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Motor Control Application

Vector Control for Permanent Magnet Synchronous Motor with Encoder (Algorithm)

Summary

This application note explains the position and speed control algorithm, using vector control method, for permanent magnet synchronous motors (PMSM) with encoder. The software implementation of the algorithm is for Renesas Electronics Corporation's microcontroller.

Contents

1. Overview

This application note explains the position and speed control algorithm, using vector control method, for permanent magnet synchronous motors (PMSM) with encoder. The software implementation of the algorithm is for Renesas Electronics Corporation's microcontroller.

2. PMSM Fundamental Equation

2.1 PMSM model in Three-Phase (U, V, W) Coordinate

Voltage equation of the permanent magnet synchronous motor (Figure 2-1) having the sinusoidal magnetic flux distribution, can be expressed as follows.

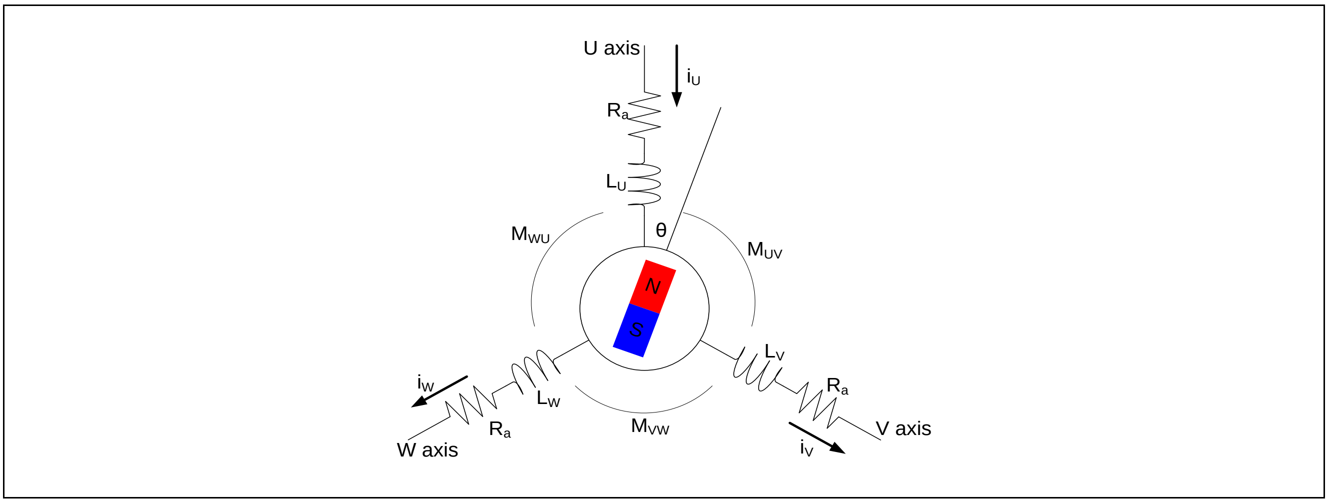


Figure 2-1 Conceptual Diagram of Three-phase Permanent Magnet Synchronous Motor

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = R_a \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} + p \begin{bmatrix} \phi_u \\ \phi_v \\ \phi_w \end{bmatrix}$$

$$\begin{bmatrix} \phi_u \\ \phi_v \\ \phi_w \end{bmatrix} = \begin{bmatrix} L_u & M_{uv} & M_{wu} \\ M_{uv} & L_v & M_{vw} \\ M_{wu} & M_{vw} & L_w \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} + \psi \begin{bmatrix} cos\theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix}$$

v_u, v_v, v_w : Stator phase voltage

i_u, i_v, i_w : Stator phase current

ϕ_u, ϕ_v, ϕ_w : Stator phase interlinkage flux

R_a : Stator phase resistance

p : Differential operator

L_u, L_v, L_w : Stator phase self-inductance

M_{uv}, M_{vw}, M_{wu} : Mutual inductance

ψ : Maximum flux linkage due to permanent magnet

θ : Rotor electrical angle from Phase U

2.2 PMSM Model in Direct-Quadrature (d, q) Coordinate

Vector control is a method to control the motor in the two-phase (d, q) coordinate system, instead of three-phase (u, v, w) coordinate system.

The d-axis is set in the direction of the magnetic flux (N pole) of the permanent magnet and the q-axis is set in the direction which progresses by 90 degrees (electrical) in the forward direction of the angle θ from the d-axis.

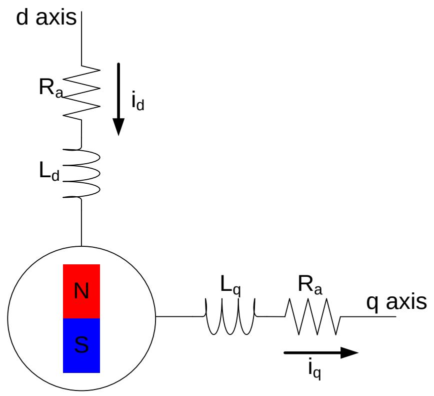


Figure 2-2 Conceptual Diagram of the Two-phase Direct Current Motor

The coordinate transformation is performed by the following transformation matrix.

$$C = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = C\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix}$$

The voltage equation in the two-phase (d, q) coordinate system is obtained as following.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi_a \end{bmatrix}$$

v_d, v_q : d-axis and q-axis voltage

i_d, i_q : d-axis and q-axis current

R_a : Stator phase resistance

ω : Angular Speed

L_d, L_q : d-axis and q-axis inductance

$$L_d = l_a + \frac{3(L_a - L_{as})}{2}, L_q = l_a + \frac{3(L_a + L_{as})}{2}$$

ψ_a : Flux linkage due to permanent magnet

$$\psi_a = \sqrt{\frac{3}{2}}\psi$$

Based on this, it can be considered that alternate current flowing in the stationary three-phase stator is equivalent to direct current flowing in the two-phase stator rotating synchronously with the permanent magnet operating as a rotor.

The torque generated can be written in the form of exterior product of the electric current vector and armature inter-linkage magnetic flux, as given bellow. The first term on the right side of this formula is called magnet torque and the second term on the right side of this formula is the reluctance torque.

$$T = P_n\left\{\psi_a i_q + \left(L_d - L_q\right) i_d i_q\right\}$$

T : Motor torque P_n : Number of pole pairs

The PMSM which has no difference between the d-axis and q-axis inductances is defined as non-salient PMSM. In this case, as the reluctance torque is 0, the total torque is proportional to the q-axis current. Due to this, the q-axis current is called torque current. In two phase (d, q) coordinate system the d-axis flux is sum of permanent magnet flux and flux generated by d-axis current. Since the equivalent rotating stator flux (in three-phase (u, v, w) coordinate system) is controlled by d-axis current, the d-axis current is called as excitation current.

3. Control System Design

3.1 Vector Control System and The Controller

The block diagram of position control system, using vector control method is shown in Figure3-1.

