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Robust Control Method of Induction Machine against Temperature Variation

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Abstract

This paper proposes a control method robust against the rotor temperature variation for the induction machine used in the xEV traction application. The rotor resistance (or time constant) of the induction machine varies with the rotor temperature so that its torque control performance will be degraded if this variation is not properly compensated. In this paper, firstly a direct vector control method, which is based on the rotor flux estimator using the current model in the synchronous reference frame, is adopted in order to control the DQ-axis rotor fluxes independently. Secondly, the rotor time constant variation is compensated utilizing the flux estimation difference between the voltage and current models. This method has no transition region which is inevitable in the conventional method that uses the current model in the low speed region and the voltage model in the high speed range for estimating the rotor flux. The robustness to the temperature change of the proposed method is validated through the experiment in the motoring and regeneration modes.

Keywords: induction machine, rotor resistance, rotor flux estimator, rotor temperature

1 Introduction

The induction machine has been widely used in the industry applications and its usage is extending throughout the automotive ones. Especially the merit that it has no rare-earth magnet which is expensive makes the induction machine the best candidate as a main propulsion machine of the EV and fuel cell hybrid EV.

But the phenomenon which the rotor time constant changes due to the rotor temperature variation raises the problem of the degradation of the torque control performance.

To tackle this matter, tried was the measure which the DQ-axis flux maps were measured at three different temperatures offline and then the current control maps were built. This method has the weak point that it takes lots of time to construct the current control maps at each temperature. After that, an indirect vector control way has been proposed that the current control map is made at the one temperature and the rotor resistance is estimated real-time in order to adjust the DQ-axis current commands. This is a simple and effective method in the steady state, but has a drawback that the exact rotor temperature is not reflected because the rotor resistance is calculated based on the stator coil temperature.

This paper proposes a new direct vector control scheme that a current control map at the one temperature is used and the rotor resistance change is compensated utilizing the difference between the rotor flux estimation values of the current model and the voltage model. In the proposed method, the estimated DQ-axis fluxes based on the current model are used to calculate the rotor flux angle. And the difference of the flux estimates between the current model and the voltage model at the synchronous reference frame is used to update online the rotor resistance value in the current model. As a result, the torque fluctuation originated from the rotor temperature variation can be minimized. The effect that the torque control error is maintained below the torque error limit is shown through several experiments.

2 Rotor Flux Estimator

A rotor flux estimator based on the rotor current equation can be expressed as the equation (1).

$$
\begin{aligned}
p\hat{\lambda}^{e}_{dr\_cm} &= r_r \frac{L_m}{L_r}\hat{i}^{e}_{ds} - \frac{r_r}{L_r}\hat{\lambda}^{e}_{dr\_cm} + \omega_{sl}\hat{\lambda}^{e}_{qr\_cm} \\
p\hat{\lambda}^{e}_{qr\_cm} &= r_r \frac{L_m}{L_r}\hat{i}^{e}_{qs} - \frac{r_r}{L_r}\hat{\lambda}^{e}_{qr\_cm} - \omega_{sl}\hat{\lambda}^{e}_{dr\_cm}
\end{aligned}
\qquad (1)
$$

where $\hat{\lambda}^{e}_{dr\_cm}, \hat{\lambda}^{e}_{qr\_cm}$ are the rotor flux estimates, r_r is the rotor resistance, L_m is the magnetizing inductance, and L_r is the rotor self-inductance, $\hat{i}^{e}_{ds}, \hat{i}^{e}_{qs}$ are DQ-axis stator currents in the synchronous reference frame, ω_{sl} is the slip angular frequency, and p is differential operator.

The above flux estimator is depicted as a block diagram form in the following figure 1.

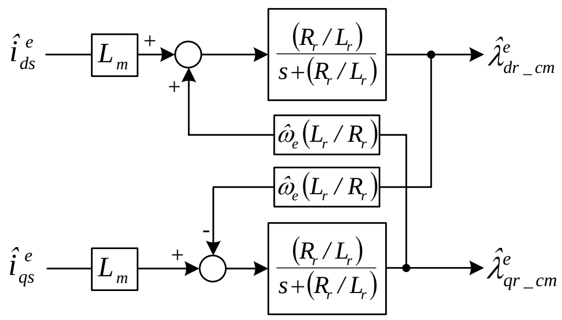

Figure 1: Rotor flux estimator (current model)

A simple way to get the flux angle is the function 'atan()'. But to obtain the more stable estimate, the PLL(Phase Locked Loop) method is adopted.

