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# A TORQUE CONTROL STRATEGY OF BRUSHLESS DIRECT CURRENT MOTOR WITH CURRENT OBSERVER

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***Abstract*** **- This paper presents a torque control strategy of brushless DC (BLDC) motor based on current observer and state feedback control algorithm. Based on establishment and in depth analysis of the BLDC mathematical model, BLDC motor torque control is transformed into BLDC motor current control. Then a full dimensional current state observer is designed to estimate armature current of BLDC motor. After observing armature current with current state observer, it is fed back to the feedback state controller and the current reference input port to generate current control signal and current error signal, respectively. The control signal and error signal can be used to control the torque of BLDC motor. After completing the torque control algorithm of BLDC motor, a simulation model is developed using Matlab/Simulink. The capability and performance of the torque control algorithm of BLDC motor is verified.**

***Index Terms - Torque control, observer, BLDC motor***

## I. INTRODUCTION

Because of simple structure, longer lifetime, faster torque response and high efficiency, BLDC motors have been widely used from home appliances to the accurate industrial servo systems. [1]

There are two types of BLDC motor. One has sinusoidal type back-EMF waveform so that ripple-free torque control can be achieved by vector control scheme. However, it is difficult to have exact sinusoidal type motor due to structural complexity, cost and size. The other has trapezoidal type back-EMF waveform for which it is possible to have constant torque without ripple by switching method. But it is also difficult to have exact one. The torque ripple is caused by motor's structure which generates vibration and noise, besides current control algorithm is the key factor, too. [2]

Based on in analysis of the BLDC mathematical model, the torque ( $T_e$ ) can be directly controlled by regulating armature current ( $i_a$ ), i.e. $T_e = K_t \cdot i$ where $K_T$ is the constant torque. A number of authors research and analyze to achieve this requirement. Such as, in [3] proposed a current control method implemented in THC motor drive, in [4] presented an improved DTC strategy that enables the eradication of the previously-depicted limitations, in [5] DTC strategy has been applied to BLDC motor to achieve instantaneous torque control and reduced torque ripple, in [6] a further studied and simplified DTC strategy is proposed by keeping the stator flux linkage amplitude almost constant, in [7] a new current control algorithm using fourier coefficients is proposed which can minimize current ripple. The DTC strategy is one of the commonly known torque control method of DC motor, but the torque ripple can't be avoided, besides the algorithm is complex.

In this paper, a new direct torque control strategy of BLDC motor is proposed by using state feedback control algorithm and current observer. The current observer can estimates armature current of BLDC motor to feed it back to the feedback state controller and the reference current input port to generate control signal and current error signal, respectively. Then the torque of BLDC motor can be directly controlled by the two signals. The performance of the proposed system will be evaluated by simulation in Matlab/Simulink.

## II. MODELLING OF BLDC MOTOR

Mathematical model of BLDC motor is similar to brushed DC motor, except that BLDC motor contains three phase stator circuit and it's rotor is not electrically connected to the stator, but brushed DC motor contains two phase stator circuit and it contains electrical brush. Fig.1 shows that the basic blocks of BLDC motor which contains three phase stator circuit.

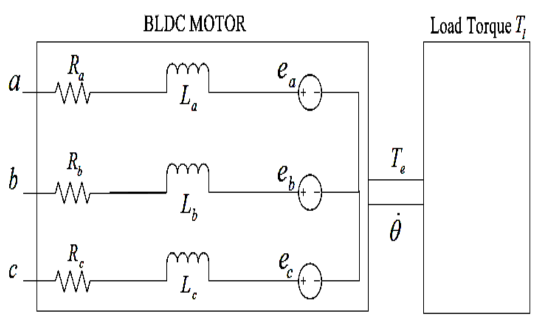


Figure1. Three phase stator circuit equivalent model of BLDC motor and mechanical part

For simplification, the mathematical model of BLDC motor is expressed for one phase stator winding.

The voltage equation of BLDC motor as given by (1), where $V$ is terminal voltage phase to phase, $R$ is terminal resistance phase to phase, $L$ is terminal inductance phase to phase, $i$ is armature current, $E$ is back-emf voltage.

$$V = R \cdot i + L \cdot \frac{di}{dt} + E \tag{1}$$

On the other hand, $E$ (back-emf voltage) can be expressed by the back-emf voltage factor $K$ and angular velocity $\dot{\theta}$, as given by (2).

$$E = K_e \cdot \dot{\theta} \tag{2}$$

And the kinematic equation of BLDC motor is expressed by (3), where $T_e$ is electromagnetic torque, $J$ is equivalent rotor inertia, $\ddot{\theta}$ is angular acceleration, $f$ is damping factor, $\dot{\theta}$ is angular velocity.

