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January 18–22, 2010
Washington, DC

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Published by the American Institute of Physics (AIP) .

 ISSN 1087-3848

The Characteristic Analysis Considering Parameter Variation according to the slip in Induction Motor

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This paper deals with the characteristic analysis of an induction motor considering parameter variation according to the slip. The existing equivalent circuit method has been analyzed using constant circuit parameter regardless of the slip. However, in the induction motor, the change of speed varies the input current and eddy current induced in the rotor bar. Owing to the change of flux density and saturation factor by the variation of the current, analysis method considering parameter variation according to the slip is needed. In order to forecast the exact characteristics in the various operation condition of the motor, equivalent circuit parameters have to be calculated accurately. So, in this paper, the equivalent circuit parameters according to the slip are computed by using finite element analysis (FEA), the characteristic analysis is carried out by application of the parameters to the equivalent circuit analysis (ECA), and the proposed method is verified by comparison of calculated and experimental results using the commercial induction machine.

Index Terms—**Equivalent circuit analysis (ECA), finite element analysis (FEA), slip, squirrel-cage induction motor.**

I. Introduction

INDUCTION MOTOR is used to operate in many different fields from the small fan to large automobile engine. Recently, electric vehicle (EV) and fuel cell electric vehicle (FCEV) needed the various operation region makes good use of the induction motor [1], [2]. Traction motor needed the various operation regions such as EV, FCEV is necessary to optimum control algorisms that can do to control according to the change of operating condition. Accordingly, the change of the impedance has to be considered in the design of the motor [3].

The commonly equivalent circuit method has been analyzed using constant circuit parameter independent of slip in the squirrel-cage three phase induction motor [4]. However, in the induction motor, the change of speed varies the input current and eddy current induced in the rotor bar. Owing to the change of flux density and saturation factor by variation of the current, analysis method considering parameter variation according to the slip is needed.

Because equivalent circuit method uses lumped parameters, it takes short computational time but it can't get the locally distributed characteristics. Specially, in the rotor region which has strong effect on the characteristics of the induction motor, that method is disadvantageous. Whereas, finite element method (FEM) is able to get the distributed characteristics of induction motors but it requires much computational time and large memory capacity. So, in this paper the merits of both methods are combined and utilized [5], [6].

The factor of the squirrel-cage induction motor such as conductivity of secondary conductor has an effect on the characteristics of a motor. Especially, if the characteristic analysis is done without considering the end-ring, the good results cannot be obtained. In order to improve the reliability, analysis method that can facilitate this problem is needed on low investment time and cost. Therefore, we calculated a new resistivity of the secondary conductor including the end-ring's resistance to apply the 2D FEM. Then, the performances of the motors are analyzed by using the new resistivity of secondary conductor which contains the end-ring resistivity [7].

In order to forecast the exact characteristic in the various operating condition of the motor, equivalent circuit parameters should be accurately calculated. So in this paper the equivalent circuit parameters are computed by using the FEM, the reliable characteristic analysis is carried out by application of the parameters to the equivalent circuit analysis. The equivalent circuit parameters and the performance of a three-phase squirrel-cage induction motor can be determined by performing tests. Induction motor tests are included the stator impedance test, the blocked-rotor test, the no-load test, and the load test. In this paper is verified by comparing with the analysis results of the suggested method and the experimental results of commercial induction machine.

The proposed method is more accurate than the results of commonly method. The proposed method in this paper will enhance the propriety of characteristics forecast on achieving reduced error between test result and analysis result.

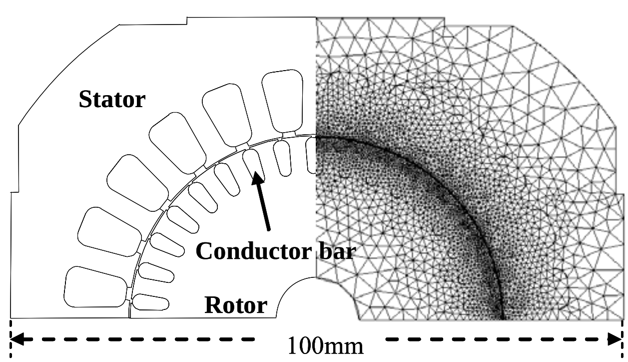

Fig. 1. The half cross-section of the analyzed motor

Manuscript received October 31, 2009.
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Digital Object Identifier inserted by IEEE