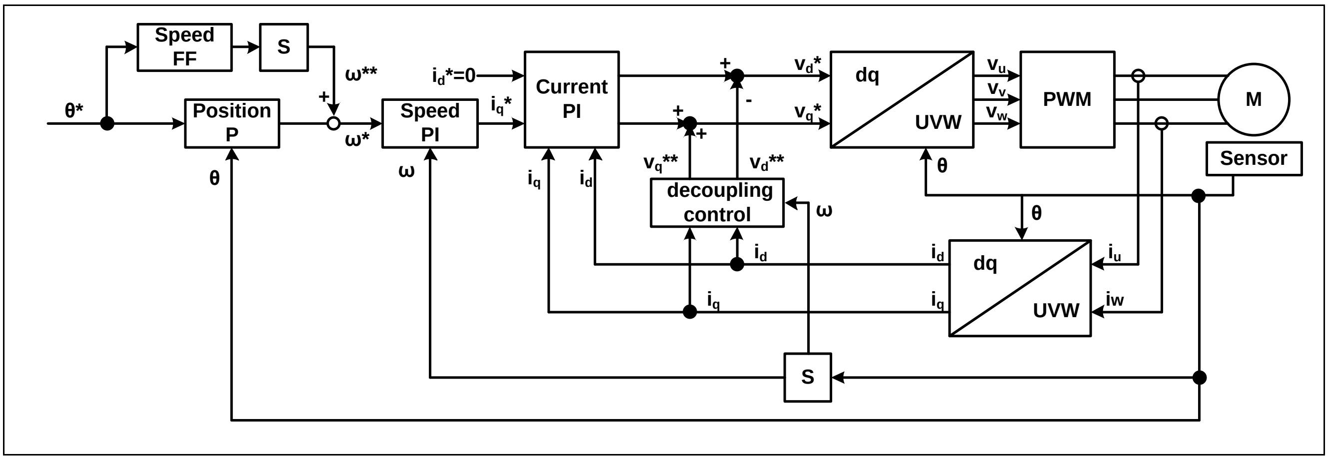


Figure 3-1 Vector Control System Block (Position Control)

As shown in Figure 3-1, this system consists of the position control system, the speed control system and the current control system. Speed and current control system use general PI controller. Position control system use P controller and speed feed-forward controller. These controller gains of each system must be designed properly to realize required control characteristics.

In decoupling control block, v_d^{**}, v_q^{**}(as the following equations) are calculated and then added to voltage command value. This realizes the high response of speed control system and enables to control the d-axis and q-axis independently.

$$v_d^{**} = -\omega L_d i_q$$

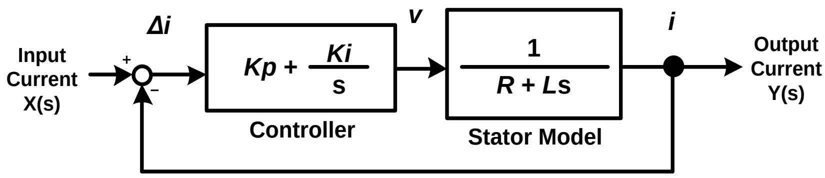
$$v_q^{**} = \omega(L_d i_d + \psi_a)$$

3.2 Current Control System

3.2.1 Design of Current Control System

The current control system is modeled by using the electrical characteristics of the motor. The stator coil can be represented by a resistance R and an inductance L. So the stator model of the motor is expressed by the transfer function of the typical RL series circuit $\frac{1}{R+Ls}$.

The current control system model can be represented by a feedback control system using PI control. (Figure 3-2)



R: Resistance of stator coils[Ω] L: Inductance of stator coils[H]

K_p: Proportional gain of the current PI control K_i: Integral gain of the current PI control

Figure 3-2 Current Control System Model

Based on this model, PI gains of the current control system are designed as the following method.

First, the closed-loop transfer function of this system is obtained as follows.

$$G(s) = \frac{Y(s)}{X(s)} = \frac{\frac{K_a}{K_b} * \left(1 + \frac{s}{a}\right)}{s^2 + \frac{1}{K_b}(1 + \frac{K_a}{a})s + \frac{K_a}{K_b}}$$

$$K_i = K_p * a, \quad K_a = \frac{K_p a}{R}, \quad K_b = \frac{L}{R}$$

The general equation of second-order lag system with zero point can be expressed as follows.

$$\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \cdot \left(1 + \frac{s}{\omega_z}\right)$$

By comparing coefficients of two equations above, the following equations are obtained.

$$\frac{\omega_n^2\left(1+\frac{s}{\omega_z}\right)}{s^2+2\zeta\omega_n s+\omega_n^2} \Leftrightarrow \frac{\frac{K_a}{K_b}*\left(1+\frac{s}{a}\right)}{s^2+\frac{1}{K_b}(1+\frac{K_a}{a})s+\frac{K_a}{K_b}}$$

$$\omega_n^2=\frac{K_a}{K_b}, \qquad 2\zeta\omega_n=\frac{1}{K_b}\left(1+\frac{K_a}{a}\right), \qquad \omega_z=a$$

From above equations, natural frequency ω_n, damping ratio ζ, zero-point frequency ω_z are written as follows.

$$\omega_n=\sqrt{\frac{K_a}{K_b}}, \qquad \zeta=\frac{1}{2K_b\sqrt{\frac{K_a}{K_b}}}(1+\frac{K_a}{a}), \qquad \omega_z=a=\frac{\omega_n^2 L}{2\zeta\omega_n L-R}$$

Current PI control gains ($K_{p\_current}$, $K_{i\_current}$) are written as the following equations.

$$K_{p\_current}=2\zeta_{CG}\omega_{CG}L-R, \qquad K_{i\_current}=K_{p\_current}a=\omega_{CG}^2 L$$

ω_{CG}: Desired natural frequency of current control system

ζ_{CG}: Desired damping ratio of current control system

Therefore, PI control gains of the current control system can be designed by ω_{CG} and ζ_{CG}.

3.3 Speed Control System

3.3.1 Design of Speed control system

The speed control system is modeled by using the mechanical characteristics of the motor. The mechanical system torque equation is written as follows.

$$T = J\dot{\omega}_{mech}$$

J : Inertia of rotor, ω_{mech}:Speed(Mechanical)

In consideration of only magnet torque, the electrical system torque equation is written as follows.

$$T = P_n \psi_a i_q$$

By using the mechanical and electrical torque equation, the speed (mechanical) is written as follows.

$$\omega_{mech} = \frac{P_n \psi_a}{sJ} i_q$$

The speed in the sample software is treated as the electrical speed. Thereby, the number of pole pairs P_n is multiplied to both sides of this equation.

$$\omega_{elec} = \frac{{P_n}^2 \psi_a}{sJ} i_q$$

ω_{elec}: Speed(Electrical)

The speed control system model can be represented by a feedback control system using PI control. (Figure 3-3)

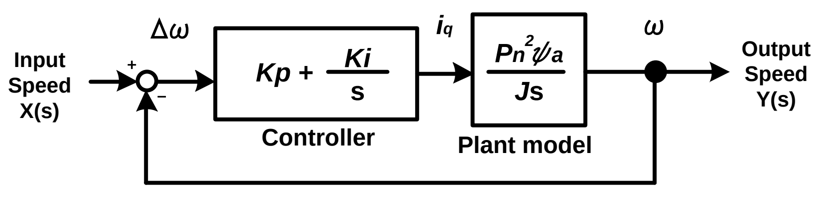


Figure 3-3 Speed Control System Model

Based on this model, PI gains of the current control system are designed as the following method.

