A New Pulse Width Modulated PFC Zeta Converter Fed Sensorless BLDC Motor Drive with Position Feedback

Sreedevi K J 1, C Sojy Rajan 2

1Department of Electrical and Electronics, Mar Baselios College of Engineering and Technology, India
2Department of Electrical and Electronics, Mar Baselios College of Engineering and Technology, India

Abstract: A New Pulse Width Modulated Zeta DC-DC Converter employed as Power Factor Correction converter feeding a BLDC (Brush less DC) motor drive is proposed. Zeta DC-DC converter which lies between an uncontrolled bridge rectifier and a dc link capacitor is used to control the voltage of the dc link capacitor. The Brush Less DC motor is fed from a single phase supply. The DC link capacitor is in between the Zeta Converter and a VSI (Voltage Source Inverter). A voltage follower approach is used to control the dc link voltage of the Zeta converter and the converter is working in DCM (Discontinuous Conduction Mode). To eliminate the requirement of Hall Effect position sensors a sensor less control of BLDC motor is used. For this sensor less operation, inverter pulses are generated by back emf estimation of the motor drive. A MATLAB/Simulink environment is used to simulate the model. A wide range of speed control is possible with high PF (Power Factor) and improved PQ (Power Quality) at the ac mains supply.

Keywords: DCM, PFC, BLDC motor, Zeta, VSI

1. Introduction

The selection of a drive mainly depends on three main factors; efficiency, cost and design simplicity. These factors play an important role for designing a motor drive for household appliances. Other main factor is the requirement of improved power quality at the AC mains as imposed by the international PQ (Power Quality) standards like IEC 61000-3-2[1]. Class D applications require the power factor to be above 0.9 and the THD (Total Harmonic Distortion) less than 5%. This paper deals with the design of such a motor drive with improved power quality at the AC mains for a wide range of speed control. Brush Less DC motors are becoming popular for low and medium power applications because of their high efficiency, high reliability, low maintenance requirements, and low noise levels[2]. BLDC motors are permanent magnet synchronous motors with three phase windings on stator and permanent magnets on the rotor. These are trapezoidal back emf motors with no brushes and commutator assembly. These are electronically commutated motors through a VSI and the rotor position is sensed with the help of hall effect position sensors or by using sensorless methods. Class D applications recommends the use of improved power quality converters for the BLDC motor drive.

Conventional BLDC motors are fed from a combination of diode bridge rectifier and a dc link capacitor followed by a voltage source inverter. This combination draws supply current from a single phase supply which is rich in harmonics and leads to a poor power factor of the order of 0.8 and hence it cannot be used for feeding the BLDC motor drive to attain an improved power quality at the AC mains. Widely used PFC converters require a two stage power conversion in which the first stage is for power factor correction and the second stage for voltage regulation. This two stage topology is more complex and results in more cost and losses and hence a single stage zeta converter is proposed which is used to control the voltage of a dc link capacitor and for power factor correction. The zeta converter is working in discontinuous conduction mode and hence a voltage follower approach is used. In continuous conduction mode a current multiplier approach is used. A sensorless control of BLDC motor is used which eliminate the requirement of Hall Effect position sensors thus making the drive more cost effective.

2. Proposed Speed Control Scheme of Sensorless BLDC Motor Drive

The proposed scheme for the Sensorless BLDC motor drive fed by a Zeta based PFC converter operating in DCM mode is shown in Fig. 1. The front end Zeta DC-DC converter maintains the DC link voltage to a set reference value. Switch of the Zeta converter is to be operated at high switching frequency for effective control and small size of components like inductors. A sensorless approach is used to detect the rotor position for electronic commutation. A blind start up is used for starting the BLDC motor. A high frequency MOSFET of suitable rating is used in the front end converter for its high frequency operation whereas an IGBT’s (Insulated Gate Bipolar Transistor) are used in the VSI for low frequency operation.

