Q-Axis Flux-Based Sensorless Vector Control of Induction Motor Taking into Account Iron Loss

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Keywords: sensorless vector control, induction motor, flux observer, iron loss

In this paper, a new sensorless vector control system is developed by using the d-q model of induction motor (IM) taking into account iron loss. Based on the observer and adaptive control theories, the flux-observer-based method is applied and the speed estimation is utilized by the q-axis rotor flux converging on zero. Since the flux observer is constructed in a synchronously rotating reference frame with respect to the rotor flux of a current model, the proposed system is very simple and easy to implement. The proposed system is shown in Fig. 1.

Choosing a synchronously rotating reference frame with respect to the rotor flux computed by the current model \( \phi^{*}_{cq} = 0 \), the d-axis rotor flux derived from this model can be expressed as

\[
\phi^{*}_{cd} = M_{\phi d} / (\tau_{d} P + 1)
\]  

where \( \tau_{d} = \tau_{\hat{d}} + \tau_{cd} \), \( \tau_{cd} = L_{r} / R_{c d}, P = d/dt \).

The angular speed of rotor flux obtained is written as follows:

\[
\omega' = \hat{\omega} + M_{\phi d} / (\tau_{d} \phi^{*}_{cq})
\]  

where \( \hat{\omega} \) is the estimated speed and \( \phi^{*}_{cq} = i_{cq}^{*} + i_{cd}^{*} \).

By neglecting the transient phenomena of the equivalent iron loss circuit, the currents of iron loss circuit can be computed by

\[
i_{cd} = \omega M_{lri} i_{cq}^{*} / R_{lri} \]

\[
i_{cq} = -\omega M (\phi^{*}_{cd} + l_{cq}^{*}) / R_{lri} \]

Here the iron loss resistance of parallel exiting circuit \( R_{c} \) related to the operating frequency is also considered. If \( R_{c} \) is set to be infinite, the currents \( i_{cd}^{*} \) and \( i_{cq}^{*} \) become zero in (3) and (4). This case is considered as neglecting iron loss.

From the viewpoint of the observer theory, the stator flux of the voltage model modified by the current model can be computed by

\[
\begin{align*}
P_{\hat{\omega}} &= e_{dq} - R_{c d} i_{dq} + \omega \hat{\phi}_{dq} + (\phi_{dq} - \hat{\phi}_{dq}) / T_{c} \quad (5) \\
\hat{\phi}_{eq} &= e_{eq} - R_{c q} i_{eq} - \omega \hat{\phi}_{eq} + (\phi_{eq} - \hat{\phi}_{eq}) / T_{c} \quad (6)
\end{align*}
\]

The q-axis rotor flux of voltage model is computed by

\[
\hat{\phi}_{eq} = L_{r} \hat{\phi}_{eq} / M - (L_{r} L_{s} / M + l_{i}) i_{eq} - l_{i} i_{eq}^{*} \quad (7)
\]

The estimated q-axis rotor flux of (7) should be zero because of \( \phi^{*}_{eq} = 0 \) when the estimated speed is correct. Therefore, the rotor speed is estimated by

\[
\hat{\omega} = K_{w} (1 + 1 / (T_{w} P)) \hat{\phi}_{eq} \quad (8)
\]

Fig. 2 shows the experimental results at 700 r/min. Fig. 2 (a) is the steady-state characteristic of load torque versus torque command and Fig. 2(b) is the one of load torque versus torque command. Fig. 2 demonstrated the improvement of torque characteristic and speed control accuracy clearly. The effectiveness of the proposed system has been verified by digital simulation and experimentation. The proposed system is considered as an extension of conventional slip frequency control and can be applied to conventional vector control easily.
Q-Axis Flux-Based Sensorless Vector Control of Induction Motor
Taking into Account Iron Loss

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This paper presents a sensorless vector control system for induction motors by taking into account iron loss, in which a flux-observer-based method is applied. Since the flux observer is constructed in a synchronously rotating reference frame with respect to the rotor flux of a current model and the iron loss resistance of parallel exiting circuit is used, the proposed system is very simple and the compensation of iron loss related to the operating frequency is directly realized while calculating rotor fluxes and slip frequency. The accuracies of estimated torque and speed are improved. The effectiveness of the proposed system has been verified by digital simulation and experimentation.