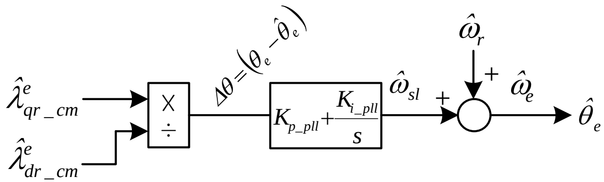

Fig.2 Flux angle calculation using PLL method

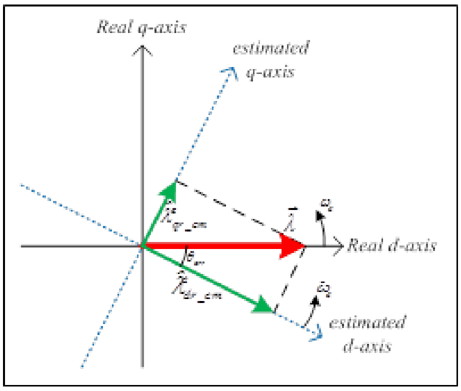

Fig.3 Real angle and estimated one of the rotor flux

The angle estimation error, $\Delta\theta_e$ is similar to the ratio of DQ flux magnitudes. Because the Q-axis flux is regulated to zero, the ratio of the DQ fluxes is well maintained below one tenth.

Thus the ratio of DQ fluxes can be used as an alternative to the flux angle estimation error. In this way, it converges more quickly when the error is large.

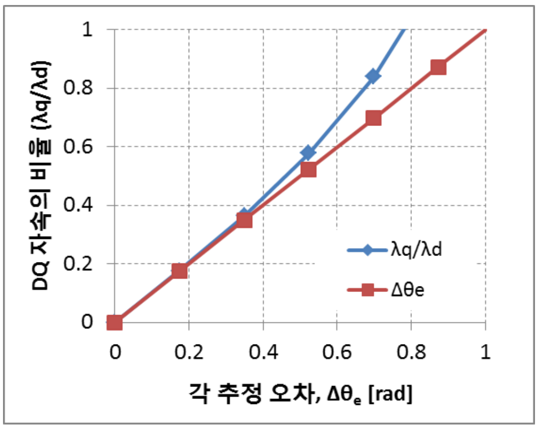

Fig. 4 Relationship between the angle estimation error and DQ flux ratio

The relationship between the angle estimation error and DQ flux ratio is described in the figure 4 and the equation (2).

$$\Delta\theta_e = \theta_e - \hat{\theta}_e \cong \tan\left(\theta_e - \hat{\theta}_e\right) = \frac{\hat{\lambda}^e_{qr\_cm}}{\hat{\lambda}^e_{dr\_cm}} \quad (2)$$

The estimated angle can be expressed as a function of the real angle like the equation (3) and (4) from the figure 2.

$$\begin{aligned} \hat{\theta}_e &= \left(\Delta\theta\left(K_{p\_pll} + \frac{K_{i\_pll}}{s}\right) + \omega_r\right)\frac{1}{s} \\ &= \left(\left(\theta_e - \hat{\theta}_e\right)\left(K_{p\_pll} + \frac{K_{i\_pll}}{s}\right) + \omega_r\right)\frac{1}{s} \end{aligned} \quad (3)$$

$$\frac{\hat{\theta}_e}{\theta_e} = \frac{K_{p\_pll}s + K_{i\_pll}}{s^2 + K_{p\_pll}s + K_{i\_pll}} \quad (4)$$

The control gains of the equation (4) are set to satisfy the second-order system response as the following equation (5).

$$\begin{cases} K_{p\_pll} = \sqrt{2}\omega_{c\_pll} \\ K_{i\_pll} = \omega^2_{c\_pll} \end{cases} \quad (5)$$

When the Q-axis flux converges to zero, the estimation angle of the rotor flux also does to the real angle.

3 Rotor Resistance Estimator

The rotor resistance can be estimated comparing the flux estimates of the rotor current model and the stator voltage model.