The proposed scheme maintains high power factor and low THD of the AC source current while controlling rotor speed equal to the set reference speed. A voltage follower approach is used for the control of Zeta DC-DC converter operating in DCM. The DC link voltage is controlled by a single voltage sensor. Vdc (sensed DC link voltage) is compared with Vdc* (reference voltage) to generate an error signal which is the difference of Vdc* and Vdc. The error signal is given to a PI (Proportional Integral) controller to give a controlled output. Finally, the controlled output is compared with the high frequency saw tooth signal to generate PWM (Pulse Width Modulation) pulse for the

Volume 3 Issue 7, July 2014

www.ijsr.net
Licensed Under Creative Commons Attribution CC BY

Paper ID: 020141154

723
MOSFET of the Zeta converter. A rate limiter is used to limit the stator current during step change in speed.

3. Design of PFC ZETA Converter

The proposed drive system is designed for Zeta converter as PFC converter fed BLDC motor drive operating in DCM. The output inductor value is selected such that the current remains discontinuous in a single switching cycle. The average input voltage \( Vin \) after the rectifier is given as,

\[
Vin = \frac{2\sqrt{2}Vs}{\pi}
\]

where \( Vs \) is the rms value of the supply voltage.

![Diagram of Zeta Converter](image)

Figure 1: Proposed Zeta converter fed Sensorless BLDC MOTOR drive with voltage follower approach for fan application

The output inductor value is selected such that the current remains discontinuous in a single switching cycle. The average input voltage \( Vin \) after the rectifier is given as,

\[
Vin = \frac{2\sqrt{2}Vs}{\pi}
\]

where \( Vs \) is the rms value of the supply voltage.

The proposed drive system is designed for Zeta converter as PFC converter fed BLDC motor drive operating in DCM.

The output inductor value is selected such that the current remains discontinuous in a single switching cycle. The average input voltage \( Vin \) after the rectifier is given as,

\[
Vin = \frac{2\sqrt{2}Vs}{\pi}
\]

where \( Vs \) is the rms value of the supply voltage.

Control of PFC Based ZETA Fed Sensorless Bldc Motor Drive

The PFC converter and the sensorless BLDC motor drive are modeled for the proposed drive scheme. The control scheme of the PFC converter consists of following three blocks.

A. 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 produce 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.

B. Speed Controller

An error of the \( Vdc^* \) and \( Vdc \) is given to a PI (Proportional Integral) speed controller which generates a controlled output corresponding to the error signal. The error voltage \( Ve \) at any instant of time \( k \) is as:

\[
Ve(k) = Vdc^*(k) – Vdc(k)
\]

and the output \( Vc(k) \) of the PI controller is given by,

\[
Vc(k) = Vc(k-1) + Kp.(Ve(k) – Ve(k-1)) + Ki.Ve(k)
\]

where \( Kp \) is the proportional gain and \( Ki \) is the integral gain constant.

C. PWM Generator

The output of the PI controller \( Vc \) 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 md(t)<Vc(t) then S=1 else S=0

where S denotes the switching signals as 1 and 0 for MOSFET to switch on and off respectively.

The flux linkages can be expressed as,

\[ \lambda_x = (L_s + M) \cdot x \]  

where \( x \) denotes a, b or c (i.e. phase terminals).

The generalized equation by using equations (11)-(13) and (18),

\[ p_x = (V_x - i_x R - e_x) / (L_s + M) \]

The developed electromagnetic torque is expressed as,

\[ T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_r \]

where \( \omega_r \) is the rotor speed in electrical rad/sec.

