Sensorless Vector Control for Permanent Magnet Synchronous Motor (Implementation) (Control over Four Motors)

RX72T, for “Evaluation System for BLDC Motor”

Abstract

This application note aims at explaining sensorless vector control software for a permanent magnet synchronous motor, by using functions of RX72T. The explanation includes, how to use the library of ‘Renesas Motor Workbench’ tool, that is support tool for motor control development. This software also uses the Smart Configurator tool.

The target software of this application note is only to be used as reference and Renesas Electronics Corporation does not guarantee the operations. Please use them after carrying out a thorough evaluation in a suitable environment.

Operation Checking Device

Operations of the target software of this application note are checked by using the following devices.

- RX72T (R5F572TKCDFB)

Target Software

The target software of this application note is as follows.

- RX72T_MRSSK2_4SPM_LESS_FOC_CSP_RV100 (IDE: CS+)
- RX72T_MRSSK2_4SPM_LESS_FOC_E2S_RV100 (IDE: e^{2}studio)
  RX72T sensorless vector control software for ‘Evaluation System for BLDC Motor’ and ‘RX72T CPU Card’

Reference

- RX72T Group User’s Manual: Hardware (R01UH0803)
- Application note: ‘Sensorless vector control for permanent magnet synchronous motor (Algorithm)’ (R01AN3786)
- Renesas Motor Workbench User’s Manual (R21UZ0004)
- Evaluation System For BLDC Motor User’s Manual (R12UZ0062)
- Smart Configurator User's Manual: RX API Reference (R20UT4360)
- RX Smart Configurator User’s Guide: CS+ (R20AN0470)
- RX Smart Configurator User’s Guide: e^2 studio (R20AN0451)

Contents

1. Overview

This application note explains how to implement the sensorless vector control software of permanent magnet synchronous motor (PMSM)*1 using the RX72T microcontroller. The explanation includes, how to use the library of 'Renesas Motor Workbench' tool, that is support tool for motor control development.

Note that the software uses the algorithm described in the application note 'Sensorless vector control for permanent magnet synchronous motor (Algorithm)'.

Note: 1. PMSM is also known as brushless DC motor (BLDC).

1.1 Development Environment

Table 1-1 and Table 1-2 show development environment of the software explained in this application note.

Table 1-1 Hardware Development Environment

Microcontroller	Evaluation board	Motor*4
RX72T (R5F572TKCDFB)	48-V 5-A inverter board for BLDC motors*1 & RX72T CPU board*2	TG-55L*3

Table 1-2 Software Development Environment

IDE version	Smart Configurator for RX	Toolchain version*5
CS+ V8.04.00	Standalone Version 2.7.0	CC-RX: V3.02.00
e^2 studio version 2021-01	Bundled with e^2 studio as plug-in	

For purchase and technical support, contact sales representatives and dealers of Renesas Electronics Corporation.

Notes: 1. This 48-V 5-A inverter board for BLDC motors (RTK0EM0000B10020BJ) is a product of Renesas Electronics Corporation.
The 48-V 5-A inverter board for BLDC motors is included in Evaluation System for BLDC Motor (RTK0EMX270S00020BJ).
2. The CPU board in use for this application note is a trial product for evaluation and is not for sale.
3. TG-55L is a product of TSUKASA ELECTRIC.
TSUKASA ELECTRIC (http://www.tsukasa-d.co.jp/)
4. Motors conforming to the inverter specifications listed in chapter 2 of Evaluation System For BLDC Motor User's Manual (R12UZ0062) can be connected to the product. When using motors other than the one included with the product, make sure to check the motor specifications carefully.
5. If the same version of the toolchain (C compiler) specified in the project is not in the import destination, the toolchain will not be selected and an error will occur.
Check the selected status of the toolchain on the project configuration dialog.
For the setting method, refer to FAQ 3000404.
(https://en-support.renesas.com/knowledgeBase/18398339)

2. System Overview

Overview of this system is explained below.

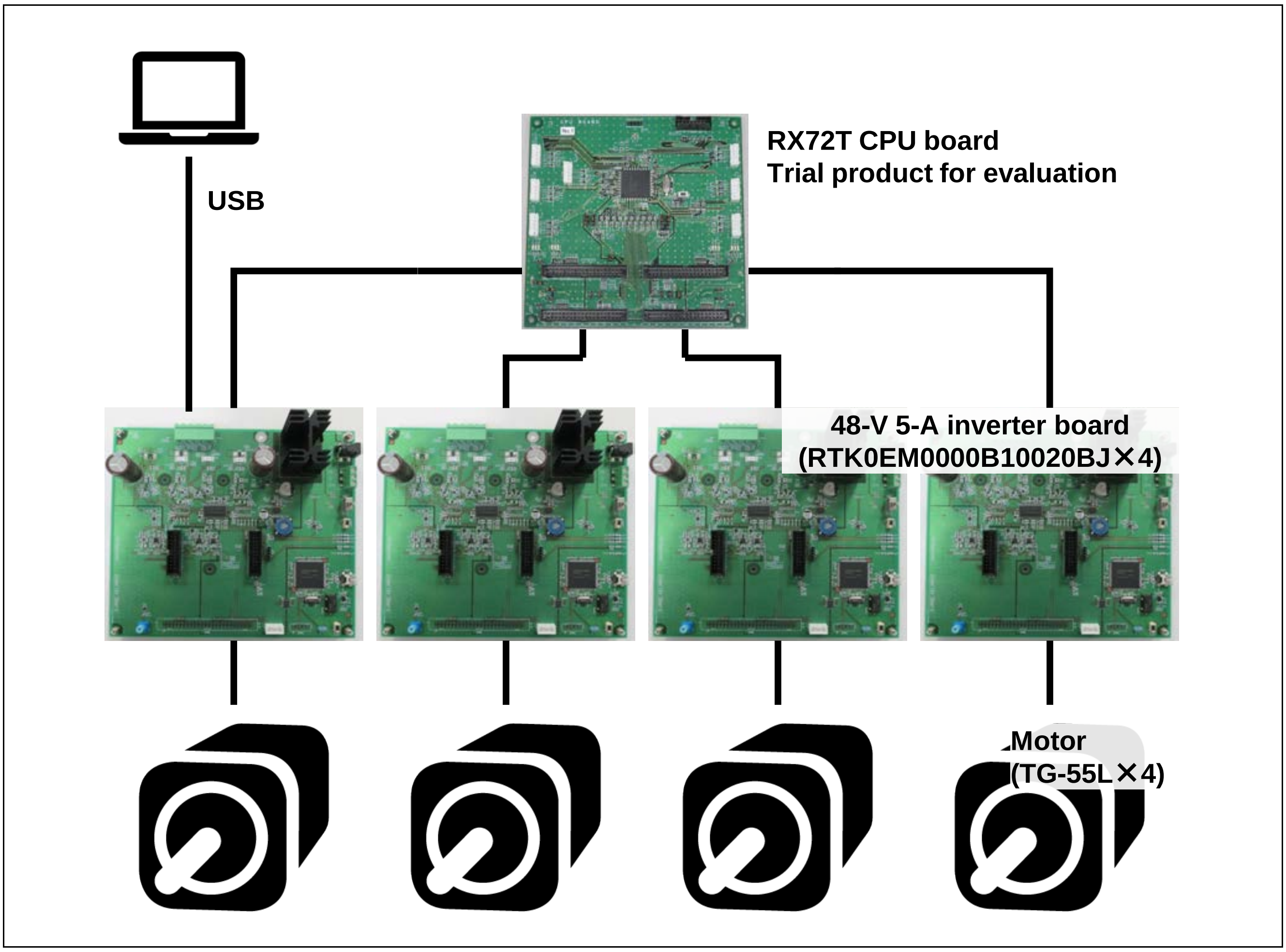


Figure 2-1 System overview

2.1 Hardware Configuration

2.1.1 Overall Configuration of Hardware

The figure below shows the overall configuration of the hardware. In the figure, 5 VDC is supplied from the inverter board for motor 1. The other inverter boards do not have 5-VDC connections to the CPU board. The CPU board selects the destination for connection of 5 VDC.

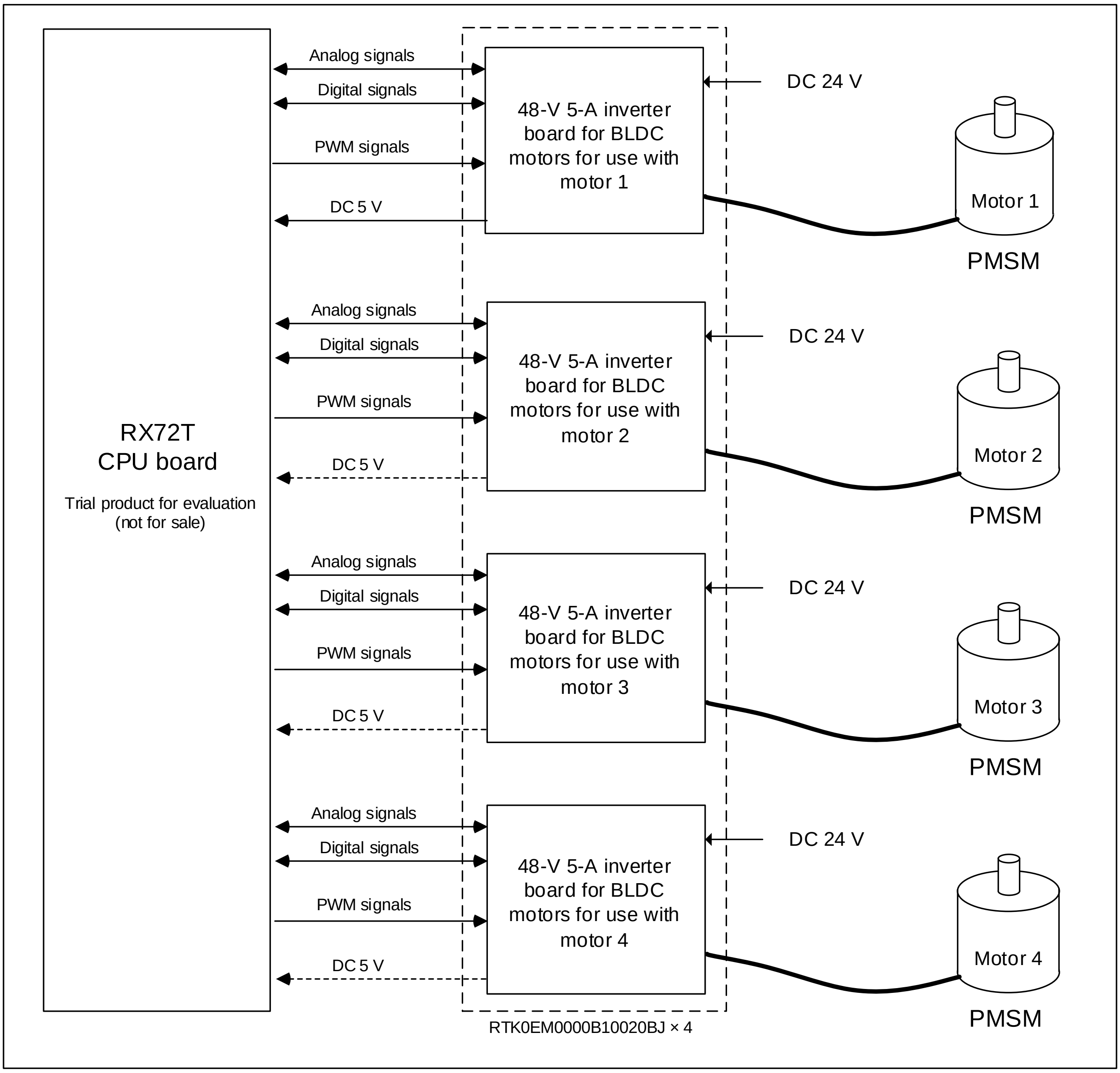


Figure 2-2 Hardware Configuration Diagram

2.1.2 Motor 1 Hardware Configuration

The figure below shows a hardware connection configuration for motor 1.

For details on the interfaces of individual pins, refer to 2.2.1, Motor 1 Hardware Specifications.

