Real-time Speed Control of Brushless DC Motor based on PID Controller

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Abstract

Nowadays, ***,*** *Brushless DC motors have become increasingly popular because of their benefits and have been appliedwidely for electric vehicles. This paper proposes an optimal set of parameters of PID controller for speed control of a brushless DC motor (BLDC). The proposed controller improves system responses as well as reduces the steady state error and overshoot.*

Keywords – *BLDC motor, PID controller, Electric Vehicle (EV), MATLAB/SIMULINK.*

I. INTRODUCTION

In modern society, electric vehicles are an urgent technology in modern work because it helps mitigate environmental pollution and at the same time fossil fuel has become exhausted. Battery-powered electric vehicles are one of the solutions to tackle this issue and are driven by DC motors considered as high efficiency, linear torque-speed characteristic and simple control. However, the main drawback of the DC motor is the need of periodic maintenance. The brushes of the mechanical commutator will wear out and need to be replaced; besides commutation also generates sparks and noise. Therefore, in this case, DC motors can be replaced by Brushless DC motors due to its advantages such as long operating life, high efficiency, better speed-torque characteristics, noiseless, sparkless and higher speed range. With the requirement of keeping speed stable, a PID controller is applied as a useful tool. Parameters of the PID controller K_P, K_I, K_D affect directly to get optimal performance. Recently, there is a variety of modern control methods for speed control of the BLDC motor [1], but the PID controller algorithm is considered as simple, stable, easy adjustment and high reliability. Finally, experimental results demonstrate the effectiveness of the system.

II. OPERATION AND MATHEMATICAL MODEL OF A BRUSHLESS DC MOTOR

A. The operation principle

A BLDC motor is a type of permanent magnet synchronous motor using rotor position detectors to control the armature currents, and its operating characteristics resemble a DC motor. Instead of using a mechanical commutator, the BLDC motor employs electronic commutation, which makes it free for maintenance. A transverse section of a BLDC motor is shown as figure 1. Stator wires are provided electrical power by the electronic commutator. When the motor runs, the stator wires are energized respectively. This means that at a time, energizing for which one is not random, but it depends completely on rotor position. Therefore, it is important to determine rotor position to decide energizing order for stator wires. Rotor position is determined by three Hall sensors that detect small magnets attached to the motor shaft. For Hall-effect sensor used in BLDC motor, whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a high or low level signal, which can be used to determine the position of the shaft.

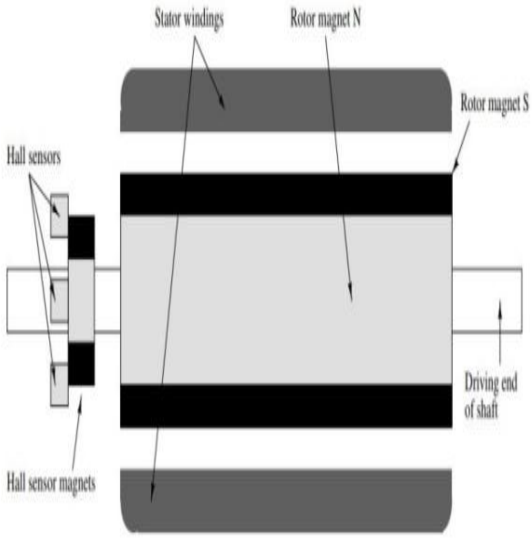

Fig 1: BLDC motor cross diagram

In order to ensure the operation of this motor, controlling open-close process of semiconductor keys to supply voltage source for wires in stator is based on understanding accurately the rotor place. The three phase BDLC motor is run in two-phase mode. In other word, the two phases producing the highest torque are supplied by voltage source while the third phase is off. Energizing for two phases depends on the rotor position. The signals from the Hall sensors produce a three digit number that changes every 60o (electrical degrees) as shown in figure 2 (H1, H2, H3).