First, the closed-loop transfer function of this system is obtained as follows.

$$G(s) = \frac{Y(s)}{X(s)} = \frac{K_b a * \left(1 + \frac{s}{a}\right)}{s^2 + K_b s + K_b a}$$

$$K_b = \frac{K_P {P_n}^2 \psi}{J} \qquad K_i = K_p * a$$

The general equation of second-order lag system with zero point can be expressed as follows.

$$\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \cdot \left(1 + \frac{s}{\omega_z}\right)$$

Similar to the current control system, by comparing coefficients of two equations above, the following equations are obtained.

$$\frac{\omega_n^2 (1 + s/\omega_z)}{s^2 + 2\zeta\omega_n s + \omega_n^2} \Leftrightarrow \frac{a K_b * \left(1 + \frac{s}{a}\right)}{s^2 + K_b s + a K_b}$$

$$\omega_n^2 = a K_b = \frac{K_p a {P_n}^2 \psi_a}{J}, \qquad 2\zeta\omega_n = K_b = \frac{K_p {P_n}^2 \psi_a}{J}, \qquad \omega_z = a$$

From above equations, natural frequency ω_n, damping ratio ζ, zero point frequency ω_z are written as follows.

$$\omega_n = \sqrt{\frac{K_p a {P_n}^2 \psi_a}{J}}, \qquad \zeta = \frac{1}{2}\sqrt{\frac{K_p {P_n}^2 \psi_a}{aJ}}, \qquad \omega_z = a = \frac{\omega_n}{2\zeta}$$

Speed PI control gains (K_{p_speed}, K_{i_speed}) are written as the following equations.

$$K_{p\_speed} = \frac{2\zeta_{SG}\omega_{SG} J}{{P_n}^2 \psi_a}, \qquad K_{i\_speed} = K_{p\_speed} * a = \frac{\omega_{SG}^2 J}{{P_n}^2 \psi_a}$$

ω_{SG}: Desired natural frequency of speed control system

ζ_{SG}: Desired damping ratio of speed control system

Therefore, PI control gains of the speed control system can be designed by ω_{SG} and ζ_{SG}.

3.4 Position Control System

3.4.1 Design of Position Control System

The position control system consists of proportional term. However, responsiveness of the proportional control is not quick, to a high rate of change of the input command value (position value). To improve the responsiveness of control the feed forward part is included in the system.

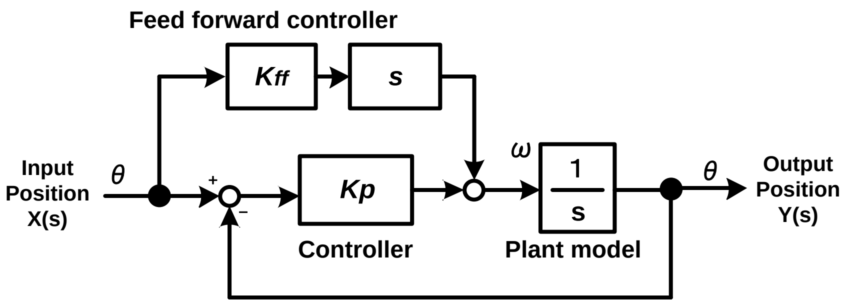


Figure 3-4 Position Control System Model

The proportion control gain term $K_{p\_position}$ for position control system, is given as natural frequency of position control system (ω_{PG}).

$$\omega = K_{p\_position} * (\theta_{ref} - \theta)$$

$$K_{p\_position} = \omega_{PG}$$

To improve the speed response, implement feedforward control of the speed command value.

$$\omega_{ff} = \mathrm{K}_{\mathrm{ff\_speed}}\,\dot{\theta}_{ref}$$

The P gain of the position control system can be designed by ω_n.

4. Control Module of Position and Speed Control

4.1 Speed Observer

In position/ velocity control using a low-resolution encoder (about few thousands [ppr]), speed ripple appears due to quantization error at low-speed. Increasing the control gain to obtain faster response will cause larger speed ripple, and the speed ripple appears as mechanic vibration and sound. So, the stability suffers due to the vibration.

The speed observer is implemented as a method to reduce the speed ripple by software implementation of speed estimation algorithm.

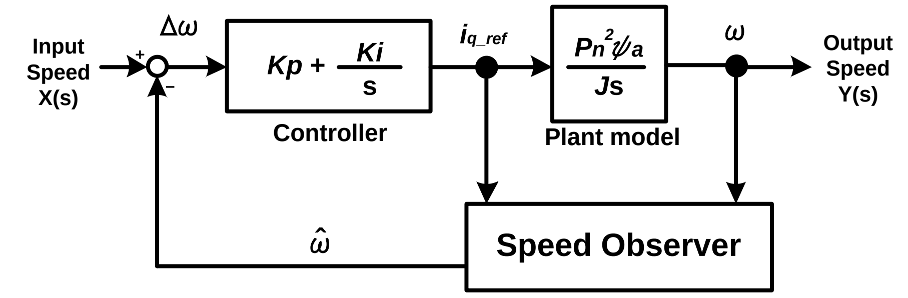


Figure 4-1 Speed observer model

The speed observer using q-axis current command value i_{q_ref} and the speed ω as inputs to estimate speed $\hat{\omega}$. By using the speed observer, speed ripple can be reduced, and it is less likely to affect the control system compared to normal low-pass filter.

4.2 IPD Controller

In the position control system with low position and velocity resolution, since the position control system cannot respond to changes that are too small, vibration occurs continually during positioning. To suppress the vibration, an integrator is required to accumulates minute changes and keep the steady-state deviation to zero.

In IPD controller, only the integrator uses the position error as input. Proportional and derivative terms only work on control input. This can improve responsiveness while reducing the vibration during positioning.

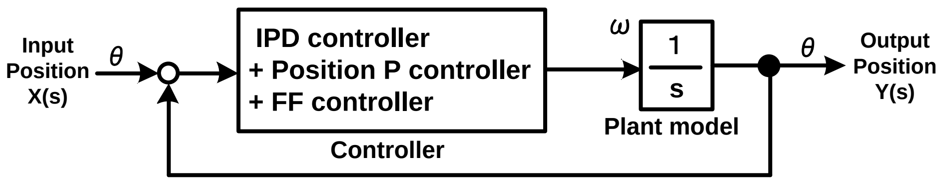


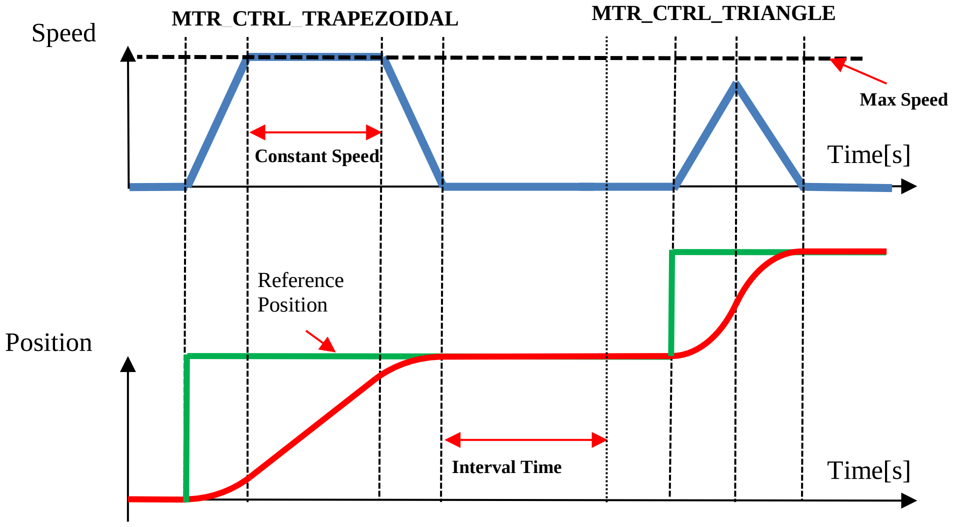
Figure 4-2 IPD controller model

In the implementation, an IPD controller is composed of a normal proportional controller and a feed-forward controller.

