

Modeling and Simulation of Closed Loop Controlled PFC Half Bridge Converter Fed PMBLDC Motor using Simulink

C. Umayal¹ and S. Rama Reddy²

*¹Research Scholar, Electrical and Electronics Engineering Department,
Easwari Engineering College, Centre for Collaborative research,
Barathi Salai, Ramapuram, Chennai-600089, India
E-mail: cumayal@yahoo.com*

*²Professor, Electrical and Electronics Engineering Department,
Jerusalem College of Engineering, Chennai, Narayanapuram,
Pallikaranai, Chennai-600100, India
E-mail: srr_victory@yahoo.com*

Abstract

Digital Simulation of a Power Factor Correction (PFC) half bridge converter based adjustable speed voltage controlled VSI fed PMBLDC motor is presented in this paper. A single-phase AC-DC converter topology based on the half bridge converter is employed for PFC which ensures near unity power factor over wide speed range. The proposed speed control scheme has the concept of DC link voltage control proportional to the desired speed of the PMBLDC motor. The speed is regulated by a PI controller. The PFC converter based PMBLDCM drive is designed, modeled and simulated using MATLAB-SimuLink environment. This drive ensures high accuracy and robust operation from near zero to high speed.

Keywords: Boost rectifier, low conduction losses, power factor correction (PFC), Hall position sensors, permanent magnet brushless DC motor, BLDC motor, closed loop speed control, PI controller.

Introduction

Research on PFC circuits for high power applications has increased. Three level boost type PFC converters is an attractive solution for high power density and high efficiency 3 phase pre regulators. Single stage PFC circuits have presented a serious challenge recently to increase the output power capability with optimized component

ratings. PFC using half bridge converters is the recent trend. In these rectifiers only half of the output voltage is applied across the switches thus reducing the stress on them to a greater extent.

Recent developments in power electronics, micro electronics and modern control technologies have greatly influenced the wide spread use of permanent magnet motors. The major classification of Permanent Magnet motors are permanent magnet synchronous motor (PMSM) and Permanent Magnet Brushless DC motors (PMBLDCM). While PMSM has sinusoidal back-emf waveform the BLDC motor has trapezoidal back-emf waveform.

The BLDC motors have a good performance, high efficiency, low maintenance, high power density, low inertia. Hence it finds widespread use in variety of applications in motion control. The classical PI controller is a wide used controller. Comparing with conventional DC motors, BLDC motors do not have brushes for commutation. Instead they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors, like better speed-torque characteristics, high dynamic response, high efficiency, noiseless operation and wide speed ranges. Torque to weight ratio is higher enabling it to be used in applications where space and weight are critical factors. A new generation of microcontrollers and advanced electronics has overcome the challenge of implementing required control functions, making the BLDC motor more practical for a wide range of uses [1], [2], [3].

Power Factor Correction Converters

In the field of inverter appliance, the application of AC/DC/AC converter is more and more popular. There are serious contaminations from harmonic currents at the mains side, making the products not pass IEC61000-3-2 and IEC61000-3-12 (harmonics standards) successfully. In order to mitigate the harmonic current pollution, most of the household inverters are equipped with power factor corrector as front AC/DC converter, and the input power factor approaches one. But the conventional active PFC has to employ uncontrolled rectifier and costly boost inductor, and these power components result in power loss, low efficiency and high cost. Nevertheless, the bridgeless PFC (BLPFC) is characteristic of small number of power switches, making room for low power loss [4]. Additionally, in the conventional active PFC the power switches are in on and off state in a whole mains period, enduring high voltage and current stresses, producing a lot of switching loss and conduction loss and limiting the efficiency.

A voltage source inverter can run the BLDC motor by applying three phase square wave voltages to the stator winding of the motor. A variable frequency square wave voltage can be applied to the motor by controlling the switching frequency of the power semiconductor switches. The square wave voltage will induce low frequency harmonic torque pulsation in the machine. Also variable voltage control with variable frequency operation is not possible with square wave inverters. Even updated pulse-width modulation (PWM) techniques used to control modern static converters such as machine drives, power factor compensators do not produce perfect waveforms, which strongly depend on the semiconductors switching frequency. Voltage or current

converters, as they generate discrete output waveforms, force the use of machines with special isolation, and in some applications large inductances connected in series with the respective load. Also, it is well known that distorted voltages and current waveforms produce additional power losses, and high frequency noise that can affect not only the power load but also the associated controllers. All these unwanted operating characteristics associated with PWM converters could be overcome with improved bridgeless PFC boost converters.

