Simulation and experimental validation of hysteresis current control technique for speed control of brushless DC motor

Hetal Patel1,3* and Hina Chandwani2

1Electrical Engineering Department, C.K.Pithawala College of Engineering and Technology, Surat-395007, Gujarat, India.
2Electrical Engineering Department, Faculty of Technology and Engineering, The Maharaja Sayajirao University, Vadodara-390001, Gujarat, India
3*hetal_ramjiwala@yahoo.co.in

Abstract. Brushless DC Motors (BLDC) are finding wide applications in household appliances and electrical vehicles. Microcontroller are widely used for controlling the BLDC motors however the realization of BLDC drive requires expertise in microcontroller programming. In this paper modelling, simulation and easy hardware implementation of BLDC motor having shaft encoder using STM32F4 series ARM Cortex-M4 microcontroller is demonstrated. A simple method of controlling the BLDC motor in closed loop, using a hysteresis current controller is implemented. The hall sensors are used to find the exact rotor position for the electronic commutation and the encoder is used to measure actual motor speed. The closed loop operation consists of an inner loop which is hysteresis current controller. The gate pulses for the three phase inverter bridge are produced by comparing the actual currents with the reference currents. The outer speed loop consists of a PI controller which compares the actual speed with the reference speed to obtain smooth speed control under varied load condition. The complete hardware circuits and MATLAB/Simulink environment blocks for programming are discussed in detail. The hardware results demonstrate the easy and accurate realisation of closed loop speed control of BLDC Motor.

1. Introduction

In countries like India, with growing demand in new machine technologies, the permanent magnet motors are gaining popularity. Generally the motors used in industries are three phase squirrel cage induction motors because of rugged construction. Nowadays they are replaced by permanent magnet brushless dc motor and permanent magnet synchronous motor due to the advancement in control techniques, reduced size of motor, reduced copper losses as well as less maintenance[1-2]. These motors finds their place in many applications such as domestic, aircraft, automotive, medical, textile industry, spacecrafts etc.as they have high power density and good dynamic performance compared to DC motors and 3-phase induction motors[1-2].

The stator winding inductance prevents the phase current commutation instantly with the change in rotor position resulting in a spike in non-conducting phase current with only two conducting phases in BLDC motor. This is the major cause of producing torque ripple in BLDC motor drive along with the inverter DC link voltage. The performance and dynamic response of the motor can be improved by incorporating current control, voltage control, flux control or torque control methods. To predict and monitor the dynamic performance of the BLDC motor drive [3] proposed an advanced simulation model using hysteresis current control. [4] has implemented the closed loop control of BLDC motor using a PID controller and tested the performance of the drive before and after addition of the load.
[5] has developed a low cost control for BLDC motor drive with one current sensor and a PI controller to regulate the speed using Arduino Mega controller.

Today most of the techniques applied for controlling the speed of BLDC motor use high speed computers, fast ARM controllers, dedicated controllers and digital signal processors, which requires immense coding ability. To control the motor, complicated programming and skilled programmers are required. In some industrial applications constant speed drives are required and when load on motor is variable closed loop operation is compulsory. The mathematical modeling of BLDC motor is accomplished using MATLAB/SIMULINK. The modeled motor is used for performing speed control of BLDC motor using hysteresis current control technique and a PI controller in MATLAB/SIMULINK so that a comparison can be made with hardware implementation. Further hardware implementation is executed using a simple technique to control the speed of BLDC motor using 32 bit arm core ARM controller by interfacing it with MATLAB/SIMULINK WAIJUNG blockset. This method does not require complex coding. WAIJUNG blockset is user friendly similar to simulink blockset.

The closed loop control of BLDC motor with trapezoidal back emf with any two phases carrying current at any instant is developed in this paper sounds to be simple and user friendly. This method does not require any complex transformations like Clarke and Park which is necessary for DTC and FOC of the BLDC and PMSM. This paper discusses the detailed modelling of closed loop controlled BLDC motor drive incorporated with a PI controller and hysteresis controller using MATLAB/SIMULINK platform in section 2. The simulation results helps to validate theoretical concept. It also provides a platform to integrate the hardware implementation with the software implementation to make the drive operation simple without using any complicated programming. The detailed hardware setup is discussed in section 3. The simulation and hardware results are discussed in section 4 and 5.

2. BLDC motor modelling and Simulation

Please The BLDC motor represented by its equivalent circuit with three phase inverter circuit acting as electronic commutator for the motor is as shown in Figure1.

