Diagnostic method for induction motor using simplified motor simulator

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In this paper, an identification method of motor parameters for the diagnosis of rotor bar defects in the squirrel cage induction motor is proposed. It is difficult to distinguish the degree of deterioration by a conventional diagnostic method such as Fourier analysis. To overcome the difficulty, a motor simulator is used to identify the degree of deterioration of rotors in the squirrel cage induction motor. Using this method, the deterioration of rotor bars in the motor can be estimated quantitatively.

1 INTRODUCTION

Squirrel cage induction motors are widely used for driving facilities of various plants because of their high reliability and ease of maintenance. As the diagnostic method of rotor bar defects of induction motor, measurement of leakage flux and frequency analysis of stators current are studied(1). However, these methods can not clearly and quantitatively recognize the extent of deterioration of the rotors. To solve the problem, we have developed a simplified mathematical model of voltage and driving torque equations for the induction motor which consists of one pair of poles and six rotor bars. In the following, mathematical models for the induction motor and its application to diagnosis are described together with an identification method of rotor bar resistance using the models.

2 MATHEMATICAL MODEL FOR INDUCTION MOTOR

Here, a simplified induction motor with a single pair of poles and six rotating slots is analyzed. The equilibrium equations for voltages and torques of induction motor are given as follows(2,3):

2.1 Equilibrium Equation For Voltages

\[
\begin{pmatrix}
V_s \\
0
\end{pmatrix} =
\begin{pmatrix}
Z_{ss} & Z_{sr} \\
Z_{sr} & Z_{rr}
\end{pmatrix}
\begin{pmatrix}
I_s \\
I_r
\end{pmatrix}
\]

(1)

As for the variables in equation (1), \(Z_{ss}\) is a matrix whose diagonal elements are \(R_s + pL_s\) and the others are \(pM_s\), \(Z_{sr}\) is a matrix whose \((i,j)\) element is \(pM_s \cos(\alpha - (i-1)(\alpha + (j-1)\beta))\) and \(Z_{rr}\) is a matrix which is the transpose of matrix \(Z_{sr}\). \(Z_{rr}\) is a matrix whose \((i,i)\) element is \(R_{bi} + R_b(i+1) + R_b + p2(l_b + l_r) + (n-1)M_r\), \((i,i+1)\) and \((i+1,i)\) elements are \(-R_b - p(l_b + M_r)\), and the other elements are \(-pM_r\). \(V_s\) is the voltage vector of the stator, \(I_s\) is the current vector of the stator, \(I_r\) is the current vector of the rotor, \(p\) is the differentiation operator, \(R_s\) is the resistance of each stator, \(R_b\) is the resistance of each rotor, \(R_{bi}\) is the end resistance of the rotor, \(L_s\) is the inductance of each stator, \(L_r\) is the leakage inductance of the rotor, \(\omega_m\) is the rotating speed, \(J\) is the rotating inertia, \(T_L\) is the loading torque, \(P\) is the number of the pair of poles, the value of \(M_m\) is the square root of the value \(3mM/2\), \(m\) is \(n/P\) and \(n\) is the number of rotor slots. Modifying equation (1) such that the left side of the equation is the differential term and the right side is the remaining term, we obtain equation (3):

\[
ApX = BX + U
\]

(3)

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Multiply the inverse of matrix $A$ to both sides of equation (3), we obtain:

$$pX = A^{-1}BX + A^{-1}U.$$  \hspace{1cm} (4)

Equations (2) and (4) are the fundamental equations used in the motor simulator describing the characteristics of the induction motor.

### 3 GENERATION OF FAILURE DATA USING MOTOR SIMULATOR

Numerical solution of the simultaneous equations (2) and (4) can be calculated by the Runge-Kutta & Gill method\(^{(4)}\). Moreover, using the calculated time series data of the solution, we can analyze it by Fourier transformation. Here, we simulated three cases of motor characteristics; First is the case where the motor load is zero, second is the case with a constant load value and third is the case of a changing load. In each case, rotor resistance is changed in three ways, first is with new rotors, second is with a single deteriorated rotor and the third is with a pair of deteriorated rotors. That is, simulation studies were made for these nine cases. In the following, the calculated result for rotating speed is described.

#### 3.1 Simulation For Non-load Operation

Figure 1 shows the rotating speed of motor for each condition. As shown in the figure, no distinction exists between the three kinds of resistance in the rotor bar. The reason for this phenomenon is apparent because no slips occur in the case of non-load operation.