Principle of the bridgeless topology

The basic topology of the bridgeless PFC boost rectifier [5] is shown in Fig. 1. Compared to the conventional PFC boost rectifier, shown in Fig. 2, one diode is eliminated from the line-current path, so that the line current simultaneously flows through only two semiconductors resulting in reduced conduction losses [6]. The bridgeless PFC topology removes the input rectifier conduction losses and is able to achieve higher efficiency. However, the bridgeless PFC boost rectifier in Fig. 1 has significantly larger common-mode noise than the conventional PFC boost rectifier [7].

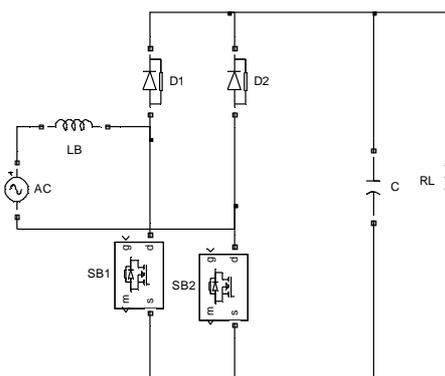


Figure 1: Bridgeless Boost Converter.

Based on the analysis above, the bridgeless PFC circuit can simplify the circuit topology and improve the efficiency as well.

Types of control techniques of PMBLDC motor

Though various control techniques are discussed in [8]. Basically two methods are available for controlling PMBLDC motor. They are sensor control and sensorless control.

To control the machine the present position of the rotor is required to determine the next commutation interval. One is by controlling the DC bus rail voltage and the next one is by PWM method. Some designs utilize both to provide high torque at high load and high efficiency at low load. Such hybrid design also allows the control of harmonic current [9].

In control methods using sensors, mechanical position sensors, such as a hall sensor, shaft encoder or resolver have been utilized in order to provide rotor position information. Hall Position sensors or simply Hall sensors are widely used and popular. The rotor position information is used to generate precise firing commands for power converter. This ensures drive stability and fast dynamic response. The speed feedback is derived from the position sensor output signals. Between the two commutation signals the angle variation is constant as the Hall Effect Sensors are fixed relative to the motor, thus reducing speed sensing to a simple division. Usually speed and position of a permanent magnet brushless direct current motor rotor is controlled in a conventional cascade structure. The inner current control loops runs at a larger width than the outer speed loop to achieve an effective cascade control [10].

Various sensorless methods for BLDC motors are analyzed in [11-18]. [11] Proposes a speed control of brushless drive employing PWM technique using digital signal processor. A PSO based optimization of PID controller for a linear BLDC motor is given in [12], Direct torque control and indirect flux control of BLDC motor with non sinusoidal back emf method controls the torque directly and stator flux amplitude indirectly using d-axis current to achieve a low-frequency torque ripple-free control with maximum efficiency[13-14]. [15] Proposes a novel architecture using a FPGA-based system. Fixed gain PI speed controller has the limitations of being suitable for a limited operating range around the operating point and having overshoot. To eliminate this problem a fuzzy based gain scheduled PI speed controller is proposed in [16]. A new module structure of PLL speed controller is proposed by [17]. A fixed structure controller (PI or PID) using time constrained output feedback is given in [18]. The above literatures does not deal with PFC in closed loop controlled PMBLDC. This work proposes PFC at the input of PMBLDC drive.

Mathematical Model of the PMBLDC motor

Modeling and simulation play an important role in the design of power electronics system. The classic design approach begins with an overall performance investigation of the system, under various circumstances through mathematical modeling.

The circuit model of PMBLDC motor is shown in Fig 2.

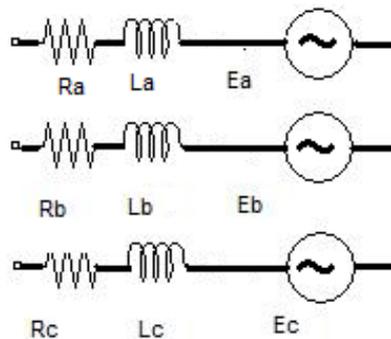


Figure 2: Motor Circuit Model.

