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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

$$\begin{pmatrix} V_s \\ 0 \end{pmatrix} = \begin{pmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{pmatrix} \cdot \begin{pmatrix} I_s \\ I_r \end{pmatrix} \tag{1}$$

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 $pMcos\{\theta - (i-1)\alpha + (j-1)\beta\}$ and Z_{rs} is a matrix which is the transpose of matrix Z_{sr}. Z_{rr} is a matrix whose (i,i) element is $R_{bi} + R_{ei} + R_{b(i+1)} + R_e + p2(l_b + l_e) + (n-1)M_r$, $(i, i+1)$ and $(i+1, i)$ elements are $-R_{b(i+1)} - p(l_b + M_r)$, 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_e is the end resistance of the rotor, L_s is the inductance of each stator, L_b is the leakage inductance of the rotor, L_e is the leakage inductance of the rotor end, M is the mutual inductance between each stator and the rotor, M_s is the mutual inductance between the stators, M_r is the mutual inductance between the rotors, α is the phase angle of the stator and β is the electric phase angle of the rotor.

2.2 Equilibrium Equation For Torque

$$Jp\omega_m + T_L = pM_m(I_{bs}I_{T1} - I_{fs}I_{T2}) \tag{2}$$

Where, I_{fs} and I_{bs} are the current components of stator current in the direction of phase angle α and its orthogonal direction respectively, I_{T1} and I_{T2} are the current components of rotor current in the direction of phase angle α and its orthogonal direction respectively, ω_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):

$$ApX = BX + U \tag{3}$$

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

$$pX = A^{-1}BX + A^{-1}U \tag{4}$$

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.

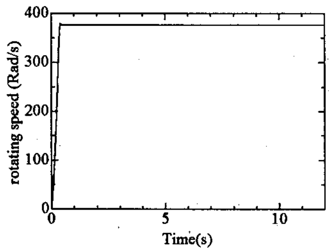


Figure 1 Rotating speed without load

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.

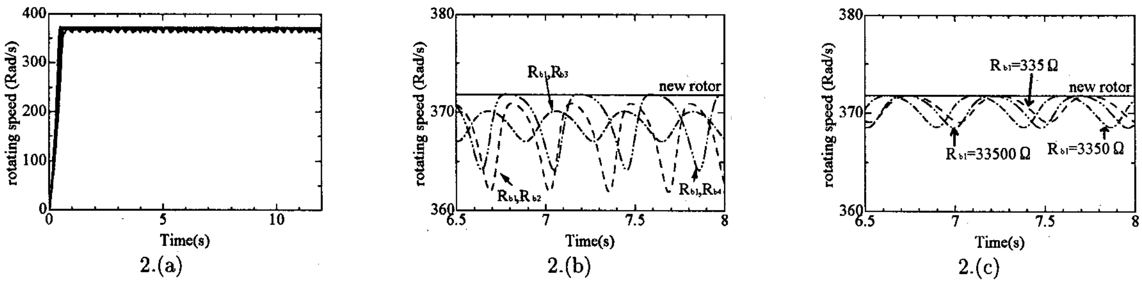


Figure 2 Effects of rotor resistance on rotating speed(constant load)

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.

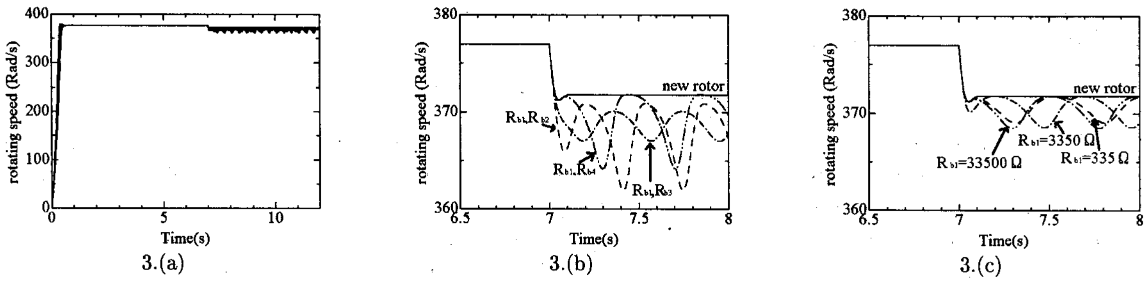


Figure 3 Effects of rotor resistance on rotating speed(changing load)

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.