The stator voltage equation can be expressed as the equation (6).

$$\begin{aligned} \hat{v}^e_{ds} &= r_s\hat{i}^e_{ds} + p\sigma L_s\hat{i}^e_{ds} + p\frac{L_m}{L_r}\hat{\lambda}^e_{dr\_vm} \\ &\quad - \omega_e\left(\sigma L_s\hat{i}^e_{qs} + \frac{L_m}{L_r}\hat{\lambda}^e_{qr\_vm}\right) \\ \hat{v}^e_{qs} &= r_s\hat{i}^e_{qs} + p\sigma L_s\hat{i}^e_{qs} + p\frac{L_m}{L_r}\hat{\lambda}^e_{qr\_vm} \\ &\quad + \omega_e\left(\sigma L_s\hat{i}^e_{ds} + \frac{L_m}{L_r}\hat{\lambda}^e_{dr\_vm}\right) \end{aligned} \quad (6)$$

where $\hat{v}^e_{ds}, \hat{v}^e_{qs}$ is the stator voltage in the rotor flux reference frame, L_s is the stator self-inductance, $\hat{\lambda}^e_{dr\_vm}, \hat{\lambda}^e_{qr\_vm}$ is the rotor flux estimates in the rotor flux reference frame, ω_e is the rotor flux angular frequency, and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.

Because the rotor flux can be also estimated using the equation (6), the rotor resistance can be calculated by comparing the flux estimates of the equation (6) with the ones of the current model explained in the chapter 2.

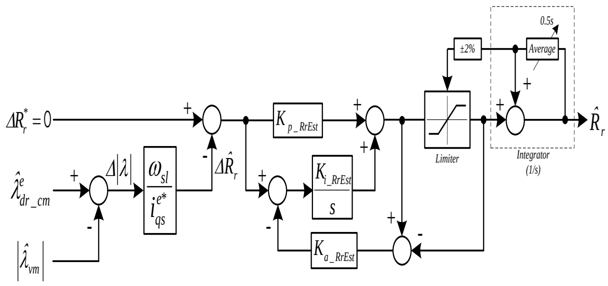

Fig. 5 Rotor resistance estimator

On condition that the Q-axis flux of the rotor current model is regulated as zero using the PLL method, the flux estimate magnitude approximates the D-axis flux estimate of the rotor current model.

$$\left|\hat{\lambda}_{cm}\right| \cong \hat{\lambda}^e_{dr\_cm} \quad (7)$$

On the other hand, the Q-axis flux estimate of the stator voltage model does not converge to zero if there is an error in the rotor resistance estimate. Therefore, the estimated flux magnitude from the stator voltage model is calculated using the equation (8).

$$\left|\hat{\lambda}_{vm}\right| = \sqrt{\left(\hat{\lambda}^{e}_{dr\_vm}\right)^2 + \left(\hat{\lambda}^{e}_{qr\_vm}\right)^2} \qquad (8)$$

From the figure 5, the relationship between the estimate and real value of the rotor resistance can be equated as the equation (9) and (10).

$$\begin{aligned} \hat{R}_r &= \Delta\hat{R}_r\left(K_{p\_RrEst} + \frac{K_{i\_RrEst}}{s}\right)\frac{1}{s} \\ &= \left(R_r - \hat{R}_r\right)\left(K_{p\_RrEst} + \frac{K_{i\_RrEst}}{s}\right)\frac{1}{s} \end{aligned} \qquad (9)$$

$$\frac{\hat{R}_r}{R_r} = \frac{K_{p\_RrEst}s + K_{i\_RrEst}}{s^2 + K_{p\_RrEst}s + K_{i\_RrEst}} \qquad (10)$$

The PI gains of the above equation are set to satisfy the second-order system response as the equation (11).

$$\begin{cases} K_{p\_RrEst} = \sqrt{2}\omega_{c\_RrEst} \\ K_{i\_RrEst} = \omega^2_{c\_RrEst} \end{cases} \qquad (식\ 11)$$

The procedure can be summarized as follows.

(1) Rotor resistance increment (or decrement) due to the rotor temperature increase (or decrease)
(2) Increment (or decrement) of the slip angular frequency and thus the synchronous angular frequency
(3) Adjustment of the inverter output voltage
(4) Increment (or decrement) of the rotor flux estimate of the stator voltage model
(5) No change in the rotor flux estimate of the rotor current model
(6) Adjustment of the rotor resistance estimate due to the flux estimate error

Figure 6 shows the whole structure of the proposed method. D-axis and Q-axis current control maps are constructed through off-line experiment at one temperature.