The voltage equations of the BLDC motor are as follows:

$$\begin{aligned}
 V_a &= R_a i_a + \frac{d}{dt} (L_{aa} i_a + L_{ab} i_b + L_{ac} i_c) + \frac{d\lambda_{ar}(\theta)}{dt} \\
 V_b &= R_b i_b + \frac{d}{dt} (L_{ba} i_a + L_{bb} i_b + L_{bc} i_c) + \frac{d\lambda_{br}(\theta)}{dt} \\
 V_c &= R_c i_c + \frac{d}{dt} (L_{ca} i_a + L_{cb} i_b + L_{cc} i_c) + \frac{d\lambda_{cr}(\theta)}{dt}
 \end{aligned}$$

In balanced system the voltage equation becomes

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ta} & L_{ta} \\ L_{tb} & L_b & L_{cb} \\ L_{ta} & L_{tb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The mathematical model for this motor is described in Equation (1) with the assumption that the magnet has high sensitivity and rotor induced currents can be neglected [3]. It is also assumed that the stator resistances of all the windings are equal. Therefore the rotor reluctance do not change with angle. Now

$$\begin{aligned}
 L_a &= L_b = L_c = L \\
 L_{ab} &= L_{bc} = L_{ca} = M
 \end{aligned}$$

Assuming constant self and mutual inductance, the voltage equation becomes

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

In state space form the equation is arranged as

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -\frac{R}{L} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \frac{1}{L} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

The electromagnetic torque is given as

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

The equation of motion is given as

$$\frac{d}{dt} \omega_r = (T_e - T_L - B\omega_r) / J \quad (3)$$

BLDC Motor Speed control

Block diagram of drive system is shown in Fig.3. In servo applications position feedback is used in the position feedback loop. Velocity feedback can be derived from the position data. This eliminates a separate velocity transducer for the speed control loop. A BLDC motor is driven by voltage strokes coupled by rotor position. The rotor position is measured using Hall sensors. By varying the voltage across the motor, we can control the speed of the motor. When using PWM outputs to control the six switches of the three-phase bridge, variation of the motor voltage can be obtained by varying the duty cycle of the PWM signal.

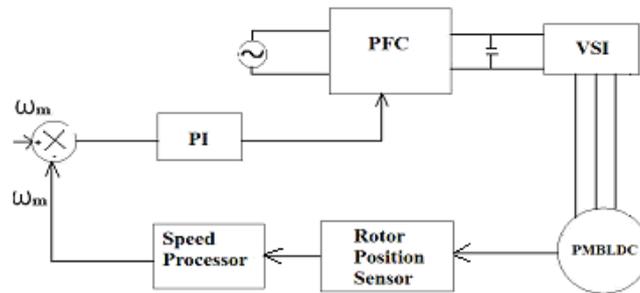


Figure 3: Block Diagram of Drive System.

PMBLDC Motor fed from a Voltage source inverter with PFC Full Bridge Converter

Schematic diagram of a three level voltage source inverter fed PMBLDC motor with PFC full bridge converter is shown in Fig.4. This is a closed loop control circuit using 3 Hall Sensors. MOSFETs are used as switching devices here. To control the speed of the motor the output frequency of the inverter is varied.

To maintain the flux constant the applied voltage is varied in linear proportion to the frequency. The MATLAB simulation is carried out and the results are presented.

For very slow, medium, fast and accurate speed response, quick recovery of the set speed is important keeping insensitiveness to the parameter variations. In order to achieve high performance, many conventional control schemes are employed. At present the conventional PI controller handles these control issues. Moreover conventional PI controller is very sensitive to step change of command speed, parameter variation and load disturbances.

With high frequency switching, the PMBLDC motor rotates at a higher speed. But without the strong magnetic field at stator, the rotor fails to catch up the switching frequency because of weak pull force. Speed of BLDC motor is indirectly determined by the applied voltage magnitude. Current in the winding is increased by increasing the voltage. This produces stronger magnetic pull to align the rotor's magnetic field faster with the induced stator magnetic field. The rotational speed or the alignment is proportional to the voltage applied to the terminals. The torque pulsation is very high as the step size is reduced.

When using PWM outputs to control the six switches of the three-phase bridge, variation of the motor voltage can be achieved easily by changing the duty cycle of the PWM signal. In this method the speed is controlled in a closed loop by measuring the actual speed of the motor. The error in the set speed and actual speed is calculated. A Proportional plus Integral (P.I) controller is used to amplify the speed error and dynamically adjust the PWM duty cycle.