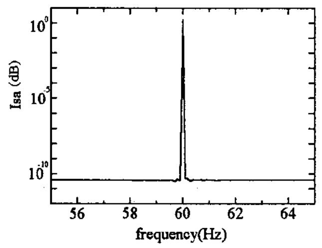


Figure 4 Fourier transform of stator current(non defect case)

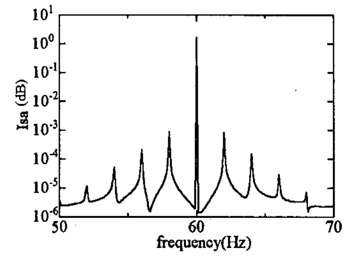


Figure 5 Fourier transform of stator current(deterioration case)

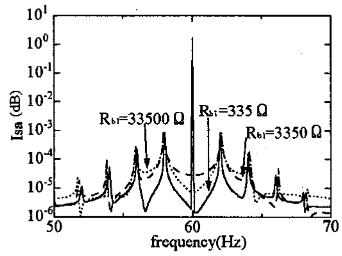


Figure 6 Fourier analysis of stator current (changing rotor resistance)

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.

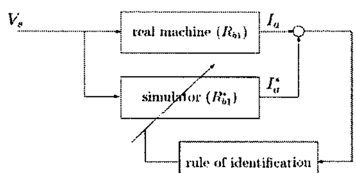


Figure 7 Identification method of rotor resistance

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_{bi} as the initial value, stator current I_{sa}^* 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 Isa and I_{sa}^* over time. Here, the ratio is defined as follows.

$$E = \frac{I_{sa}}{I_{sa}^*} \tag{5}$$

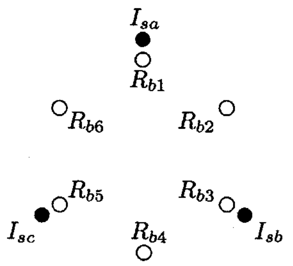


Figure 8 Initial arrangement of stators and rotors

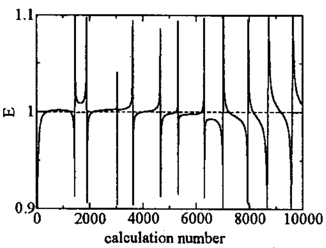


Figure 9 Variation of E over time

As shown in figure 9, the ratio of I_{sa} with I^*_{sa} 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:

$$R_{bi}(n+1) = R_{bi}(n) \cdot E(n)^{s_j} \qquad i = 1, \cdots, 6 \tag{6}$$

$$E(n) > 0 \tag{7}$$

$$s_j = \begin{cases} -s_{j-1} & if \quad E_0(n) < E_0(n-1) < 1 \quad or \quad 1 < E_0(n-1) < E_0(n) \\ s_{j-1} & else \end{cases} \tag{8}$$

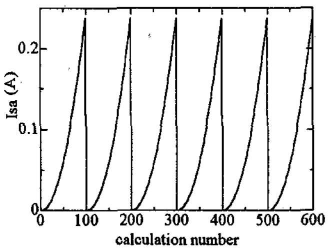
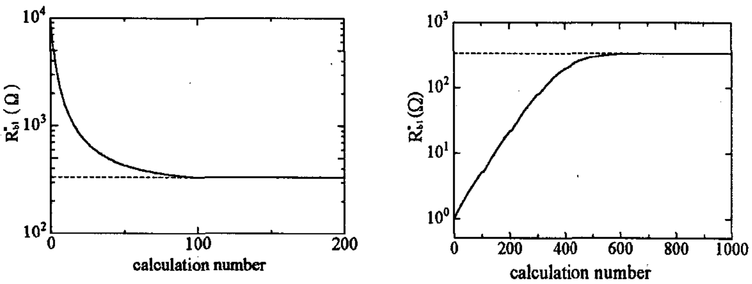


