CUK CONVERTER BASED POWER FACTOR CORRECTION AND SPEED CONTROL OF PMBLDC MOTOR USING PI CONTROLLER

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Abstract—Permanent magnet brushless DC motor (PMBLDCM) drives are being employed in many variable speed applications due to their high efficiency, silent operation, compact size, high reliability, ease of control, and low maintenance requirements. These drives have power quality problems and poor power factor at input AC mains as they are mostly fed through diode bridge rectifier based voltage source inverters. To overcome such problems a single-phase single-switch power factor correction AC-DC converter topology based on a Cuk converter is proposed to feed voltage source inverters based PMBLDCM. The proposed PFC converter topology is modelled and its performance is simulated in Matlab-Simulink environment and results show an improved power quality and good power factor in wide speed range of the drive.

Keywords- PMBLDCM drive, Power factor correction, Cuk converter, Air-conditioning, VSI.

I. INTRODUCTION

A permanent magnet brushless DC motor (PMBLDCM) is a kind of three-phase synchronous motor having permanent magnets on the rotor [1-5]. It is regarded as a rugged and efficient machine for variety of applications. Usually, the PMBLDCMs are powered from single-phase AC mains through a diode bridge rectifier (DBR) with smoothing DC capacitor and a three-phase voltage source inverter (VSI) [2-3, 5]. Due to the uncontrolled charging of DC link capacitor, the AC mains current waveform is a pulsed waveform featuring a peak value higher than the peak of the fundamental input current as shown in Fig. 1.1. The power factor (PF) is 0.738, crest factor (CF) is 2.24 with 67% efficiency of the drive.

![Supply Current and Harmonic Spectrum](image_url)

This is due to the fact that, the DBR does not draw any current from the AC mains when the AC voltage is less than the DC link voltage, as the diodes are reverse biased during that period; however, it draws a large current when the AC voltage is higher than the DC link voltage. Therefore, many power quality (PQ) problems arise at input AC mains including poor power factor, increased total harmonic distortion (THD) and high crest factor (CF) of AC mains current etc. These PQ problems become more severe for the utility when many such drives are employed simultaneously at various places.

To mitigate PQ and associated problems several international standards have come up in the recent past including IEC 61000-3-2 which is specially meant for low power drives. Therefore, the drive system having inherent power factor correction (PFC) are more in demand and PFC converters...
have become preferred feature of new drives. Since the PMBLDCM drives have to be operated from the utility supply, therefore they should conform to the international PQ standards.

To comply with the PQ standards in the low power range, the power factor correction (PFC) converter topology using active wave shaping techniques is a popular and preferred solution in domestic applications. The PFC converter forces the drive to draw sinusoidal AC mains current in phase with its voltage.

Moreover, for PFC converter fed PMBLDCM drives, the additional cost and complexity of the PFC converter are not justified, therefore, converter topologies with inherent feature of PFC are preferred in these drives. Therefore, a DC-DC converter topology is mostly preferred amongst several available topologies e.g., buck, boost, buck-boost, Cuk, SEPIC, zeta converters with variations of capacitive/inductive energy transfer. The net result is improved performance, such as reduction of AC mains current harmonics, reduction of acoustic noise and electromagnetic pollution, minimum number of components, enhanced efficiency, utilization of the full input voltage range etc. PM motor drives have been an area of interest for the past thirty years. Different researcher have carried out modelling, analysis and simulation of PMBLDCM drives. This content offers a brief review of some of the published work on the PMSM drive system.

Extra-high energy magnets are used in PM motor to improve the performance characteristics of the rotor. In this method Sebastian, T. Slemon, G. R. and Rahman, M. A. in 1986, presented equivalent electric circuit models for these motors and compared estimated parameters with measured parameters.

Pillay and Krishnan, R. in 1988, presented views on PM motor drives and classified them into two types. These are permanent magnet synchronous motor drives and brushless dc motor (BDCM) drives. The PMSM had a sinusoidal back emf and required sinusoidal stator currents which produced constant torque while the BDCM had a trapezoidal back emf, required rectangular stator currents for producing constant torque.

