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Speed Control of Brushless DC Motor: A Review

Halavadia Akash Natvarlal[1], Prof. M. J. Modi[2]

[1,2]Department of Instrumentation and Control,
L D college of Engineering,
Ahmedabad-380015, Gujarat,
INDIA.

***Abstract**: This paper gives the review of the Brushless DC motor and the speed control method for it. Brushless DC Motor (BLDC) is one of the best electrical drives that have increasing popularity due to their high efficiency, reliability, good dynamic response, and very low maintenance. Due to these advantages, the BLDC motors are recently used in Automobile, HVAC, CNC-machines and domestic appliance. It is electronically commuted motor. The operation of the BLDC motor control is based on the rotor position sensing method. For the rotor position sensing used mainly two strategy, sensor and sensor less scheme. This paper gives idea about various sensing methods, control for BLDC motors and recent research trend in BLDC motor.*

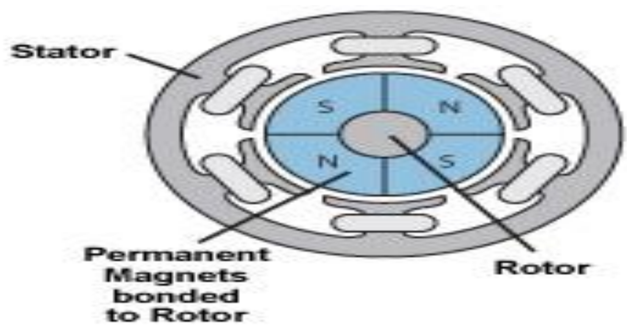
***Keywords**: Brushless DC (BLDC), Heating-Ventilation & Air Conditioner (HVAC), Automobile, Sensor less*

I. Introduction

DC motors have commutator and brushes. While this function of commutator and brushes were implemented by the solid state switches, the maintenance free motor were realized this motor is known as Brushless DC motor(BLDCM). BLDC motor is also known as Permanent magnet synchronous motor. BLDC motors have advantages like high efficiency, reliability, good dynamic response, very low maintenance, large torque to inertia ratio etc. Due to this many advantage now a days BLDC motor is mostly used in Automobile and Home appliance. This motor is electronically commuted and requires rotor position information for proper commutation of current. [1], [9]

In the BLDC motors, stator is three phase star or delta winding and rotor is permanent magnet. As per the rotor position, the phase current is energized through the commutation of the three phase inverter. BLDC motors are having sinusoidal and trapezoidal back EMF but mostly used is the trapezoidal one.[2]

Figure 1 Structure of BLDC motor

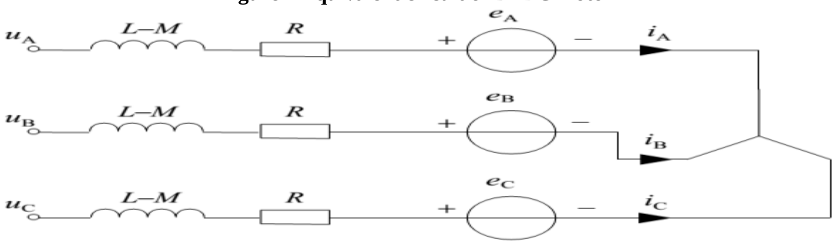


The speed control of BLDC motor can be done in sensor or sensor less mode. For sensor technique Low-cost Hall-effect sensors are used. Accelerometers have been extensively applied to measure motor position and speed. Reduce overall cost of actuating devices, sensor less control techniques are normally used. As a result, many researchers have been reported for sensor less drives that can speed control position and/or torque without shaft-mounted position sensors. [7]

II. Mathametical Modeling of BLDC motor

The mathematical model of the BLDC motor is fundamental for the corresponding performance analysis and control system design. The structure characteristics and working modes of the BLDC motor should be considered when we are building its model. Assuming that the stator resistances of all the windings are equal and also self and mutual inductance are constant. [10]

Figure 2 Equivalent circuit of BLDC motor [4]



L = self-inductance, M = mutual inductance, e_A= phase back EMF, i_A= phase current, v_A= phase voltage

