Speed and Rotor Resistance Estimation of AC Induction Motor

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Abstract: The speed estimation method based on Extended Kalman Filter (EKF) is widely used in speed sensorless induction motor. The method has high accuracy and good robustness. However, EKF is sensitive to parameters. In particular, the rotor resistance becomes up to twice the original when the motor is running. This greatly affects the speed identification accuracy. This paper achieves online estimation of rotor resistance utilizing the Model Reference Adaptive Controller (MRAC) based on reactive power. This ensures that the speed is estimated with high accuracy even if the rotor resistance changes suddenly. Simulation results have been presented to verify the effectiveness of the method.

1 INTRODUCTION

Speed estimation methods of AC induction motor mainly include motor anisotropy-based method and motor model-based method.

The motor anisotropy-based method is not sensitive to motor parameters, but requires high measurement accuracy and additional hardware.

The motor model-based method mainly includes: direct calculation method [1], model reference adaptive system-based method, observer-based speed estimation method and intelligent control method. This class of method is sensitive to motor parameters because it is based on motor model. The direct calculation method is sensitive to load and poor in anti-interference. When the reference model of Model Reference Adaptive System (MRAS) contains other motor parameters, it will greatly affect the recognition accuracy. The intelligent control method requires additional hardware. It is computationally intensive and still at the stage of theoretical research. Observer-based speed estimation method is mainly comprised of full-order adaptive state observer, EKF and sliding mode observer method. The full-order adaptive state observer is not stable in the low-speed power generation area. The sliding mode observer has a problem of jitter, which restricts its use. EKF is more accurate and has been widely used in speed sensorless induction motors.

There exists many methods for online estimation of rotor resistance, such as signal injection-based method, MRAS [2]-[3], least squares method, model observation method and intelligent control method. The least squares method is sensitive to measuring noise and changes in speed. And it is poor in anti-interference. Model observation method is complex in calculation and it is difficult to select the gain of the observer. If the

observation gain is not properly selected, it will cause system instability. The reference model of reactive power-based MRAS is independent of stator resistance and is very popular. This method is simple, small in computation, easy to implement and has good real-time performance.

This paper utilizes EKF to estimate motor speed. This method is sensitive to motor parameters, especially rotor resistance. Therefore, it is necessary to add online identification of the rotor resistance. This paper utilizes reactive power-based MRAS method to achieve online estimation in order to ensure the speed estimation accuracy.

2 SPEED ESTIMATION OF AC INDUCTION MOTOR

This paper uses EKF to estimate the speed of AC induction motor. The EKF linearizes complex nonlinear systems such as induction motors by removing high-order terms. This linearization is only a sub-optimal approximation of the original nonlinear system and it may cause errors. But these errors can be included in the system noise or measurement noise to overcome the linearization deficiencies. After the induction motor is linearized, the rotor speed is derived by derivation.

2.1 Basic Principles Of Extended Kalman Filter Theory

Assume that the nonlinear discrete system is as follows:

$$\begin{cases} x(k+1) = f(x(k), u(k)) \\ y(k+1) = h(x(k+1)) \end{cases} \quad (1)$$

where $x(k)$ is the state variable. $u(k)$ is the input variable. $y(k+1)$ is the output variable.

The EKF algorithm is relatively mature and its iteration process is as follows:

Set initial values, such as: system noise, measurement noise.

State prediction: Use the k th state estimate value $\hat{x}(k)$ to calculate the $k+1$ state prediction value $\tilde{x}(k+1)$.

Update the Jacobian matrix:

$$G(k+1) = \frac{\partial f(x(k+1), u(k+1))}{\partial x} \Big|_{x(k+1)=\tilde{x}(k+1)} \quad (2)$$

Estimate the error covariance matrix:

$$\tilde{P}(k+1) = G(k+1)\hat{P}(k)G^T(k+1) + Q_k \quad (3)$$

where Q_k is the system noise matrix.

Update the Hessians of the output matrix:

$$H(k+1) = \frac{\partial h(x(k+1))}{\partial x} \Big|_{x(k+1)=\tilde{x}(k+1)} \quad (4)$$

Calculate the Kalman gain matrix:

$$K(k+1) = \tilde{P}(k+1)H^T \left[H\tilde{P}(k+1)H^T + R_k \right]^{-1} \quad (5)$$

State Estimation:

$$\hat{x}(k+1) = \tilde{x}(k+1) + K[y(k+1) - h(\tilde{x}(k+1))] \quad (6)$$

where $y(k+1)$ is the measurement vector.

Calculate the error covariance matrix:

$$\hat{P}(k+1) = \tilde{P}(k+1) - K(k+1)H(k+1)\tilde{P}(k+1) \quad (7)$$

2.2 Rotation Speed Estimation Based on EKF

The stator current, rotor flux, and motor speed are selected as state variables to establish a continuous state equation of the AC induction motor in the two-phase stationary coordinate system. In order to complete programming in the embedded system, we discretized the continuous state equation. After removing the high-order items in the system matrix and the input matrix, the discrete state equations of AC induction motor in the two-phase stationary coordinate system are as follows:

$$\begin{cases} x(k+1) = A^d(k)x(k) + B^d u(k) \\ y(k+1) = C^d x(k+1) \end{cases} \quad (8)$$

where $A^d(k)$ is the discrete system matrix. B^d is the discrete input matrix. C^d is the discrete output matrix.