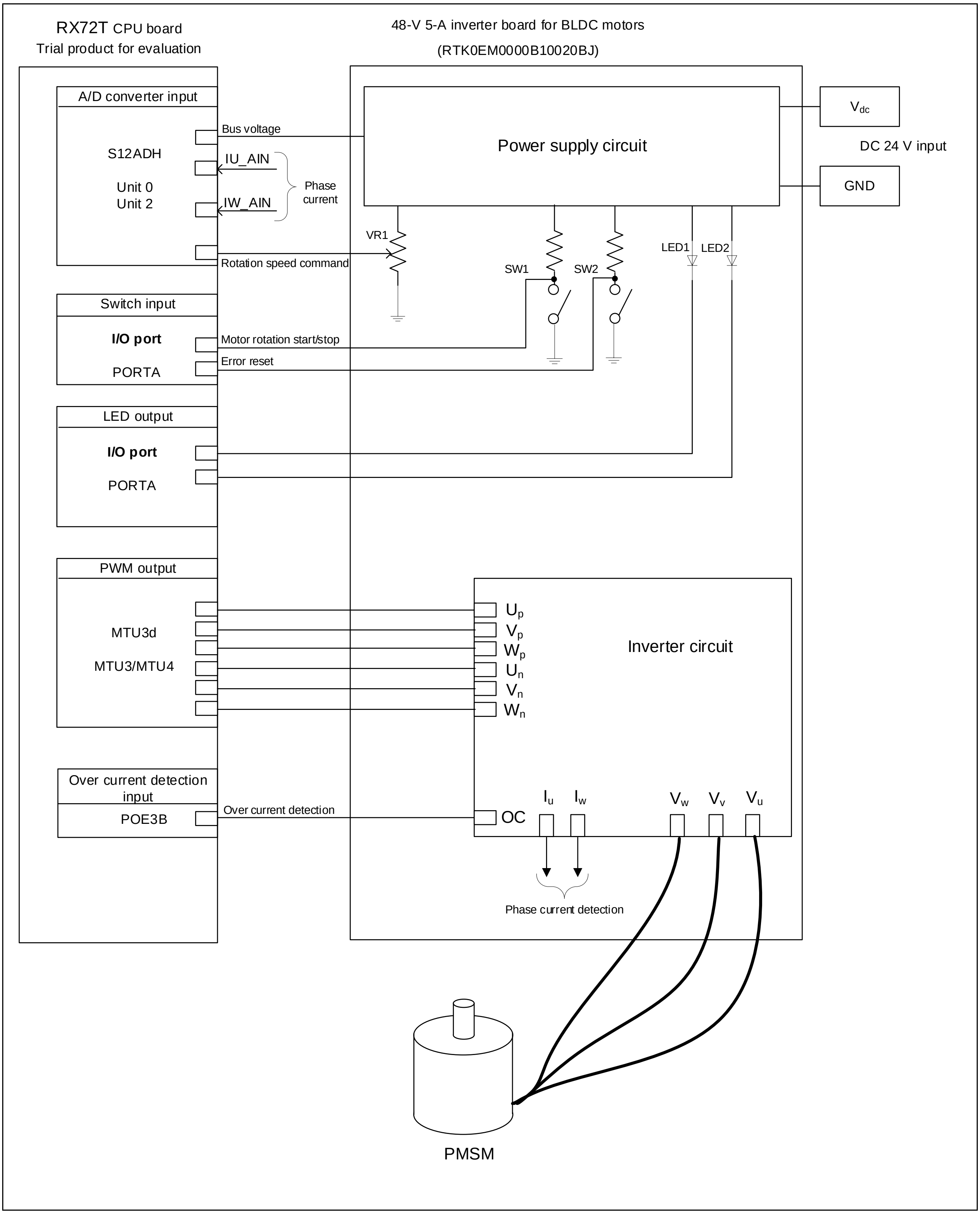


Figure 2-3 Hardware Connection Configuration Diagram for Motor 1

2.1.3 Motor 2 Hardware Configuration

The figure below shows a hardware connection configuration for motor 2.

For details on the interfaces of individual pins, refer to 2.2.2, Motor 2 Hardware Specifications.

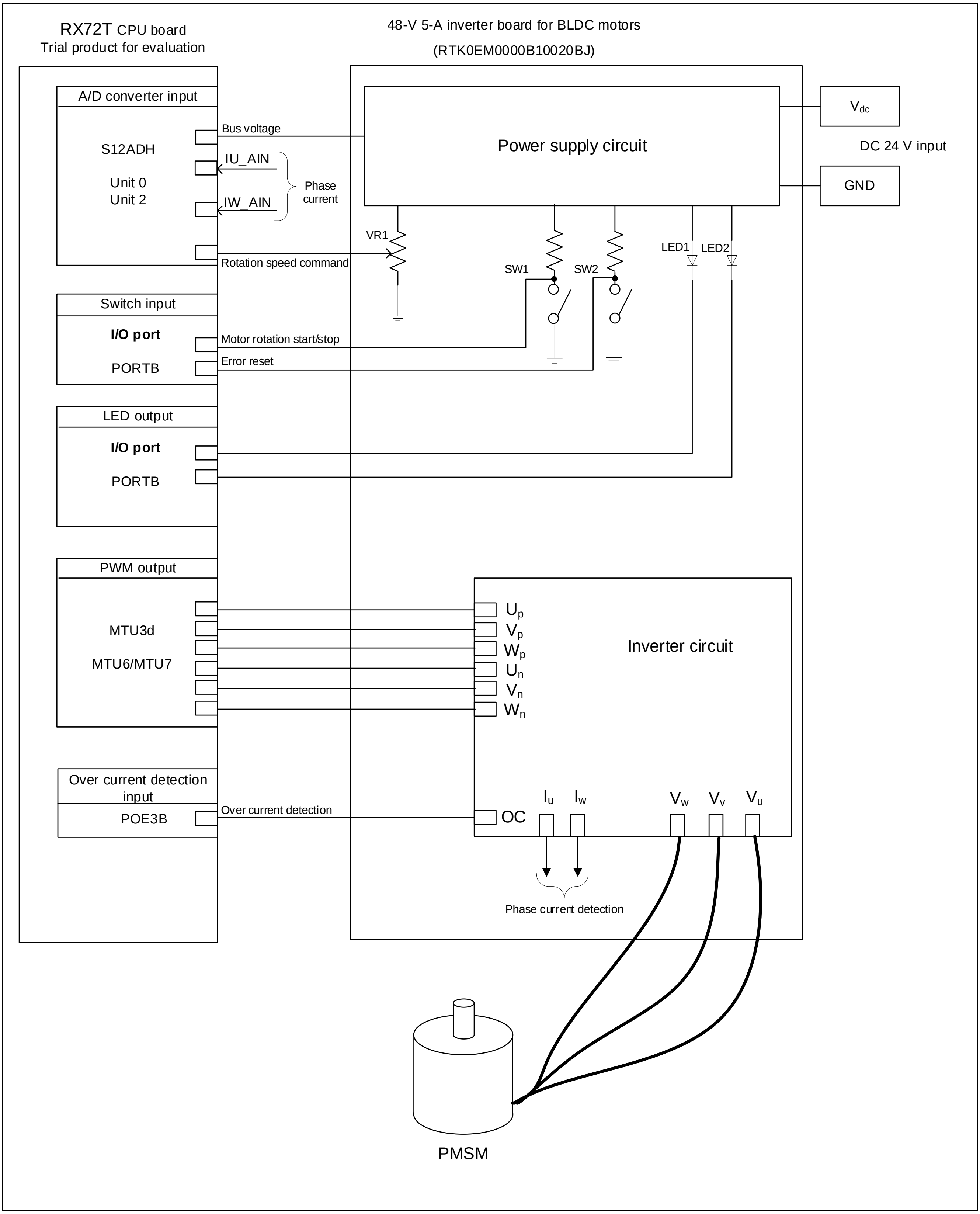


Figure 2-4 Hardware Connection Configuration Diagram for Motor 2

2.1.4 Motor 3 Hardware Configuration

The figure below shows a hardware connection configuration for motor 3.

For details on the interfaces of individual pins, refer to 2.2.3, Motor 3 Hardware Specifications.

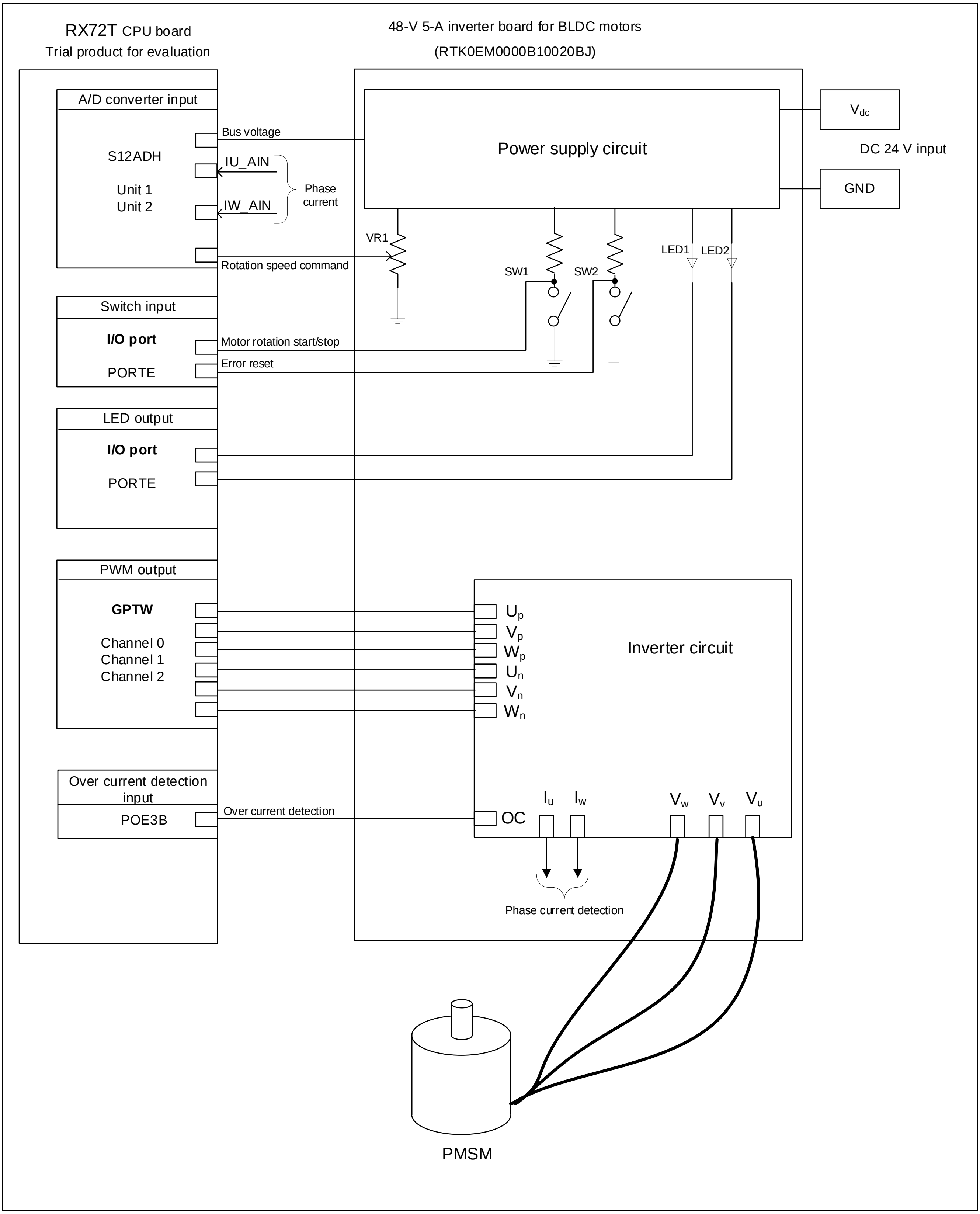


Figure 2-5 Hardware Connection Configuration Diagram for Motor 3

2.1.5 Motor 4 Hardware Configuration

The figure below shows a hardware connection configuration for motor 4.

For details on the interfaces of individual pins, refer to 2.2.4, Motor 4 Hardware Specifications.

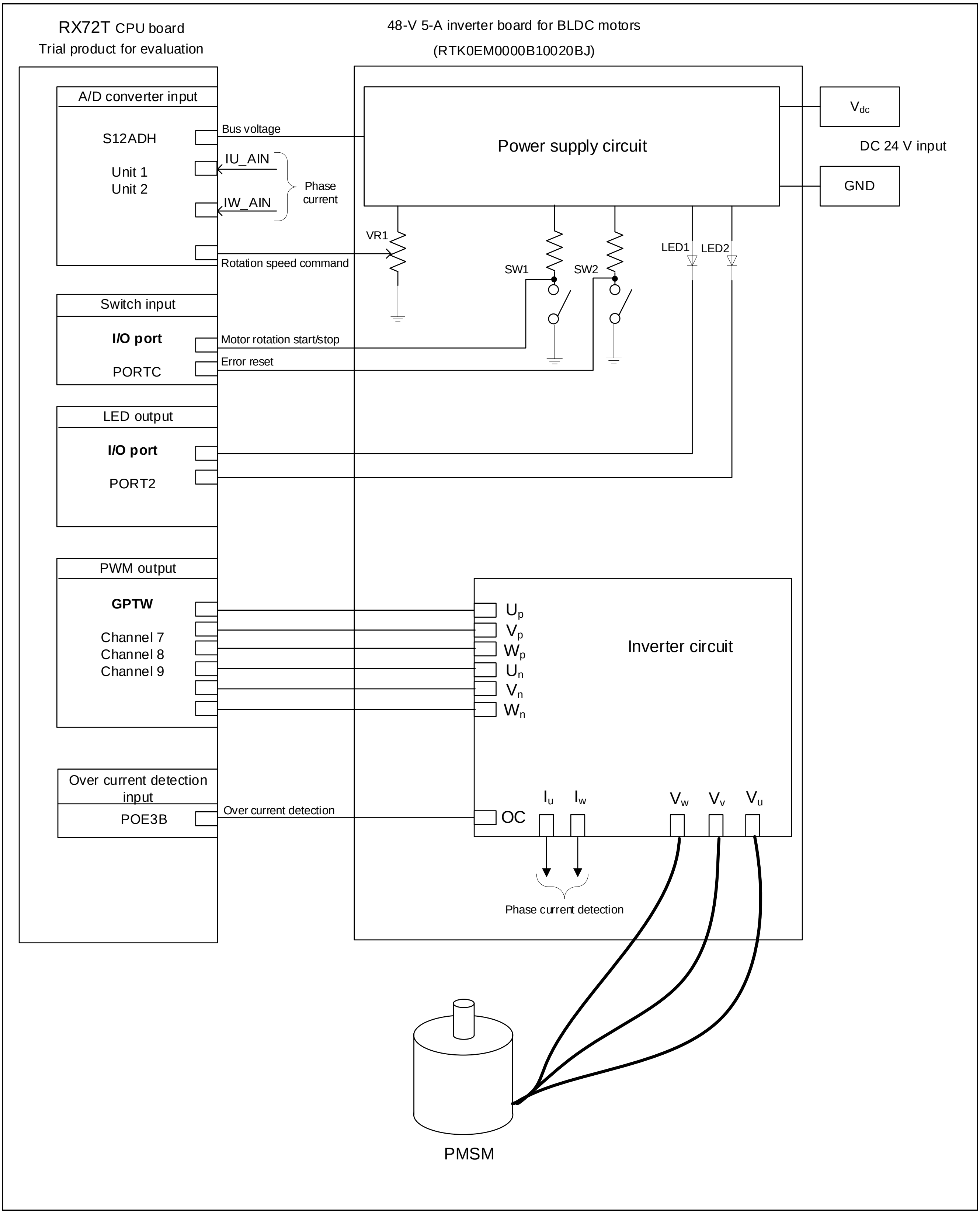


Figure 2-6 Hardware Connection Configuration Diagram for Motor 4

2.2 Hardware Specifications

2.2.1 Motor 1 Hardware Specifications

(1) User Interface

Table 2-1 lists the parts for the user interface for motor 1.

