

IMPLEMENT HIGH-EFFICIENCY BIDIRECTIONAL CONVERTER FOR BLDC MOTOR DRIVE CONTROL

1.CHUTLA RAMBABU, 2.M.V. LAKSHMAIAH

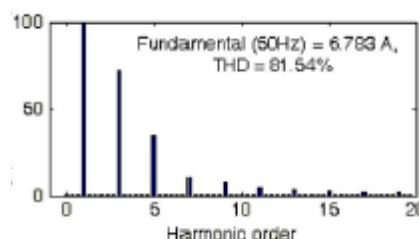
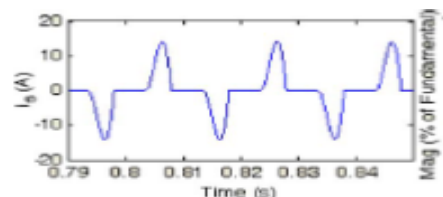
1. M. Tech Student, Dept. Of EEE, ABR College of Engineering and Technology, Kanigiri , A.P

2. Guide, Dept. Of EEE, ABR College of Engineering and Technology, Kanigiri , A.P

ABSTRACT: This paper deals with a Cuk dc-dc converter as a single-stage power-factor-correction converter for a permanentmagnet (PM) brushless dc motor (PMBLDCM) fed through a diode bridge rectifier from a single-phase ac mains. A three-phase voltage-source inverter is used as an electronic commutator to operate the PMBLDCM driving an air-conditioner compressor. The speed of the compressor is controlled to achieve optimum air-conditioning using a concept of the voltage control at dc link proportional to the desired speed of the PMBLDCM. The stator currents of the PMBLDCM during step change in the reference speed are controlled within the specified limits by an addition of a rate limiter in the reference dc link voltage. The proposed PMBLDCM drive (PMBLDCMD) is designed and modeled, and its performance is evaluated in Matlab-Simulink environment. Simulated results are presented to demonstrate an improved power quality at ac mains of the PMBLDCMD system in a wide range of speed and input ac voltage. Test results of a developed controller are also presented to validate the design and model of the drive.

The stored energy in the battery provides maximum power to the BLDC motor, while during regenerative braking operation the energy is fed back to the source by the same bidirectional buck-boost converter. The simulation will be done for Brushless DC motor with fuzzy logic controller using MATLAB/Simulink software

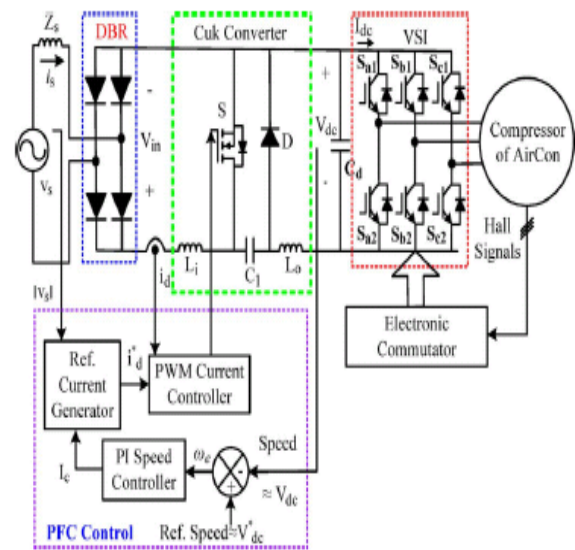
INTRODUCTION: THE use of a permanent-magnet (PM) brushless dc motor (PMBLDCM) in low-power appliances is increasing because of its features of high efficiency, wide speed range, and low maintenance [1]-[4]. It is a rugged three-phase synchronous motor due to the use of PMs on the rotor. The commutation in a PMBLDCM is accomplished by solid state switches of a three-phase voltage-source inverter (VSI). Its application to the compressor of an air-conditioning (Air-Con) system results in an improved efficiency of the system if operated under speed control while maintaining the temperature in the airconditioned zone at the set reference consistently. The Air-Con exerts constant torque (i.e., rated torque) on the PMBLDCM while operated in speed control mode. The Air-Con system with PMBLDCM has low running cost, long life, and reduced mechanical and electrical stresses compared to a single-phase