$$A^d(k) = \begin{bmatrix} 1-T_s\eta & 0 & T_s\lambda/\tau_r & T_s\lambda w_r(k-1) & 0 \\ 0 & 1-T_s\eta & -T_s\lambda w_r(k-1) & T_s\lambda/\tau_r & 0 \\ T_s L_m/\tau_r & 0 & 1-T_s/\tau_r & -T_s w_r(k-1) & 0 \\ 0 & T_s L_m/\tau_r & T_s w_r(k-1) & 1-T_s/\tau_r & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B^d = \begin{bmatrix} \frac{T_s}{\sigma L_s} & 0 \\ 0 & \frac{T_s}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, C^d = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T, \hat{x} = \begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \\ \psi_\alpha(t) \\ \psi_\beta(t) \\ \omega_r(t) \end{bmatrix}$$

$$\hat{u} = [u_\alpha(t) \ u_\beta(t)]^T, y = [i_\alpha(t) \ i_\beta(t)]^T, \tau_r = L_r / R_r$$

$$\eta = (R_s L_r^2 + R_r L_m^2) / (L_r^2 L_s \sigma), \lambda = L_m / (\sigma L_s L_r)$$

Only by adding the system matrix update $A^d(k+1)$ before the state prediction, the EKF algorithm can be used to estimate the motor speed.

3 ROTOR RESISTANCE ONLINE ESTIMATION OF AC INDUCTION MOTOR

Due to the skin effect and saturation level caused by temperature and frequency, motor parameters will change. In particular, the rotor resistance becomes up to twice the original when the motor is running. EKF is sensitive to motor parameters. Rotor resistance changes will produce speed estimation error, and even make motor run unstable. Therefore, to ensure accuracy of the speed estimation, it is necessary to perform online estimation of the rotor resistance.

3.1 Basic Principles of MRAS

MRAS is mature and has been widely used in motor control. It consists of a reference model, an adjustable model and an adaptive mechanism. The outputs of the two models are the same physical variables. The difference of the outputs is subjected to the adaptive mechanism to obtain the estimated variable. The estimated physical variable is brought back to the adjustable model to achieve real-time tracking to the reference model. The MRAS block diagram is as follows:

Figure 1: Model reference adaptive block diagram

3.2 Rotor Resistance Online Estimation Based on MRAS

MRAS based on flux observation is more commonly used. Its reference model is the voltage model with stator resistance. When the motor is running, the stator resistance will change with temperature. This results in inaccuracy of the flux observed by reference model. Therefore, the rotor resistance is inaccurate. The reference model of reactive power-based MRAS does not consist of stator resistance. It can avoid the effect of stator resistance, thereby improving the accuracy of rotor resistance.

The reference model is instantaneous reactive power:

$$Q_{ref} = v_{qs} i_{ds} - v_{ds} i_{qs} \quad (9)$$

where v_{ds} (v_{qs}) is the d(q) component of the stator voltage vector. i_{ds} (i_{qs}) is the d(q) component of the stator current vector.

The adjustable model is steady-state reactive power:

$$Q_{adj} = \sigma L_s w_e (i_{ds}^2 + i_{qs}^2) + w_e \frac{L_m^2}{L_r} i_{ds}^2 \quad (10)$$

where L_s is the stator inductance. L_m is the mutual inductance. L_r is the rotor inductance. w_e is the synchronously rotating angular velocity. $\sigma = 1 - L_m^2 / (L_s L_r)$ is the total leakage factor.

The error is obtained by subtracting the steady state reactive power from the instantaneous reactive power. It is used as the input to the proportional-integral control. And the output is the change in the rotor resistance, which can then be applied to the real-time adjustment of rotor resistance.

4 SIMULATION

4.1 Speed and Rotor Resistance Estimation Block Diagram

The block diagram of EKF-based speed estimation and MRAS-based rotor resistance estimation for indirect field oriented controlled (IFOC) induction motor (IM) is as follows:

Figure 2: The block diagram of EKF-based speed estimation and MRAS-based rotor resistance estimation for IFOC IM

4.2 Simulation Results and Analysis

In order to verify the effectiveness of the speed and rotor resistance estimation method, a simulation model is constructed according to the block diagram of FIG. 2.

Simulation conditions are as follows: Setting the mechanical speed to 1000r/min, 300r/min, 60r/min; $t = 0.1s$, giving the load of 10Nm; $t = 0.6s$, the rotor time constant changing from 1.083 to 1.5; $t = 1.2s$, adding the rotor resistance online estimation; setting simulation time to 2s. The identification results are shown from FIG. 3 to FIG. 5.

Figure 3: 1000r/min speed and speed error waveform

Figure 4: 300r/min speed and speed error waveform

Figure 5: 60r/min speed and speed error waveform

From Fig. 3 to Fig. 5, it can be seen that the abrupt change of the rotor resistance at 0.6 s causes great fluctuations and errors of estimation speed. After adding rotor resistance online estimation at 1.2 s, the fluctuation of speed and errors are reduced to be equal to those before the rotor resistance change. Therefore, the effectiveness of estimation algorithm at low speed, medium speed, and high speed is verified.

5 CONCLUSIONS

This paper presents a method for speed and rotor resistance estimation of AC induction motor. EKF-based speed estimation method is sensitive to motor parameters, especially rotor resistance. Therefore, reactive power-based MRAS is used to perform the rotor resistance online estimation. This paper gives the block diagram of speed and rotor resistance estimation for IFOC IM. A simulation model is constructed based on the block diagram. The simulation results verified the effectiveness of the proposed method at low, medium and high speeds, respectively.

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