Simulation Results

The technical specifications of the drive system are as follows $C= 2200$ microfarad. $T_{ON}= 5.88 \mu\text{secs}$. $T_{OFF}= 5.88\mu\text{secs}$. $T= 11.76 \mu\text{secs}$. Stator Resistance is 2.875 ohms, Stator Inductance is 8.5e-3mH and inertia of the motor is 0.8e-3J. With the help of the designed circuit parameters, the MATLAB simulation is done and results are presented here. Speed is set at 1800 rpm and the load torque disturbance is applied at time $t=0.6$ sec. The speed response is obtained . The waveforms of input voltage and current are shown in Fig. 5. The waveforms of the phase voltage and currents are shown in Figs 6 and 7 respectively. The waveforms of back EMF are shown in Fig.8. From Fig.5 it can be seen that the power factor is 0.98. The stator current waveforms are shown in Fig 7. They are quasi sinusoidal in shape and are displaced by 120° .

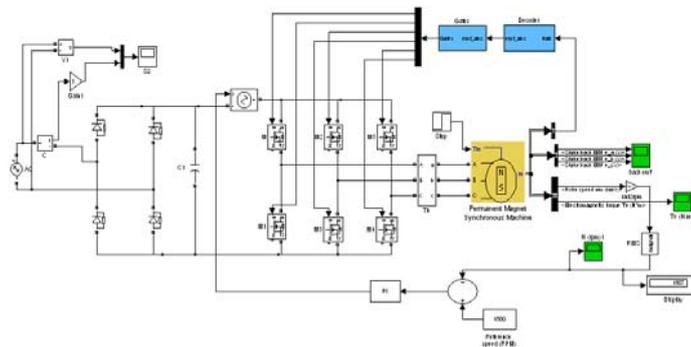


Figure 4: Closed Loop model of PMBLDC Motor.

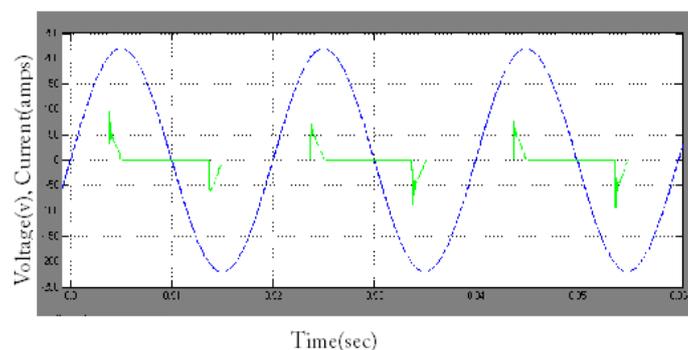


Figure 5: Input voltage and current (PF=0.98).

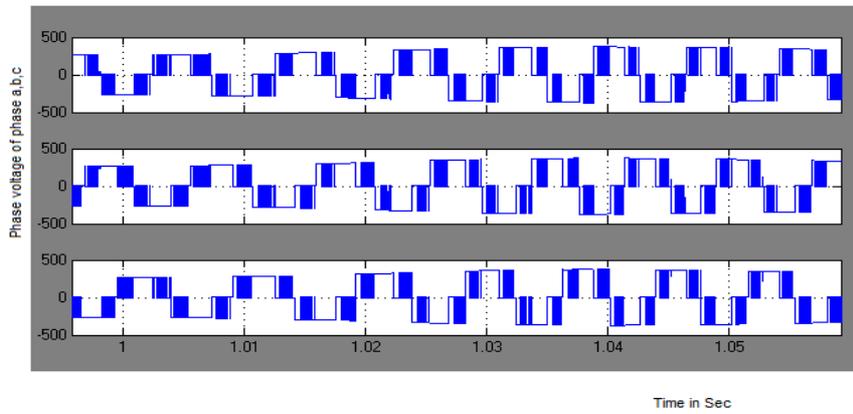


Figure 6: Phase Voltage supplied to the stator windings.