Further as an extension of his previous work Pillay and Krishnan, R. in 1989 presented the vector control as well as complete modelling of the drive system in rotor reference frame except damper windings. Traditional Hysteresis control method is used due to its simplicity in implementation, fast control response, and inherent current (peak) limiting ability. Zhonghui Zhang, Jiao Shu simulated the field oriented vector control of PMSM drive using current reference tracking and PWM inverter switching. This work used conventional PI controller for tracking purpose. B. Adhavan, A. Kuppuswamy, G. Jayabaskaran and Dr. V Jagannathan used fuzzy logic controller instead of PI for the same and did performance comparison analysis of both the types of controller. Zhuqiang Lu, Honggang Sheng, Herbert L. Hess, Kevin M. Buck applied principle of direct torque control to the PMSM drive system. This method directly controlled the speed of drive by estimating the torque and flux linkage value and selecting the appropriate switching vector from the look-up table without any kind of mechanical sensor. Few efforts have been made to introduce PFC feature in PMBLDCM motors using unipolar excitation and bipolar excitation of PMBLDCMs. For air-conditioners, a PMBLDCM with boost PFC converter and PMSM with improved power quality converter have been reported for power quality improvement. However, a PMBLDCM is best suited for air-conditioning system due to simple control, high average torque produced and few torque ripples.

BLDC motor drives, systems in which a permanent magnet excited synchronous motor is fed with a variable frequency inverter controlled by a shaft position sensor. There appears a lack of commercial simulation packages for the design of controller for such BLDC motor drives. One main reason has been that the high software development cost incurred is not justified. For their typical low cost fractional/integral kW application areas such as NC machine tools and robot drives, even it could imply the possibility of demagnetizing the rotor magnets during commissioning or tuning stages. Nevertheless, recursive prototyping of both the motor and inverter may be involved in novel drive configurations for advance and specialized applications, resulting in high developmental cost of the drive system. Improved magnet material with high (B.H), product also helps push the BLDC
motors market to tens of kW application areas where commissioning errors become prohibitively costly. Modeling is therefore essential and may offer potential cost savings.

A brushless dc motor is a dc motor turned inside out, so that the field is on the rotor and the armature is on the stator. The brushless dc motor is actually a permanent magnet ac motor whose torque-current characteristics mimic the dc motor. Instead of commutating the armature current using brushes, electronic commutation is used. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator-brush arrangement, thereby, making a BLDC more rugged as compared to a dc motor. Having the armature on the stator makes it easy to conduct heat away from the windings, and if desired, having cooling arrangement for the armature windings is much easier as compared to a dc motor.

![Fig 2. Cross section view of BLDC Motor](image)

In effect, a BLDC is a modified PMSM motor with the modification being that the back-emf is trapezoidal instead of being sinusoidal as in the case of PMSM. The “commutation region” of the back-emf of a BLDC motor should be as small as possible, while at the same time it should not be so narrow as to make it difficult to commutate a phase of that motor when driven by a Current Source Inverter. The flat constant portion of the back-emf should be 120° for a smooth torque production. The position of the rotor can be sensed by using an optical position sensors and its associated logic. Optical position sensors consist of phototransistors (sensitive to light), revolving shutters, and a light source. The output of an optical position sensor is usually a Logical signal.

**II. CUK CONVERTER**

The Cuk converter is named for Slobodan Cuk of the California Institute of Technology. It is the result of applying the duality principle to the buck-boost converter to use a capacitor instead of an inductor as the primary energy storage device. As a result, the DC transfer function is nominally the same as that of the Buck-Boost converter,

$$V_o = DV_s/ (1-D) - A$$

Where,

- $D$ represents the PWM duty cycle of the transistor $Q$.
- $V_s$ represents the source voltage.
- $V_o$ represents the output voltage.

An advantage of the Cuk converter topology is that the current pulsing occurs within the converter itself and both the input and output currents are not pulsed. Furthermore, if integrated magnetics are used, the input or output current can (theoretically) be nullified as the ripple is transferred to the other side of the converter. Because only one capacitor suffers the losses associated
with (internal) current pulsing, the Cuk converter is more efficient than a filtered Buck-Boost converter.