Current waveform at ac mains and its harmonic spectra for the PMBLDCM drive (PMBLDCMD) without

PFC.

induction motor-based Air-Con system operating in “on/off” control mode. A PMBLDCM has the developed torque proportional to its phase current and its back electromotive force (EMF), which is proportional to the speed. Therefore, a constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDCM under variable speed operation. A speed control scheme is proposed which uses a reference voltage at dc link proportional to the desired speed of the permanent-magnet brushless direct current (PMBLDC) motor. However, the control of VSI is only used for electronic commutation based on the rotor position signals of the PMBLDC motor. The PMBLDCMD is fed from a single-phase ac supply through a diode bridge rectifier (DBR) followed by a capacitor at dc link. It draws a pulsed current as shown in Fig. 1, with a peak higher than the amplitude of the fundamental input current at ac mains due to an uncontrolled charging of the dc link capacitor. This results in poor power quality (PQ) at ac mains in terms of poor power factor (PF) of the order of 0.728, high total harmonic distortion (THD) of ac mains current at the value of 81.54%, and high crest factor (CF) of the order of 2.28. Therefore, a PF correction (PFC) converter among various available converter topologies is almost inevitable for a PMBLDCMD. Moreover, the PQ standards for low power equipments, such as emphasize on low harmonic contents and near unity PF current to be drawn from ac mains by these drives. There are very few publications regarding PFC in PMBLDCMDs despite many PFC topologies for switchedmode power supply and battery charging applications. This paper deals with an application of a PFC converter for the speed control of a PMBLDCMD. For the proposed voltagecontrolled drive, a Cuk dc–dc converter is used as a PFC converter because of its continuous input and output currents, small output filter, and wide output voltage range as compared to other single switch converters. Moreover, apart from PQ improvement at ac mains, it controls the voltage at dc link for the desired speed of the Air-Con. The detailed current at ac mains due to an uncontrolled charging of the dc link capacitor. This results in poor power quality (PQ) at ac mains in terms of poor power factor (PF) of the order of 0.728, high total harmonic distortion (THD) of ac mains current at the value of 81.54%, and high crest factor (CF) of the order of 2.28. Therefore, a PF correction (PFC) converter among various available converter topologies is almost inevitable for a PMBLDCMD. Moreover, the PQ standards for low power equipments, such as emphasize on low harmonic contents and near unity PF current to be drawn from ac mains by these drives.



Control scheme of the proposed Cuk PFC converter-fed VSI-based PMBLDCMD.

modeling, design, and performance evaluation of the proposed drive are presented for an air-conditioner driven by a 0.816-kW 1500-r/min PMBLDC motor. Permanent magnet brushless DC motors (PMBLDCMs) are considered as better option in various low power (less than 5 kW) applications due to their energy efficiency and ease of control [1-3]. The PMBLDCM is a three-phase synchronous motor with permanent magnets (PMs) on the rotor. The commutation in a PMBLDCM is accomplished by solid state switches of a three-phase voltage source inverter (VSI). The combination of VSI and PMBLDCM is referred as PMBLDCM drive [4-10]. The efforts of researchers towards improvement in the performance of traditionally used motors such as induction motors, DC motors and synchronous motors has opened up new application areas of the PMBLDCMD. Moreover, the advancements in power electronics and digital signal processors (DSPs) have added many features to the PMBLDCM drives to make them preferred choice for various industrial installations. The most commonly used topology for PMBLDCMD fed from single-phase AC mains uses a diode bridge rectifier (DBR) followed by a smoothing DC capacitor. It draws an uncontrolled charging current for the DC capacitor resulting in a pulsed current from the AC mains as resulting in various power quality (PQ) disturbances at AC mains such as poor power factor (PF), increased total harmonic distortion (THD) of AC mains current and its high crest factor (CF). The power quality (PQ) disturbances at AC mains of a PMBLDCMD are

represented in terms of various power quality indices such as PF, CF, total harmonic distortion (THDi) of AC mains current, displacement power factor (DPF) and ripples in DC link voltage (@Vdc).

