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SPEED SENSORLESS CONTROL FOR PMSM DRIVES USING EXTENDED KALMAN FILTER

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Graphical abstract
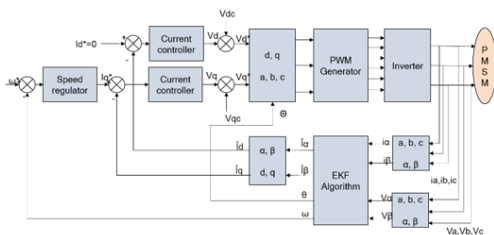
SENSORLESS PMSM DRIVE USING EKF

Abstract

In this paper, Sensorless Permanent Magnet Synchronous Motor (PMSM) using Extended Kalman Filter (EKF) is presented. The previous PMSM drive uses a sensor to measure the motor's speed. Then the idea is to replace the sensor by using sensorless drives based on the observer. For the conventional observer, it's only good for low current and low-speed applications. Moreover, it is hard to detect the phase voltage due to the non-existence of neutral wire. Therefore, this project proposes sensorless control using an EKF. This method provides an optional estimation algorithm for the non-linear system that can produce a fast and accurate estimation of state variables. The accurate estimation will reduce the noise and ripple of the system. Additionally, the EKF do not require the information of mechanical parameters and the initial position of the rotor, making the construction is easy and simple. In this paper, the fundamental of the EKF algorithm is explained and the simulation results for different speeds and loads are presented. The noise reduction test is also conducted to measure the flux current with and without the filter. The simulation study is achieved using MATLAB/Simulink to verify the effectiveness of the proposed method. The results of the simulation show that the sensorless PMSM drives using EKF have lower overshoot and faster rise time during start-up conditions and have lower undershoot during the loaded condition. It also can be concluded that the proposed sensorless PMSM drive using EKF has good speed control accuracy and can reduce the current noise.

Keywords: Permanent Magnet Synchronous Motor (PMSM), Extended Kalman Filter (EKF), Sensorless Drive, Noise reduction

Abstrak

Dalam kertas kerja ini, Motor Segerak Magnet Kekal (PMSM) Tanpa Sensor menggunakan "Extended Kalman Filter" (EKF) adalah dibentangkan. Pemacu PMSM sebelumnya menggunakan sensor untuk mengukur kelajuan motor. Kemudian ideanya adalah untuk menggantikan sensor dengan menggunakan pemacu tanpa sensor menggunakkan "observer". Bagi "observer" konvensional, ia hanya baik untuk aplikasi arus rendah dan kelajuan rendah. Selain itu, sukar untuk mengesan voltan-fasa kerana ketiadaan wayar neutral. Oleh itu, projek ini mencadangkan kawalan tanpa sensor menggunakan EKF. Kaedah ini menyediakan algoritma anggaran untuk sistem bukan linear yang boleh menghasilkan anggaran pembolehubah keadaan yang cepat dan tepat. Anggaran yang tepat akan mengurangkan bunyi dan riak sistem. Selain itu, EKF tidak memerlukan maklumat parameter mekanikal dan kedudukan awal rotor, menjadikan pembinaannya mudah dan ringkas. Dalam kertas ini, asas algoritma EKF diterangkan dan keputusan simulasi untuk kelajuan dan beban yang berbeza dibentangkan. Ujian

$$Te = \frac{3}{2}\left(\frac{p}{2}\right)\left(\lambda_d\, i_q - \lambda_q\, i_d\right) \qquad (8)$$