![Fig 3. CUK converter](image)

The proposed PFC Cuk converter is designed bdcl motor drive with main considerations on the speed control of the A PQ improvement at ac mains. The dc link voltage of the PFC converter is given as

\[ V_{dc} = \frac{V_{in} D}{1 - D} \]  

Where \( V_{in} \) is the average output of the DBR for a given ac input voltage (Vs) related as

\[ V_{in} = \frac{2\sqrt{2}Vs}{\pi} \]  

The Cuk converter uses a boost inductor (Li) and a capacitor (C1) for energy transfer. Their values are given as

\[ L_i = \frac{D V_{in}}{f_s \Delta I_{li}} \]  
\[ C_1 = \frac{D I_{dc}}{f_s \Delta V_{C1}} \]  

Where \( \Delta I_{li} \) is a specified inductor current ripple, \( \Delta V_{C1} \) is a specified voltage ripple in the intermediate capacitor (C1), and \( I_{dc} \) is the current drawn by the PMBLDCM from the dc link. A ripple filter is designed for ripple-free voltage at the dc link of the Cuk converter. The inductance (Lo) of the ripple filter restricts the inductor peak-to-peak ripple current (\( \Delta I_{lo} \)) within a specified value for the given switching frequency (fs), whereas the capacitance (Cd) is calculated for the allowed ripple in the dc link voltage (\( \Delta V_{Cd} \)). The values of the ripple filter inductor and capacitor are given as

\[ L_o = \frac{(1 - D)V_{dc}}{f_s \Delta I_{lo}} \]  
\[ C_d = \frac{I_{dc}}{2\omega \Delta V_{cd}} \]  

The PFC converter is designed for a base dc link voltage of \( V_{dc} = 200 \) V at \( V_s = 220 \) V for fs = 20kHz, Is = 4.5 A, \( \Delta I_{li} = 0.45 \) A (10% of \( I_{dc} \)), \( I_{dc} = 3.5 \) A, \( \Delta I_{lo} = 3.5 \) A (\( \approx I_{dc} \)), \( \Delta V_{Cd} = 4 \) V (1% of \( V_o \)), and \( \Delta V_{C1} = 220 \) V (\( \approx V_s \)).

The design values are obtained as \( L_i = 2.5 \) mH, \( C_1 = 0.66 \) \( \mu \)F, \( L_o = 4.3 \) mH, and \( C_d = 2200 \) \( \mu \)F.

### III. CUK CONVERTER BASED PMBLDC DRIVE

This project explains the operation of DC-DC converter for feeding a BLDC motor drive as a cost effective solution for low power applications. The single phase supply is fed to uncontrolled bridge rectifier. The output of bridge rectifier is fed to a PFC DC-DC converter which is used to control the voltage of DC link capacitor which feeds the Voltage Source Inverter. The BLDC motor is...
fed from Voltage Source Inverter. Voltage of a DC link capacitor of Cuk converter is controlled to achieve the speed control of BLDC motor. A MATLAB Simulation and hardware is studied to simulate the model to study a wide range of speed control.

![Fig 4. Proposed system circuit diagram](image)

**Figure** shows the proposed topology of Cuk PFC converter fed PMBLDCM drive with control scheme for the speed control as well as PFC with DC link voltage control. For the speed control of the PMBLDCM, a proportional-integral (PI) controller is used to drive a constant torque compressor in air-conditioning system. The rotor position of PMBLDCM is sensed using Hall effect sensors and converted to speed signal, which is compared with a reference speed. The speed error signal is passed through a speed controller to give the torque equivalent which is converted to current equivalent signal. This signal is multiplied with a rectangular unit template in phase with top flat portion of motor’s back EMF to get reference currents of the motor. The reference motor currents are compared with the sensed motor currents. These current errors are amplified and amplified signals are then compared with triangular carrier wave to generate the PWM pulses for turning on/off the VSI switches. The control of PMBLDCM requires rotor-position information only at the commutation points, e.g., every 60° electrical in the three-phases, therefore, comparatively simple controller is required for commutation and current control.

