SPEED AND POSITION ESTIMATION OF BRUSHLESS DC MOTOR IN VERY LOW SPEEDS

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ABSTRACT

The paper proposes a method to detect and control the speed and the position of a BLDC motor with a low resolution position encoder in very low speeds of several rad/sec. The low resolution encoder could be the Hall Effect sensor that have a resolution of maximum 60 electrical degrees, according to the pole number of the motor. The proposed algorithm used a Kalman Filter (KF). The position and the current are sampled. The algorithm was simulated on MATLAB©, and the simulation results were valuable.

1. INTRODUCTION

To control the speed and/or the position of an electrical motor we have to know its real speed and position. This could be done by measurement or by mathematical estimation. The position measurement could be done by an optical encoder. Generally, the optical encoder has large number of lines per revolution, e.g., 4,096 lines/revolution, to improve the resolution of the measurement, quality encoders could have much as 50,000 lines per revolution, but they are very expensive and quite large in size. The encoder resolution becomes critical especially when a low speed of several rad/sec is controlled. Several approaches were already proposed to overcome the encoder poor resolution at low speed control. They include a fixed-position time measurement (T-method) and a combination of a T-method with a fixed time Position measurement (M-method) called M/T method [1]. Another approach consist of a speed estimation based on a Second Order Sliding Mode derivation [2]. However these approaches use yet an optical encoder with more then1,024 line/revolution. The paper presents an algorithm to detect the speed and the position of a BLDC motor by using a very low resolution encoder of 60 electrical degree. The encoder could be the Hall Effect sensor that provides the timing signals for the BLDC motor phase switching, or the internal back emf wave of the motor itself. In this case, the control becomes sensorless. The low resolution of the encoder is equivalent to a large measurement noise in the position estimation. Furthermore, the presence of an unknown load torque and system parameter errors are equivalent to a large system noise. Therefore, the chosen solution was Kalman Filter (KF), while the measurement quantities are the position and the motor current. Furthermore, the BLDC motor model is introduced as a part of the KF. Moreover, to improve the algorithm, the Second Order Sliding Mode is used to approximate the motor position and its acceleration. The KF is used to estimate the load torque too. Therefore, the inputs of the KF are the real motor current, the approximate position and acceleration given by the Second Order Sliding Mode derivation. The KF outputs are the estimated position, speed and load torque or even the more general disturbance torque.

2. KALMAN FILTER CONFIGURATION

The general configuration of a KF governed by a linear stochastic equation is $X_{n+1} = AX_n + BU_n + W_n$ where W is the system noise with Q covariance. The measurement stochastic equation $Z_n = HX_n + V_n$ were V is the measurement noise with R covariance. The recursive process of KF is:

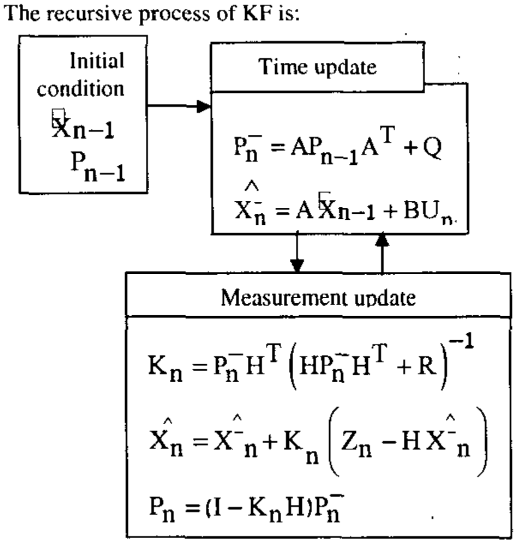

Fig. 1. Kalman Filter recursive process

3.THE MOTOR MODEL

The equation of the motor are simplified as:

$$V_K = I_K R_m + L_K \frac{dI_K}{dt} + k_B \omega$$

$$T_m = K_m I_K$$

$$T_m - T_L = J\frac{d\omega}{dt} + B\omega$$

and by assumption that the load changes very slow

$$\frac{dT_L}{dt} = 0$$

The state equations are [3]:

$$\underbrace{\begin{bmatrix} I_E \\ \omega \\ \theta \\ T_L \end{bmatrix}}_{X} = \underbrace{\begin{bmatrix} \frac{-R_m}{L_E} & \frac{-K_m}{L_E} & 0 & 0 \\ \frac{K_m}{J} & \frac{-B}{J} & 0 & \frac{-1}{J} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} I_E \\ \omega \\ \theta \\ T_L \end{bmatrix}}_{X} + \underbrace{\begin{bmatrix} \frac{1}{L_E} \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{B} V_E$$

The state equations in the discrete case are:

$$\underbrace{\begin{bmatrix} I_{n+1} \\ \omega_{n+1} \\ \theta_{n+1} \\ T_{L_{n+1}} \end{bmatrix}}_{X_{n+1}} = \underbrace{\begin{bmatrix} 1-\frac{R_m}{L_E}dt & \frac{-K_m}{L_E}dt & 0 & 0 \\ \frac{K_m}{J}dt & 1-\frac{B}{J}dt & 0 & \frac{-dt}{J} \\ 0 & dt & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} I_n \\ \omega_n \\ \theta_n \\ T_{L_n} \end{bmatrix}}_{X_n} + \underbrace{\begin{bmatrix} \frac{dt}{L_E} \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{B} V_n$$

The measurement equations are:

$$\underbrace{\begin{bmatrix} I \\ \theta \\ a \end{bmatrix}}_{Z} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \frac{k}{J} & \frac{-B}{J} & 0 & \frac{-1}{J} \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} I \\ \omega \\ \theta \\ T_L \end{bmatrix}}_{X}$$

The position and the acceleration were estimated by using the Second Order Sliding Mode method [2].

