http://dx.doi.org/10.11142/jicems.2014.3.3.272

Research on Speed Estimation Method of Induction Motor based on Improved Fuzzy Kalman Filtering

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Abstract – An improved fuzzy Kalman filtering speed estimation scheme was proposed by means of measuring stator side voltage and current value based on vector control state equation of induction motor. The designed fuzzy adaptive controller conducted recursive online correction of measurement noise covariance matrix by monitoring the ratio of theory residuals and actual residuals to make it approach real noise level gradually, allowing the filter to perform optimal estimation to improve estimation accuracy of EKF. Meanwhile, co-simulation scheme based on MATLAB and Ansoft was proposed in order to improve simulation accuracy. Field-circuit coupling problems of induction motor under the action of vector control were solved and the parameter optimization accuracy was improved dramatically. The simulation and experimental results show that this algorithm has a strong ability to inhibit the random measurement noise. It is able to estimate motor speed accurately, and has superior static and dynamic characteristics.

Keywords: Brushless DC motor, Equivalent circuit, Loss, Efficiency

1. Introduction

In recent years, speed closed loop high performance AC speed control system had developed rapidly. However, some troubles such as installation and connection of speed sensor will complex structure of the system, increase cost, reduce reliability and performance are vulnerable to the impact of working conditions, so the range of applications is limited. Therefore, high-performance control without speed sensor of the induction motor had become one of the hotspots.

Based on fuzzy Kalman filtering technique, served induction motor speed as state variables, state equation and output equation were established, in which stator current and rotor flux serve as state variables, stator voltage serve as input variables and stator current serve as output variables. The rotor speed had been estimated. And a fuzzy adaptive controller was designed to monitor ratio of residual actual measured variance and theoretical variance on every step of EKF, online real-time adjust variance yields of measurement noise according to fuzzy inference rules to improve speed estimation accuracy [1]-[4].

2. Induction Motor Speed Estimation Based EKF

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Received 03 April 2014; Accepted 09 April 2014

In two-phase stationary coordinate system, mathematical model of the induction motor can be expressed as [5]

Where in,

$$X = \begin{bmatrix} i_{\alpha s} & i_{\beta s} & \phi_{\alpha r} & \phi_{\beta r} \end{bmatrix}^T \tag{2}$$

$$U = \begin{bmatrix} u_{\alpha s} & u_{\beta s} \end{bmatrix}^T \tag{3}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 & 0 \end{bmatrix}^T \tag{4}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$A = \begin{bmatrix} -(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}) & 0 & \frac{L_m}{\sigma L_s L_r \tau_r}\frac{1}{\tau_r} & \omega_r \frac{L_m}{\sigma L_s L_r} & 0 \\ 0 & -(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}) & -\omega_r \frac{L_m}{\sigma L_s L_r} & \frac{L_m}{\sigma L_s L_r \tau_r}\frac{1}{\tau_r} & 0 \\ \frac{L_m}{\tau_r} & 0 & -\frac{1}{\tau_r} & -\omega_r & 0 \\ 0 & \frac{L_m}{\tau_r} & \omega_r & \frac{1}{\tau_r} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

wherein, R_s 、 R_r 、 L_s 、 L_r 、 τ_r 、 ω_r 、 σ represent stator resistance, rotor resistance, stator inductance, rotor

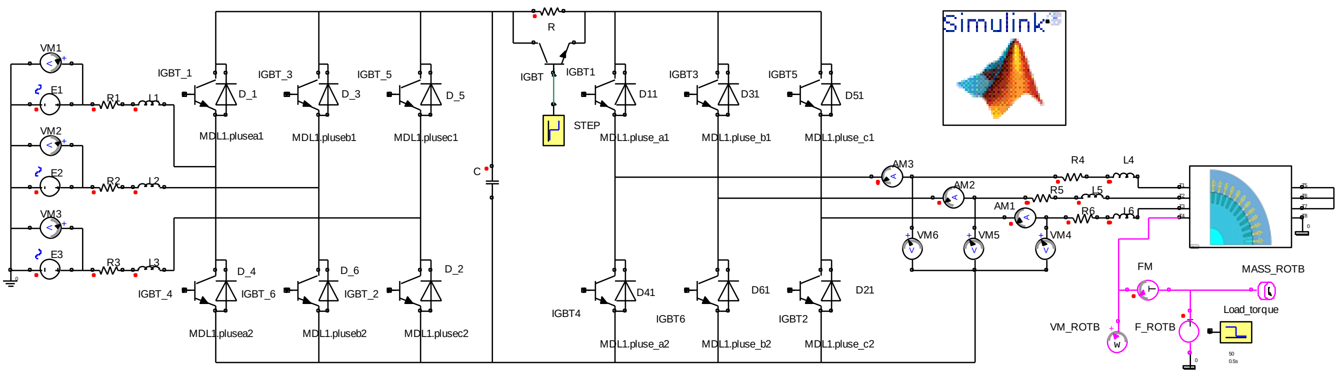


Fig. 1. Co-simulation model

inductance, rotor time constant, rotor speed and leakage coefficient respectively.

