Simulation of Fuzzy Controller Based PFC Cuk Converter Fed BLDC Motor Drive

K. Sakthi Priya[1], V. Jayalakshmi[2]

[1]P.G. Scholar, Department of Electrical and Electronics Engineering, Bharath University, Chennai – 600002, India

[2]Assistant professor, Department of Electrical and Electronics Engineering, Bharath University, Chennai – 600002, India

Abstract: ***The use of permanent-magnet brushless dc motor (BLDC) in low-power appliances is increasing because of its features of high efficiency, wide speed range, and low maintenance. This project 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. 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. Performance of the PFC Cuk converter is evaluated in four different operation condition of discontinuous and continuous conduction mode (CCM) and a comparison is made to select a best suited mode of operation.***

Keywords: Converter, BLDC Motor, Fuzzy Controller, Matlab.

1. Introduction

BRUSHLESS DC (BLDC) motors are recommended for many low and medium power drives applications because of their high efficiency, high flux density per unit volume, low maintenance requirement, low EMI problems, high ruggedness and a wide range of speed control. Due to these advantages, they find applications in numerous areas such as household application, transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning (HVAC), motion control and robotics, renewable energy application etc. The BLDC motor is a three phase synchronous motor consisting of a stator having a three phase concentrated windings and a rotor having permanent magnets. It doesn't have mechanical brushes and commutator assembly, hence wear and tear of the brushes and sparking issues as in case of conventional DC machines are eliminated in BLDC motor and thus has low EMI problems. This motor is also referred as electronically commutated motor (ECM) since an electronic commutation based on the Hall-Effect rotor position signals is used rather than a mechanical commutation.

There is a requirement of an improved power quality as per the international power quality (PQ) standard IEC 61000-3-2which recommends a high power factor (PF) and low total harmonic distortion (THD) of AC mains current for Class-A applications (<600W, <16A) which includes many household equipments. The conventional scheme of a BLDC motor fed by a diode bridge rectifier (DBR) and a high value of DC link capacitor draws a non-sinusoidal current, from AC mains which is rich in harmonics such that the THD of supply current is as high as 65%, which results in power factor as low as 0.8. These types of power quality indices can't comply with the international PQ standards such as IEC 61000-3-2. Hence, single-phase power factor correction (PFC) converters are used to attain a unity power factor at AC mains. These converters have gained attention due to single stage requirement for DC link voltage control with unity power factor at AC mains. It also has low component count as compared to multistage converter and therefore offers reduced losses.

Conventional schemes of PFC converters fed BLDC motor drive utilize an approach of constant DC link voltage of the VSI and controlling the speed by controlling the duty ratio of high frequency pulse width modulation (PWM) signals. The losses of VSI in such type of configuration are considerable since switching losses depend on the square of switching frequency (Psw_loss α fS2). Ozturk have proposed a boost PFC converter based direct torque controlled (DTC) BLDC motor drive. They have the disadvantages of using a complex control which requires large amount of sensors and higher end digital signal processor (DSP) for attaining a DTC operation with PFC at AC mains. Hence, this scheme is not suited for low cost applications. Ho have proposed an active power factor correction (APFC) scheme which uses a PWM switching of VSI and hence has high switching losses. Wu have proposed a cascaded buck-boost converter fed BLDC motor drive, which utilizes two switches for PFC operation. This offers high switching losses in the front end converter due to doubles witch and reduces the efficiency of overall system.

Selection of operating mode of front end converter is a trade-off between the allowed stresses on PFC switch and cost of the overall system. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two different modes of operation in which a front end converter is designed to operate. A voltage follower approach is one of the control techniques which is used for a PFC converter operating in DCM. This voltage follower technique requires a single voltage sensor for controlling the DC link voltage with a unity power factor. Therefore, voltage follower control has an advantage over a current multiplier control of requiring a single voltage sensor. This makes the control of voltage follower a simple way to achieve PFC and DC link voltage control, but at the cost of high stress on PFC converter switch. On the other hand, the current multiplier approach offers low stresses on the PFC switch, but requires three sensors for PFC and DC link voltage control.

2. Block Diagram & Explanation

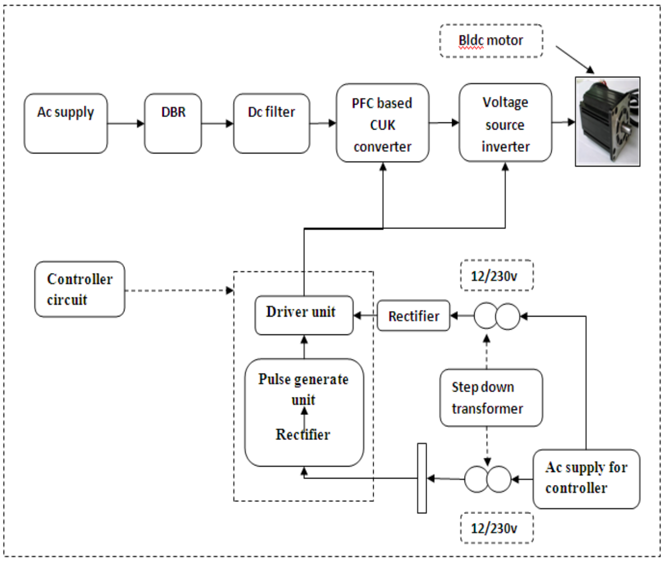


Figure 2.1: Block diagram of proposed system

The proposed system consists of a AC supply, Diode bridge rectifier, Dc filter , Cuk converter and a Voltage source inverter. The controller unit and a pulse generation unit is used to give a pulses during commutation.

