Online Identification Method of Induction Motor Parameters Based on Rotor Flux Linkage

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Abstract. High-performance control of induction motors is inseparable from accurate motor parameters. Online identification of parameters can provide accurate parameters for motor control in real time, so it is particularly important. In this paper, the traditional voltage flux observer is improved. The high-pass filter is connected in series with low-pass filter, and then the amplitude and phase compensation methods are used to obtain the improved voltage-type flux linkage observation method. The current-type flux linkage observation method is also introduced. Then the principle of the model reference adaptive system is studied. Combined with the super-stability theory, an algorithm for identifying the rotor time constant on-line is designed based on the rotor flux linkage. Through the combination of simulation and experiment, the observation effect of two flux linkage observation methods is verified on a 160kW motor. At the same time, the online identification algorithm of rotor time constant is studied under different speeds and different parameters. The results verify its accuracy and effectiveness.

1. Introduction
In recent years, China's high-speed railways have developed rapidly, and emu trains have reached 46% in the proportion of railway-passenger transport[1]. High-performance control of traction motor is vital for efficient and comfortable train operation, and accurate motor parameters could have an important role in it. Off-line identification can only provide initial parameters for motor control. As the train speed and environment change, factors such as temperature, frequency and excitation will all affect the parameters of induction motor[2]. Particularly, the rotor-time constant will change greatly. If it is different from the true value of motor in the control of the induction motor, problems like the inaccurate of magnetic field orientation and the incomplete decoupling of stator current can be caused, and thus affect the motor torque output, speed control and the efficient operation of the train[3].

For online identification of rotor time constant of induction motor, scholars at home and abroad have proposed methods such as extended Kalman filter, synovial observer, neural network intelligent algorithm to achieve online parameters identification[4]-[6]. However, these methods are complex and difficult to achieve. In practical applications, the model reference adaptive system (MRAS) is preferred because of simple structure and high efficiency. In this paper, the traditional voltage flux observer is studied and improved, and the current flux observer is introduced. Then a MRAS on-line identification algorithm for parameters based on rotor flux linkage was designed, by combining with
the principle of MRAS and the characteristics of two kinds of flux observer. Finally, the effect of flux observation and identification algorithm is verified by simulation and experiment on 160kW induction motor.

2. Rotor flux observation of induction motor

The observation methods of rotor flux of induction motor usually include voltage model, current model and hybrid model[7]. In this paper, the improved voltage model and current model will be selected to obtain the accurate rotor flux linkage.

2.1. Traditional voltage rotor flux observer

The expression of the voltage rotor flux observer in the static coordinate system is as follows[8]:

\[
\begin{align*}
\psi_{r\alpha} &= \frac{L_r}{L_m} \left[ \int (u_{s\alpha} - R_s i_{s\alpha}) dt - \sigma L_s i_{s\alpha} \right] \\
\psi_{r\beta} &= \frac{L_r}{L_m} \left[ \int (u_{s\beta} - R_s i_{s\beta}) dt - \sigma L_s i_{s\beta} \right]
\end{align*}
\]

(1)

In the formula, \(\psi_{r\alpha}, \psi_{r\beta}, u_{s\alpha}, u_{s\beta}\) and \(i_{s\alpha}, i_{s\beta}\) respectively the flux linkage, stator voltage and stator current component of induction motor in static coordinates, and \(R_s, L_r, L_m, \sigma\) are the stator resistance, rotor inductance, mutual inductance, stator inductance and leakage inductance of the induction motor.

Due to the existence of pure integrator, there is a problem with the integral drift saturation. The usual solution is to replace the integral part with the first order low-pass filter[9]:

\[
\begin{align*}
\psi_{r\alpha} &= \frac{L_r}{L_m} \left[ \frac{1}{s + \omega_\ell} (u_{s\alpha} - R_s i_{s\alpha}) - \sigma L_s i_{s\alpha} \right] \\
\psi_{r\beta} &= \frac{L_r}{L_m} \left[ \frac{1}{s + \omega_\ell} (u_{s\beta} - R_s i_{s\beta}) - \sigma L_s i_{s\beta} \right]
\end{align*}
\]

(2)

Although the method can eliminate the phenomena of integral saturation to some extent, it can’t obtain exact rotor flux due to the low frequency of DC bias and the amplitude and phase errors caused by the low-pass filter method.

