International Journal of Current Research and Modern Education (IJCRME)
ISSN (Online): 2455 – 5428 & Impact Factor: 3.165
Special Issue, NCFTCCPS - 2016

POWER FACTOR CORRECTION IN BLDC MOTOR BASED ON CUK CONVERTER USING SPWM TECHNIQUE

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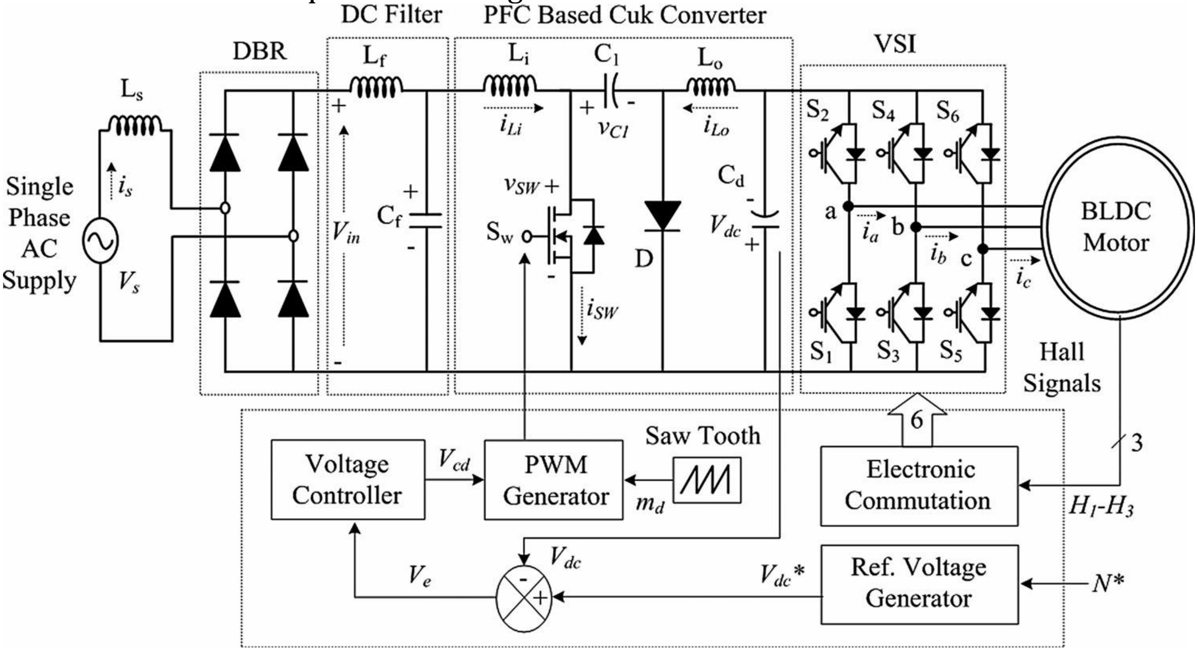
Abstract:

This paper presents a PFC (Power Factor Corrected) based cuk converter fed BLDC (Brushless Direct Current) motor drive as a cost effective solution for low power applications. An approach of speed control of BLDC motor by controlling the DC link voltage of VSI (Voltage Source Inverter) is used with a single voltage sensor. This facilitates the operation of VSI at fundamental frequency switching by using the electronic commutation of BLDC motor which offers reduced switching losses. The proposed drive utilises a Cuk converter operating in discontinuous inductor current mode (DICM) for the power factor correction (PFC) and improved power quality (PQ) at the AC mains for a wide range of speed control.The SPWM technique is gives input pulses to the switches in converter and inverter. The performance of proposed drive is simulated in MATLAB/Simulink environment and the obtained results are validated experimentally on a developed prototype of the drive.

Introduction:

Brushless dc (BLDC) motors are recommended for many low- and medium-power 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. It does not 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 it has low EMI problems. This motor is also referred as an electronically commutated motorsince an electronic commutation based on the Hall-effectrotor position signals is used rather than a mechanical commutation. 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.