The block diagram of proposed system is shown in fig 3.1 .The AC supply is given as input to the diode bridge rectifier, where it is converted into dc output and given to DC filter. Where the filter is used to remove the unwanted or undesirable frequencies from a signal of a rectifier output .Then the cuk converter unit is operated as continuous or discontinuous conduction mode. Voltage source inverter is commutated and the speed of the motor is controlled as per variation of voltages.

2.1 AC Supply

This is a normal 440V, 50Hz, three phase voltage. This voltage is used to supply the thyristors i.e., the MOSFETs. This voltage primarily depends on the MOSFETs ratings and the load. For high power applications this voltage proportionately increases to supply the required load current levels. Since the proposed project reduces the supply voltage harmonics, a perfect sine wave is obtained. The next level of block requires a split voltage to make the inverter function, summing up these voltages later. Hence this makes it mandatory to give a supply same in magnitude and frequency. The voltage level required for the specified MOSFETs ratings is 50V, 50Hz, three phase AC supply. So, it becomes mandatory to step down the available 440V to 50V, without changing the frequency and phase. Hence a Step-Down Transformer or an auto-transformer is used to supply the vital voltage.

2.2 Rectifier

Rectifiers are used to change ac to dc. They work one way valve, allowing current to flow in only one direction. The diode is forward biased for one half cycles of the applied voltage and reverse biased for other half cycle. The output waveform is pulsating dc wave .this wave form can then be filtered to removed unwanted variations.

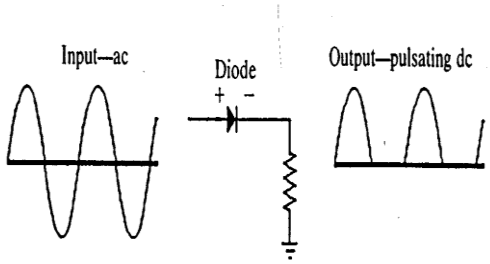


Figure 2.2: Model input and output waveforms of rectifier.

Rectifiers are widely used in power supplies that provide dc voltage necessary for the almost all active devices to work. The three basic rectifier circuits are the half wave; the center tapped full wave, and full wave bridge rectifier's circuits. The most important bridge parameter for choosing diodes for these circuits are maximum forward current and the peak inverse voltage rating of the diode. The peak inverse voltage that appears across a diode depends on a type of the circuits in which it is connected .some characteristics of three rectifiers are investigated.

2.3 CUK Converter

2.3.1 Buck converter

The output voltage is lower than the input voltage and of same polarity. It is called buck converter.

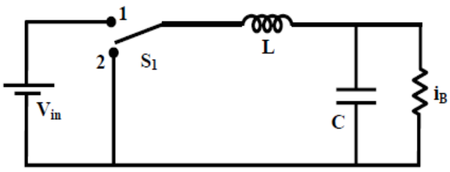


Figure 2.3: Circuit schematic of a buck converter

Features of a buck converter are

- Pulsed input current, requires input filter.
- Continuous output current results in lower output voltage ripple.
- Output voltage is always less than input voltage

2.3.2 Boost converter

The output voltage is greater than the input voltage. so, it is called boost converter and or step up converter.

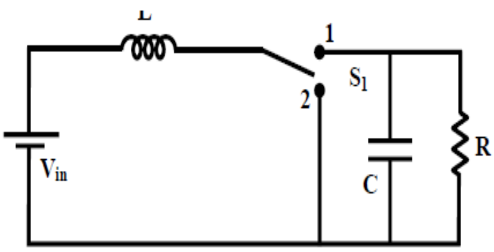


Figure 2.4: Circuit schematic of a boost converter

Features of a boost converter are
- Continuous input current, eliminates input filter.
- Pulsed output current increases output voltage ripple.
- Output voltage is always greater than input voltage.

2.3.3 Buck - Boost converter

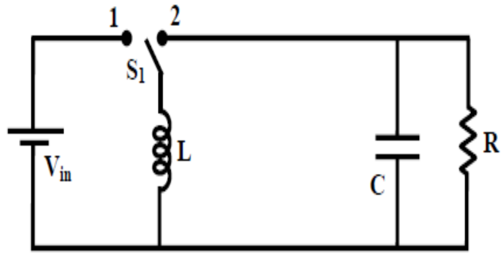


Figure 2.5: Circuit schematic of a buck boost converter

Features of a buck - boost converter are
- Pulsed input current, requires input filter.
- Pulsed output current increases output voltage ripple
- Output voltage can be either greater or smaller than input voltage.

It will be desirable to combine the advantages of these basic converters into one converter. Cuk converter is one such converter. It has the following advantages.
- Continuous input current.
- Continuous output current.
- Output voltage can be either greater or less than input voltage.

Cuk converter is actually the cascade combination of a boost and a buck converter.

