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THE EFFECT OF VARIABLE TORQUE CONSTANT ON BRUSHLESS DC MOTOR

Chung-Wen Hung*, Chu-Lin Hsu, Wei-Lung Mao and Yun-Ruei Lu
Department of Electrical Engineering
National Yunlin University of Science and Technology
No. 123, University Road, Sec. 3, Douliou, Yunlin 64002, Taiwan
*Corresponding author: wenhung@yuntech.edu.tw

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Abstract. *The brushless DC (BLDC) motor is an important part in auto system, because of its high power density, high efficiency and easy maintenance. However, the torque load measurement is difficult in the most motor systems. If one likes to control the motor more accurately, the torque estimator is indispensable in motor system, and the torque constant is a key. However, the experimental results show the torque constant is variable by different speed. The variation of the torque constant is discussed in this paper. In order to verify the influence of variable torque constant, a simulation is proposed. The simulated results show that the variable torque would cause different responses of a BLDC motor.*
Keywords: BLDC motor, Torque constant, Simulation

1. **Introduction.** The BLDC motor is an important part in auto system, because of its high power density, high efficiency and easy maintenance. Usually, hall sensors built in BLDC motors are used to get the rotor position information which is applied to determining the commutation among the armature windings and estimated motor speed. However, the torque load measurement is difficult in most motor systems. And, the torque load is always estimated by stator current and torque constant. If the torque constant is variable, the estimated torque is more inaccurate.

There are some papers discussing the BLDC motor control and trying to improve the speed or torque response. [1] discussed the variable sampling because of the different feedback time. It showed the response difference between variable and fixed sampling system in a same PI controller, and proposed a torque estimator which included the variable sampling mode to improve dynamic response when torque load was changing. [2] proposed a method to reduce the torque ripple of a BLDC system. In the conventional commutation method, the current amplitude is kept constant. In the proposed method, the current amplitude is adapted to the rotor position. The optimum reference current is calculated based on the phase back-EMF waveform. A new sensorless control algorithm for BLDC was discussed in [3]. The torque constant of a BLDC is used as a reference signal for position detection because it is constant during the entire speed range and can be estimated by calculating the ratio of the back electromotive force (EMF) to the rotor speed. By using both a disturbance observer and the torque constant estimation error, the rotor speed can be obtained. The estimated back EMF decreases simultaneously with the estimated torque constant at the commutation point. Based on phenomenon, the commutation of the phase currents can be detected at the drop point of the estimated torque constant. [4] discussed about the torque compensation methods which included close loop and open loop. After analysis, the interpolation method using look-up tables (LUTs), torque closed-loop method with torque estimation and maximum torque

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per-ampere (MTPA) online calculation are the available methods. [5] proposed a speed sensor-less vector control method in ultra-low speed. The disturbance torque is caused by an error between the calculated rotor frequency and actual frequency. To solve this problem, the disturbance torque is compensated by torque current error controller. The method is verified by simulations and experiments. [6] analyzed the dynamic response of induction motor with maximum torque per ampere (MTPA) control and proposed a new MTPA control to improve the torque response during the rotor flux linkage transient process and the maximum torque-current ratio. The experimental results showed the method is effective. These studies may discuss about variable sampling control and torque compensation; however, it is a lack of the discussion about the variance of the torque current ratio at different speed.

This paper explores the phenomenon, the variable torque constant at different speed. The most of previous studies, [1-5], only focused on torque compensation, but not torque constant variance; [6] only discussed about the variance caused by temperature change. The motor model will be described in the next section, then the simulated and experimental results are shown, and finally, the conclusion is discussed. By the results, people could design more accurate and fast control under considering the torque constant variance.

2. **The Model of BLDC Motor and Variable Torque Constant.**

2.1. **The model equation of BLDC motor.**

The equation of BLDC motor can be described as (1)

$$\begin{bmatrix} V_{aN} \\ V_{bN} \\ V_{cN} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dx} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where R and L are resistance and armature inductance; V_{xN}, i_x and e_x indicate the a, b and c phase terminal voltage, current and back EMF. The mechanical and electrical equation of BLDC motor can be described as the following:

$$J\frac{d\omega}{dt} + D\omega = \tau_e - \tau_L \tag{2}$$

$$\tau_e = K_\tau \cdot i \tag{3}$$

$$v = R \cdot i + L\frac{di}{dt} + K_e \cdot \omega \tag{4}$$

where J, D, ω, τ_e, τ_L, K_τ, K_e, v and i are rotor interia and damping, motor speed, torque electromagnetic, torque load, torque constant, back EMF constants, terminal voltage and stator current.

