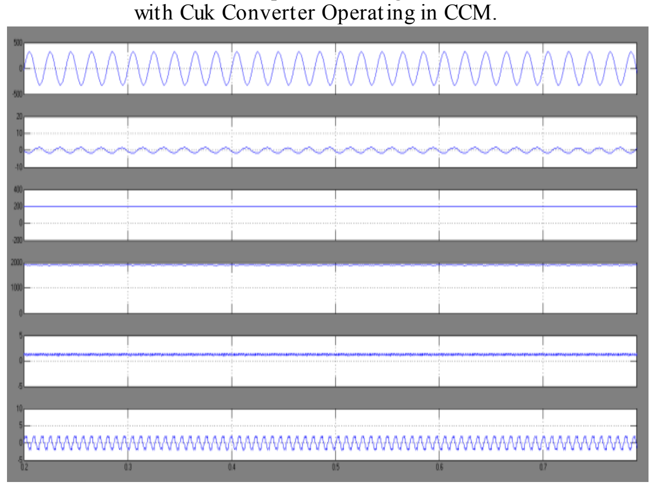

Fig.12.Simulated waveform Source Voltage and Current DC Voltage, Speed, Torque, Armature Current of BLDC motor drive with Cuk Converter Operating in DICM (Li).

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e-ISSN: 2348-795X
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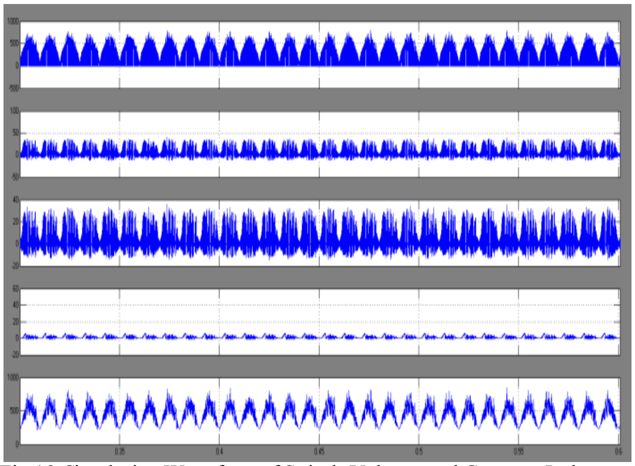

Fig.13.Simulation Waveform of Switch Voltage and Current, Inductor Current, Load Current and Capacitor Voltage of BLDC motor drive with Cuk Converter Operating in DICM (Li).

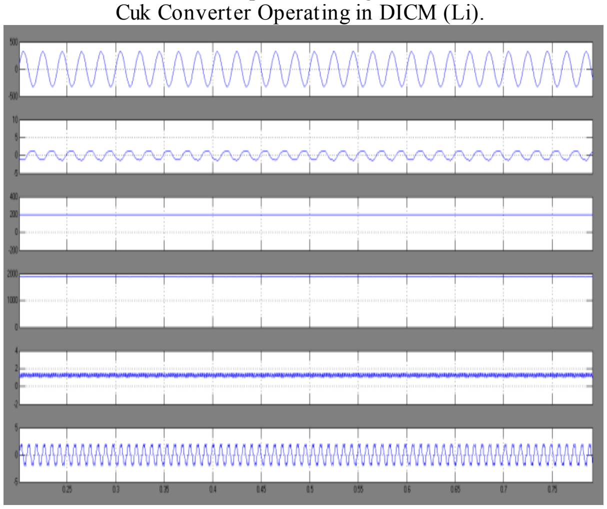

Fig.14.Simulated waveform Source Voltage and Current DC Voltage, Speed, Torque, Armature Current of BLDC motor drive with Cuk Converter Operating in DICM (Lo).