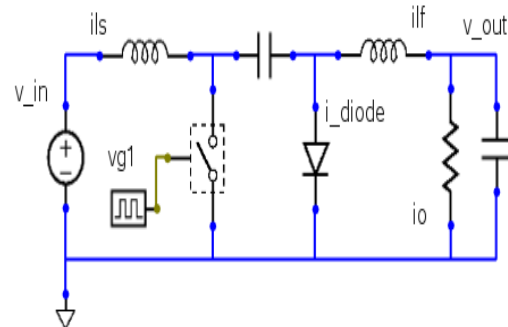
. Current waveform at AC mains and its harmonic spectra for the PMBLDCMD topology shown in Fig. 1 These PQ disturbances result in transformer and neutral conductor heating, heating of motors and cables, EMI, power supply failure (brownout or blackout) and component failure. Reduction of harmonic currents and voltage distortion at AC mains with near unity PF are referred as power factor correction (PFC) and mitigation of PQ disturbances. Various DC-DC converters are operated as PFC converters for variety of applications. The performance of a PFC converter is evaluated on the basis of these PQ indices. For the monitoring and mitigation of these PQ problems in the low power applications, there are international standards such as. These standards emphasize on low harmonic contents and near unity power factor current to be drawn from AC mains by various loads. As reported in the literature, the PFC converter topologies in various commercial applications possess two-stages of DC-DC converters. A boost DC-DC converter is used as a power factor pre-regulator (PFP) at the front-end followed by second stage DC-DC converter for voltage regulation. The second converter is usually a flyback or a forward converter for low power application (less than 1 kW) and a full-bridge converter for higher power applications (1-5kW). However, the high cost and complexity in operation of two DC-DC converters are the constraints of the two stage PFC converters resulting in the use of a single stage PFC converter in many applications. Moreover, the additional cost and complexity of two-stage PFC is not justified for low power applications, therefore, the converter topologies with features of PFC as well as voltage regulation in single stage are preferred in the PMBLDCMD drives. There are many DC-DC converter topologies e.g. buck, boost, buck-boost, Ćuk, SEPIC, zeta, push-pull, half bridge and full bridge, reported in the literature for general purpose loads, which can be modeled and designed for PMBLDCMD drives. There are various control strategies reported in the literature for PFC. This paper primarily focuses on the two control strategies which are based on current multiplier control and voltage follower control due to their inherent advantages of PFC with other added features. The current multiplier control is further investigated in terms of peak current control and average current control for PFC at AC mains. The current multiplier control uses continuous conduction mode (CCM) operation of the PFC converters as shown in , whereas, the voltage follower control uses

discontinuous conduction mode (DCM) operation of PFC converters. The current multiplier control requires additional sensors for input current (id) and supply voltage (vs). High-frequency PWM and hysteresis current control techniques are usually employed for the current control loop and wide-bandwidth controllers in voltage loop to provide fast response and desired PQ at input AC mains. The current multiplier control results in current control at input AC mains and DC link voltage control of the PMBLDCMD drives along with improved power quality at AC mains. The voltage follower control has been reported in the literature with a variety of applications such as switched mode power supplies (SMPS) and electronic ballasts, due to inherent advantages of PFC with reduced sensors and single control loop, however, it has a disadvantage of increased peak current rating of the solid state switches. Cuk Converter :