The mechanical Torque equation is:

$$T_e = T_l + B\omega_m + J\frac{d\omega_m}{dt} \qquad (9)$$

Solving for the rotor mechanical speed form Equation (9):

$$\omega_m = \int\left(\frac{T_e - T_l - B\omega}{J}\right)dt \qquad (10)$$

$$\omega_m = \omega_r\left(\frac{2}{P}\right) \qquad (11)$$

In the above equations, ω_r is the rotor electrical speed where ω_m is the rotor mechanical speed. Figure 2 presents the overall simulation block diagram of Sensorless PMSM Drive Using EKF.
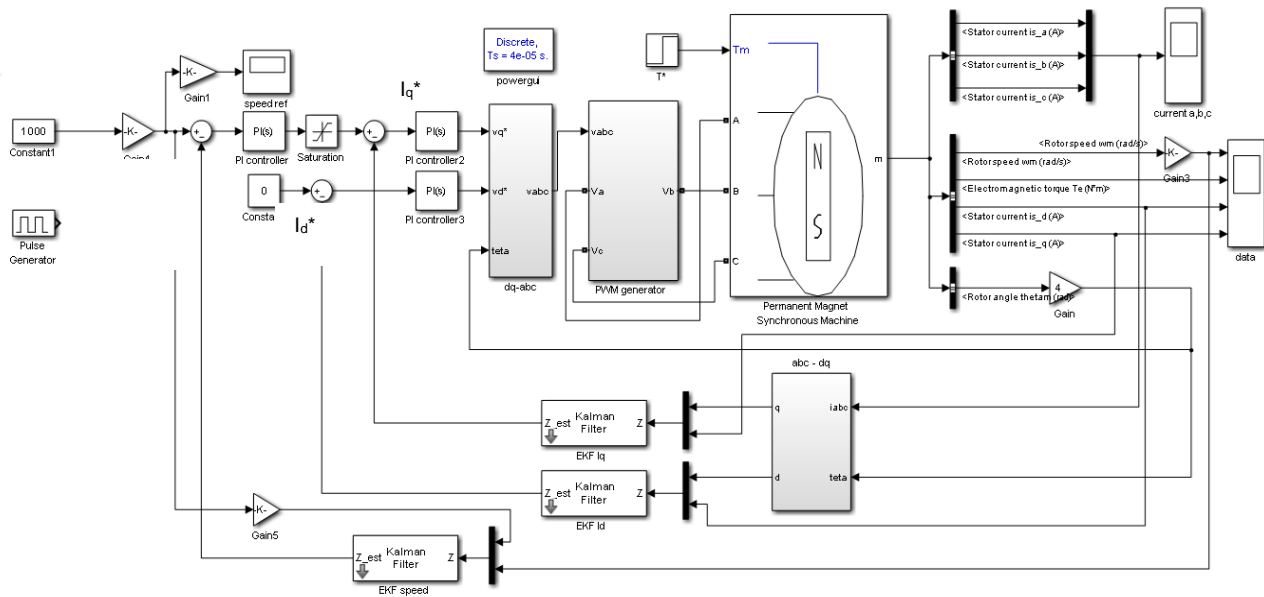
Figure 2 Overall Simulation Block Diagram for Sensorless PMSM Drive Using EKF

The drives system in Figure 2 starts with the reference torque current (I_d*) which is equal to zero. This reference torque for current and speed is fed into the summation block to compare with the actual torque producing current and actual speed gain by PMSM. The comparison in the summation block producing error. The error from torque current will be moved into the current controller while an error from speed will move into the speed regulator block producing reference current of flux (I_q*) and into the current controller block. Both current controllers producing torque voltage and flux voltage. Then it will be compared with coupling voltage in the summation block to produce the reference voltage. Both reference voltages (V_d*, V_q*) then fed into the converter which is converted from the d-q component into 3-phase voltages, V_a, V_b and V_c. The voltages now entering PWM generator block then into inverter block before supplying the PMSM. The currents and voltages from the motor are then converted into alpha and beta components. Both components entering the EKF algorithm block to calculate producing I_α, I_β, rotor angle(θ) and speed reference(ω). The reference currents now are converted into actual torque and flux currents including the speed, then are compared in the summation block earlier. The actual rotor angle is fed into park converter. So that is the overall scheme of sensorless vector control for PMSM using EKF.