![Figure 1. Equivalent circuit of BLDC motor with 3-phase Inverter as electronic commutator](image)

Let,

\( V_a, V_b, V_c = \) Stator phase voltages
\( i_a, i_b, i_c = \) Stator phase currents
\( e_a, e_b, e_c = \) trapezoidal phase back emf
\( R = \) stator resistance per phase
\( L = \) stator inductance per phase,
\( M = \) mutual inductance

From Figure1, the three phase stator winding can be expressed in terms of motor electrical constants for a balanced 3-Φ system \((i_a+i_b+i_c=0)\) is given by (1) as
From (1) three phase currents $I_a$, $I_b$ and $I_c$ are generated in Simulink. Here line to line voltages and back emf are considered for generation of stator phase currents.

The back emf of BLDC motor is trapezoidal in nature and is a function of rotor position with a magnitude $E$ as expressed in (2)

$$\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} = \omega_m \lambda_s \begin{bmatrix}
f_a(\theta_r) \\
f_b(\theta_r) \\
f_c(\theta_r)
\end{bmatrix}$$

(2)

Where,

$\omega_m$ = rotor speed in radians per sec.

$\lambda_s$ = flux linkage

$\theta_r$ = the rotor position in radian

The electromagnetic torque is expressed as in (3)

$$T_e = (e_a i_a + e_b i_b + e_c i_c) \frac{1}{\omega_m} (N.m)$$

(3)

Equation (4) is expressed in terms of electromagnetic torque, load torque, inertia $J$, friction coefficient $B$ widely known as motion Equation.

$$T_e - T_l = J \frac{d\omega_m}{dt} + B \omega_m$$

(4)

Electrical rotor speed is obtained by differentiating the rotor position as given by (5)

$$\frac{d\theta}{dt} = \frac{P}{2} \omega_m$$

(5)

Based on the above Equations a simulink model describing the BLDC motor as well as the drive operation is incorporated in MATLAB/Simulink environment.

**Figure 2.** Simulink model of a hysterisis current controlled BLDC drive
Figure 2 shows the overall Simulink model of a hysteresis current controlled BLDC motor model consisting of a back emf generation block, three phase current generation block, torque and speed control using a PI controller, reference current generation block and generation of switching logic using a hysteresis current controller block.

Equation [1] is used for BLDC motor model represented in Figure 1. The trapezoidal back emf is generated using Equation (2) where \( f_{ae}(\theta) \) is function of rotor position and is formulated using Equation (6) as shown in Figure 3.

\[
e_{ae} = \begin{cases} 
\left( \frac{6E}{\Pi} \right) \omega r + 6E & 0 < \omega r < \frac{\Pi}{6} \\
\left( \frac{6E}{\Pi} \right) \omega r & \frac{\Pi}{6} < \omega r < \frac{5\Pi}{6} \\
\left( \frac{6E}{\Pi} \right) \omega r - 12E & \frac{5\Pi}{6} < \omega r < \frac{7\Pi}{6} \\
E & \frac{7\Pi}{6} < \omega r < \frac{11\Pi}{6} \\
-6E & \frac{11\Pi}{6} < \omega r < 2\Pi 
\end{cases}
\]  

(6)

The line voltages and back emf are used to generate the three phase currents as only two phases are conducting from Equation (1) as shown in Figure 4.

The electromagnetic torque is a function of back emf, current and speed as represented in Equation (3). The electrical rotor position is obtained by integrating the motor speed. is as shown in Figure 5. A PI controller block is used to process the error produced by comparison of the set speed with the actual speed as shown in Figure 5. The output of which is torque reference which when divided by torque constant \( K_t \) gives the maximum current \( I^* \) which is used to generate three reference currents. Tuning of a PI controller is generally done using a trial and error method. A simple way to tune the drive is discussed using the mechanical and electrical time constants as given in Equations (6) and (7). This time constants depends on the motor parameters. Using this time constant a transfer function is obtained using Equation (8).

\[
T_{eq} = \frac{J3R}{K_eK_i} 
\]  

(8)
\[ \tau_e = \frac{L}{3R} \]  
(7)

\[ G_s = \frac{1}{K_e \tau_m L + \tau_m S + 1} \]  
(8)

Figure 5. Transfer function based BLDC motor modelling for PI controller tuning.

Figure 6. Torque and speed control block

This BLDC transfer function is obtained using Equation (8) is utilized as shown in Figure 5 to tune the PI controller. The tuned block is then placed in Figure 6 which process the error signal from which maximum torque is obtained. To generate the maximum current the maximum torque is divided by torque constant \( K_t \) as

Using the knowledge of the maximum current \( I^* \) obtained from Figure 6, three reference currents are generated as shown in Figure 7 based on the rotor position as given in Table 1.