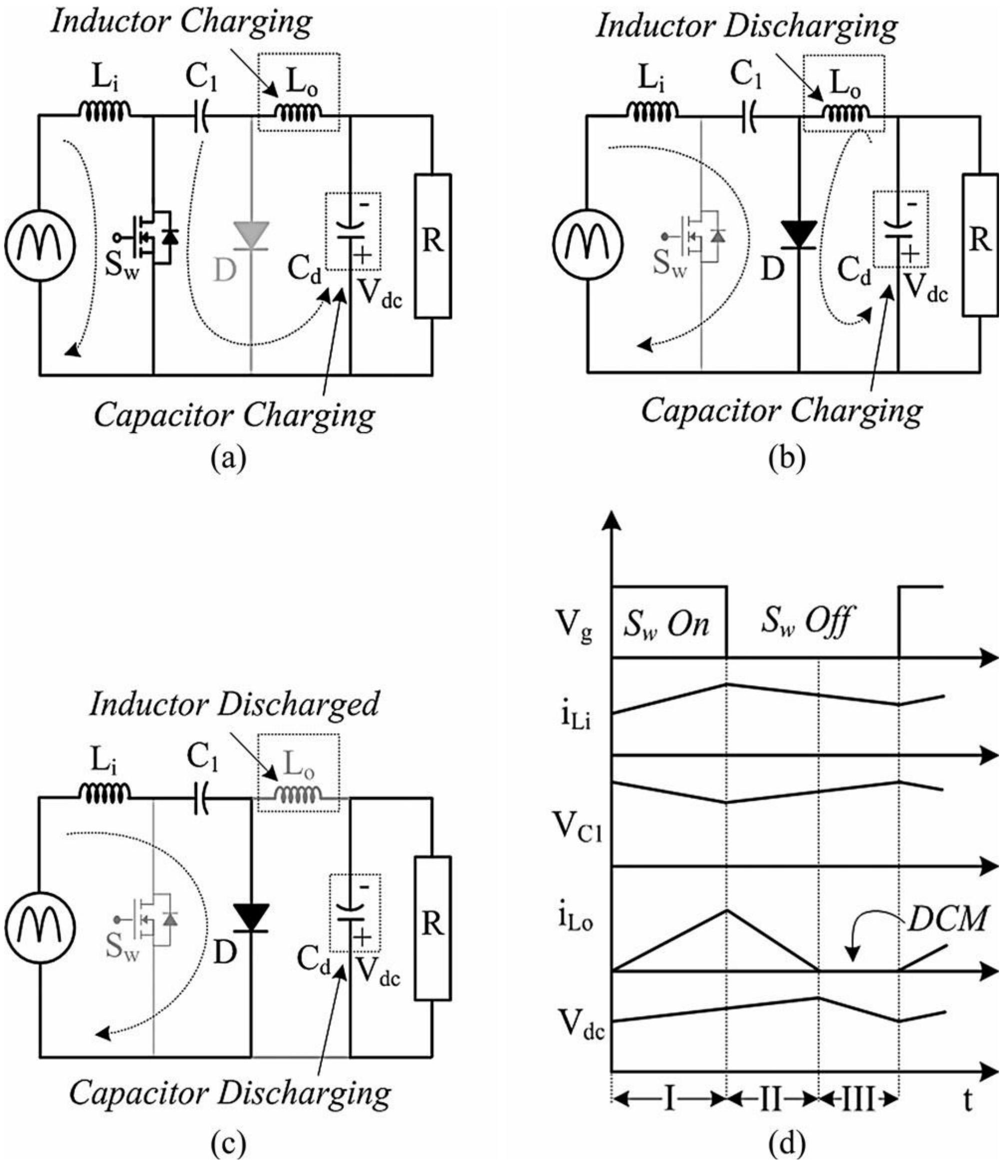
The conventional scheme of a BLDC motor fed by a diode bridge rectifier (DBR) and a high value of dc-link capacitor draws a nonsinusoidal current, from ac mains which is rich in harmonics such that the THD of supply current is as high as 65%, which results in PF as low as 0.8 . Hence, single-phase power factor correction (PFC) converters are used to attain a unity PF at ac mains. These converters have gained attention due tosingle-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 highfrequency 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 (P_{sw} loss $\propto f^2_S$). 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 PWMswitching ofVSI 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, 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 .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.