Table 2-1 User Interface for Motor 1

Item	Parts for the User Interface	Function
Rotation speed	Variable resistor (VR1_1)	Reference value of rotation speed input (analog value)
START/STOP	Toggle switch (SW1_1)	Motor rotation start/stop command
ERROR RESET	Push switch (SW2_1)	Command of recovery from error status
LED1_1	Orange LED	• At the time of motor rotation: ON • At the time of stop: OFF
LED2_1	Orange LED	• At the time of error detection: ON • At the time of normal operation: OFF
RESET	Push switch	System reset (shared by the other motors)

(2) Port Interfaces

Table 2-2 lists the port interfaces for motor 1.

Table 2-2 Port Interfaces for Motor 1

R5F572TKCDFB port name	Function
P50/AN204	Inverter bus voltage measurement
P51/AN205	For rotation speed command value input (analog value)
PA4	START/STOP toggle switch
PA5	ERROR RESET toggle switch
PA0	LED1 ON/OFF control
PA1	LED2 ON/OFF control
P40/AN000	U phase current measurement
P42/AN002	W phase current measurement
P71/MTIOC3B	PWM output (U_p) / Low active
P72/MTIOC4A	PWM output (V_p) / Low active
P73/MTIOC4B	PWM output (W_p) / Low active
P74/MTIOC3D	PWM output (U_n) / High active
P75/MTIOC4C	PWM output (V_n) / High active
P76/MTIOC4D	PWM output (W_n) / High active
P70/POE0#	PWM emergency stop input at the time of over-current detection

(3) Peripheral Functions

Table 2-3 lists the peripheral functions used for motor 1.

Table 2-3 List of the Peripheral Functions

12-bit A/D Converter	CMT	MTU3d	POE3B
• Rotation speed command value input • Current of each phase U and W measurement • Inverter bus voltage measurement	500 [µs] interval timer	Complementary PWM output	Set PWM output ports to high impedance state to stop the PWM output.

(a) 12-Bit A/D Converter (S12ADH)

U phase current (I_u), W phase current (I_w), inverter bus voltage (V_{dc}) and rotation speed reference are measured by using the single scan mode (use hardware trigger). The sample-and-hold function is used for U phase current (I_u) and W phase current (I_w) measurement.

(b) Compare Match Timer (CMT)

The channel 0 compare match timer is used as 500 [µs] interval timer.
Note: This timer is shared by the other motors.

(c) Multi-Function Timer Pulse Unit 3 (MTU3d)

On channels 3 and 4, output (p-side active level: low, n-side active level: high) with dead time is performed by using the complementary PWM mode.

(d) Port Output Enable 3 (POE3B)

Detecting an overcurrent (detecting a falling edge of the signal on the POE0# pin corresponding to the given motor) and a short-circuit between outputs places the PWM output ports in the high-impedance state.

2.2.2 Motor 2 Hardware Specifications

(1) User Interface

Table 2-4 lists the parts for the user interface for motor 2.

Table 2-4 User Interface for Motor 2

Item	Parts for the User Interface	Function
Rotation speed	Variable resistor (VR1_2)	Reference value of rotation speed input (analog value)
START/STOP	Toggle switch (SW1_2)	Motor rotation start/stop command
ERROR RESET	Push switch (SW2_2)	Command of recovery from error status
LED1_2	Orange LED	• At the time of motor rotation: ON • At the time of stop: OFF
LED2_2	Orange LED	• At the time of error detection: ON • At the time of normal operation: OFF
RESET	Push switch	System reset (shared by the other motors)

(2) Port Interfaces

Table 2-5 lists the port interfaces for motor 2.

Table 2-5 Port Interfaces for Motor 2

R5F572TKCDFB port name	Function
P52/AN200	Inverter bus voltage measurement
P53/AN201	For rotation speed command value input (analog value)
PB4	START/STOP toggle switch
PB5	ERROR RESET toggle switch
PB0	LED1 ON/OFF control
PB1	LED2 ON/OFF control
P43/AN003	U phase current measurement
PH2/AN005	W phase current measurement
P92/MTIOC6D	PWM output (U_p) / Low active
P91/MTIOC7C	PWM output (V_p) / Low active
P90/MTIOC7D	PWM output (W_p) / Low active
P95/MTIOC6B	PWM output (U_n) / High active
P94/MTIOC7A	PWM output (V_n) / High active
P93/MTIOC7B	PWM output (W_n) / High active
P96/POE4#	PWM emergency stop input at the time of over-current detection

(3) Peripheral Functions

Table 2-6 lists the peripheral functions used for motor 2.

Table 2-6 List of the Peripheral Functions

12-bit A/D Converter	CMT	MTU3d	POE3B
• Rotation speed command value input • Current of each phase U and W measurement • Inverter bus voltage measurement	500 [µs] interval timer	Complementary PWM output	Set PWM output ports to high impedance state to stop the PWM output.

(a) 12-bit A/D Converter

U phase current (I_u), W phase current (I_w), inverter bus voltage (V_{dc}) and rotation speed reference are measured by using the single scan mode (use hardware trigger). The sample-and-hold function is used for U phase current (I_u) and W phase current (I_w) measurement.

(b) Compare Match Timer (CMT)

The channel 0 compare match timer is used as 500 [µs] interval timer.
Note: This timer is shared by the other motors.

(c) Multi-Function Timer Pulse Unit 3 (MTU3d)

On channels 6 and 7, output (p-side active level: low, n-side active level: high) with dead time is performed by using the complementary PWM mode.

(d) Port Output Enable 3 (POE3B)

Detecting an overcurrent (detecting a falling edge of the signal on the POE4# pin corresponding to the given motor) and a short-circuit between outputs places the PWM output ports in the high-impedance state.

2.2.3 Motor 3 Hardware Specifications

(1) User Interface

Table 2-7 lists the parts for the user interface for motor 3.

Table 2-7 User Interface for Motor 3

Item	Parts for the User Interface	Function
Rotation speed	Variable resistor (VR1_3)	Reference value of rotation speed input (analog value)
START/STOP	Toggle switch (SW1_3)	Motor rotation start/stop command
ERROR RESET	Push switch (SW2_3)	Command of recovery from error status
LED1_3	Orange LED	• At the time of motor rotation: ON • At the time of stop: OFF
LED2_3	Orange LED	• At the time of error detection: ON • At the time of normal operation: OFF
RESET	Push switch	System reset (shared by the other motors)

(2) Port Interfaces

Table 2-8 lists the port interfaces for motor 3.

Table 2-8 Port Interfaces for Motor 3

R5F572TKCDFB port name	Function
P54/AN202	Inverter bus voltage measurement
P55/AN203	For rotation speed command value input (analog value)
PE4	START/STOP toggle switch
PE5	ERROR RESET toggle switch
PE0	LED1 ON/OFF control
PE1	LED2 ON/OFF control
P44/AN100	U phase current measurement
P46/AN102	W phase current measurement
PD7/GTIOC0A	PWM output (U_p) / Low active
PD5/GTIOC1A	PWM output (V_p) / Low active
PD3/GTIOC2A	PWM output (W_p) / Low active
PD6/GTIOC0B	PWM output (U_n) / High active
PD4/GTIOC1B	PWM output (V_n) / High active
PD2/GTIOC2B	PWM output (W_n) / High active
P01/POE12#	PWM emergency stop input at the time of over-current detection

(3) Peripheral Functions

Table 2-9 lists the peripheral functions used for motor 3.

Table 2-9 List of the Peripheral Functions

12-bit A/D Converter	CMT	GPTW	POE3B
• Rotation speed command value input • Current of each phase U and W measurement • Inverter bus voltage measurement	500 [µs] interval timer	PWM output	Set PWM output ports to high impedance state to stop the PWM output.

(a) 12-bit A/D Converter

U phase current (I_u), W phase current (I_w), inverter bus voltage (V_{dc}) and rotation speed reference are measured by using the single scan mode (use hardware trigger). The sample-and-hold function is used for U phase current (I_u) and W phase current (I_w) measurement.

(b) Compare Match Timer (CMT)

The channel 0 compare match timer is used as 500 [µs] interval timer.
Note: This timer is shared by the other motors.

(c) General PWM Timer (GPTW)

On channels 0, 1 and 2, output (p-side active level: low, n-side active level: high) with dead time is performed by using the PWM mode.

(d) Port Output Enable 3 (POE3B)

Detecting an overcurrent (detecting a falling edge of the signal on the POE12# pin corresponding to the given motor) and a short-circuit between outputs places the PWM output ports in the high-impedance state.

2.2.4 Motor 4 Hardware Specifications

(1) User Interface

Table 2-10 lists the parts for the user interface for motor 4.

Table 2-10 User Interface for Motor 4

Item	Parts for the User Interface	Function
Rotation speed	Variable resistor (VR1_4)	Reference value of rotation speed input (analog value)
START/STOP	Toggle switch (SW1_4)	Motor rotation start/stop command
ERROR RESET	Push switch (SW2_4)	Command of recovery from error status
LED1_4	Orange LED	• At the time of motor rotation: ON • At the time of stop: OFF
LED2_4	Orange LED	• At the time of error detection: ON • At the time of normal operation: OFF
RESET	Push switch	System reset (shared by the other motors)

(2) Port Interfaces

Table 2-11 lists the port interfaces for motor 4.

Table 2-11 Port Interfaces for Motor 4

R5F572TKCDFB port name	Function
P60/AN206	Inverter bus voltage measurement
P61/AN207	For rotation speed command value input (analog value)
PC3	START/STOP toggle switch
PC4	ERROR RESET toggle switch
P20	LED1 ON/OFF control
P21	LED2 ON/OFF control
P47/AN103	U phase current measurement
PH6/AN105	W phase current measurement
P15/GTIOC7B	PWM output (U_p) / Low active
P16/GTIOC8B	PWM output (V_p) / Low active
P17/GTIOC9B	PWM output (W_p) / Low active
P12/GTIOC7A	PWM output (U_n) / High active
P13/GTIOC8A	PWM output (V_n) / High active
P14/GTIOC9A	PWM output (W_n) / High active
PK0/POE14#	PWM emergency stop input at the time of over-current detection

(3) Peripheral Functions

Table 2-12 lists the peripheral functions used for motor 4.

Table 2-12 List of the Peripheral Functions

12-bit A/D Converter	CMT	GPTW	POE3B
• Rotation speed command value input • Current of each phase U and W measurement • Inverter bus voltage measurement	500 [µs] interval timer	PWM output	Set PWM output ports to high impedance state to stop the PWM output.

(a) 12-bit A/D Converter

U phase current (I_u), W phase current (I_w), inverter bus voltage (V_{dc}) and rotation speed reference are measured by using the single scan mode (use hardware trigger). The sample-and-hold function is used for U phase current (I_u) and W phase current (I_w) measurement.

(b) Compare Match Timer (CMT)

The channel 0 compare match timer is used as 500 [µs] interval timer.
Note: This timer is shared by the other motors.

(c) General PWM Timer (GPTW)

On channels 7, 8 and 9, output (p-side active level: low, n-side active level: high) with dead time is performed by using the PWM mode.