TABLE I
SPECIFICATION OF INDUCTION MOTOR

	Unit	Value	Note
No. of pole	EA	4	-
No. of slot	EA	24	-
No. of slot in rotor	EA	34	aluminum bar
Rated speed	rpm	1350	slip : 0.1
Rated power	W	134	-
Winding type	-	Distributed	Short pitch (5/6)
Operation Temperature	℃	75	-

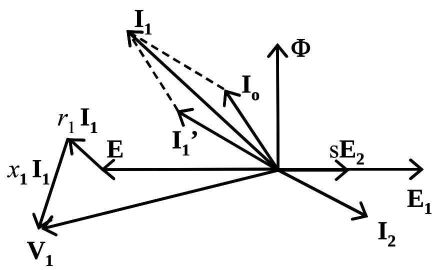


Fig. 2. Phasor diagram of three phase induction motor

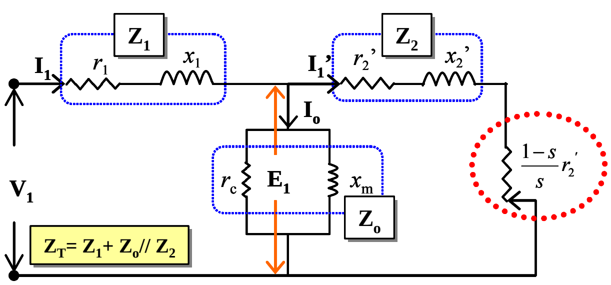


Fig. 3. Equivalent circuit of three phase induction motor

II. MODEL AND METHOD

A. Analysis induction motor model

In this paper, a 135W three phase squirrel-cage induction motor is analyzed. It has 4 poles 24 slots with distributed windings arranged in the stator part. In the rotor core, the aluminum conductor bars are inserted into the radial cavity and connected end ring. The rated speed is 1350 rpm, input frequency is 50 Hz. The detail specification of this motor is listed in Table I. And the half cross-section of this motor is shown in Fig. 1.

B. Equivalent Circuits Method (ECM)

Fig. 2 shows the phasor diagram of the induction motor. Equivalent circuit of three phase induction motor is shown in Fig. 3. Base on them, the squirrel-cage three phase induction motor dynamic mathematic model is described by (1)-(4).

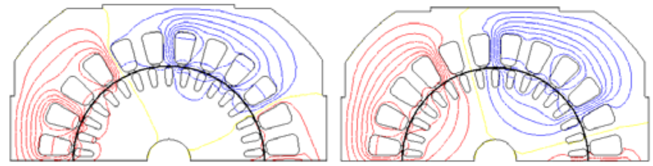
$$\mathbf{V_1} = \mathbf{E_1} + \mathbf{I_1 Z_T} \quad (1)$$

$$\mathbf{I_1} = \mathbf{I_o} + \mathbf{I_1'} \quad (2)$$

$$P_{out} = m_1 \mathbf{I}_1'^{2} \left[\frac{(1-s)}{s} r_2' \right] [W] \quad (3)$$

$$T = \frac{P_{out}}{\omega} \; [Nm] \quad (4)$$

where r_1 is armature winding resistance, x_1 is leakage reactance in the stator. And r_2' is secondary resistance, x_2' is leakage reactance in the rotor and x_m is magnetizing reactance.



(a) slip =0.8 (b) slip =0.1

Fig. 4. Equi-potential distribution of analysis model according to the slip

Equivalent circuit method (ECM) is organized lumped parameter Characteristic of the machine such as input current, power factor, efficiency and output power is obtained by characteristic analysis using Equivalent circuit in the induction motor.

The commonly equivalent circuit method has been analyzed using the fixed constant circuit parameter independent of slip. So, estimated characteristic of motor on the rated operations are similar in result value to test results. But estimated characteristic on the starting operations have large error. Consequently, the change of the slip can cause induced eddy current variation in the rotor bar as undergo a change the distribution of magnetic flux. In order to consider the change of flux density and saturation factor, analysis method considering parameter variation according to the slip is needed.

