International Journal of Science Engineering and Advance Technology, IJSEAT, Vol. 3, Issue 12 | ISSN 2321-6905 December-2015

IJSEAT International Journal of Science Engineering and Advance Technology

A DCM Based PFC CUK Converter-Speed Adjustable BLDC Drive

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***Abstract*—**This paper proposes a DCM based PFC cuk converter-speed adjustable BLDC drive. This system has major advantages like: it is a money-making solution for low-power applications and it operates in discontinuous conduction mode also. The speed of the BLDC motor is controlled by dc-bus voltage of a voltage source inverter (VSI). VSI uses a low switching frequency to reduce the switching losses. A diode bridge rectifier followed by a Cuk converter functioning in a discontinuous conduction mode (DCM) is used for control of dc-link voltage. And also it will keep unity power factor at ac mains. Performance of the PFC Cuk converter is evaluated under four different operating conditions of discontinuous and continuous conduction modes (CCM). The performance of the proposed system is simulated in MATLAB/Simulink environment to validate its performance over a wide range of speed with unity power factor at ac mains.

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

I. INTRODUCTION

BLDC motors are recommended for many low- and medium-power drives applications because of their high efficiency, high flux density per unit volume, lowmaintenance requirement, low electromagnetic interference (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, motion control and robotics, renewable energy applications 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.

There is a requirement of an improved power quality (PQ) as per the international PQ standard IEC 61000-3-2 which recommends a high power factor (PF) and low total harmonic distortion (THD) of ac mains current for Class-A applications (<600 W, <16 A) 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 nonsinusoidal current, from ac mains which is rich in harmonics such that the THD of supply current is as high as 65%, which results in PF as low as 0.8. These types of PQ indices cannot 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 PF at ac mains.

These converters have gained attention due to single-stage requirement for dc-link voltage control with unity PF at ac mains. It also has low component count as compared to a multistage converter and therefore offers reduced losses. Conventional schemes of PFC converter-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 $\propto f2S$). Ozturk *et al.* 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 *et al.* have proposed an active power factor correction scheme which uses a PWM switching of VSI and hence has high switching losses.Wu *et al.* 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 double switch and reduces the efficiency of the overall system. Gopalarathnam *et al.* have proposed a single-ended primary inductance converter (SEPIC) as a front-end converter for PFC with a dc-link voltage control approach, but utilizes a PWM switching of VSI which has high switching losses. Bridgeless configurations of PFC buck–boost, Cuk, SEPIC, and Zeta converters have been proposed in [22]–[25], respectively.

These configurations offer reduced losses in the front-end converter but at the cost of high number of passive and active components. Selection of operating mode of the front-end converter is a tradeoff 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 [16], [17].Avoltage follower approach is one of the control techniques which is used for a PFC converter operating in the DCM. This voltage follower technique requires a single voltage sensor for controlling the dc-link voltage with a unity PF. 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. Depending on design parameters, either approach may force the converter to operate in the DCM or CCM. In this study, a BLDC motor drive fed by a PFC Cuk converter operating in four modes/control combinations is investigated for operation over a wide speed range with unity PF at ac mains. These include a CCM with current multiplier control, and three DCM techniques with voltage follower control.

II. 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. A high frequency MOSFET is used in the Cuk converter for PFC and voltage control, whereas insulated-gate bipolar transistors (IGBTs) are used in the VSI for its low frequency operation. The BLDC motor is commutated electronically to operate the IGBTs of VSI in fundamental frequency switching mode to reduce its switching losses. The PFC Cuk converter operating in the CCM using a current multiplier approach is shown in Fig. 1; i.e., the current flowing in the input and output inductors (*Li* and *Lo*), and the voltage across the intermediate capacitor (*C*1) remain continuous in a switching period, whereas Fig. 2 shows a Cuk converter-fed BLDC motor drive operating in the 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 (*C*1) becomes discontinuous in a switching period for a PFC Cuk converter operating in the DCM. A Cuk converter is planned to operate in all three DCMs and a CCM of operation and its performance is evaluated for a wide voltage control with unity PF at ac mains.