Keywords: sensorless vector control, induction motor, flux observer, iron loss

1. Introduction

Various control algorithms based on the adaptive control theory have been proposed for speed sensorless vector control of induction motor (IM)\(^{(5)-(14)}\). We proposed a method for sensorless vector control, which is based on a flux observer and the adaptive control method\(^{(9)-(10)}\). According to the vector control theory of IM, we utilized the q-axis rotor flux converging on zero for speed estimation. In order to solve the problems of flux estimation using only the voltage model, the flux-observer-based method was applied. As the proposed model is constructed on a synchronously rotating reference frame with respect to the rotor flux of a current model, the advantages of this system are that the fluxes from the current model are easily obtained and all of the variables are dc quantities, which are convenient for control and checking.

Fundamental principles of vector control of IMs are derived by neglecting iron loss. However, iron loss does exit in practice. From the viewpoints of high accuracy torque control, the iron loss must be considered. A variety of different schemes have been proposed\(^{(5)-(8)}\). However, a number of them, in which the flux control is not considered or the vector control calculation is different from conventional slip frequency control and complicated, are proposed. It is unable to say that the study on consideration of iron loss is enough.

In this paper, a new sensorless vector control method based on a d-q model of IM, in which the iron loss related to the operating frequency is taken into account, is developed. The structure of the proposed system is easy to implement and considered as an extension of conventional slip frequency control. As the result, the accuracies of estimated torque and speed are improved. The effectiveness of the proposed system has been verified by digital simulation and experimentation.

2. Mathematical Model Considering Iron Loss

By considering the iron loss as an additional short circuit shown in Fig. 1, a model of induction motor in arbitrary rotating reference frame is derived as follows\(^{(9)-(10)}\):

\[ e_{sd} = R_s i_{sd} + P \psi_{sd} - \omega \psi_{sq} \tag{1} \]
\[ e_{sq} = R_s i_{sq} + P \psi_{sq} + \omega \psi_{sd} \tag{2} \]
tizing currents and linkage fluxes are defined as follows:

\[ M \]

shown in Fig. 3, we can get the following equation (11):

\[ IM \]

is very small and can be ignored (5), only the mutual induc-

Because the leakage inductance of equivalent iron loss circuit

Fig. 1. Winding model of IM taking into account iron loss

Fig. 2. Steady-state equivalent circuit of IM

In the above equations, all variables of rotor windings and

iron loss circuit windings are referred to the stator windings.

Because the leakage inductance of equivalent iron loss circuit

is very small and can be ignored (5), only the mutual induc-

tance \( M \) is considered in (5) and (6). In addition, the magnet-

izing currents and linkage fluxes are defined as follows:

\[ i_{md} = i_{sd} + i_{rd} + i_{rd} \]

(7)

\[ i_{mq} = i_{sq} + i_{rq} + i_{rq} \]

(8)

\[ \psi_{sd} = L_{rd}i_{rd} + M_{imd} \]

(9)

\[ \psi_{sq} = L_{rq}i_{rq} + M_{imq} \]

(10)

\[ \psi_{rd} = L_{rd}i_{rd} + M_{imd} \]

(11)

\[ \psi_{rq} = L_{rq}i_{rq} + M_{imq} \]

(12)

In the above mathematical model of IM, the parameters of

IM are defined as shown in Fig. 2.