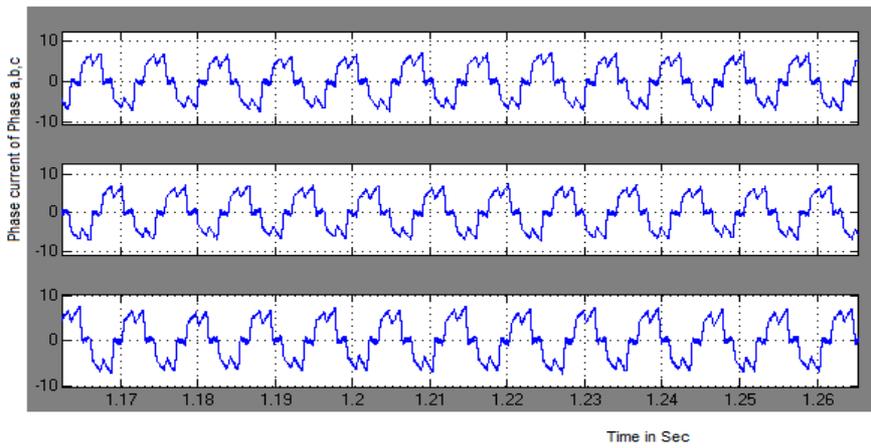


Figure 7: Three phase inverter stator current.

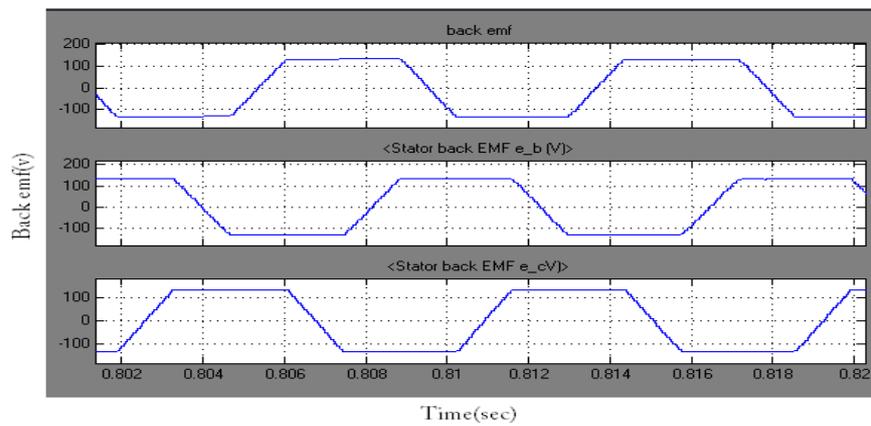


Figure 8: Back emf.

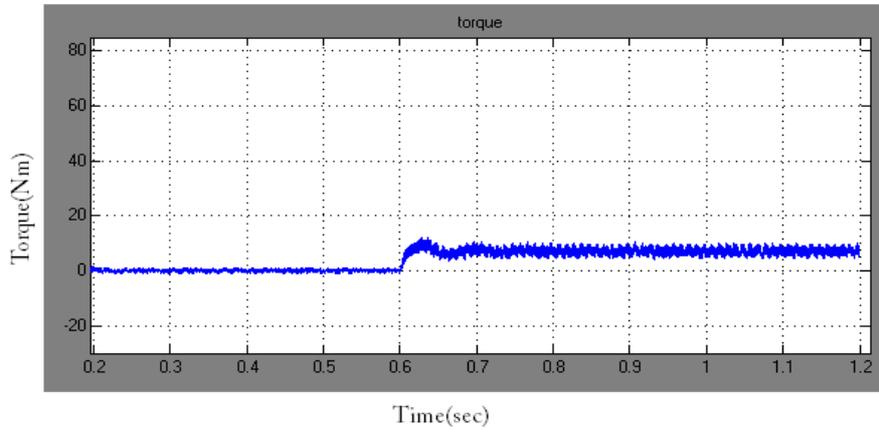


Figure 9: Load Torque disturbance applied at t= 0.6 sec.

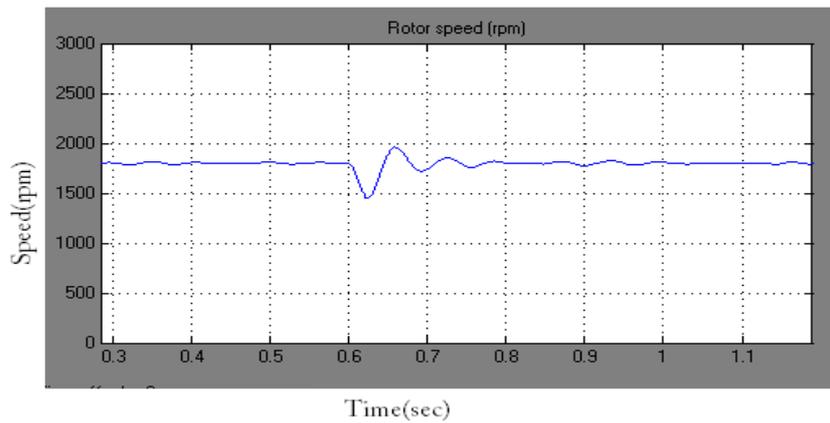


Figure 10: Rotor speed in rpm.