S_1 and S_2 operate synchronously with same duty ratio. Therefore there are only two switching states

i)$0 < t \leq DT$

S_1 To (1)

&

S_1 To (1^1)

The circuit configuration is given below

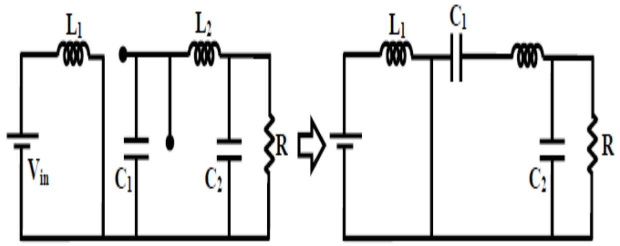


Figure 2.6: Circuit topology of a boost-buck converter at zero interval

ii)$DT < t < T$; S_1 to(2) S_2 to (2) & S_2 to (2^1)

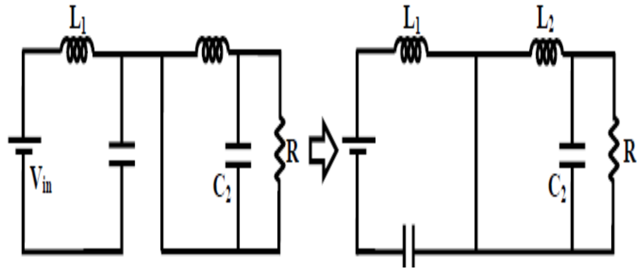


Figure 2.7: Circuit topology of a boost-buck converter during different switching intervals

The Cuk converter is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. These two topologies can also be obtained from the following circuit which is the so called Cuk converter.

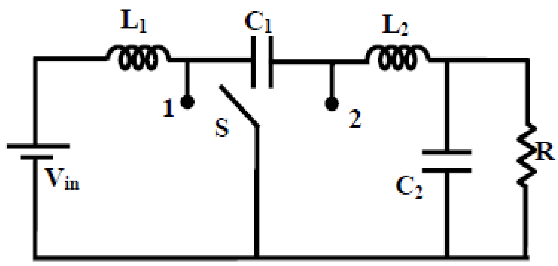


Figure 2.8 (a): Schematic representation of cuk converter.

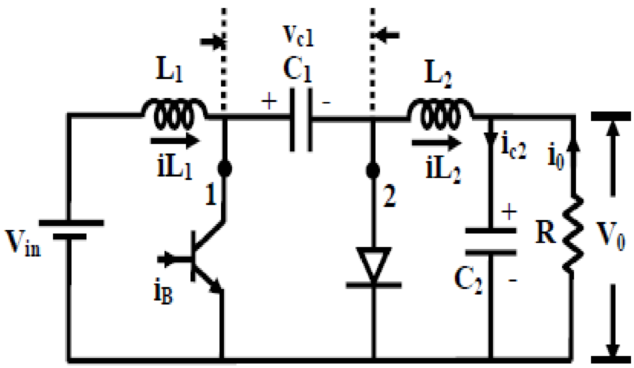


Figure 2.8(b): Circuit representation of cuk converter.

Expression for average output voltage and inductor currents

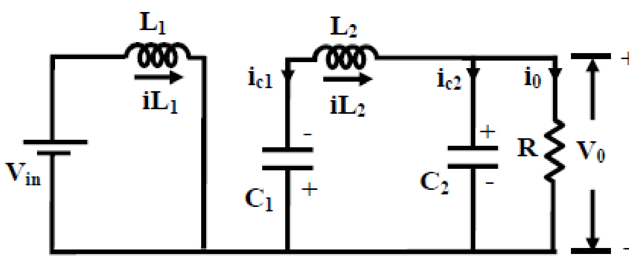


Figure 2.9: (a) Equivalent Circuit of a Cuk converter during initial conduction modes.

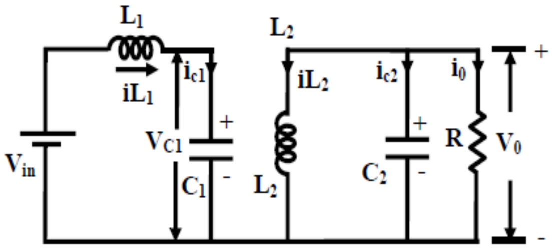


Figure 2.9(b): Equivalent Circuit of a Cuk converter during different conduction modes

$$(V_0+V_{c1})DT+V_0(1-D)T=0$$

Or $V_0+DV_{c1}=0$

Or $V_0=-DV_{c1}=-\frac{DV_{in}}{1-D}$

Expression for average inductor current can be obtained from charge balance of C_2

$$I_{L2}+I_0=0$$

$$I_{L2}=-I_0=-\frac{V_0}{R}=\frac{D}{1-D}\frac{v_{in}}{R}$$

From power balance

$$V_{in}I_{L1}=V_0 I_o=\frac{v\_0\hat{}2}{R}=\frac{D^2}{(1-D)^2}\frac{v_{in}^2}{R} \qquad I_{l1}=\frac{D^2}{(1-D)^2}\frac{v_{in}}{R}$$

3. Circuit Configuration

3.1 System Configuration

Fig.3.1 - shows 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.