4.SECOND ORDER SLIDING MODE METHOD

The second order sliding mode method uses an observer for the second derivative [2].The improvement of this method is that the speed and the position are continues in time . The block diagram of Second Order Sliding Mode method is shown in Fig. 2.

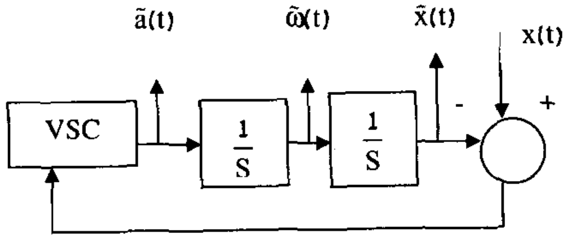

Fig . 2. .Seconde Order Sliding Mode Observer

The VSC function is defined as: $\tilde{a}[k] = U_M \text{sign}\{\varepsilon 1[k] - \varepsilon 1M[k]\}$ where:

$$\varepsilon 1M[k] = \begin{Bmatrix} \varepsilon 1[k] & \text{if } \Delta[k] < 0 \\ \varepsilon 1M[k-1] & \text{otherwise} \end{Bmatrix} \text{ and}$$

$$\begin{cases} \Delta[k] = (\varepsilon 1[k-2] - \varepsilon 1[k-1])(\varepsilon 1[k-1] - \varepsilon 1[k]) \\ \varepsilon 1[-2] = 0; \ \ \varepsilon 1[-1] = \varepsilon 1[0]; \ \ \varepsilon 1M[-1] = \varepsilon 1[0] \end{cases}$$

The constant U_M affects the speed convergence and the ripple of X (t).

5. THE PROPOSED SPEED AND LOAD ESTIMATOR

As mentioned before, we use a combination of second order sliding mode method with KF. Firstly, we estimate the position and the acceleration with second order sliding mode method, and, secondly, we used KF. The propose system is shown in Fig 3

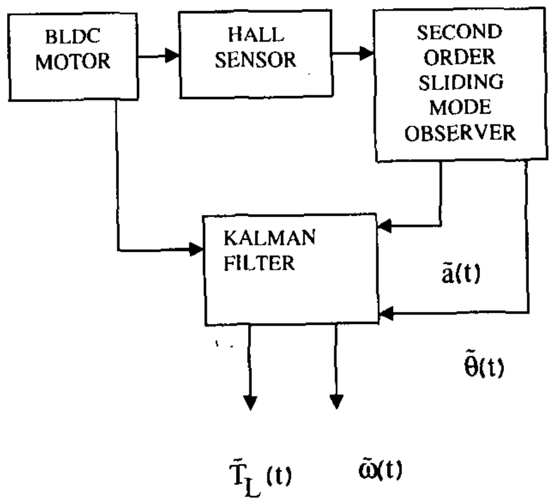

Fig .3. The proposed system

6.THE SIMULATION RESULTS

Fig. 4 and Fig. 5 show the simulation results of the low speed motor with load change by sin(2*t)+1)*0.02. The parameters of the motor, resistance, inductance, and torque constant were changed by 10%.

Fig. 4 shows the real and estimate speed, Fig. 5 shows the real and estimate load.