III. PARAMETER CALCULATION

In order to consider the distributions of magnetic field according to slip and nonlinearity of magnetic material, parameter is calculated by FEM such as Fig. 4. But, FEM 2D analysis can't consider the end coil has a weak point. In order to calculation of accurate circuit parameter, analysis method has to consider a resistivity and inductance of the secondary conductor including the end-ring's resistance and inductance. Especially, if the characteristic analysis is done without considering the end-ring, the good results can't be obtained. Therefore, we calculated a new resistivity of the secondary conductor including the end-ring's resistance to apply the 2D FEM. Then, the performances of the motors are analyzed by using the new resistivity of secondary conductor which contains the end-ring resistivity.

A. Leakage and magnetizing inductance

The equation for the flux linkage of the stator and rotor is simplified as shown in (5), (6).

$$\lambda_{abcs} = \left(L_{ls} + \frac{3}{2} L_{ms} \right) \mathbf{i_{abcs}} + \frac{3}{2} L_{ms} \mathbf{i_{abcr}} e^{j\theta_r} \quad (5)$$

$$\lambda_{abcr} = \left(L_{lr} + \frac{3}{2} L_{ms} \right) \mathbf{i_{abcr}} + \frac{3}{2} L_{ms} \mathbf{i_{abcs}} e^{-j\theta_r} \quad (6)$$

where L_{ms} is 2 times of mutual inductance between stator coil, L_{ls} is leakage inductance of the stator winding and L_{lr} is converting leakage inductance of the rotor coil [8]. The flux linkage equation as (5), (6) is composed the self inductance and mutual inductance and self inductance is composed the leakage inductance and L_{ms}. For the input current the one phase of stator coil, Equation (7) is shown the linkage inductance. Then, the leakage inductance is calculated by all sum of the flux linkage in one phase. And magnetizing inductance are -2/3 times of sum of the flux linkage in others phase. In the rotor, inductance calculation method has the same. Base equation calculated inductance is as (8).

$$L_s = \begin{bmatrix} L_{ls}+L_{ms} & 0 & 0 \\ -\frac{L_{ms}}{2} & 0 & 0 \\ -\frac{L_{ms}}{2} & 0 & 0 \end{bmatrix} \quad L_r = \begin{bmatrix} L_{lr}+L_{mr} & 0 & 0 \\ -\frac{L_{mr}}{2} & 0 & 0 \\ -\frac{L_{mr}}{2} & 0 & 0 \end{bmatrix} \tag{7}$$

$$L = \frac{\lambda}{I} \tag{8}$$

B. Core loss resistance and secondary resistance

In order to consider the distributions of magnetic field and nonlinearity of magnetic material, core loss analysis is carried out the FEM analysis [9]. After calculating total core loss, ω_{total}, the core loss resistance r_c can be calculated by (9). In the induction motor, the change of speed varies the input current and eddy current induced in the rotor bar. Accordingly, those results make the difference of secondary resistance. Induced eddy current and secondary cupper loss is calculated by FEM. After calculating total cupper loss, W_{c2}, the secondary resistance r_2' can be calculated by (10).

$$W_i = \frac{\mathbf{E_1}^2}{r_c} \tag{9}$$

$$W_{c2} = r_1\mathbf{I_1}^2 + r_2'\mathbf{I_1}'^2 \tag{10}$$

Back EMF, $\mathbf{E_1}$, is the voltage across the magnetizing branch, found from

$$\mathbf{E_1} = \mathbf{V_1} - \left[\mathbf{I}_1\left(r_1 + x_1\right)\right] \tag{11}$$

Fig. 5 presents the equivalent circuit considering parameters variation. The functional expressions of the parameters according to the slip are in Table II.