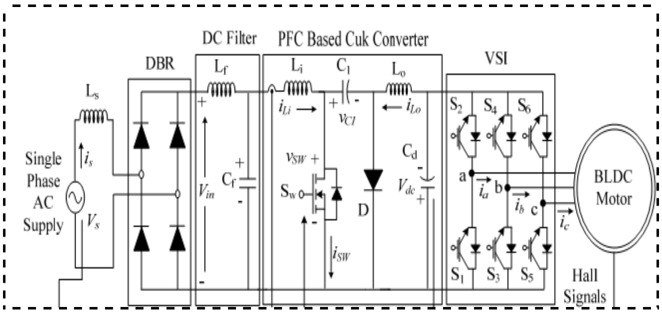


Figure 3.1: A BLDC motor drive fed by a PFC Cuk converter

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 Fig4.1; i.e. the current flowing in the input and output inductors (Li and Lo), and the voltage across the intermediate capacitor (C1) remain continuous in a switching period. 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 a continuous conduction mode of operation and its performance is evaluated for a wide voltage control with unity power factor at AC mains.

3.2 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 C1remain 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 Li or Lo becomes discontinuous in their respective modes of operation.

While in DCVM operation, the voltage appearing across the intermediate capacitor C1 becomes discontinuous in a switching period. Different modes for operation of CCM and DCM are discussed as follows.

3.2.1 CCM Operation

The operation of Cuk converter in CCM is described as follows. Figs.4. 2(a) and (b) show the operation of Cuk converter in two different intervals of a switching period and Fig.4.2(c) shows the associated waveforms in a complete switching period.

Interval I: When switch Sw in turned on inductor Li stores energy while capacitor C1 discharges and transfers its energy to DC link capacitor Cd as shown in Fig.4.2(a). Input inductor current i_{Li} increases while the voltage across the intermediate capacitor VC1 decreases as shown in Fig4.2(c).

Interval II: When switch Sw is 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 Fig4.2(b).

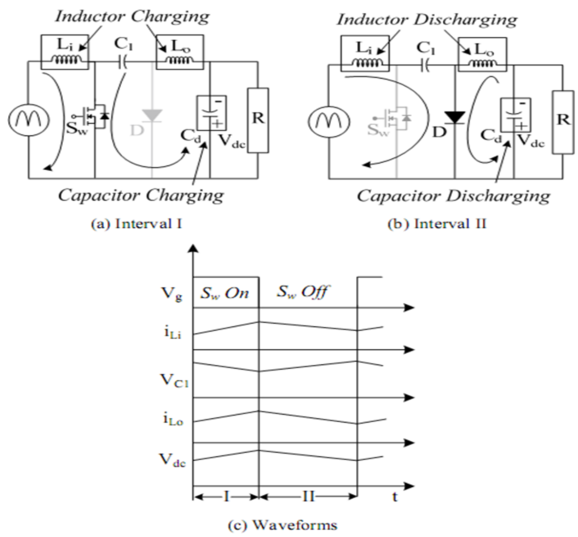


Figure 3.2: Operation of Cuk converter in CCM during different intervals of switching period(a)Sw On and (b)Sw Off (c) the associated waveforms

3.2.2.DICM (Li) Operation

The operation of Cuk converter in DICM (Li) is described as follows. Figs.3.3(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig. 3.3 (d) shows the associated waveforms in a switching period.

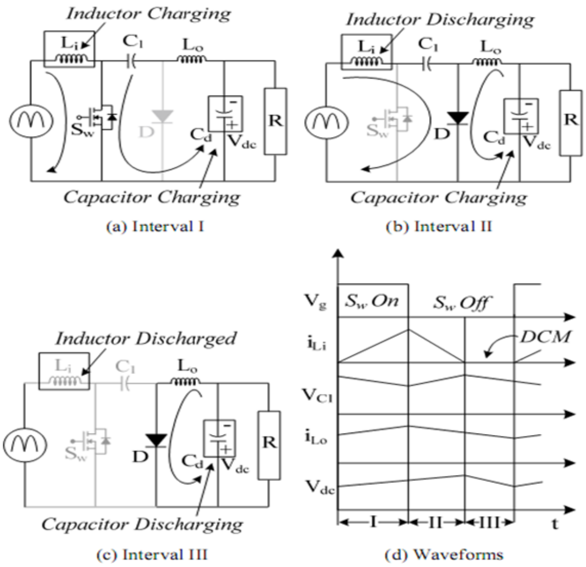


Figure 3.3: Operation of Cuk converter in DICM (Li) during (a-c) different intervals of switching period and (d) the associated waveforms

Interval I: When switch Sw in turned on, inductor Li stores energy while capacitor C1 discharges through Switch Sw to transfer its energy to the DC link capacitor Cd as shown in Fig.3.3 (a). Input inductor current i_{Li} increases while the voltage across the capacitor C1 decreases as shown in Fig. 3.3(d).

Interval II: When switch Sw is turned off, then the energy stored in inductor Li is transferred to intermediate capacitor C1via 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_{Li} becomes zero. Moreover, inductor Lo operates in continuous conduction to transfer its energy to DC link capacitor C_d.

3.2.3. DICM (Lo) Operation

The operation of Cuk converter in DICM (Lo) is described as follows. Figs.3.4(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.3.4(d) shows the associated waveforms in a switching period.

Interval I: As shown in Fig3.4(a), when switch Sw in turned on, inductor Li stores energy while capacitor C1 discharges 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 C1 and DC link capacitor Cd respectively.