2.2. Improved voltage rotor flux observer

Based on the above problems, we connect high and low-pass filters in series, and then use the method of amplitude and phase compensation to obtain exact stator flux. The improved stator flux linkage expression is as follows:

\[
\begin{align*}
\Psi_s &= \frac{s}{s + \omega_\ell} \frac{1}{s + \omega_h} u_s - \frac{s}{s + \omega_\ell} \frac{1}{s + \omega_h} R_s i_s
\end{align*}
\]

(3)

In the formula, \(\Psi_s, u, i\) are respectively the stator flux linkage, voltage and current vector, \(\omega_\ell, \omega_h\) are respectively the cut-off frequencies of high and low-pass filters.

Then the stator flux linkage is compensated for amplitude and phase:

\[
M = \sqrt{\frac{(\omega_\ell^2 + \omega_h^2)}{(\omega_r^2 + \omega_\ell^2)}}
\]

(4)

\[
\phi = \arctan\left(\frac{\omega_\ell}{\omega_r}\right) - \arctan\left(\frac{\omega_h}{\omega_r}\right) - \frac{\pi}{2}
\]

(5)

Where \(M\) and \(\phi\) are respectively the amplitude and phase compensation values, while \(\omega_r\) is the electrical frequency.
After the stator flux linkage is known, the rotor flux linkage is obtained by the following formula:

$$\psi_r = (\psi_s - \sigma L_s i_s) \frac{L_t}{L_m}$$  \hspace{1cm} (6)

2.3. Current rotor flux observer

The current rotor flux observer is based on the relationship between the stator current and the flux linkage. The flux linkage equation is formulated as follows:

$$\begin{align*}
p\psi_{ra} &= -\frac{1}{T_s} \psi_{ra} - \omega_r \psi_{rb} + \frac{L_m}{T_s} i_{ra} \\
p\psi_{rb} &= -\frac{1}{T_s} \psi_{rb} + \omega_r \psi_{ra} + \frac{L_m}{T_s} i_{rb}
\end{align*}$$  \hspace{1cm} (7)

In order to engineering applications, the labrador transform and discretization method can be used to obtain:

$$\begin{align*}
\psi_{ra(t+\Delta t)} &= \frac{\Delta t}{T_s + \Delta t} (L_m i_{ra} - \omega_r T_s \psi_{rb}) + \frac{T_s}{T_s + \Delta t} \psi_{ra(t)} + \Delta \psi_{ra(t)} \\
\psi_{rb(t+\Delta t)} &= \frac{\Delta t}{T_s + \Delta t} (L_m i_{rb} + \omega_r T_s \psi_{ra}) + \frac{T_s}{T_s + \Delta t} \psi_{rb(t)} + \Delta \psi_{rb(t)}
\end{align*}$$  \hspace{1cm} (8)

Where $\psi_{ra(t)}$ and $\psi_{rb(t)}$ are respectively the rotor flux components calculate result of this and last time, $\Delta t$, $T_s$ and $\omega_r$ are respectively the sampling time, rotor time constant and rotor frequency.

3. Principle and design of model reference adaptive system

The model reference adaptive system is relatively easy to implement and has been widely used for its characteristics like high adaptive speed and high performance.

3.1. Principle of model reference adaptive system

The model reference adaptive system is mainly composed of three parts: reference model, adjustable model and adaptive mechanism[10].

![Block diagram of model reference adaptive system (MRAS)](image)

For a system that can establish a mathematical model and unmeasurable parameters, an adjustable model with unknown parameters and a reference model without unknown parameters are designed and made to have output with the same physical meaning. The output error of the two models is adjusted by the adaptive mechanism to generate control signals, then the parameters to be identified in the adjustable model are updated to realize dynamic tracing. Finally, the output error of the two models approaches close to zero, thus the unknown parameters are identified.

3.2. MRAS parameter identification method based on rotor flux linkage
Based on the analyses above, an adaptive system for on-line identification based on rotor time constants of rotor flux linkage can be established.

3.2.1. Adjustable model and reference model

As shown in the figure above, the voltage model without rotor time constant can be used as a reference model, and the current model with rotor time constant can be used as an adjustable model.

