Motor Control Application

Vector Control of Three Phase Induction Motor (Algorithms)

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Introduction

This application note describes the three phase induction motor vector control algorithms used in a sample program for Renesas microcontrollers.

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1. Overview

This application note describes the three phase induction motor vector control algorithms used in a sample program for Renesas microcontrollers.

2. Voltage Equations of Three Phase Induction Motor

2.1 Control Model of Three Phase Induction Motor

The voltage equations for three phase induction motors can be expressed as shown below.

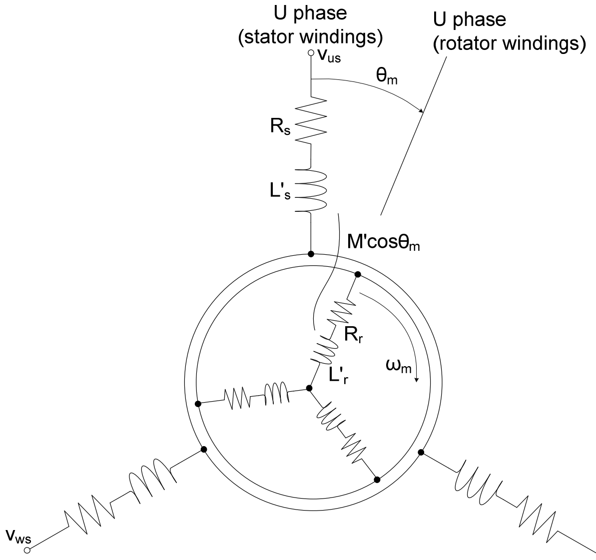

Figure 2.1 Overview of Three Phase Induction Motor

$$\begin{pmatrix} v_{us} \\ v_{vs} \\ v_{ws} \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + PL_s' & -P\frac{M'}{2} & -P\frac{M'}{2} & PM'\cos\theta_m & PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) & PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) \\ -P\frac{M'}{2} & R_s + PL_s' & -P\frac{M'}{2} & PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) & PM'\cos\theta_m & PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) \\ -P\frac{M'}{2} & -P\frac{M'}{2} & R_s + PL_s' & PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) & PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) & PM'\cos\theta_m \\ PM'\cos\theta_m & PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) & PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) & R_r + PL_r' & -P\frac{M'}{2} & -P\frac{M'}{2} \\ PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) & PM'\cos\theta_m & PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) & -P\frac{M'}{2} & R_r + PL_r' & -P\frac{M'}{2} \\ PM'\cos\left(\theta_m - \frac{2\pi}{3}\right) & PM'\cos\left(\theta_m + \frac{2\pi}{3}\right) & PM'\cos\theta_m & -P\frac{M'}{2} & -P\frac{M'}{2} & R_r + PL_r' \end{pmatrix} \begin{pmatrix} i_{us} \\ i_{vs} \\ i_{ws} \\ i_{ur} \\ i_{vr} \\ i_{wr} \end{pmatrix} \quad \text{... (1)}$$

$$L_s' = l_s + M', \quad L_r' = l_r + M'$$

v_u, v_v, v_w : Stator voltages for each phase

i_{us}, i_{vs}, i_{ws} : Stator currents for each phase

i_{ur}, i_{vr}, i_{wr} : Rotor currents for each phase

R_s : Stator winding resistance

R_r : Rotor winding resistance

P : Differential operator

θ_m : Angle from the U phase stator windings to the U phase rotator windings

L_s': Stator winding self inductance

L_r': Rotor winding self inductance

l_s : Stator winding leakage inductance

l_r : Rotor winding leakage inductance

M': Mutual inductance between windings

2.2 Motor Control System Voltage Equations

2.2.1 αβ Transformation

Here, a coordinate transformation is performed on the voltage equations for the three phases to express them as two phases DC.

First, to express these as two phases DC, the following transformation matrix is used to perform an αβ transformation.

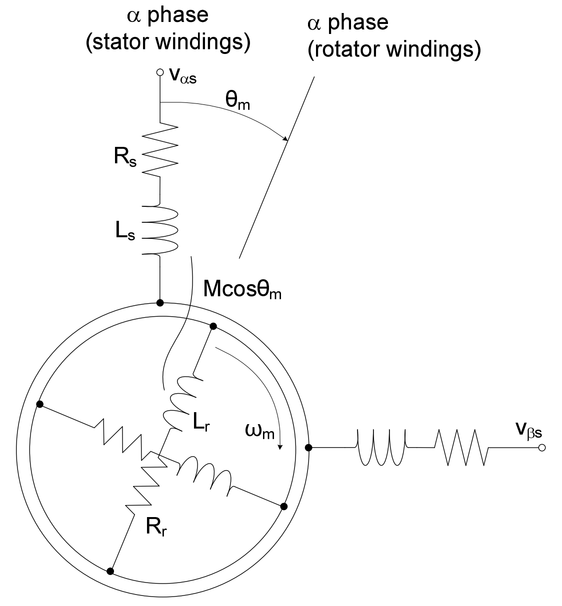

Figure 2.2 αβ Transformation Overview

$$C=\sqrt{\frac{2}{3}}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & 0 & 0 & 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \quad \text{...(2)}$$

