Sensorless Speed Control of Surface PMSM using DTC Control Based on Extended Kalman Filter

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Abstract__

Speed control of permanent magnet synchronous motor (PMSM) using Direct Torque Control has rapid response and good static and dynamic performance but less accurate since current, torque and flux linkage wave forms contain big ripples. To overcome these disadvantages stator flux linkage and rotor speed are estimated using Extended Kalman Filter. Therefore, sensorless speed control of surface permanent magnet synchronous motor using DTC control based on Extended Kalman Filter is realized. Simulation results have proved that this method has rapid torque response of DTC control as well as robust to motor parameters and load disturbance because of EKF.

Key words__ Permanent magnet synchronous motor, Direct Torque Control, Stator flux linkage observation, Extended Kalman filter, Sensorless Speed control.

I. Introduction

The work presented in this project relates to Surface Permanent Magnet Synchronous Motor (PMSM). It mainly to develop Sensorless Speed Control of Surface Permanent Magnet Synchronous Motor using DTC control.

II. Necessity of Sensorless speed Control

System with mechanic speed sensor has lower reliability and higher system cost. Direct torque controlled permanent magnet synchronous motor (PMSM) has fast response and good static and dynamic performance. In this method, performance of the entire system depends upon the observation accuracy of stator flux linkage. So how to get stator flux linkage and speed information has become the research hotspot.

Traditional Direct Torque Control method uses pure voltage integration to observe stator flux linkage. It is simple method but Integrator is sensitive to initial value and DC offset which influence the accuracy of stator flux linkage observation. These problems can be solved by using an improved method to observe stator flux linkage. In the next approach, Integrator is replaced by Low-pass filter to observe flux linkage, which results in flux linkage phase ahead and its amplitude smaller. Even though Amplitude and phase compensation is researched, it cannot overcome disadvantages of pure integrator.

To solve these problems, sensorless speed control using direct torque control for surface permanent magnet synchronous motor is realized. In this method, Extended Kalman Filter observer is used instead of sensor to estimate both stator flux linkage and rotor speed. This method over comes the disadvantages of problems resulting from mechanical speed sensor as well as pure integrator. It has the advantages of DTC method such as rapid torque response and strong robustness at the same time, the system based on EKF is robust to motor parameters and load disturbance. The dynamic and static performances are dramatically improved.

III. Modeling of SPMSM and EKF

3.1 Modeling of SPMSM

α-β Coordinate is chosen in order to design Extended Kalman Filter observer. The voltage equation of SPMSM is as following

$$\mathbf{u_\alpha=R_si_\alpha+L_sdi_\alpha/dt-\omega_r\psi_rSin\theta_r}$$
$$\mathbf{u_\beta=R_si_\beta+L_sdi_\beta/dt-\omega_r\psi_rCos\theta_r \text{ --- } (1)}$$

Equation (2) is gotten from (1).

$$\mathbf{u_\alpha=R_si_\alpha+d\psi_\alpha/dt}$$
$$\mathbf{u_\beta=R_si_\beta+d\psi_\beta/dt \text{ ------------------ } (2)}$$

Where

u_α, u_β are stator voltage components
i_α, i_β are stator current components
ψ_α, ψ_β are stator flux linkage components
R_s, L_s are stator resistance and inductance
θ_r, ω_r are rotor position angle and speed

3.2 Design of EKF Observer

The state and output equations of discrete linear system with random interference is as following

$$\mathbf{x_{k+1}=A_kx_k+B_ku_k+w_k}$$
$$\mathbf{y_k=C_kx_k+v_k \text{ ----------------------- } (3)}$$

Where w(k) represents system noise takes into account the system disturbances and model errors, while measurement noise v(k) takes into account all measure noise and measure errors. Both v (k) and w (k) are zero-mean white noise with covariance of *R* and *Q*, respectively and independent from each other.

Optimal state and its covariance are calculated in two-steps. Prediction step performs a prediction of both quantities based on the previous estimates. The equations are as the following:

$$X^{\wedge}_{k/k-1}=A_{k/k-1}x^{\wedge}_{k-1}+B_{k/k-1}u_{k-1} \text{ ---------- } (4)$$

$$P^{\wedge}_{k/k-1}=A_{k/k-1}P_{k-1}\,A^{T}_{k/k-1}+Q \text{ --------- } (5)$$

The Innovation step corrects the predicted state and estimation and its covariance matrix through a feedback correction scheme that makes use of the actual measured quantities, which are realized by the following equations.