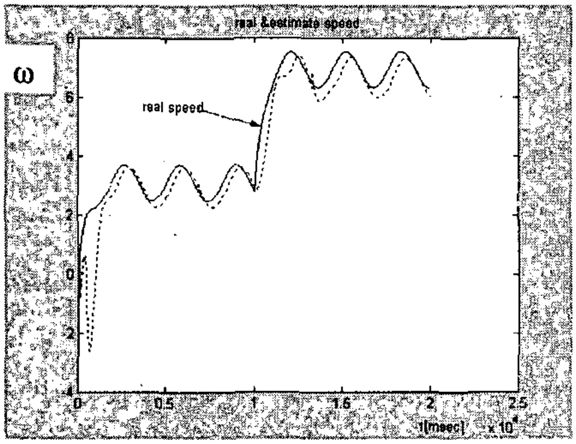

Fig.4. The real and estimate speed

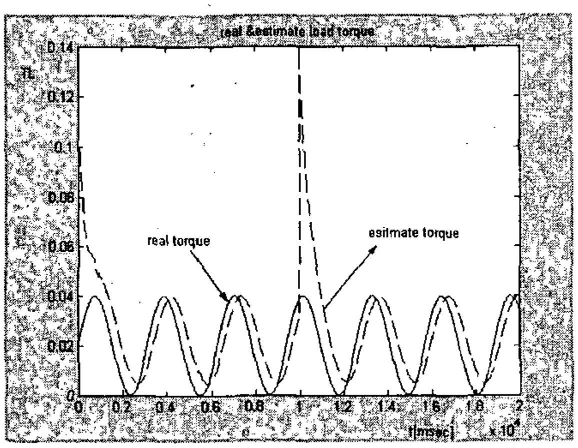

Fig.5. The real and estimate load

As shown in Fig. 4 and Fig. 5 we got a good estimation of the real values for the speed and the load, although there is a phase shift between the real speed and real load, and the estimated speed and the estimated load. This phase shift causes problems with a conventional control method, for example a PI controller. The phase shift in the simulation was arbitrarily dependent on the motor parameters, speed, and load. We did not find any connection between these parameters and the phase shift. Furthermore, we tried to control the speed by using a resonant controller, by the assumption that the load torque is of constant frequency for any given speed.

7. RESONANT CONTROL: SIMULATION RESULTS

The basic concept of resonant controller is to reject a constant frequency disturbance, by adding a transfer function to PI controller with poles at the disturbance frequency. It is called PIS compensator [4]. We could use two kinds of transfer functions with poles at the disturbance frequency. For time domain $r(t) = A\cos(\omega_0 t)$, the transfer function is $G1(s) = \dfrac{As}{s^2 + \omega_0^2}$. This transfer function has a pole at ω_0. For $r(t) = A\sin(\omega_0 t)$, the transfer function is $G2(s) = \dfrac{A\omega_0}{s^2 + \omega_0^2}$. This transfer function has a pole at ω_0. The sum of the two functions has a pole at ω_0, but with a different phase.

The propose system is shown in Fig. 6.

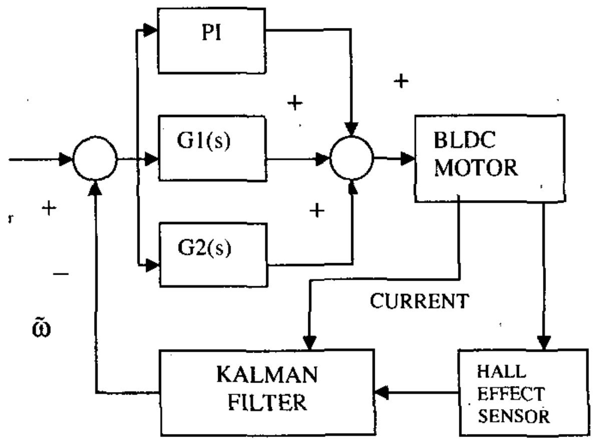

Fig .6. The proposed system

We add the two transfer function to compensate the phase shift between the real speed and the estimated speed. The sum of sin function and cos function with deferent constant coefficients would eliminate the disturbance effects. We didn't found a systematic way to choose the coefficients, but by a trail and error approach we succeeded to find the coefficient for the simulated case of 2[rad/sec] with load of Fig. 5. We got good results for this special case. The simulation results are shown in Fig. 7. It will be interesting to find a systematic way to choose the best coefficient for the sin and cos transfer function.

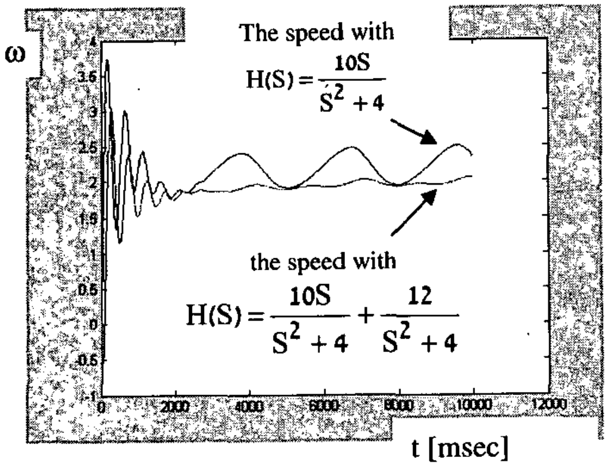

Fig. 7. Real speed with only cos function, and the speed with sin and cos function

As we see in Fig. 7, it is possible to control the speed of BLDC MOTOR when we estimate the speed with KF by using a low-resolution encoder.

8. CONCLUTIONS

1. It would be possible to detect low rotation speeds with a low-resolution position encoder by using a KF, while the position and the current are measured. Errors in the system model and the measurement quantities are permitted.
2. It would be possible to detect the load and the speed with changing load torques by permitting a system noise.
3. The adding of the second order sliding mode method to the KF improves the estimation when the load changes in a relatively fast manner.
4.It is possible to control the speed with load that changes with a constant frequency, by estimating the speed with KF and PIS control systems.
5. More research is required to find a systematic way to get the coefficients of the sin and cos functions of the resonant controller.

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