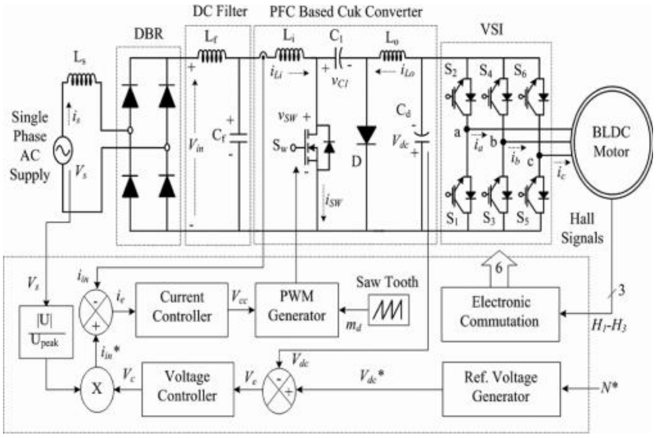


Fig. 1 BLDC motor drive fed by a PFC Cuk converter using a current multiplier approach

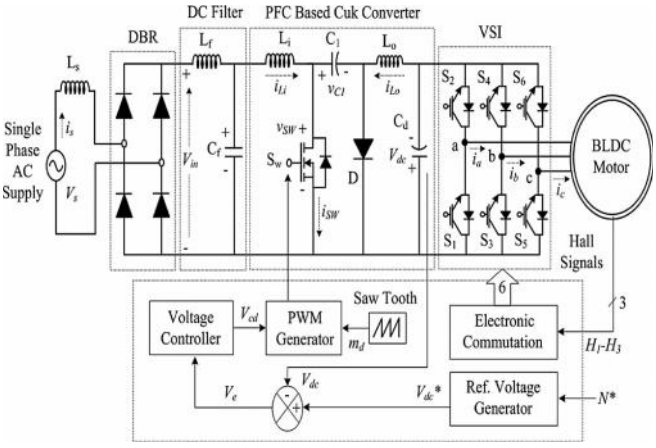


Fig. 2 BLDC motor drive fed by a PFC Cuk converter using a voltage follower approach

III. OPERATION OF THE CUK CONVERTER

The operation of the 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 *C*1 remain continuous in a switching period. Moreover, the DCM operation is further classified into two broad categories of a discontinuous inductor current mode (DICM) and a discontinuous capacitor voltage mode (DCVM). In the 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 *C*1 becomes discontinuous in a switching period. Different modes for operation of the CCM and DCM are discussed as follows.

A. CCM Operation

The operation of the Cuk converter in the CCM is described as follows. Fig. 3(a) and (b) shows the operation of the 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 *Sw* in turned ON, inductor *Li* stores energy while capacitor *C*1 discharges and transfers its energy to dc-link capacitor *Cd* as shown in Fig. 3(a). Input inductor current *iLi* increases while the voltage across the intermediate capacitor *VC*1 decreases as shown in Fig. 3(c).

Interval II: When switch *Sw* is turned OFF, the energy stored in inductor *Lo* is transferred to dc-link capacitor *Cd,* and inductor *Li* transfers its stored energy to the intermediate capacitor *C*1 as shown in Fig. 3(b). The calculated values of *Li, Lo,* and *C*1 are large enough such that a finite amount of energy is always stored in these mechanism in a switching period.

B. DICM (Li) Operation

The operation of the Cuk converter in the DICM (*Li*) is described as follows. Fig. 4(a)–(c) shows the operation of the 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 *Sw* in turned ON, inductor *Li* stores energy while capacitor *C*1 discharges through Switch *Sw* to transfer its energy to the dc-link capacitor *Cd* as shown in Fig. 4(a). Input inductor current *iLi* increases while the voltage across the capacitor *C*1 decreases as shown in Fig. 4(d).

Interval II: When switch *Sw* is turned OFF, the energy stored in inductor *Li* is transferred to intermediary capacitor *C*1 via diode D, till it is completely discharged to enter DCM operation.