4.3 Position Profile Generation

(Position profile of trapezoidal curve for speed command value)

In vector control software for PMSM with encoder, the position profile is used as input command value (position value). The implementation of position profile is used as method of managing acceleration and the maximum speed value with respect to target position value.



MTR_CTRL_TRIANGLE :Max Speed * Acceleration Time >= Position Error

MTR_CTRL_TRAPEZOIDAL :Max speed * Acceleration Time < Position Error

Figure 4-3 Position Profile Generation

4.4 Switching Between Position/Speed Calculation Methods

As a method of calculating position/ speed from the encoder signal, it is popular to count the edges of the signal. However, with a low-resolution encoder, since the interval between two encoder pulses is larger than the control cycle, accuracy of speed calculation at low speed suffers. Because of this, a method calculating speed at low-speed is implemented. The method measures the pulse interval with a free-run timer, and calculates speed and position by the pulse interval in interrupt generated by the encoder signal.

On the other hand, with a high-resolution encoder, high speed rotation increase the number of interrupt occurrences within one control cycle, and the dramatically increasing CPU usage may cause breakdown of control.

To prevent this, if the speed becomes higher than a specified threshold, the speed calculation method is switched from the method that calculate speed in encoder signal interrupt, to the method that calculate speed in carrier interrupt.

4.4.1 Switching Process

As shown in Figure 4-4, at high speed, method is switched from the calculate speed in encoder signal interrupt, to the method that calculate speed in carrier interrupt.

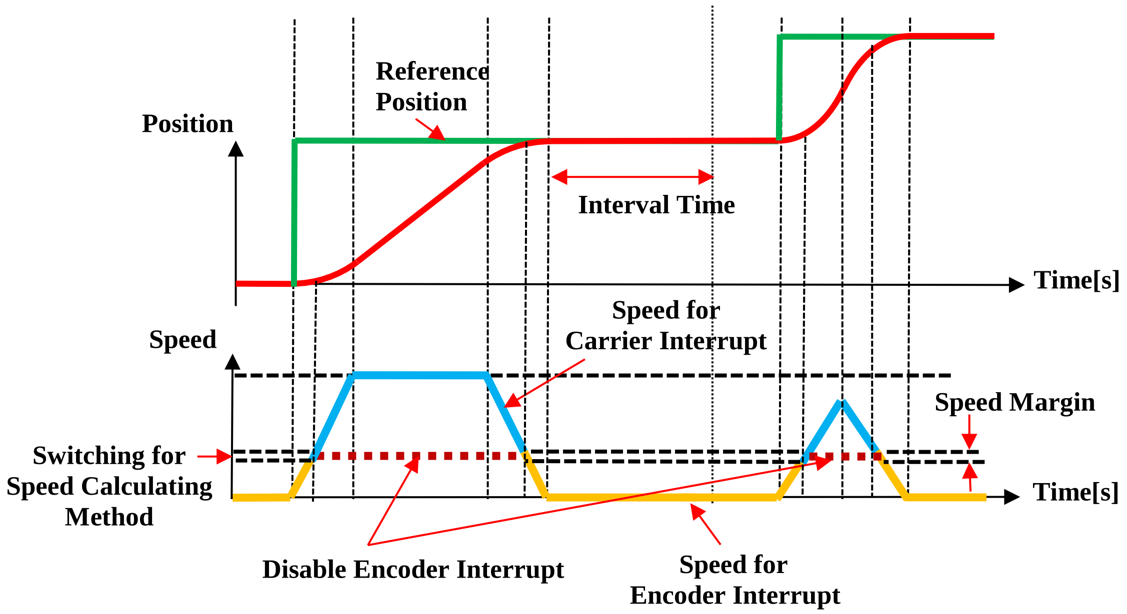


Figure 4-4 Switching Process of Position and Speed Calculation Method

4.5 Position and Speed Calculation Method by Vector Control

In the vector control, the rotor position is required to calculate output voltage. Therefore, position sensors such as encoder, hall sensor, and resolver are used.

4.5.1 Position and Speed Calculation Method Using a Position Sensor

To use an encoder as position sensor, since the absolute position of magnetic poles is not measurable with only the encoder, initial position information must be known before starting driving motor. Following the procedure shown in Figure 4-5, the d-axis is aligned to a specified current vector. The start-up sequence is shown in Figure 4-6.