The Cuk PFC converter topology has a conventional DBR fed from single-phase AC mains followed by the Cuk DC-DC converter, an output ripple filter and a three-phase VSI to feed the PMBLDCM motor. The DC-DC converter provides a controlled DC voltage from uncontrolled DC output of DBR, while controlling the power factor (PF) through high frequency switching of the PFC switch. The regulated output DC voltage from the DC-DC converter is decided by its duty ratio (D). The switching frequency ($f_s$) is decided by the switching device used, operating voltage, power level and switching losses of the device. In this work, a set of insulated gate bipolar transistors (IGBTs) are used as the switching devices in the PFC switch as well as in VSI bridge, because IGBTs can operate in wide switching frequency range to make optimum balance between magnetics, size of filter components and switching losses. The use of current multiplier approach with average current control scheme in continuous conduction mode (CCM) of the PFC converter makes this topology an efficient option. The control loop employed to execute PFC action involves outer voltage loop and inner current loop. For control action, the DC link voltage is sensed and compared with the set reference voltage at DC link. The error voltage is passed through a voltage PI controller to give the
modulating current signal. This signal is multiplied with a unit template of input AC voltage which is compared with DC current sensed after the DBR. Hall effect voltage and current sensors are employed for voltage and current sensing. This current error is amplified and amplified signal is then compared with saw tooth carrier wave to generate the PWM pulses for turning on/off the DC-DC converter switch. The complete control strategy consists of selection of sensors, design of control algorithm and PWM controller for the drive. The modeling of the proposed PFC converter fed PMBLDCM drive involves modeling of a PFC converter and modeling of PMBLDCM drive. The PFC converter consists of a DBR at front end and a Cuk converter with output ripple filter. Therefore, its modeling mainly includes the modeling of the voltage controller, reference current generator and PWM controller. The various components of PMBLDCM drive are a speed controller, a reference current generator, a PWM current controller and a PMBLDC motor. Each of the above components of a PMBLDCM drive are modeled by mathematical equations and combination of such models represent complete PMBLDCM drive. The modeling of a PFC converter mainly consists of the modeling of the voltage controller, reference current generator and a PWM controller. These components require various signals sensed from the system e.g. DC link voltage, current after DBR and input voltage template. The accuracy of the controller depends on these sensed signals. The PFC converter and the sensor less BLDC motor drive are modelled for the proposed drive scheme. The control scheme of the PFC converter consists of following three blocks.

Reference Voltage Generator
The speed of BLDC motor is proportional to the DC link voltage of the VSI, hence a reference voltage generator is required to produces an equivalent voltage corresponding to the particular reference speed of the BLDC motor. The reference voltage generator produces a voltage by multiplying the speed with a constant value known as the voltage constant (Kb) of the BLDC motor.

Speed Controller
An error of the \( V_{dc}^* \) and \( V_{dc} \) is given to a PI (Proportional Integral) speed controller which generates a controlled output corresponding to the error signal. The error voltage \( V_e \) at any instant of time \( k \) is as;
\[
V_e(k) = V_{dc}^*(k) - V_{dc}(k)
\]
and the output \( V_c(k) \) of the PI controller is given by,
\[
V_c(k) = V_c(k-1) + K_p.(V_e(k) - V_e(k-1)) + K_i.V_e(k)
\]
where \( K_p \) is the proportional gain and \( K_i \) is the integral gain constant.

PWM Generator
The output of the PI controller \( V_c \) is given to the PWM generator which produces a PWM signal of fixed frequency and varying duty ratio. A saw tooth waveform is compared with the output of PI controller as shown in Fig. 3 and PWM is generated as;
If \( m_d(t)<V_c(t) \) then \( S=1 \) else \( S=0 \) (10)
Where \( S \) denotes the switching signals as 1 and 0 for MOSFET to switch on and off respectively. L2, and the diode, D, have been swapped so that the output polarity is the same as the input polarity. This can be an advantage in certain applications, because the negative terminals of both the input also requires a high side switch (either a P-Channel FET or an N-Chanel FET with a high side driver). This topology can work well when integrated with another topology (such as the buck-boost) to generate both positive and negative output rails. There are very few publications regarding PFC in PMBLDCMds despite many PFC topologies for switched mode power supply and battery charging applications. Here we studied an application of a PFC converter for the speed control of a PMBLDCMD. For the voltage controlled 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-Conditioners

I. SIMULATION RESULTS
To verify the feasibility of the proposed strategy, simulations are carried out.
Fig 5. Proposed system simulink diagram

Fig 6. Speed waveform using PI controller
Fig. 7. Torque waveform of the BLDC motor

Fig. 8. Proposed input AC voltage to the DBR

Fig. 9. Proposed input AC current due to the DBR
The figure 12 shows the THD value, the CUK converter will reduce THD by providing constant voltage to the load.

IV. CONCLUSION

A Cuk converter based PFC topology for a PMBLDCM drive has been proposed. The PFC converter has ensured reasonable high power factor of the order of 0.998 in wide range of the speed as well as input AC voltage. Moreover, performance parameters show an improved power quality with less torque ripple, smooth speed control of the PMBLDCM drive. The THD of AC mains current has been observed well below 6% in most of the cases and completely satisfies the international norms. The performance of the drive has been found very good in the wide range of input AC voltage with desired power quality parameters. This topology has been found suitable for the applications involving speed control at constant torque load.

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