Interval III: During this interval, no energy is left in input inductor *Li;* hence, current *iLi* becomes zero. Moreover, inductor *Lo* operates in continuous conduction to convey its energy to dc-link capacitor *Cd.*

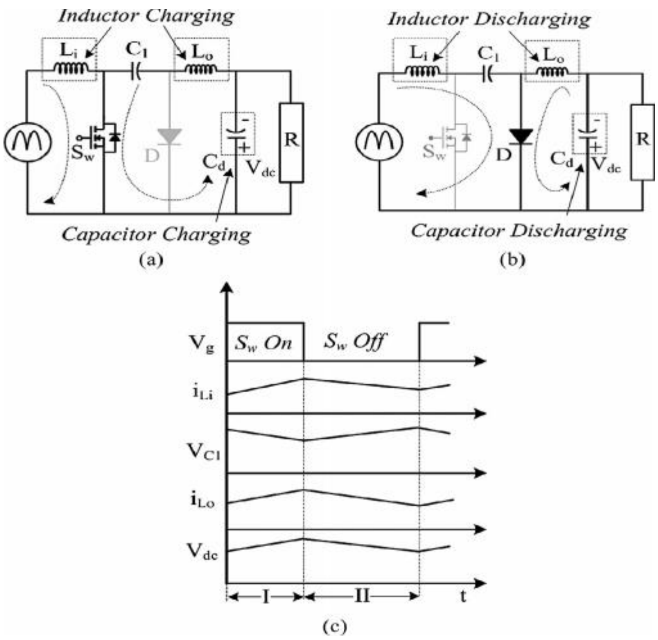


Fig. 3 Operation of the Cuk converter in the CCM during (a, b) different intervals of switching period and (c) associated waveforms (a) Interval I (b) Interval II (c) Waveforms

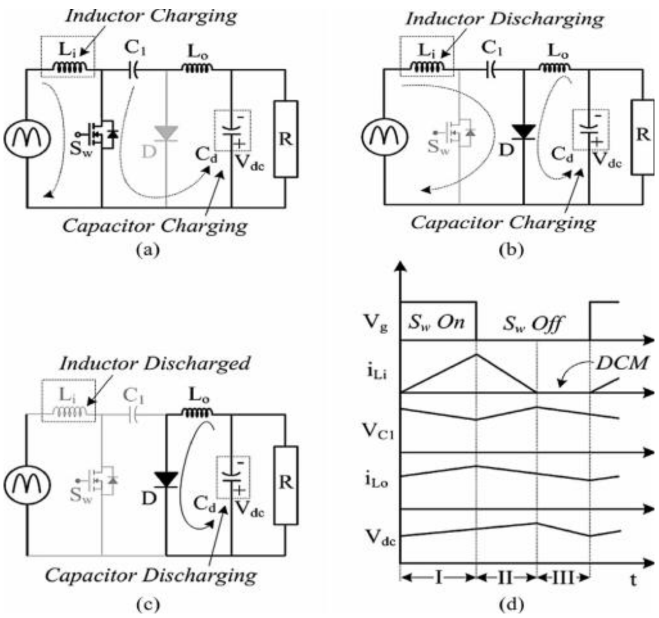


Fig. 4 Operation of the Cuk converter in the DICM (*Li)* during (a)–(c) different intervals of switching period and (d) associated waveforms (a) Interval I (b) Interval II (c) Interval III (d) Waveforms

C. DICM (Lo) Operation

The operation of the Cuk converter in the DICM (*Lo)* is described as follows. Fig. 5(a)–(c) shows the operation of the 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 *Sw* in turned ON, inductor *Li* stores energy while capacitor *C*1 discharges through switch *Sw* to transfer its energy to the dc-link capacitor *Cd*.

Interval II: When switch *Sw* is turned OFF, the energy stored in inductor *Li* and *Lo* is transferred to intermediate capacitor *C*1 and dc-link capacitor *Cd* , respectively.

