A novel flux observer in sensorless PMSM drives

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Abstract. This paper investigates problems associated with direct torque control (DTC) of PMSM, such as the stator resistance variations, the integration drift and the integration saturation in order to reduce the system ripples. The standard particle filter (PF) algorithm was introduced to DTC system of PMSM. The motor terminal voltages and stator currents are the system input and output variables, and the two stator fluxes are used as system state variables. Then the flux can be estimated according to PF algorithm when the voltages and stator currents have been measured. The method was implemented in Simulink. The simulation results indicate that the system based on PF observer has good performance.

1 Introduction
Permanent magnet synchronous motor (PMSM) has been widely used in various high-performance situation, because of its advantages, such as high reliability and high efficiency. Direct torque control (DTC) has many advantages such as fast response speed, simple algorithm and good dynamic performance. It was paid more and more attention and has been developed rapidly in recent years [1-6].

In traditional DTC, the stator flux is calculated by integration of back electromotive force:

$$\psi_s = \int_0^t (u_s - R_s i_s)dt + \psi'_s|_{t=0}$$

(1)

where, $\psi'_s|_{t=0}$ is initial value of stator flux at $t=0$, $R_s$, $u_s$, $i_s$ are stator resistance, voltage and current respectively.

The calculated value of stator flux deviates from the real value of stator flux because the pure integration has many disadvantages, such as integration drift and integration saturation. Besides, the stator resistance variations decenter the calculation. So the system with traditional DTC has large flux and torque ripples large and nonsinusoidal current wave.

In this paper, the particle filter algorithm is introduced in the direct torque control system of PMSM, and the stator flux observer based on particle filter is proposed. With this observer, the stator flux of PMSM can be estimation on-line by measured motor terminal voltage and stator current.

2 Direct Torque Control Principle
DTC technology uses the stator flux orientation and directly select stator voltage vectors to control the Status of inverter power switching devices according to the differences between estimated and given value of stator flux $\psi_s$ and torque $T_e$ [7]. The stator flux $\psi_s$ and torque $T_e$ can be calculated by the following equation:

$$T_e = \frac{3}{2} p \psi_{ss} i_{dq} - \psi_{sd} i_{du}$$

(2)
\[ |\psi_s| = \sqrt{|\psi_{sa}|^2 + |\psi_{sb}|^2} \]  

(3)

where, \( p \) is the pole number.

Obviously, \( T_e, |\psi_s| \) and \( \theta_s \) are determined by \( \psi_{sa} \) and \( \psi_{sb} \). Thus the stator flux estimation is critical in DTC system in order to control the motor accurately.

3 Particle Filter Algorithm

Particle filter is a statistical estimation method, and its theoretical foundation is Bayes filtering principle, which is suitable for the optimal estimation of nonlinear non Gauss state space model [8]. Particle filter uses priori probability density of the system model state to predict the posterior probability density. Then, the value is modified by latest observation information to improve the estimation accuracy of the next time. Finally, the best estimated value of required state will be get the, and it has minimum error. The Steps of standard particle filter (PF) are as follows:

(1) Initialization

At the \( k = 0 \) moment, the \( N \) samples, which is randomly sampled from the prior probability, is the particle swarm \( \{x'_i, 1/N\}_{i=1}^N \), take \( k \) to be one.

(2) Update

The particle swarm updated \( \{x'_i\}_{i=1}^N \) is selected according to the importance density function \( q(x_k | x'_{k-1}, z_k) \).

(3) Weighting

Estimating the importance weights when \( z_k \) is obtained:

\[ \omega_k^i = \omega_{k-1}^i \frac{p(z_k | x'_i) p(x'_i | x'_{k-1})}{q(x'_i | x'_{k-1}, z_k)} \]  

(4)

Calculating importance weight normalization:

\[ \tilde{\omega}_k^i = \frac{\omega_k^i}{\sum_{j=1}^N \omega_k^j} \]  

(5)

(4) Resampling

The high weight value particles are copied from \( \{x'_i\}_{i=1}^N \), and the low weight particles are discarded. And the weighted samples \( \{x'_i, \tilde{\omega}_k^i\}_{i=1}^N \) are mapped into equal weight samples \( \{x'_i, 1/N\}_{i=1}^N \) as the new particle swarm.

(5) Filtering

Optimal minimum variance estimation of state can be get by:

\[ \hat{x}_k = \sum_{i=1}^N \tilde{\omega}_k^i x'_i \]  

(6)

Exiting the algorithm if the filtering has finished, otherwise returning to step (2).

The process of particle filtering is shown in figure 1. In this figure, a hollow circle represents a particle, solid circles represent the particles before resampling. Particle number is 12, namely \( N=12 \). The diameter of particles before resampling is proportional to its weight. Generally, the number of large particles increased as it is copied, yet the small particles are ignored. All the hollow round after re sampling have the same diameter. It menas that all the particle weights are assigned to 1/N.