The electromagnetic torque of IM is expressed as

\[ \tau_{e} = \frac{P}{L_{r}} (\psi_{rd}(i_{rd} + i_{rd}) - \psi_{rq}(i_{rd} + i_{rd})) \] (13)

3. Proposed System

Choosing a synchronously rotating reference frame with

respect to the rotor flux computed by the current model shown in

Fig. 3, we can get the following equation (14):

\[ \psi_{rd}^* = 0 \]

(14)

The \( d \)-axis rotor flux derived from (3), (7), (11) and (14)
can be expressed as

\[ \psi_{rd}^* = \frac{M}{\tau_{e}}P + \tilde{i}_{d} \] (15)

where \( \tilde{i}_{d} \equiv \tilde{i}_{sd} + \tilde{i}_{rd} \).

The angular speed of rotor flux obtained from (4), (8), (12) and (14) is written as follows:

\[ \omega^* = \omega_{r} + \frac{M}{\tau_{e}} \tilde{i}_{d} \] (16)

where \( \tilde{i}_{d} \equiv \tilde{i}_{sd} + \tilde{i}_{rd} \).

In (16), the estimated rotor speed is used instead of the ac-

tual motor speed. From (7) and (11), we have

\[ \tilde{i}_{md} = \frac{\psi_{rd}^*}{L_{r}} = \frac{L_{r}}{L_{r}} \tilde{i}_{d} \] (17)

Substitution of (14) into (8) and (12) gives

\[ \tilde{i}_{mq} = \frac{L_{r}}{L_{r}} \tilde{i}_{d} \] (18)

By neglecting the transient phenomena of the equivalent

iron loss circuit, the differential operator \( P \) in (5) and (6) is

set to be zero. The currents of iron loss circuit can be computed by

\[ \tilde{i}_{md} = \frac{\omega^* M_{im}}{L_{r}} \tilde{i}_{q} \] (19)

\[ \tilde{i}_{mq} = \frac{\omega^* M_{im}}{L_{r}} (\psi_{rd} - \psi_{rd}) \] (20)

Using the voltage model of (1) and (2) modified by the current

model of (14) and (15) from the viewpoint of the ob-

server theory, we compute stator flux as

\[ P \tilde{\psi}_{rd} = e_{sd} - R_{s}i_{sd} + \omega \tilde{\psi}_{sq} + \frac{\psi_{rd} - \tilde{\psi}_{rd}}{T_{c}} \] (21)

\[ P \tilde{\psi}_{rq} = e_{rq} - R_{s}i_{rq} - \omega \tilde{\psi}_{sq} + \frac{\psi_{rq} - \tilde{\psi}_{rq}}{T_{c}} \] (22)

Here the stator fluxes of current model are computed by

\[ \psi_{rd}^* = l_{r} i_{rd} + M_{imq} \] (23)

\[ \psi_{rq}^* = l_{r} i_{rq} + M_{imq} \] (24)

The \( q \)-axis rotor flux of voltage model is computed by

\[ \tilde{\psi}_{rq} = \frac{L_{r}}{M} \tilde{\psi}_{sq} - \left( \frac{L_{r} l_{r}}{M} + b_{r} \right) i_{sq} - l_{i} i_{rq} \] (25)
The estimated \( q \)-axis rotor flux of (25) should be zero because of (14) when the estimated speed is correct. Therefore, the rotor speed is estimated by

\[
\hat{\omega}_r = K_w \left( 1 + \frac{1}{T_h p} \right) \hat{\theta}_{rq} \tag{26}
\]

The proposed sensorless vector control system taking into account iron loss is shown in Fig. 4.

4. Simulation and Experimentation

The proposed control system was implemented by a DSP (TMS320C32) based PWM inverter. The experimental system is shown in Fig. 5. The sampling period is 200\( \mu \)s. In order to diminish the output voltage error caused by the dead time and the non-ideal features of IGBT, a compensating algorithm has been applied to the experimental system (4).

The tested induction machine has the following rated and nominal values: 1.5 kW; \( R_s = 1.54 \Omega; R_r = 0.787 \Omega; L_s = L_r = 0.115 \text{ H}; M = 0.11 \text{ H}; p = 2; J = 0.0126 \text{ kgm}^2 \). The above motor parameters are used in the digital simulation and the experimental system.

