Designing an Efficient Three Phase Brushless DC Motor
Fuzzy Control Systems (BLDCM)

Rafid Ali Ridha Ibrahim
Department of Physics
University of Kirkuk /College of Science
Kirkuk, Iraq
ibrahim_aslanuz@yahoo.com

Inas Bahaa Abedalrazzaq Deaibil
Department of electrical engineering
University of Kirkuk/College of Engg.
Kirkuk, Iraq
inasrafed@yahoo.com

Abstract

In this paper presented a model of three phase BLDC motor. Also presented the construction and operation also derived the state space model of brushless Dc motor. Matlab/simulink models are derived to observed and analyzed the dynamic characteristics of the BLDC motor speed, torque, currents and voltages of the inverter components. Fuzzy control presented in this paper.

Keywords: component; BLDC Motor, FLC control, PWM Pulse Width Modulation

Introduction

Brushless Direct Current (BLDC) motors are among the motor types, which are becoming popular in recent years. The stator of a BLDC motor consists of stacked steel laminations[1],[2]. The windings are placed in the slots that are axially cut along the inner periphery or around the stator. The rotor is made of permanent magnets and can vary from two to eight pole pairs with alternating south poles and north poles. The stator windings should be energized in a sequential order in order to operate the BLDC motor properly. Hence it is necessary to know the rotor position in order to understand the winding to be energized at a specific time instant. In the BLDC motor, power transistors are used for changing the polarity, which is performed by switching the transistors in synchronization with the rotor position. BLDC motors often include either internal or external position sensors to sense the actual rotor position.

In a traditional DC motor (brushed DC motor), the brushes make mechanical contact with a set of electrical contacts on the rotor. These contacting materials are called as commutator. This mechanical contact causes an electrical conduction between the armature coil windings and the DC electrical source[3],[4]. The stationary brushes contact with different sections of the rotating commutator as the armature rotates on its
axis. The brushes and the commutator system forms a set of electrical switches, each firing in sequence, such that electrical power always flows through the armature coil closest to the stationary stator permanent magnet.

In a BLDC motor, the permanent magnets rotate and the armature coils remains static[5]. The problem is how to transfer current to a moving armature. Replacing the commutator assembly with an intelligent electronic controller solves this problem. The controller performs the same power distribution observed in a brushed DC motor. However BLDC use a solid-state circuit instead of a mechanical commutator. BLDC motor has a trapezoidal back-EMF and rectangular stator currents are necessary to produce a constant electrical torque. Usually hysteresis or pulse width modulated (PWM) current controllers are used to maintain the actual currents as close as possible to the rectangular reference values[6], [7]. Although some steady-state analysis has been performed, the design of the BLDC motor servo system usually requires a long time trial and error process, and fails to exhibit an improvement in the performance. In practice, the design of the BLDC motor drive requires some complex tasks to be completed such as devising of control scheme, modeling, simulation and parameters adjustment. The proportional integral (PI) controllers are generally suitable for the linear motor control and they have been widely proposed for BLDC motors. But in practice, BLDC motors have many non-linear factors imposed by the driver and the load causing a decrease in the performance. In order to achieve desired level of performance the motor needs appropriate speed controllers and that is only possible with fine-tuning of controller parameters. Usually the speed control is achieved by using PI controller in case of permanent magnet motors. In industry, conventional PI controllers are preferred due to ease of implementation and as they possess simple control structure. The drawback of PI controllers arises when there are some control complexities like nonlinearities, parametric variations and load disturbances. Moreover PI controllers need precise linear mathematical models, however the permanent magnet BLDC machine has a nonlinear model, hence the linear PI may no longer be suitable.

The Fuzzy Logic (FL) approach applied to speed control leads to an improved dynamic behavior of the motor drive system and they can be easily implemented for disturbance like load. Fuzzy logic controller (FLC) provides an improvement in the quality of the speed response. Most of these controllers use mathematical models and are sensitive to parametric changes. These controllers are inherently robust to load disturbances. In addition, FLCs could be easily implemented. Due to these properties it is designed to use a FLC for the BLDC motor.
BLDC Motor Mathematical Model

A. Principal Construction BLDC Motor

BLDC motor has two important components: the rotor part and the stator part. BLDC motor can be categorized as DC motor that is turning inside out, so that the armature is on the stator side and the permanent magnet is on the rotor side. It can also be categorized as a permanent magnet AC motor whose torque-current characteristics resembles the DC motor. In a BLDC motor, electronic commutation is used instead of commutating the armature current using brushes. Besides, as the armature lie on the stator, it is easier to conduct the heat produced in the motor away from the windings hence the cooling facility of the motor is provided automatically.