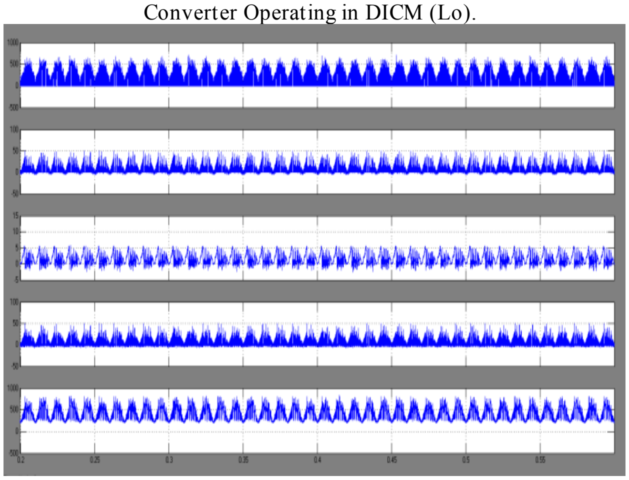

Fig.15.Simulation Waveform of Switch Voltage and Current, Inductor Current, Load Current and Capacitor Voltage of BLDC motor drive with Cuk converter operating in DICM (Lo).

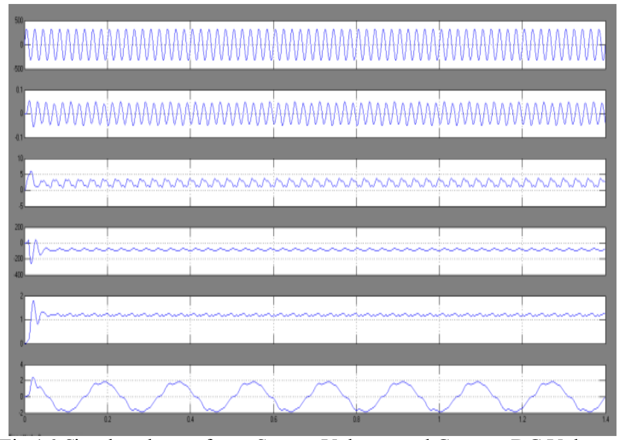

Fig.16.Simulated waveform Source Voltage and Current DC Voltage, Speed, Torque, Armature Current of BLDC motor drive with Cuk converter operating in DCVM.

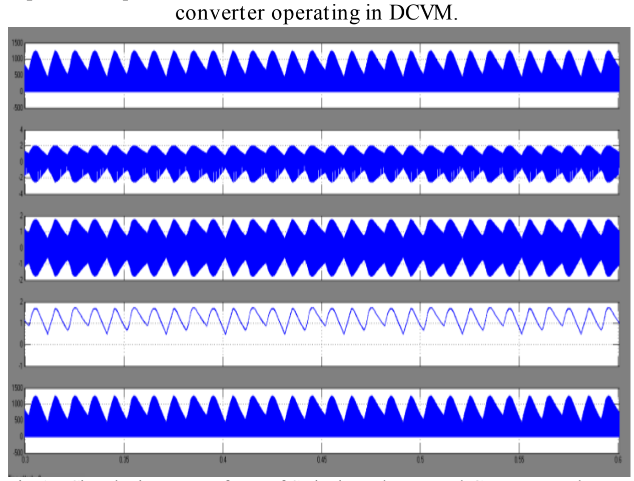

Fig.17.Simulation Waveform of Switch Voltage and Current, Inductor Current, Load Current and Capacitor Voltage of BLDC motor drive with Cuk converter operating in DCVM.