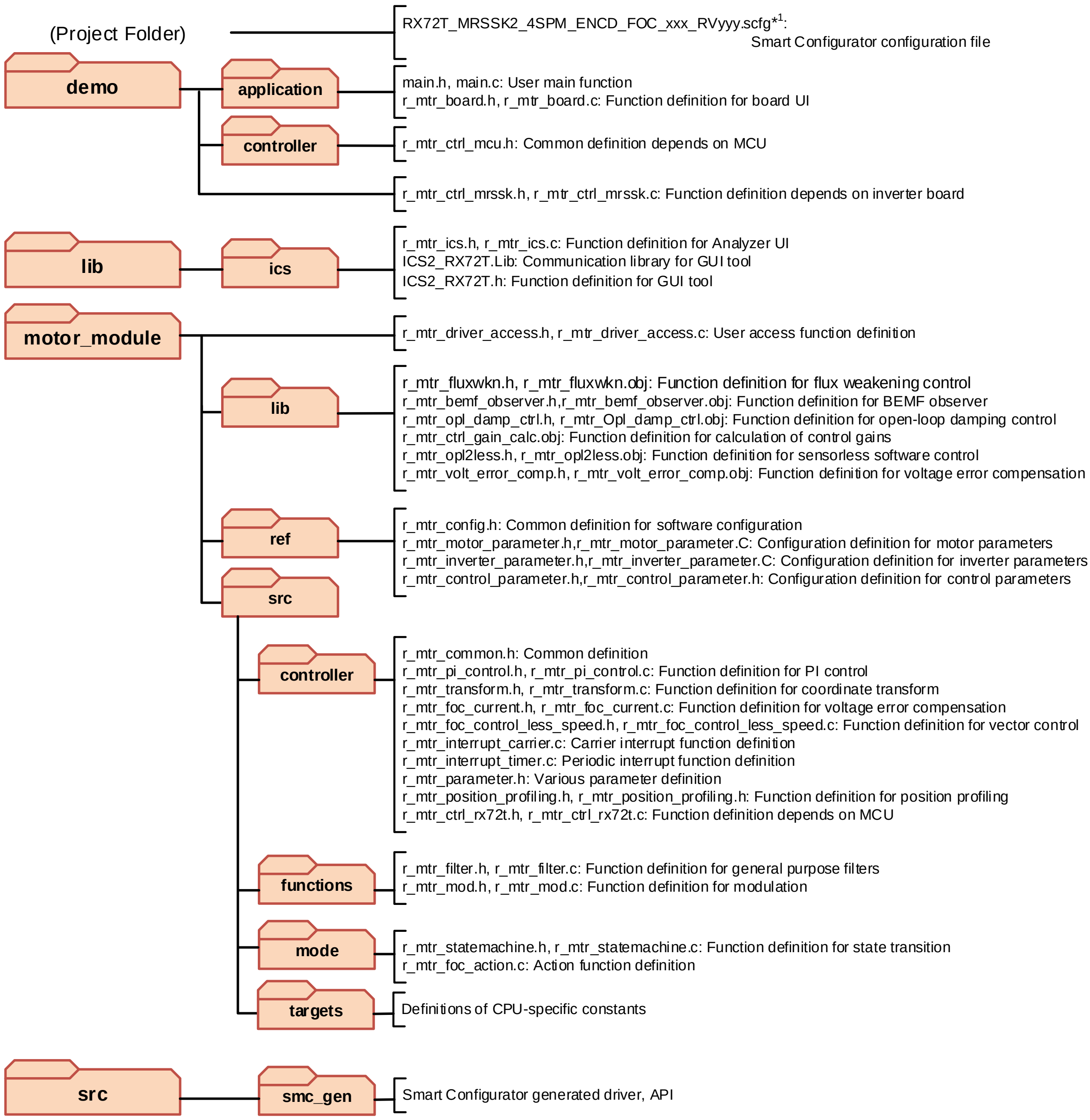
(d) Port Output Enable 3 (POE3B)

Detecting an overcurrent (detecting a falling edge of the signal on the POE14# pin corresponding to the given motor) and a short-circuit between outputs places the PWM output ports in the high-impedance state.

2.3 Software Configuration

2.3.1 Software File Configuration

Folder and file configuration of the software are given below.



Notes: 1. xxx: CSP refers to CS+ version. E2S refers to e[2] studio version. yyy: revision version number e.g.110: Rev.version 1.10
2. Regarding the specification of Analyzer function in the motor control development support tool ‘Renesas Motor Workbench’, please refer to the section 4.The identifier ‘ics/ICS (ICS is previous motor control development support tool ‘In Circuit Scope’) is attached to the name of folders, files, functions, variables related to ‘Renesas Motor Workbench’.

Figure 2-7 Folder and File Configuration

2.3.2 Smart Configurator File Configuration

Peripheral drivers were configured easily by using Smart Configurator tool for this project.

When three or more motors are to be driven, individually set up the software components such as those for the multi-function timer pulse unit, general-purpose PWM timer, and 12-bit A/D converter instead of using the motor-dedicated components.

Smart Configurator saves information such as the target MCU, peripheral, clock and pin functions setting for the project in *.scfg file.

Refer to the file, RX72T_MRSSK2_4SPM_LESS_FOC_xxx_RVyyy.scfg in the root folder to see the peripheral settings of this project.
(xxx: CSP refers to CS+ version. E2S refers to e^2 studio version. yyy: revision version number)

Folder and file configuration of Smart Configurator generated output are shown below.

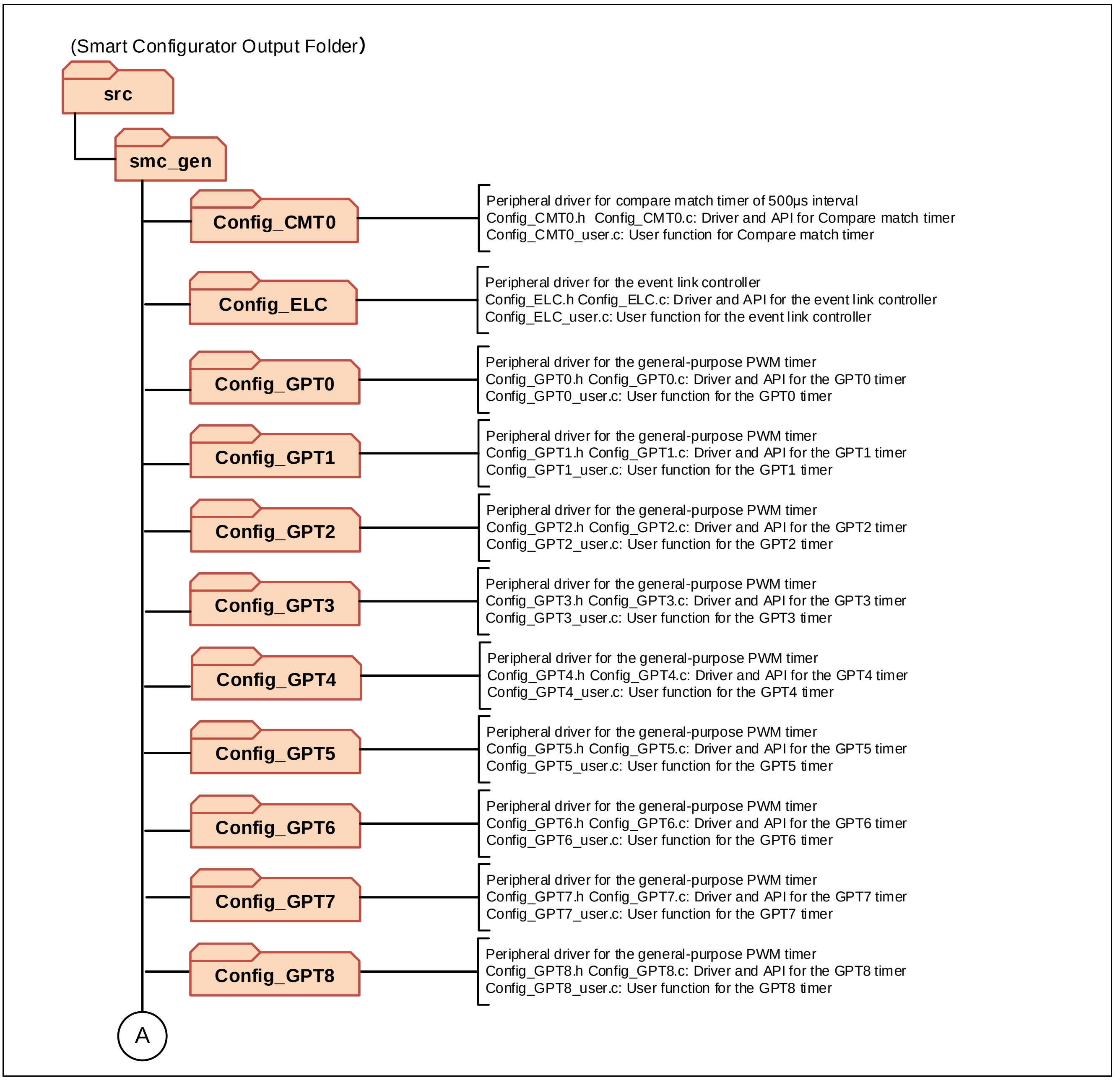
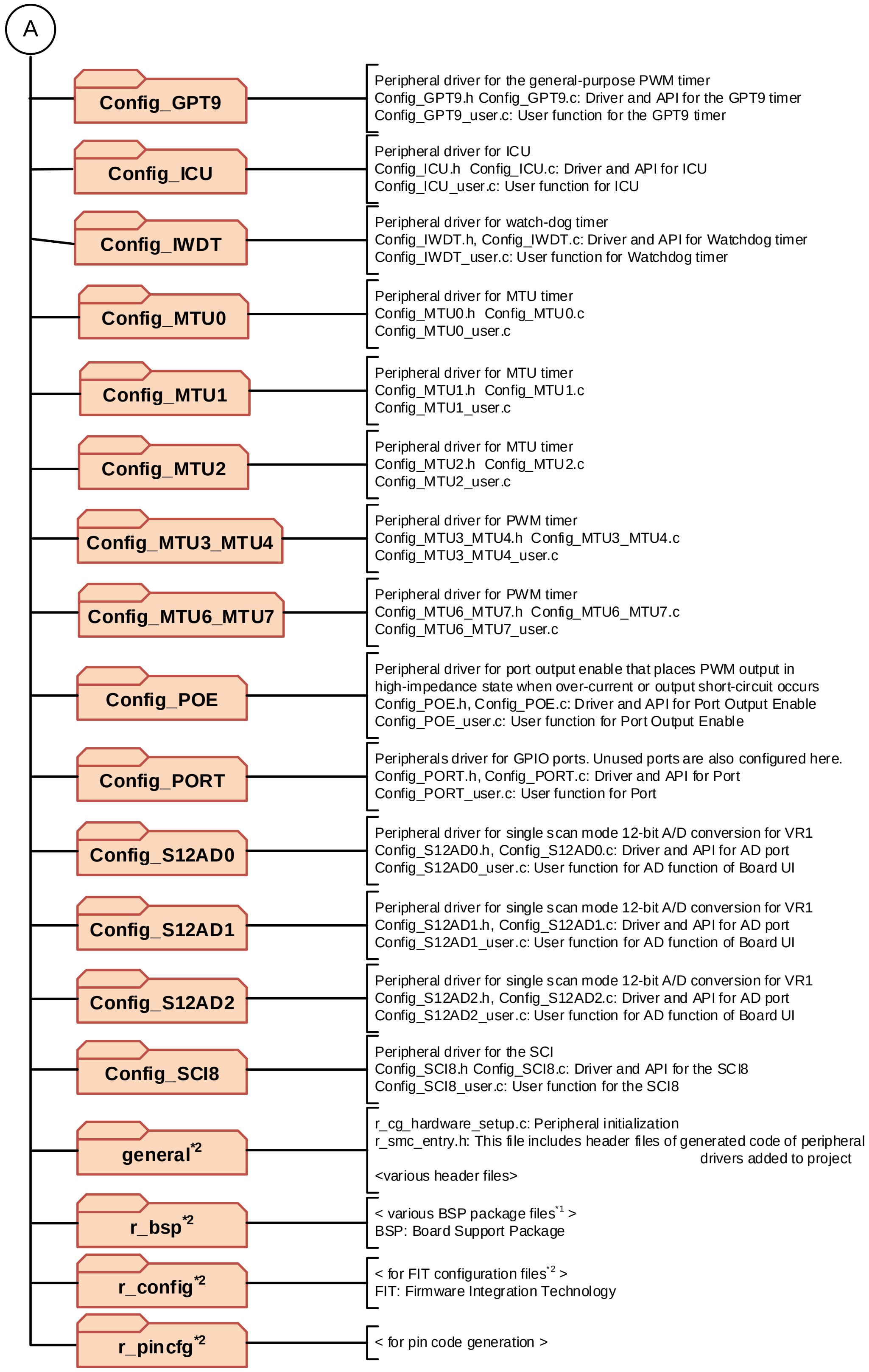


Figure 2-8 Smart Configurator Folder and File Configurations (1/2)



Notes: 1. xxx: CSP as this string indicates the CS+ version and E2S indicates the e[2] studio version. yyy indicates the version and revision number. For example, 110 is rev. 1.10.

2. Regarding the specifications of the analyzer function in the Renesas Motor Workbench support tool for motor control development, refer to section 4.
The identifier ics or ICS (for In Circuit Scope, an earlier version of the Renesas motor control development support tool) may be attached to the names of folders, files, functions, and variables related to the 'Renesas Motor Workbench'.

Figure 2-8 Smart Configurator Folder and File Configurations (2/2)

2.3.3 Module Configuration

Module configuration of the software is described below.