The αβ transformation allows the three phase induction motor voltage equations to be expressed in the αβ coordinate system as shown below.

$$\begin{pmatrix} v_{\alpha s} \\ v_{\beta s} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s+PL_s & 0 & PM\cos\theta_m & -PM\sin\theta_m \\ 0 & R_s+PL_s & PM\sin\theta_m & PM\cos\theta_m \\ PM\cos\theta_m & PM\sin\theta_m & R_r+PL_r & 0 \\ -PM\sin\theta_m & PM\cos\theta_m & 0 & R_r+PL_r \end{pmatrix} \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{pmatrix} \quad \text{... (3)}$$

$$L_s = l_s + M\,,\quad L_r = l_r + M\,,\quad M = \frac{3}{2}M'$$

v_α , v_β : Stator voltages for each phase

$i_{\alpha s}, i_{\beta s}$: Stator currents for each phase

$i_{\alpha r}, i_{\beta r}$: Rotor currents for each phase

L_s : Stator winding inductance

L_r : Rotor winding inductance

M : Mutual inductance between windings

2.2.2 dq Transformation

A dq transformation is performed and the following transformation matrix is used to express the result in a fixed orthogonal coordinate system. The d axis can be taken to be anywhere, but here the u phase (α phase) is used.

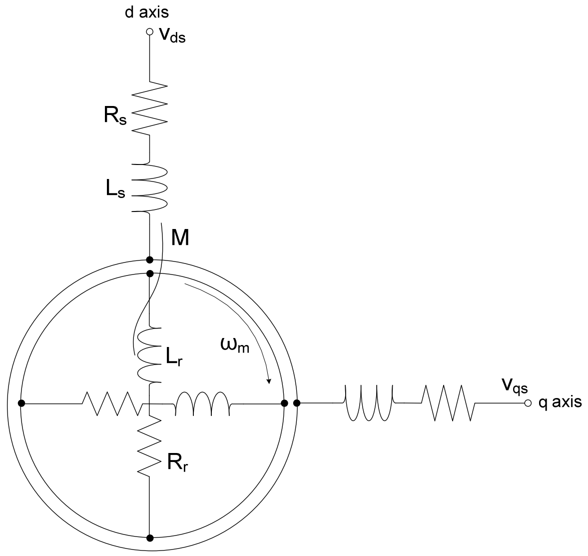

Figure 2.3 dq Transformation Overview

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\theta_m & -\sin\theta_m \\ 0 & 0 & \sin\theta_m & \cos\theta_m \end{pmatrix} \quad \text{... (4)}$$

The dq transformation allows the three phase induction motor voltage equations to be expressed in the dq coordinate system as shown below.

$$\begin{pmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + PL_s & 0 & PM & 0 \\ 0 & R_s + PL_s & 0 & PM \\ PM & \omega_m M & R_r + PL_r & \omega_m L_r \\ -\omega_m M & PM & -\omega_m L_r & R_r + PL_r \end{pmatrix} \begin{pmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{pmatrix} \quad \text{... (5)}$$

v_{ds}, v_{qs} : Stator voltages for each phase

i_{dr}, i_{qr} : Rotor currents for each phase

i_{ds}, i_{qs} : Stator currents for each phase

ω_m : Stator angular speed

2.2.3 γδ Transformation

A γδ transformation is performed and the following transformation matrix is used to express the result as two phases DC.

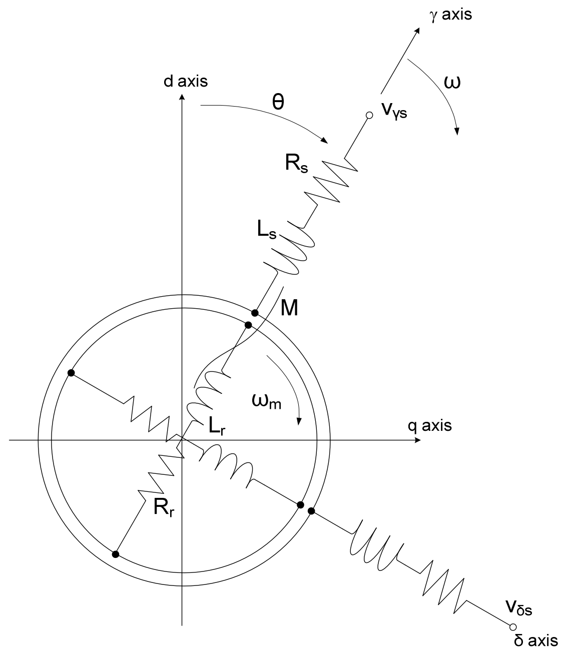

Figure 2.4 γδ Transformation Overview

$$C = \begin{pmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \end{pmatrix} \quad \text{... (6)}$$