So, the equation for the single phase voltage is,

$$v = Ri + L\frac{di}{dt} + e \tag{1}$$

The phase voltage of each winding, which includes the resistance voltage drop and the induced EMF, can be expressed as,

$$v_x = R_x i_x + e_{\psi x} \tag{2}$$

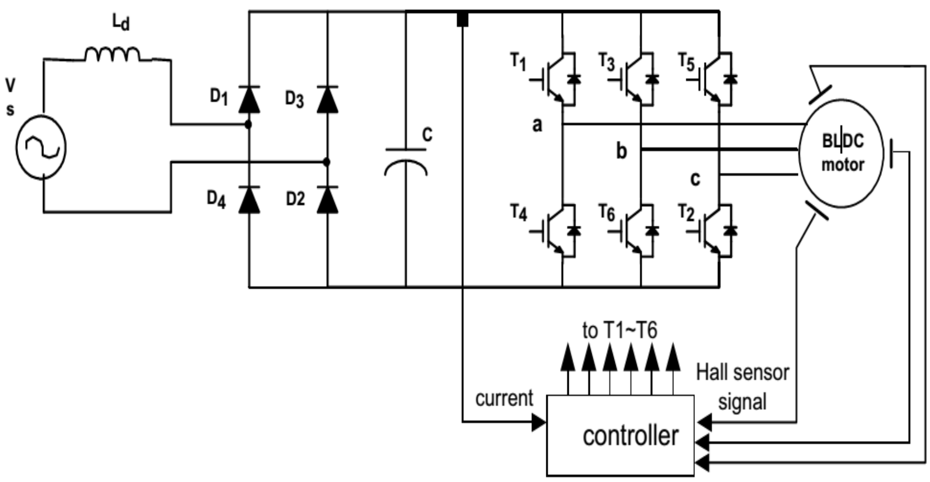
The matrix form of phase voltage equation of BLDC motor can be expressed as [4]

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{3}$$

III. Control of BLDC motor

For BLDC motor control, the rotor position detection is most important part. Because, the commutation sequence is energized after the rotor position is known. In the control of BLDC motor the main part is rotor position detection, PWM generation and three phase inverter. In the BLDC motor among the 3-phase of the BLDC motor two phases are energized at a time while another third phase is not energized. Every phase is energized till 120˚ electrical degrees.

Figure 3 Control system of BLDC motor [11]



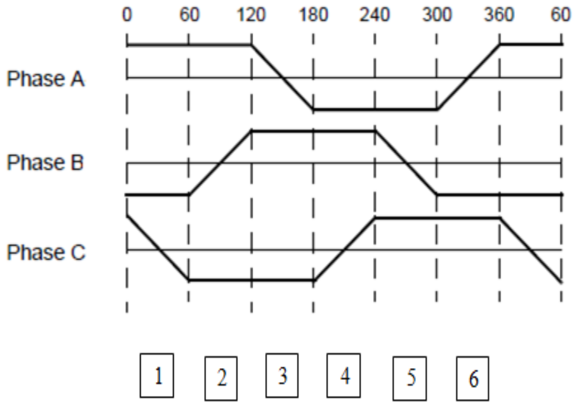
In this control system the output of the Hall sensor, which gives the rotor position, is given to the controller. The controller generates the six PWM signals which can trigger the six switches to control the phase current. The commutation sequence is given in Table 1. This shows 60˚ electrical degree commutation. After each 60˚, the commutation sequence is changed.

Table 1 commutation sequence based on the rotor position

h_A	h_B	h_C	Emf_A	Emf_B	Emf_C	T_1	T_2	T_3	T_4	T_5	T_6
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	1	-1	0	+1	0	1	0	0	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
1	1	0	0	+1	-1	0	0	1	0	0	1
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0

This table gives the idea about which switch is trigger and which phase is energize. The output of this commutation is gives that each phase is energizing at 120˚ apart. [1]

Figure 4 back EMF and phase commutation



State	A	B	C
1	A_H	B_L	--
2	A_H	--	C_L
3	--	B_H	C_L
4	A_L	B_H	--
5	A_L	--	C_H
6	--	B_L	C_H

IV. Review on Sensor method

This is the first method to detect the rotor position; the sensors used for rotor position detection are Hall-Effect sensor, Electromagnetic variable reluctance (VR) sensors. Among this Hall-Effect sensor is mostly used. These kinds of devices are based on Hall-effect theory, which states that if an electric current- carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers that tends to push them to one side of the conductor. A build-up of charge at the sides of the conductors will balance this magnetic influence producing a measurable voltage between the two sides of the conductor. [2]

To rotate the BLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall-effect sensors embedded into the stator.

