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Slip Compensation of Induction Motor using Sensorless Control

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Abstract– An induction motor is a kind of AC motor. It is known that this motor is rotated later than synchronous speed, by applying a load. Therefore, the present study is estimated rotational speed by using an observer, and compensates the slip of an induction motor in sensorless control in order to control the rotational speed against the synchronous speed.

1. Introduction

To describe the operating principles of the squirrel-cage induction motor. Figure 1 shows the structure of the motor. When current is applied to the stator, the induced current is flowed through the rotor. Then, it becomes an electromagnet, and the mechanism that rotates according to the rotating magnetic field created by the stator. The structure of this motor is also simple, and low cost because it is not using the precious metal. In addition, it can be driven by a maintenance-free because the commutator is not exist.

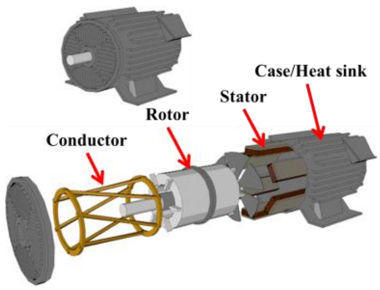

Fig.1 The construction of squirrel-cage induction motor

There is a phenomenon of slip in an induction motor. The slip is difference between the actual rotor and synchronous speed. This motor rotates slightly delayed by the slip. When the load is applied, the torque corresponding to the load is increase. And the slip is increase by torque, the rotational speed is reduced. Accordingly, the purpose of present study is to compensate for the slip using the sensorless control.

Moreover, in the present study, driving an induction motor using the model equation of the synchronous motor as a new method. In Ref [2], being described that the induction motor and synchronous motor can be adapted to a common. By the model equation in common, it can be controlled with a small amount of the program, such as the parameter measurement and the sensorless control. There is an advantage that can be more easily driven.

2. Estimation Method

2.1 $\alpha-\beta$ Coordinate Transformation

It is extremely difficult to control the induction motor in the state of the three-phase AC. Thereby, perform a-b transform to convert from the three-coordinate system to the two-coordinate system, and to simplify the control of the motor. The three-phase AC has a property to become zero when add to three sine waves. By use of this property, it is possible to handle the three-phase AC as an equivalent two-phase AC.

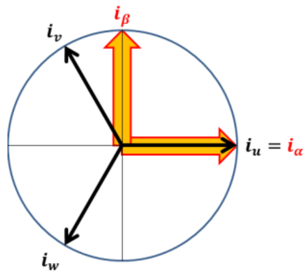

Fig.2 $\alpha-\beta$ Coordinate Transformation

Let the three-phase current be i_u, i_v, i_w and the two-phase transformation of the current be i_α, i_β, represented in the following equation.

$$\boldsymbol{i_u + i_v + i_w = 0}$$

$$\boldsymbol{i_\alpha = i_u\,,\quad i_\beta = \frac{(i_u + 2i_v)}{\sqrt{3}}}$$

2.2 $\mathrm{d}-\mathrm{q}$ Coordinate Transformation

Rotating coordinate system can handle current as a DC. Thus, by converting from the fixed coordinate to the rotating coordinate, analysis and control becomes very easy. Moreover, the rotating coordinate system can be divided current into two components, handle q-axis as the torque current component and the d-axis as the field current component. And it is possible to control them independently.

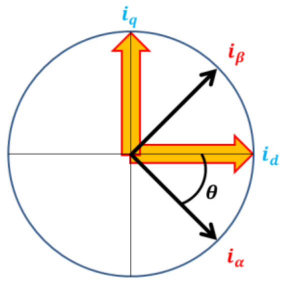

Fig.3 d − q Coordinate Transformation

Let the fixed coordinate be (i_α, i_β), the rotating coordinate be (i_d, i_q) and the rotation angle be θ, represented in the following equation.

$$i_d = i_\alpha * cos\theta + i_\beta * sin\theta$$
$$i_q = -i_\alpha * sin\theta + i_\beta * cos\theta$$

2.3 Speed Sensorless Control Method

As estimation method, assemble the controlled object of the system on a microcomputer. Then, give the same input to the actual and assembled system, and compare outputs. By adjusting to eliminate the error of the output, the system on the microcomputer and controlled system becomes almost same parameter. Thus, the information of the motor can be obtained.