Serving high-order harmonic as white noise $W(k)$ disturbance, taking measurement noise $V(k)$ into account at the same time, (7) can be obtained after discretization and linearization processing on (1).

$$\begin{cases} x(k+1) = f\left(x(k),u(k)\right) + Mw(k) \\ y(k) = h(x(k)) + v(k) \end{cases} \tag{7}$$

wherein,

$$f\left(x(k),u(k)\right) = T_s \begin{bmatrix} (T_s^{-1} - \alpha)x_1 + \tau_r \beta x_3 + 2\beta x_4 x_5 + u_1/(\sigma L_s) \\ (T_s^{-1} - \alpha)x_2 - 2\beta x_3 x_5 + \tau_r \beta x_4 + u_2/(\sigma L_s) \\ L_m \tau_r x_1 + (T_s^{-1} - \tau_r)x_3 - 2x_4 x_5 \\ L_m \tau_r x_2 + (T_s^{-1} - \tau_r)x_4 + 2x_3 x_5 \\ T_s^{-1} x_5 \end{bmatrix} \tag{8}$$

$$h(x(k)) = \left[x_1(k) \quad x_2(k)\right]^T \tag{9}$$

wherein, $\alpha = \dfrac{L_m^2 R_r}{\sigma L_s L_r^2} + \dfrac{R_s}{\sigma L_s}$, $\beta = \dfrac{L_m}{L_s L_r}$, $1-\beta L_m$ orde r $x_5 = \omega_r$, conducted Kalman iterative operation for (7) [6].

A- Estimation

$$\begin{cases} x(k+1|k) = f\left(x(k|k),u(k)\right) \\ P(k+1|k) = F(k)P(k|k)F(k)^T + Q \end{cases} \tag{10}$$

B- Filtering

$$\begin{cases} P(k+1|k+1) = P(k+1|k) - K(k+1)HP(k+1|k) \\ x(k+1|k+1) = x(k+1|k) + K(k+1)[y(k+1 - hx(k+1|k)] \\ K(k+1) = P(k+1|k)H^T\left[HP(k+1|k)H^T + R(k+1|k)\right] \end{cases}$$

wherein, $H = \dfrac{\partial h(x(k))}{\partial x(k)}$。 Induction motor speed can be estimated by calculating (10) and (11).

3. Speed Estimation of Induction Motor Based on Improved Fuzzy EKF

Ideally, residual mean value is 0 and theoretical value of variance is equal to measured value. System parameters should be obtained accurately. However, in actual process, both environment and temperature will bring error to the measurement system. A fuzzy adaptive controller was designed to monitor ratio of actual measured variance and theoretical variance and to adjust variance value of the measurement noise.

$$K(k) = P(k|k-1)H^T\left[HP(k|k-1)H^T + R(k|k-1)\right] \tag{12}$$

Introduced adjustment factor cdz_k of measurement noise matrix estimated value $R(k|k-1)$ on the $k-1$ step, it can be obtained that,

$$R(k|k) = cdz_k R(k|k-1) \tag{13}$$

cdz_k was used for real-time adjustment on variance value of measurement noise. Fuzzy controller input was the ratio of residuals measured value and theoretical variance in the calculation of EKF filtering. The following equation holds.

$$\begin{cases} M_k = \dfrac{1}{n}\sum D_j D_j^T \\ N_k = C_k(A_{k-1}P_{k-1|k-1}A_k^T + Q)C_k^T + R_{k|k-1} \end{cases} \tag{14}$$

Order

$$G_k = \frac{trace(M_k)}{trace(N_k)} \qquad (15)$$

Wherein, $trace()$ presents trace operation for the matrix.

The designed fuzzy inference system includes: fuzzification process, fuzzy control rule generation, anti-fuzzy process and so on. Set G_k as input value, cdz_k as output adjustment value. Fuzzified G_k, defuzzified cdz_k and solved its membership function, the measured values can be corrected to improve EKF speed estimation accuracy.