![Figure 1 Rotating speed without load](image)

#### 3.2 Simulation For Operation With Load

Figure 2 shows the rotating speed with three different rotor resistances in the case of constant load. As shown in the figure, rotating speed fluctuates according to rotor deterioration.

![Figure 2 Effects of rotor resistance on rotating speed(constant load)](image)

#### 3.3 Simulation Of Load Change Cases

As is shown in figure 3, rotating speed fluctuates with change of load similar to the deterioration of rotor.

![Figure 3 Effects of rotor resistance on rotating speed(changing load)](image)
4 DATA ANALYSIS BY FOURIER TRANSFORM

Simulated data can be analyzed by Fourier transformation. Figure 4 shows the analyzed result for non defect rotors. As shown in the figure 4, a single clear peak exists at source frequency. For the comparison, deteriorated data are analyzed by Fourier transformation and the results are shown in figure 5. As is apparent from these figures, there exist sub peaks related to the power source frequency. So, the occurrence of the deterioration can be detected from the existence of such sub peaks by the Fourier transformation.

Next, the progress of deterioration is analyzed by the same method. Figure 6 shows the results of Fourier analysis for changing rotor resistance. As is apparent from this figure, it is difficult to distinguish the change in rotor resistance. The difficulty in recognizing the degree of deterioration is revealed from the results. For more precise analysis, it is necessary to develop a new analyzing method of deterioration.

5 IDENTIFICATION METHOD OF MOTOR PARAMETERS USING MOTOR SIMULATOR

To overcome the problem stated above, we studied a new diagnostic method using the motor simulation model described in the previous sections. In our method, the value of rotor resistance is identified using data of the stator current and those of the input voltage which are measurable.

The identification is carried out by the procedure as shown in figure 7.

As shown in figure 7, input voltage $V_s$ is used to calculate stator current $I_s$ by a mathematical model of the induction motor, assuming the value of rotor resistance $R_b$. Then, calculated stator current $I_s^*$ is compared with measured stator current $I_s$. If a difference exists between $I_s^*$ and $I_s$, rotor resistance is modified reflecting the difference in the estimation of stator current. After iteration of these procedures, the value of $R_b$ converges to its real value.

5.1 Identification Of One Unknown $R_b$

Initial arrangement of three phase current type stators and six rotors are given as shown in figure 8. As shown in the figure, variables of stator currents and rotor resistances are named. These are from $a$ to $c$ for $I_s$ and from 1 to 6 for $R_b$ respectively.

Taking $R_{b1}$ as the initial value, stator current $I_s^*$ is calculated using the mathematical model of the induction motor. These $I_{sa}$ values over time are compared with measured $I_{sa}$ time series data. Figure 9 shows the variation of $E$ which is the ratio of $I_{sa}$ and $I_{sa}^*$ over time. Here, the ratio is defined as follows.

$$E = \frac{I_{sa}}{I_{sa}^*}$$

(5)
As shown in figure 9, the ratio of $I_{na}$ with $I_{na}^*$ has a certain relation only at the starting stage of rotation. Combining data in these duration repeatedly, data for identification is made. An example of such data for the stator current is shown in figure 10.

Using these data, the value of $E$ tends to lie at less than one. Therefore the algorithm for identification is set to the following:

$$R_{b_i}(n+1) = R_{b_i}(n) \cdot E(n)^{s_i} \quad i = 1, \ldots, 6$$  \hspace{1cm} (6)

$$E(n) > 0$$  \hspace{1cm} (7)

$$s_i = \begin{cases} -s_{i-1} & \text{if } E_0(n) < E_0(n-1) < 1 \text{ or } 1 < E_0(n-1) < E_0(n) \\ s_{i-1} & \text{else} \end{cases}$$  \hspace{1cm} (8)

where $s_j$ is the control factor to stabilize the convergence of the identification algorithm, $n$ is the repeating number of data. $E_0$ means the value of $E$ at the starting points of repeat of data as shown in figure 10.

The identification processes by this algorithm are shown in figures 11 and 12. Figure 11 shows the convergence processes for different initial values. As shown in these figures, the values of $R_{b1}$ and $R_{b2}$ successfully converge to their real values after several hundred iterations. Starting from sufficiently large rotor resistance, it approaches its real value smoothly.

