Offline Measurement of Induction Motor Rotor Time Constant Based on Least Squares Algorithm

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Abstract. In order to solve the problems of disturbance and error accumulation in the traditional off-line strategy of rotor time constant, this paper optimizes the off-line measurement method of rotor time constant of induction motor. The off-line measurement method of rotor time constant based on recursive least squares (RLS) algorithm is analyzed in detail. Through the static characteristics of induction motor, the mathematical model of induction motor is simplified, and then the linear model of RLS algorithm is derived. The simulation results show that the rotor time constant measured by the least square method is more stable than that measured by the conventional method, which proves the practicability of the off-line measurement method. Finally, the error analysis of the main factors affecting the off-line measurement results of the rotor time constant based on the least square algorithm is given.

1. Introduction
The vector control of induction motors based on the current model has the advantage of low speed and stability, which makes the current model widely used in induction motor control, but the current model is very dependent on the rotor time constant. The inaccuracy of the rotor time constant will lead to deviations in the field orientation, affecting the output torque of the motor, and then affecting the performance of the control system.

Generally, the identification of the rotor time constant is divided into offline measurement and online correction[1]. The online correction is realized on the basis of offline measurement. The error of the rotor time constant is obtained by means other than the current model, and then the motor is running to eliminate it. Changes caused by factors such as temperature and magnetic field. This article mainly focuses on off-line measurement. Off-line measurement is a commonly used method in current drives. It is an important step to complete the rotor time constant identification [2]. In the past ten years, the literature [3-4] has discussed many offline parameter measurement methods of induction motors in a stationary state. Literature [5-9] is a conventional off-line parameter measurement method. It uses DC experiments to measure resistance, single-phase experiments to measure rotor resistance and leakage inductance, and no-load experiments to measure mutual inductance, that is, before the motor runs, different types of currents are applied to the motor. And the voltage signal, and then detect the response of current and voltage, and calculate the required motor parameters according to the equivalent circuit relationship. Literature [10-14] uses the recursive least squares algorithm to measure the parameters of the induction motor, derives the estimated model from the dynamic model of the
induction motor, and gives a detailed description of the specific measurement process. However, most
of these methods use second-order filters or even third-order filters to convert the voltage and current
signals, which increases the complexity of the algorithm. This paper mainly uses the recursive least
squares algorithm and reduces the second-order filter to the first-order filter. This method only needs
current and voltage sensors, effectively. The complexity of the algorithm is reduced, and the
effectiveness of the method is verified by simulation.

2. Mathematical Model of Induction Motor and Least Square Algorithm

2.1. Mathematical Model of Induction Motor

Figure 1 introduces the equivalent circuit of an induction motor in a two-phase stationary coordinate
system. The α-axis and β-axis equivalent circuits are coupled with each other.

![Figure 1. The equivalent circuit diagram of induction motor](image)

The mathematical model of the induction motor in the two-phase stationary coordinate system is:

\[ u_{\alpha s} = (R_s + L_s p) i_{\alpha s} + L_m p i_{\alpha r} \]

\[ u_{\beta s} = (R_s + L_s p) i_{\beta s} + L_m p i_{\beta r} \]

\[ 0 = L_m p i_{\alpha s} + \omega_s L_m i_{\alpha r} + (R_s + L_s p) i_{\alpha s} + \omega_s L_s i_{\beta r} \]

\[ 0 = L_m p i_{\beta s} - \omega_s L_m i_{\beta r} + (R_s + L_s p) i_{\beta s} - \omega_s L_s i_{\alpha r} \]

\[ T_e = \frac{n_p L_m}{L_r} (\varphi_{\alpha s} i_{\beta r} - \varphi_{\beta s} i_{\alpha r}) \]

Among them, \( R_s \) and \( R_r \) are stator and rotor resistances respectively, \( L_m \) is mutual inductance, \( L_s \) and \( L_r \) are stator and rotor inductances respectively, \( i_{\alpha s} \) and \( i_{\beta s} \) are the stator currents of α axis and β axis respectively, and \( u_{\alpha s} \) and \( u_{\beta s} \) are the stators of α axis and β axis respectively. Voltage, \( i_{\alpha s} \) and \( i_{\beta s} \) are the
rotor currents of the α axis and β axis respectively. \( \omega_s \) is the motor speed, and \( p = d / dt \) is the
differential operator.