2.2. **Torque estimation and variable torque constant.**

Torque load is difficult to be directly measured in the most motor system. However, according to (2) and (3), torque load can be expressed as (5). The torque estimator based on (5) measures the load change in real time. And then, the controller will provide torque compensation to speedup response.

$$\tau_L = K_\tau i - \left(J\frac{d\omega}{dt} + D\omega\right) \tag{5}$$

According to (3), torque load is proportional to stator current. After experimenting, the proportional of torque constant and the stator current is shown in Figure 1. The torque constant (K_τ) will change at different motor speed. So, torque load and stator current will have different ratios at different motor speed. And the torque constant is not a fixed value. The controller should adapt to different torque constants in torque compensation.

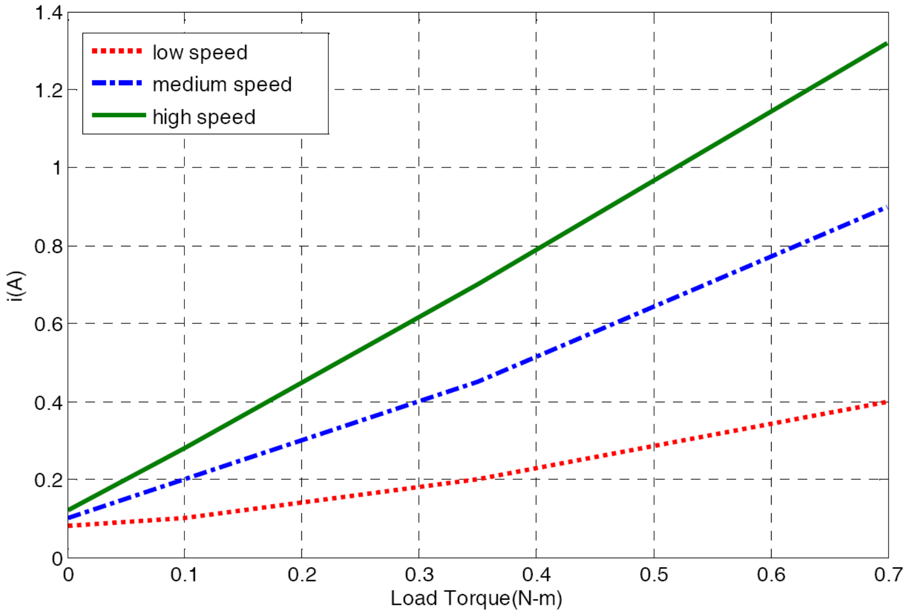

Figure 1. The relationship between torque load and stator current

In order to simplify the calculation and calculate the torque constant, the acceleration, $\frac{d\omega}{dt}$, in (5) could be assumed to zero in steady state. The equation can be rewritten as (6) and (7). When no load in steady state, the (8) could be derived, where i_{nL} is the stator current in no load. After subtracting (7) and (8), (9) will be obtained. The variable torque constant at different speed will be calculated with Equation (9).

$$\tau_L = K_{\tau x} i - D\omega \tag{6}$$

$$K_{\tau x} = \frac{D\omega + \tau_L}{i} \tag{7}$$

$$K_{\tau x} = \frac{D\omega}{i_{nL}} \tag{8}$$

$$K_{\tau x} = \frac{\tau_L}{i - i_{nL}} \tag{9}$$

3. **Simulation Result.** A BLDC motor with variable torque constant is simulated in the Matlab/Simulink environment. This proposed simulation system is an open loop structure and runs in continuous time mode. A look-up table block is used to adapt the variable torque constant. The simulation system is built to compare the speed responses between the fixed rated torque constant and variable torque constant.

The simulated block of the open loop BLDC motor system in continuous time is shown in Figure 2. The BLDC model contains two transfer functions which are according to (2) and (4). In order to compare the difference between the fixed torque constant and the variable torque constant, the torque constant uses the interpolation method which is according to the measurement results of Figure 1 to estimate the variable torque constants. And the fixed torque constant is the motor rated torque constant. Figure 3 shows that the variable torque constant is gradually approaching the rated torque constant when the speed is increasing. And the variable torque constant will affect the speed response. The simulated results are shown in Figure 4 and Figure 5. The error of torque affects the rising and falling speed response. However, the error of torque will affect the speed response, but it will not cause a huge influence in the practical application. When using the PI controller in the motor controller, the PI controller will remove the effect of the error value.