5.2 Identification Of Two Unknown $R_{b}$s

In the case of two unknown $R_b$ values, it is necessary to use current data from two stators. Similar to one unknown $R_b$ case, we define two ratios $E_1$ and $E_2$ as follows.

$$E_1 = \frac{I_{na}}{I_{na}^*}$$  \hspace{1cm} (9)

$$E_2 = \frac{I_{nb}}{I_{na}^*}$$  \hspace{1cm} (10)

In the case of two unknown $R_{b}$, both $E_1$ and $E_2$ are used for the identifications of $R_{b1}$ and $R_{b2}$ simultaneously. The algorithm of the identification is as follows:

$$R_{b1}(n+1) = R_{b1}(n) \cdot E_1(n)^{s_1} \cdot E_2(n)^{s_2}$$  \hspace{1cm} (11)

$$R_{b2}(n+1) = R_{b2}(n) \cdot E_1(n)^{s_1} \cdot E_2(n)^{s_2}$$  \hspace{1cm} (12)

$$s_{1j} = \begin{cases} -s_{1j-1} & \text{if } E_{10}(n) < E_{10}(n-1) < 1 \text{ or } 1 < E_{10}(n-1) < E_{10}(n) \\ s_{1j-1} & \text{else} \end{cases}$$  \hspace{1cm} (13)

$$s_{2j} = \begin{cases} -s_{2j-1} & \text{if } E_{20}(n) < E_{20}(n-1) < 1 \text{ or } 1 < E_{20}(n-1) < E_{20}(n) \\ s_{2j-1} & \text{else} \end{cases}$$  \hspace{1cm} (14)
where \( s_{ij} \) and \( s_{kj} \) are the control factors stabilizing the convergence of the identification algorithm, \( n \) is the repeating number of the data and \( z_1 \) and \( z_2 \) are reflecting factors of \( E_1 \) and \( E_2 \) for iterative modification. \( E_{10} \) and \( E_{20} \) mean the value of \( E_1 \) and \( E_2 \) at the starting points of repeat of data, the same as one unknown \( R_b \) case.

The identification process by this algorithm is shown in figure 13. As shown in the figure, the \( R_{b1} \) and \( R_{b2} \) values successfully converge to their real values after several hundred iterations.

![Graphs showing identification process](image)

(a) For the case of constant load \( T_L = 0.5 \)

(b) For the case of time decreasing load \( T_L = 0.5/t \)

Figure 13 Identified result of \( R_{b1} \) and \( R_{b2} \)

### 6 EXPERIMENTAL RESULTS

In the latter half of the previous section, the case of two unknown \( R_b \)s were dealt with. As is shown there, \( R_{b1} \) and \( R_{b2} \) are mainly dependent on the ratios \( E_1 \) and \( E_2 \) respectively. From the standpoint of actual application, 6 \( R_b \)s are to be identified using this algorithm. So, we defined the following algorithm:

\[
R_{b1}(n + 1) = R_{b1}(n) \cdot E_1(n)^{z_1} \cdot E_2(n)^{z_2}
\]

\[
R_{b2}(n + 1) = R_{b2}(n) \cdot E_1(n)^{z_1} \cdot E_2(n)^{z_2}
\]

Using the algorithm stated above, rotor resistance are identified. In the table 1 tested results are summarized.

<table>
<thead>
<tr>
<th>( R_{b1} )</th>
<th>( R_{b2} )</th>
<th>( R_{b3} )</th>
<th>( R_{b4} )</th>
<th>( R_{b5} )</th>
<th>( R_{b6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{b1} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( R_{b2} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( R_{b3} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( R_{b4} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( R_{b5} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( R_{b6} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
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</tr>
</tbody>
</table>

In the table 1, a circle means a successful result and a cross means a failed identification.

### 7 CONCLUSION

Mathematical models for the induction motor have been developed. Using the model we can simulate the dynamic characteristics of induction motor. We have also developed an identification algorithm for rotor bar resistance. By this method we can quantitatively monitor the progress of rotor deterioration. The usability of the method was ascertained using the simulated data based on the actual motor specifications. Compared with conventional Fourier analysis, this method has the advantage of diagnosing plural rotor bars simultaneously. Using this method, we can obtain the following advantages.

1. It is not necessary to install a new sensor to diagnose the rotor bars.
2. The diagnosis can be carried out regardless of loading conditions.
3. The progress of deterioration of rotor bars can be monitored calculating rotor bar resistances continuously.

### REFERENCES

2. I. Morita: Trans. IEE Japan, n0-D, (1990), 798.