Since the rotor current cannot be measured, in order to eliminate the rotor current, equations (6) and
(7) can be obtained:

\[ -p^2 i_{\alpha s} = \frac{1}{\sigma_s T_s} \frac{1}{T_r} p i_{\alpha s} + \frac{1}{\sigma_s T_s} i_{\alpha s} - \frac{1}{\sigma_s L_s} p u_{\alpha s} - \frac{1}{\sigma_s T_s} u_{\alpha s} \]

\[ T_s = \frac{L_s}{R_s} \]

\[ T_r = \frac{L_r}{R_r} \]

\[ \sigma_s = \frac{1}{\sigma_s T_s} \]

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Where \( T_s = L_s / R_s \) is the rotor time constant, \( T_r = L_r / R_r \) is the stator time constant, \( \sigma \) is the
leakage inductance coefficient.

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In equations (6) and (7), the coefficients of voltage, current and their derivatives can be defined as follows:

\[ K_i = \frac{1}{\sigma \left( T_i + T_s \right)} \quad K_2 = \frac{1}{\sigma T_s} \frac{T_i}{T_s} \quad K_3 = \frac{1}{\sigma L_s} \quad K_4 = \frac{1}{\sigma L_s} \frac{T_i}{T_s} \]

Thus, equations (6) and (7) can be rewritten as equation (9):

\[
\begin{cases}
-p^2 i_{\alpha a} = K_1 i_{\alpha a} + K_2 p i_{\alpha a} - K_3 p u_{\alpha a} - K_4 u_{\alpha a} \\
-p^2 i_{\beta a} = K_1 i_{\beta a} + K_2 p i_{\beta a} - K_3 p u_{\beta a} - K_4 u_{\beta a}
\end{cases}
\]

Assuming that the stator leakage inductance is equal to the rotor leakage inductance, some parameters of the induction motor are as follows:

\[
\begin{aligned}
T_c &= \frac{K_{s r} R_s}{K_i} \\
L_s &= \frac{K_4 K_r - K_2 K_s}{K_4^2} 
\end{aligned}
\]

2.2. Least Square Algorithm

In the recursive least squares algorithm, the control model needs to be written in the form of a regression equation.

\[ \hat{y}(\hat{\theta}|t) = \hat{\Gamma}^T(t) \]

Among them \( \hat{y}(\hat{\theta}|t) \) is the prediction vector, \( \Gamma(t) \) is the regression matrix, and \( \hat{\theta} \) is the estimated parameter vector. The regression model can be derived as follows:

\[ \hat{y}(\hat{\theta}|t) = i_{\alpha a} \]

\[ \Gamma(t) = \begin{bmatrix} \Gamma_1(t) & \Gamma_2(t) & \Gamma_3(t) & \Gamma_4(t) \end{bmatrix} \]

\[ \hat{\theta} = \begin{bmatrix} k_1 & k_2 & k_3 & k_4 \end{bmatrix} \]

The recursive least squares algorithm is as follows:

\[ \hat{\theta}(N+1) = \hat{\theta}(N) + M_{N+1} \left[ \begin{bmatrix} \hat{y}(N+1) - \Gamma(N+1) \hat{\theta}(N) \end{bmatrix} \right] \]

\[ M_{N+1} = \frac{P_N \Gamma^T(N+1)}{\hat{\lambda} + \Gamma(N+1) P_N \Gamma^T(N+1)} \]

\[ P_{N+1} = \frac{P_N - M_{N+1} \Gamma(N+1) P_N}{\hat{\lambda}} \]

In the formula, \( M_{N+1} \) is the gain matrix; \( P_N \) is the covariance matrix, usually the initial value \( P_0 = 10^9 I \), \( I \) is the identity matrix, and \( \hat{\lambda} \) takes a larger positive integer; \( \hat{\lambda} \) is the forgetting factor \((0 < \hat{\lambda} < 1)\).
which can solve data saturation. In this case, the previous data is gradually "forgotten" through exponential decay to show the effect of the new data. Generally take $\lambda \in [0.8, 1]$, and take $\lambda = 1$ for offline identification.

3. Implementation of the Offline Measurement Algorithm for the Rotor Time Constant

The offline measurement structure diagram of the rotor time constant of the induction motor is shown in Figure 2. It includes four parts: single-phase rotor test module, digital filter, least square algorithm estimation module and parameter calculation module.

