RL78/G14

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Motor control by RL78/G14 micro controller
Sensorless vector control of permanent magnetic synchronous motor

Summary

This application note aims at explaining the sample program for operating the sensorless vector control of permanent magnetic synchronous motor, by using functions of RL78/G14.

The sample program is only to be used as reference and Renesas Electronics Corporation does not guarantee the operations. Please use this sample program after carrying out a thorough evaluation in a suitable environment.

Operation checking device

Operations of the sample program are checked by using the following device.

• RL78/G14 (R5F104LEAFP)

Contents

1. Overview

This application note explains the sample program of the sensorless vector control of permanent magnetic synchronous motor (henceforth referred to as PMSM) by using the RL78/G14 micro controller.

1.1 Usage of the system

This system (sample program) enables sensorless vector control by using RSSK (Note 1) for motor control (Low Voltage Motor Control Starter-Kit Evaluation System and surface permanent magnetic synchronous motor (FH6S20E-X81 Note 2)).

For installation and technical support of 'RSSK for motor control', contact Sales representatives and dealers of Renesas Electronics Corporation.

Notes:

1. RSSK (Renesas Solution Starter Kit) is the product of Renesas Electronics Corporation.
2. FH6S20E-X81 is the product of NIDEC SERVO CORPORATION.
   NIDEC SERVO CORPORATION. (http://www.nidec-servo.com/en/index.html)

1.2 Development environment

(1) Software development environment

Integrated development environment	CubeSuite+ (V1.03.00)

(2) Hardware environment

On-chip debug emulator	E1
Micro controller used	RL78/G14 (R5F104LEAFP)
Inverter board for motor control	Low Voltage Motor Control Starter-Kit Evaluation System (P03401-D1-001)
Motor	FH6S20E-X81 (SPMSM)

2. System overview

Overview of this system is explained below.

2.1 Hardware configuration

The hardware configuration is shown below.

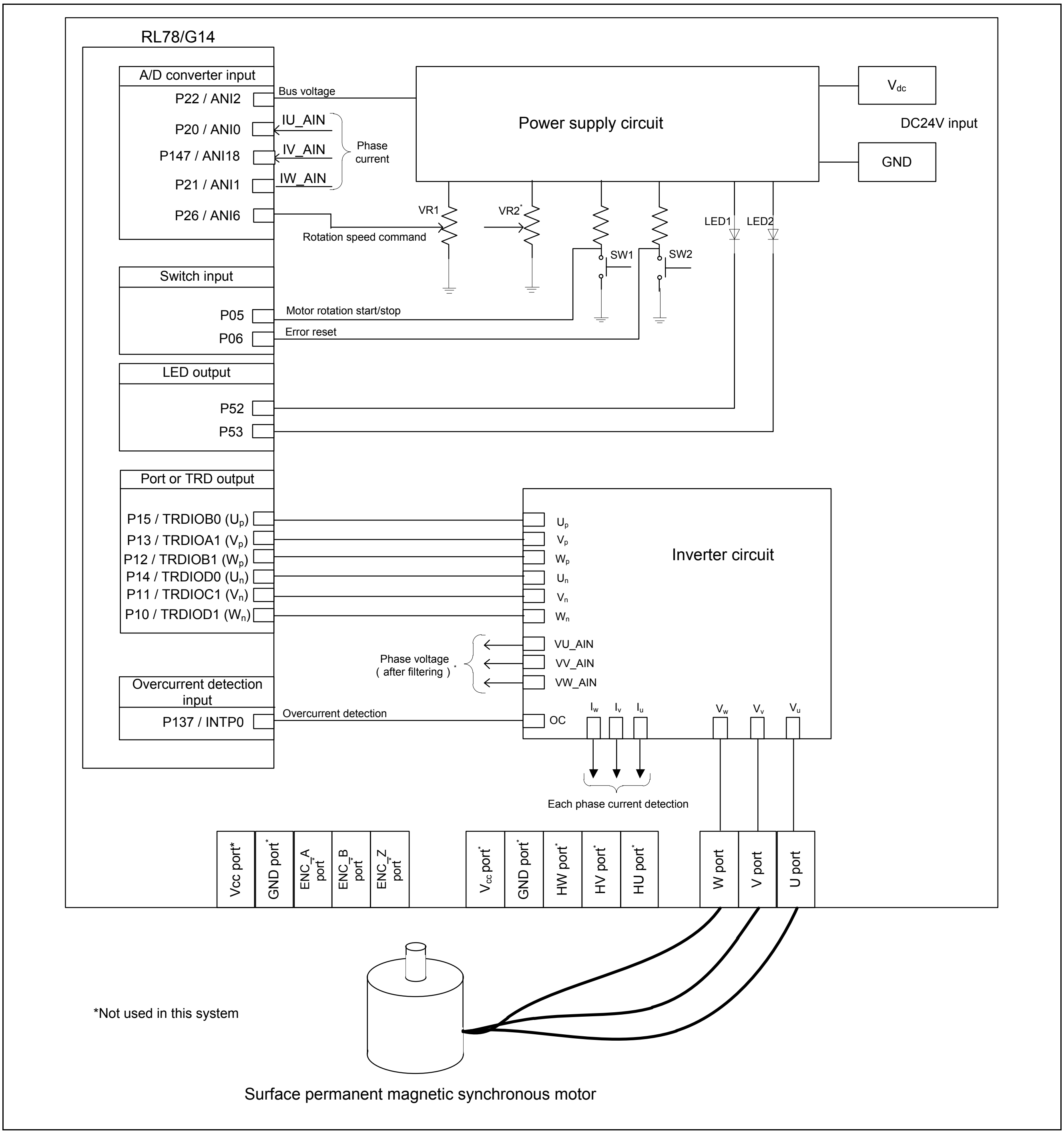


Figure 2-1 Hardware Configuration Diagram

2.2 Hardware specifications

2.2.1 User interface

List of user interfaces of this system is given in Table 2-1.

Table 2-1 User Interface

Item	Interface component	Function
Rotation speed	Variable resistance (VR1)	Rotation speed command value input (analog value)
START/STOP	Push switch (SW1)	Motor rotation start/stop command
ERROR RESET	Push switch (SW2)	Command of recovery from error status
LED1	Yellow Green LED	・At the time of motor rotation: ON ・At the time of stop: OFF
LED2	Yellow Green LED	・At the time of error detection: ON ・At the time of normal operation: OFF
RESET	Push switch (RESET)	System reset

List of port interfaces of RL78/G14 micro controller of this system is given in Table 2-2.

Table 2-2 Port Interfaces

Port name	Function
P22 / ANI2	Inverter bus voltage measurement
P26 / ANI6	For rotation speed command value input (analog value)
P05	START/STOP push switch
P06	ERROR RESET push switch
P52	LED1 ON/OFF control
P53	LED2 ON/OFF control
P20 / ANI0	U phase current measurement
P147 / ANI18	V phase current measurement
P21 / ANI1	W phase current measurement
P15 / TRDIOB0	Complementary PWM output (U_p)
P13 / TRDIOA1	Complementary PWM output (V_p)
P12 / TRDIOB1	Complementary PWM output (W_p)
P14 / TRDIOD0	Complementary PWM output (U_n)
P11 / TRDIOC1	Complementary PWM output (V_n)
P10 / TRDIOD1	Complementary PWM output (W_n)
P137 / INTP0	PWM emergency stop input at the time of over current detection
RESET#	RESET

2.2.2 Peripheral functions

List of the peripheral functions used in this system is given in Table 2-3.

Table 2-3 List of the Peripheral Functions

Peripheral function	Usage
10-bit A/D converter (ANI2, ANI6)	・Rotation speed command value input ・Inverter bus voltage measurement ・U, W phase current measurement
Timer Array Unit (TAUS)	・1 [ms] interval timer ・300 [μs] interval timer
Timer RD (TRD)	Complementary PWM output (six outputs)
INTP0 input	In the case of over current detection, set PWM output to high impedance

(1) 10-bit A/D converter

The rotation speed command value input, U phase current (I_u), W phase current (I_w), and inverter bus voltage (V_{dc}) are measured by using '10-bit A/D converter'.

For A/D conversion, set the channel selection mode to 'Select mode' and the conversion operation mode to 'One shot conversion mode' (use software trigger).

(2) Timer Array Unit (TAUS)

300 [μs] (carrier cycle × 3) interval timer uses the channel 0 of the Timer Array Unit (TAUS).

1 [ms] interval timer uses the channel 1 of the Timer Array Unit (TAUS).

(3) Timer RD (TRD)

The 6-phase PWM output with dead time is performed by using the complementary PWM mode.

2.3 Software configuration

2.3.1 Software file configuration

Folder and file configuration of the sample program is given below.

Table 2-4 Folder and File Configuration of the Sample Program

RL78G14_RSSK_SSNS_LESS_FOC_ICS_CSP_V100	inc	Ics.h	ICS header
		main.h	Main function, user interface control header
		mtr_common.h	Common definition header
		mtr_ctrl_rssk.h	Board dependent processing part header
		mtr_ctrl_rl78g14.h	RL78/G14 dependent processing part header
		mtr_ssns_less_foc.h	Sensorless vector control dependent part header
		r_dsp.h	Digital Signal Controller library header
		r_stdint.h	Variable declaration for the Digital Signal Controller library header
	lib	ics_rl78g14.lib	ICS Library
		R_dsp_rl78.lib	Digital Signal Controller library
		angle_speed.lib	Estimating position and speed Library
	src	main.c	Main function, user interface control
		mtr_ctrl_rssk.c	Board dependent processing part
		mtr_ctrl_rl78g14.c	RL78/G14 dependent processing part
		mtr_interrupt.c	Interrupt handler
		mtr_ ssns _less_foc.c	Sensorless vector control dependent part

2.3.2 Module configuration

Module configuration of the sample program is described below.