A permanent magnet is fixed at the end of a rotary shaft and the magnetic sensor is placed below, and the magnet creates a magnetic field parallel to the sensor surface. This surface corresponds to the sensitive directions of the magnetic sensor. Three-phase brushless DC motors need three signals with a phase shift of 120° for control, so a closed-loop regulation may be used to improve the motor performance. So for the better performance three Hall sensors are used which are 120˚ apart. [1]

This Hall sensor gives the good performance and good transient response. Hall sensor will increase the volume and the cost of the motor. Unbalance phase leads to an increase in torque pulsation, vibration and acoustic noise as well as reduced overall electromechanically performance of motor. To remove this unbalanced Hall sensor problem used the, averaging filter, extrapolating filter and other filtering techniques. To improve the performance of the motor used digital control or DSP based control used. [3] Hall sensor cannot work in high temperature and high humidity environment. [5][6] Hence the sensor less control of the BLDC motor technique becomes a hot research field.

V. Review on Sensorless method

Due to some disadvantage of using sensor technique in research field, the recent trend is to minimize the size and reduce the cost of overall system. So the implementation of low cost, reduced parts BLDC motor is desired with high system reliability is taken by sensor less technique. When the current is passing through the phases it generates the flux and back EMF in every phase. So based on this the new sensor less technique, in the recent years, there are various sensor less technique is available for detection of the rotor position. Earlier; direct back EMF sensing, back EMF integration, direct phase current sensing, freewheeling diode conduction techniques were used. Now a day a new sensor less technique is available which is independent of the speed of the motor. The new sensor less technique is based on the flux function, intelligent estimated method, and inductance based methods are used for rotor position detection.

A. Back EMF Sensing Method[5]

In PM brushless DC machines, the magnitude of the back EMF is a function of the instantaneous rotor position and has trapezoidal variation with 120º flat span. However, in practice, it is difficult to measure the back EMF, because of the rapidly changing currents in machine windings and induced voltages due to phase switching. The back EMF is not sufficient enough at starting until the rotor attains some speed. Therefore, it is a usual practice to make the initial acceleration under open-loop control using a ramped frequency signal so that the back-EMF is measurable for the controller to lock in. When a BLDC motor rotates, according to the Lenz's law, each winding generates BEMF which opposes the main voltage supplied to the windings. The polarity of this BEMF opposes the energizing voltage polarity. BEMF can then be calculated using the given expression:

$$BEMF = NlrB\omega \tag{4}$$

N = number of windings per phase, l = length of the rotor,
r = radius of the rotor, B = rotor magnetic field, ω = rotor angular velocity

Back-EMF sensing methods for the BLDC motors are split into two categories; direct and indirect back-EMF detection,

- **Direct Back-EMF Sensing Method**

The back-EMF of floating phase is sensed and its zero crossing is detected by comparing it with neutral voltage. This technique suffers from high common mode voltage and high frequency noise due to the PWM switching, so it requires voltage dividers and low-pass filters to reduce the common-mode voltage and the higher harmonics.

- **Indirect Back-EMF Sensing Method**

Since filtering introduces commutation delay at high speeds and attenuation causes reduction in signal sensitivity at low speeds, the speed range is limited in direct back-EMF sensing methods. In order to reduce high frequency noise due to the PWM switching, the indirect back-EMF sensing methods are used. These methods are, Back-EMF Integration, Third Harmonic Voltage Integration, Free-wheeling Diode Conduction or Terminal Current Sensing.

B. Back EMF Integration Method[5]

In this technique, the position information is extracted by integrating unexcited phase's back-EMF. The integration starts at the zero crossing points of unexcited phase's back-EMF. When the integrated value reaches a threshold value, the integration stops, which gives the corresponding commutation point and the phase current gets commutated. The integration approach has reduced switching noise sensitivity and automatically adjusts the inverter switching instants for rotor speed changes, but has poor operation at low speeds. This approach suffers from error accumulation and offset voltage problems at low speed due to integration.