Interval III: In this mode of operation, the output inductor Lois completely discharged hence its current i_{Lo} becomes zero. An inductor Li operates in continuous conduction to transfer its energy to the intermediate capacitor C1 via diode D.

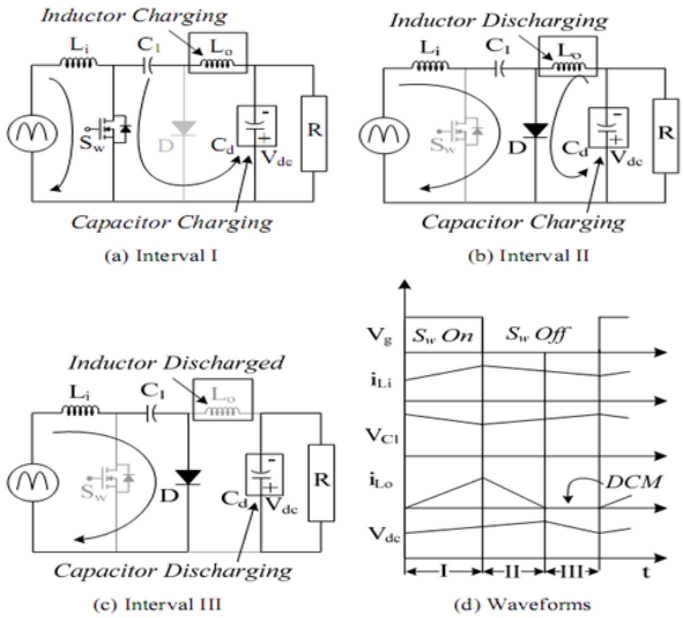


Figure 3.4: Operation of Cuk converter in DICM (Lo) during (a-c) different intervals of switching period and (d) the associated waveforms

3.2.4. DCVM (C1) Operation

The operation of Cuk converter in DCVM (C1) is described as follows. Figs.3.5(a)-(c) show the operation of Cuk converter in three different intervals of a switching period and Fig.3.5 (d) shows the associated waveforms in a switching period.

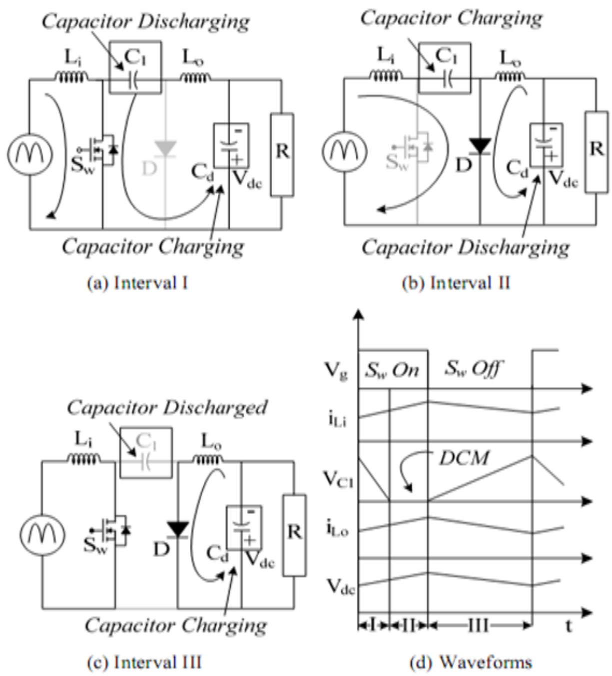


Figure 3.5: Operation of Cuk converter in DCVM (C1) during (a-c) different intervals of switching period and (d) the associated waveforms

Interval I: When switch Sw in turned on as shown in Fig.3.5(a), inductor Li stores energy while capacitor C1 discharges through switch Sw to transfer its energy to the DC link capacitor Cd as shown in Fig3.5(d).

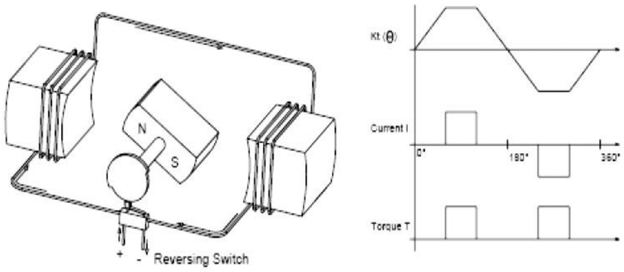
Interval II: The switch is in conduction state but intermediate capacitor C1 is completely discharged, hence the voltage across it becomes zero. Output inductor Lo continues to supply energy to the DC link capacitor.

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

4. Brushless DC Motor

4.1. Principle

BLDC motors are basically inside-out DC motors. In a DC motor the stator is a permanent magnet. The rotor has the windings, which are excited with a current. The current in the rotor is reversed to create a rotating or moving electric field by means of a split commutator and brushes. On the other hand, in a BLDC motor the windings are on the stator and the rotor is a permanent magnet. Hence the term inside-out DC motor. Many motor types can be considered brushless; including stepper and AC-induction motors, but the term "brushless" is given to a group of motors that act similarly to DC brush type motors without the limitations of a physical commutator.



(a) (b)

Figure 4.1: Basic operation of BLDC motor and Waveform of current and torque of basic BLDC motor

This orientation follows the same basic principle of rotary motors; the torque produced by the rotor varies trapezoidal with respect to the angle of the field. As the angle θ increases, the torque drops to an unusable level. Because of this, the reversible switch could have three states: positive current flow, negative current flow, and open circuit. In this configuration, the torque based on rotary position will vary as the current is switched.