In BLDC motors it is important to precisely determine the position of the rotor since the commutation is performed electronically due to the rotor position. The position of the rotor may be sensed using optical position sensors. Optical position sensors consist of a light source and phototransistors’ revolving shutters. The output of an optical position sensor is generally a logical signal.

B. Architecture of BLDC System

The block diagram of a BLDC motor control system is shown in the Fig. 1. The block diagram contains four main parts. These parts are the power converter, controller, motor and sensors.

![Block diagram of BLDC motor control](image)

**Figure 1** Block diagram of BLDC motor control

In Fig. 2 the circuit diagram of the power converter is given. The power converter consists of a three-phase power semiconductor bridge. The main task of the power converter is to transform DC power from the DC source to a balanced three-phase AC power. This AC power is used to convert electrical energy to mechanical energy.
In order to operate the BLDC motor the controller needs feedback information about the rotor position[9,10]. The controller generates signals, which drive the power converter by using a pulse width modulation (PWM) modulator. The internal block diagram of the power converter and controller is shown in Fig. 3. In BLDC motor the rotor speed and supplied voltage are directly proportional. In a PWM controller, the PWM duty cycle controls the voltage [8]. When the voltage is applied, a current flows through the windings of the motor and this current generates torque in order to spin the motor. The motor can spin either in clockwise or counterclockwise direction depending on polarity of the applied voltage. The sensors are used to determine the rotor position and this information is also sent to the controller.
C. BLDC Drives Operation with Inverter

The circuit diagram of a BLCD motor with controller and power source inverter is shown in Fig. 4. The inverter in self-control mode acts as an electronic commutator. It receives the switching logical pulse from the position sensors[11]. This kind of motor drive is known as an electronically commutated motor. Mainly the inverter can work by using the following two modes

• (2π/3) angle switch-on mode

• Voltage and current control PWM mode

![Figure 4 Brushless DC Motor Drive System](image)

BLCD Motor Dynamic Model

In Fig. 5, the BLDC motor electrical model with voltage source inverter is shown. In this model the motor is connected to the output of the inverter, and a constant voltage is supplied to the terminals of the inverter. While constructing the model it is also assumed that there are no power losses in the inverter and the windings of the motor[12].
We can write the phase voltage equations of BLDC motors as follow:

\[ V_a = R_a I_a + L_a \frac{dI_a}{dt} + M_{ab} \frac{dI_b}{dt} + M_{ac} \frac{dI_c}{dt} + e_a \]
\[ V_b = R_b I_b + L_b \frac{dI_b}{dt} + M_{ba} \frac{dI_a}{dt} + M_{bc} \frac{dI_c}{dt} + e_b \]
\[ V_c = R_c I_c + L_c \frac{dI_c}{dt} + M_{cb} \frac{dI_b}{dt} + M_{ca} \frac{dI_a}{dt} + e_c \]

(1)

In these equations \( V_a \), \( V_b \) and \( V_c \) are the respective phase voltages of the windings, \( I_a \), \( I_b \) and \( I_c \) are the stator currents for each phase, \( R_a \), \( R_b \) and \( R_c \) are the stator resistance values per phase, \( M_{ab} \), \( M_{ba} \), \( M_{bc} \), \( M_{cb} \), \( M_{ac} \) and \( M_{ca} \) represent mutual inductance values between each phase and \( L_a \), \( L_b \) and \( L_c \) stand for self inductance values per each corresponding phases.

We can assume that
\[ L_a = L_b = L_c = L \]

And
\[ M_{ab} = M_{ba} = M_{ac} = M_{ca} = M_{bc} = M_{cb} = M \]

As the windings are symmetrical and identical.

We can also take
As we are assuming the system is a three phase balanced system. Using above assumptions we can rewrite Equation 1, as follow:

\begin{align*}
V_a &= RI_a + L \frac{dl_a}{dt} + M \frac{dl_b}{dt} + M \frac{dl_c}{dt} + e_a \\
V_b &= RI_b + L \frac{dl_b}{dt} + M \frac{dl_a}{dt} + M \frac{dl_c}{dt} + e_b \\
V_c &= RI_c + L \frac{dl_c}{dt} + M \frac{dl_b}{dt} + M \frac{dl_a}{dt} + e_c
\end{align*}