C. Freewheeling Diode Conduction Method[5]

In this technique, the rotor position information is determined based on the conducting state of antiparallel connected freewheeling diodes in the unexcited phase. Detecting the free-wheeling diode conducting status in the unexcited phase gives the zero-crossing point of the back EMF waveform. A simple starting procedure and uniform control performance over various operating conditions are of key advantages of this technique. This methodology makes it possible to find the rotor position over a wide speed range, especially at a lower speed. Alike other back-EMF based methods; this method has a position error of commutation points in the transient state. Even though it has the above mentioned attractive features, the most serious drawbacks of this method is the use of six isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode and requires complicated sensing circuits, which prohibits this method for use in practical applications.

D. Flux Linkage Based Method[5][6]

In this method, the flux linkage is calculated using measured voltages and currents. The fundamental idea is to take the voltage equation of the machine and by integrating the applied voltage and current, flux can be estimated. From the initial position, machine parameters, and the flux linkages' relationship to rotor position, the rotor position can be estimated. This method also has significant estimation error in low speed. Improper error of parameters and sampled current is reason for accumulation error at low speeds in which the voltage equation is integrated in a relatively large period of time. The flux is dependent on speed of rotor means at low speed the flux is low and at high the flux is high. So, this method is not useful at very low speed. Now another speed independent function is obtain which is known as G-function method.

- **G-Function Based Method**

When we measure the line voltage is dependent on the rotor speed.

$$v_a = Ri_a + L\frac{di_a}{dt} + k_e\frac{d\theta}{dt}\frac{d(f_{ar}(\theta))}{d\theta} \tag{5}$$

R = phase resistance, f_{ar} = flux function related to rotor position
K_e = back EMF coefficient, $\frac{d\theta}{dt} =$ angular velocity

Now in above equation, it is seen that the phase voltage is dependent on the rotor speed. This is the line voltage of BLDC motor. So the new function is generated which is independent of the rotor speed. This is based on the line to line voltage. [6]

$$G(\theta)_{\frac{ab}{ca}} = \frac{H(\theta)_{ab}}{H(\theta)_{ca}} = \frac{U_{ab} - Ri_{ab} - L\frac{di_{ab}}{dt}}{U_{ca} - Ri_{ca} - L\frac{di_{ca}}{dt}} \tag{6}$$

This technique makes it possible to detect the rotor position over a wide speed range from near zero to high speeds. The capability of position detection at around 1.5% of the rated speed makes the starting procedure much simpler than conventional methods. The flux function can be estimated by using line-line voltage and current. The flux function can follow up the rotor position agilely and is not speed-related. Under this method, the commutation point can be detected accurately even at very low speed, which is important for improving the startup performance of BLDC motor sensor less control. [6]

VI. Torque Ripple

Torque-ripple reduction is always a key issue in BLDC motor control systems. As in other motors, some phenomena like the cogging effect and the eddy-current effect cannot be completely avoided in BLDC motor design. Therefore, cogging torque, which should be considered in torque-ripple reduction of BLDC motors, can be restrained with good results by using skewed and fractional slots. Torque ripple is an effect seen in many electric motors, referring to periodic increase or decrease output torque as the output shaft rotate. The torque ripple can be divided in two parts: the torque pulsation due to current ripple and torque pulsation due to commutation time. [8]

There are many drawback of torque ripple like reduction of the performance of motor, decrease in torque/ampere ratio, it also produces vibration and noise and reduces the lifetime of machine.

VII. Recent Trend in BLDC Motor Drives

Currently BLDC motor is used more compared to other motors due to its high efficiency, low maintenance. The current researches mainly focus in the following areas: (1) Develop a new position-sensor less control technology to improve system reliability and further reduce the motor size and weight and increase performance. (2) Torque ripple reduction for BLDC motors, from motor design and control aspects, to improve the servo precision and expand the scope of application. (3) Design new BLDC motor controllers. [4]

VIII. Conclusion

BLDC motors have many advantages over brushed DC motors and induction motors, such as a superior speed versus torque characteristics, high dynamic response, more efficiency and reliability, cheaper, longer life, quieter, higher speed ranges, and reduction of arcing. In addition, the BLDC motor has higher delivered torque to size ratio. All the above advantages make it useful in applications where space and weight are critical factors, particularly in aerospace applications. BLDC motors can be controlled either in sensor or sensor less mode, but to reduce general cost and size of motor assembly, sensor less control techniques are normally employed.

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