This expression for the torque faces computational difficulty at zero speed as induced emf's are zero. Hence, it is reformulated by expressing back-emf as a function of position \( \theta \), which can be written as,

\[ e_a = k_{ba} f_a(\theta) \omega_r \]

\[ e_b = k_{fb} f_b(\theta) \omega_r \]

\[ e_c = k_{fc} f_c(\theta) \omega_r \]

Substituting equations (22)-(24) into equation (21), the torque expression becomes,

\[ T_e = k_b \{ f_a(\theta) i_a + f_b(\theta) i_b + f_c(\theta) i_c \} \]

where \( k_b \) is the back emf constant and \( f_a(\theta) \), \( f_b(\theta) \) and \( f_c(\theta) \) are rotor position function having a maximum magnitude of plus or minus 1 and is given as,

\[ f_a(\theta) = 1; \text{ for } 0 < \theta < 120^\circ \]

\[ f_a(\theta) = \left( \frac{6}{\pi} - \frac{\pi}{\theta} \right) ^{-1}; \text{ for } 120^\circ < \theta < 180^\circ \]

\[ f_a(\theta) = -1; \text{ for } 180^\circ < \theta < 300^\circ \]

\[ f_a(\theta) = \left( \frac{6}{\pi} - \frac{2\pi}{\theta} \right) ^{-1}; \text{ for } 300^\circ < \theta < 360^\circ \]

The functions for b and c phase can be calculated by using a 120° and 240° phase difference respectively. The torque balance equation is given as,

\[ T_e = T_L + B \omega_r + J \cdot (2/P) \cdot d \omega_r / dt \]

where \( T_e \) is developed electromagnetic torque, \( T_L \) is load torque, \( B \) represents the frictional coefficient in Nms/rad, \( P \) is the number of poles and \( J \) represents the moment of inertia in kg-m².

The potential of neutral terminal with respect to zero potential (Vno) is required to be considered in order to avoid unbalance in applied voltage. Substituting equation (14) in equation (11) to (13) and adding them together gives,

\[ V_{ao} + V_{bo} + V_{co} - 3V_{no} = R(i_a + i_b + i_c) + (L_s + M) (p_i a + p_i b + p_i c) + (e_a + e_b + e_c) \]

Substituting equation (18) in equation (31) one gets,

\[ V_{ao} + V_{bo} + V_{co} - 3V_{no} = (e_a + e_b + e_c) \]

Thus, \( V_{no} = \{V_{ao} + V_{bo} + V_{co} - (e_a + e_b + e_c)\} / 3 \)

A dynamic model of a BLDC motor is represented in equations (11)-(33).
**B. Voltage Source Inverter**

The output of the VSI for phase ‘a’ is expressed as,

\[ \text{Van} = \frac{V_{dc}}{2} \text{ for } S1=1; \quad (34) \]

\[ \text{Van} = -\frac{V_{dc}}{2} \text{ for } S2=1; \quad (35) \]

\[ \text{Van} = 0 \text{ for } S1=0, S2=0; \quad (36) \]

where \( V_{dc} \) is the DC link voltage and the values for \( S1 \) and \( S2 \) as 1 and 0 represent the on and off condition of the IGBT’s \( S1 \) and \( S2 \). When switch \( S1 \) and \( S4 \) are on then phase ‘a’ and ‘b’ are connected and the current \( i_a \) (\( i_a = i_b \)) flows through the motor windings and the third phase ‘c’ remains in floating condition as shown in Fig. 4.

The equation for line voltage \( \text{Vab} \) is given as,

\[ \text{Vab} = V_{dc} = R_a + L_a \frac{di_a}{dt} + e_a + R_b + L_b \frac{di_b}{dt} + e_b \quad (37) \]

If \( L_a = L_b = L, R_a = R_b = R, i_a = i_b \) and \( e_{ab} = e_a + e_b \) then,

\[ V_{dc} = 2R_{ia} + 2L \frac{di_a}{dt} + e_{ab} \quad (38) \]

where \( i_a \) is the line current (or the phase current) of the motor. Similarly the other combination of switches can be obtained.

**C. Electronic Commutation**

The switching sequence of VSI for different positions of the rotor as estimated by sensorless scheme.