$$K_k=P^{\wedge}_{k/k-1}C^{T}_{k}[C_kP^{\wedge}_{k/k-1}C^{T}_{k}+R] \quad (6)$$

$$x^{\wedge}_{k/k}=x^{\wedge}_{k/k-1}+K_k[y_k-C_kx^{\wedge}_{k/k-1}] \quad (7)$$

$$P_{k/k}=(1-K_kC_k)P^{\wedge}_{k/k-1} \quad (8)$$

IV. Design of EKF Based DTC for PMSM

The flux linkage equation of SPMSM is as the following

$$\psi_{\alpha}=L_si_{\alpha}+\psi_f\,\mathrm{Cos}\theta_r$$

$$\psi_{\beta}=L_si_{\beta}+\psi_f\,\mathrm{Sin}\theta_r \text{ ---}(9)$$

From (2) & (9), (10) can be obtained.

$$d\psi_{\alpha}/dt = -(R_s/L_s)\psi_{\alpha}+(R_s/L_s)\psi_f\,\mathrm{Cos}\theta_r+u_{\alpha}$$

$$d\psi_{\beta}/dt =-(R_s/L_s)\psi_{\beta}+(R_s/L_s)\psi_f\,\mathrm{Sin}\theta_r+u_{\beta} \text{ ---- } (10)$$

As sampling interval time is so smaller than dynamic process of SPMSM, speed can be considered unchanged

i.e $d\omega/dt=0$

Also we have the equation

$$d\theta_r/dt=0$$

$x(t)= [\psi_{\alpha}\ \ \psi_{\beta}\ \ \omega_r\ \ \theta_r\ ]^T$ is selected as state variable, $U=[u_{\alpha}\ \ u_{\beta}]^T$ and $y=[i_{\alpha}\ i_{\beta}]^T$ are chosen as input and output variable respectively which can easily obtained from the measurements.

Thus the dynamic state model for SPMSM was as following.

$$\dot{x} = f(x)+Bu$$

$$y=g(x) \qquad \text{----------------}(11)$$

Where

$$f(x)=\begin{pmatrix} -(R_s/L_s)\psi_{\alpha}+(R_s/L_s)\psi_f\mathrm{Cos}\theta_r \\ -(R_s/L_s)\psi_{\beta}+(R_s/L_s)\psi_f\mathrm{Sin}\theta_r \\ 0 \\ \omega_r \end{pmatrix}$$

$$g(x)=\begin{pmatrix} \frac{-1}{Ls}(\psi_{\alpha}-\psi_f\,\mathrm{Cos}\theta_r) \\ \frac{-1}{Ls}(\psi_{\beta}-\psi_f\,\mathrm{Sin}\,\theta_r) \end{pmatrix}, B=\begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

Equation (12) is obtained by linearization and discretization of (11).

$$x(k+1)=A(k)x(k)+H(k)u(k)+w(k)$$

$$y(k)=C(k)x(k)+v(k) \qquad \text{---------}(12)$$

Where

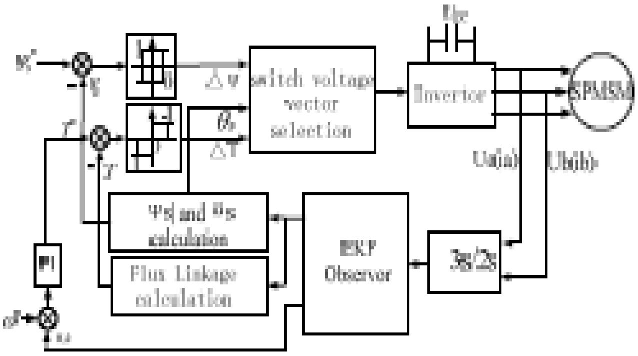
$$A=\begin{pmatrix} -R_s/L_s & 0 & 0 & -(R_s/L_s)\psi_f\,\mathrm{Sin}\,\theta_r \\ 0 & R_s/L_s & 0 & (R_s/L_s)\psi_f\,\mathrm{Cos}\,\theta_r \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}, H(k)=\begin{pmatrix} T & 0 \\ 0 & T \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$$C=\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1/L_s & 0 & 0 & (\psi_f/L_s)\mathrm{Sin}\,\theta_r \\ 0 & 1/L_s & 0 & -(\psi_f/L_s)\,\mathrm{Cos}\,\theta_r \end{pmatrix}$$

System noise $w(k\ )$ represents the error caused by parameter changes and linearization and discretization, while $v(k\ )$ represents errors caused by input and output measurements. Given system initial state, state estimates can be determined by recursive operation according to (4) to (8).