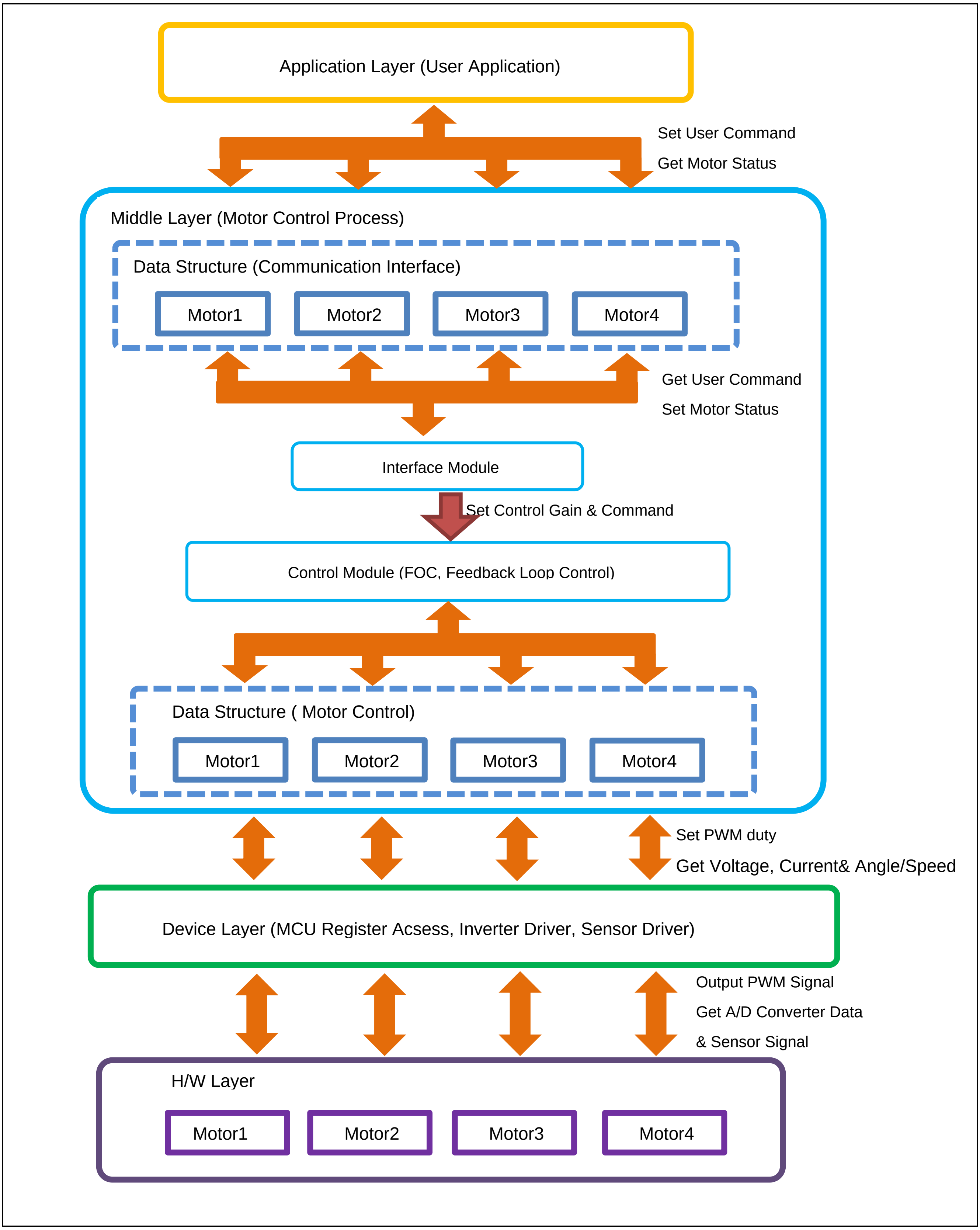


Figure 2-9 Module Configuration

2.4 Software Specifications

2.4.1 Basic Specifications of Sensorless Vector Control Software

Table 2-13 shows basic software specification of this system. For details of the sensorless vector control, refer to the application note ‘Sensorless vector control for permanent magnet synchronous motor (Algorithm)’.

Table 2-13 Basic Specifications of Sensorless Vector Control Software

Item	Content	
Control method	Vector control	
Position detection method	Sensorless	
Motor rotation start/stop	Determined depending on the level of SW1 (‘Low’: rotation start, ‘High’: stop) or input from Analyzer	
Input voltage	DC 24 [V]	
Carrier frequency (PWM)	20 [kHz] (Carrier cycle: 50 [μs])	
Dead time	2 [μs]	
Control period	Current control / Position and speed estimation: 50 [μs] Speed control: 500 [μs]	
Rotation speed control range	CW: 0 [rpm] to 2650 [rpm] CCW: 0 [rpm] to 2650 [rpm] When less than 600 [rpm], the motor is driven under Speed Open-loop control.*	
Natural frequency of each control system	Current control system: 300 [Hz] Speed control system: 3 [Hz] BEMF estimation system: 1000 [Hz] Position estimation system: 50 [Hz]	
Optimization setting of compiler	Optimization level	2 (-optimize = 2) (default setting)
	Optimization method	Size priority (-size) (default setting)
Processing stop for protection	• Disables the motor control signal output (six outputs), under any of the following conditions. 1. Current of each phase exceeds 0.89 [A] (monitored every 50 [μs]) 2. Inverter bus voltage exceeds 28 [V] (monitored every 50 [μs]) 3. Inverter bus voltage is less than 14 [V] (monitored every 50 [μs]) 4. Rotation speed exceeds 3000 [rpm] (monitored every 50 [μs]) • When an external over-current signal is detected (when a falling edge of the POE0# port is detected) or when the output short circuit is detected, the PWM output ports are set to high impedance state.	

Note: * Set rotation speed command value higher than 600 [rpm] in order to rotate motor by Sensorless vector control.

2.4.2 Handling Control over Four Motors

In this system, the timing of execution of the various types of processing such as control processing for each of the motors and A/D conversion for use in current detection is designed for driving four motors at the same time. The MTU and GPTW are used to output complementary PWM pulses as the patterns for driving the motors. These modules each drive two motors.

Moreover, in this system, A/D conversion module units 0 and 1 are used in current detection for the motors driven by the MTU and GPTW (4 motors in total), respectively. Since the motor currents must be detected at the intended times, the A/D conversion module units for use in current detection of the motors are handled such that their operations are not delayed.

A three shunt resistor-based current sensing circuit is used for this system and current can be detected while the lower arm of the inverter is on. When a single A/D conversion module is to be used for current detection for two motors, current can be detected unless periods over which the lower arm of one inverter is on overlap with those for the other inverter.

For this reason, this system employs a method of switching the normal- and inverse-phase outputs on the PWM output pins and the signals for the upper and lower arms of the inverter with respect to the motors respectively driven by the MTU and GPTW as indicated in Table 2-2, Table 2-5, Table 2-8, and Table 2-11. This makes the PWM signal switching pattern for one motor the inverse of that for the other, thus preventing overlaps between the periods over which the lower arms of the corresponding inverters are on.

How to use the method above to implement the sensorless vector control software which is described on the previous page for four motors is described on the following pages.

2.4.3 Implementing the Software for Control over Four Motors

Figure 2-10 and Figure 2-11 below and on the next page show the times at which PWM interrupt processing and A/D conversion for use in current detection proceed and the PWM output level is transferred to the buffer. Figure 2-10 is for the case of motors 1 and 2 (for which MTU3, MTU4, MTU6, and MTU7 and the S12AD module are in use) and Figure 2-11 is for the case of motors 3 and 4 (for which GPTW0 to GPTW2 and GPTW7 to GPTW9 and the S12AD1 module are in use).

If the timers for the MTU and GPTW in the cases described in Figure 2-10 and Figure 2-11 are to be started simultaneously with the same carrier frequency settings, the PWM periodic interrupt processing for use with the MTU and GPTW will be executed with the same timing. In this case, as these interrupts have the same priority level, the interrupt processing is executed in order, starting with the interrupt that was first to have been issued.

The processing for these two PWM interrupts proceeds within half of the PWM carrier cycle (25 µs at the carrier frequency of 20 kHz), so the difference in times does not create a problem.

(1) Timing of processing for motors 1 and 2

The times at which A/D conversion proceeds are distributed to the crests and valleys of the PWM carrier cycles by synchronizing the MTU timers for motors 1 and 2 with each other as shown in Figure 2-10. The times at which the PWM periodic interrupt processing is executed and the value of the buffer register is transferred are adjusted according to the times to which the A/D conversion is distributed.

Moreover, A/D conversion with the use of the group scan mode enables a single A/D converter unit to detect the currents for two motors.

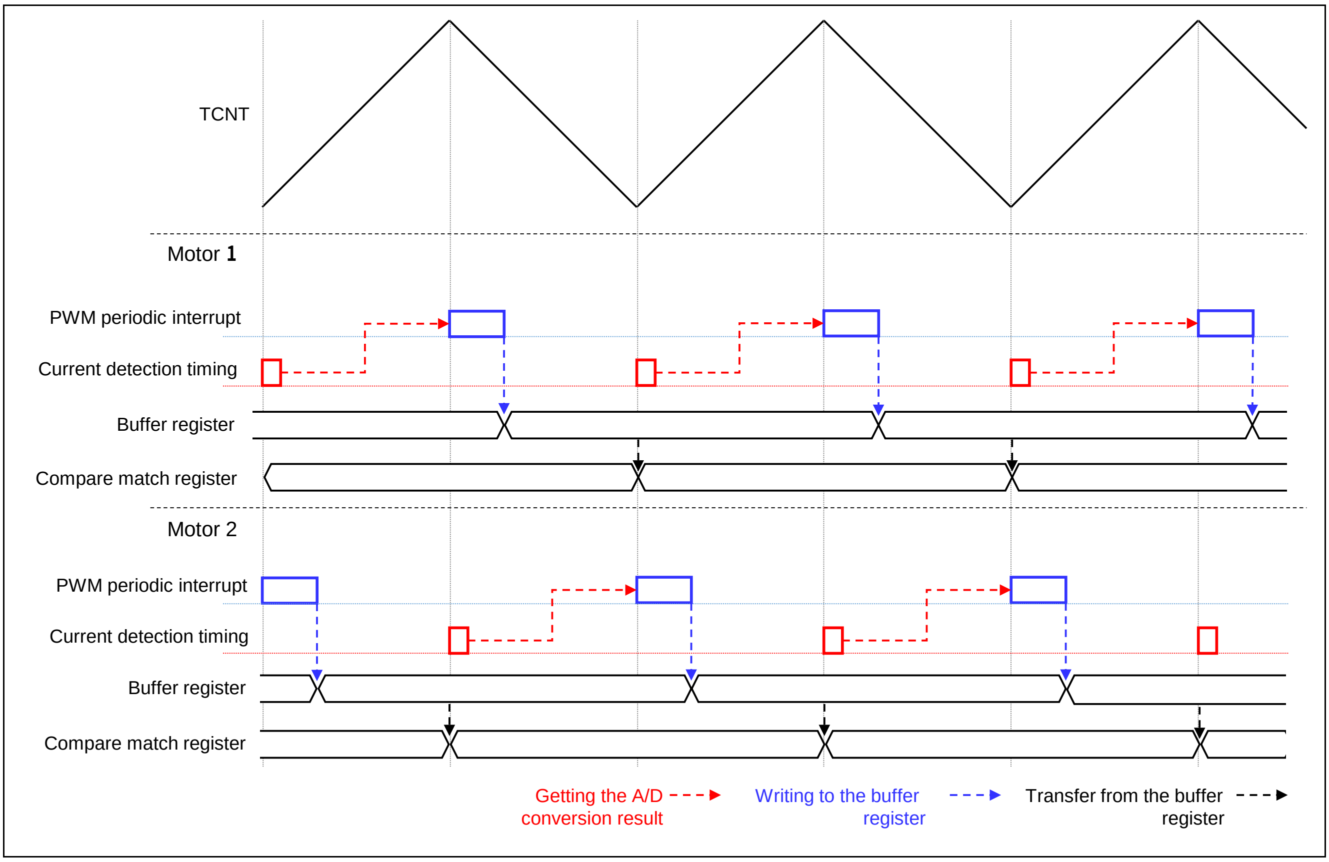


Figure 2-10 Timing of the Various Types of Processing for Motors 1 and 2

(2) Timing of processing for motors 3 and 4

Figure 2-11 shows the timing of the various types of processing for motors 3 and 4. Only the timing of transfer from the buffer register for motor 4 differs from that for the other motors, as is seen in the figures. In transfer at valleys, however, the value will not have been updated, so the actual operation is effectively the same as that for motors 1 and 2. This timing specific to motor 4 is because the GPTW, which is used with motors 3 and 4, does not have a setting for buffer transfer only at crests.