The main applications of this circuit are in regulated dc power supplies, where a negative polarity output may be desired with respect to the common terminals of the input voltage and the average output is either higher or lower than the dc input voltage. The typical schematic circuit for the Cuk Converter is as shown in Fig. 1. The capacitor C1 acts as a primary means to store and transfer the power from input to output. The voltage v_{c1} is always greater than either input or output voltage. The average output to input relations are similar to that of a buck-boost converter circuit. The output voltage is controlled by controlling the switch-duty cycle. The ratio of output voltage to input voltage is given by

$$\frac{V_o}{V_{in}} = D \cdot \frac{1}{1-D} = \frac{I_{in}}{I_o} \quad (1)$$

Where, V_o and V_{in} are the output and input voltages, respectively. The term I_o and I_{in} are the output and input currents, respectively. The term D is the duty ratio and defined as the ratio of the on time of the switch to the total switching period. This shows the output voltage to be higher or lower than the input voltage, based on the duty-ratio D.



The Schematic circuit for the Cuk converter
Sample Plots

The sample simulation plots are shown in Fig. 2. Here, the _rst upper plot shows the gate driver pulse. The second plot shows the input and output voltages. The third plot shows the switch current, diode current and the source current. All the plots are steady and plotted for one cycle with reference to the time scale. Few sample exercises are given here to get the complete understanding of the topic.

PMBLDCMD Under Speed Control:

the performance of PMBLDCMD for speed control at constant rated torque ($5.2 \text{ N} \cdot \text{m}$) and 220-V ac mains voltage during transient and steady-state conditions of the PMBLDCM.

1) *Transient Condition:* The performance of the drive during the speed transients is evaluated for acceleration and retardation of the compressor. The reference speed is changed from 1000 to 1500 r/min and from 1000 to 500 r/min for the performance evaluation of the compressor at rated load under speed control. It is observed that the speed control is fast and smooth in either directions, i.e., acceleration or retardation, with PF maintained at near unity value. Moreover, the stator current of PMBLDCM is less than twice the rated current due to the rate limiter introduced in the reference voltage.

2) *Steady-State Condition:* The performance of PMBLDCMD under steady-state speed condition is obtained at different speeds as summarized in Table II which demonstrates the effectiveness of the proposed drive in a wide speed range. Fig. 5 shows the linear relation between motor speed and dc link voltage. Since the reference speed is decided by the reference voltage at dc link, it is observed that the control of the reference dc link voltage controls the speed of the motor.

PQ Performance of the PMBLDCMD:

The performance of PMBLDCMD in terms of PQ indices, i.e., THD_i, CF, DPF, and PF, is obtained for different speeds as well as loads. These results near unity PF and reduced THD of ac mains current in wide speed range of the PMBLDCM. The THD_i and harmonic spectra of ac mains current drawn by the proposed drive at 500- and 1500-r/min speeds are shown in Fig. 7(a) and (b) demonstrating less than 5% THD_i in a wide range of speed.

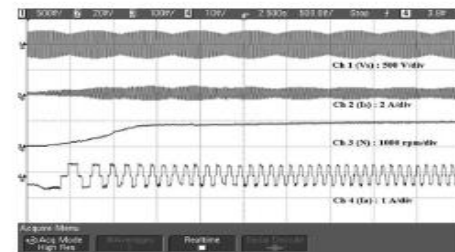
Performance of the PMBLDCMD Under Varying Input AC Voltage:

The performance of the proposed PMBLDCMD is evaluated under varying input ac voltage at rated load (i.e., rated torque and rated speed) to demonstrate the effectiveness of the proposed drive for Air-Con system in various practical situations as summarized in the current and its THD at ac mains, DPF, and PF with ac input voltage. The THD of ac

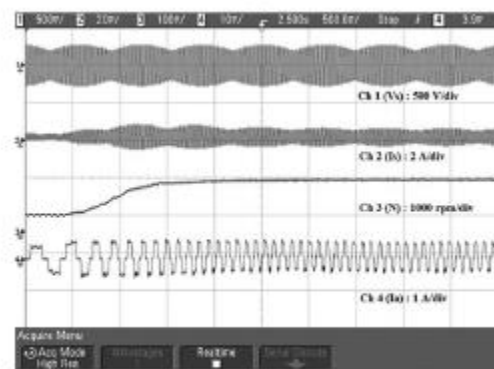
mains current is within specified limits of international norms at near unity PF in a wide range of ac input voltage.