Figure 10 Data prepared for identification

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 Rb1 and Rb2 successfully converge to their real values after several hundred iterations. Starting from sufficiently large rotor resistance, it approaches its real value smoothly.



11.(a) 11.(b)

Figure 11 Identified result of R_{b1}

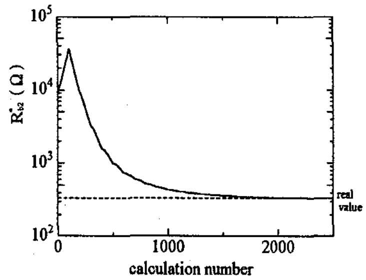


Figure 12 Identified result of R_{b2}

5.2 Identification Of Two Unknown R_bs

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.

$$E_1 = \frac{I_{sa}}{I^*_{sa}} \tag{9}$$

$$E_2 = \frac{I_{sb}}{I^*_{sb}} \tag{10}$$

In the case of two unknown R_{bs}, 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:

$$R_{b1}(n+1) = R_{b1}(n) \cdot E_1(n)^{z_1 s_{1j}} \cdot E_2(n)^{z_2 s_{2j}} \tag{11}$$

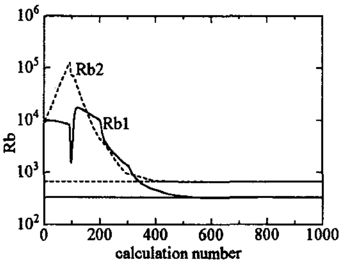
$$R_{b2}(n+1) = R_{b2}(n) \cdot E_1(n)^{z_2 s_{1j}} \cdot E_2(n)^{z_1 s_{2j}} \tag{12}$$

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

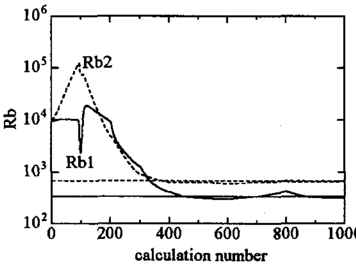
$$s_{2j} = \begin{cases} -s_{2j-1} & if \quad E_{20}(n) < E_{20}(n-1) < 1 \quad or \quad 1 < E_{20}(n-1) < E_{20}(n) \\ s_{2j-1} & else \end{cases} \tag{14}$$

where s_{1j} and s_{2j} 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.



(a)For the case of costantload $T_L = 0.5$



(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

Table 1 Identified results for 6 rotor bars

		R_{by}					
		R_{b1}	R_{b2}	R_{b3}	R_{b4}	R_{b5}	R_{b6}
R_{bx}	R_{b1}		○	○	×	○	○
	R_{b2}	○		○	○	○	○
	R_{b3}	×	○		○	○	○
	R_{b4}	×	○	○		○	○
	R_{b5}	○	○	○	○		○
	R_{b6}	○	○	○	×	○	

In the latter half of the previous section, the case of two unknown R_bs 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_bs are to be identified using this algorithm. So, we defined the following algorithm:

$$R_{bx}(n+1) = R_{bx}(n) \cdot E_1(n)^{z_1 s_{1j}} \cdot E_2(n)^{z_2 s_{2j}} \qquad (15)$$

$$R_{by}(n+1) = R_{by}(n) \cdot E_1(n)^{z_2 s_{1j}} \cdot E_2(n)^{z_1 s_{2j}} \qquad (16)$$

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

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.

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