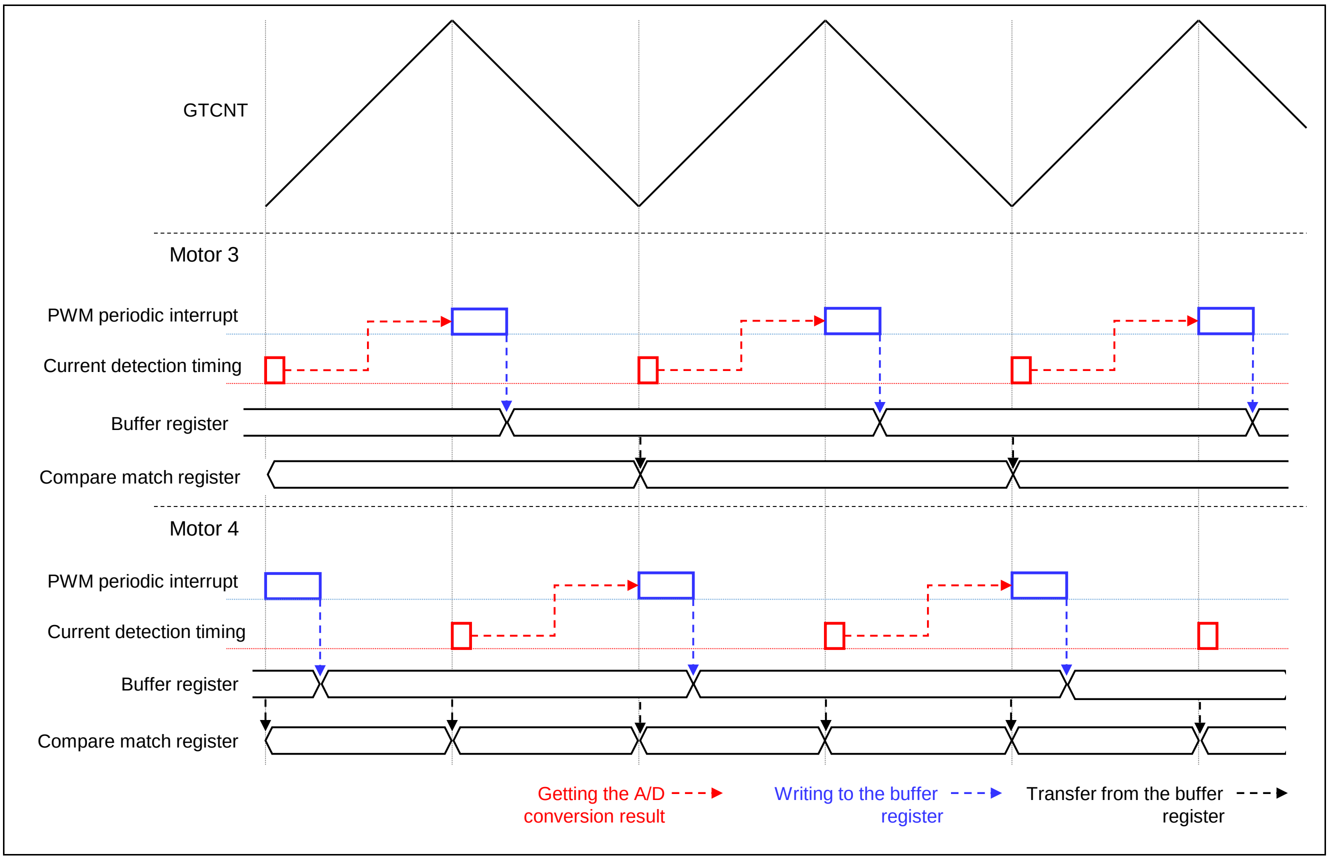


Figure 2-11 Timing of the Various Types of Processing for Motors 3 and 4

2.4.4 A/D Conversion Configuration

Table 2-14 lists the intended uses of conversion by the A/D converter units.

Table 2-14 Intended Uses of Conversion by the A/D Converter Units

A/D Converter Unit	Use
S12AD	Current measurement for motors 1 and 2
S12AD1	Current measurement for motors 3 and 4
S12AD2	Inverter bus voltage measurement, by reading the voltage across VR1

3. Descriptions of the Control Program

The target software of this application note is explained here.

3.1 Contents of Control

3.1.1 Motor Start/Stop

The start and stop of the motor are controlled by input from Analyzer function of ‘Renesas Motor Workbench’ or SW1 switch of inverter board.

A general-purpose port is assigned to SW1. The port is read within the main loop. When the port is at a ‘Low’ level, the software determines that the motor should be started. Conversely, when the level is switched to ‘High’ level, the software determines that the motor should be stopped.

3.1.2 A/D Converter

(1) Motor Rotation Speed Reference

The motor rotation speed reference can be set by Analyzer input or A/D conversion of the VR1 output value (analog value). The A/D converted VR1 value is used as rotation speed command value, as shown below.

Table 3-1 Conversion Ratio of the Rotation Speed Reference

Item	Conversion ratio (Reference: A/D conversion value)		Channel
Rotation speed reference	CW	0 rpm to 2700 rpm: 07FFH to 0000H	AN205: Motor 1 AN201: Motor 2 AN203: Motor 3 AN207: Motor 4
	CCW	0 rpm to 2700 rpm: 0800H to 0FFFH	

(2) Inverter Bus Voltage

Inverter bus voltage is measured as given in Table 3-2.

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

Table 3-2 Inverter Bus Voltage Conversion Ratio

Item	Conversion ratio (Inverter bus voltage: A/D conversion value)	Channel
Inverter bus voltage	0 [V] to 111 [V]: 0000H to 0FFFH	AN204: Motor 1 AN200: Motor 2 AN202: Motor 3 AN206: Motor 4

(3) U, W Phase Current

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

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

Item	Conversion ratio (U, W phase current: A/D conversion value)	Channel
U, W phase current	-12.5 [A] to 12.5 [A]: 0000H to 0FFFH*	Iu: AN000: Motor 1 Iw: AN002 Iu: AN003: Motor 2 Iw: AN004 Iu: AN100: Motor 3 Iw: AN102 Iu: AN103: Motor 4 Iw: AN105

Note: * For more details of A/D conversion characteristics, refer to 'RX72T Group User's Manual: Hardware'.

3.1.3 Modulation

The target software of this application note uses pulse width modulation (hereinafter called PWM) to generate the input voltage to the motor. And the PWM waveform is generated by the triangular wave comparison method.

(1) Triangular Wave Comparison Method

The triangular wave comparison method is used to output the voltage command value. By this method, the pulse width of the output voltage can be determined by comparing the carrier waveform (triangular wave) and voltage command value waveform. The voltage command value of the pseudo sinusoidal wave can be output by turning the switch on or off when the voltage command value is larger or smaller than the carrier wave respectively.

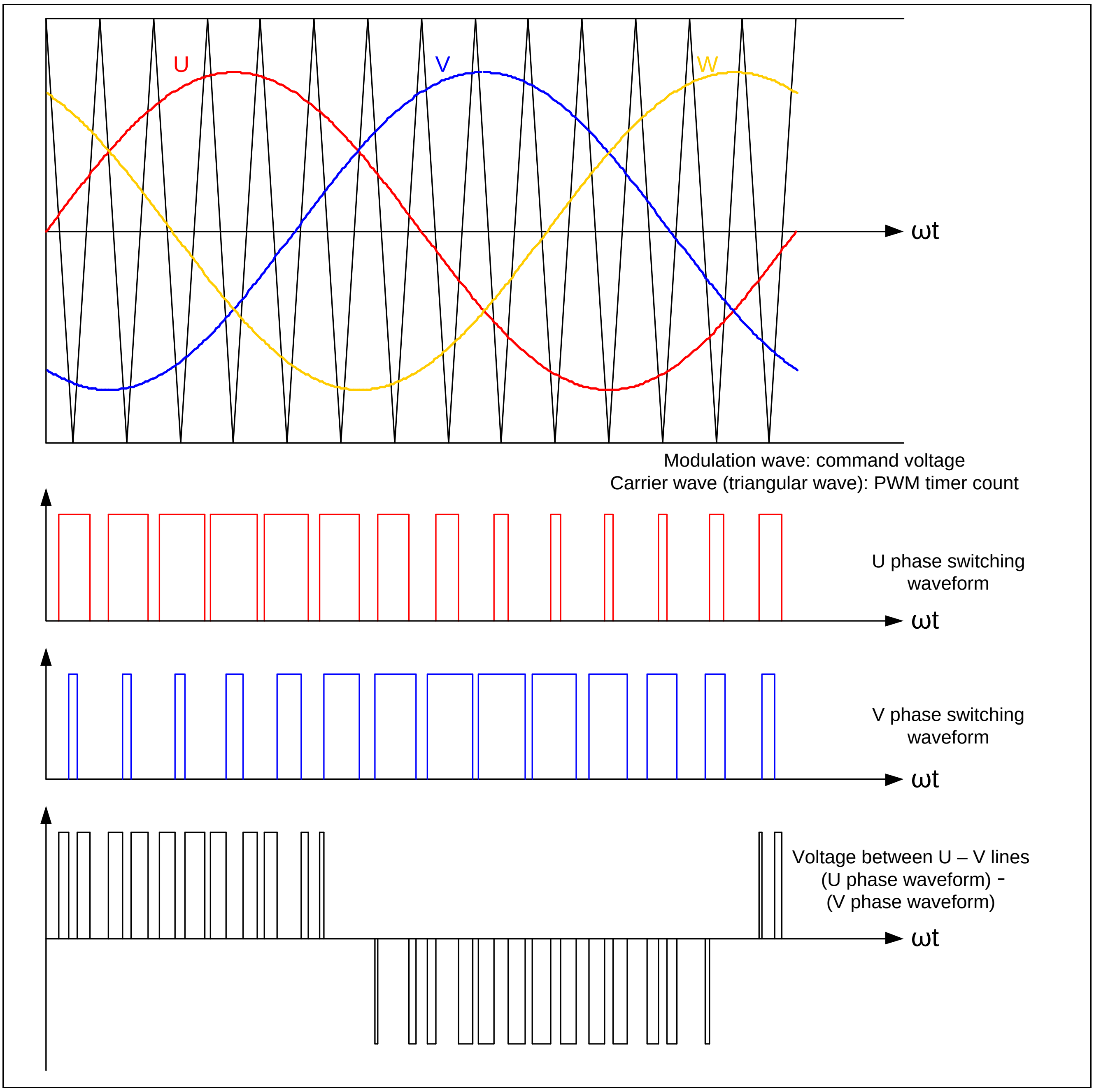


Figure 3-1 Conceptual Diagram of the Triangular Wave Comparison Method

As shown in Figure 3-2, ratio of the output voltage pulse to the carrier wave cycle is called duty.

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

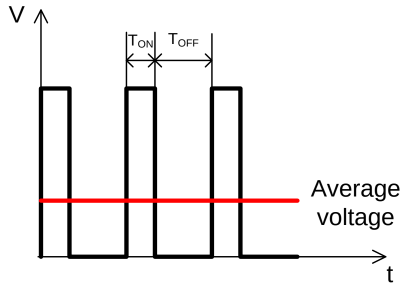


Figure 3-2 Definition of Duty

Modulation factor m is defined as follows.

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

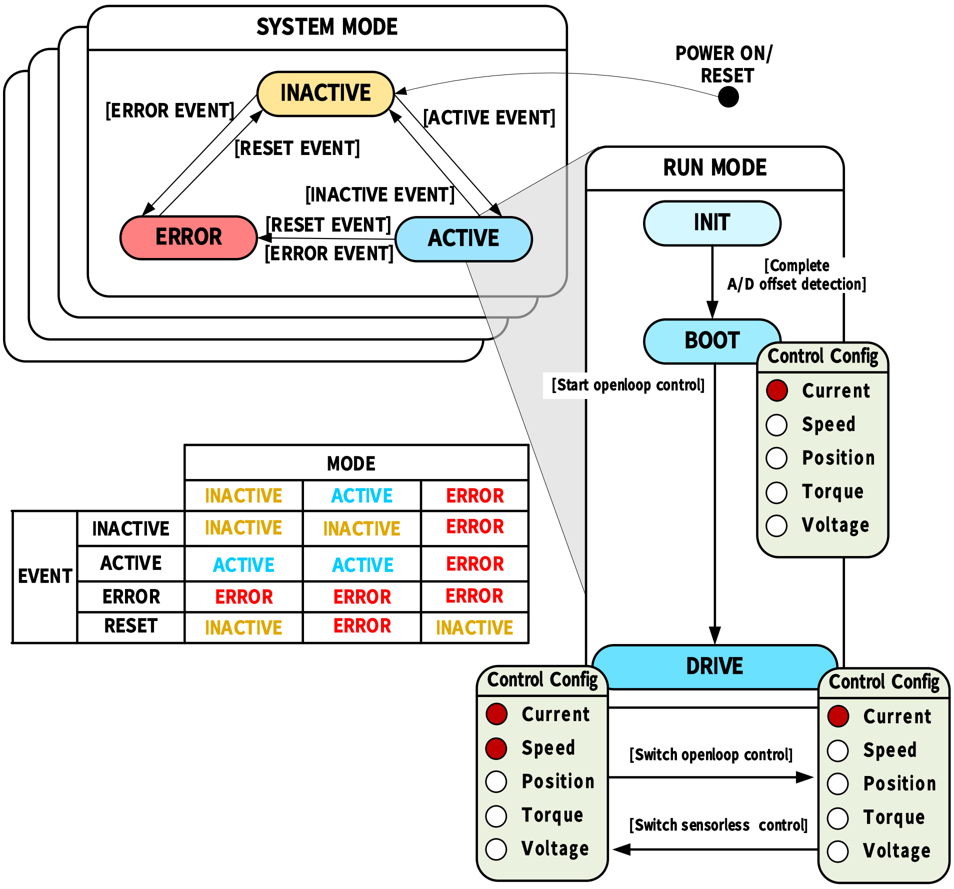
m: Modulation factor V: Voltage command value E: Inverter bus voltage

The voltage command can be generated by setting PWM compare register properly to obtain the desired duty.

3.1.4 State Transition

Figure 3-3 is a state transition diagram of the sensorless vector control software. In the target software of this application note, the software state is managed by 'SYSTEM MODE' and 'RUN MODE'. And 'Control Config' shows the active control system in the software.

Transitions between and within system mode and run mode, and related events are shown below and described on the following page. These are individually managed per motor, allowing independent control.