![Figure 2. Offline measurement structure diagram based on least square method](image)

3.1. Design of digital filter

Laplace transform on both sides of the state equation (9), the transfer function (18) can be obtained. The transfer function is not only conducive to the evolution of linear models, but also suitable for analyzing state variables in the frequency domain.

$$\frac{i_{sa}}{u_{sa}} = \frac{K_3s + K_4}{s^2 + K_3s + K_2} \quad (18)$$

To perform the least squares recursive operation on the transfer function (18), the form needs to be transformed into a linear model. Generally, the voltage and current differentials are obtained in the voltage and current signals, which will introduce very strong noise, which requires filtering. Since the equation is second-order, it may be better to use a second-order filter first. Select the filter $G(s) = (s + h_0)(s + h_1)$, in order to reduce the complexity of the algorithm, the second-order filter is simplified to the filter, defining $z = s^2 \frac{i_{sa}}{G(s)}$, according to the transfer function equation (18), the formula (19) can be obtained:

$$z = [-K_1 -K_2 K_3 K_4] \begin{bmatrix} \frac{s i_{sa}}{G(s)} \\ \frac{i_{sa}}{G(s)} \\ \frac{s u_{sa}}{G(s)} \\ \frac{u_{sa}}{G(s)} \end{bmatrix} \quad (19)$$

According to the definition of $z$:

$$i_{sa} = z + \frac{(h_0 + h_1)s + h_1 h_2}{G(s)} i_{sa} = \frac{h_0 + h_1 - K_1 h_2}{G(s)} i_{sa} + \frac{K_3 s + K_4}{G(s)} u_{sa} \quad (20)$$

After derivation, the linear parameter model can be obtained as follows:

$$i_{sa} = \hat{\Theta}^T(t) \quad (21)$$
Where, \[ \hat{\theta} = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{bmatrix} = \begin{bmatrix} K_4 - K_1 h_1 \\ K_1 J h_1 - K_4 \\ h_0 - h_1 \\ h_0 - h_1 \end{bmatrix} \]

\[ \Gamma(t) = \begin{bmatrix} \Gamma_1(t) \\ \Gamma_2(t) \\ \Gamma_3(t) \\ \Gamma_4(t) \end{bmatrix} = \begin{bmatrix} \frac{1}{s + h_1} u_{sw} \\ \frac{1}{s + h_0} u_{sw} \\ \frac{1}{s + h_1} i_{sw} \\ \frac{1}{s + h_0} i_{sw} \end{bmatrix} \]

The vector \( \hat{\theta} \) is the parameter vector to be identified, and \( \Gamma(t) \) is the input voltage and current signals. The relationship between these parameters and the actual parameters is as follows:

\[
\begin{align*}
K_1 &= h_0 + h_1 - k_3 - k_4 \\
K_2 &= h_0 h_1 - h_0 k_3 - h_4 k_4 \\
K_3 &= k_1 + k_2 \\
K_4 &= h_0 k_1 + h_1 k_2
\end{align*}
\] (22)

In order to realize the algorithm on the digital controller, the system and the filtering link need to be discretized. So when it comes to the selection of the sampling period, if the sampling period is too short, the correlation of the sampling data will increase, and then relying on these data to solve the parameter estimates, will produce many ill-conditioned equations; if the sampling period is too long, the input cannot be fully utilized Information in the signal excitation process, which in turn affects parameter identification. Combining the above situation, the sampling period selected in this article is 0.0001s, and because the first-order filter parameters \( h_0 \) and \( h_1 \) are related to parameter calculations, in principle \( 1/h_i (i=0,1) \) is greater than the sampling period. In addition, the first-order filter \( 1/(s+h_i) \) is subjected to a bilinear transformation, so that the discretization model of the first-order filter can be obtained:

\[
H(z) = \frac{Tz + T}{(2 + Th_i)z - 2 + Th_i} \times (i = 0,1)
\] (23)

Among them, \( H(z) \) is the output of the filter, \( x \) is \( i_{sw} \) or \( u_{sw} \), and \( T \) is the sampling period. The Bode plot of this filter is shown in Figure 3.

**Figure 3.** The amplitude-frequency and phase-frequency response curves of the filter measurement structure diagram based on least square method

According to the amplitude-frequency and phase-frequency response curves of the first-order filter, when \( h_i \) is between 10 and 100, the response speed and dynamic performance of the filter are better, so this article \( h_0 = 40, h_1 = 90 \).

3.2. *Conditions to be met by the excitation signal*
In order to make the identified parameters converge to the true value, it is necessary to ensure that the input voltage and current signals are continuously excited and bounded, where continuous excitation means that the frequency spectrum of the signal is sufficient. $u_{sa}$ and $i_{sa}$ obtained through the output of the motor, and the bounded situation completely depends on the excitation signal. In most cases, the excitation signal contains at least $n/2$ sine waves of different frequencies. Finally, a linear combination of a DC signal and two sinusoidal signals of different frequencies is selected as the excitation signal we need.