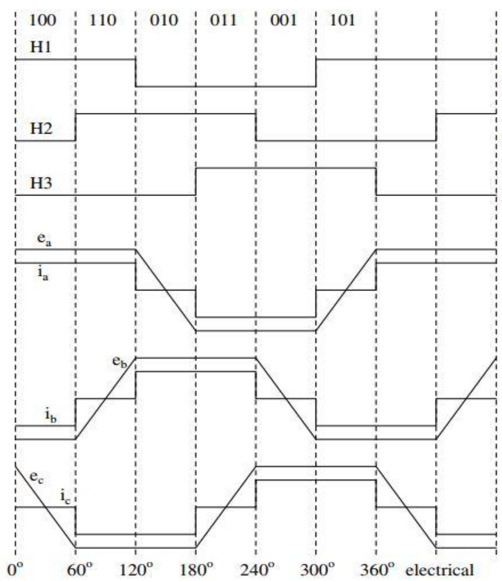

Fig 2: H1, H2, H3 sensor signals, back-emf and ideal currents

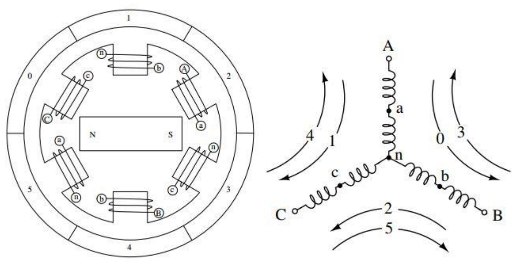

Fig 3: BLDC motor cross diagram and phase energizing sequence

Figure 3 shows a cross section of a three-phase motor connected according to star form and its phase energizing sequence. When the field lines are perpendicular makes torque maximum. Current commutation is inverted by six switches which are bipolar junction transistors shown as figure 4

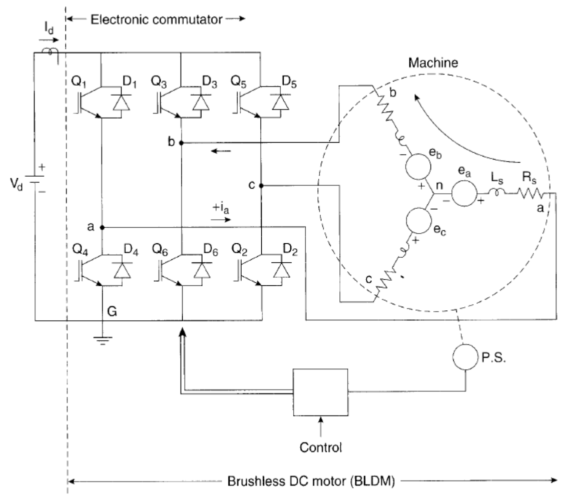

Fig 4: Simplified BLDC drive

H1, H2, H3 position sensor signals control switching sequence of switches from Q1 to Q6 and decide current direction. Switching law is indicated in table 1.

TABLE I - SWITCHING SEQUENCE

Switching interval	*Seq. number*	*Pos. sensors*			*Switch closed*		*Phase current*		
		H1	*H2*	*H3*			*A*	*B*	*C*
$0^o – 60^o$	0	1	0	0	Q1	Q6	+	-	off
$60^o – 120^o$	1	1	1	0	Q1	Q2	+	off	-
$120^o – 180^o$	2	0	1	0	Q3	Q2	off	+	-
$180^o – 240^o$	3	0	1	1	Q3	Q4	-	+	off
$240^o – 300^o$	4	0	0	1	Q5	Q4	-	off	+
$300^o – 360^o$	5	1	0	1	Q5	Q6	off	-	+

B. Mathematical model of a BLDC motor

The three-phase star-connected BLDC motor can be represented by following four equations:

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \ (1)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \ (2)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \ (3)$$

$$T_e = k_f \omega_m + J\frac{d\omega_m}{dt} + T_L \ (4)$$

Where v, i and e denote the phase-to-phase voltages, phase currents and phase back-emf's respectively in three phases a, b and c; the resistance R and inductance L of each phase; T_e, T_L are the electrical torque and the load torque. J is the rotor inertia, k_f is a friction constant and ω_m is the rotor speed. The back-emf's and the electrical torque can be described as equations (4-8):

$$e_a = \frac{k_e}{2}\omega_m F(\theta_e) \ (5)$$

$$e_b = \frac{k_e}{2}\omega_m F(\theta_e - \frac{2\pi}{3}) \ (6)$$

$$e_c = \frac{k_e}{2}\omega_m F(\theta_e - \frac{4\pi}{3}) \ (7)$$

$$T_e = \frac{k_t}{2}\left[F(\theta_e)i_a + F(\theta_e - \frac{2\pi}{3})i_b + F(\theta_e - \frac{4\pi}{3})i_c\right] \ (8)$$

The symbol k_e and k_t demonstrate the back-emf constant and torque constant. The electrical angle $\theta_e$is equal to the rotor angle times the number of pole pairs $(\theta_e = \frac{p}{2}\theta_m)$.