![Block diagram of rotor time constant MRAS identification based on rotor flux linkage](image)

3.2.2. Adjustable model and reference model

The generalized error is defined as: \( e_r = \psi_r - \hat{\psi}_r \), plug into the adjustable model and expand by derivation on both sides. The left side of the equation is:

\[
\begin{pmatrix}
\frac{1}{T_r} - \omega_r & 0 \\
0 & \frac{1}{T_r} - \omega_r
\end{pmatrix}
\begin{pmatrix}
e_r \\
eg_r
\end{pmatrix}
- \frac{1}{T_r} \left( \begin{pmatrix}
\psi_r \\
\hat{\psi}_r
\end{pmatrix} - L_m \begin{pmatrix}
i_m \\
i_\beta
\end{pmatrix} \right)
\]

(9)

Further simplification is obtained:

\[
\frac{de_r}{dt} = Ae_r - W
\]

(10)

In the formula: 
\( A = \begin{pmatrix}
\frac{1}{T_r} - \omega_r & 0 \\
0 & \frac{1}{T_r} - \omega_r
\end{pmatrix} \), 
\( W = \begin{pmatrix}
\frac{1}{T_r} - \omega_r & 0 \\
0 & \frac{1}{T_r}
\end{pmatrix} \left( \begin{pmatrix}
\psi_r - L_m i_\beta
\end{pmatrix} \right) \)

According to the theory of super stability, the nonlinear link in equation (10) should satisfy Popov integral inequality, and the linear link should be confirmed rigorously.

Make \( A = A, B = I, C = I \), and \( I \) is the unit matrix, so that \( H(s) = C(sI - A)^{-1}B = (sI - A)^{-1} \), the exist of matrix \( P = P^T > 0 \), \( Q = Q^T > 0 \) is the necessary and sufficient conditions of \( H(s) \) to be the positive real function of \( s \), and it needs to satisfy:

\[
\begin{cases}
PA + A^T P = -Q \\
PB = C^T
\end{cases}
\]

(11)

In the formula, let \( P = I \) to satisfy \( Q = \begin{pmatrix}
\frac{2}{T_r} & 0 \\
0 & \frac{2}{T_r}
\end{pmatrix} \).

The feedback loop must meet the Popov integral inequality, that is to say:

\[
\eta(0, t) = \int_0^t \nu^T(t) w(t) dt \geq -r_0^2 \quad \forall t \geq 0, r_0^2 \geq 0
\]

(12)
In the formula: \( v(t) = e(t) \).

According to the common mechanism of model reference adaptation, the reciprocal of rotor time constant is turned into the following form of proportional integral:

\[
\frac{1}{T_r} = \int_0^t F_i(v, t, \tau) d\tau + F_z(v, t)
\]

(13)

Plug \( W \) into equations (12) and (13), the left side of the equation becomes:

\[
\int_0^t e'\left(t\right)\left(\int_0^t F_i(v, t, \tau)d\tau + \frac{1}{T_r}\right)\left(L_1e_1 - \psi_1\right)d\tau + \int_0^t e'\left(t\right)F_z(v, t)(L_1e_1 - \psi_1)d\tau
\]

(14)

In order to satisfy \( \eta(0, t) \geq -e_0^2 \), we can respectively take:

\[
F_i(v, t, \tau) = K_ie'\left(t\right)(L_1e_1 - \psi_1) \quad K_i > 0
\]

(15)

\[
F_z(v, t) = K_ze'\left(t\right)(L_1e_1 - \psi_1) \quad K_z > 0
\]

(16)

Plug equations (15) (16) into equation (14) can surely meet Popov integral inequality, therefore the feedback system in equation (10) must be asymptotically stable.

By combining equations (13), (15) and (16), the adaptive mechanism of rotor time constant can be obtained as follows:

\[
\frac{1}{T_r} = K_i\int_0^t [(\psi_{\alpha\alpha} - \psi_{\alpha\alpha})(L_2\alpha - \psi_{\alpha\alpha}) + (\psi_{\alpha\beta} - \psi_{\alpha\beta})(L_2\beta - \psi_{\alpha\beta})]d\tau + K_z\int_0^t [(\psi_{\alpha\alpha} - \psi_{\alpha\alpha})(L_2\alpha - \psi_{\alpha\alpha}) + (\psi_{\alpha\beta} - \psi_{\alpha\beta})(L_2\beta - \psi_{\alpha\beta})]
\]

(17)

In the formula, \( Ki \) and \( Kp \) are respectively the integral and proportional constants.