5. Fuzzy Logic

5.1 Fuzzy Logic Controller

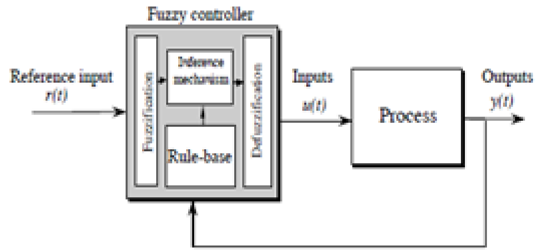


Figure 4.1: Fuzzy controller

Fuzzy logic uses

FL offers several unique features that make it a particularly good choice for many control problems.

1) It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.
2) Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
3) FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.
4) Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated.
5) FL can control nonlinear systems that would be difficult or impossible to model mathematically.

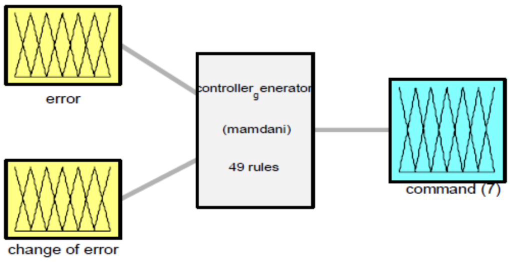
Adaptive PID Fuzzy controller

Controllers based on fuzzy logic give the linguistic strategies control conversion from expert knowledge in automatic control strategies. The development of the control system based on fuzzy logic involves the following steps.

- Fuzzification strategy;
- Data base building;
- Rule base elaboration;
- Inference machine elaboration;
- Deffuzification stratergy.

Fuzzy sets are defined for each input and output variable .There are seven fuzzy level are (LN-Large negative, MN-Medium negative, SN-Small negative, Z-Zero, SP-Small positive, MP-Medium positive, LP-Large positive).Each of 49 control rules represents the desired controller response to a particular situation. The following table represent the control outputs.

de/e	LN	MN	SN	Z	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	MP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	MP	SP	Z	SN	SN	MN	LN
MP	SP	Z	SN	MN	MN	MN	LN
LP	Z	SN	MN	MN	LN	LN	LN



System controller generator: 2 inputs, 1 outputs, 49 rules

5.2 FLC controller in the matlab Simulation

The inputs of PID-like FLC are defined as the voltage error and the change of error. The fuzzy controller ran with the input and output normalized universe [-1,1].The fig shows the FLC controller using Matlab simulation .

6. Simulation Results

6.1 General

Simulation has become a very powerful tool on the industry application as well as in academics, nowadays. It is now essential for an electrical engineer to understand the concept of simulation and learn its use in various applications. Simulation is one of the best ways to study the system or circuit behavior without damaging it .The tools for doing the simulation in various fields are available in the market for engineering professionals. Many industries are spending a considerable amount of time and money in doing simulation before manufacturing their product. Without simulation it is quiet impossible to proceed further. It should be noted that in power electronics, computer simulation and a proof of concept hardware prototype in the laboratory are complimentary to each other. However computer simulation must not be considered as a substitute for hardware prototype. The objective of this chapter is to describe simulation of impedance source inverter with R, R-L and RLE loads using MATLAB tool.