System Configuration:

Fig show the PFC Cuk converter-based VSI-fed BLDC motor drive using a current multiplier and a voltage follower approach, respectively.Ahigh frequency metal–oxide–semiconductor field-effect transistor (MOSFET) is used in the Cuk converter for PFC and voltage control [26]–[30], whereas insulated-gate bipolar transistors (IGBTs) are used in theVSI 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 [31], [32] for a PFC Cuk converter operating in the DCM. A Cuk converter is designed 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.

Operation of the CUK Converter in DICM Mode:



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:

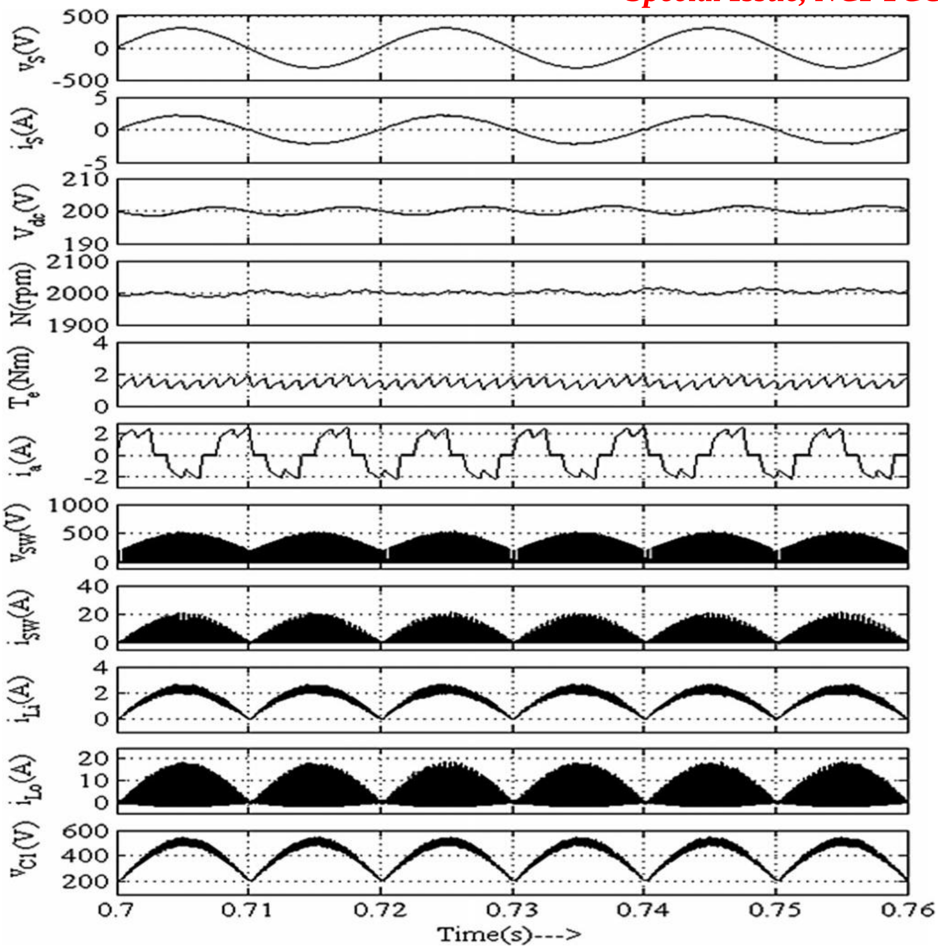
In this mode of operation, the output inductor *Lo* is completely discharged; hence, its current *iLo* becomes zero.An inductor *Li* operates in continuous conduction to transfer itsenergy to the intermediate capacitor *C*1 via diode D.