4. Analysis and verification by simulation and experiment

Based on the above theoretical analysis, simulation and experiment analysis were carried out by using Matlab/Simulink and induction motor experiment platform respectively. The simulated motor and support motor have the same parameters, and the details are shown in the following table:

| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|-----------|-------|
| \( R_s(\Omega) \) | 0.223 | \( R_r(\Omega) \) | 0.103 | \( L_{1s}(mH) \) | 0.00158 | \( L_{1r}(mH) \) | 0.002076 |
| \( L_m(mH) \) | 0.0438 | \( n_p \) | 2 | \( P_e(kW) \) | 160 | \( V_e(V) \) | 1287 |

4.1. Results of rotor flux observer

The effects of traditional voltage flux observer, improved voltage flux observer and current flux observer were simulated and tested by simulation and experiment respectively. The results are as follows:
As shown in figure 3, the rotor flux component obtained by the traditional voltage flux observer has an obvious problem of DC bias.

The simulation waveforms of figure 4 and figure 5 show that the improved voltage and current flux observer can both accurately observe the rotor flux linkage, and the two methods have almost no amplitude and phase deviation.

Based on simulation, the control algorithm is realized by adopting the TMS320F28335 chip, and the experimental verification was completed on the experimental supporting platform of induction motor. It can be concluded from figure 6 and figure 7, that the two flux observation methods can both
obtain the accurate flux linkage with little error at different speeds, laying a foundation for the next step of parameter identification.

4.2. MRAS parameter identification method based on rotor flux linkage

After verifying the two flux observation methods can both obtain the accurate flux linkage though the simulation and experiment, the identification effect of the MRAS parameter identification method based on rotor flux linkage under different conditions is analyzed and studied.

Table 2. Identification results

| Speed (s⁻¹) | Parameter (s⁻¹) | Actual value (s⁻¹) | Estimated value (s⁻¹) | Errors (s⁻¹) |
|-------------|-----------------|--------------------|----------------------|--------------|
| 60          | 0.5Tr           | 0.2272             | 0.2324               | 0.023        |
| 60          | 1.2Tr           | 0.5453             | 0.5584               | 0.024        |
| 120         | 0.5Tr           | 0.2272             | 0.2329               | 0.025        |
| 120         | 1.2Tr           | 0.5453             | 0.5578               | 0.023        |

Firstly, the simulation analysis was carried out with different speed operation conditions and step changes of different parameters. From figure 8-11 and table 2, it can be concluded that the proposed online parameters identification algorithm can quickly identify the actual values of parameters under different speed operation conditions with an error less than 2.5% and has high identification speed and accuracy.
After that, it can be seen from figure 12 and figure 13, with the gradual change of parameters at different speeds, the algorithm can follow the change well, and when the parameter becomes stable, the maximum error of parameter is only 0.002, and the identification accuracy is higher.

Based on the online identification simulation of parameter step and gradient change, the DSP program was programmed and verified by experiments. During the experiment, the motor was operating at a constant speed. After the parameter identification results were stable, the motor temperature was measured and compared with the inherent parameters of the motor. The results are shown in figure 14 and figure 15. By calculation, the $T_r$ identification error at a constant speed of 60 Hz is 0.025, and the $T_r$ identification error at a constant speed of 120 Hz is 0.022. Through the simulation and experimental verification above, it can be concluded that the designed MRAS parameter identification method based on rotor flux linkage is easy to accomplish, and has high identification speed and accuracy.

5. Conclusion
This paper analyzes the shortcomings of the traditional voltage flux observer, and puts forward an improved voltage flux observer which connects high and low-pass filter in series and then compensates in phase and amplitude. After that, the current flux observer is introduced, and made easy to engineering application by transformation. Then combined with the MRAS principle and the characteristics of two kinds of flux observers, the MRAS parameter identification method based on rotor flux linkage is designed, and the adaptive mechanism is designed according to the theory of super stability. On this basis, through simulation and experiment, the effect of flux observation and identification algorithm is verified under different speed conditions and different parameters variations. The results show the magnetic flux observation is accurate, and the algorithm has the characteristics of fast identification, high accuracy and easy implementation, which can provide accurate parameters in real time for improving motor control performance.

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