***Speed Sensorless DTC Control*:-**

Schematic diagram of speed Sensorless DTC control for SPMSM based on EKF is shown in below Figure.



Switch voltage vector selection is shown in below table

△ ψ	△ T	①	②	③	④	⑤	⑥
1	1	Us2	Us3	Us4	Us5	Us6	Us1
	0	Us7	Us8	Us7	Us8	Us7	Us8
	-1	Us6	Us1	Us2	Us3	Us4	Us5
-1	1	Us3	Us4	Us5	Us6	Us1	Us2
	0	Us8	Us7	Us8	Us7	Us8	Us7
	-1	Us5	Us6	Us1	Us2	Us3	Us4

V. SIMULATION RESULTS & DISCUSSIONS

Simulation model is established using MATLAB/SIMULINK tools. EKF algorithm is achieved by S function. Parameters of SPMSM are shown in table below

Motor parameters	value
R_s	1.26 Ω
P_n	4
L_s	6.5 H
P ψ_r	0.175 W_b
J	0.0008 $K_g.m^2$

Parameters of EKF are as following to ensure filter not divergent

$$Q=\begin{pmatrix}0.3 & 0 & 0 & 0\\ 0 & 0.3 & 0 & 0\\ 0 & 0 & 3 & 0\\ 0 & 0 & 0 & 0.3\\ 0.1 & 0 & 0 & 0\end{pmatrix}, \quad R=\begin{pmatrix}0.2 & 0\\ 0 & 0.2\end{pmatrix}$$

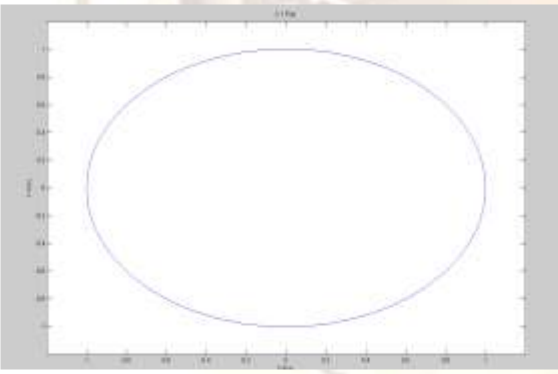
$$P(0)=\begin{pmatrix}0.1 & 0 & 0 & 0\\ 0 & 0.1 & 0 & 0\\ 0 & 0 & 200 & 0\\ 0 & 0 & 0 & 10\end{pmatrix}, \quad x(0)=\begin{pmatrix}0\\ 0\\ 0\\ 0\end{pmatrix}$$

Simulation results of DTC control based on EKF for all the cases in Comparison of with traditional DTC control are illustrated in figures below

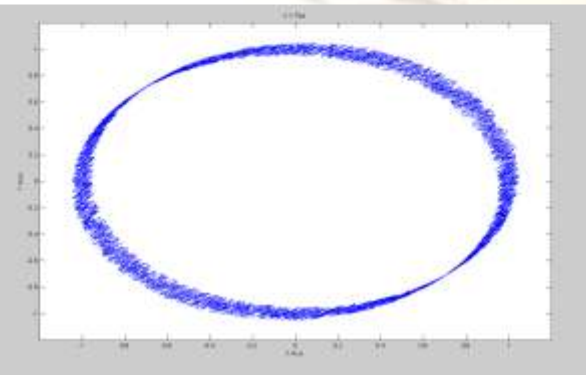
Case 1: Sudden decrease of torque

Given rotor speed is 500rpm, at 0.2 seconds, load torque decreases from 30 N-m to 0N-m. Corresponding stator flux linkage and electromagnetic torque waves using traditional DTC method and DTC-based on EKF method are respectively shown in Figure 1 & 2.