$$T_e = J \cdot \ddot{\theta} + f \cdot \dot{\theta} \tag{3}$$

The production of electromagnetic torque can be expressed by (4), where $K_t$ is torque constant factor.

$$T_e = K_t \cdot i \tag{4}$$

The four equations above are the mathematical model of BLDC motor, but these equations can't be used to design algorithm directly. The equations should be simplified to state equation as given by (5) and (6).

$$\dot{x} = Ax + Bu \tag{5}$$

and

$$y = Cx \tag{6}$$

Where $x, u, y$ represent the state variable, control input and output vectors, respectively. To control the armature current, the state matrix $x$, $u$ and $y$ are chosen as $x = [i \quad \dot{\theta}]^T$, $u = V$, $y = i$. And the coefficient matrix $A, B, C$ can be derived from the mathematical model of BLDC motor. $A = [-R/L \quad -K_e/L; \quad K_t/J \quad -f/J]$, $B = [1/L; \quad 0]$, $C = [1 \quad 0]$.

In this paper, the BLDC motor EC-i-40 is chosen for designing torque control algorithm. The main motor parameters are listed in TABLEI. By referring to the motor manual, the elements of A and B will be calculated as:

$$A = [-2038.8 \quad -9.72; \quad 6498.5 \quad -31.13]$$
$$B = [5555.6; \quad 0]$$

.

TABLE I

Main parameters of EC-i-40

| Pole pairs | Terminal inductance/mH | Terminal resistance/Ω |
|---|---|---|
| 7 | 0.180 | 0.36 |
| Torque Constant(mN/A) | Speed Constant (rpm/V) | Rotor Inertia (gcm$^2$) |
| 16.7 | 572 | 24.2 |

## III. TORQUE CONTROL STRATEGY OF BLDC MOTOR

### *A. The Principle of BLDC Motor Torque Control*

The diagram of BLDC motor torque control based on current observer is shown by Fig.2. The torque reference ($T_{e,ref}$) can be transformed into the current reference ($i_{ref}$) by dividing the torque constant ($K_t$). At the same time, the current observer can estimates the armature current $i_g$ by input voltage u and rotate velocity of motor which can be got by optical-electricity encoder. Then the current ($i_g$) estimated by current observer is fed back to the feedback state controller and the current reference input port to generate current control signal and current error signal, respectively. The current control signal and error signal can be used to control the torque of BLDC motor.

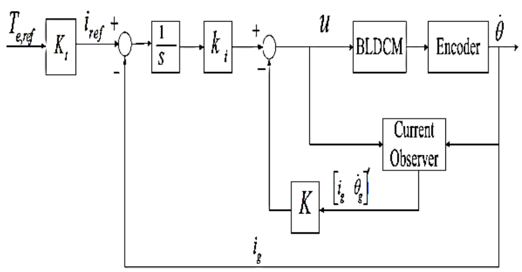


Figure2. The diagram of BLDC motor torque control

### *B. Design Algorithm*

The first step of designing torque control of BLDC motor is to test state equation according to the controllability and observability criterion. Namely, calculate the rank of controllability matrix $\begin{bmatrix} B & AB & \cdots & A^{n-1}B \end{bmatrix}$ and observability matrix $\begin{bmatrix} C & CA & \cdots & CA^{n-1} \end{bmatrix}$ to see if it is equal to the dimension of the system matrix *A*. By calculating the rank of controllability matrix and observability matrix of the state equation (5) and (6), find that the rank, which are 2, are both equal to the dimension of the system matrix *A*. Then the conclusion that the state equation of the EC-i-40 motor is controllable and observable can be drawn.

As the state equation of BLDC motor is controllable and observable, the dominant closed-loop poles can be obtained according to the control index (namely, adjustment time $t_s \le 0.1s$ , and overshot $Q \le 10\%$ ). By calculating the dominant closed-loop poles are chosen as $\lambda_{1,2} = -42.5 \pm 26.33 \cdot i$. Due to the BLDC motor state equation is two order, the desired closed-loop poles is same as the dominant closed-loop poles. Namely, the desired closed-loop poles are chosen as $P_1 = [-42.5 + 26.33 \cdot i \quad -42.5 - 26.33 \cdot i]$. After the desired poles are obtained, the state feedback coefficient *K* will be calculated by the state feedback control algorithm in Simulation software. The final state feedback coefficient is $K = [-0.2817 \quad -0.0021]$.