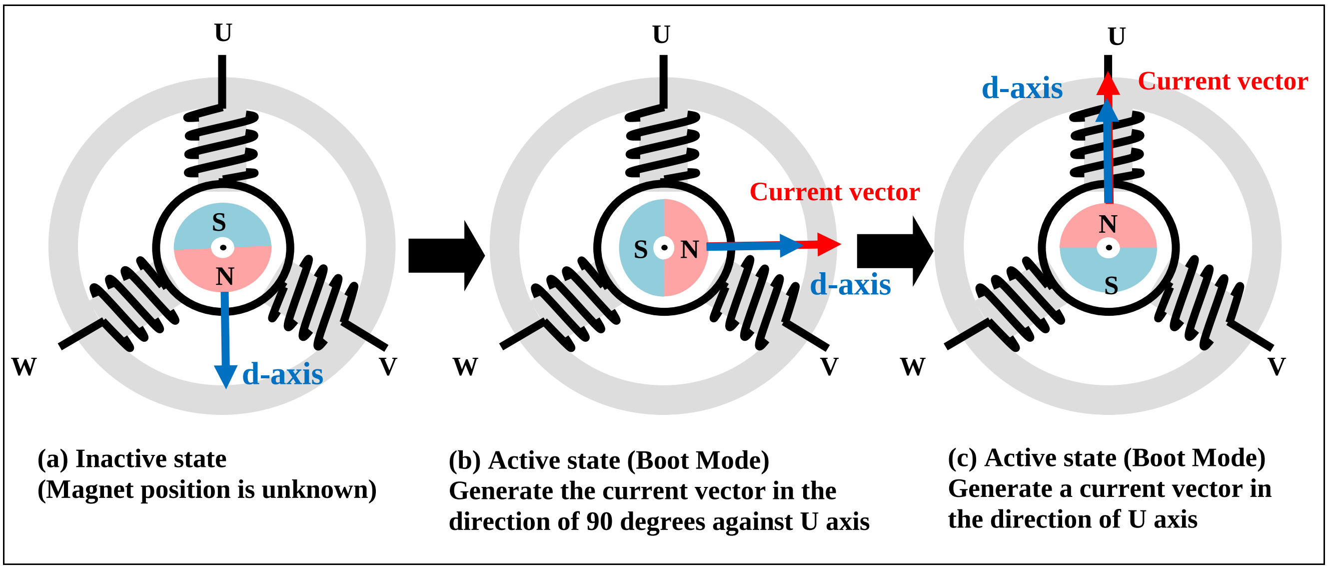


Figure 4-5 Determination of Position of Permanent Magnet

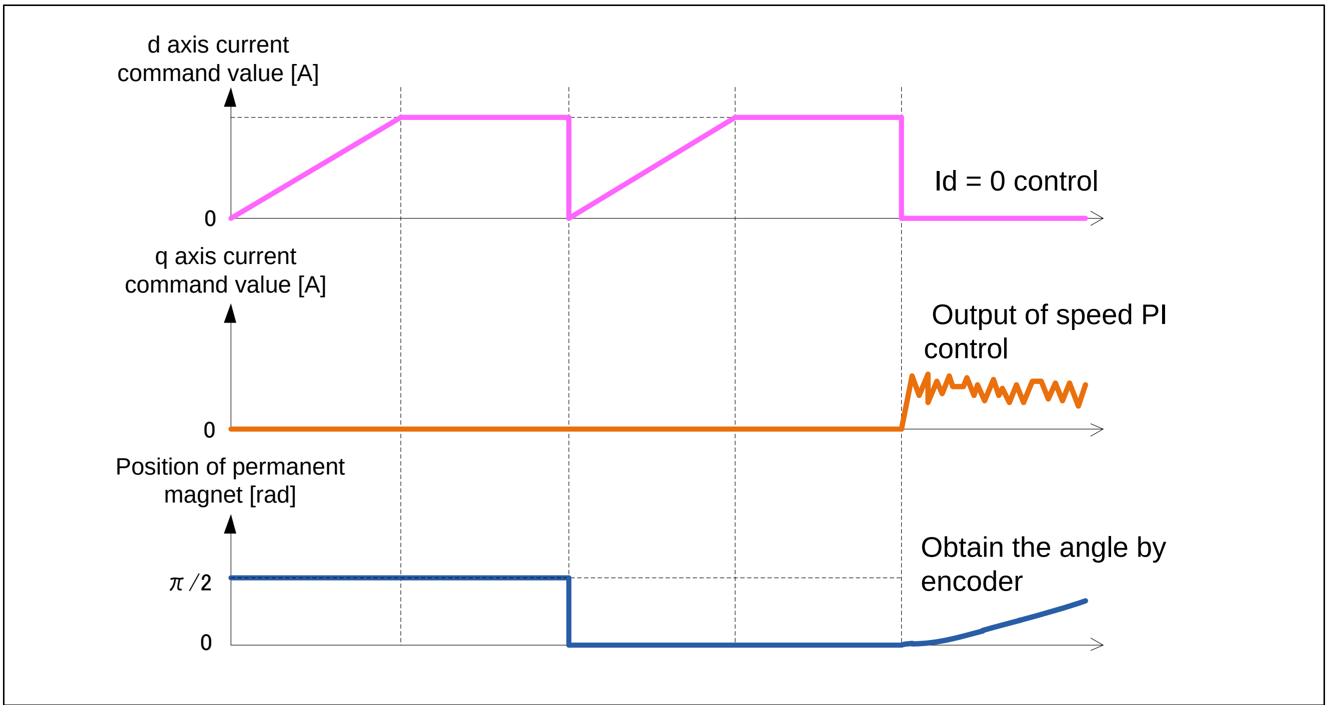


Figure 4-6 Startup Control (Example)

4.5.2 Magnet Position Detection Using Hall Sensor

We can also use both hall sensor and encoder to obtain the position of magnetic pole. Figure 4-7 shows the method to determine the magnetic pole position with Hall sensors.

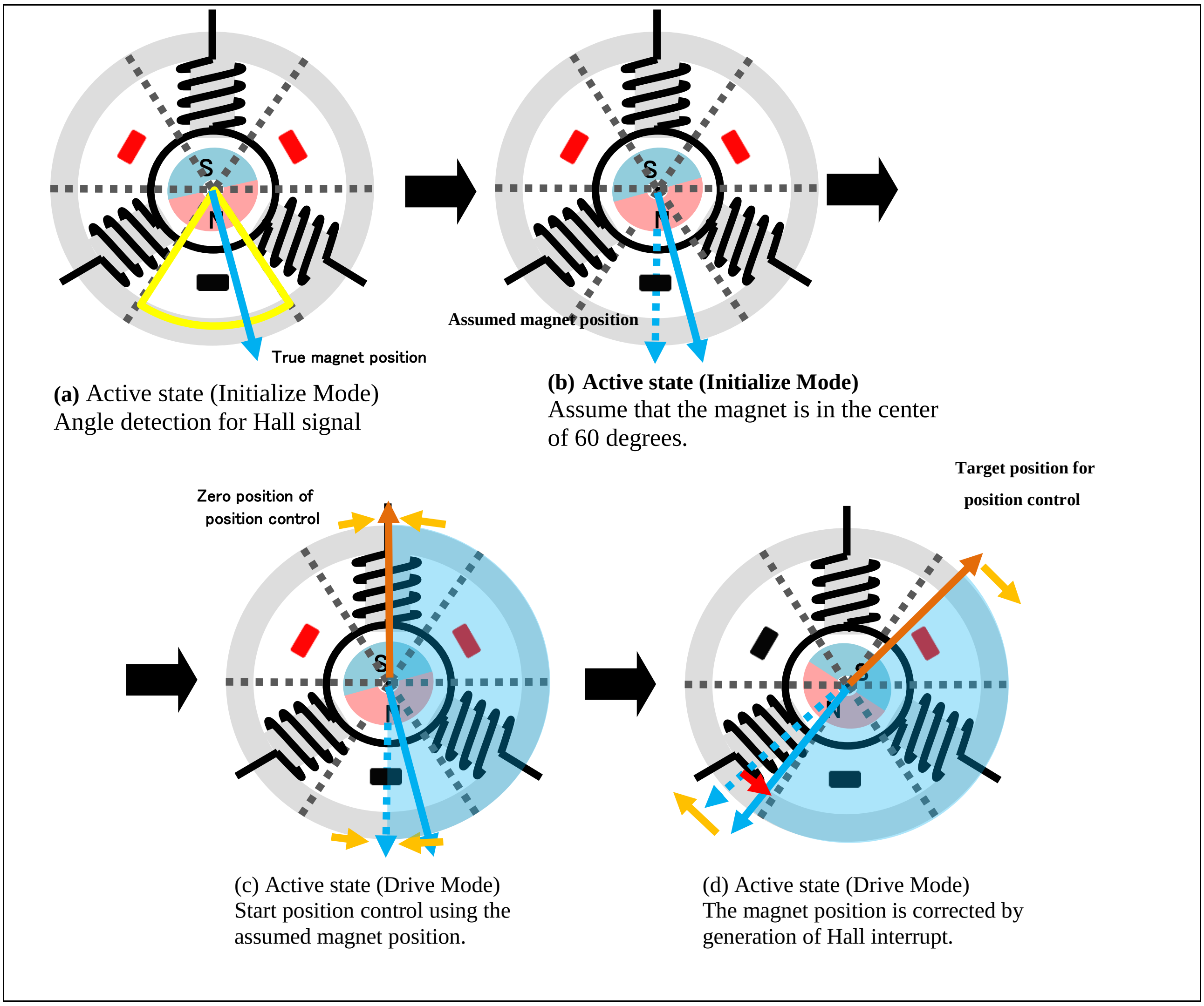


Figure 4-7 Procedure for Detecting Magnet Position

(a) The detection of magnetic pole position, that in which 60-degrees-sector the rotor is positioned, is performed by using six patterns of the Hall sensor signals.