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

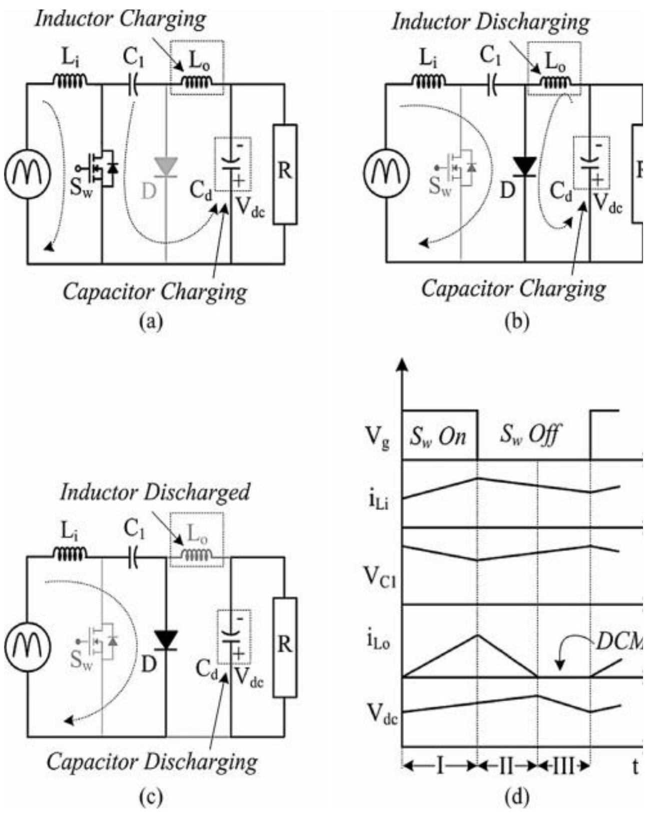


Fig. 5 Operation of the Cuk converter in DICM (*Lo*) during (a)–(c) different intervals of switching period and (d) associated waveforms (a) Interval I (b) Interval II (c) Interval III (d) Waveforms

D. DCVM (C1) Operation

The operation of the Cuk converter in the DCVM (*C*1) is described as follows. Fig. 6(a)–(c) shows the operation of the 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 *Sw* in turned ON as shown in Fig. 6(a), inductor *Li* stores energy while capacitor *C*1 discharges 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 *C*1 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.

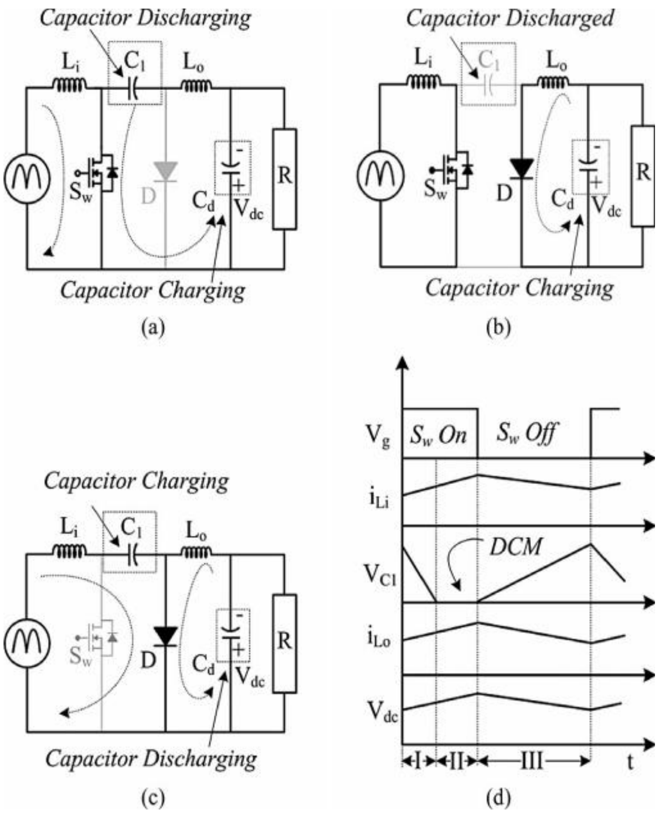


Fig. 6 Operation of the Cuk converter in the DCVM (*C*1) during (a)–(c) different intervals of switching period and (d) associated waveforms (a) Interval I (b) Interval II (c) Interval III (d) Waveforms