After complete the state feedback control algorithm, current observer also need to design. Current observer is essentially dual system of BLDC motor, which mainly lies in obtaining the feedback coefficient matrix *G*. Matrix *G* can be calculated by the pole place method. First of all, the desired poles should be chosen between 2 to 5 times than the desired closed-loop poles $P_1$ so that the current observer is faster than the BLDC motor system. Hence, the desired poles of the current observer are chosen as $P_2 = [-85 + 52.66 \cdot i \quad -85 - 52.66 \cdot i]$. Then the state feedback coefficient matrix can be calculated as $G = [-1815 \quad 553.5]^T$ by the pole place algorithm in Matlab. The diagram of the current observer is shown in Fig3.

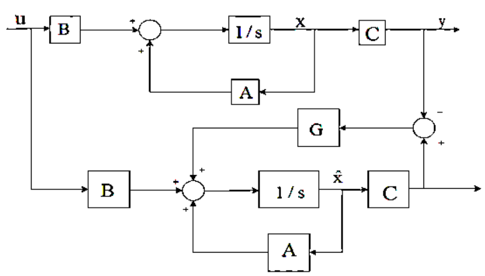


Figure3. The diagram of the current observer

## IV. SIMULATION AND ANALYSIS

To verify the torque control algorithm of BLDC motor, a simulation model is built by using Simulink.

The simulation results with torque control algorithm are shown in Fig.4. It can be observed that the torque of BLDC is controlled at its reference in 0.1s and the overshot is less than 10%. Besides, the estimated torque tracks the actual torque with a small margin of error.

Fig.5 shows the simulation results without the torque control algorithm. It can be clearly seen that the torque is not controlled at the torque reference and the overshot is more than almost 95%.

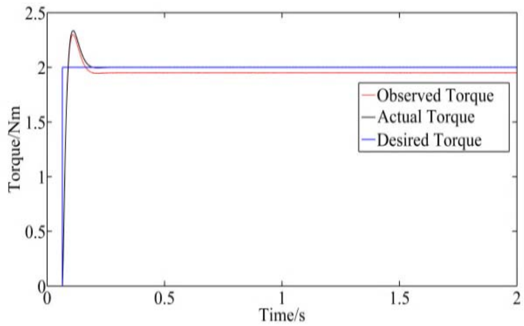


Figure.4.The torque control of BLDC motor simulation

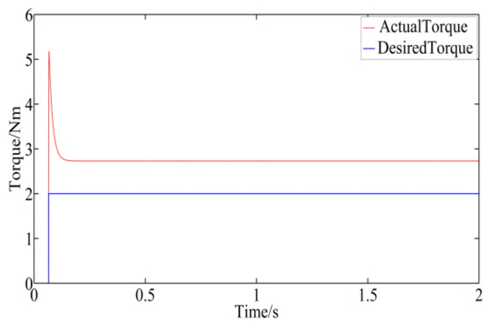


Figure.5.The output torque of BLDC motor without torque control algorithm

The Fig.7 shows the simulation results when white noise is added into input port. And the Fig.6 shows the white Gauss perturbation signal. The results show that the torque is controlled in 0.05s and the error between the output torque and the torque reference is controlled in a small range. Besides, the estimated torque tracks the output torque very well.

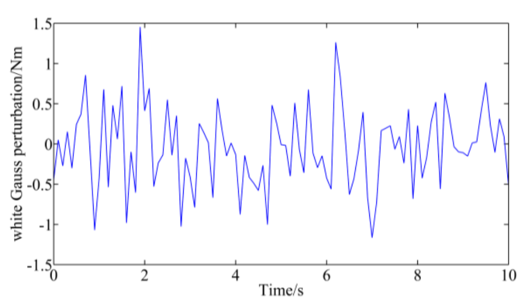


Figure.6.The white Gauss perturbation signal.

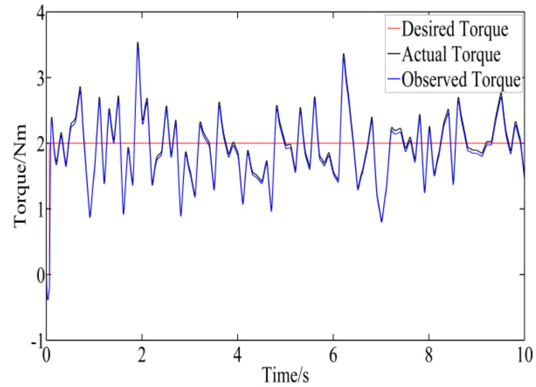


Figure.7.The simulation with white noise

## V. CONCLUSIONS

This paper presented the modelling and a new torque control algorithm for BLDC motor. Compared with the conventional torque control algorithm of BLDC motor, this algorithm is simple, inexpensive and easy to implement. The core part of this algorithm is the current observer which is actually a kind of theory algorithm to estimate the current of BLDC motor with the voltage and rotate velocity of motor. The simulation results show that this algorithm can control the torque of BLDC motor. Besides, it is fast, stable and accurate.

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