(b) Assume that the initial magnetic pole position is the center of the 60-degrees-sector.

(c) Starting position control.

With the assumption in (b) there is possibility that the assumed initial magnet position deviate by ±30 degree from its correct position, until a Hall interrupt occurs.

(d) Once an edge of hall sensor signal is detected, the angle used in the vector control is corrected to the actual position.

By using Hall sensors, position control can be started without alignment.

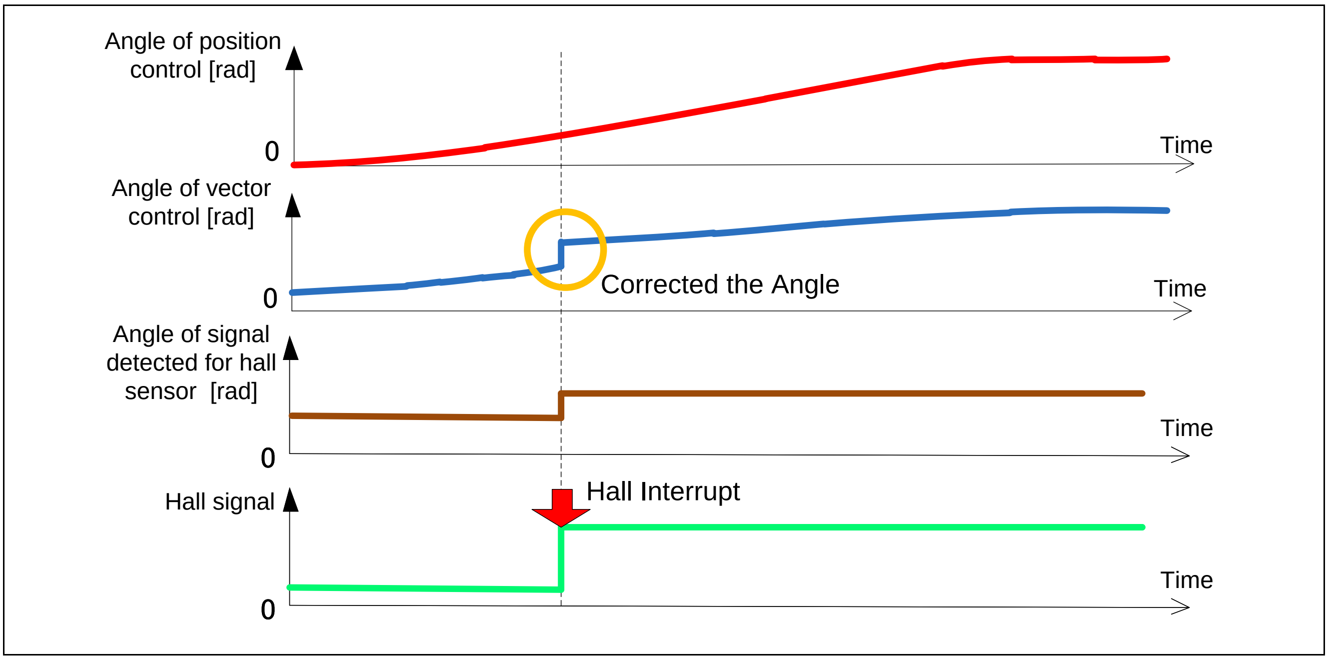
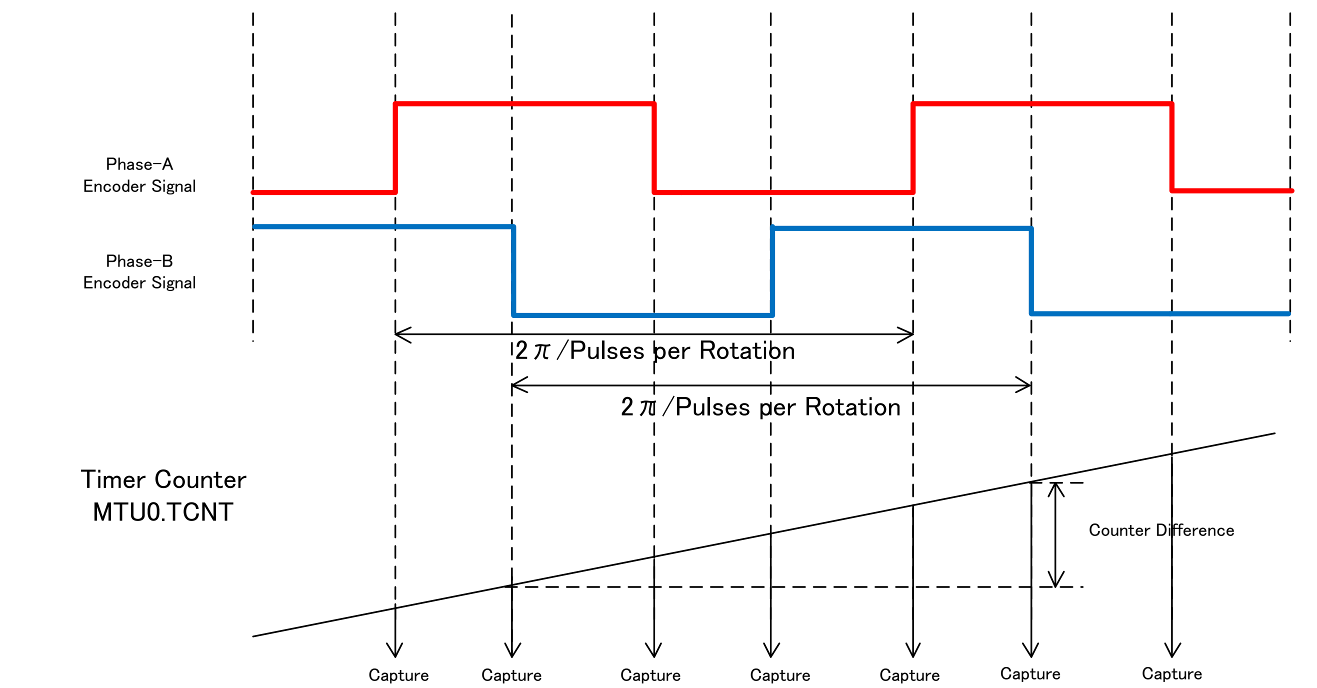


Figure 4-8 Magnet Position Detection Using Hall Sensor

4.5.3 Speed Calculation Using Encoder

Speed calculation using an encoder is explained in Figure 4-.



$$\text{Motor Rotation Speed[rad/s]} = \left(\frac{2\pi}{\text{Pulse Per Rotation}}\right) / \left(\frac{\text{Counter Difference}}{\text{Timer Clock Frequency}}\right)$$

Figure 4-9 Speed Calculation Using Encoder

4.6 Voltage Error Compensation

The 3-phase inverter has dead-time to prevent short circuit between upper and lower arm of switching devices. Therefore the voltage reference and the voltage applied the motor have error. This error causes degradation of control accuracy. The voltage error compensation is implemented to reduce this error.