IV. SIMULATED PERFORMANCE OF THE PROPOSED BLDC MOTOR DRIVE

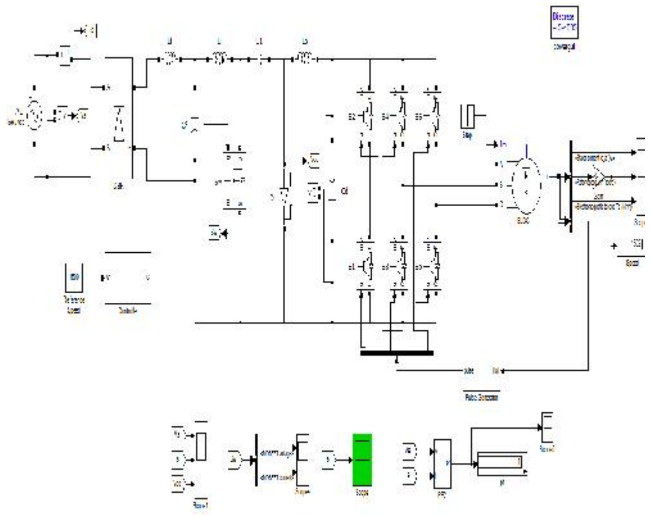
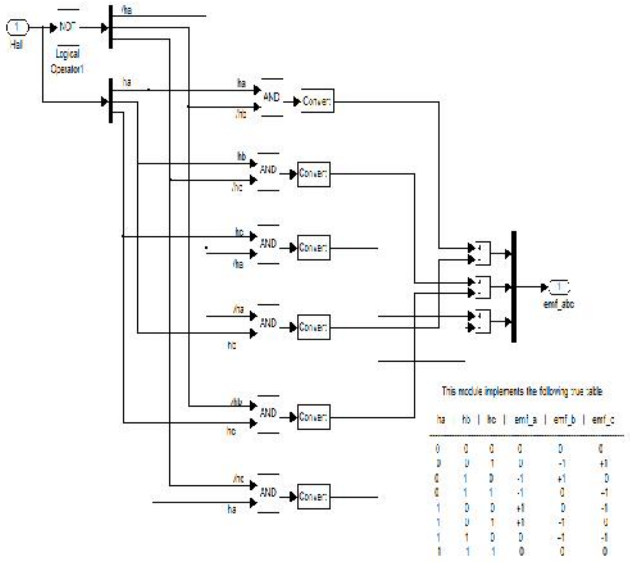


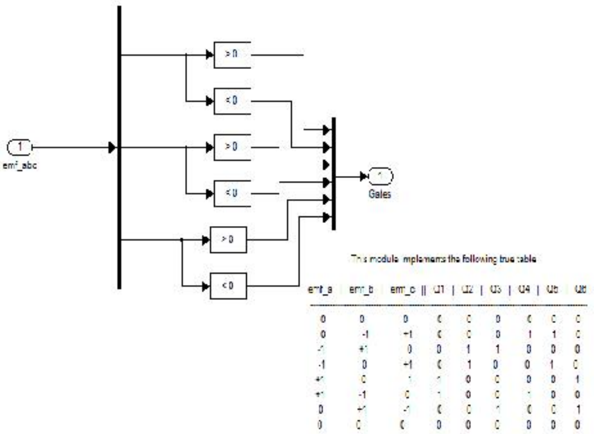
Fig 7 simulation diagram of proposed system



This module implements the following true table

ha	hb	hc	emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	-1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	-1	-1
1	1	1	0	0	0

Fig 8 simulation diagram of hall signals to generate emf signals



This module implements the following true table

emf_a	emf_b	emf_c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

Fig 9 simulation diagram of emf signals to generate pulse signals

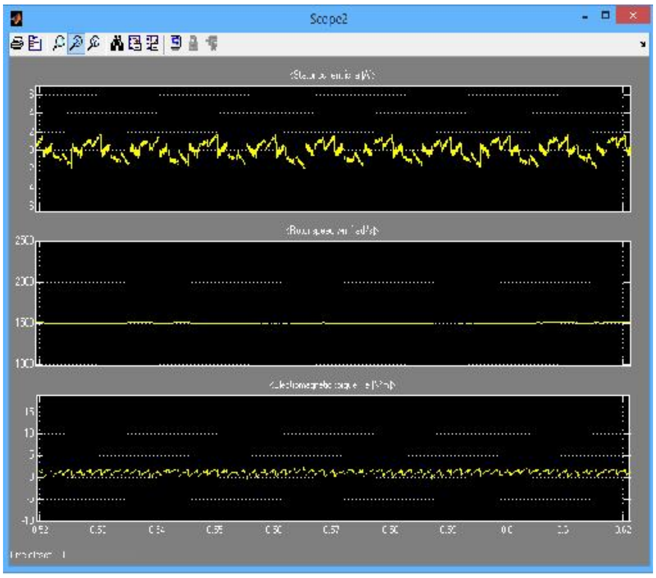


Fig 10 simulation results of stator current, rotor speed and electromagnetic torque