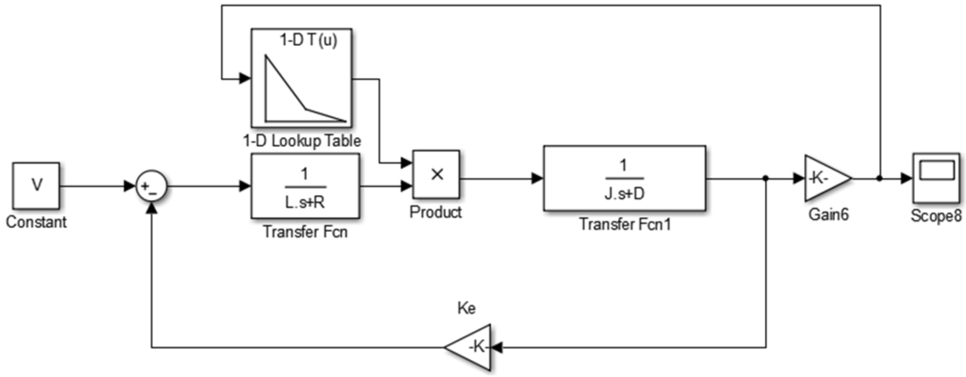

Figure 2. The simulation of open loop BLDC motor system in continuous time

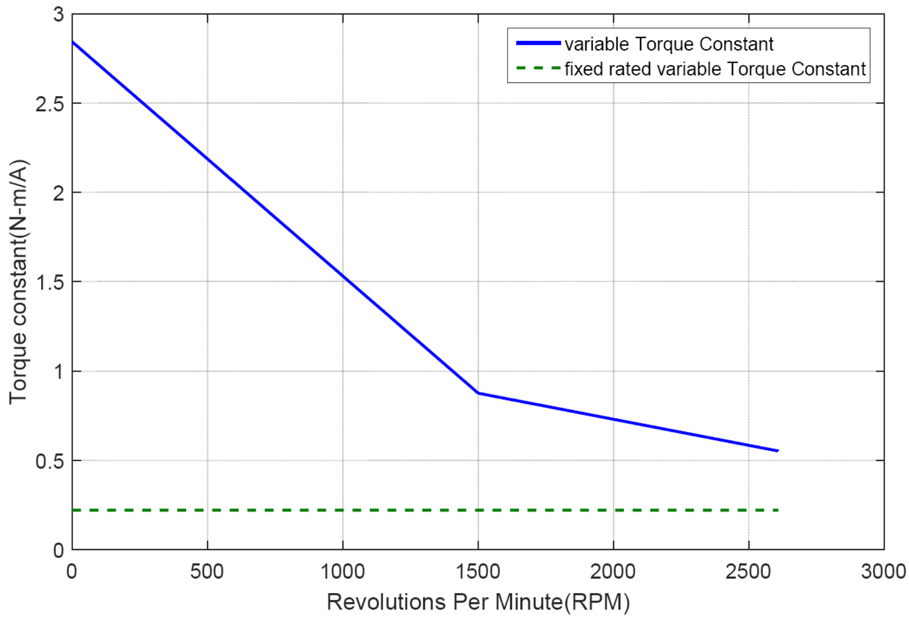

Figure 3. The amount of changing torque constant and fixed torque constant

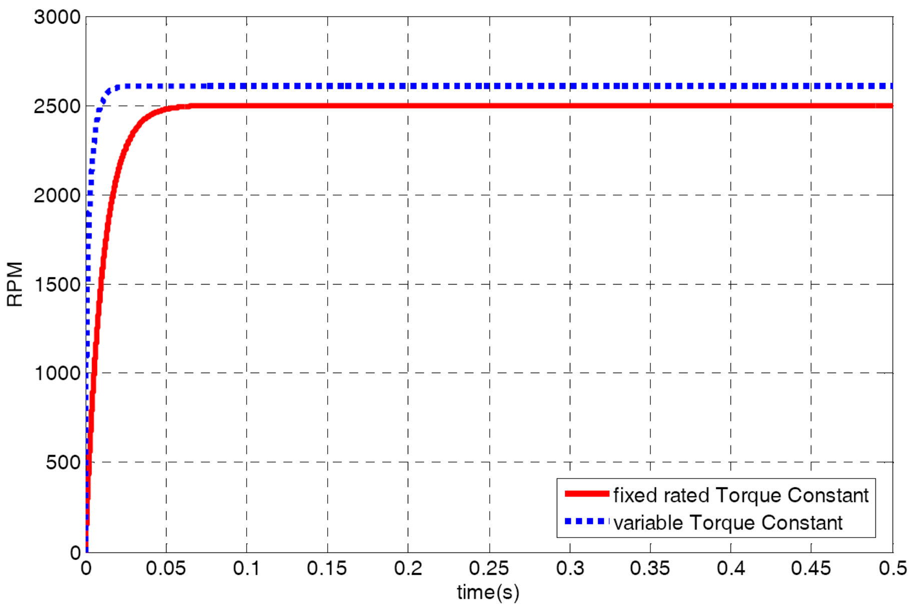

Figure 4. The speed response in motor specifications speed

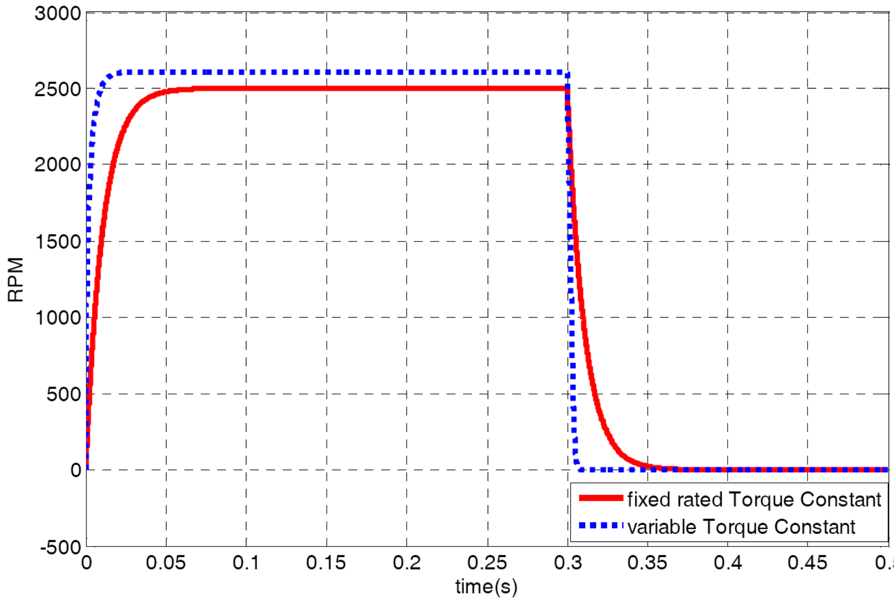

Figure 5. The speed response of motor deceleration

4. **Conclusion.** This paper discusses a phenomenon which the torque constant is variable at different speed. The torque load and stator current ratios are different at different speed, and the variable ratio is measured in the real experiment. This paper proposes a simplified torque equation and a variable torque constant equation. And the torque constant is gradually approaching the rated torque constant while the motor speed is approaching the rated speed. The simulation results show the variable torque constant affects the speed response obviously. However, a controller is expected to compensate this torque constant error in close loop motor system. By the results proposed in this paper, a more accurate and fast BLDC control which considers the torque constant variance will be researched and designed in the future.

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REFERENCES