Figure 1: Stator flux linkage waves

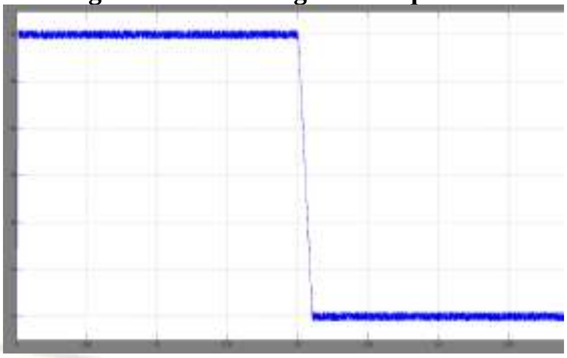


(a) DTC-based on EKF method

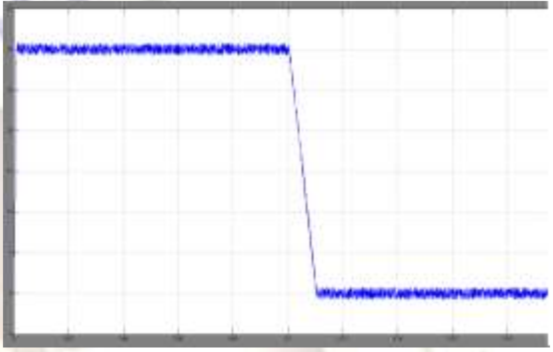


(b) Traditional DTC method

Figure 2: Electromagnetic torque waves



(a) DTC-based on EKF method



(b) Traditional DTC method

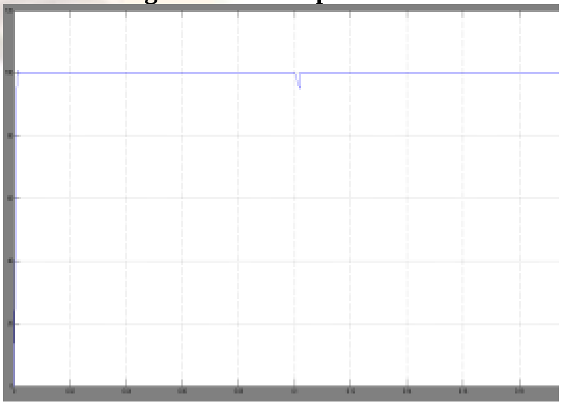
Flux linkage under traditional DTC is not smooth and has sharp fluctuation especially in the start-up, while, under DTC-based on EKF flux linkage has no obvious ripples due to more accurate EKF observer. Torque dynamic response time is basically the same, which indicates EKF control method do not affect the DTC dynamic performance.

The torque ripples using DTC-based on EKF method is significantly reduced and steady performance has been greatly improved.

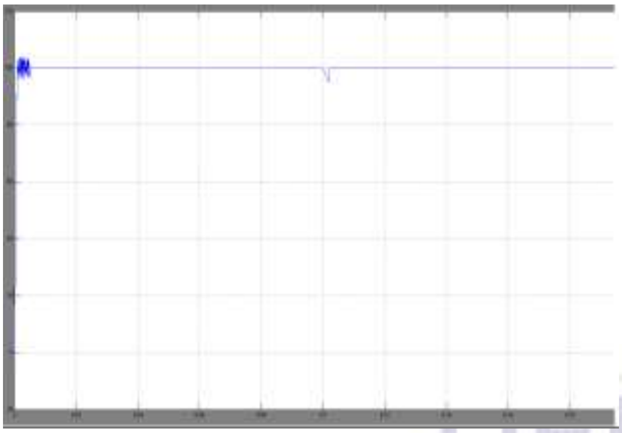
Case 2: Sudden increase of torque

Given rotor speed is 100rpm, at 0.1 seconds, load torque increases from 0N.m to 6N.m. Corresponding rotor speed and current waves using traditional DTC method and DTC-based on EKF method are respectively shown in Figure 3 & 4.