HARDWARE IMPLEMENTATION:

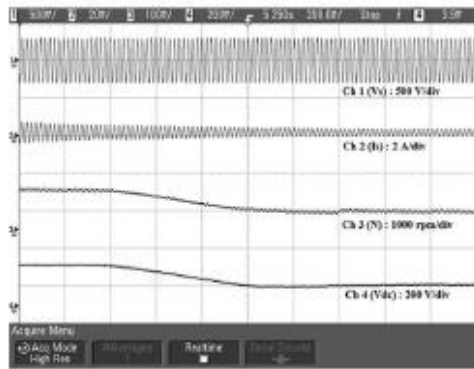
The designed proposed PFC controller is validated on a developed prototype of the drive in the laboratory. The developed hardware prototype for the speed control of PMBLDCMD uses a VSI along with a single-phase DBR and a dc capacitor. The data of a PMBLDC motor used for hardware implementation are given in the Appendix. The shaft of the PMBLDCM is coupled with a separately excited dc generator for application of mechanical load in terms of an equivalent electrical load. For the implementation of the PWM current control algorithm, a digital signal processor (DSP) developed by Microchip named as dsPIC 30F6010 is used in this system, which also generates switching signals for VSI acting as an electronic commutator for the PMBLDCM. The switching signals for the VSI are obtained using the PWM channels of the dsPIC 30F6010, whereas the PWM signal for the PFC switch is generated at one of the I/O pins. The feedback signals of current and voltage are obtained using voltage and current sensor circuits designed in the voltage range of analog-to-digital converters of the processor. The unit template is generated using a zero-crossing detector circuit from the input ac mains voltage signal. The switching frequency of the PWM signal is kept constant at



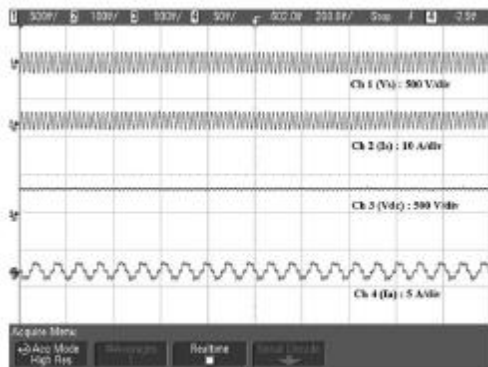
(a)



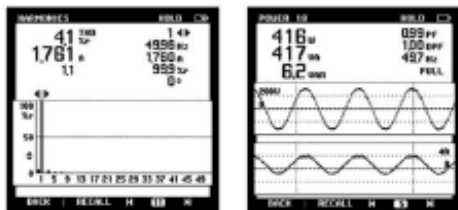
(b)



(c)



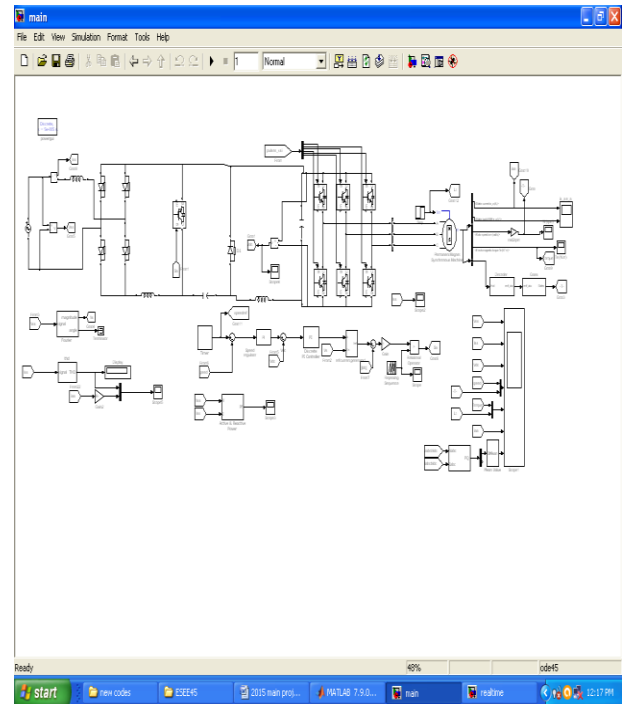
(d)