		MODE		
		INACTIVE	ACTIVE	ERROR
EVENT	INACTIVE	INACTIVE	INACTIVE	ERROR
	ACTIVE	ACTIVE	ACTIVE	ERROR
	ERROR	ERROR	ERROR	ERROR
	RESET	INACTIVE	ERROR	INACTIVE

Figure 3-3 State Transition Diagram of Sensorless Vector Control Software

(1) SYSTEM MODE

'SYSTEM MODE' indicates the operating states of the system. The state transits on occurrence of each event (EVENT). 'SYSTEM MODE' has 3 states that are motor drive stop (INACTIVE), motor drive (ACTIVE), and abnormal condition (ERROR).

(2) RUN MODE

'RUN MODE' indicates the condition of the motor control. 'RUN MODE' transits sequentially as shown in Figure 3-3 when 'SYSTEM MODE' is 'ACTIVE'.

(3) EVENT

When 'EVENT' occurs in each 'SYSTEM MODE', 'SYSTEM MODE' changes as shown in the table of Figure 3-3, according to that 'EVENT'.

Table 3-4 List of EVENT

EVENT name	Occurrence factor
INACTIVE	By user operation
ACTIVE	By user operation
ERROR	When the system detects an error
RESET	By user operation

3.1.5 Startup Method

Figure 3-4 shows startup control of sensorless vector control software. Each reference value setting of d-axis current, q-axis current and speed is managed by respective status.

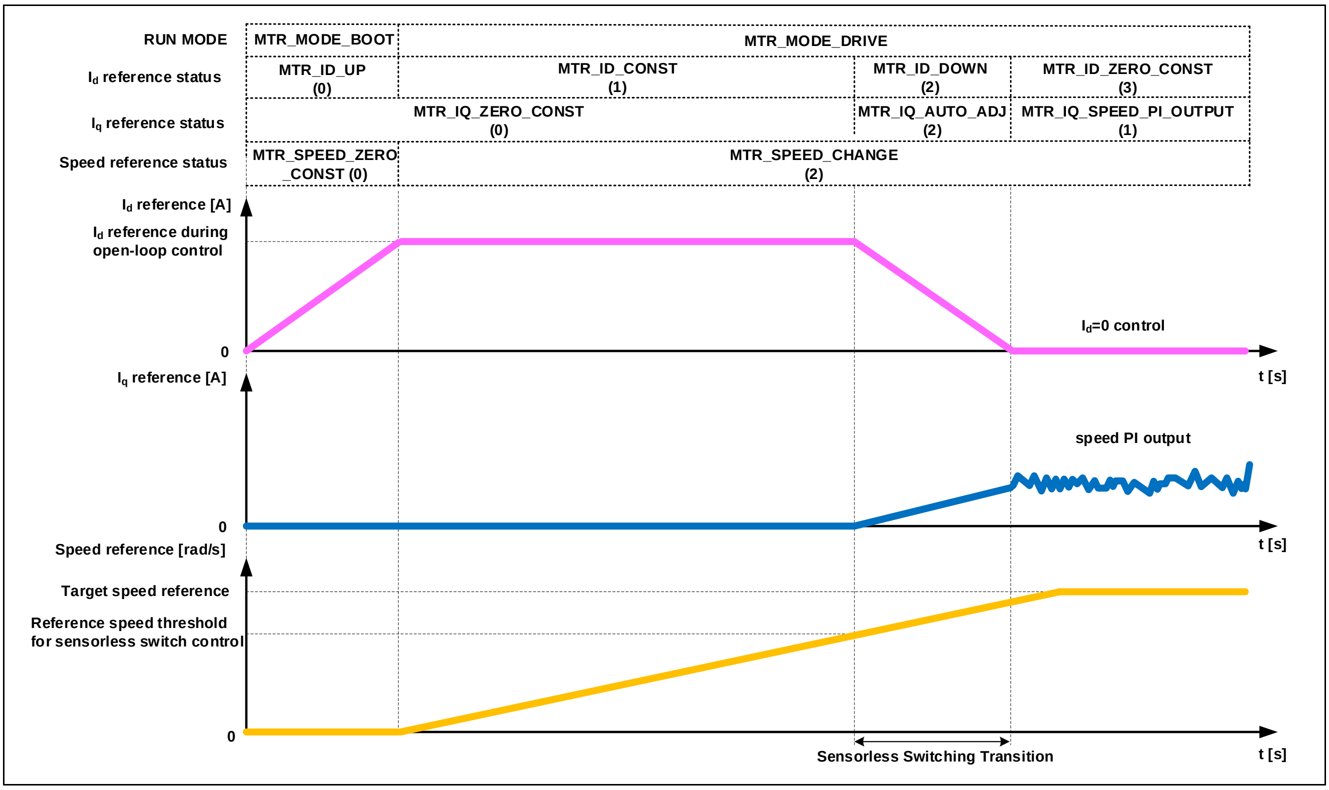


Figure 3-4 Startup Control of Sensorless Vector Control Software

3.1.6 System Protection Function

This control software has the following error status and executes emergency stop functions in case of occurrence of respective errors. Table 3-5 shows each setting value for the system protection function.

- Over-current error
  The over-current detection is performed by both hardware detection method and software detection method. In response to over-current detection, an emergency stop signal is generated from the hardware (hardware detection). When the emergency stop signal is generated, the PWM output ports are set to high impedance state.
  In addition, U, V, and W phase currents are monitored in every over-current monitoring cycle. When an over-current is detected, the CPU executes emergency stop (software detection). The over-current limit value is calculated from the nominal current of the motor [MP_NOMINAL_CURRENT_RMS].

- Over-voltage error
  The inverter bus voltage is monitored in every over-voltage monitoring cycle. When an over-voltage is detected, the CPU performs emergency stop. Here, the over-voltage limit value is set in consideration of the error of resistance value of the detect circuit.

- Under-voltage error
  The inverter bus voltage is monitored in every under-voltage monitoring cycle. The CPU performs emergency stop when under-voltage is detected. Here, the under-voltage limit value is set in consideration of the error of resistance value of the detect circuit.

- Over-speed error
  The rotation speed is monitored in every rotation speed monitoring cycle. The CPU performs emergency stop when the speed is over the limit value.

Table 3-5 Setting Values of the System Protection Function

Over-current error	Over-current limit value [A]	0.89
	Monitoring cycle [μs]	50
Over-voltage error	Over-voltage limit value [V]	28
	Monitoring cycle [μs]	50
Under-voltage error	Under-voltage limit value [V]	14
	Monitoring cycle [μs]	50
Over-speed error	Speed limit value [rpm]	3000
	Monitoring cycle [μs]	50

3.2 Function Specifications of Sensorless Vector Control Software

The control process of the target software of this application note is mainly consisted of 50 [µs] period interrupt (carrier interrupt) and 500 [µs] period interrupt. In Figure 3-5 and Figure 3-6, the control process in the red broken line part is executed every 50 [µs] period, and the control process in the blue broken line part is executed every 500 [µs] period.

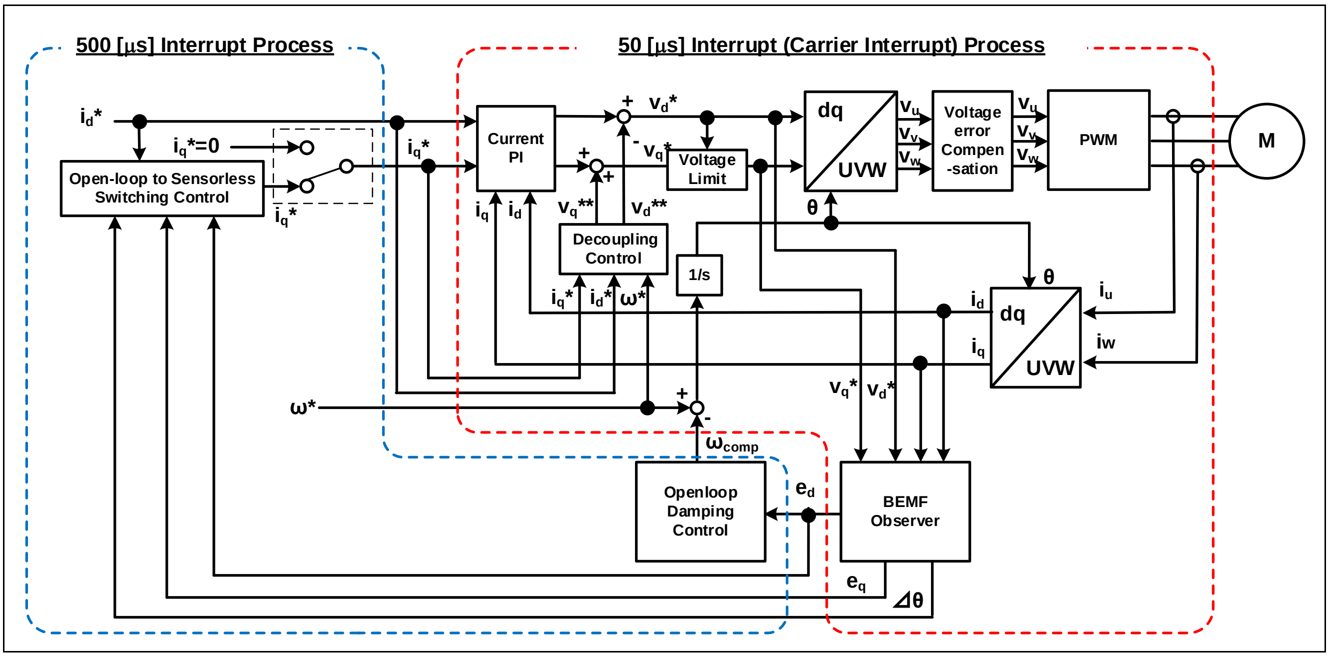


Figure 3-5 Block Diagram of Sensorless Vector Control (Open-loop Control)

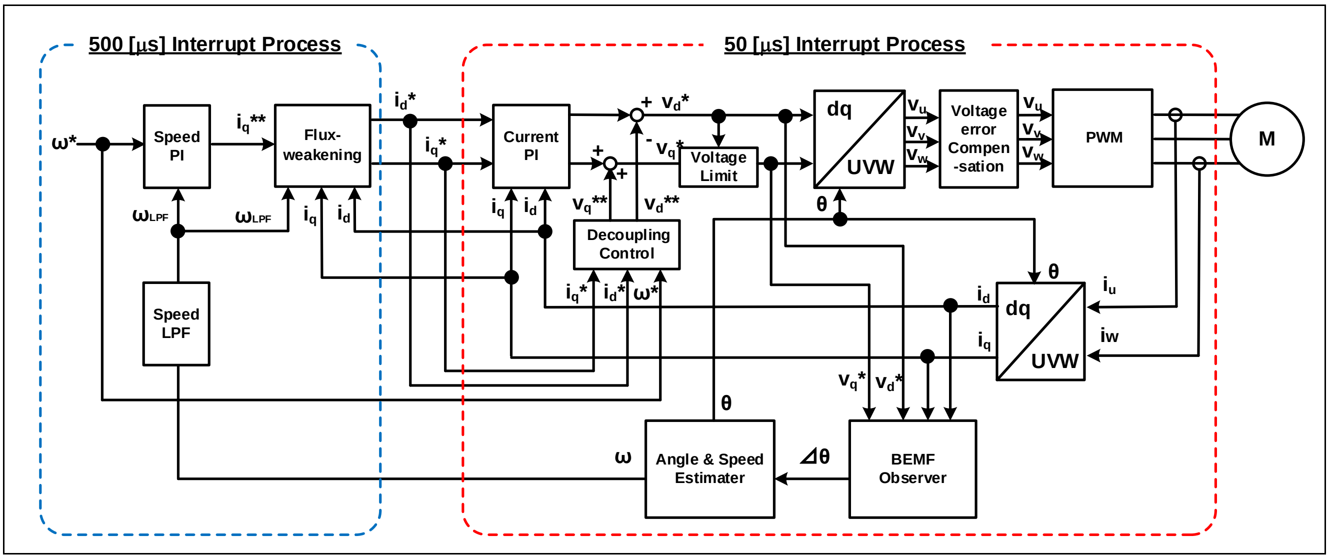


Figure 3-6 Block Diagram of Sensorless Vector Control (Sensorless Control)

This chapter shows the specification of 2 interrupt functions and functions executed in each interrupt period. In the following tables, only primary functions of the sensorless vector control are listed. Regarding the specification of functions not listed in the following tables, refer to source codes.