θ : Angle from the d axis to the γ axis.

The γδ transformation allows the three phases induction motor voltage equations to be expressed in the γδ coordinate system as shown below.

$$\begin{pmatrix} v_{\gamma s} \\ v_{\delta s} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + PL_s & -\omega L_s & PM & -\omega M \\ \omega L_s & R_s + PL_s & \omega M & PM \\ PM & -(\omega - \omega_m)M & R_r + PL_r & -(\omega - \omega_m)L_r \\ (\omega - \omega_m)M & PM & (\omega - \omega_m)L_r & R_r + PL_r \end{pmatrix} \begin{pmatrix} i_{\gamma s} \\ i_{\delta s} \\ i_{\gamma r} \\ i_{\delta r} \end{pmatrix} \quad \text{... (7)}$$

$v_{\gamma s}, v_{\delta s}$: Stator voltages for each phase $i_{\gamma r}, i_{\delta r}$: Rotor currents for each phase

$i_{\gamma s}, i_{\delta s}$: Stator currents for each phase ω : Angular frequency of the current

As shown above, the three phase currents flowing in the stator and rotor can be expressed as two phases DC by viewing them from a coordinate system that is rotating at angular speed ω.

2.2.4 Expressions Based on the Rotor Interlinkage Flux

When the rotor interlinkage flux is used instead of the rotor current in equation (7), the equations become as follows.

$$\begin{pmatrix} v_{\gamma s} \\ v_{\delta s} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_s + PL_\sigma & -\omega L_\sigma & P\dfrac{M}{L_r} & -\omega\dfrac{M}{L_r} \\ \omega L_\sigma & R_s + PL_\sigma & \omega\dfrac{M}{L_r} & P\dfrac{M}{L_r} \\ -R_r\dfrac{M}{L_r} & 0 & \dfrac{R_r}{L_r} + P & -\omega_s \\ 0 & -R_r\dfrac{M}{L_r} & \omega_s & \dfrac{R_r}{L_r} + P \end{pmatrix} \begin{pmatrix} i_{\gamma s} \\ i_{\delta s} \\ \phi_{\gamma r} \\ \phi_{\delta r} \end{pmatrix}$$

... (8)

$$\phi_{\gamma r} = Mi_{\gamma s} + L_r i_{\gamma r}, \quad \phi_{\delta r} = Mi_{\delta s} + L_r i_{\delta r}, \quad L_\sigma = L_s - \frac{M^2}{L_r}, \quad \omega_s = \omega - \omega_m$$

$\phi_{\gamma r}, \phi_{\delta r}$: Rotor interlinkage flux for each phase ω_s : Slip frequency

2.2.5 Torque

The magnitude of the torque can be expressed as shown below by the rotor current and rotor flux due to the stator current.

$$T = P_n \frac{M}{L_r}\left(\phi_{\gamma r} i_{\delta s} - \phi_{\delta r} i_{\gamma s}\right)$$

... (9)

T : Motor torque P_n : Number of poles

3. Indirect Vector Control

3.1 Vector Control of Three Phase Induction Motor

Vector control is a method in which the flux and generated torque are controlled by independently currents that flow perpendicularly to the flux and current that generates the rotor flux. When we take as a premise that the rotor flux will be controlled so that it is held constant, it is necessary to detect the rotor flux. Here, there are two techniques: direct vector control, in which a flux sensor is directly attached to detect the flux, and indirect vector control (which is used in this sample program) in which the flux is calculated from the detected values of the terminal voltages, currents, and rotational speed.

3.2 Principles of Indirect Vector Control

In indirect vector control, the torque and rotor interlinkage flux are taken to be the objects of control, and current control is substituted for the control of the two parameters.