Performance of the BLDC Motor Fed by a Cuk Converter Operating in the DICM (Lo):

The circuit configuration and control of the PFC Cuk converter operating in the DICM of operation with output inductor (*Lo*) operating in discontinuous conduction are shown in Fig

V_{dc} (V)	Speed (rpm)	THD of I_s (%)	DPF	PF	I_s (A)
40	320	5.89	0.9959	0.9942	0.446
60	530	5.69	0.9965	0.9949	0.581
80	740	4.98	0.9971	0.9959	0.719
100	940	4.52	0.9978	0.9968	0.855
120	1150	4.11	0.9985	0.9977	0.993
140	1360	3.62	0.9992	0.9985	1.128
160	1560	2.85	0.9998	0.9994	1.265
180	1770	2.25	0.9999	0.9996	1.403
200	1980	1.81	0.9999	0.9997	1.537

Fig. 10 shows the performance of the proposed BLDC motor drive fed by a PFC Cuk converter operating in the DICM (*Lo)*. A discontinuous output inductor current *iLo* is obtained while the input inductor current *iLi* and intermediate capacitor's voltage *VC*1 remain in continuous conduction operation. Table shows the performance of the BLDC motor drive fed by a Cuk converter operating in the DICM (*Lo)* over a wide range of dc-link voltage control (i.e., speed control). An improved PQ operation is achieved for the complete range of speed control. The peak voltage and current stress of 560 V and 20.5 A, respectively, is obtained under rated condition in this mode of the DICM (*Lo)* as shown in Table which is quite acceptabl for a power rating of 350 W.

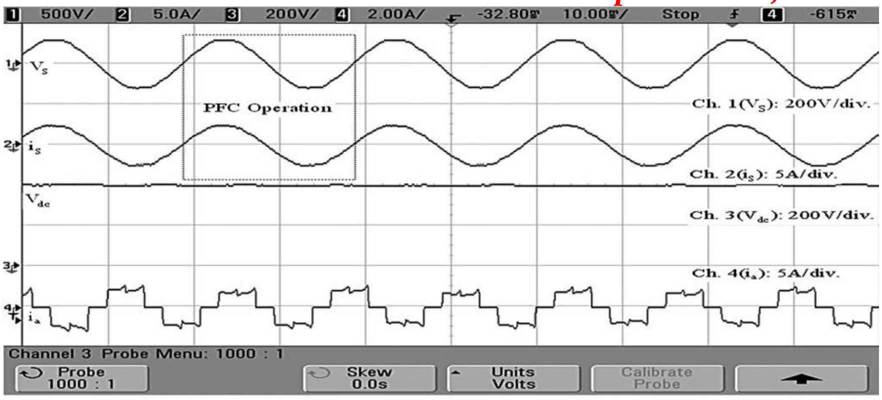


Hardware Validation of the Proposed Drive:

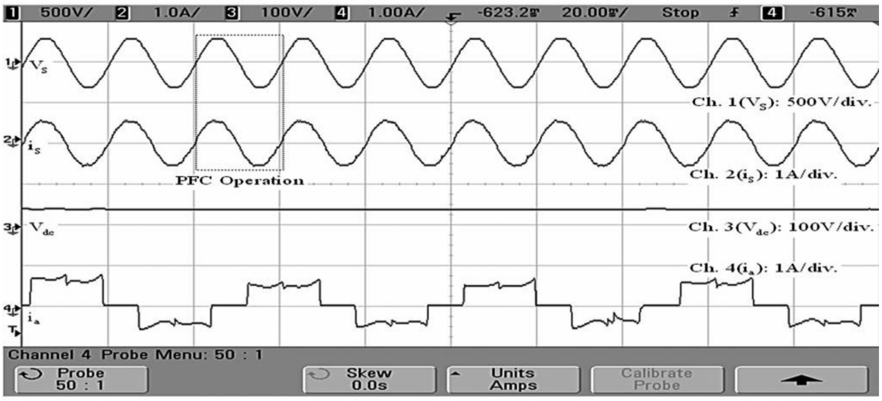
A DSP (TI-TMS320F2812) is used for the development of the proposed BLDC motor drive. Isolation between the DSPbased controller and gate drivers of solid state switches of VSI and PFC converter is provided using an opto-coupler. The prefiltering and isolation circuits for a Hall-effect position sensor are also developed for sensing the rotor position signals. Moreover, software-based moving average filter is also developed for sensing the Hall signals [37]. The performance of the proposeddrive is evaluated for a wide range of speed control with unity PF operation at ac mains.