After altering equations and combinating with the current relationship: $i_a + i_b + i_c = 0$. Equations from (1) to (3) become:

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \ (9)$$

$$v_{bc} = R(i_a + 2i_b) + L\frac{d}{dt}(i_a + 2i_b) + e_b - e_c \ (10)$$

Hence, the mathematical model of a BLDC motor can be written in state-space form [6] as equation (11):

$$\begin{bmatrix} i'_a \\ i'_b \\ \omega'_m \\ \theta'_m \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & -\frac{k_f}{J} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_L \end{bmatrix} \quad (11)$$

III. DESIGN PID CONTROLLER

The Proportional – Integral – Derivative(PID) controller isthe most common and useful algorithm in engineering control systems[5]. In most cases, feedback loops are controlled by using the PID algorithm. The PID controller that is a dark block in figure….is used to control the process and in order to keep output stable and make the difference between output and input minimum with certain disturbances. The parameters of the controller including proportional (K_p), integral (K_i), and derivative (K_d) gains have direct effect on effective performances of the system. Its transfer function is:

$$G_{PID} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right), \text{ where: } T_i = \frac{K_p}{K_i}; T_d = \frac{K_p}{K_d}$$

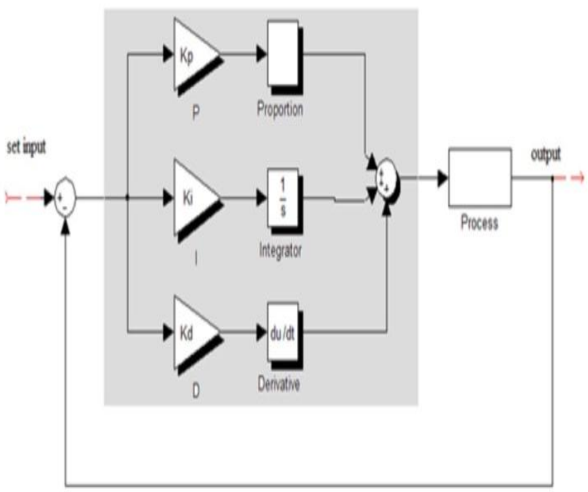

Fig 5: The structure diagram of the system using PID controller

Before a detail analysis is done, a quick look at the tuning methods is considered as first and thereafter, specific tuning parameters are computed for the BLDC. Some of the generally used tuning methods are the Trial and Error method, the Ziegler-Nichols method (1st), Improved Ziegler-Nichols method (2nd), Cohen-Coon method, Genetic Algorithms and so on. For this work, the Ziegler-Nichols method [4] would be given a priority.

The Ziegler-Nichols method bases on obtaining the open loop transfer function and thereafter gaining the necessary parameters needed for the various evaluations of the P, PI and PID parameters.

The open loop step response is characterized by two main parameters, the L stands for delay time parameter and T stands for time constant. These two parameters are computed by drawing a tangent to the open loop step response at its inflection points (basically two points). The inflection points are particularly determined so that there would be an intersection with the vertical (voltage axis which correlates with the steady-state value) and horizontal (time axis) axes.

Based on the Ziegler-Nichols, a set of control parameters is derived from the required modelshown in equations (12)

$$K_P = 1.2\frac{T}{L}$$
$$T_I = 2L \qquad (12)$$
$$T_D = 0.5L$$

The way how to evaluate the two parameters (L and T) isillustrated in figure6.

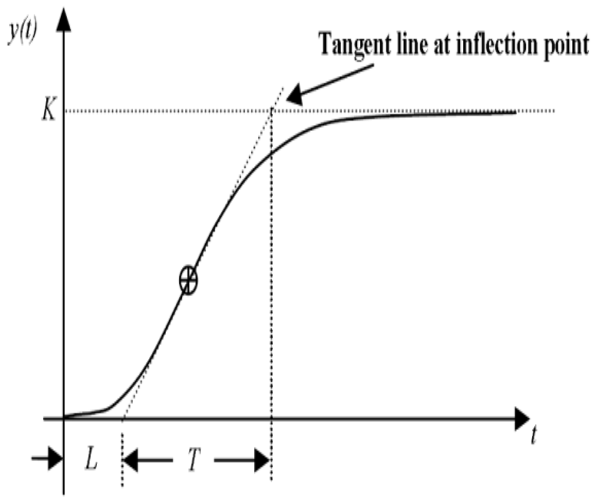

Fig 6: Ziegler-Nichols step response tuning method

IV. REAL TIME SPEED CONTROL

The speed controller for BLDC motor was designed on a real experiment system including a BLDC motor connected to MATLAB-Simulink software installed in computer. PID algorithm is programmed and set into Arduino card. Speed and position feedback signals from Hall sensors are alsosent to Arduino card connected to the computer. The control signal from PID controller is sent to Arduino to control BLDC motor. In this system, the BLDC motor rotates a variable load.The system is shown as figure 7