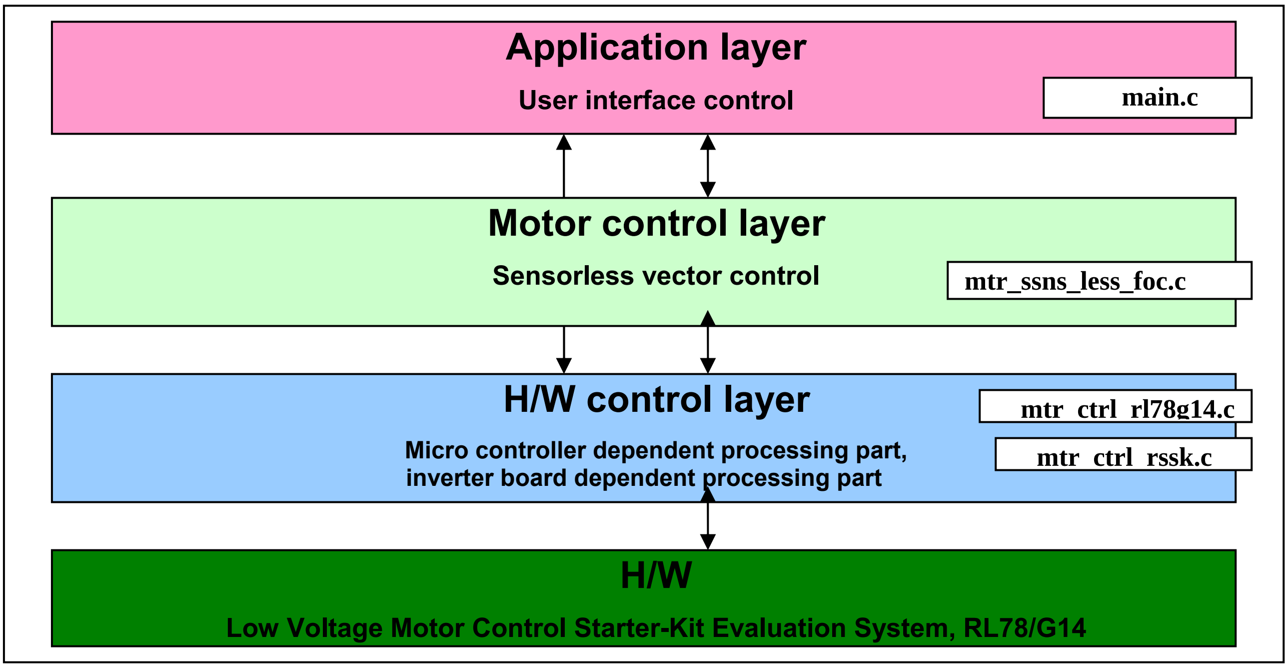


Figure 2-2 Module Configuration of the Sample Program

2.4 Software specifications

Basic specifications of software of this system are given in Table 2-5.

Table 2-5 Basic Specifications of the Software

Item	Content
Control method	Vector control
Motor rotation start/stop	Determined depending on the level of SW1 (P05) (”Low”: Rotation start “High”: Stop)
Position detection of rotor magnetic pole	Sensorless
Carrier frequency (PWM)	10 [kHz]
Control cycle	300 [μsec] (carrier cycle × 3)
Rotation speed control range	CW: 600 [rpm] to 2000 [rpm]
Processing stop for protection	･Disables the motor control signal output (six outputs), under any of the following four conditions. 1. Current of each phase exceeds 10 [A] (monitored per 300 [μs]) 2. Inverter bus voltage exceeds 28 [V] (monitored per 300 [μs]) 3. Inverter bus voltage is less than 0 [V] (monitored per 300 [μs]) 4. Rotation speed exceeds 2200 [rpm] (mechanical angle) (monitored per 300 [μs]) ･In the case of over current detection, set the PWM output to high impedance (“Low” is input to the INTP0 port).

3. Motor control method

The SPMSM vector control used in the sample program is explained here.

3.1 Voltage equation of the motor control system

Voltage equation of the permanent magnetic synchronous motor (Figure 3-1) having the magnetic flux distribution of sine-wave shape can be expressed as follows.

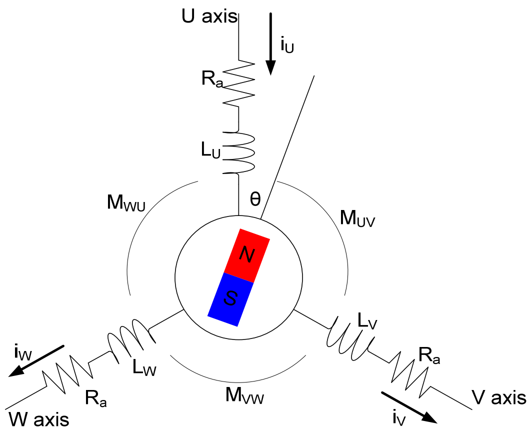


Figure 3-1 Conceptual diagram of the three phase permanent magnetic synchronous motor

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

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

v_u, v_v, v_w : Each phase armature voltage L_u, L_v, L_w : Each phase self inductance

i_u, i_v, i_w : Each phase armature current M_{uv}, M_{vw}, M_{wu} : Each phase mutual inductance

ϕ_u, ϕ_v, ϕ_w : Each phase armature interlinkage flux

ψ : Maximum value of armature interlinkage flux depending on permanent magnet

R_a : Each phase armature resistance

θ : Lead angle of permanent magnet (rotor) from U phase p : Differential operator

Here, self-inductance and mutual inductance are expressed as shown in the following formula.

$$\begin{cases} L_u = l_a + L_a - L_{as}\cos(2\theta) \\ L_u = l_a + L_a - L_{as}\cos(2\theta + 2\pi/3) \\ L_u = l_a + L_a - L_{as}\cos(2\theta - 2\pi/3) \end{cases}$$

$$\begin{cases} M_{uv} = -L_a/2 - L_{as}\cos(2\theta - 2\pi/3) \\ M_{vw} = -L_a/2 - L_{as}\cos 2\theta \\ M_{wu} = -L_a/2 - L_{as}\cos(\theta + 2\pi/3) \end{cases}$$

l_a : Leakage inductance for one phase

L_a : Average value of effective inductance for one phase

L_{as} : Amplitude of effective inductance for one phase

3.2 Vector control

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 from the d axis. Then by using the following conversion matrix, coordinate conversion is performed.

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

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

The voltage equation in the dq coordinate system is obtained as follow.

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

v_d, v_q : Each phase armature voltage

L_d, L_q : Each phase self inductance

i_d, i_q : Each phase armature current

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

ψ_a : Value of armature interlinkage flux depending on permanent magnet

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

R_a : Each phase armature resistance

Based on this, it can be assumed that 3 phase alternating current is 2 phase direct current.

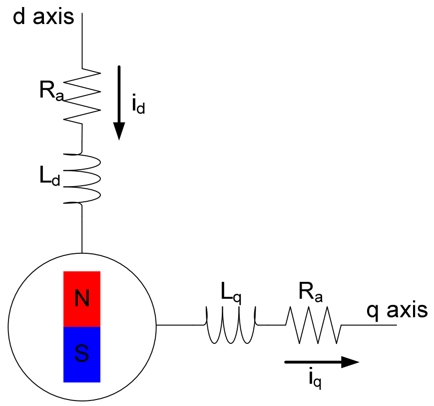


Figure 3-2 Conceptual diagram of the two phase direct current motor

Size of the torque generated in the motor can be obtained as follows from the exterior product of the electric current vector and armature interlinkage magnetic flux. The first term on the right side of this formula is called magnetic torque and the second term on the right side of this formula is the reluctance torque.

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

T : Motor torque P_n : Number of pole pairs

The motor which has no difference between the d axis and q axis inductance is defined as a motor which does not have saliency. In this case, as the reluctance torque is 0, the torque increases proportionally to the q axis current. Due to this, the q axis current is called torque current. On the other hand, d axis current is sometimes called excitation current, because it can be assumed that the d axis current increase is the magnetic flux of permanent magnet decrease for q axis voltage.