A. Steady-State Performance of the Proposed Drive:

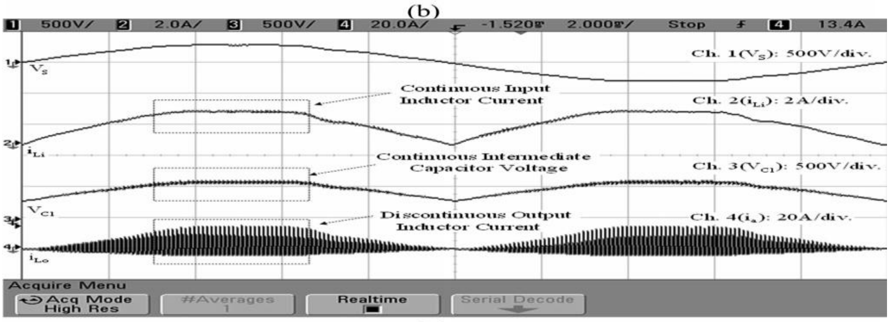
Fig. 14(a) and (b) shows the operation of the proposed BLDC motor drive for a dc-link voltage (*V*dc) of 200 and 50V respectively.The supply current *is* achieved is sinusoidal in nature and is in phase with the supply voltage *vs* demonstrating the unity PF at ac mains. The dc-link voltage *V*dc is maintained at the desired value and the frequency of stator current *ia* of the BLDC motor is used for the determination of speed of the BLDC motor.The frequency of the statorcurrent as shown in Fig. 14(a) and (b) is of the order of 80 and 18 Hz, respectively (electronic commutation of the BLDC motor). This frequency is very low as compared to PWM-based control of VSI for controlling the speed of the BLDC motor drive. Hence, the switching lossesein VSI corresponding to such low frequency are very low ascompared to PWM based switching of VSI. The variation ofspeed and the dc-link voltage with reference voltage at analogto-digital converter (ADC) of DSP is shown in Table X.


PFC Operation
Ch. 1(Vs): 200V/div.
Ch. 2(is): 5A/div.
Ch. 3(Vdc): 200V/div.
Ch. 4(ia): 5A/div.

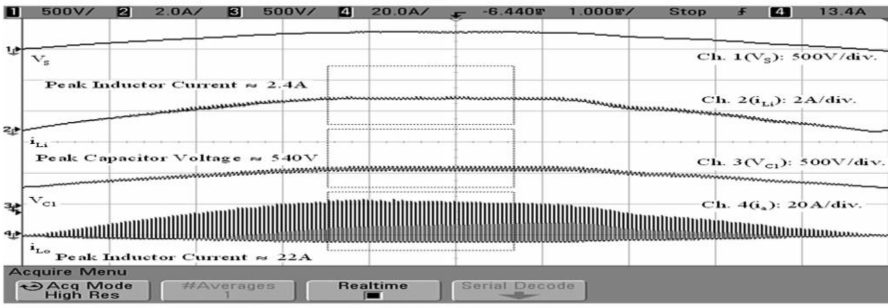
(a)


PFC Operation
Ch. 1(Vs): 500V/div.
Ch. 2(is): 1A/div.
Ch. 3(Vdc): 100V/div.
Ch. 4(ia): 1A/div.

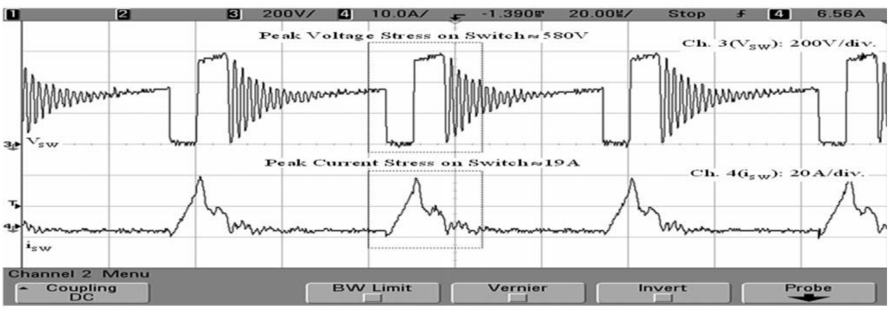
(b)


Continuous Input Inductor Current
Continuous Intermediate Capacitor Voltage
Discontinuous Output Inductor Current
Ch. 1(Vs): 500V/div.
Ch. 2(iLi): 2A/div.
Ch. 3(VC1): 500V/div.
Ch. 4(ia): 20A/div.