Table 1. Generation of three reference currents

| Rotor Position \( \theta \) (degree) | Three Reference Currents \( I_{\text{aref}}, I_{\text{bref}}, I_{\text{cref}} \) |
|-------------------------------------|---------------------------------|
| 0-60                                | \(-I^*\) \( + I^* \) \(- \) |
| 60-120                              | \(-I^*\) \(- \) \( + I^* \) |
| 120-180                             | \(- \) \(-I^*\) \( + I^* \) |
| 180-240                             | \( + I^*\) \(-I^*\) \(- \) |
| 240-300                             | \( + I^*\) \(- \) \(-I^*\) |
| 300-360                             | \(- \) \( + I^*\) \(-I^*\) |

The reference currents are compared with the actual currents using a hysteresis current controller. A hysteresis controller is modeled with a narrow hysteresis band of \( \pm 0.1 \). If the error is greater than the hysteresis band upper switch is ON and if error is less than the hysteresis band lower switch conducts to produce pulse width modulated gate pulses as shown in Figure 8 for the three-phase inverter shown in Figure 1.
3. System Implementation

Hardware implementation of closed loop control of BLDC motor is implemented as shown in Figure 9. The Hardware setup consists of a current sensor card, driver card, 3-phase inverter card acting as electronic commutator, BLDC motor with hall sensor/shaft encoder, STM32 discovery card.

Figure 10 shows the interfacing of Hardware circuit with MATLAB/ SIMULINK WAIJUNG block set to generate gate pulses for the IGBT switches of the three-phase bridge inverter circuit. BLDC motor with the parameters as given in Table 2 is used for experimentation.

For operating BLDC motor the key factor is the acknowledgement of rotor position and energizing two phase windings. In sensored BLDC motor magnetic hall sensors are used for acknowledgment of correct rotor position. Here a shaft encoder is used for detecting the rotor position is used. In some motors hall sensors are available to provide rotor position. Generally 120° hall sensing technique is used. Three different hall sensors are located at three different places in stator winding. When they are moved in bipolar magnetic field they generate TTL compatible output [6] that can be interfaced with logic circuit or controllers.

For every hall sequence there are two possible combinations of inverter switches that with one combination the motor will rotate in clockwise (forward) direction and for other it will rotate in
counter clockwise(reverse) direction. The hall sequence and the respective switching combinations are discussed in brief in this paper. For changing the direction of rotation of motor the only thing required is the selection of proper switches at a particular hall sequence[7].

In BLDC motor with trapezoidal back emf, at any instant only two phases of the stator winding conducts. For closed loop operation of motor, inner current loop with low computational time than outer speed loop is used. A hysteresis controller acting as a current comparator is used to compare the actual motor current with the reference currents within a hysteresis band to produce six pulse width modulated signals for the six inverter switches. A PI controller is used to process the error produced by comparing the actual speed with the set speed[5]. The closed loop speed control of BLDC motor requires the following hardware as well as software implementation:

- BLDC motor set with Encoder/Hall sensors.
- IGBT Driver and Power Card
- STM32 Discovery Card
- ARM Cortex M4 - WJ - 32 Bit Kit
- Matlab 2014a
- MDK516a (Keil ARM IDE)
- STM32 ST-LINK Utility_v2.3.0
- WAIJUNG14_12a or higher

3.1 BLDC motor with Shaft Encoder

A permanent magnet brushless DC motor of 36 volt, with concentrated winding producing a trapezoidal back emf and quasi square wave currents with only two phases excited at a time is used for hardware implementation. A shaft encoder with resolution of 5000 PPR is mounted on the shaft. The speed of the motor is calculated from the output of the encoder using controller. Unlike the DC motor which have mechanical commutator BLDC motor requires electronic commutator. The switching of the electronic commutator depends on the rotor position. The rotor position required for producing the commutation logic for the inverter circuit is also obtained using encoder. The motor is provided with a loading arrangement which helps to study motor behavior with change in load.