B. Extended Kalman Filter Algorithm

In actual applications, the processes to be estimated are usually non-linear. Now the extended Kalman filter observer is applied to estimate the rotor speed that is feedback controlled by the PI regulator. By referring to Figure 2, the EKF observer is predicated on the error of the stator currents generated from their measured and estimated values that should be converged toward zero via defined style. Figure 3 shows the complete picture of the Kalman filter operation.

Figure 3 Kalman Filter Operation

The general problem of estimating the state $x \in \Re^{\Re}$ of a discrete-time process that is expressed by a linear stochastic difference equation. However, in actual applications, the processes to be estimated are usually non-linear. An extended Kalman filter (EKF) therefore is derived from the Kalman filter to solve this problem.

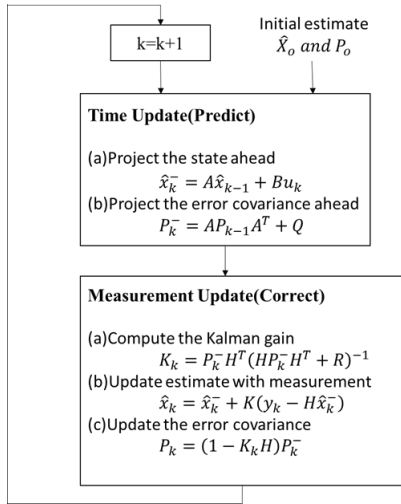The non-linear relationships around the current time step can be linearized by using the partial derivatives of the process and measurement functions. To realize the linearization of a non-linear process, some parts in solution equations of the Kalman filter must be modified. Assuming $x \epsilon R^n$ to be a state vector of a process, it can then be governed by the non-linear stochastic difference equation;

$$X_k = f(x_{k-1}, u_k, \sigma_{k-1}) \tag{12}$$

With measurement $y \epsilon R^n$,

$$y_k = h(x_k, \rho_k) \tag{13}$$

Where the random variable σ_{k-1} and ρ_k represent the process and measurement noise. From Equation (12), the non-linear function f relates the state at the previous time step k-1 to the state at the current time step k, and includes driving function U_k and the zero-mean process noise σ_{k-1}. In the measurement Equation (13), the non-linear function h shows the relationship between the state vector x_k and the measurement vector y_k.

The individual values of the noise σ_k and ρ_k at each time step are not known in actuality. However, the state and measurement vectors without noise could be approximated as:

$$\tilde{x}_k = f(\hat{x}_{k-1}, u_k, 0) \tag{14}$$
$$\tilde{y}_k = h(\tilde{x}_k, 0) \tag{15}$$

where $\hat{x}_{k-1}$ is the posterior state estimation at the previous time step k-1. Thus a non-linear process can be approximately linearized as:

$$x_k = \tilde{x}_k + A_k(x_{k-1} - \hat{x}_{k-1}) + W_k\sigma_{k-1} \tag{16}$$
$$y_k \approx \tilde{y}_k + H_k(x_k - \tilde{x}_k) + V_k\rho_k \tag{17}$$

The prediction error and the measurement residual are define as:

$$\tilde{e}_{x_k} \approx x_k - \tilde{x}_k \tag{18}$$
$$\tilde{e}_{y_k} \approx y_k - \tilde{y}_k \tag{19}$$

EKF equations can be split into two groups:
   1) Time update equations

$$\hat{x}_k^- = f(\hat{x}_{k-1}, u_k, 0) \tag{20}$$
$$P_k^- = A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T \tag{21}$$

   2) Measurement update equations

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + V_k R V_k^T)^{-1} \tag{22}$$
$$\hat{x}_k = \hat{x}_k^- + K_k(y_k - h(\hat{x}_k^-, 0)) \tag{23}$$
$$P_k = (1 - K_k H_k)P_k^- \tag{24}$$

The basic computing cycle of the discrete EKF is the same as that of the linear discrete Kalman filter shown in Figure 3.