Neglecting the mutual inductance values (M) from the Equations 2, 3 and 4 we obtain:

\begin{align*}
V_a &= RI_a + L \frac{dl_a}{dt} + e_a \\
V_b &= RI_b + L \frac{dl_b}{dt} + e_b \\
V_c &= RI_c + L \frac{dl_c}{dt} + e_c
\end{align*}

We can combine Equations 5, 6 and 7 in a matrix as follow:

\begin{equation}
\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 & 0 & 0 \\
0 & L & 0 \\
0 & 0 & L
\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}
\end{equation}

Using equation (8) we can also find:

\begin{equation}
V_{ab} - e_{ab} = R(I_a - I_b) + L \frac{d}{dt}(I_a - I_b)
\end{equation}
\[ V_{bc} - e_{bc} = R(I_b - I_c) + L \frac{d}{dt}(I_b - I_c) \]
\[ V_{ca} - e_{ca} = R(I_c - I_a) + L \frac{d}{dt}(I_c - I_a) \]

(9)

Defining the loop current as I1, I2 and I3 we can also write
\[ I_a = I_1 - I_3 \]
\[ I_b = I_2 - I_1 \]
\[ I_c = I_3 - I_2 \]

(10)

In Fig. 6 generation the three phase current Ia, Ib, Ic is show.

As only two phases are exited through a conduction period Equation in 9 can be rewritten as,
\[ V_{ab} - e_{ab} = 2RI_1 + 2L \frac{dI_1}{dt} \]
\[ V_{bc} - e_{bc} = 2RI_2 + 2L \frac{dI_2}{dt} \]
\[ V_{ca} - e_{ca} = 2RI_3 + 2L \frac{dI_3}{dt} \]

(11)
In terms of functionality BLDC motors are generally put in the category of Permanent Magnet Alternating Current (PMAC) motors. PMAC motors can be grouped into two types. The first type is represented as permanent magnet synchronous motor (PMSM). This motor produce sinusoidal back-EMF and it must be supplied with sinusoidal current / voltage source. The second type is BLDCD motor and it has trapezoidal back-EMF. The back-EMF voltage is produced over the windings of the motor, while the motor is rotating. The polarity of back-EMF is in reverse direction compared to the corresponding phase voltage. Basically back-EMF depends on three factors: magnetic field generated by rotor magnets, mechanical angular velocity of the rotor and the number of turns in the stator windings. Hence, the produced trapezoidal back-EMFs for each phase are functions of the rotor position, and mathematically they can be written as[13-14]:

\[
e_a = f_a(\theta)K_e W_m \\
e_b = f_b(\theta)K_e W_m \\
e_c = f_c(\theta)K_e W_m
\]  

(12)

In Equation 12, \( \theta \) represented the rotor electrical position, \( w_m \) represents the rotor mechanical speed, \( f_a(\theta), f_b(\theta) \) and \( f_c(\theta) \) are the functions of rotor position and \( K_e \) is the motor voltage constants for each phase. The modeling of the back-EMF waveforms is implemented according to the assumption that all three phases have identical trapezoidal periodical back-EMF waveforms with 120 degrees phase difference between each of them. The functions of the rotor position \( f_a(\theta), f_b(\theta) \) and \( f_c(\theta) \) in a single period can be represented using the equations below:

\[
f_a(\theta) = \begin{cases} 
\left( \frac{6}{\pi} \right) \theta & 0 < \theta < \frac{\pi}{6} \\
1 & \frac{\pi}{6} < \theta < \frac{5\pi}{6} \\
-\left( \frac{6}{\pi} \right) \theta + 6 & \frac{5\pi}{6} < \theta < \frac{7\pi}{6} \\
-1 & \frac{7\pi}{6} < \theta < \frac{11\pi}{6} \\
\left( \frac{6}{\pi} \right) \theta + 12 & \frac{11\pi}{6} < \theta < 2\pi 
\end{cases}
\]  

(13)
\[
\begin{align*}
\text{f}_b(\theta) &= \begin{cases} 
-1 & 0 < \theta < \frac{\pi}{2} \\
\left(\frac{6}{\pi}\right) \theta - 4 & \frac{\pi}{2} < \theta < \frac{5\pi}{6} \\
1 & \frac{5\pi}{6} < \theta < \frac{9\pi}{6} \\
-\left(\frac{6}{\pi}\right) \theta + 10 & \frac{9\pi}{6} < \theta < \frac{11\pi}{6} \\
-1 & \frac{11\pi}{6} < \theta < 2\pi
\end{cases} \\
\text{f}_c(\theta) &= \begin{cases} 
-1 & 0 < \theta < \frac{\pi}{6} \\
\left(\frac{6}{\pi}\right) \theta - 4 & \frac{\pi}{6} < \theta < \frac{\pi}{2} \\
1 & \frac{\pi}{2} < \theta < \frac{7\pi}{6} \\
-\left(\frac{6}{\pi}\right) \theta + 10 & \frac{7\pi}{6} < \theta < \frac{9\pi}{6} \\
-1 & \frac{9\pi}{6} < \theta < 2\pi
\end{cases}
\end{align*}
\]

\(f_a(\theta), f_b(\theta)\) and \(f_c(\theta)\) can take values between 1 and -1.