As SPMSM generally does not have saliency, the d axis current unnecessary for generating torque is controlled to 0 while controlling the speed. This is known as id = 0 control. On one hand, the motion equation of the motor in this case is expressed as follows. This equation shows that motor speed is increased by increasing the q axis current.

$$I \frac{d\omega}{dt} = P_n \psi_a i_q - T_L$$

T_L : Load torque I : Motor intertia momentum

This system uses not motion equation but PI control for speed control. The q axis current command value is calculated by the following formula.

$$i_q^* = (K_{P\omega} + \frac{K_{I\omega}}{s})(\omega^* - \omega)$$

$K_{P\omega}$: Speed PI ratio gain $K_{I\omega}$: Speed P I integral gain s : Laplace operator

To achieve early stabilization, the PI control is also used for the d axis and q axis current values. A command voltage value is acquired by current PI control.

$$v_d^* = (K_{Pi_d} + \frac{K_{Ii_d}}{s})(i_d^* - i_d)$$

K_{Pi_d} : d axis current PI propotional gain K_{Ii_d} : d axis current PI integral gain

$$v_q^* = (K_{Pi_q} + \frac{K_{Ii_q}}{s})(i_q^* - i_q)$$

K_{Pi_q} : q axis current PI propotional gain K_{Ii_q} : q axis current PI integral gain

Inductive voltage is generated when the motor is rotated. The effect on d axis voltage due to q axis current and on q axis voltage due to d axis current and magnetic flux of permanent magnet becomes significant along with the increase in speed. This d axis and q axis interference may delay the stability of a current value. In order to avoid this, the voltage of each axis is calculated by performing feed forward so that the interference term of each axis can be canceled beforehand.

$$v_d^* = (K_{Pi_d} + \frac{K_{Ii_d}}{s})(i_d^* - i_d) - \omega L_q i_q$$

$$v_q^* = (K_{Pi_q} + \frac{K_{Ii_q}}{s})(i_q^* - i_q) + \omega(L_d i_d + \psi_a)$$

This method to eliminate the effect of the interference term is known as decoupling control. This enables to control the d axis and q axis independently.

Vector control is a method by which the 3 phase alternating current motor is converted to the 2 phase direct current motor that can be controlled each phase (d,q) independently while managing the position, speed and torque of the rotor. Control flow of the vector control is shown below.

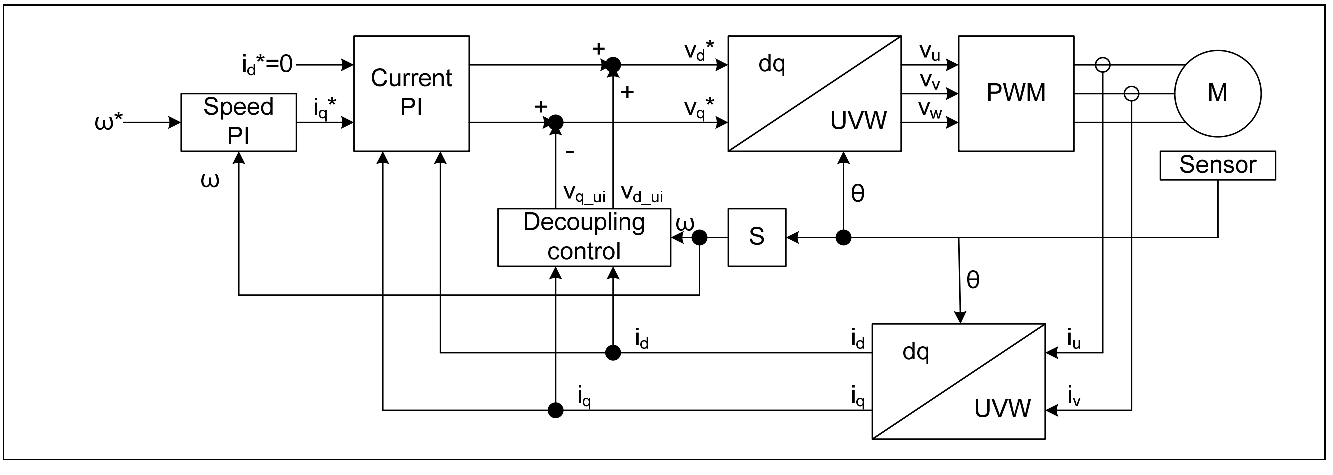


Figure 3-3 Control Flow of the Vector Control

3.3 Sensorless vector control based on the current estimation error

For the vector control, position sensors of the encoder and resolver etc are required as voltage is set according to the rotor position. When the position sensors are not used, in other words, in the case of the sensorless vector control, it is necessary to estimate the position by some methods. These days, the demand for motor control by sensorless has increased and several methods are provided for estimating the position This part introduces the sensorless vector control used in this system, which is using current estimation error.

Position of the d axis is not clear as the position information of the actual motor is not available. As shown in the below figure, when γ axis is set in the location which lags behind by Δθ from the d axis and δ axis is set in the location 90 degrees ahead of the γ axis, the conversion formula from d q axis to the γ δ axis can be indicated as follows.

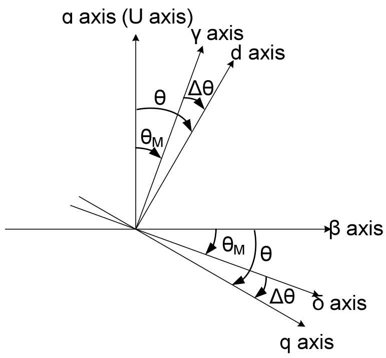


Figure 3-4 Relation between d q axis and γ δ axis

$$\begin{pmatrix}\gamma\\ \delta\end{pmatrix}=\begin{pmatrix}\cos\Delta\theta & \sin\Delta\theta\\ -\sin\Delta\theta & \cos\Delta\theta\end{pmatrix}\begin{pmatrix}d\\ q\end{pmatrix}$$

The equation in which above is applied to the SPMSM voltage equation and written in the electric current state equation format is as follows.

$$p\begin{pmatrix}i_\gamma\\ i_\delta\end{pmatrix}=-\begin{pmatrix}\frac{R}{L} & -\dot{\theta}_M\\ \dot{\theta}_M & \frac{R}{L}\end{pmatrix}\begin{pmatrix}i_\gamma\\ i_\delta\end{pmatrix}+\frac{1}{L}\begin{pmatrix}v_\gamma\\ v_\delta\end{pmatrix}-\frac{K_E\dot{\theta}}{L}\begin{pmatrix}-\sin\Delta\theta\\ \cos\Delta\theta\end{pmatrix}$$

Discretization is performed by using backward differential approximation (Euler's approximation) to this state equation.

$$\begin{pmatrix}i_\gamma(n)\\ i_\delta(n)\end{pmatrix}=\begin{pmatrix}i_\gamma(n-1)\\ i_\delta(n-1)\end{pmatrix}+\frac{T}{L}\left\{\begin{pmatrix}v_\gamma(n-1)\\ v_\delta(n-1)\end{pmatrix}-R\begin{pmatrix}i_\gamma(n-1)\\ i_\delta(n-1)\end{pmatrix}-\dot{\theta}_M(n-1)L\begin{pmatrix}-i_\delta(n-1)\\ i_\gamma(n-1)\end{pmatrix}-e(n-1)\begin{pmatrix}-\sin\Delta\theta(n-1)\\ \cos\Delta\theta(n-1)\end{pmatrix}\right\}$$

$$\because e(n-1)=K_E\dot{\theta}(n-1)$$

As a motor model here, given that the motor parameters are written as R_M, L_M and e_M which are sufficiently equal to motor parameters of an actual motor and Δθ is set to 0, the current value at a sample point n can be represented as follows.

$$\begin{pmatrix} i_{\gamma M}(n) \\ i_{\delta M}(n) \end{pmatrix} = \begin{pmatrix} i_\gamma(n-1) \\ i_\delta(n-1) \end{pmatrix} + \frac{T}{L_M}\left\{ \begin{pmatrix} v_\gamma(n-1) \\ v_\delta(n-1) \end{pmatrix} - R_M \begin{pmatrix} i_\gamma(n-1) \\ i_\delta(n-1) \end{pmatrix} - \dot{\theta}_M(n-1) L_M \begin{pmatrix} -i_\delta(n-1) \\ i_\gamma(n-1) \end{pmatrix} - e_M(n-1)\begin{pmatrix} 0 \\ 1 \end{pmatrix} \right\}$$

Depending on the difference between actual motor current and motor model current, the current estimation error can be indicated as follows.

$$\begin{pmatrix} \Delta i_\gamma(n) \\ \Delta i_\delta(n) \end{pmatrix} = \frac{T}{L}\begin{pmatrix} e(n-1)\sin\Delta\theta(n-1) \\ e_M(n-1) - e(n-1)\cos\Delta\theta(n-1) \end{pmatrix}$$

When Δθ is sufficiently small, the current estimation error can be approximated as follows.

$$\begin{pmatrix} \Delta i_\gamma(n) \\ \Delta i_\delta(n) \end{pmatrix} \approx \frac{T}{L}\begin{pmatrix} e(n-1)\Delta\theta(n-1) \\ -\Delta e(n-1) \end{pmatrix}$$
$$\Delta e(n-1) = e(n-1) - e_M(n-1)$$

If both Δe and Δθ are 0, it can be considered that the actual model is synchronized with the motor model. e_M is estimated by feeding back Δi_δ such that Δe becomes 0. Similarly, the θ_M value is estimated by feeding back Δi_γ such that Δθ becomes 0. The motor model is thus matched with the actual model. The e_M estimation equation can be expressed as follows.

$$e_M(n) = e_M(n-1) - K_e \Delta i_\delta(n)$$

Here, K_e is the speed electromotive force gain. Similarly, the θM estimation equation can be written as follows.

$$\theta_M(n) = \theta_M(n-1) + \frac{T}{K_{EM}} e_M(n) + K_\theta \,\mathrm{sgn}\{\dot{\theta}_M(n-1)\}\Delta i_\gamma(n)$$
$$\mathrm{sgn}\{\dot{\theta}_M(n-1)\} = \begin{cases} 1 & ; \dot{\theta}_M(n-1) \geq 0 \\ -1 & ; \dot{\theta}_M(n-1) < 0 \end{cases}$$

Here, K_{EM} is the electromotive force coefficient of the motor model and K_θ is the position estimation gain. Also, $p\theta_M$ sign is used instead of the pθ sign.

$$\dot{\theta}_M = \frac{1}{T}\{\theta_M(n) - \theta_M(n-1)\} = \frac{e_M}{K_{EM}} + \Delta\dot{\theta}_M(n)$$

$$\Delta\dot{\theta}_M(n) = \frac{K_\theta}{T}\operatorname{sgn}\{\dot{\theta}_M(n-1)\}\Delta i_\gamma(n)$$

In the control, LPF for the speed correction term is used as follows. Here, $0 < K < 1$.

$$\dot{\theta}_{Mo}(n) = \frac{e_M(n)}{K_{EM}} + \Delta\dot{\theta}_{Mo}(n)$$

$$\Delta\dot{\theta}_{Mo}(n) = \Delta\dot{\theta}_{Mo}(n-1) + K\{\Delta\dot{\theta}_M(n) - \Delta\dot{\theta}_{Mo}(n-1)\}$$

Control flow of this control method is shown below.