4 PMSM Control System Based on PF

Through the particle filter analysis above, the simulation model of PMSM DTC system based on particle filter (DTC-PF) is established. Then the performance of DTC-PF is discussed.
4.1 Mathematical Model of PMSM

The basis of designing the stator flux observer based on particle filter is the establishment of state space model. $T$ is selected as the state variable, the two stator fluxes, the rotor speed and position are used as system state variables:

$$x = [\psi_\alpha, \psi_\beta, \omega_r, \theta_r]^T \quad (7)$$

The system input and output are the stator voltage and current, respectively:

$$u = [u_\alpha, u_\beta]^T \quad (8)$$

$$y = [i_\alpha, i_\beta]^T \quad (9)$$

With the assumptions above and in order to match to the PF equations, the state equation and observation equations of PMSM control system are given as:

$$\dot{x} = f[x(t), t] + Bu(t) + w(t) \quad (10)$$

$$y = h[x(t), t] + v(t)$$

where, $w(t)$ and $v(t)$, whose variance matrices are $Q$ and $R$, are zero-mean Gaussian noises, and use to describe the normalized model and measurement disturbances, respectively.

$$f[x(t), t] = \begin{bmatrix}
\frac{R}{L_s} \psi_\alpha + \frac{R_s}{L_s} \psi_f \cos \theta \\
\frac{R}{L_s} \psi_\beta + \frac{R_s}{L_s} \psi_f \sin \theta \\
0 \\
\omega_r
\end{bmatrix} \quad (11)$$
$$B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

(12)

$$h[x(t), t] = \begin{bmatrix} \frac{\psi_r - \psi_f \cos \theta_r}{L_s} \\ \frac{\psi_f - \psi_f \sin \theta_r}{L_s} \end{bmatrix}$$

(13)

where $L_s$ and $\psi_f$ are motor inductance and rotor flux. $\omega_r$ and $\theta_r$ are rotor speed and position, and $d\theta_r/dt = \omega_r$.

4.2 Design of Control System

The control signal is basically unchanged in the sampling interval when the sampling period $T$ is small enough. Discretization of equation (10) can be obtained by first order Euler integration algorithm:

$$\begin{cases} x_{k+1} = x_k + [f(x_k) \cdot T + Bu_k] \cdot T + w_k \\ y_k = h(x_k, k) + v_k \end{cases}$$

(14)

As is shown in the previous item, a direct torque control system of PMSM based on particle filter observer is designed, as shown in figure 2.

![Figure 2 Block diagram of DTC-PF](image)

Figure 2 Block diagram of DTC-PF

5 Performance of PMSM System Based on PF

The estimation method discussed above has been implemented in MATLAB R2010a/Simulink. In order to simulate the actual motor operation, using a fixed step size algorithm in ode4, and the step value is set to 1e-6s. Simulation conditions: Particle number $N$ was 300. Reference speed suddenly changed from 1000 $r/min$ to 1200 $r/min$ at 0.5 $s$.

Figure 3 shows modeling results of PMSM system based on DTC-PF. In figure 3 it is assumed that system initial state was zero, that is $x_0 = [0 0 0 0]^T$. For comparison, the stator flux amplitude waveform of traditional DTC system is given in figure 4.

From figure 3(a) it is can be seen that the actual speed can track the reference value within a short time. The bottom waveform is the difference between actual and reference speed. It is can be seen that the error is small when motor is started and reference speed mutates, and it can be eliminated quickly. Figure 3(b) shows that the stator flux trajectory deviates from the ideal track at initial stage, because the selected particle swarm is not accurate. However, the particle filter observer can accurately estimate stator flux value very soon. The stator flux amplitude waveform based on DTC-PF shown in figure 3(c) is narrower than stator flux amplitude waveform based on traditional DTC shown in figure 4. It is indicate that the PMSM system with DTC-PF contains fewer ripples. In figure 3(d) the three-
phase current is shown for the DTC-PF system. In steady-state the three-phase current is symmetrical, and has near-sinusoidal.

![Graph](image1)

![Graph](image2)

**Figure 3** Simulation waveforms of PMSM DTC-PF. (a) rotor speed, (b) stator flux trajectory, (c) stator flux amplitude (d) stator current.

![Graph](image3)

**Figure 4** Simulation waveforms of traditional DTC

The harmonic analysis results of the stator current in the A phase of the two DTC methods (traditional DTC and DTC-PF) are shown in figure 5. In this figure, the 15 periods beginning with 0.1s is analysed.
A comparison of the performance of the two DTC methods is given in Table 1. It can be seen that the performance of DTC-PF system is superior to the traditional DTC system when particles number N=300. The DTC-PF control system contains less current harmonic than traditional DTC system.

| Methods        | Traditional DTC | DTC-PF |
|---------------|-----------------|--------|
| Flux Ripples (Wb) | 0.02            | 0.008  |
| THD (%)        | 2.85            | 1.33   |

6 Conclusion
A novel stator flux observer based on particle filter in PMSM drives has been presented. The procedure addresses PMSMs, which are widely used in the related areas. The main feature is the combination of both the controlled system model and the PF algorithm. The stator flux observer proposed in this paper can calculate stator flux accurately and reduce flux ripples greatly. Additionally, the rotor speed is also identified with sufficient accuracy. The DTC-PF system has better performance and less harmonic than traditional DTC system.

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