Figure 9 show the load torque disturbance applied at time t=0.6 sec for a set speed of 1800 rpm. From Fig 10, it can be seen that the closed loop system brings the speed to the normal value.

PMBLDC Motor fed from a Voltage source inverter with PFC Half Bridge Converter

Simulink model of closed loop controlled PMBLDC motor with PFC half bridge converter and a PI controller is shown in Fig 11. A boost converter is used at the input to improve the power factor. AC input voltage and current waveforms are shown in Fig 12. The waveforms of back emf are shown in Fig 13. Step change in load torque is shown in Fig 14.

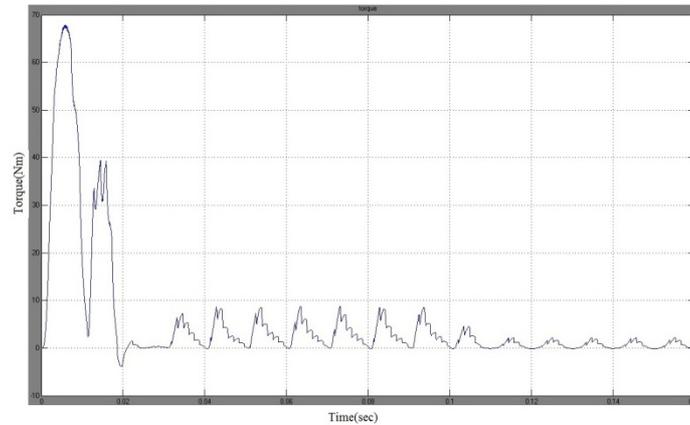


Figure 14: Load torque disturbance applied at t=0.1 sec.

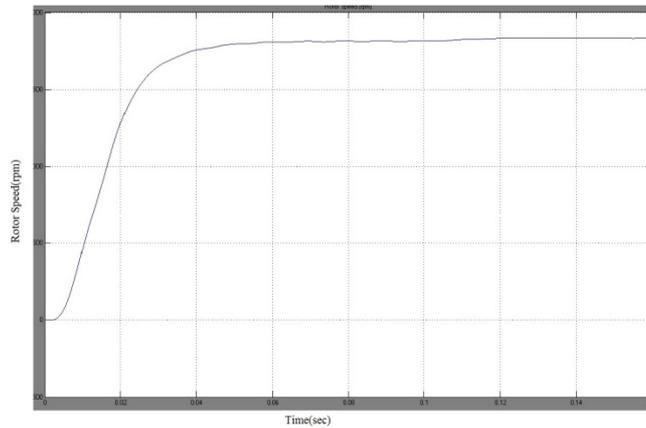


Figure 15: Rotor speed in rpm.

From Fig 15, it can be seen that the closed loop system brings the speed to the normal value and is maintained constant with the disturbance in the load torque. From Fig 12, it can be seen that the power factor is improved by using half bridge PFC converter.

Conclusion

Closed loop controlled VSI fed PMBLDC motor with PFC full bridge and half bridge converters are modeled and simulated. Feedback signals from the PMBLDC motor representing speed and position are utilized to get the driving signals for the inverter switches through a PI controller. The simulation results shown are on par with the theoretical predictions. The power factor is corrected by using PFC converter. PFC converter fed PMBLDC drive is a viable alternative since it has improved power factor.