Fig 7: The control model in thecomputer

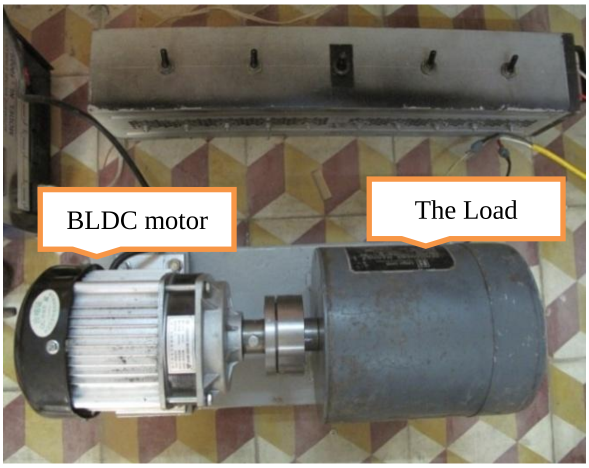

Fig 8: Brushless DC motor and load

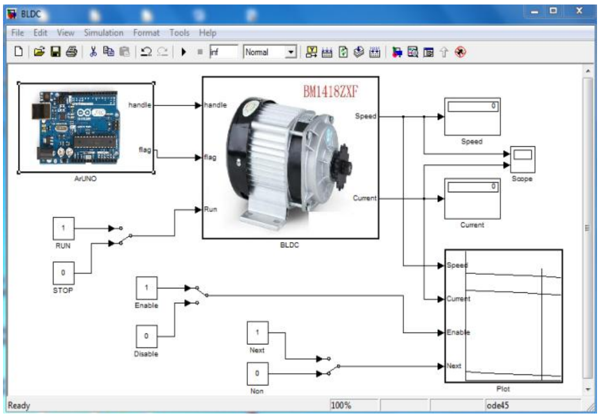

Fig 9: The control model and Arduino card in MATLAB-Simulink

TABLE III
PHYSICAL PARAMETERS OF THE BLDC MOTOR

Symbol	*Definition*	*Value*	*Unit*
R	Stator Winding Resistance	1.4	Ω
L	Stator Winding Inductance	0.0066	H
J	Rotor inertia	0.00176	Kg-m^2
k_f	Motor Viscous Friction Coefficient	0.0003888	Nm/rad/sec
k_t	Torque Constant	0.03	Nm/Amp
k_e	Velocity Constant	0.0000181	Volts/rad

TABLE IIIII-PID PARAMETERS

PID gains	*Values*
K_p	0.5
T_i	10s
T_d	1s

A simulation of a brushless DC motor system with the PID gains calculated using the above equations (11)
was performed by using MATLAB. The calculated gains of PID controller are provided in Table 3.

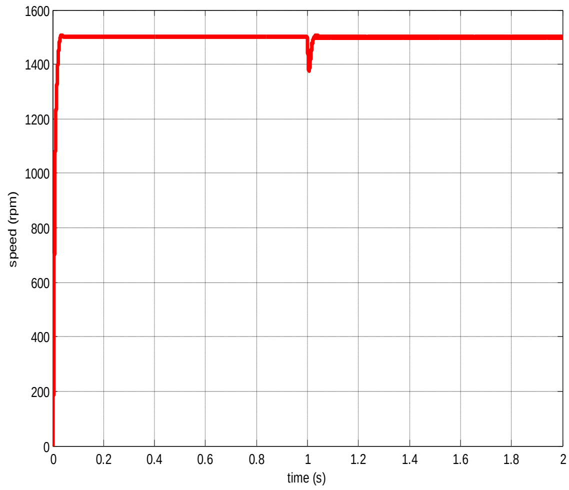

Fig 10: Speed of brushless motor

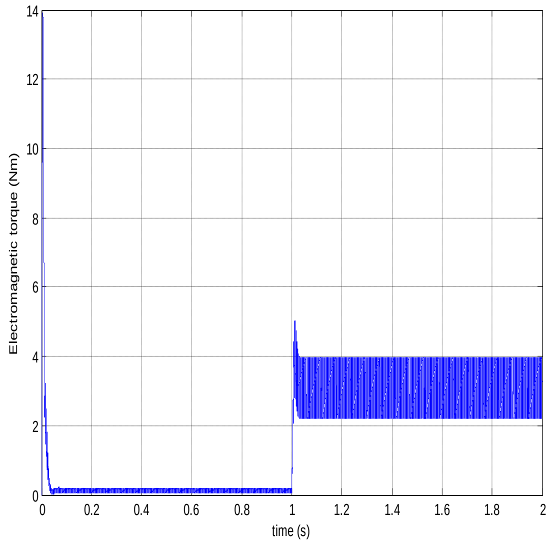

Fig 11: Electromagnetic torque of brushless motor

Thespeed responsesaredepicted in figure 10, 11. So it can be concluded that a direct PID tuning method is suitable to designate self-tuning technique for BLDC motor, where the overshoot in the speed response of the motor isapproximately zero and the error steady state alsogoes to zero. Particularly, if the load appears, the system will respond quickly by increasing dramatically torque to follow the reference speed.

V. CONCLUSIONS

The paper proposes the design of PID controller and real time operation to control speed for BLDC motors. Beside other control methods that are applied and developed, the performance and control quality can be improved many times by using a more effective design technique for the PID-basedcontrol system accompanied with optimizing and adapting-parameter methods of regulators.

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