(a)


Peak Inductor Current ≈ 2.4A
Peak Capacitor Voltage ≈ 540V
Peak Inductor Current ≈ 22A
Ch. 1(Vs): 500V/div.
Ch. 2(iLi): 2A/div.
Ch. 3(VC1): 500V/div.
Ch. 4(ia): 20A/div.

(b)


Peak Voltage Stress on Switch≈580V
Peak Current Stress on Switch≈19A
Ch. 3(VSW): 200V/div.
Ch. 4(iSW): 20A/div.

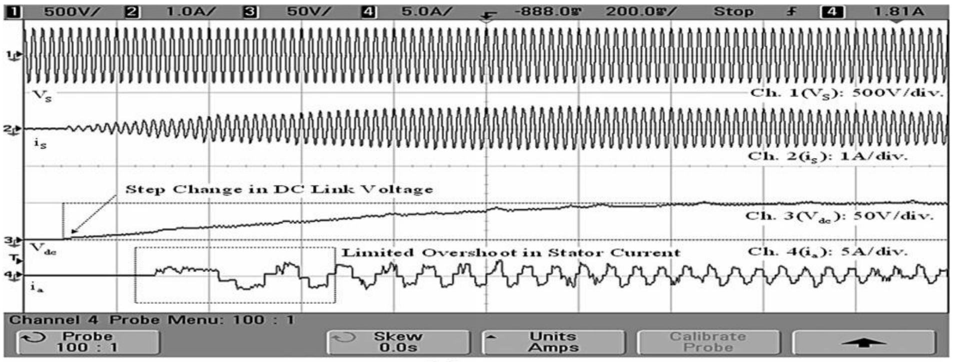
(c)

B. Operation of the Cuk Converter Operating in the DICM (Lo):

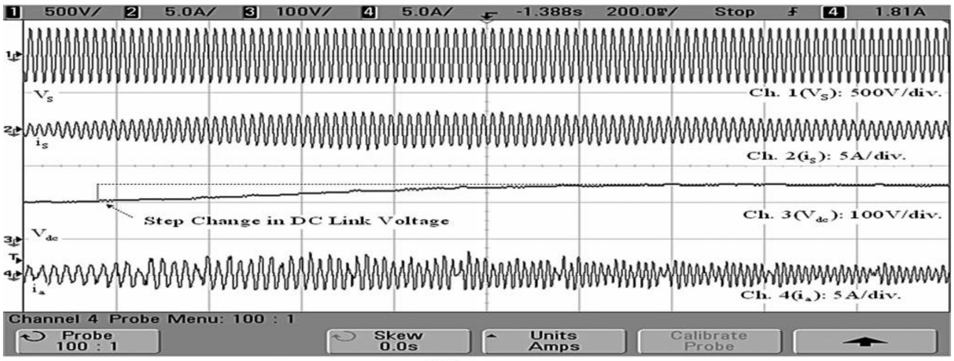
Fig. 15(a) and (b) shows the waveforms of current in input and output inductors (*iLi* and *iLo*) and intermediate capacitor's voltage (*VC*1) to demonstrate the DICM operation of output inductor *Lo* . As shown in these figures, the current in input inductor (*iLi*) and voltage across intermediate capacitor (*VC*1) remain continuous but the current in output inductor becomes discontinuous for a switching period. Fig. 15(c) shows the voltage and current of the PFC converter's switch with peak voltage and current stress of 580 V and 19 A, respectively.