3.0 RESULTS AND DISCUSSION

The simulation was performed based on three different tests which are, the speed-accuracy test, noise reduction test and the load torque test. The results are presented in Figures 4-6 below.

A. Speed Accuracy Test

In this simulation, the speed-accuracy for the proposed PMSM algorithm is tested for different speeds and depicted in Figure 4. This simulation test is divided by three conditions, 100%, 50% and 75% of rated speed which is 1000 rpm.
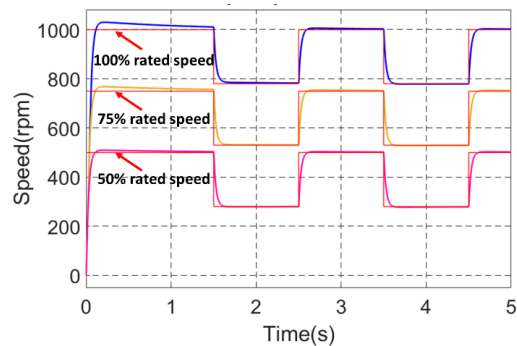

Figure 4 Speed behavior with EKF estimator

The average steady-state speed error is 0.0004% at 1000 rpm, 0.00021% at 500 pm and 0.0092% at 250 rpm. The absolute value of the average steady-state speed error increase as the speed decreases because of the chopping noise factor and the dead time of PWM drive. The above result is listed in Table I. From the results of the simulation, it can be concluded that the proposed sensorless PMSM drive using EKF has good speed control accuracy, except at low speeds.

Table 1 Speed error of the simulation for speed accuracy test

Reference speed ω_{ref}	Speed		
	1000 rpm	500 rpm	250 rpm
Steady-state error $\omega_{act} - \omega_{filter}$	-0.004rpm	-0.006rpm	-0.023rpm
Steady-state speed error ratio $\frac{\omega_{act} - \omega_{filter}}{\omega\_ref} \times 100$	-0.0004%	-0.0012%	-0.0092%

B. Noise Reduction Test

The simulation for the noise reduction test of the proposed sensorless PMSM drive using EKF is based on the results shown in Figure 5 and Table 2.
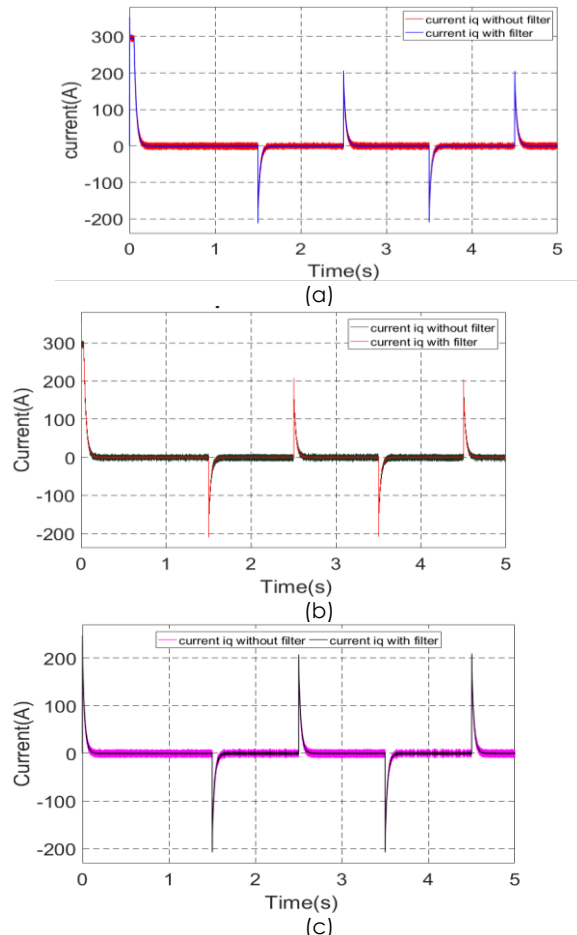

(a)

(b)

(c)

Figure 5 Simulation result of (a)current Iq at 1000 rpm, (b)current Iq at 500 rpm, (c)current Iq at 250 rpm

Figure 5(a), Figure 5(b) and Figure 5(c) show the wave-forms of the current I_q with and without a filter at 1000 rpm, 500 rpm and 250 rpm. From the results of the simulation, it can be concluded that the proposed sensorless PMSM drive using EKF has good noise reduction, except at low speeds.