Since the iron loss resistance of series exiting circuit is proportional to \( (\omega^*)^{1.6} \), the iron loss resistance of parallel circuit, \( R_{c*} \) as shown in Fig. 2, can be expressed as

\[
R_{c*} = R_{c0}(f/f_0)^{0.4} \tag{27}
\]

Fig. 7 shows the steady-state characteristic of load torque versus torque command at 300\( \text{r/min} \). Fig. 7(a) is the simulated result. Fig. 7(b) is the experimental result under the same condition with that of the simulation. The torque command \( \tau^* \) is computed by

\[
\tau^* = \frac{pM}{L_r} \psi^*_{r*} i_q^* \tag{28}
\]

Here, \( R_{c0} = 391 \Omega \) is measured by the no-load test at \( f_0 = 60 \text{ Hz} \), based on the standard of JEC-37. Fig. 6 shows the frequency characteristic of iron loss resistance calculated...
Fig. 7. Steady-state characteristic of load torque versus torque command at 300 r/min by (27).

The torque command is very close to the actual load torque in the case of considering iron loss, compared with the case of neglecting iron loss. If the iron loss resistance $R_c^*$ is set to be infinite, the currents $i_{cd}^*$ and $i_{cq}^*$ become zero in (19) and (20). The result of this case is considered as neglecting iron loss.

Fig. 8 shows the steady-state characteristic of load torque versus torque command at 700 r/min. Fig. 9 shows the steady-state characteristic of load torque versus torque command at 1000 r/min. From the above results, it is found that the experimental results agree with the computed results. The experimental results clearly demonstrated the improvement of torque characteristic by the proposed method.

Fig. 10 shows the computed steady-state characteristic of load torque versus actual motor speed at 300 r/min, 700 r/min and 1000 r/min. It is found that the actual speed is equal to the speed command when the iron loss is considered. Fig. 11 shows the experimental results. Because the values of controller’s parameters are different to the actual ones of IM, the deviation between the actual speed and the speed command exists still, as shown in Fig. 11. However, the actual speed deviation between the results obtained by neglecting iron loss and those of considering iron loss is similar to those of Fig. 11.

Fig. 12 shows the transient responses for the step change of speed command from 1000 r/min to 1100 r/min. The experimental result of neglecting iron loss is shown in Fig. 12(a) and that of considering iron loss is shown in Fig. 12(b). It is found that good transient responses are obtained in both cases. But the deviation between the command torque and the actual one is about 12% while neglecting iron loss in Fig. 12(a). Although a little pulsation of estimated speed $\hat{N}$ is observed in the experimental results, good transient responses of actual speed are obtained. On the other hand, the digital simulation is carried out by using a numerical
integration. In this simulation, the voltage commands $e_{sd}^*$ and $e_{sq}^*$ change stepwise every 200 µs and it is assumed that the actual $d$ and $q$ voltages are equal to those commands. The simulated result is in good agreement with the experimental result.

5. Conclusions

This paper has introduced a speed sensorless vector control method of induction motor by taking into account iron loss. Since the control algorithm is constructed from a model of induction motor in a synchronously rotating reference frame and the iron loss related to the operating frequency is taken into account, the proposed system is simple and easy to apply to conventional vector control. It is confirmed by digital simulation and experiment that the precision of the estimated torque and speed are well improved by the proposed method.

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Fig. 11. Steady-state characteristic of rotor speed versus load torque (experimental result)

- (a) Experimental result neglecting iron loss
- (b) Experimental result considering iron loss
- (c) Simulated result considering iron loss

![Graphs showing steady-state characteristic with and without iron loss.]

Fig. 12. Transient responses for the step change of speed command between 1000 r/min and 1100 r/min

- (a) Experimental result neglecting iron loss
- (b) Experimental result considering iron loss
- (c) Simulated result considering iron loss

References

sensorless vector control considering iron loss


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