C. Dynamic Performance of the Proposed Drive:

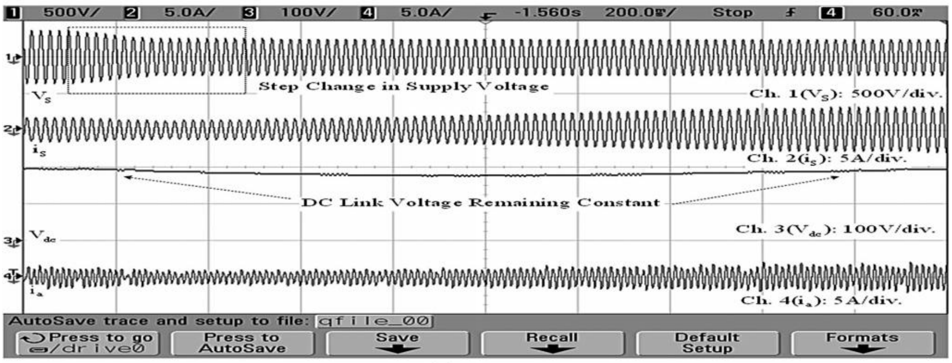
Fig. 16(a) shows the dynamic performance of the proposed BLDC motor drive during starting at dc-link voltage of 50 V. This stator current (*ia)* of the BLDC motor and supply currentwaveforms are recorded to show the limited overshoot under the dynamic conditions. Fig. 16(b) shows the dynamic performance of the proposed BLDC motor drive during speed control which is obtained by step change in dc-link voltage from 100 to 150 V. Moreover, the dynamic performance of the proposed BLDC motor drive during step change in supply voltage from 250 to 180 V is shown in Fig. 16(c). The change in dc-link voltage is obtained with smooth transition and limited overshoot in supply current.



(a)



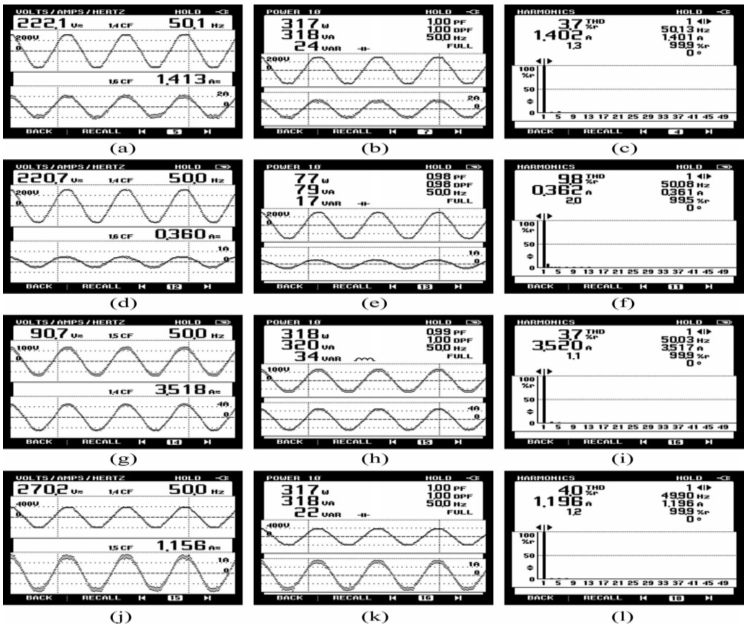
(b)



(c)

D. Unity PF Operation of the Proposed Drive:

Supply voltage v_s , supply current i_s , active P_{ac} , reactive P_r , and apparent P_a powers are measured on a "Fluke" make PQ analyzer to demonstrate the PQ indices such as PF, DPF, andTHD of supply current. Fig. 17(a)–(c) and (d)–(f) shows the results obtained at dc-link voltage of 200 and 50 V, respectively. Moreover, Fig. 17(g)–(i) and (j)–(l) shows the performance at supply voltages of 90 and 270 V, respectively. An improved PQ is obtained in all these conditions and the obtained PQ indices are within the recommended limits of IEC 61000-3-2 [14]. A satisfactory performance of the proposed BLDC motor drive fed by a PFC Cuk converter is achieved and is demonstrated through simulated and experimental results. Thus, the proposed drive is suitable for achieving a unity PF at ac mains over a wide range of speed control at universal ac mains.



Conclusion:

A Cuk converter for VSI-fed BLDC motor 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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