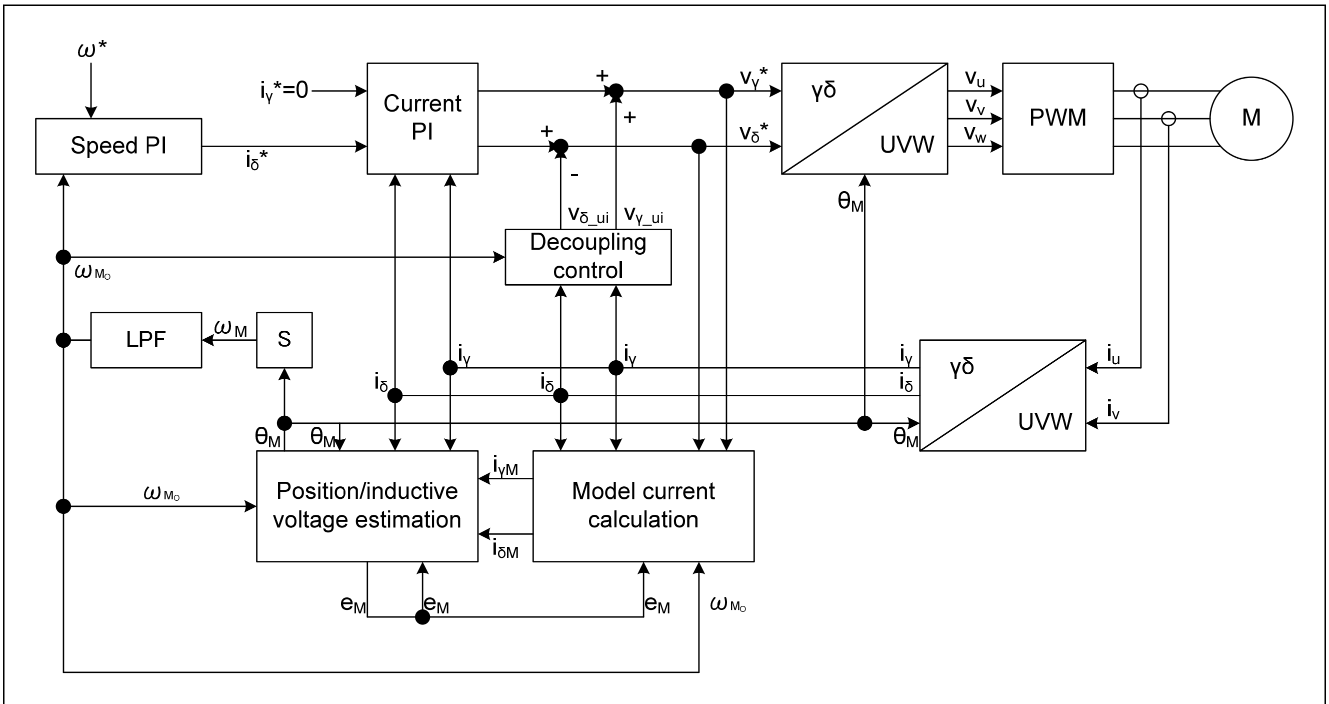


Figure 3-5 Control flow of the sensorless vector control based on the current estimation error method

3.4 Triangular wave comparison method

In order to actually output the voltage command value, the triangular wave comparison method which determines the pulse width of the output voltage by comparing the carrier waveform (triangular wave) and voltage command value waveform is used. By using this PWM formula, output of the voltage command value of the pseudo sinusoidal wave can be performed.

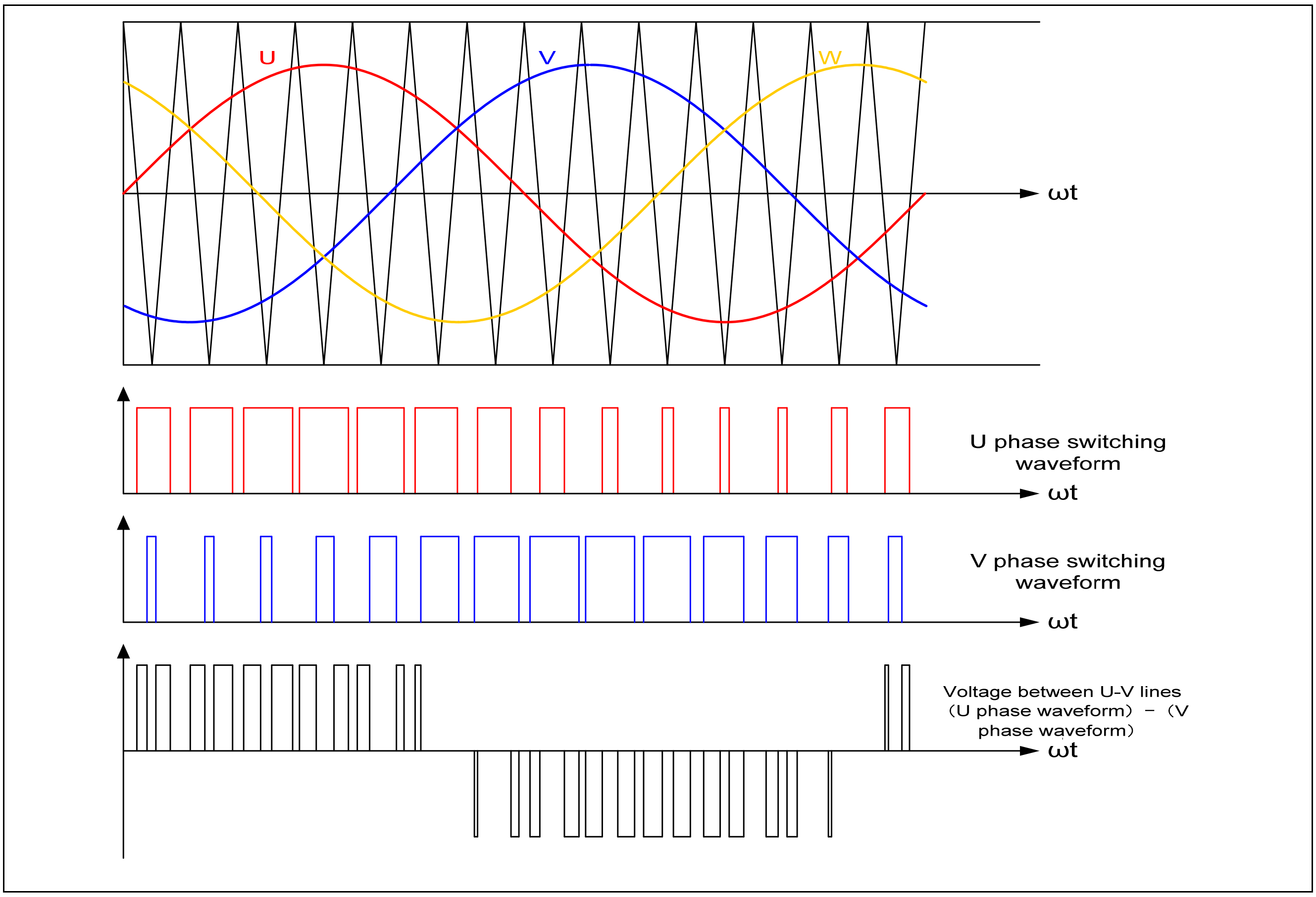


Figure 3-6 Conceptual diagram of the triangular wave comparison method

Here, as shown in the Figure 3-7, ratio of the output voltage pulse to the carrier wave is called as duty.

$$\text{Duty} = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times 100\ [\%]$$

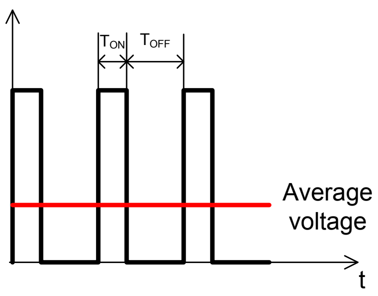


Figure 3-7 Definition of duty

Modulation factor m is defined as follows.

$$m = \frac{V}{E}$$

M: Modulation factor V: Command value voltage E: Inverter bus voltage

A request control can be performed by setting this modulation factor on the register which determines PWM duty.

4. Description of the control program

Control program of this system is explained here.

4.1 Contents of Control

4.1.1 Motor start/stop

Starting and stopping of the motor are controlled by input from SW1.

A general-purpose port (P05) is assigned to SW1. The P05 port is read within the main loop. When P05 is at a "Low" level, it is determined that the start switch is being pressed. Conversely, when the level is switched to "High", the program determines that the motor should be stopped.