We know that the torque produced per phase is directly proportional with the phase current and back-EMF and inversely proportional with the mechanical angular velocity of the motor. Hence torque produced at each phase can be written as:

\[
\begin{align*}
T_a &= \frac{e_a}{W_m} \\
T_b &= \frac{e_b}{W_m} \\
T_c &= \frac{e_c}{W_m}
\end{align*}
\]

(16)

The total electromagnetic torque is the result of summation of the torques produced at each phase. Thus we obtain,

\[
T_e = T_a + T_b + T_c
\]

(17)
In Equation 17, $T_e$ is the total electromagnetic torque. The equation of motion for the BLCD motor can be written as,

$$\frac{d\omega_m}{dt} = \frac{1}{J} (T_e - T_1 - BW_m)$$

(18)

In Equation 18 $T_1$ is the load torque, $B$ is the damping constant and $J$ is the moment of inertia of the motor. The relation between the mechanical angular speed of the motor and the electrical angular frequency of the motor depends on the number of poles found on the motor and it can be written as,

$$\omega_r = \frac{p}{2} \omega_m$$

(19)

In Equation (19), $\omega_r$ is the electrical angular frequency (speed) of the motor and $p$ is the number of poles. In order to find the rotor position vector $\theta$, we can use Equation (2.22) and the Fig. 7 show who we obtain $(\theta, I_{max}, W_r)$.

$$\frac{d\theta}{dt} = W_r$$

(20)

Fig. 7 Block diagram for speed and torque control

The mechanical angular speed of the motor is controlled by a control signal, which is the reference torque value $T_{max}$ produced by the controller. This control signal $T_{max}$ is converted to the current value $I_{max}$ (the reference current value) by the torque equation

$$I_{max} = \frac{T_{max}}{K_t}$$

In Equation (21) $k_t$ is the torque constant of the motor.
FLC Controller

In this section instead of using P or PI controller we decided to use FLC to stabilize the BLCD motor speed. In order the see the efficiency of the FLC we used two different rule base structures. These rule base structures are given at Table 1 and 2.

![Table 1: Rule of Fuzzy Logic control case1](image)

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<th>3</th>
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![Table 2: Rule of Fuzzy Logic control case2](image)

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In the first simulation the rule-base structure in Table 1 is used. The normalization factors are taken as $N_{e1} = 1/220$, $N_{e2} = 1/5000000$ and $N_u = 1500$. As the result of the simulation the mechanical angular speed profile shown in Fig. 8 is obtained.

![Fig. 8: Mechanical speed of FLC case 1](image)
In the second simulation the rule-base structure in Table 2 is used. The normalization factors are taken as $N_{e_1} = 1/220$, $N_{e_2} = 1/5000000$ and $N_u = 1500$. As the result of the simulation the mechanical angular speed profile shown in Fig. 11 is obtained.
From Fig. 11, we obtained the following performance indices:

There is no overshoot in the response, $t_r = 0.0124$ second, $w_{m, ss} = 399.91$, $t_s = 0.0119$. The equivalent torque and the Imax graphs for this simulation are shown in Fig. 12 and 13 respectively. As we observe there is not so much difference between these performance indices of these two FLC simulations however the steady state value of the second simulation is slightly better the first simulation.
Conclusion

BLDC are used replacing DC motors in different application. These applications like steering wheel, pumps, and blowers. In this thesis a Matlab/simulink model for BLDC motor drives is proposed. We implemented Fuzzy controller (FLC). Also this simulink allows as to see many dynamic characteristics such as mechanical angular velocity, voltages, mechanical torque phase currents. We can conclude that FLC is the best method because desired speed and torque values could be reached in a short time and we take four indices to show the different between the controller. these indices are: the comparison of the steady state value and the reference set point value of the mechanical angular speed, maximum overshoot value, rise time (tr) and the fourth one is the settling time value (ts). This reason FLC used widely in industrial applications in comparison with other controller.

References