4. Simulation Verification

Using MATLAB to carry on simulation, this paper has made simulation verification on the off-line measurement of rotor time constant based on the recursive least square algorithm and the conventional method in literature [9]. The parameters selected in the simulation are based on a 3.7 KW induction motor, the number of pole pairs is 2, the rated current is 9.1 A, the rated voltage is 380 V, the rated speed is 1500 rpm, the stator resistance is 1.029 Ohm, the rotor resistance is 0.84 Ohm, the mutual inductance is 0.1198 H, stator leakage inductance is 5.51 mH, the rotor leakage inductance is 5.51 mH.

From the given parameters, the rotor time constant can be calculated as:

$$T_e = \frac{L_m + L_{lr}}{R_e} = 0.1492\ \text{s}$$

(24)

The simulation parameter identification curve is shown in Figure 4-Figure 7, and red line is reference value, black line is Identification value.

**Figure 4.** $R_e$ identification value under different algorithms

**Figure 5.** $L_{lr}$ identification value under different algorithms
The error values measured based on the least square method and the conventional method are shown in Table 1. Where, the error is the ratio of the difference between the true value and the measured value.

| Parameter | $R_r/\Omega$ | $L_m/H$ | $L_n/H$ | $T_r/s$ |
|-----------|--------------|---------|---------|---------|
| True value | 0.840        | 0.1198  | 0.00551 | 0.1492  |
| Least squares measured value | 0.8387      | 0.120   | 0.00549 | 0.1496  |
| Error     | 0.155%       | 0.167%  | 0.309%  | 0.268%  |
| Conventional measured value | 0.8274      | 0.1164  | 0.00540 | 0.1472  |
| Error     | 1.50%        | 2.838%  | 1.906%  | 1.340%  |

According to Table 1, the error value measured based on the least square method is smaller than the error value measured by the conventional method.

Regarding the error produced by the least square method measurement, this article makes the following analysis:

Error 1: the influence of excitation signal

For the above situation, to ensure that the parameters completely converge to the true value, the excitation signal needs to be fully excited, that is, the excitation signal with enough frequency points is required.

Figure 8 shows the rotor time constant identification curve of the excitation signal without the DC component, and Figure 9 shows the $T_r$ identification curve of the sum of the sinusoidal signal with the DC component and four frequency points.

It can be seen from the figure that when the DC component is not added, a relatively large rotor time constant error is obtained. After the DC component is added, the more frequency points the
excitation voltage contains, the closer the measured rotor time constant is to its true value. Although the parameters converge to the true value in a long time, with the increase of the excitation signal frequency, the rotor time constant changes greatly in a short time, and the jitter with different frequencies will be more serious.

Figure 8. Tr identification curve without DC component

![Image](image_url)

Figure 9. Sine signal and Tr identification curve of four different frequency points

It can be seen from the figure that when the DC component is not added, a relatively large rotor time constant error is obtained. After the DC component is added, the more frequency points the excitation voltage contains, the closer the measured rotor time constant is to its true value. Although the parameters converge to the true value in a long time, with the increase of the excitation signal frequency, the rotor time constant changes greatly in a short time, and the jitter with different frequencies will be more serious.

Error 2: The filter design is inappropriate

Through a lot of simulation analysis, the rotor time constant measurement method based on the least square method is more sensitive to the cut-off frequency of the filter. Within a certain range, the increase of the cut-off frequency may make the measured value of the rotor time constant smaller; the cut-off frequency may decrease. Increase the measured value of the rotor time constant.

Error 3: Reference value and calculation error

The reference value in the simulation is obtained through the identification result of the high-performance inverter and the high-precision LCR meter, and there may be a certain error with the real value. In addition, the error caused by parameter calculation will also affect the accuracy of the simulation results.

5. Conclusion

This article analyzes and discusses each link in the rotor time constant measurement process based on the least square method. By reducing the second-order filter to the first-order filter, avoiding the second derivative of the filtered signal, and introducing the design of the filter and the selection of the excitation signal. Then, compare the rotor time constant measured values of the conventional method and the least square method. The results show that the error of the least square method designed in
this paper is less than 0.4%, which is far better than the conventional method.

In addition, although the rotor time constant has been measured off-line, with the operation of the motor, temperature, magnetic saturation and other factors will lead to changes in the rotor time constant. Therefore, it is necessary to further study the on-line identification scheme of rotor time constant of induction motor in the future.

6. References

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