4.1.2 Motor rotation speed command value, Inverter bus voltage, motor 3 phase voltage

(1) Motor rotation speed command value

The motor rotation speed command value can be set by A/D conversion of the VR1 value (analog value). The A/D converted VR1 values are used as rotation speed command values, as shown in Table 4-1.

Table 4-1 Conversion Ratio of the Speed Command Value

Item		Conversion ratio (Command value: A/D conversion value)	Channel
Rotation speed command value	CW	600 [rpm] to 2000 [rpm]: 0000H to 03FFH	ANI6

(2) Inverter bus voltage

Inverter bus voltage is measured as given in Table 4-2.

It is used for modulation factor calculation and over voltage detection (When an abnormality is detected, PWM is stopped).

Table 4-2 Inverter Bus Voltage Conversion Ratio

Item	Conversion ratio (Inverter bus voltage V_{dc}: A/D conversion value)	Channel
Inverter bus voltage	0 [V] to 30 [V]: 0000H to 03FFH	ANI2

(3) U, W phase current

The U, W phase currents are measured as shown in Table 4-3 and used in vector control.

Table 4-3 Conversion Ratio of U and W Phase Current

Item	Conversion ratio (U, W phase current: A/D conversion value)	Channel
U, W phase current	-10 [A] to 10 [A]: 0000H to 03FFH	ANI0, ANI1

4.1.3 Control method

The motor is driven in an open loop at the time of startup. After a fixed time has passed, the motor is driven by the sensorless vector control based on the current estimation error explained in chapter 3 (please refer to the block diagram in Figure 3-5). PI control is used to control the speed.

4.1.4 System protection function

This control program has the following four types of error status and executes emergency stop functions in case of occurrence of respective errors.

• Over current error

High impedance output is made to the PWM output port in response to an emergency stop signal (over current detection) from the hardware (emergency stop without involving CPU). The INTP0 port is used.

In addition, U, V, and W phase currents are monitored by 300 [µs] intervals. When an over current (when the current exceeds 10 [A]) is detected, the CPU executes emergency stop.

• Over voltage error

The inverter bus voltage is monitored by 300 [µs] intervals. When an over voltage is detected (when the voltage exceeds 28 [V]), the CPU performs emergency stop. Here, the over voltage limit value 28 [V] is set by considering the error of resistance value and error of supply voltage by AC adapter etc.

• Low voltage error

The inverter bus voltage is monitored by 300 [µs] intervals. The CPU performs emergency stop when low voltage (when voltage falls below 0 [V]) is detected.

• Over speed error

The rotation speed is monitored by 300 [µs] intervals. The CPU performs emergency stop when the speed is over 2200 [rpm] (mechanical angle)

4.2 Function Specifications

Multiple control functions are used in this control program. Lists of control functions are given below.

For detailed processing, please refer to flowcharts or source files.

Table 4-4 List of Control Functions (1/4)

File name	Function name	Process overview
main.c	main Input: None Output: None	・Hardware initialization function call ・User interface initialization function call ・Initialization function call of the variable used in the main process ・Status transition and event execution function call ・Main process ⇒Main process execution function call ⇒Watchdog timer clear function call
	ctrl_ui Input: None Output: None	・Motor status change ・Determination of rotation speed command value
	software_init Input: None Output: None	Initialization of variables used in the main process
mtr_ctrl_rssk.c	get_vr1 Input: None Output: (int16) ad_data / A/D conversion result	VR1 status acquisition A/D conversion execution function call
	get_sw1 Input: None Output: (uint8) tmp_port / SW1 level	SW1 status acquisition
	get_sw2 Input: None Output: (uint8) tmp_port / SW2 level	SW2 status acquisition
	led1_on Input: None Output: None	Making LED1 ON
	led2_on Input: None Output: None	Making LED2 ON
	led1_off Input: None Output: None	Making LED1 OFF
	led2_off Input: None Output: None	Making LED2 OFF

Table 4-4 List of Control Functions (2/4)

File name	Function name	Process overview
mtr_ctrl_rl78g14.c	R_MTR_InitHardware Input: None Output: None	Initialization of the clock and peripheral functions
	init_ui Input: None Output: None	Initialization of the peripheral functions used by the user
	mtr_ctrl_start Input: None Output: None	Motor startup process
	mtr_ctrl_stop Input: None Output: None	Motor stop process
	mtr_get_adc Input: (uint8)ad_ch / A/D conversion channel Output: (int16)u2_temp / A/D conversion result	Executing the A/D conversion of a specified channel
	clear_wdt Input: None Output: None	Clearing the watchdog timer
	mtr_clear_oc_flag Input: None Output: None	Clearing the overcurrent detection flag
	mtr_inv_set_uvw Input: (int16)s2_u / U phase voltage (int16)s2_v / V phase voltage (int16)s2_w / W phase voltage Output: None	PWM duty setting
mtr_interrupt.c	mtr_over_current_interrupt Input: None Output: None	Overcurrent detection process ・Event processing selection function call ・Changing the motor status ・Pulse output forced cutoff flag clearing function call
	mtr_tau00_interrupt Input: None Output: None	Calling per 300 [μs] ・Vector control ・Current PI control
	mtr_tau01_interrupt Input: None Output: None	Calling per 1 [ms] ・Start control ・Speed PI control

Table 4-4 List of Control Functions (3/4)

File name	Function name	Process overview
mtr_ssns_less_foc.c	R_MTR_InitSequence Input: None Output: None	Initialization of the sequence process
	R_MTR_ExecEvent Input: (uint8)u1_event/ occurred event Output: None	· Changing the status · Calling an appropriate process execution function for the occurred event
	mtr_act_run Input: (uint8)u1_state/ motor status Output: (uint8)u1_state/ motor status	· Variable initialization function call upon motor startup · Motor control startup function call
	mtr_act_stop Input: (uint8)u1_state/ motor status Output: (uint8)u1_state/ motor status	Motor control stop function call
	mtr_act_none Input: (uint8)u1_state/ motor status Output: (uint8)u1_state/ motor status	No processing is performed.
	mtr_act_reset Input: (uint8)u1_state/ motor status Output: (uint8)u1_state/ motor status	Global variable initialization
	mtr_act_error Input: (uint8)u1_state/ motor status Output: (uint8)u1_state/ motor status	Motor control stop function call
	mtr_act_init Input: (uint8)u1_state/motor status Output: (uint8)u1_state/motor status	Initial setting
	mtr_start_init Input: None Output: None	Initializing only the variables required for motor startup
	mtr_angle_speed Input: None Output: None	Position, speed calculation process
	mtr_pi_ctrl Input: MTR_PI_CTRL *vdq/ PI control structure Output: (int16)s2_ref/ PI control output value	Current PI control

Table 4-4 List of Control Functions (4/4)

File name	Function name	Process overview
mtr_ssns_less_foc.c	R_MTR_SetSpeed Input: (int16) ref_speed / Speed command value Output: None	Speed command value setting
	R_MTR_SetDir Input: (uint8) g_u1_rot_dir/ Rotation direction Output: None	Rotation direction setting
	R_MTR_GetSpeed Input: None Output: (int16) Speed calculation value	Obtaining the speed calculation value
	R_MTR_GetStatus Input: None Output: (uint8)g_u1_mode_system / motor status	Obtaining the motor status
	mtr_error_check Input: None Output: None	Error monitoring and detection
	R_MTR_SetMaxSpeed Input: (int16) s2_set_max_speed Output: None	Setting the maximum rotation speed command value
	R_MTR_SetMinSpeed Input: (int16) s2_set_min_speed Output: None	Setting the minimum rotation speed command value

4.3 List of variables

Lists of variables used in this control program are given below. However, the local variables are not mentioned.

Table 4-5 List of Variables (1/3)

Variable name	Type	Content	Remarks
g_s2_max_mecha_speed_rad	int16	Speed command maximum value	Mechanical angle [rad/s]
g_s2_min_mecha_speed_rad	int16	Speed command minimum value	Mechanical angle [rad/s]
g_s2_set_speed	int16	User rotation speed command value	Electrical angle [rad/s]
g_u1_motor_status	uint8	User motor status management	0 : Stop 1 : Rotating 2 : Error
g_u1_reset_req	uint8	Reset request flag	0: Turning SW2 ON at the time of error status 1: Turning SW2 OFF at the time of error status
g_u1_sw1_cnt	uint8	SW1 determining counter	Chattering removal
g_u1_sw2_cnt	uint8	SW2 determining counter	Chattering removal
g_u1_mode_system	uint8	State management	0: Stop mode 1: Run mode 2: Error mode
g_u2_run_mode	uint16	Operation mode management	2: Start mode 6: Normal operation mode
g_u1_error_status	uint8	Error status management	1: Over current error 2: Over voltage error 3: Over speed error 7 : Low voltage error 0xFF: Undefined error
g_u1_cnt_ics	uint8	Counter for ICS call	
g_u2_vdc_ad	uint16	Inverter bus voltage A/D value	[V]
g_s2_vd_ref	int16	d axis voltage command value	Current PI control output value [V]
g_s2_vq_ref	int16	q axis voltage command value	Current PI control output value [V]
g_s2_iu_ad	int16	U phase current	[A]
g_s2_iv_ad	int16	V phase current	[A]
g_s2_iw_ad	int16	W phase current	[A]
g_s2_offset_iu	int16	U phase current offset value	[A]
g_s2_offset_iw	int16	W phase current offset value	[A]
g_s2_ia_ad	int16	α axis current	[A]
g_s2_ib_ad	int16	β axis current	[A]
g_s2_id_lpf	int16	d axis current	[A]
g_s2_iq_lpf	int16	q axis current	[A]
g_s2_ex_id_lpf	int16	Previous value of d axis current	[A]
g_s2_ex_iq_lpf	int16	Previous value of q axis current	[A]
g_s2_kp_id	int16	d axis current PI proportional term gain	
g_s2_ki_id	int16	d axis current PI integral term gain	
g_s2_kp_iq	int16	q axis current PI proportional term gain	
g_s2_ki_iq	int16	q axis current PI integral term gain	