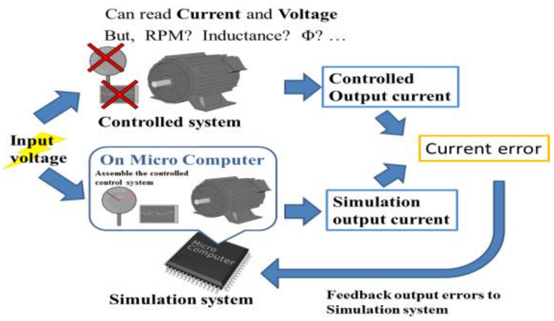

Fig. 4 The operation fig of model simulator

$$p\begin{bmatrix} i_d \\ i_q \\ \varphi_d \\ \varphi_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \frac{\omega L_q}{L_d} & 0 & -\frac{\omega}{L_d} \\ -\frac{\omega L_d}{L_q} & -\frac{R}{L_q} & \frac{\omega}{L_q} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ \varphi_d \\ \varphi_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} \\ \frac{v_q}{L_q} \\ 0 \\ 0 \end{bmatrix} \cdots (1)$$

i_d, i_q : $d - q$ *axis current* φ_d, φ_q: $d - q$ *axis flux linkage*
v_d, v_q : $d - q$ *axis vlotage* R : *armature resistance*
L_d, L_q : $d - q$ *axis self-inductance*
ω : *Electrical angle* p : *Differential operator* $p = \frac{d}{dt}$

The present study, to estimate the rotational speed by using the model adaptive reference system (MARS). The rotational speed of the speed operating range without a sensor is calculated from the current error based on the MARS. The mathematical modeling of a synchronous motor is based on Equation (1). From this equation, the error equation of actual current and estimated current is determined based on the following equation (2).

$$P\begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} = \begin{bmatrix} 0 & \Delta\omega \\ -\Delta\omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -\Delta\omega \\ \Delta\omega & 0 \end{bmatrix}\begin{bmatrix} \varphi_d \\ \varphi_q \end{bmatrix} \cdots (2)$$
$$\varepsilon_d = (\hat{i_d} - i_d) \quad \varepsilon_q = (\hat{i_q} - i_q)$$

The previous equation is input. Create a feedback system to input $-w$ and output v, and set the vector to be stable.

$$v = [i_d \quad i_q]\begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} \quad \cdots (3)$$
$$-w = [i_d \quad i_q]\left\{\begin{bmatrix} 0 & \Delta\omega \\ -\Delta\omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -\Delta\omega \\ \Delta\omega & 0 \end{bmatrix}\begin{bmatrix} \varphi_d \\ \varphi_q \end{bmatrix}\right\} \quad \cdots (4)$$

$\Delta\omega_r$ is obtained by the transfer function $G = -\frac{v}{w} = 1$, the estimated speed value is obtained by inputting the PI compensator.

$$\Delta\omega = -\frac{\varepsilon_d - \varepsilon_q}{\varphi_d} \quad \cdots (5)$$

$$\hat{\omega} = K_p\Delta\omega + K_I \int \Delta\omega dt \quad \cdots (6)$$
K_p, K_I : *Positive Constant*

3. Experimental Results

3.1 Experimental Systems

An inverter consists of the hall effect sensors, an intelligent power module, a microcomputer which is RENESAS RX62T. The specifications of induction motors are power output 0.75 kW and 1.5kW, 4-poles, MITSUBISHI squirrel-cage induction motor.