IV. Verification through the Test

Use In order to verify the characteristic analysis method, simulation result compared with the test result. Test of parameter calculation using the approximate equivalent circuits have some assumptions. First, sum of the resistance of primary and secondary, sum of the leakage reactance in the stator and rotor is calculated in the short test. There are assumed that magnetizing inductance terms are much larger than the remaining parameters and that the primary leakage inductance is the same value as secondary leakage inductance. But its assumption is not the same as practical experience. Because induction motor has slip, rotor doesn't rotate at synchronous speed. Accordingly, current is induced in the conductor bar at the no-load test. But no-load test assume that current isn't induced in the conductor bar. Therefore magnetizing inductance and core loss registration have some errors. In order to reduce the error, we calculate the parameter using the detailed equivalent circuit by test. Fig. 6 presents the equivalent circuit for parameters calculations by test. At the no-load test, rotor is rotated at synchronous speed by any outer motor. Then, we calculate the parameters. And after removed the rotor, primary inductance is calculated. The short test is used to calculate secondary impedance considering the primary impedance and magnetizing reactance terms. Fig. 7 presents the testing apparatus for parameter measurement.

V. Result and Discussion

Fig. 8 shows the comparison of the calculated parameters using simulation and test. These results prove that the parameters are changed according to the slip. The results show that the calculated parameter by simulation such as core loss and secondary registration, secondary reactance has good aspect estimating the measurement result. But magnetizing reactance and primary reactance is large error. Fig. 9 show the comparison of the simulated and measured input current, torque, efficiency and power factor according to the slip. The results show that the dynamic simulation result considering slip has good aspect estimating the measurement results. At the low speed near slip=1, the measurement error is relatively large because the current is inputted at the acceleration time of the machine and include a lot of harmonics.

VI. Conclusion

The parameter computation methods are introduced to estimate the characteristics of squirrel-cage induction motor by using the equivalent circuit with the consideration of saturation according to the slip. Especially, as the equivalent circuit parameters are computed by using the FEM, the reliable characteristic analysis is carried out by application of the parameters to the equivalent circuit analysis. Consequently,

TABLE II
Functional Expression of the Parameters According to the Slip

Parameter	Unit	Funcion	Note
Primary resistance	Ω	constant	r_1
Primary leakage reactance	Ω	$4.52 - 0.849\exp(s)$	x_1
Secondary resistance	Ω	$5.46 + 1.08 \times s^{1.77}$	r_2'
Secondary leakage reactance	Ω	$3.5 + 5.84\exp\left(-\frac{s}{0.13}\right)$	x_2'
Core loss resistance	Ω	$456.8 + 2040.5\exp\left(-\frac{s}{0.183}\right)$	r_c
Magnetizing reactance	Ω	$39.70 - 14.83 \times s^2$	x_m

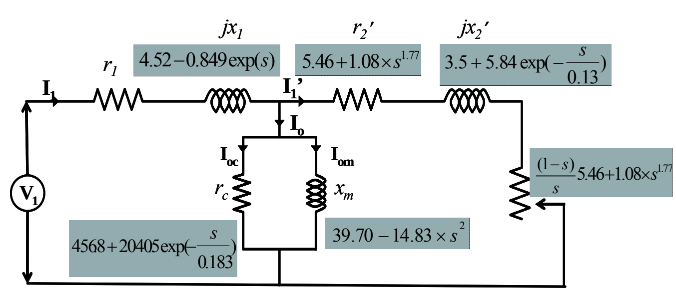
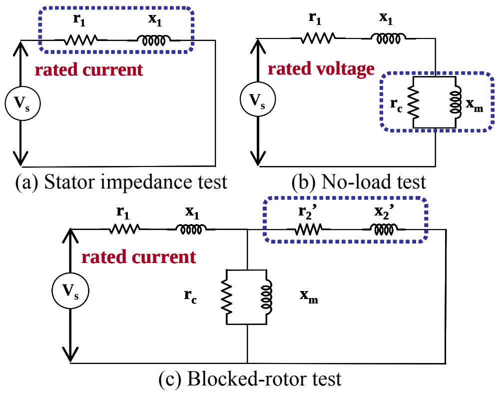