Table 4-5 List of Variables (2/3)

Variable name	Type	Content	Remarks
g_s2_kp_speed	int16	Speed PI control proportional term gain	
g_s2_ki_speed	int16	Speed PI control integral term gain	
g_s2_limit_id	int16	d axis current PI limit	[V]
g_s4_ilimit_id	Int32	d axis current PI limit value	[V]
g_s2_limit_iq	Int16	q axis current PI limit value	[V]
g_s4_ilimit_iq	Int32	q axis current PI limit value	[V]
g_s2_id_ref	int16	d axis current command value	[A]
g_s2_iq_ref	int16	q axis current command value	[A]
g_s2_va_ref	int16	α axis voltage command value	[V]
g_s2_vb_ref	int16	β axis voltage command value	[V]
g_s2_ma_ref	int16	α axis voltage command correction value	[V]
g_s2_mb_ref	int16	β axis voltage command correction value	[V]
g_s2_speed_rad	int16	Speed operation value	Electrical angle [rad/s]
g_s2_ref_speed_rad	int16	Speed command value	Electrical angle [rad/s]
g_s2_ref_speed_rad_ad	int16	Speed adjustment value	Electrical angle [rad/s]
g_s2_angle_rad	int16	Rotor position	Electrical angle [rad]
g_s4_angle_rad	int32	Rotor position	Electrical angle [rad]
g_s2_max_speed_rad	int16	Maximum speed value	Electrical angle [rad/s]
g_s2_min_speed_rad	int16	Minimum speed value	Electrical angle [rad/s]
g_s4_iq_pip	int32	Speed PI control proportional term	[A]
g_s4_iq_pii	int32	Speed PI control integral term	[A]
g_s2_refu	int16	U phase voltage	[V]
g_s2_refv	int16	V phase voltage	[V]
g_s2_refw	int16	W phase voltage	[V]
g_s2_inv_limit	int16	Phase voltage limit value	[V]
vd	MTR_PI_CTRL	d axis current PI control structure	
vq	MTR_PI_CTRL	q axis current PI control structure	
g_u1_flag_id_open	uint8	Start mode determination flag 1	
g_u1_flag_wr_open	uint8	Start mode determination flag 2	
g_s2_cnt_adjust	int16	Counter for offset	
g_s2_id_open	int16	d axis current command value in start mode	[A]
g_s2_iq_open	int16	q axis current command value in start mode	[A]
g_s2_ol_speed_rad	int16	Speed in start mode	[rad/s]
g_u2_cnt_wr_open	uint16	Counter in start mode	
g_s2_i_gamma	int16	γ axis current	[A]
g_s2_i_delta	int16	δ axis current	[A]
g_s4_i_gamma	int32	γ axis current	[A]
g_s4_i_delta	int32	δ axis current	[A]
g_s4_emf_est	int32	Estimation value of inductive voltage	[V]
g_s2_emf_est	int16	Estimation value of inductive voltage	
g_s2_k_emf	int16	Speed electromotive force estimation gain	
g_s2_k_theta	int16	Position estimation gain	

Table 4-5 List of Variables (3/3)

Variable name	Type	Content	Remarks
g_s4_ex_tdspeed_lpf	int32	Previous cycle ×difference in speed	
g_s2_set_max_speed	int16	Maximum speed	Electrical angle [rad/s]
g_s2_set_min_speed	int16	Minimum speed	Electrical angle [rad/s]
g_s2_margin_min_mecha_speed_rad	int16	Minimum value of motor stop speed command	Mechanical angle [rad/s]
g_u1_rot_dir	uint16	Rotation direction	
g_u1_stop_req	uint16	Request for stop	
g_s2_ex_iu	int16	Previous value of U phase current	[A]
g_s2_ex_iw	int16	Previous value of W phase current	[A]
g_s4_di_gamma	int32	Difference in γ axis current value	[A]
g_s4_di_delta	int32	Difference in δ axis current value	[A]
g_u1_direction	uint8	Rotation direction management	0: CW 1: CCW
g_s2_est_speed_rad	int16	Rotation estimated speed operation value	Electrical angle [rad/s]
g_s4_speed_rad	int32	Rotation speed operation value	Electrical angle [rad/s]
g_u1_def_state	uint8	Motor status definition	Array members ・Stop mode ・Adjust mode ・Run mode ・Error mode
gp_u1_def_action	uint8	Action definition	Array members ・Stop action ・Run action ・Initialize action ・Error action ・Reset action ・No action

4.4 Macro definitions

Lists of macro definitions used in this control program are given below.

Table 4-6 List of Macro Definitions (1/5)

File name	Macro name	Definition value	Remarks
main.h	MAX_SPEED	2000	Rotation speed command maximum value (mechanical angle) [rpm]
	MIN_SPEED	600	Rotation speed command minimum value (mechanical angle) [rpm]
	SPEED_RANGE	MAX_SPEED-MIN_SPEED	Rotation speed range (mechanical angle) [rpm]
	MARGIN_SPEED	50	Constant for creating rotation speed command minimum value for stopping (mechanical angle) [rpm]
	MARGIN_MIN_SPEED	MIN_SPEED - MARGIN_SPEED	Rotation speed command minimum value for motor stop (mechanical angle) [rpm]
	RPM_RAD	65536*3.14159/30	(pi/30) 2^16
	SW_ON	0	Active in case of “Low”
	SW_OFF	1	
	CHATTERING_CNT	10	Chattering removal
	VR1_SCALING	RPM_RAD*SPEED_RANGE/1023	Speed command value creation constant RPM_RAD*SPEED_RANGE/2^10
	POLE_PAIR	7	Number of pole pairs
	M_CW	0	CW rotation
	M_CCW	1	CCW rotation
	REQ_CLR	0	VR1stop command flag clearing
	REQ_SET	1	VR1 stop command flag setting
	ADJUST_OFFSET	0x1FF	Constant for creating speed command value

Table 4-6 List of Macro Definitions (2/5)

File name	Macro name	Definition value	Remarks
mtr_ctrl_rl78g14.h	MTR_PWM_TIMER_FREQ	64.0f	Timer count frequency [MHz]
	MTR_CARRIER_FREQ	10.0f	Carrier frequency [kHz]
	MTR_DEADTIME_SET	MTR_DEADTIME * MTR_PWM_TIMER_FREQ / 1000	Dead time
	MTR_CARRIER_SET	(MTR_PWM_TIMER_FREQ * 1000 / MTR_CARRIER_FREQ / 2)+ MTR_DEADTIME_SET – 2	Carrier setting value
	MTR_HALF_CARRIER_SET	MTR_CARRIER_SET / 2	Carrier setting value/2
	MTR_PWM_DUTY_RANGE	4096	PWM setting range
	MTR_PORT_UP	P1.5	U phase (Positive phase) output port
	MTR_PORT_UN	P1.4	U phase (Negative phase) output port
	MTR_PORT_VP	P1.3	V phase (Positive phase) output port
	MTR_PORT_VN	P1.1	V phase (Negative phase) output port
	MTR_PORT_WP	P1.2	W phase (Positive phase) output port
	MTR_PORT_WN	P1.0	W phase (Negative phase) output port
	MTR_ADCCH_IU	0	U phase current channel
	MTR_ADCCH_IW	1	W phase current channel
	MTR_ADCCH_VDC	2	VDC channel
	MTR_ADCCH_VU	3	U phase voltage channel
	MTR_ADCCH_VV	4	V phase voltage channel
	MTR_ADCCH_VW	5	W phase voltage channel
	MTR_ADCCH_VR1	6	VR1 channel
	MTR_ADCCH_VR2	7	VR2 channel
	MTR_ADCCH_IV	18	V phase current channel
	MTR_AD_BIT_SGN	0x8000U	For converting current value
	MTR_MAX_VDC	24.0f	Maximum voltage value
	MTR_VDC_RESOLUTION	30.0f / 1023	Voltage resolution
	MTR_PORT_SW1	P0.5	SW1 input port
	MTR_PORT_SW2	P0.6	SW2 input port
	MTR_PORT_LED1	P5.2	LED1 output port
	MTR_PORT_LED2	P5.3	LED2 output port
	MTR_LED_ON	0	Active in case of “Low”
	MTR_LED_OFF	1	

Table 4-6 List of Macro Definitions (3/5)