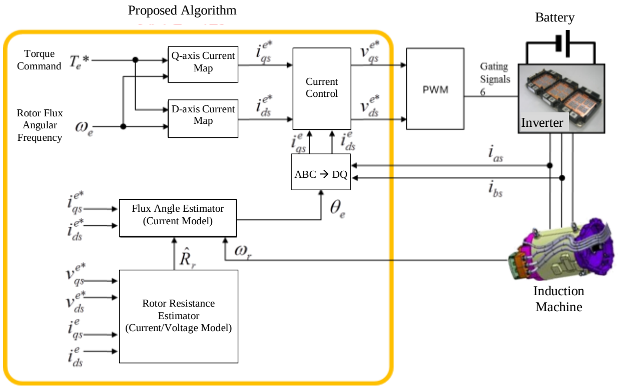

Figure 6 : Proposed control scheme

4 Experimental Results

The experiment setup of the figure 7 was built to prove the effectiveness of the proposed method. The rear part of the machine was carved to monitor the rotor temperature by the thermographic camera.

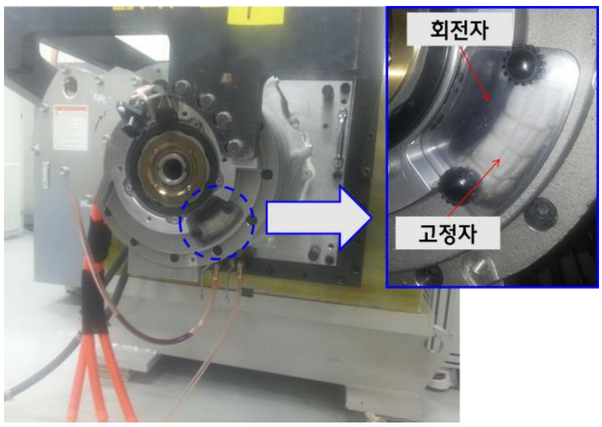

Figure 7 : Experimental setup

Parameters of the induction machine used are summarized in the table 1.

Table 1 : Parameters of the induction machine

Parameter	Value
Max. output power	100kW
Max. torque	265Nm
Max. speed	11000rpm
Rated voltage	287V
No. of poles	4
Wiring configuration	Delta
Stator resistance	0.0141Ω
Rotor resistance	0.0143Ω
Stator inductance	3.620mH
Stator leakage inductance	117.0uH
Rotor leakage inductance	81.78uH

Figure 8 shows the result when the rotor resistance is adjusted using the stator temperature measurement at the continuous output condition of 3600rpm and 141Nm. Torque changes 3.3Nm and is equal to 47% of the upper limit 7.05Nm, or 2.3% of the torque command.

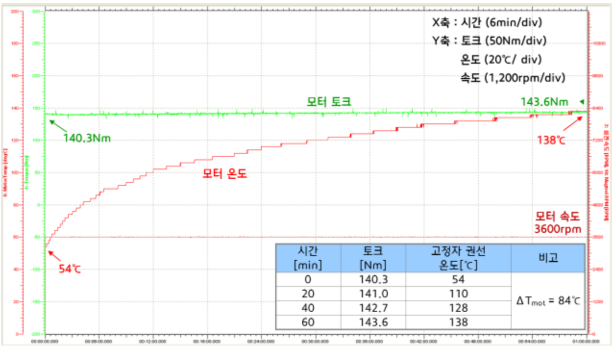

Fig. 8 Experimental results when the rotor resistance is calculated using the stator temperature (rotor speed 3600rpm and torque command 141Nm); time duration 60 minutes.

Figure 9 shows the results when the proposed method is applied that the rotor resistance is estimated using the flux estimation difference of the current and voltage models (3600rpm and 141Nm). Final torque differs from the initial one by 0.9Nm and the difference is below 13% of the upper limit 7.05Nm, or equal to 0.6% of the torque command.

The estimation error of the rotor temperature is 17.6℃. And this is 41% of the minimum difference of the rotor and stator temperatures.