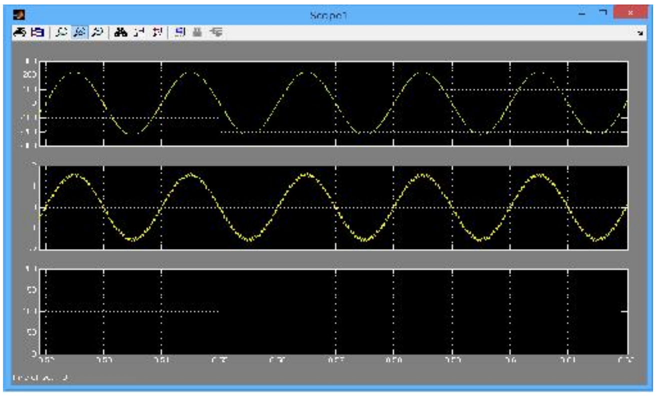
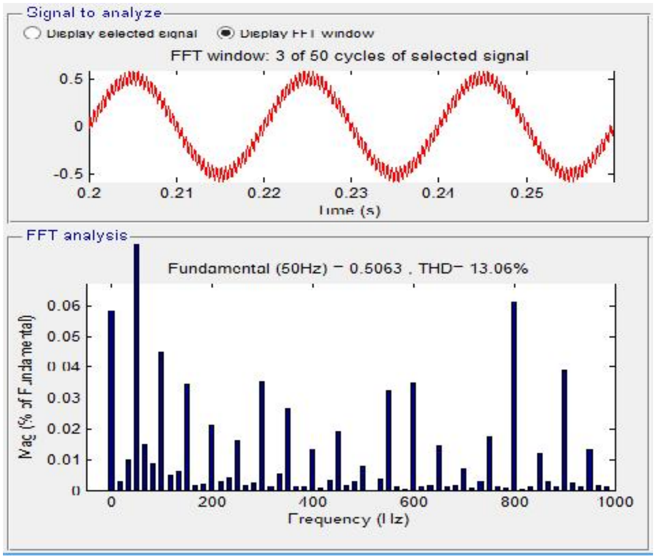


Fig 11 simulation results of voltage, current and Vdc


Signal to analyze

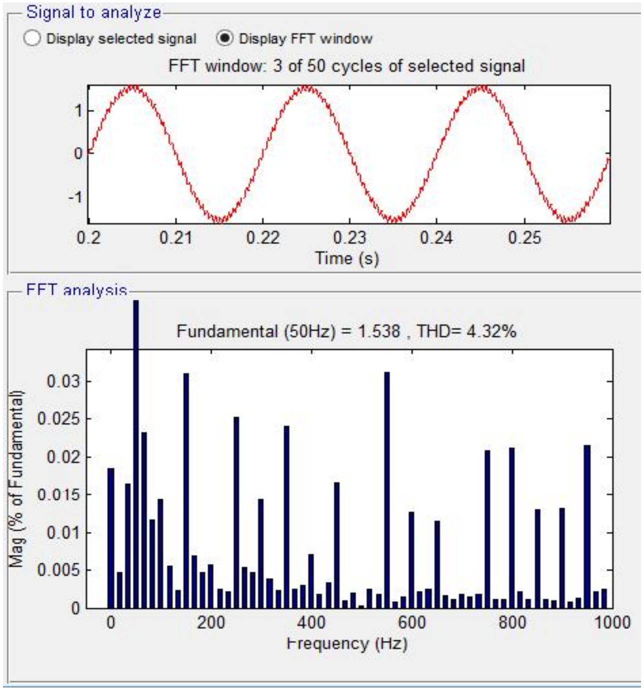
○ Display selected signal ● Display FFT window

FFT window: 3 of 50 cycles of selected signal

FFT analysis

Fundamental (50Hz) = 0.5063 , THD= 13.06%

Fig 12. % THD for 500 rpm



○ Display selected signal ● Display FFT window

FFT window: 3 of 50 cycles of selected signal

Fundamental (50Hz) = 1.538 , THD= 4.32%

Fig 13. % THD for 1500 rpm

CONCLUSION

A DCM based PFC cuk converter-speed adjustable BLDC drive has been designed for achieving a unity PF at ac mains for the development of the 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 the fundamental frequency switching mode for reduced switching losses. Four different modes of the Cuk converter operating in the CCM and DCM have been explored for the development of the BLDC motor drive with unity PF 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 the Cuk converter with output inductor current operating in the 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.

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