File name	Macro name	Definition value	Remarks
mtr_ssns_less_foc.h	MTR_DEADTIME	1500	Dead time setting value [ns]
	MTR_INT_DECIMATION	2	Number of interrupt decimation times
	MTR_CTRL_PERIOD	((MTR_INT_DECIMATION + 1) / (MTR_CARRIER_FREQ*1000) * 131072)	Control cycle [s]
	MTR_CONTROL_FREQ	((MTR_CARRIER_FREQ*1000)/ (MTR_INT_DECIMATION + 1))	Control frequency [Hz]
	MTR_M	0.006198f * 65536	Magnetic flux [Wb] 2^16
	MTR_R	0.453f * 16384	Resistance [Ω] 2^14
	MTR_L	0.0009447f * 65536	L [H] 2^16
	MTR_T_L	MTR_CTRL_PERIOD/MTR_L * 4096	T/L [s/H] 2^12
	MTR_1_M	MTR_CTRL_PERIOD/MTR_M * 8192	T/M [s/Wb] 2^13
	MTR_SPEED_LIMIT	7*2*3.14159265*2200*16/60	Speed limit value (electrical angle) [rad/s] 2^4
	MTR_OVERCURRENT_LIMIT	10*2048	Current limit value [V] 2^11
	MTR_OVERVOLTAGE_LIMIT	28*1024	Upper limit of voltage value [V] 2^10
	MTR_UNDERVOLTAGE_LIMIT	0	Lower limit of voltage value [V]
	TWOPI	4096	Circular constant*2 2^12/2π
	MTR_ID_PI_KP	2.5f * 4096	d axis current proportional term gain 2^12
	MTR_ID_PI_KI	0.005f * 32768	d axis current integral term gain 2^15
	MTR_IQ_PI_KP	2.5f * 4096	q axis current proportional term gain 2^12
	MTR_IQ_PI_KI	0.005f * 32768	q axis current integral term gain 2^15
	MTR_SPEED_PI_KP	0.006f * 131072	Speed proportional term gain 2^17
	MTR_SPEED_PI_KI	0.00003f * 131072	Speed integral term gain 2^17
	MTR_EMF_THETA_K	0.1f * 8192	Speed electro-motive force gain 2^13
	MTR_SPEED_EST_K	0.15f * 8192	Position estimation gain 2^13
	MTR_ID_PI_LIMIT	10 * 1024	d axis current PI limit value 2^10
	MTR_ID_PI_ILIMIT	32768 * 4096	d axis current PI integral term limit value 2^10
	MTR_IQ_PI_LIMIT	10 * 1024	q axis current PI limit value 2^12
	MTR_IQ_PI_ILIMIT	32768 * 4096	q axis current PI integral term limit value 2^12
	MTR_LPF_K	0.04f * 4096	LPF coefficient 2^12
	MTR_IQ_LIMIT	2 * 2048	q axis current limit value 2^11
	MTR_CW	0	CW rotation
	MTR_CCW	1	CCW rotation

Table 5-10 List of Macro Definitions (4/5)

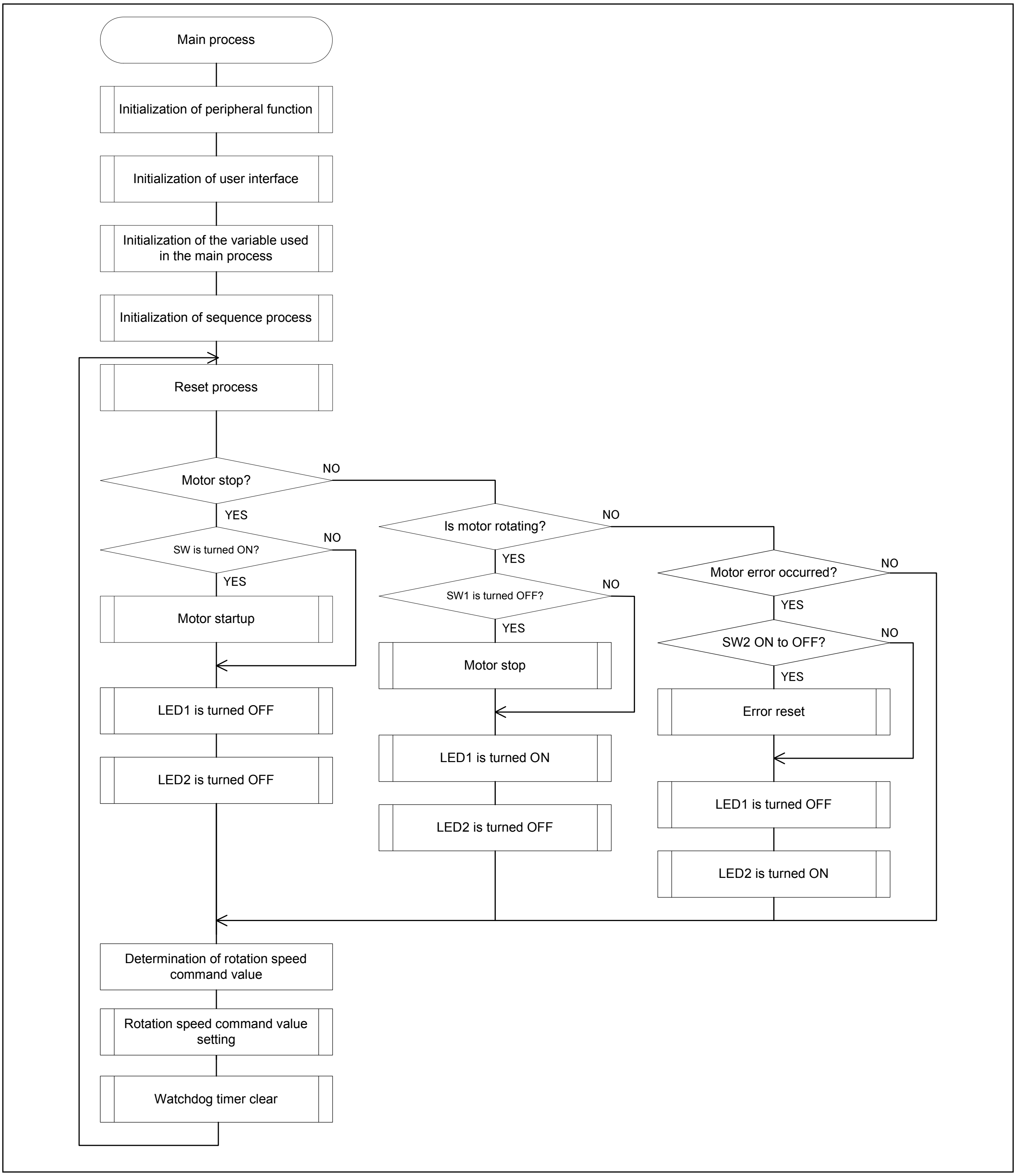
File name	Macro name	Definition value	Remarks
mtr_ssns_less_foc.h	MTR_START_OL_ID	1.0f	d axis current in start mode [A]
	MTR_START_OL_ID_UP_TIME	512	d axis current adding time [ms]
	MTR_START_OL_ID_DOWN_TIME	512	d axis current subtracting time [ms]
	MTR_START_OL_REF_ID	2048*MTR_START_OL_ID	d axis current command value in start mode [A]
	MTR_START_OL_ID_UP_STEP	MTR_START_OL_REF_ID /MTR_START_OL_ID_UP_TIME	Command d axis current adding value
	MTR_START_OL_ID_DOWN_STEP	MTR_START_OL_REF_ID /MTR_START_OL_ID_DOWN_TIME	Command d axis current subtracting value
	MTR_START_OL_SPEED	2.0*3.14159f*70	Command q axis current adding value [A]
	MTR_START_OL_SPEED_UP_TIME	2048	Speed adding time in open loop mode [ms]
	MTR_START_OL_SPEED_CONST_TIME	512	Constant speed time in open loop mode [ms]
	MTR_START_REF_SPEED_CONST_TIME	1024	Time during which speed command value is constant after speed PI control start [ms]
	MTR_START_OL_REF_SPEED	MTR_START_OL_SPEED*16	Speed command value in start mode (electrical angle) [rad/s] 2 ^ 4
	MTR_START_OL_SPEED_UP_STEP	MTR_START_OL_REF_SPEED /MTR_START_OL_SPEED_UP_TIME	Command speed adding value in start mode (electrical angle) [rad/s]
	MTR_START_REF_SPEED_UP_STEP	2.0*3.14159f*16*35/512	Adding value for reflecting command speed by VR1 in start mode (electrical angle) [rad/s] 2 ^ 4
	MTR_START_REF_SPEED_DOWN_STEP	2.0*3.14159f*16*35/512	Subtracting value for reflecting command speed by VR1 in start mode (electrical angle) [rad/s] 2 ^ 4

Table 5-10 List of Macro Definitions (5/5)