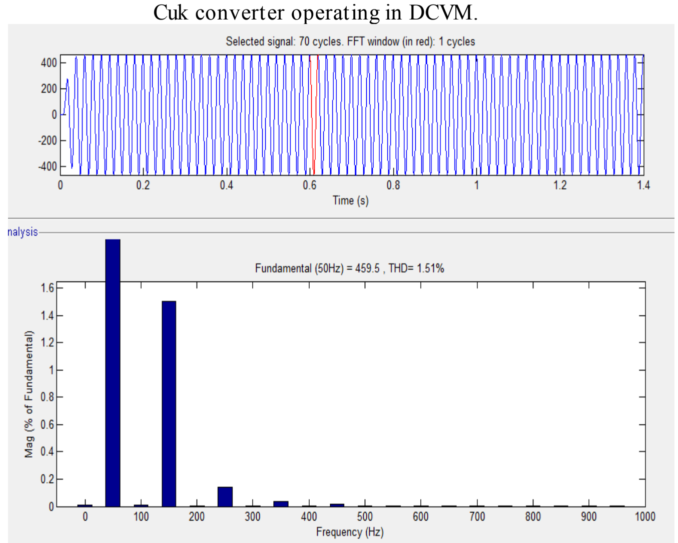

Fig.18.THD for Source Current with PI Controller.

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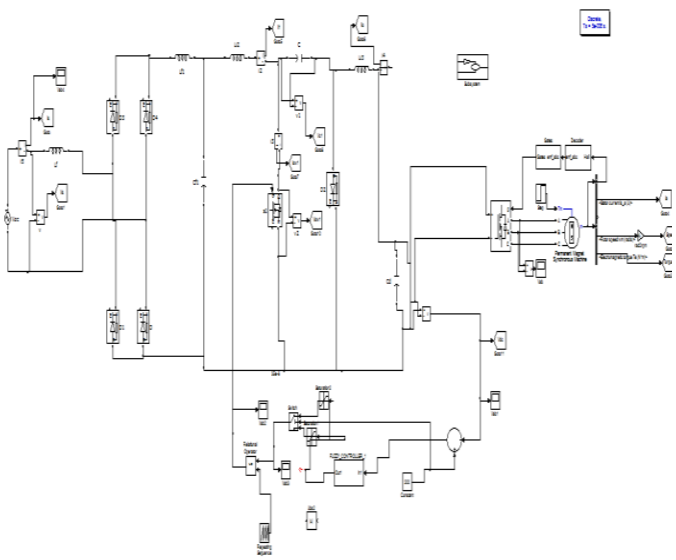

Fig.19.Matlab/Simulink model of A BLDC Motor Drive Fed by a PFC Cuk Converter with Fuzzy Logic Controller.

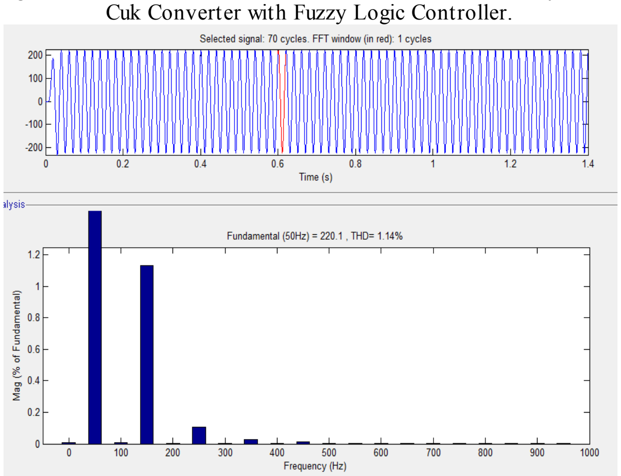

Fig.20.THD for Source Current with Fuzzy Logic Controller.

VII.CONCLUSION

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. A detailed comparison of all modes of operation has been presented on the basis of feasibility in design and the cost constraint in the development of such drive for low power applications. The proposed drive system has shown satisfactory results in all aspects and is a recommended solution for low power BLDC motor drives.The suitable controller for PFC operation of BLDC motor drives has been analysed. FLC seems to be the best controller in performance improvement of BLDC motor drives for attaining the power factor near to unity. Moreover, voltage and current stresses on the fuzzy basedPFC switch have been evaluated for determining the practicalapplication of the proposed scheme. The proposed drive has been developed tovalidate the performance of the proposed BLDC motor driveunder speed control with improved power quality at acmains. The proposed scheme has shown satisfactoryperformance, and it is a recommended solution applicable tolow-power BLDC motor drives.

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