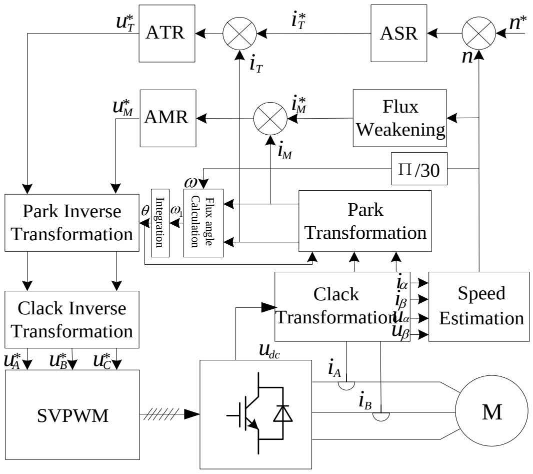
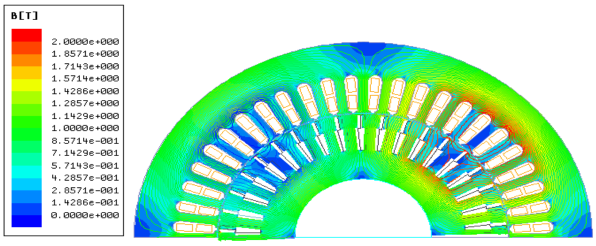
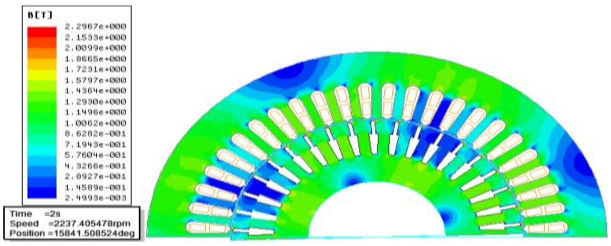


Fig. 2. Vector control strategy.

4. Simulation and Experiment Analysis



1) 22Hz.



2) 80Hz.

Fig. 3. Magnetic field distribution of induction motor under different frequency Vector control strategy.

Considering actual situation, simulation should approach actual situation as far as possible. Co-simulation technology based on MATLAB and Ansoft was proposed in this paper. Road problems of speed estimation based on Fuzzy Kalman were converted into field problems, under the action of induction motor vector control. Simulation accuracy had been improved, error between simulation and actual parameter had been shorten. Fig. 1 shows the co-simulation model. Fig. 2 shows vector control strategy of speed estimation of induction motor based on improved fuzzy Kalman. Fig. 3 illustrates magnetic field distribution of induction motor under different frequency, Fig. 4 is comparison of estimation speed and measured speed of induction motor, Fig. 5 shows speed estimation error.

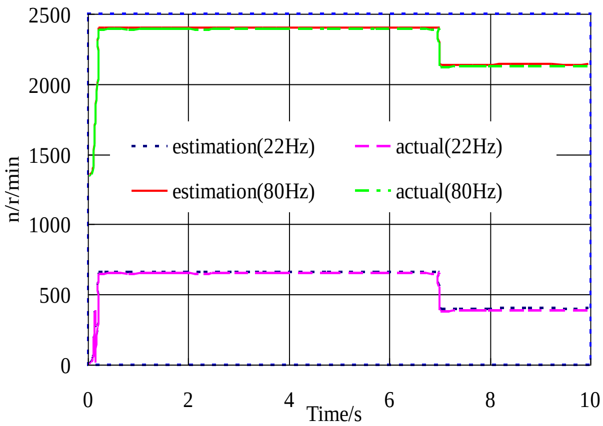


Fig. 4. Comparison of estimated rotating speed and measured rotating speed of induction motor.

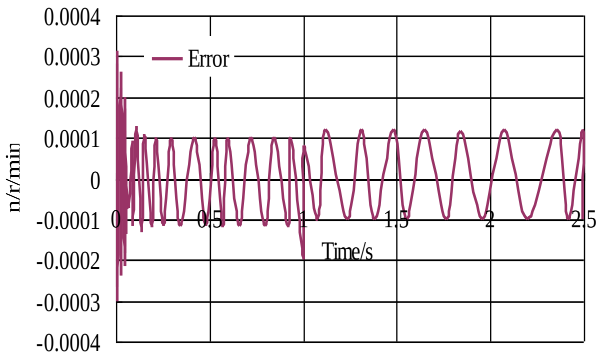


Fig. 5. Speed estimation error.

It can be seen from Fig. 5 that it can achieve stable withi n a wide speed range and ensure a high accuracy of estimati on based on fuzzy adaptive Kalman filtering technique. Sim ulation and experimental results are closer. It had verified c orrectness and feasibility of the simulation method.

5. Conclusion

Rotating speed of 1140V/75kW induction motor was estimated based on fuzzy Kalman filtering technique in this paper. Set speed as state variable, thus improving identification error caused by the reason that stator current cannot deliver rotor variable information accurately at low speed, it had overcome shortcomings of traditional estimation method. Stability can be achieved within a wide speed range. It has advantages that algorithm is simple and precision is high. Meanwhile, in simulation process, a co-simulation technology was constructed by using MATLAB and Ansoft, it combined the advantages of both, can reflect the real situation of the control system accurately, contribute to the analysis of the effect of vector control algorithm on magnetic field of induction motor, by simulation and experiment comparison, system speed estimation error was minor, which saves time for optimization of speed estimation parameters. It has practical guiding significance for project implementation.

Acknowledgment

Thanks for the supporting of National Natural Science Foundation（Grant No. 51277122） and Doctoral Foundation of Ministry of Education of China (Grant No. 20122102130001).

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