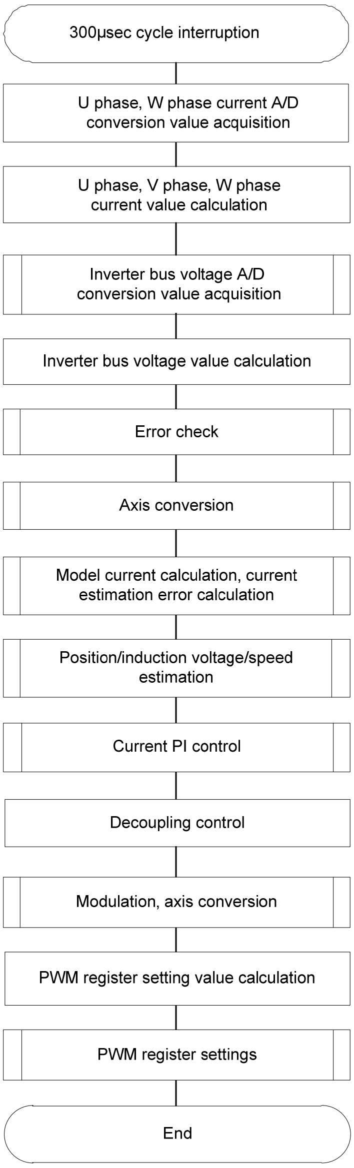
File name	Macro name	Definition value	Remark
mtr_ssns_less_foc.h	MTR_START_REF_ACCEL_LIMIT	2.0*3.14159f*16*35	Command rotation speed limit value (electrical angle) [rad/s] 2^4
	MTR_1_2PI	0.159155f * 65536	1/2π 2^16
	MTR_T_2PI	MTR_1_2PI*MTR_CTRL _PERIOD/4096	Cycle/2π 2^12
	MTR_START_DUTY_SET	(((MTR_CARRIER_SET + 1) / 100) * MTR_START_DUTY) - 1	PWM duty setting register initial value
	MTR_MAX_PWM_DUTY	2000	PWM duty setting register upper limit value
	MTR_MIN_PWM_DUTY	20	PWM duty setting register lower limit value
	MTR_ADSCALE_CUR	2565	Current scaling
	MTR_ADSCALE_VDC	7688	Voltage scaling
	MTR_TIME_FORWORD	MTR_CTRL_PERIOD*1.5/6.283185	Phase delay compensation
	MTR_BOOT_MODE	0x00	Boot mode
	MTR_OPENLOOP_MODE	0x01	Open loop mode
	MTR_START_MODE	0x02	Start mode
	MTR_HALL_120_MODE	0x03	Hall sensor 120-degree operation mode
	MTR_BEMF_120_MODE	0x04	BEMF sensorless 120-degree operation mode
	MTR_ENCD_FOC_MODE	0x05	Encoder vector operation mode
	MTR_LESS_FOC_MODE	0x06	Sensorless vector operation mode
	MTR_OVER_CURRENT_ERROR	0x01	Over current error
	MTR_OVER_VOLTAGE_ERROR	0x02	Over voltage error
	MTR_OVER_SPEED_ERROR	0x03	Over speed error
	MTR_TIMEOUT_ERROR	0x04	Timeout error
	MTR_UNDER_VOLTAGE _ERROR	0x07	Low voltage error
	MTR_UNKNOWN_ERROR	0xff	Undefined error
	MTR_MODE_STOP	0x00	Stop status
	MTR_MODE_RUN	0x01	Rotating status
	MTR_MODE_ERROR	0x02	Error status
	MTR_SIZE_STATE	0x03	Status count
	MTR_EVENT_STOP	0x00	Motor stop event
	MTR_EVENT_ADJUST	0x01	Adjustment event
	MTR_EVENT_RUN	0x02	Motor run event
	MTR_EVENT_ERROR	0x03	Motor error event
	MTR_EVENT_RESET	0x04	Motor reset event
	MTR_SIZE_EVENT	5	Events count

4.5 Control flow (flow chart)

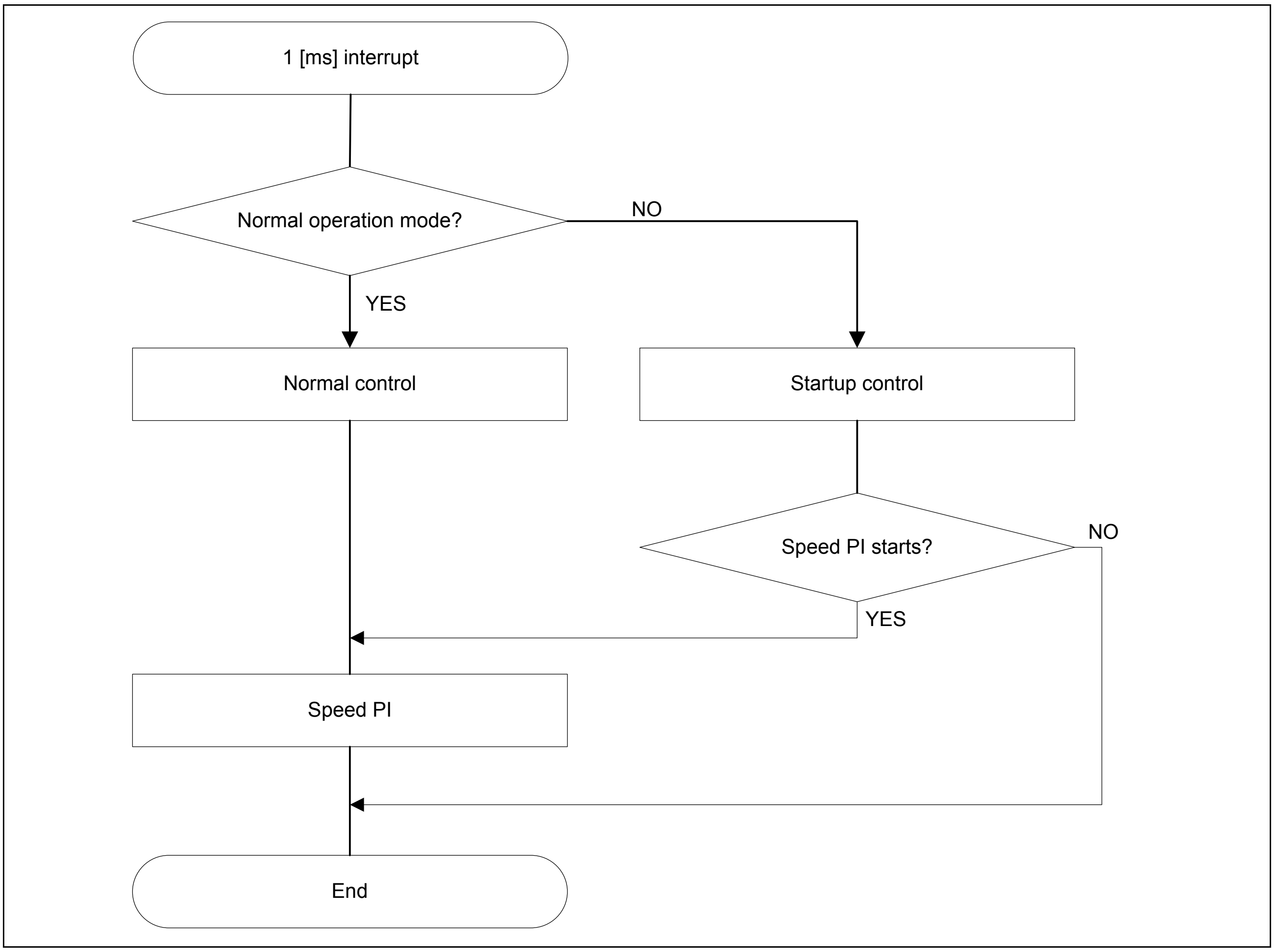
(1) Main process



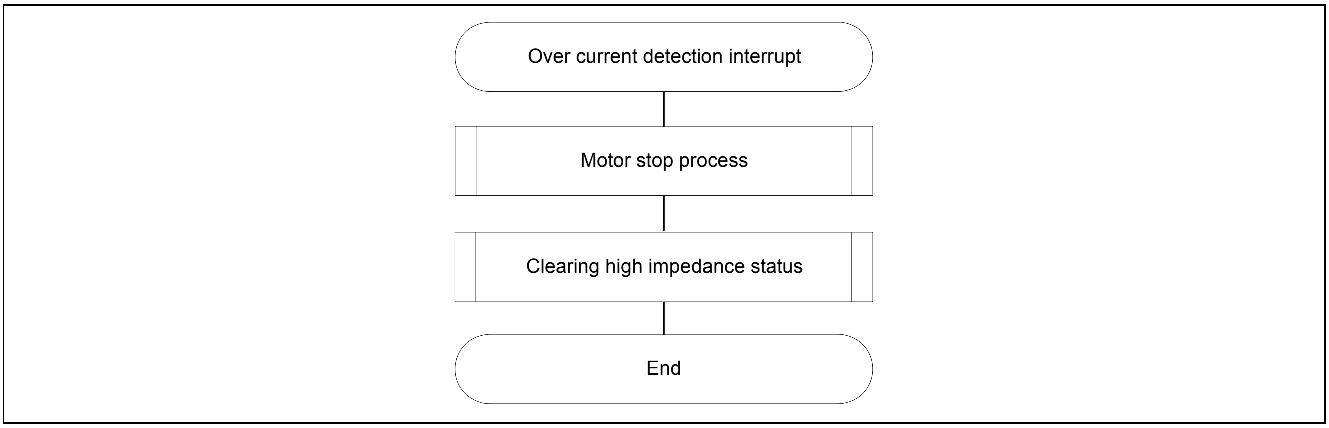
(2) 300 [μs] cycle interrupt process



(3) 1 [ms] interrupt process



(4) Over current interrupt process



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Rev.	Issued on	Revision Details	
		Page	Summary
1.00	Apr 11, 2013	—	First edition issued

General Precautions in the Handling of MPU/MCU Products

The following usage notes are applicable to all MPU/MCU products from Renesas. For detailed usage notes on the products covered by this manual, refer to the relevant sections of the manual. If the descriptions under General Precautions in the Handling of MPU/MCU Products and in the body of the manual differ from each other, the description in the body of the manual takes precedence.

1. Handling of Unused Pins
   Handle unused pins in accord 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 one with a different type number, confirm that the change will not lead to problems.
   — The characteristics of MPU/MCU in the same group but having different type numbers may differ because of the differences in internal memory capacity and layout pattern. When changing to products of different type numbers, implement a system-evaluation test for each of the products.

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