The voltage error depends on the current (direction and magnitude), the dead-time and the switching device characteristic. The voltage error dependence on phase current is shown in Figure 4-. The voltage error compensation can be realized by adding the voltage opposite to the voltage error, to the voltage reference.

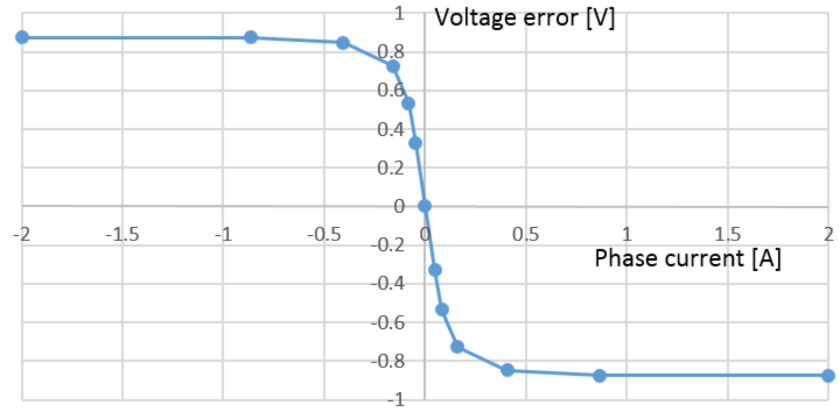


Figure 4-10 Current Dependence of Voltage Error (Example)

4.7 Pulse Width Modulation (PWM)

As a general implementation of the vector control for PMSMs, phase voltage references are generated as sine wave. However, when sine wave voltage reference is used as modulation wave for PWM generation, voltage utilization factor is limited by 86.7 [%]. To increase the voltage utilization factor, the modified three phase voltage reference is used as modulation wave. The modified three phase voltage reference (V_u', V_v', V_w') is calculated by subtracting average value of maximum and minimum from three phase voltage (V_u, V_v, V_w). Then, without changing line-to-line voltage, the maximum amplitude of the modulation wave becomes $\sqrt{3}/2$ times, and as a result the voltage efficiency rate becomes 100[%].

$$\begin{pmatrix} V_u' \\ V_v' \\ V_w' \end{pmatrix} = \begin{pmatrix} V_u \\ V_v \\ V_w \end{pmatrix} + \Delta V \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\because \Delta V = -\frac{V_{max}+V_{min}}{2} \ , \ V_{max} = max\{V_u, V_v, V_w\} \ , \ V_{min} = min\{V_u, V_v, V_w\}$$

V_u, V_v, V_w: U, V, W phase voltage reference

V_u', V_v', V_w': U, V, W phase voltage reference for PWM generation (Modulation wave)

4.8 Encoder Vector Control System Block

Figure 4-9 shows the system block of the encoder vector control system.

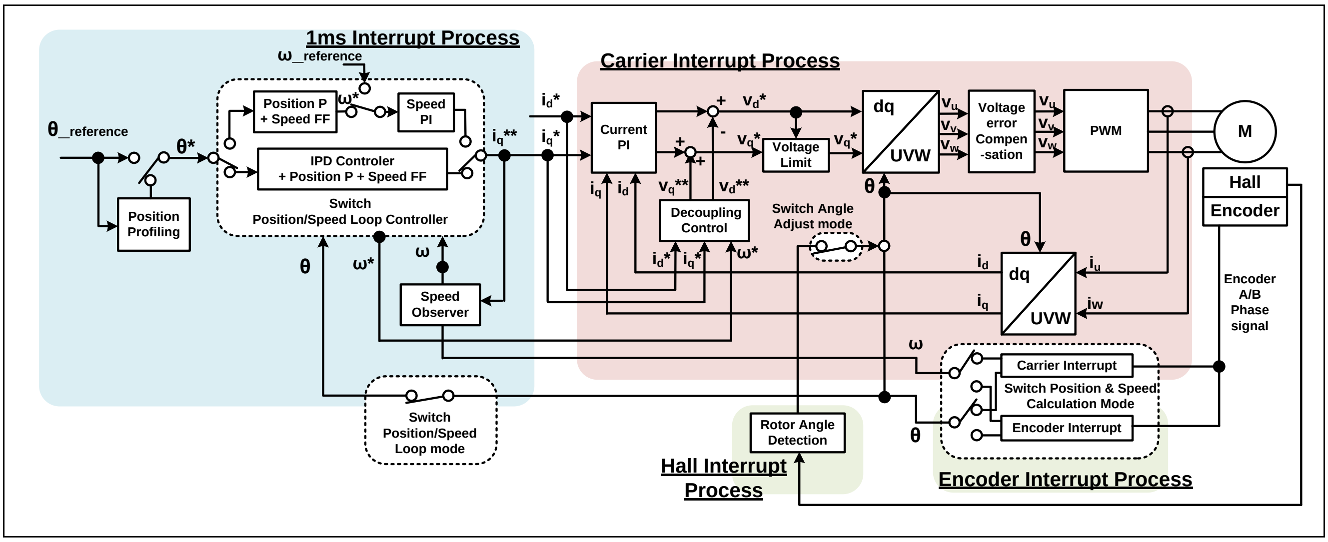


Figure 4-9 System Block of Vector Control with Encoder

4.9 Startup Sequence

Figure 4-10 shows the software implementation of d-axis alignment method. The d-axis alignment method used as startup control of position control method in initialization mode (MTR_MODE_INIT) and Boot mode (MTR_MODE_BOOT). In drive mode (MTR_MODE_DRIVE) vector control is implemented for PMSM with Encoder. Each reference value setting of d-axis current, q-axis current and speed and position is managed by respective status.