(c)

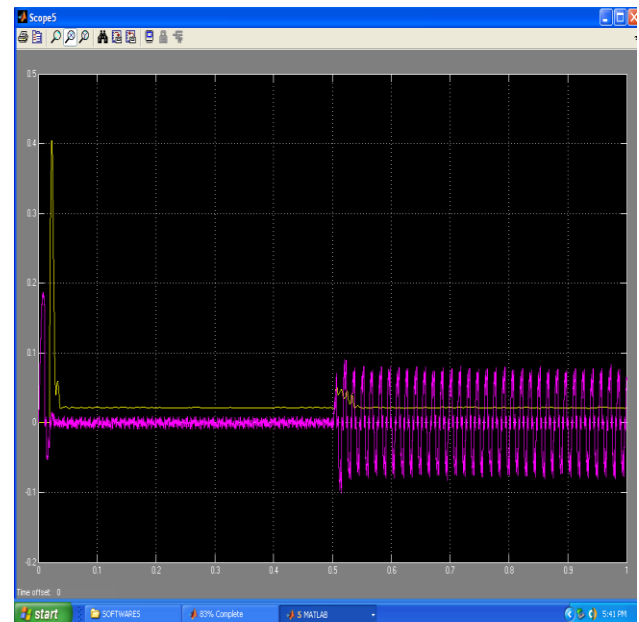
(a) Test results of nonisolated Cuk PFC converter-fed PMBLDCMD during starting at reference speed of 1000 r/min. (b) Test results of nonisolated Cuk PFC converter-fed PMBLDCMD during speed control from 500 to 1500 r/min. (c) Test results of nonisolated Cuk PFC converter-fed PMBLDCMD demonstrating speed control through voltage control from 1000 to 500 r/min. (d) Test results of nonisolated Cuk PFC converter-fed PMBLDCMD during steady-state condition at reference speed of 1500 r/min. (e) Test results in terms of harmonic spectrum and waveform of ac mains current of nonisolated Cuk PFC converter-fed PMBLDCMD during steady-state condition at reference speed of 1500 r/min.

SCREEN SHOT AND RESULTS:



Main circuit

Source current THD and Stator Current



Active and Reactive Power currents



Source Voltage, source current, DC voltage, speed & ref speed, torque & load torque, stator current, mean power

CONCLUSION:

A new speed control strategy for a PMBLDCMD using the reference speed as an equivalent voltage at dc link has been simulated for an air-conditioner employing a Cuk PFC converter and experimentally validated on a developed controller. The speed of PMBLDCM has been found to be proportional to the dc link voltage; thereby, a smooth speed control is observed while controlling the dc link voltage. The introduction of a rate limiter in the reference dc link voltage effectively limits the motor current within the desired value during the transient conditions. The PFC Cuk converter has ensured near unity PF in a wide range of the speed and the input ac voltage. Moreover, PQ indices of the proposed PFC drive are in conformity to the International Standard. The proposed PMBLDCMD has been found as a promising variable speed drive for the Air-Con system. Moreover, it may also be used in the fans with PMBLDC motor drives on the trains recently introduced in Indian Railways. These PMBLDC motor drivebased fans have similar PQ

problems as they use a simple single-phase diode rectifier and no speed control. These fans also have inrush current problems. All these PQ problems of poor PF, inrush current, and speed control in these fans on the trains in Indian Railways may be mitigated by the proposed voltage-controlled PFC Cuk converter-based PMBLDCMD. The advantages of this proposed method are excellent speed control, smooth transition between the quadrants and efficient conservation of energy.

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