**A. Open Loop Starting**

In open loop startup technique, a rotating field at the stator is given with gradually increasing magnitude and frequency such that it can overcome the rotor inertia and friction at standstill position and begins rotating at low speed. The voltage applied should be such that the current should not exceed the maximum current rating of the BLDC motor.

**B. Switching from Starting to Sensorless Mode**

When the rotor rotates above a certain speed in the open loop starting, and proper estimation of the virtual Hall Effect position signals are obtained then the motor is switched from open loop starting mode to sensorless mode of operation.

**C. Sensorless Operation**

There are numerous methods for the estimation of rotor position [12, 13]. A basic approach of determining line voltage is by the measurement of phase voltage with the virtual ground and then calculating the line voltage is used. A ZCD detects the zero crossing of the voltage and then the virtual Hall signals for electronic commutation are generated. Fig. 6 shows the starting, switching from starting to sensorless mode and the sensorless operation of the BLDC motor drive. As shown in this figure the estimated virtual Hall Effect rotor position signal and the actual hall signals are overlapping showing the accurate detection of position using the sensorless algorithm. Moreover, the stator current is much less than the maximum current rating of motor during open loop starting and a smooth transition from open loop starting to sensorless mode is also achieved.

**6. Performance Evaluation**

The proposed model is simulated in MATLAB/Simulink environment for a 500W sensorless BLDC motor drive system for fan application. The fan load is considered as load proportional to the square of speed, so at very low speed the load torque on the motor is very less and as the speed increases the load torque increases rapidly. Parameters like THD, CF (crest Factor), DPF (Displacement Power Factor) and PF at the AC mains of the proposed PFC drive are used for performance evaluation. The detailed specifications of the motor are mentioned in Appendix. Table I shows the steady state performance evaluation parameters at speed control of the Zeta converter fed Sensorless BLDC motor drive. A satisfactory performance is achieved over a wide speed range with improved power quality at the AC mains. The THD is maintained below 5% and power factor near unity for a wide range of speed control following IEC 61000-3-2 standard. Fig. 8 shows the various parameters of the front end converter and the BLDC motor in steady state at near rated speed. The voltage and current stress on the switch is 600V and 40A respectively as shown in Fig. 8 The DC link voltage is changed from 100V to 200V and a smooth transition with low amount of transients is obtained.
Figure 5: Sensorless BLDC MATLAB/Simulink model

Figure 6: MATLAB model of zeta converter fed BLDC motor drive
7. Conclusion and Future Scope

A simple control using a voltage follower approach has been used for voltage control and power factor correction of a PFC Zeta converter fed BLDC motor drive. A novel scheme of speed control using a single voltage sensor has been proposed for a fan load. A sensorless operation for the further reduction of position sensor has been used. A single stage PFC converter system has been designed and validated for the speed control with improved power quality at the AC mains for a wide range of speed. The performance of the proposed drive system has also been evaluated for varying input AC voltages and found satisfactory. The power quality indices for the speed control and supply voltage variation have been obtained within the limits by International power quality standard IEC 61000-3-2. The proposed drive system has been found a suitable candidate among various adjustable speed drives for many low power applications. As a future expansion, we will be going for a hardware implementation of the work.

8. Appendix

BLDC Motor Rating: 4 pole, Prated (Rated Power) = 424.11W, Trated (Rated Torque) = 1.35 Nm, ω rated (Rated Speed) = 3000 rpm, Kb (Back EMF Constant) = 51 V/krpm, Kt (Torque Constant) = 0.49 Nm/A, Rph (Phase Resistance) = 7.20Ω, L (Phase Inductance) = 4.77 mH, J (Moment of Inertia) = 0.37 kg-cm².

References


Author Profile

Sreedevi K J is currently pursuing her M Tech in Power Control & Drives from University of Kerala. Her areas of interest include Power Electronics, Drives and Digital Signal Processing.

C. Sojoy Rajan is working as Assistant Professor in Mar Baselios College of Engineering and Technology. Her areas of interest include Power System, Power Electronics and Machines.