Fig. 5. Equivalent circuit considering parameters variation



(a) Stator impedance test (b) No-load test

(c) Blocked-rotor test

Fig. 6. Equivalent circuit for parameters calculation by test

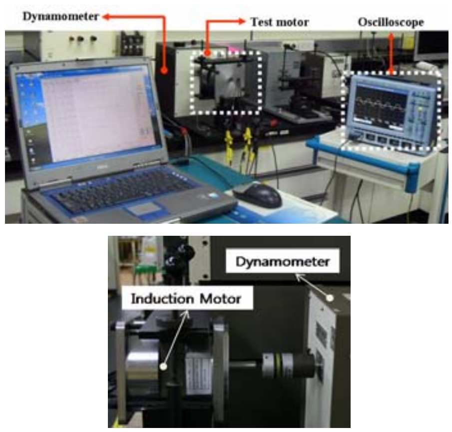
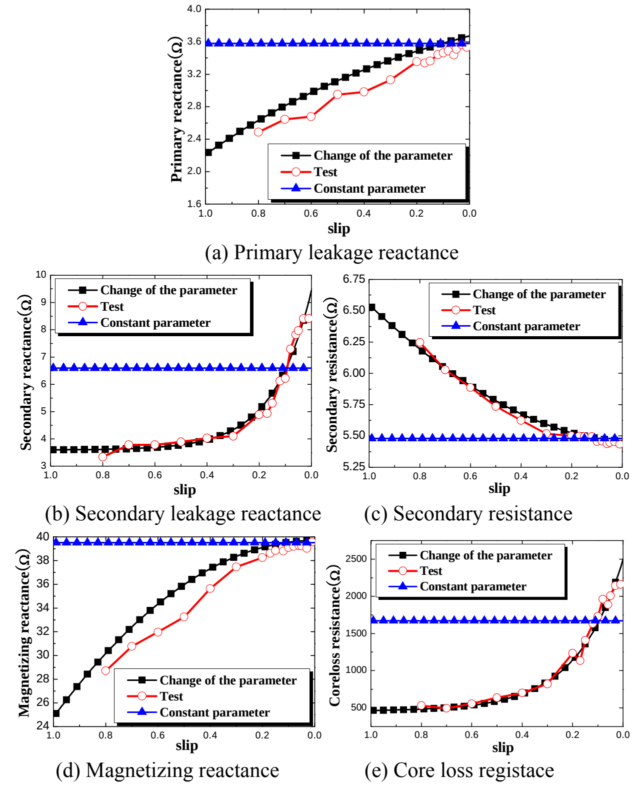


Fig. 7. Testing apparatus for parameter measurement

this method enhances the value of characteristics forecast under the various operating condition of the motor. In this paper is verified by comparing with the analysis results of the suggested method and the experimental results of commercial induction machine. The proposed method is more accurate than the results of commonly method. We confirm that out proposed method is useful for the design of the squirrel-cage induction motor.

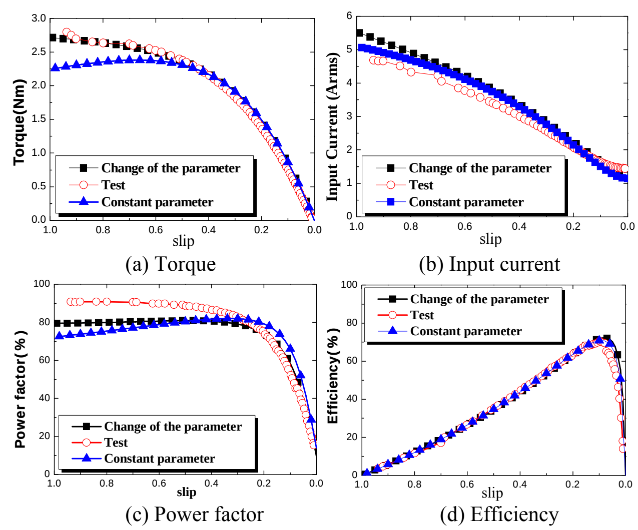


(a) Primary leakage reactance

(b) Secondary leakage reactance (c) Secondary resistance

(d) Magnetizing reactance (e) Core loss registace

Fig. 8. Equivalent circuit of three phase induction motor



(a) Torque (b) Input current

(c) Power factor (d) Efficiency

Fig. 9. Equivalent circuit of three phase induction motor

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