C. Load Torque Test

This simulation test is divided into two tests which are rotor speed at 100% and 50% rated speed. At each rotor, speed stages are applied with 100%, 120% and 50% of rated load torque which are 100 Nm, 120 Nm and 50 Nm. Figure 6 presents the rotor speed with load torque behaviour.
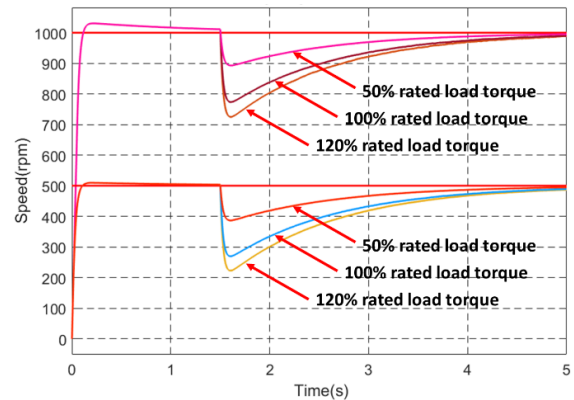
Figure 6 Speed with load torque behaviour

Figure 6 shows the waveform of the 2 different actual speeds which are 1000 rpm and 500 rpm, with Torque Load TL applied at t=1.5 s. Figure 6 also shown three different TL which are 120 Nm, 100 Nm and 50 Nm.

The overshoot and rise time for responses are represented in Table 2. And the overshoot during load applied is tabulated in Table 3.

Table 2 Overshoot and rise time of the speed response

Ref. speed ω_{ref}	Overshoot (rpm)	Rise Time (s)
1000 rpm	30	0.2
500 rpm	9	0.2

Table 3 undershoot and settling time during the loaded condition

Load, TL (NM)	Speed 1000rpm		Speed 500rpm	
	Undershoot (rpm)	Settling Time (s)	Undershoot (rpm)	Settling Time (s)
120	247.8	3.4	277.9	3.4
100	226.8	3.1	230.3	3.2
50	107.1	2.9	113.4	3.0

From the result, it can be summarized that overshoot will increase as speed reference increase.

Next, undershoot and recovery time will increase as load torque is increase. From the result of simulation, it can be concluded that the proposed sensorless PMSM drive using EKF has good robustness for variation of load.

4.0 CONCLUSION

In this paper, the modelling, analysis and design validation of a robust and noise reduction sensorless control method for permanent magnet synchronous motor (PMSM) using Extended Kalman Filter (EKF) to accurately estimate rotor speed and current has been presented. A Matlab/Simulink based dynamic model and modulation technique for the PMSM has been developed and implemented. Detailed simulations and analysis of the proposed sensorless PMSM drive using EKF have been presented which validate the robustness, noise reduction and accuracy of the proposed sensorless method. The specifications of the PMSM are listed in Table 4.

Table 4 Specifications of the PMSM

No.	Parameter	Specification
1	Motor Power	20 KW / 14.92 HP
2	Rated Speed	1000 RPM
3	Rated torque	100 Nm
4	Rated current	296 A
5	Rated voltage	176 V
6	Number of poles	4
7	L_d	0.3595 mH
8	L_q	0.695 mh
9	R_s	6.5 mΩ
10	Flux(φ_m)	0.080 Wb
11	Inertia(J)	0.1 kgm^2
12	Damping Coefficient(B)	0

Acknowledgement

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