References

- [1] Tay Siang Hui, K.P. Basu and V.Subbiah, "Permanent Magnet Brushless Motor Control Techniques", National Power and Energy Conference (PECon) 2003 Proceedings, Bangi, Malaysia
- [2] P.Thirusakthimurugan, P.Dananjayan,"A New Control Scheme for the Speed Control of PMBLDC Motor Drive", 1-4244-0342-1/06/\$20.00 ©2006 IEEE
- [3] Nicola Bianchi,Silverio Bolognani, Ji-Hoon Jang, Seung-Ki Sul," Comparison of PM Motor structures and sensorless Control Techniques for zero-speed Rotor position detection",IEEE transactions on Power Electronics, Vol 22, No.6, Nov 2006.
- [4] Woo-Young Choi, Jung-Min Kon, Eung-Ho Kim, Jong-Jae Lee and Bong-Hwan Kwon, "Bridgeless Boost Rectifier with Low Conduction Losses and Reduced Diode Reverse-Recovery Problems", IEEE Transactions on Industrial Electronics, Vol 54, No.2, pp.769-780, April 2007.
- [5] J. C. Salmon, "Circuit topologies for PWM boost rectifiers operated from 1-phase and 3-phase ac supplies and using either single or split dc rail voltage outputs", in Proc. IEEE Applied Power Electronics Conf.,
- [6] Laszlo Huber, Yungtaek Jang, Milan M. Jovanovic, "Performance Evaluation of bridgeless PFC Boost Rectifiers", IEEE Trans ,Power Electronics., Vol.23, No.3, May 2008
- [7] B. Lu, R. Brown, and M. Soldano, "Bridgeless PFC implementation using one cycle control technique", IEEE Applied Power Electronics (APEC) Conf. Proc., pp. 812-817, Mar. 2005 Mar. 1995, pp. 473-479.
- [8] R.Krishnan, Electric Motor Drives Modeling, Analysis, and Control, [Prentice-Hall International Inc., New Jersey, 2001].
- [9] Yong-Ho Yoon Tae-Won Lee Sang-Hun Park Byoung-Kuk Lee Chung, "New Approach to Rotor Position Detection and Precision Speed Control of the BLDC Motor", 1-4244-0136-4/06/\$20.00 '2006 IEEE
- [10] Ling KV, WU Bingfang HE Minghua and Zhang Yu, "A Model predictive controller for multirate cascade system", Proc.of the American Control Conference, ACC 2004, USA, pp.1575-1579.2004
- [11] G.Madhusudhanrao, B.V.Sanker Ram, B.Sampath Kumar, K.Vijay Kumar, Speed, "Control of BLDC Motor using DSP", International Journal of Engineering Science and Technology Vol.2(3), 2010.
- [12] Yingfa Wang, Changliang Xia, Zhiqiang Li, Peng Song, "Sensorless Control for BLDC motor using support vector machine based on PSO", IJCIIS September 2010 Vol. 1 No. 7
- [13] Salih Baris Ozturk, Hamid A.Toliyat, "Sensorless Direct Torque and Indirect Flux Control of Brushless DC Motor with Non-Sinusoidal back-emf", 978-1-4244-1766-7/08 ©2008 IEEE
- [14] Salih Baris Ozturk, William C.Alexander, Hamid A.Toliyat, "Direct Torque Control of four-switch brushless DC motor with non-sinusoidal back emf", IEEE transactions on power electronics", Vol 25, No-2 Feb 2010

- [15] Kuang-Yao Cheng ,”Novel Architecture of a mixed-mode sensorless control IC for BLDC motors with wide speed ranges”, 978-1-422-2812-0/09 ©2009 IEEE.
- [16] M.S.Srinivas, K.R.Rajagopal,”Fuzzy Logic based gain scheduled PI speed controller for PMBLDC motor”, 978-1-4244-4859-3/09 © 2009.
- [17] Ting-Yu-Chang, Ching-Tsai-Pan,Emily Fang,”A novel high performance variable speed PMBLDC motor drive system”, 978-1-4244-4813-5/10 ©2010 IEEE.
- [18] Shinn-Ming Sue, Kun-Lin Wu,”A voltage controlled brushless DC motor over extended speed range”, 978-i-4244-1709-3/08 ©2008 IEEE

Authors Biography



C. Umayal has obtained her ME degree from Anna University, Tamil Nadu, India, in the year 2005. She has 11 years of teaching experience and 8 years of Industrial experience .She is doing her research on PMBLDC motors .She is currently working in Easwari Engineering College, Chennai, TamilNadu, India



B. Rama Reddy Sathi obtained the ME degree from Anna University, Tamil Nadu, India, in the year 1989. He has pursued research in the area of resonant converters in 1995. He has 2 years of industrial experience and 18 years of teaching experience. He has secured A.M.I.E institution Gold medal for obtaining higher marks. He has secured AIMO best project award. He is a life member of IEE, IETE, ISTE, SSI, and SPE. He has worked in Tata Consulting Engineers, Bangalore and Anna University. He has authored textbooks on power electronics and electronic circuits. He has published 20 technical papers in National and International Conference proceedings / journals in the area of power electronics and FACTs.