[1] C.-W. Hung, C.-T. Lin and J.-H. Chen, A variable sampling PI control with variable sampling torque compensation for BLDC motors, *The 5th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pp.1234-1237, 2010.

[2] V. Manzolini, A. Darba and F. De Belie, Improving the torque generation in self-sensing BLDC drives by shaping the current waveform, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2016.

[3] J. Park, S. Hwang and J. Kim, Sensorless control of brushless DC motors with torque constant estimation for home appliances, *IEEE Trans. Industry Applications*, vol.48, no.2, pp.677-684, 2012.

[4] S. Li, B. Sarlioglu, S. Jurkovic, N. Patel and P. Savagian, Comparative analysis of torque compensation control algorithms of interior permanent magnet machines for automotive applications considering the effects of temperature variation, *IEEE Trans. Transportation Electrification*, vol.3, no.3, pp.668-681, 2017.

[5] N. Kobayashi, K. Kondo and O. Yamazaki, Induction motor speed sensor-less vector control with the mechanical simulator with disturbance torque compensation, *Proc. of Int. Symp. Power Electron. Elect. Drives, Autom. Motion (SPEEDAM'14)*, pp.1160-1165, 2014.

[6] H. Xu, F. Zhao, W. Cong, W. Peng and J. Zhang, A novel MTPA control strategy of induction motor based on torque current compensation, *The 19th International Conference on Electrical Machines and Systems (ICEMS)*, 2016.