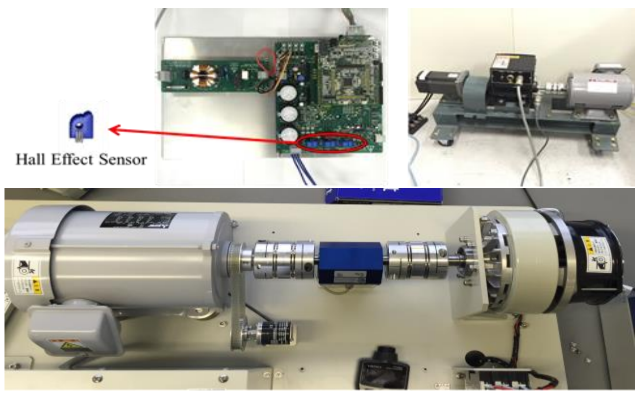

Fig.5 Experimental Devices

3.2 Experimental results

The actual q-axis current is followed by the q-axis command value. Figure 6 is the graph obtained by adding the load until 0.8Nm to the induction motor.

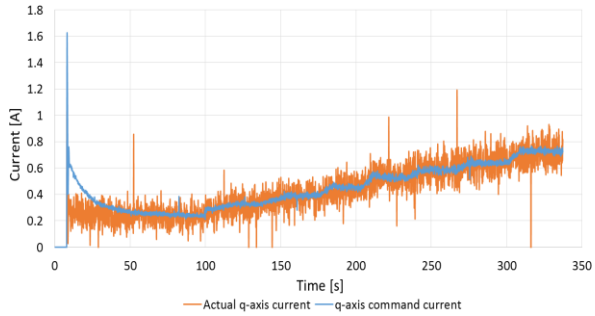

Fig.6 q-axis command current and Actual q-axis current of 0.75kw motor.

These results, increased about 2 rpm per 0.5 Nm, the amount of q-axis current raised about 0.07 A. Therefore, the increase of the q-axis command value is divided by 0.035[A], and substituted into the estimated speed value as shown in Figure 7. The result of inputting this value is shown in Figure 8. This graph is the result of torques and rotational speeds.

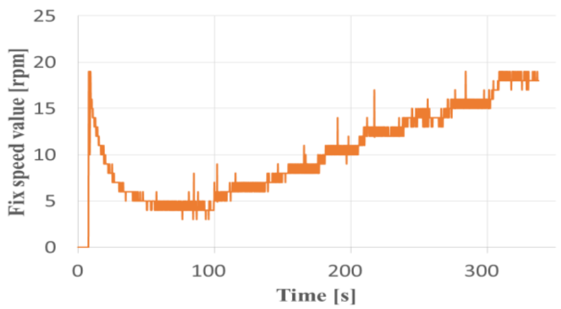

Fig.7 Compensation speed value

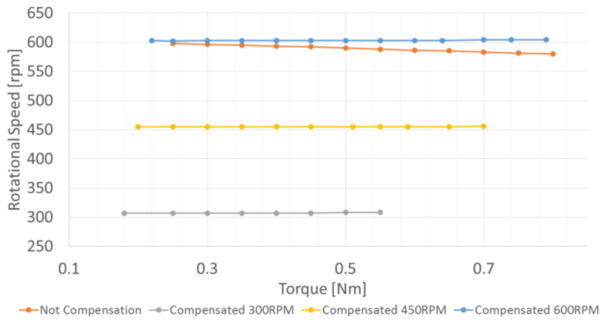

Fig.8 Slip compensation result of 0.75kWmotor.

From these results, the slip may be obtained from the amount of increase q-axis current, and the slip is compensated by the q-axis current.

In addition, since the characteristic equation to compensate for the slip from the model equations of the induction motor is present, to examine the equation to compensate for the slip. The basic equation for the d-q coordinate system of the induction motor is represented by the following equation.

$$\begin{bmatrix} v_{1d} \\ v_{1q} \\ v_{2d} \\ v_{2q} \end{bmatrix} = \begin{bmatrix} R_1 + pL_1 & -\omega_1 L_1 & pL_m & -\omega_1 L_m \\ \omega_1 L_1 & R_1 + pL_1 & \omega_1 L_m & pL_m \\ pL_m & -\omega_s L_m & R_2 + pL_2 & -\omega_s L_2 \\ \omega_s L_m & pL_m & \omega_s L_2 & R_2 + pL_2 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{bmatrix} \cdots (7)$$