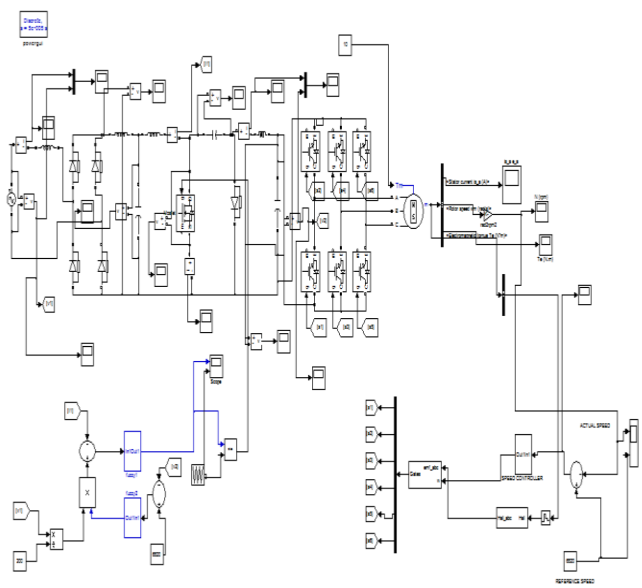


Figure 6.1: Simulation Diagram

i)Input curent and voltage

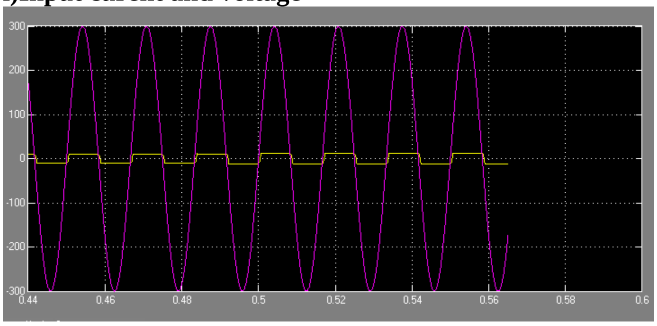


Figure 6.2: (a) Input current and voltage waveform

ii) Dc input voltage waveform

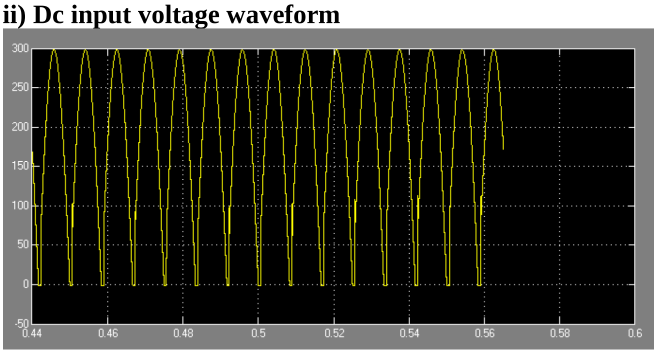


Figure 6.3: (b) Dc input voltage waveform

iii)Crest factor (cf) waveform

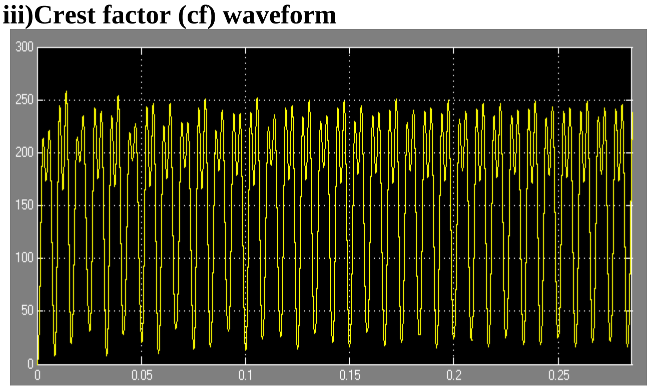


Figure 6.4: (a) output waveform of crest factor

iv) Switch voltage (Vsw) waveform

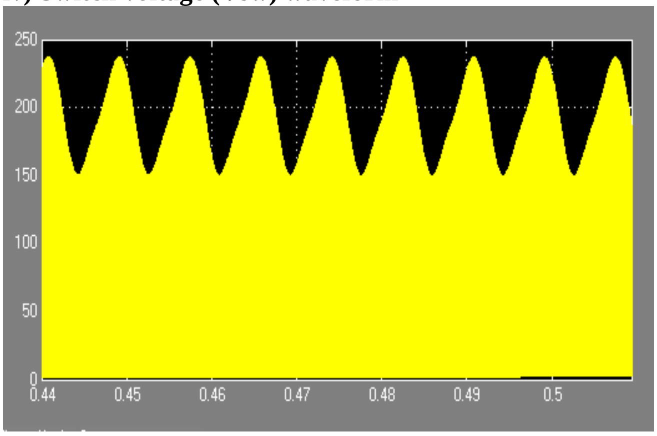


Figure 6.4: (b) output waveform for switch voltage

v)Output waveform for intermediate Capacitor c1

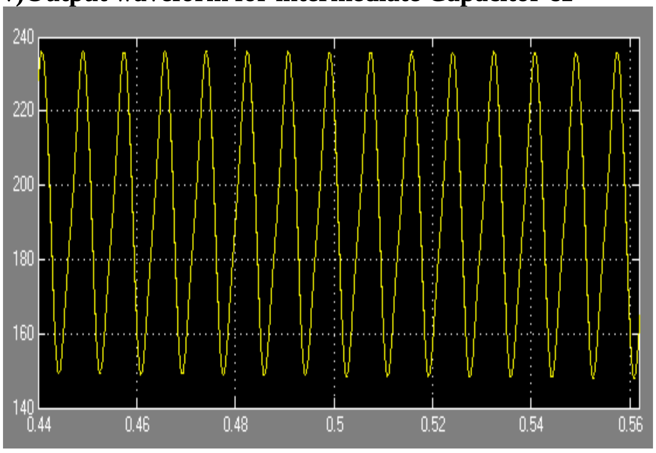


Figure 6.5: (a) Output waveform for intermediate capacitor

vi) Switch current (Isw) waveform

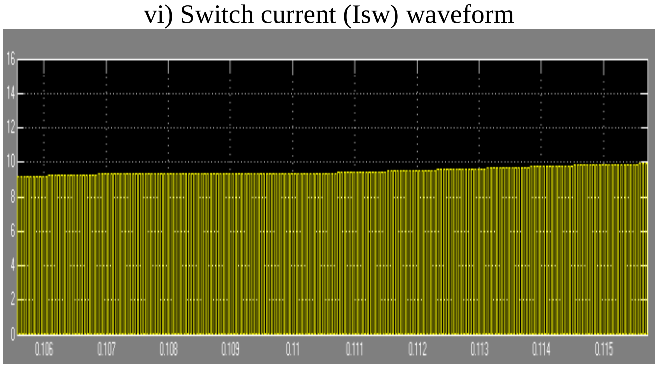
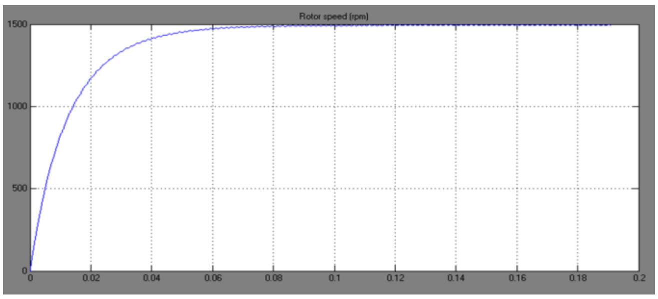