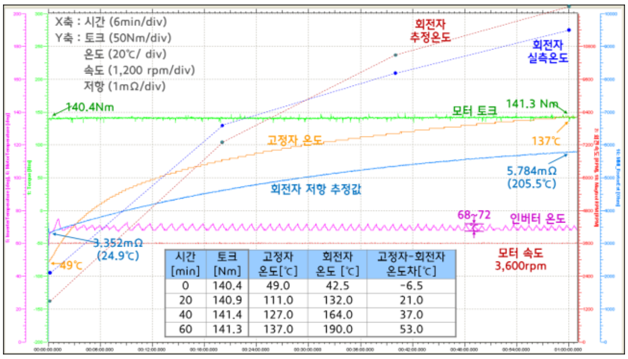

Figure 9 : Experimental results of the proposed method (spped 3600rpm and torque command 141Nm); time duration 60 minutes.

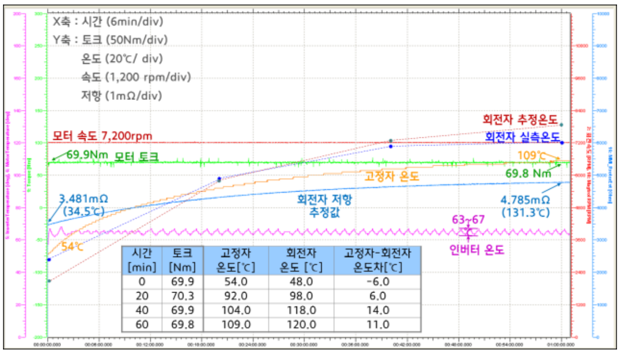

Figure 10 : Experimental results of the proposed method (speed 7200rpm and torque command 70Nm); time duration 60 minutes.

Figure 10 shows the results when the proposed method is applied (7200rpm and 70Nm). Torque varies 0.1Nm and is equal to 2.5% of the upper limit 4Nm. When the torque command is below 80Nm, the upper limit is set to 4Nm.

Figure 11 shows the efficiency map when the rotor resistance is calculated using the stator temperature measurement. The average efficiency is 84.4%.

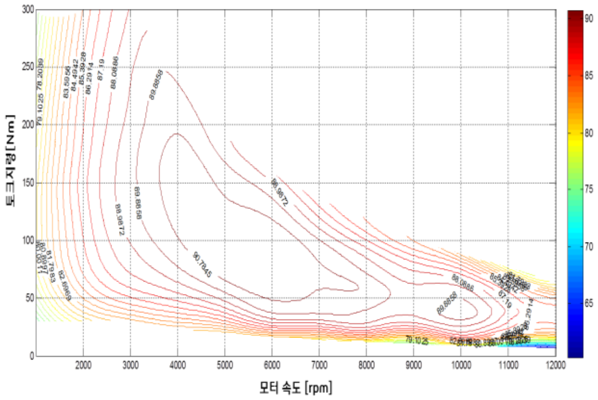

Fig. 11 Efficiency map of the conventional method.

Figure 12 shows the efficiency map when the proposed method is used. The average efficiency 88.4% and this is 4% improved result compared with the conventional one.

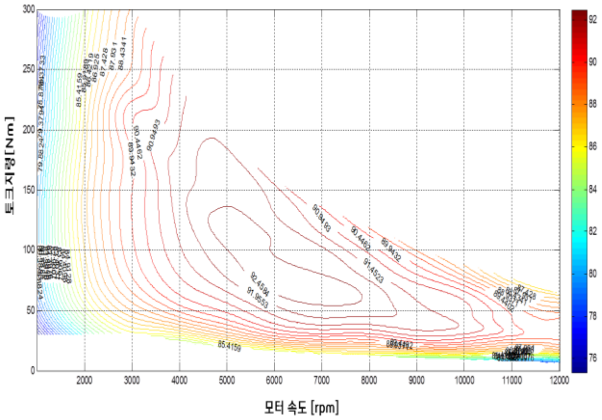

Fig. 12 Efficiency map of the proposed method

5 Conclusion

This paper proposed a robust control method of the induction machine against rotor temperature variation. The rotor flux was estimated using the rotor current model and a rotor resistance estimator is proposed. In the proposed method, the rotor is adjusted using the difference of the flux estimates between the current and voltage models.

The effectiveness of the proposed method is validated using the automotive 100kW induction machine. There is no transition region which is the demerit of the Gopinath model.

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