$v_{1d}, v_{1q}\ v_{2d}, v_{2q}$: *Primary and Secondary d-q axis voltage*
$i_{1d}, i_{1q}\ i_{2d}, i_{2q}$: *Primary and Secondary d-q axis current*
R_1, R_2: *Primary and Secondary resistances*
L_1, L_2 : *Primary and Secondary self-inductance*
L_m : *Mutual inductance*
ω_s : *Slip frequency* ω_1 : *Electrical angle*

Depending on the characteristics of the squirrel-cage induction motor, the voltage on the secondary is zero because it is shorted circuit. The flux linkage can be expressed by the following equation.

$$\varphi_{2d} = L_m i_{1d} + L_2 i_{2d} \cdots (8)$$
$$\varphi_{2q} = L_m i_{1q} + L_2 i_{2q} \cdots (9)$$

The following equation is obtained by substituting these equations to the basic equation.

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -L_m R_2 & 0 & R_2 + pL_2 & -\omega_s L_2 \\ 0 & -L_m R_2 & \omega_s L_2 & R_2 + pL_2 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \\ \varphi_{2d} \\ \varphi_{2q} \end{bmatrix} \cdots (10)$$

When the direction of the secondary flux linkage φ_2 is coincident with the d-axis, φ_{2q} is zero. Thus, the slip frequency ω_s is represented by the following equation.

$$\omega_s = \frac{R_2 L_m}{L_2 \varphi_2} i_{1q} \cdots (11)$$
$$\varphi_2 = \frac{L_m i_{1d}}{1 + p\left(\frac{L_2}{R_2}\right)}$$

From this equation, the slip frequency is calculated by the secondary resistance and q-axis current. And, the estimated rotor speed can be compensated by the calculated slip frequency ω_s.

3.3 Slip Compensation Result

When the q-axis current increases the amount of 0.035 A, the rotational speed has decreased 1 rpm. Using the characteristic equation of the induction motor from the results, the slip is compensated using two induction motors. These results are shown in Figures 9, 10.

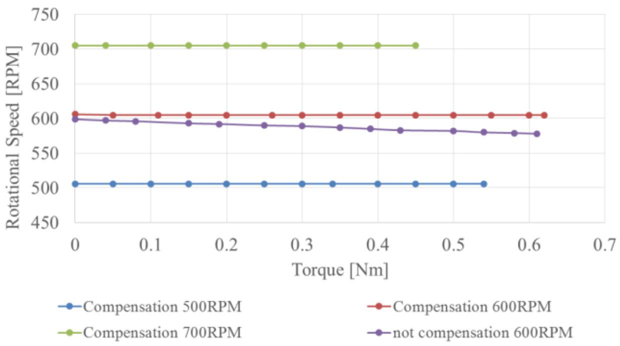

Fig.9 Slip compensation result of 0.75kw induction motor.

As a result, compensating for slip in the same manner as when compensated using q-axis current 0.035 A. In addition, the slip of the induction motor of 1.5kW was almost compensated.

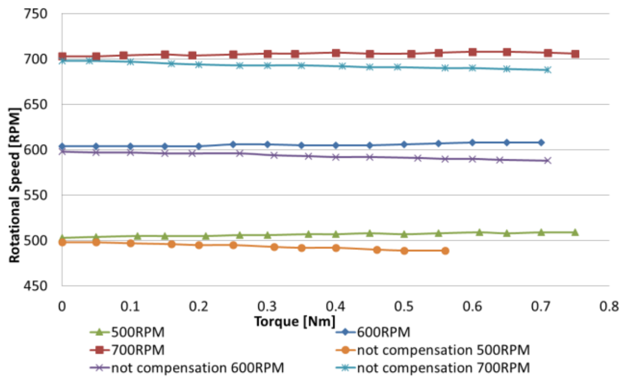

Fig.10 Slip compensation result of 1.5kw induction motor.

4. Conclusion

In this study, it was possible to compensate for slip from the q-axis current command of the induction motor using a sensorless control. Moreover, using a characteristic equation of the induction motor, it was able to compensate to the slip by calculating the slip frequency from the increase in the q-axis current. Future issues are examining the rotational speed when applied a greater load than 0.8 Nm.

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