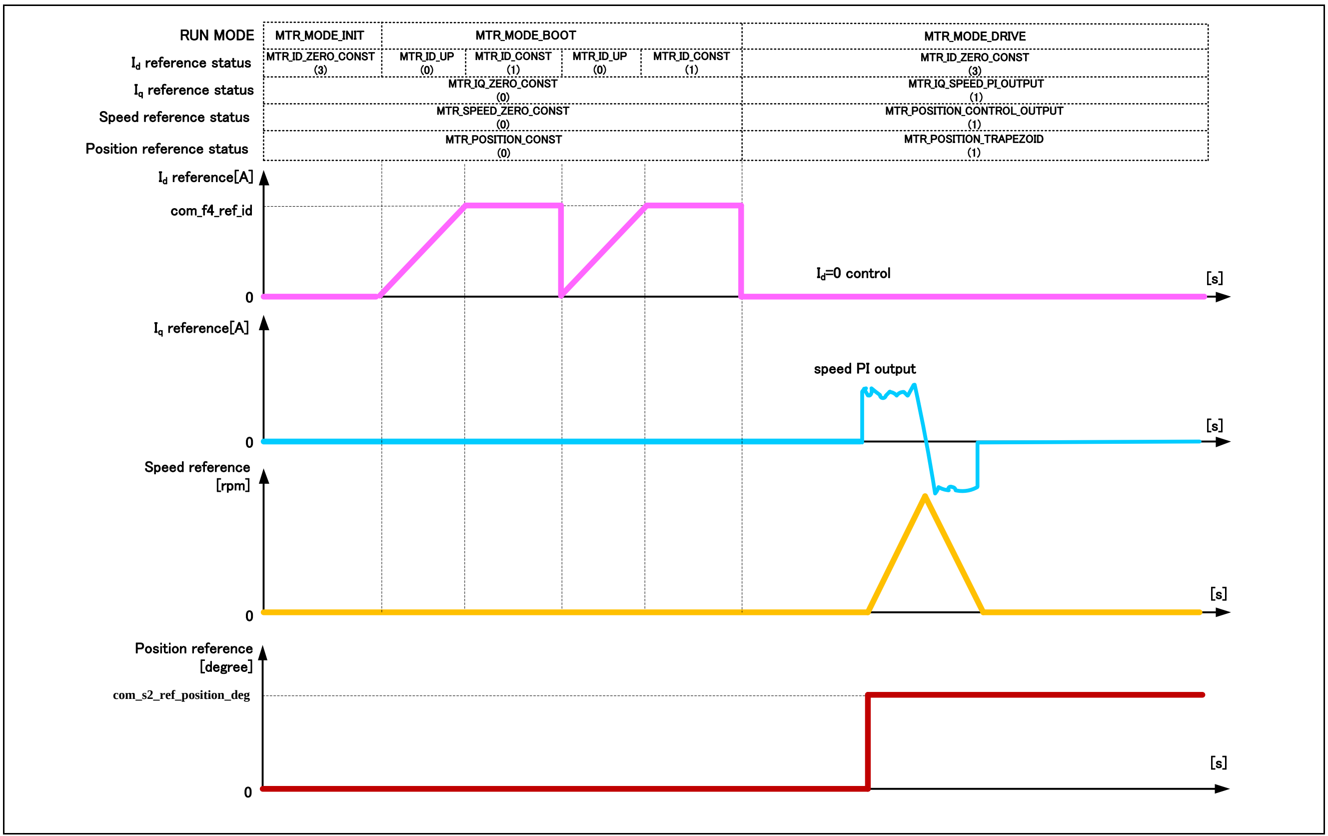


Figure 4-10 Startup Position Control of Vector Control PMSM with Encoder Software

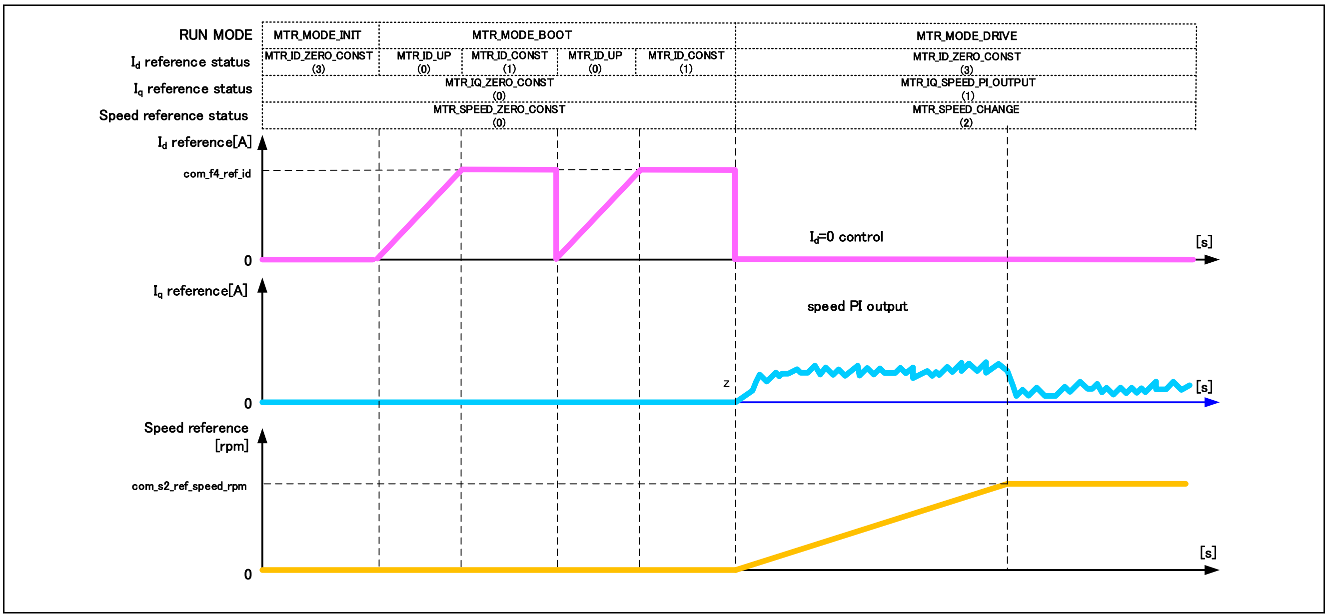


Figure 4-11 Startup Speed Control of Vector Control PMSM with Encoder Software

RENESAS

Website and Support

Renesas Electronics Website
http://www.renesas.com/

Inquiries
http://www.renesas.com/contact/

Revision History

Rev.	Date	Description	
		Page	Summary
1.00	Apr.05. 2017	-	First edition issued
1.01	July.07. 2017	-	Fixed typo error in document

General Precautions in the Handling of Microprocessing Unit and Microcontroller Unit Products

The following usage notes are applicable to all Microprocessing unit and Microcontroller unit products from Renesas. For detailed usage notes on the products covered by this document, refer to the relevant sections of the document as well as any technical updates that have been issued for the products.

1. Handling of Unused Pins

   Handle unused pins in accordance with the directions given under Handling of Unused Pins in the manual.

   — The input pins of CMOS products are generally in the high-impedance state. In operation with an unused pin in the open-circuit state, extra electromagnetic noise is induced in the vicinity of LSI, an associated shoot-through current flows internally, and malfunctions occur due to the false recognition of the pin state as an input signal become possible. Unused pins should be handled as described under Handling of Unused Pins in the manual.

2. Processing at Power-on

   The state of the product is undefined at the moment when power is supplied.

   — The states of internal circuits in the LSI are indeterminate and the states of register settings and pins are undefined at the moment when power is supplied.
   In a finished product where the reset signal is applied to the external reset pin, the states of pins are not guaranteed from the moment when power is supplied until the reset process is completed.
   In a similar way, the states of pins in a product that is reset by an on-chip power-on reset function are not guaranteed from the moment when power is supplied until the power reaches the level at which resetting has been specified.

3. Prohibition of Access to Reserved Addresses

   Access to reserved addresses is prohibited.

   — The reserved addresses are provided for the possible future expansion of functions. Do not access these addresses; the correct operation of LSI is not guaranteed if they are accessed.

4. Clock Signals

   After applying a reset, only release the reset line after the operating clock signal has become stable. When switching the clock signal during program execution, wait until the target clock signal has stabilized.

   — When the clock signal is generated with an external resonator (or from an external oscillator) during a reset, ensure that the reset line is only released after full stabilization of the clock signal. Moreover, when switching to a clock signal produced with an external resonator (or by an external oscillator) while program execution is in progress, wait until the target clock signal is stable.

5. Differences between Products

   Before changing from one product to another, i.e. to a product with a different part number, confirm that the change will not lead to problems.

   — The characteristics of Microprocessing unit or Microcontroller unit products in the same group but having a different part number may differ in terms of the internal memory capacity, layout pattern, and other factors, which can affect the ranges of electrical characteristics, such as characteristic values, operating margins, immunity to noise, and amount of radiated noise. When changing to a product with a different part number, implement a system-evaluation test for the given product.

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