Table 2. BLDC Motor Parameters

| Parameters       | Values          |
|------------------|-----------------|
| Voltage (V)      | 36 volt         |
| Poles (P)        | 4               |
| Rated Speed (N)  | 4000 rpm        |
| Rated Torque (T) | 0.32 Nm         |
| Resistance per phase (R) | 0.5 Ω      |
| Inductance per phase (L-L) | 1.65 mH |
| Moment of inertia (J) | 17.3*10⁶ Kg-m² |
| Torque Constant (Kt) | 0.061 Nm/A |

3.2 Operation of 3-Φ Inverter as Electronic Commutator

The output of the incremental shaft encoder is given to the QEI pins of the controller to collect the information of rotor position. There are six commutation states in one electrical cycle depending on the rotor position. To obtain correct switching combinations for the electronic commutator a simple method is discussed for motor with hall sensors. For example if the present hall sensor state is 101 and the possible switch combinations are 1&2, 2&3, 3&4, 4&5, 5&6, 6&1. Out of these six combinations only two combinations are correct. For that two combinations the motor will rotate once in forward direction and then in reverse direction. The switching pattern matches with that of 3-Φ, 120° conduction mode inverter. This can be obtained by a switch matrix at initial stage. For every
commutation state or hall sequence there are two possible combinations of inverter switches that with one combination the motor will rotate in forward direction and for other it will rotate in reverse direction as shown in Table 3

| Commutation States | Switch Combinations |
|--------------------|---------------------|
| H_A                | H_B                | H_C    | Forward | Reverse |
| 1                  | 0                  | 1      | S3, S4  | S1, S6  |
| 1                  | 0                  | 0      | S4, S5  | S1, S2  |
| 1                  | 1                  | 0      | S5, S6  | S2, S3  |
| 0                  | 1                  | 0      | S6, S1  | S3, S4  |
| 0                  | 1                  | 1      | S1, S2  | S4, S5  |
| 0                  | 0                  | 1      | S2, S3  | S5, S6  |

3.3 Driver Circuit
The driver circuit is used for driving the IGBTs of Inverter card as well as to provide isolation between control circuit and power circuit. Here a Infineon made driver card is used for driving the six IGBT switches. Each switches are provided separate isolation from a coreless transformer to isolate their supply and ground terminals.

3.4 Current Sensor
Current sensors are used to measure the three-phase stator current. For this current transformers are used. The measured current is fed to the ADC of STM32 discovery card. A unipolar signal is to be provided to the ADC whose operating range is from 0-3.3 volts.

3.5 STM32Discovery Card with WAIJUNG
STM32F407VGT6 microcontroller is a 32-bit ARM controller with FPU core[8]. The controller is featured with 1MB Flash memory for coding large data, 192-Kbyte RAM which helps in storing large data with LQFP100 package is used in hardware, which facilitates the closed loop control of drive. STM32 bit Arm controller has generic core which facilitates C coding. The software requirement is MATLAB 2014a which has a WAIJUNG block set. Installation of MDK516a (Keil ARM IDE) and STM32 ST-LINK Utility_v2.3.0 along with MATLAB 2014a to interface STM32Discovery card with WAIJUNG block set is required.

In this hardware implementation of BLDC drive, the hysteresis current controller and PI controller are modeled in MATLAB/SIMULINK WAIJUNG block set which generates C code automatically for STM32 ARM controller. For this the MATLAB model is interfaced with the microcontroller to dump the code generated by WAIJUNG block set.

3.6 Generation of Gate pulses for 3-phase Inverter Bridge
Generally closed loop operation of BLDC motor using 32 bit ARM Controller requires knowledge of assembly language or C coding. In this paper a simple technique is used in which no coding is required. The 32 it ARM controller is interfaced with the MATLAB/SIMULINK model. Programming of the microcontroller is done using WAIJUNG block set in MATLAB/SIMULINK library [9].

At first, target set up from the device configuration block is done as shown in Figure 11. The selection of ADC, DAC, timers etc. is done from the onchip peripherals readily available. From hardware modules the Character LCD display is selected to display set speed and actual speed. ADC is used to convert analog value in digital value. As ADC is 12 bit, hence 4095 count is available. This count can be calibrated in terms of speed, current, voltage, frequency, modulation index etc.. Maximum voltage to ADC is 3.3 volt. For an analog signal of 0 to 3.3-volt, ADC gives a 0 to 4095
count. Here three phase currents are measured by the CT. The value of current is calibrated as 5A (rms) to 3 Vpp. DAC converts digital signal to analog. Here it is used to convert angle theta into analog value. Actual speed of motor is calculated from theta. The actual speed is compared with the set speed. A PI controller is used to process the error. The output of the PI controller is torque reference from which maximum current is obtained. This signal is used to generate three reference current based on rotor position as mentioned in Table 1.

This reference currents are compared with the actual measured currents within a narrow band of 0.05 using hysteresis controller to generate gate pulses. Advanced Timer-8 is used to generate the six gate pulses for the three-phase inverter. A dead band of 1-micro second is kept between the upper and lower switch of the same phase leg, to avoid shoot through. Execution time of the overall system as shown in Figure 11 is approximately 100 µs. WAIJUNG also facilitates the display of set speed and actual speed on the LCD display.