Figure 3: Rotor speed waves

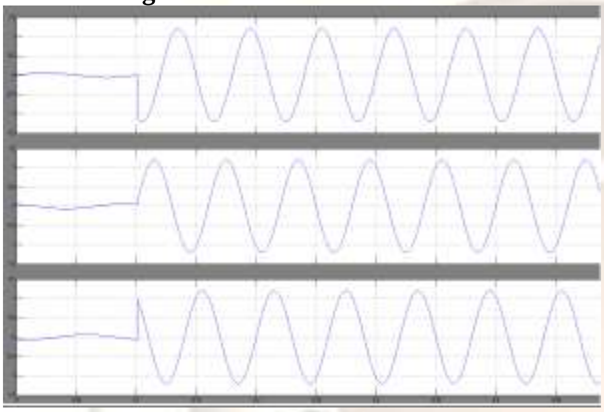


(a) DTC-based on EKF method

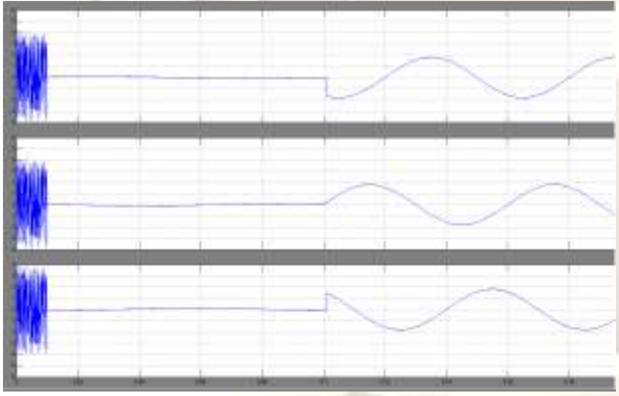


(b) Traditional DTC

Figure 4: Phase current waves



(a) DTC-based on EKF method



(b) Traditional DTC

The system robustness to the load disturbance using DTC-based on EKF method has been greatly enhanced. When disturbance occurred, speed and current is regulated fast to avoid large overstrike and oscillation. Their waves are more smoothing, especially in the start-up.

Case 3: Sudden increase of speed

At 0.5 seconds, given rotor speed increases from 1000rpm to 1500rpm, and Load torque is 6N-m. Corresponding rotor speed and rotor angle waves are shown in Figure 5 & 6

Fig 5: Estimated speed & real speed waves

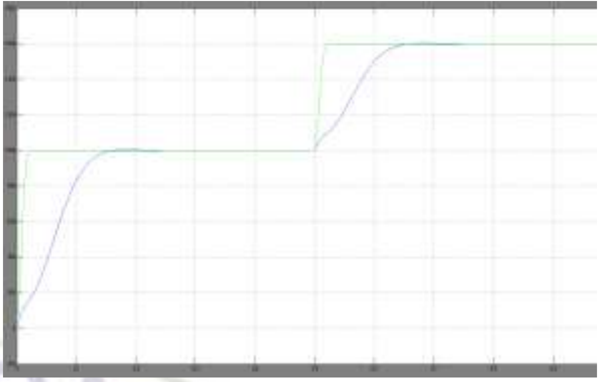


Figure 6(a) Real rotor angle wave

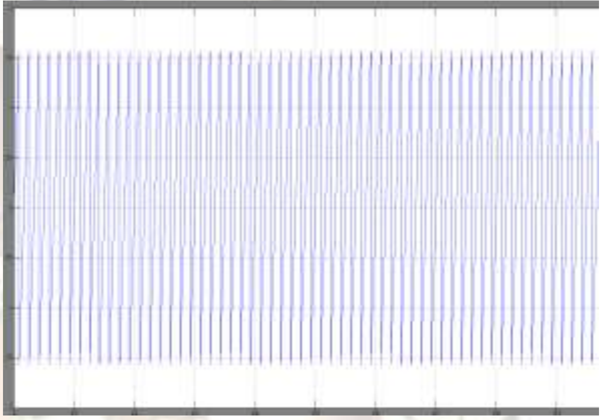
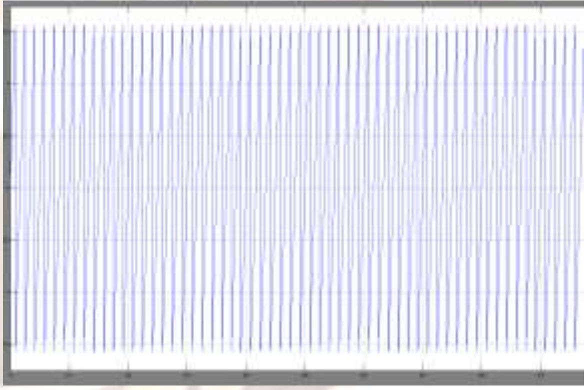


Figure 6 (b) Estimated rotor angle waves



The estimated speed and rotor angle lag behind real speed and angle respectively when motor starts and given speed mutates, but it also satisfies performance demand for motor control, while, at steady operation the estimated speed follows up real speed only with small error, which reflects EKF algorithm has good filtering effect.

VI. CONCLUSIONS

A complete structure of the Sensorless speed control of SPMSM using Direct Torque Control based on Extended Kalman Filter developed. The controller's performance has been verified with sudden change in load torque as well as sudden change in speed, using MATLAB /SIMULINK mathematical models. The simulation results obtained are discussed in each case. With this, it can be concluded that for a relatively accurate SPMSM model, flux linkage and rotor speed and rotor position can be estimated more precisely by EKF algorithm. Ripples on torque and stator flux are reduced. The motor start problems are solved as EKF do not need accurate initial rotor position information to achieve observer stability convergence.

The key benefit of the new approach is that it eliminates the problems occurred with sensor and it also improve the system performance.

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