When the torque can be determined from equation (9) as shown below when the rotor interlinkage flux is defined so that it matches the γ axis.

$$\phi_{\gamma r} = \phi_r \qquad \phi_{\delta r} = 0 \qquad \text{... (10)}$$

$$T = P_n \frac{M}{L_r} \phi_r i_{\delta s} \qquad \text{... (11)}$$

Also, the rotor interlinkage flux can be determined from equation (8) as shown below.

$$\phi_r = \frac{M}{1+PT_r} i_{\gamma s} \qquad \text{... (12)}$$

$T_r = \frac{L_r}{R_r}$: Rotor time constant

Using the above, the torque and the rotor interlinkage flux can be controlled by controlling the stator current.

Furthermore, the slip angular frequency can be determined from equations (8) and (12) as shown below.

$$\omega_s = \frac{M}{T_r \phi_r} i_{\delta s} = \frac{i_{\delta s}}{T_r \left(\frac{1}{1+PT_r} \right) i_{\gamma s}} \qquad \text{... (13)}$$

The γ axis angle, which is the direction of the rotor interlinkage flux, can be determined by integrating the sum of the slip angular frequency and the rotor angular frequency.

This method is called indirect vector control since the γ axis angle is determined indirectly from the slip frequency. It is also called slip frequency control.

3.3 Speed Sensorless Vector Control

When vector control is used without a speed sensor, it is necessary to infer the speed by some method. While there are a variety of methods for inferring the speed, this application note presents a method based on voltage control.

If the rotor interlinkage flux is fixed, the slip angular frequency has a proportional relationship with the torque current as shown in equation (13). This means that vector control is possible by controlling the stator angular frequency so that the torque value and that control value match.

$$\omega_s = \frac{i_{\delta s}}{T_r\left(\dfrac{1}{1+PT_r}\right)i_{\gamma s}} = K_s i_{\delta s} \qquad \text{... (14)}$$

K_s : Constant

The rotor angular frequency can be determined by subtracting the slip angular frequency from the stator angular frequency as shown below.

$$\omega_m = \omega - \omega_s \qquad \text{... (15)}$$

The conversion from control current to control voltage is performed using equation (8) as shown below.

$$\begin{aligned} v_{\gamma s} &= R_s i_{\gamma s} - \omega L_\sigma i_{\delta s} \\ v_{\delta s} &= R_s i_{\delta s} + \omega L_s i_{\gamma s} \end{aligned} \qquad \text{... (16)}$$

If the detected torque current and command current do not match when this voltage is applied, it means that the γ axis does not match the rotor interlinkage flux direction. Here, the γ axis phase can be taken to be the integral over time of the result of PI amplification of that error.

The figure below shows the block diagram for the flow of control in this control method.

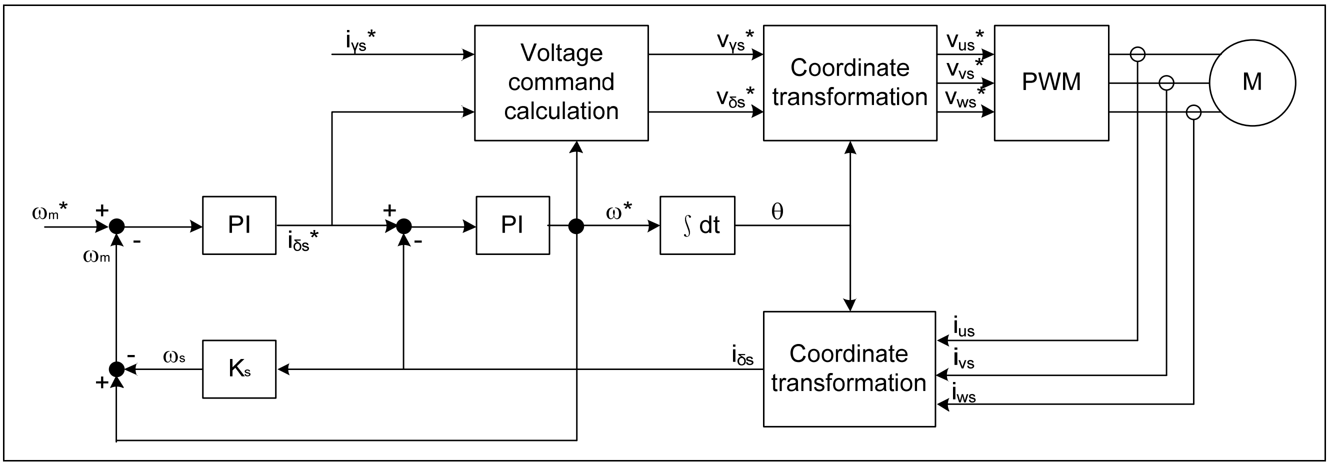

Figure 3.1 Speed Sensorless Vector Control Flowchart

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Revision History

Rev.	Date	Description	
		Page	Summary
1.00	Sep 05, 2014	—	First edition issued

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