Figure 6.5: (b) Output waveform for switch current



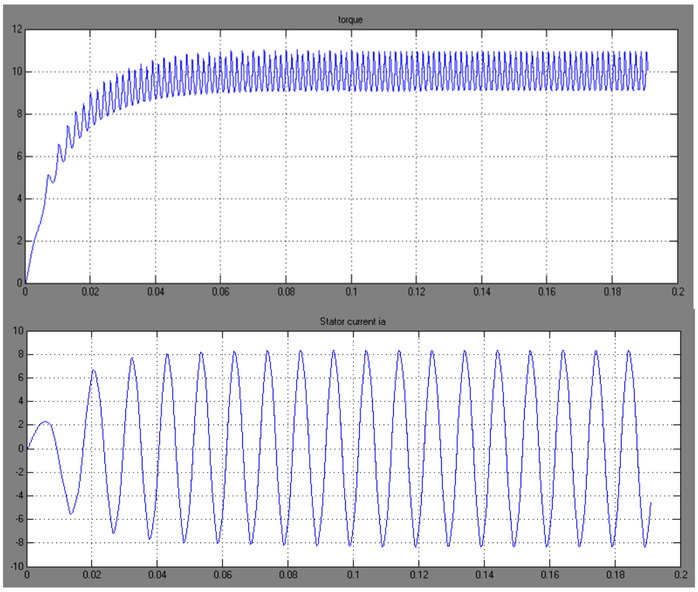


Figure 6.6: Variation of rotor speed, torque and stator current

7. 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 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. 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. Finally, a best suited mode of Cuk converter with output inductor current operating in DICM has been selected for experimental verifications. The proposed drive system has shown satisfactory results in all aspects and is a recommended solution for low power BLDC motor drives.

References

[1] C. L. Xia, Permanent Magnet Brushless DC Motor Drives and Controls,Wiley Press, Beijing, 2012.

[2] Y. Chen, Y, C. Chiu, C, Y. Jhang, Z. Tang and R. Liang, “A Driver for the Single-Phase Brushless DC Fan Motor with Hybrid Winding Structure,” *IEEE Trans. Ind. Electron.*, Early Access, 2012.

[3] X. Huang, A. Goodman, C. Gerada, Y. Fang and Q. Lu, “A SingleSided Matrix Converter Drive for a Brushless DC Motor in AerospaceApplications,” *IEEE Trans. Ind. Electron.*, vol.59, no.9, pp.3542-3552,Sept. 2012.

[4] W. Cui, Y. Gong and M. H. Xu, “A Permanent Magnet Brushless DC Motor With Bifilar Winding for Automotive Engine Cooling Application,” *IEEE Trans. Magnetics*, vol.48, no.11, pp.3348-3351,Nov. 2012.

[5] N. Milivojevic, M. Krishnamurthy, A. Emadi and I. Stamenkovic, “Theory and Implementation of a Simple Digital Control Strategy for Brushless DC Generators,"

IEEE Trans. Power Electron., vol.26, no.11,pp.3345-3356, Nov. 2011

[6] T. J. Sokira and W. Jaffe, Brushless DC Motors: Electronic Commutation and Control, Tab Books, USA, 1989.

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

[8] N. Mohan, T. M. Undeland and W. P. Robbins, *Power Electronics: Converters, Applications and Design*, John Wiley and Sons Inc, USA,2009.

[9] B. Singh, S. Singh, A. Chandra and K. Al-Haddad, "Comprehensive Study of Single-Phase AC-DC Power Factor Corrected Converters With High-Frequency Isolation," *IEEE Trans. on Industrial Informatics*,vol.7, no.4, pp.540-556, Nov. 2011.

[10] T. Y. Ho, M. S. Chen, L. H. Yang and W. L. Lin, "The Design of a High Power Factor Brushless DC Motor Drive," *2012 Int. Symposium on Computer, Consumer and Control (IS3C)*, pp.345-348, 4-6 June 2012.

[11] T. Gopalarathnam and H. A. Toliyat, "A new topology for unipolar brushless DC motor drive with high power factor," *IEEE Trans. Power Elect.*, vol.18, no.6, pp. 1397-1404, Nov. 2003.

[12] V. Bist and B. Singh, "An Adjustable Speed PFC Bridgeless Buck-Boost Converter Fed BLDC Motor Drive", *IEEE Trans. Ind. Electron.*, vol.61,no.6, pp.2665-2677, June 2014.

[13] B. Singh and V. Bist, "An Improved Power Quality Bridgeless Cuk Converter Fed BLDC Motor Drive for Air Conditioning System", *IET Power Electron.*, vol. 6, no. 5, p. 902–913, 2013.

[14] A. Ionovici, "A new computer-aided approach to the analysis of Cuk converter by using the alternator equations," *IEEE Trans. Power Electron.*, vol.4, no.3, pp.319-330, Jul 1989.