**Figure 11.** Generation of gate pulses for three phase inverter circuit using MATLAB/SIMULINK WAIJUNG block

4. Simulation Result and Discussion

Simulation result of BLDC motor drive with hysteresis current control technique is as shown in Figure 12 to Figure 17. The results are obtained from Figure 2. Initially the motor speed is set at 1000 rpm. At time t=0.8 sec the set speed is changed to 2000 rpm. The change in back emf, stator current and torque is observed in the results. Again at time t= 1.5 sec, the motor speed is reduced to 1500 rpm. It is observed that the time taken by the controller to reach the set speed is very less and is not noticeable for higher speed. Figure 12 shows the variation in phase back emf with the zoomed results of phase back emf as shown in Figure 13. Figure 14 shows the variation in stator phase current with the zoomed stator phase current as shown in Figure 15. The variation in speed according to the set speed can be observed in Figure 16. The behavior of electromagnetic torque with respect to time with the applied speed is as shown in Figure 17.
5. Experimental Results and Discussion

Experimental results prove the workability of the method in actual practice. It provides the actual behavior of the system and a platform to compare the simulation results with the actual results. Hardware results of closed loop control of BLDC motor are captured using DSO. The control scheme is tested on 36volts BLDC motor with motor parameters described in Table 3. Waveforms of back emf, stator current, rotor position theta as well as the variation of actual speed with the set speed can be seen in the following figures. It can be seen from Figure 18, that the motor back emf is trapezoidal in
nature with quasi square wave currents. The variation of back emf and stator current with rotor position can be seen in Figure 19 and 20.

Precise tuning of the PI controller is done to allows the actual speed to vary according to the reference speed as shown in Figure 21. It can be seen that as the load vary the PI controller takes corrective actions to reduce the error and maintains the actual speed of motor equal to the set speed of 2000 rpm. A maximum loading of up to 2.5 ampere is given on the motor.

![Figure 18](image1.png) ![Figure 19](image2.png)

**Figure 18.** Back emf and Stator Current at a speed of 2000 rpm  
**Figure 19.** Back emf and Theta at a speed of 2000 rpm

![Figure 20](image3.png) ![Figure 21](image4.png)

**Figure 20.** Theta and Stator Phase Current at a speed of 2000 rpm  
**Figure 21.** Variation in Actual speed with defined set speed

6. CONCLUSIONS

The popularity of the BLDC motor in the international drive market is increasing very fast especially in automobile engineering, textile industry and home appliances. This paper depicts a simple and effective speed controlling technique with MATLAB Waijung blockset which does not require 32bit coding or C programming. The BLDC motor is first modelled with actual motor parameters and then simulation of the same is carried with a hysteresis current control technique in MATLAB/SIMULINK. To validate the simulation results, hardware implementation is carried out on a 36volt motor by interfacing the hardware modules with MATLAB/SIMULINK simulation which is used to produce six gate pulses for the 3-phase inverter bridge which drives the motor using correct switching logic. The loading to the motor is given with the belt and pulley arrangement. It can be observed from hardware results that fine tuning of PI controller makes the motor to follow the set speed despite of variation in load.

References

[1] P. Pillay and R. Krishnan (1989). Modelling, simulation, and analysis of permanent-magnet motor drives, part II: the brushless DC motor drive, *IEEE Trans. on Industry Applications*, vol. 25, no. 2, pp. 274–279.
[2] T.J.E. Miller (1989). *Brushless Permanent Magnet & Reluctance Motor Drives*. Clarendon Press, Oxford, Vol.2, pp: 199.

[3] B. K. Lee and M. Ehsani (2003). *Advanced Simulation Model for Brushless DC Motor Drives*, Electric Power Components and Systems, 31:9, 841-868.

[4] Huazhang WAN (2012). *Design and Implementation of Brushless DC Motor Drive and Control System* International Workshop on Information and Electronics Engineering (IWIEE), Procedia Engineering 29 (2012) 2219 – 2224.

[5] Ghen Mohamed Dahbi, Said Doubabi, Ahmed Rachid (2020). *European Journal of Electrical Engineering*, vol. 22. No. 1, February, 2020, pp 63-69.

[6] Padmaraja Yedamale, *Brushless DC (BLDC) Motor Fundamentals*, Microchip, Application Note AN885

[7] B. K. Lee and M. Ehsani(2001). A simplified functional model for 3-phase voltage-source inverter using switching function concept,” *IEEE Trans. on Industrial Electronics*, vol. 48, no. 2, pp. 309–321, April 2001.

[8] https://www.st.com

[9] http://waijung.aimagin.com