Table 3-6 List of Interrupt Functions

File name	Function overview	Process overview
Config_MTU3_MTU4_user.c	r_Config_MTU3_MTU4_tgia3_interrupt Input: None Output: None	Calling every 50 [µs] Processing for motor 1 Calling the mtr_foc_interrupt_carrier function RMW communications processing
Config_MTU6_MTU7_user.c	r_Config_MTU6_MTU7_c7_tciv7_interrupt Input: None Output: None	Calling every 50 [µs] Processing for motor 2 Calling the mtr_foc_interrupt_carrier function
Config_GPT0_user.c	r_Config_GPT0_gtciv0_interrupt Input: None Output: None	Calling every 50 [µs] Processing for motor 3 Calling the mtr_foc_interrupt_carrier function
Config_GPT7_user.c	r_Config_GPT7_gtciu7_interrupt Input: None Output: None	Calling every 50 [µs] Processing for motor 4 Calling the mtr_foc_interrupt_carrier function
Config_CMT0_user.c	r_Config_CMT0_cmi0_interrupt Input: None Output: None	Calling every 500 [µs] Processing for motors 1 to 4 Calling the mtr_foc_interrupt_500us function Automatically setting parameters

Table 3-7 List of Functions Executed in 50 [μs] Period Interrupt (Carrier Interrupt) (1/2)

File name	Function overview	Process overview
r_mtr_interrupt_carrier.c	mtr_foc_interrupt_carrier Input: (mtr_foc_control_t *) st_foc / Pointer to a structure for vector control Output: None	Calling the functions described below for use in management of the 50 [μs] period interrupt
r_mtr_ctrl_mrssk.c	mtr_get_current_iuiw Input: (float*) f4_iu_ad / U phase current A/D conversion value pointer (float*) f4_iw_ad / W phase current A/D conversion value pointer (uint8_t) u1_id / Motor ID Output: None	Obtaining the U/W phase current
	mtr_get_vdc Input: (uint8_t) u1_id / Motor ID Output: (float) f4_temp_vdc / Vdc value	Obtaining the Vdc
r_mtr_foc_control.c	mtr_error_check Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: None	Error monitoring
	mtr_current_offset_adjustment Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: None	Cancel current offset
	mtr_calib_current_offset Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: None	Calculation of current offset
	mtr_angle_speed Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: None	Position and speed estimation
	mtr_foc_voltage_limit Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: None	Limiting voltage reference
r_mtr_foc_current.c	mtr_current_pi_control Input: (mtr_current_control_t *) st_cc / Structure pointer for current control Output: None	Current PI control
	mtr_foc_current_decoupling Input: (mtr_current_control_t *) st_cc / Structure pointer for current control (float)f4_speed_rad / Rotation speed (const mtr_parameter_t *) p_mtr / Structure pointer for motor parameter Output: None	Decoupling control
r_mtr_transform.c	mtr_transform_uvw_dq_abs Input: (const mtr_rotor_angle_t *) p_angle / Structure pointer for phase management (const float*) f4_uvw / UVV phase pointer (float*) f4_dq / dq-axis pointer Output: None	Coordinate transform UVW to dq
	mtr_transform_dq_uvw_abs Input: (const mtr_rotor_angle_t *) p_angle / Structure pointer for phase management (const float*) f4_dq / dq-axis pointer (float*) f4_uvw / UVW phase pointer Output: None	Coordinate transform dq to UVW

Table 3-7 List of Functions Executed in 50 [µs] Period Interrupt (Carrier Interrupt) (2/2)

File name	Function overview	Process overview
r_mtr_volt_err_ comp.obj	mtr_volt_err_comp_main Input: (mtr_volt_comp_t *) st_volt_comp / Structure pointer for voltage error compensation (float*) p_f4_v_array / Array pointer for 3-phase voltage compensation amount (float*) p_f4_i_array / Array pointer for 3 phase current (float) f4_vdc / Inverter bus voltage Output: None	Voltage error compensation
r_mtr_ctrl_rx72t.c	mtr_inv_set_uvw Input: (float) f4_duty_u / U phase modulation factor (float) f4_duty_v / V phase modulation factor (float) f4_duty_w / W phase modulation factor (uint8_t) u1_id / Motor ID Output: None	PWM output setting
r_mtr_bemf_ observer.obj	mtr_bemf_observer Input: (mtr_bemf_observer_t *) st_bemf_obs / Structure pointer for BEMF observer (float) f4_vd_ref / d-axis voltage reference (float) f4_vq_ref / q-axis voltage reference (float) f4_id / d-axis current (float) f4_iq / q-axis current Output: None	Calculation for BEMF observer
	mtr_bemf_calc_d Input: (mtr_bemf_observer_t *) st_bemf_obs / Structure pointer for BEMF observer (float) f4_speed_rad / Estimated speed (float) f4_iq / q-axis current Output: (float) f4_temp / Estimated d-axis BEMF	Calculation for estimated d-axis BEMF
	mtr_bemf_calc_q Input: (mtr_bemf_observer_t *) st_bemf_obs / Structure pointer for BEMF observer (float) f4_speed_rad / Estimated speed (float) f4_id / d-axis current Output: (float) f4_temp / Estimated q-axis BEMF	Calculation for estimated q-axis BEMF
	mtr_angle_speed_pll Input: (mtr_pll_est_t *) st_pll_est / Structure pointer for position and speed estimation (float) f4_phase_err / Phase error (float*) f4_speed / Estimated speed pointer Output: None	Calculation for position and speed estimation

Table 3-8 List of Functions Executed in 500 [μs] Period Interrupt

File name	Function overview	Process overview
r_mtr_interrupt_timer.c	mtr_foc_interrupt_500us Input: (mtr_foc_control_t *) st_foc /Pointer to a structure for vector control Output: None	Calling the functions described below for use in management of the 500 [μs] period interrupt
r_mtr_foc_control_less_speed.c	mtr_set_speed_ref Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: (float) f4_speed_rad_ref_buff / Speed reference	Speed reference setting
	mtr_set_iq_ref Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: (float) f4_iq_ref_buff / q-axis current reference	q-axis current reference setting
	mtr_set_id_ref Input: (mtr_foc_control_t *) st_foc / Structure pointer for vector control Output: (float) f4_id_ref_buff / d-axis current reference	d-axis current reference setting
r_mtr_foc_speed.c	mtr_speed_pi_control Input: (mtr_speed_control_t *) st_sc / Structure pointer for speed control (float) f4_speed_rad / Rotation speed Output: (float) f4_iq_ref_calc / q-axis current reference	Speed PI control
r_mtr_opl2less.obj	mtr_opl2less_iq_calc input: (float) f4_ed / Estimated d-axis BEMF (float) f4_eq / Estimated q-axis BEMF (float) f4_id / d-axis current reference when open-loop (float) f4_torque_current / Torque current when open-loop control (float) f4_phase_err / Phase error Output: (float) f4_temp_iq_ref / q-axis current reference	Generating q-axis current reference for sensorless switching control
r_mtr_fluxwkn.obj	R_FLUXWKN_Run Input: (fluxwkn_t *) p_fluxwkn / Structure pointer for flux weakening control (float) f4_speed_rad / Rotation speed (const float*) p_f4_idq / dq-axis current pointer (float*) p_f4_idq_ref / dq-axis current reference pointer Output: (uint16_t) u2_fw_status / Status of flux-weakening control	Flux-weakening control
r_mtr_opl_damp_ctrl.obj	mtr_opl_damp_ctrl Input: (mtr_opl_damp_t *) st_opl_damp / Pointer to a structure for open-loop damping control (float) f4_ed / Estimated d-axis BEMF (float) speed_ref / Speed reference Output: (float) f4_temp_damp_comp_speed / Feedback value for speed reference	Open-loop damping control

3.3 Macro Definition of Sensorless Vector Control Software

The macro definitions in the target software of this application note are listed below. In the following tables, only definitions set the software configuration are listed. Regarding the macro definitions not listed in the following tables, refer to source codes.

Table 3-9 List of Macro Definitions 'r_mtr_motor_parameter.h'

File name	Motor	Macro name	Definition value	Remarks
r_mtr_motor_parameter.h	1	MP_1_POLE_PAIRS	2	Number of pole pairs
		MP_1_MAGNETIC_FLUX	0.02159f	Flux [Wb]
		MP_1_RESISTANCE	8.5f	Resistance [Ω]
		MP_1_D_INDUCTANCE	0.0045f	d-axis inductance [H]
		MP_1_Q_INDUCTANCE	0.0045f	q-axis inductance [H]
		MP_1_ROTOR_INERTIA	0.0000028f	Rotor inertia [kgm^2]
		MP_1_NOMINAL_CURRENT_RMS	0.42f	Nominal current [A(rms)]
	2	MP_2_POLE_PAIRS	2	Number of pole pairs
		MP_2_MAGNETIC_FLUX	0.02159f	Flux [Wb]
		MP_2_RESISTANCE	8.5f	Resistance [Ω]
		MP_2_D_INDUCTANCE	0.0045f	d-axis inductance [H]
		MP_2_Q_INDUCTANCE	0.0045f	q-axis inductance [H]
		MP_2_ROTOR_INERTIA	0.0000028f	Rotor inertia [kgm^2]
		MP_2_NOMINAL_CURRENT_RMS	0.42f	Nominal current [A(rms)]
	3	MP_3_POLE_PAIRS	2	Number of pole pairs
		MP_3_MAGNETIC_FLUX	0.02159f	Flux [Wb]
		MP_3_RESISTANCE	8.5f	Resistance [Ω]
		MP_3_D_INDUCTANCE	0.0045f	d-axis inductance [H]
		MP_3_Q_INDUCTANCE	0.0045f	q-axis inductance [H]
		MP_3_ROTOR_INERTIA	0.0000028f	Rotor inertia [kgm^2]
		MP_3_NOMINAL_CURRENT_RMS	0.42f	Nominal current [A(rms)]
	4	MP_4_POLE_PAIRS	2	Number of pole pairs
		MP_4_MAGNETIC_FLUX	0.02159f	Flux [Wb]
		MP_4_RESISTANCE	8.5f	Resistance [Ω]
		MP_4_D_INDUCTANCE	0.0045f	d-axis inductance [H]
		MP_4_Q_INDUCTANCE	0.0045f	q-axis inductance [H]
		MP_4_ROTOR_INERTIA	0.0000028f	Rotor inertia [kgm^2]
		MP_4_NOMINAL_CURRENT_RMS	0.42f	Nominal current [A(rms)]

Table 3-10 List of Macro Definitions 'r_mtr_control_parameter.h' (1/4)

File name	Motor	Macro name	Definition value	Remarks
r_mtr_control_parameter.h	—	CP_CARRIER_FREQ_MTU	20.0f	Carrier frequency [kHz]
		CP_CARRIER_FREQ_GPT	20.0f	Carrier frequency [kHz]
	1	CP_1_INT_DECIMATION	0	Number of times the interrupt is skipped.
		CP_1_CURRENT_OMEGA	300.0f	Natural frequency of current control system [Hz]
		CP_1_CURRENT_ZETA	1.0f	Damping ratio of current control system
		CP_1_SPEED_OMEGA_1	3.0f	Natural frequency of speed control system [Hz]
		CP_1_SPEED_ZETA	1.0f	Damping ratio of speed control system
		CP_1_MIN_SPEED_RPM	0	Minimum speed (mechanical) [rpm]
		CP_1_E_OBS_OMEGA	1000.0f	Natural frequency of BEMF estimation system [Hz]
		CP_1_E_OBS_ZETA	1.0f	Damping ratio of BEMF estimation system
		CP_1_PLL_EST_OMEGA	20.0f	Natural frequency of position estimation system [Hz]
		CP_1_PLL_EST_ZETA	1.0f	Damping ratio of position estimation system
		CP_1_ID_DOWN_SPEED_RPM	600	Speed (mechanical) when start decreasing d-axis current reference [rpm]
		CP_1_ID_UP_SPEED_RPM	400	Speed (mechanical) when start increasing d-axis current reference [rpm]
		CP_1_MAX_SPEED_RPM	2650	Maximum speed (mechanical) [rpm]
		CP_1_OVERSPEED_LIMIT_RPM	3000	Speed limit value (mechanical) [rpm]
		CP_1_SPEED_RATE_LIMIT	0.5f	Limit on the rate of change in speed [rpm/ms]
		CP_1_OL_ID_REF	0.3f	d-axis current at low speed [A]

Table 3-10 List of Macro Definitions 'r_mtr_control_parameter.h' (2/4)

File name	Motor	Macro name	Definition value	Remarks
r_mtr_control_parameter.h	2	CP_2_INT_DECIMATION	0	Number of times the interrupt is skipped.
		CP_2_CURRENT_OMEGA	300.0f	Natural frequency of current control system [Hz]
		CP_2_CURRENT_ZETA	1.0f	Damping ratio of current control system
		CP_2_SPEED_OMEGA_1	3.0f	Natural frequency of speed control system [Hz]
		CP_2_SPEED_ZETA	1.0f	Damping ratio of speed control system
		CP_2_MIN_SPEED_RPM	0	Minimum speed (mechanical) [rpm]
		CP_2_E_OBS_OMEGA	1000.0f	Natural frequency of BEMF estimation system [Hz]
		CP_2_E_OBS_ZETA	1.0f	Damping ratio of BEMF estimation system
		CP_2_PLL_EST_OMEGA	20.0f	Natural frequency of position estimation system [Hz]
		CP_2_PLL_EST_ZETA	1.0f	Damping ratio of position estimation system
		CP_2_ID_DOWN_SPEED_RPM	600	Speed (mechanical) when start decreasing d-axis current reference [rpm]
		CP_2_ID_UP_SPEED_RPM	400	Speed (mechanical) when start increasing d-axis current reference [rpm]
		CP_2_MAX_SPEED_RPM	2650	Maximum speed (mechanical) [rpm]
		CP_2_OVERSPEED_LIMIT_RPM	3000	Speed limit value (mechanical) [rpm]
		CP_2_SPEED_RATE_LIMIT	0.5f	Limit on the rate of change in speed [rpm/ms]
		CP_2_OL_ID_REF	0.3f	d-axis current at low speed [A]

Table 3-10 List of Macro Definitions 'r_mtr_control_parameter.h' (3/4)

File name	Motor	Macro name	Definition value	Remarks
r_mtr_control_parameter.h	3	CP_3_INT_DECIMATION	0	Number of times the interrupt is skipped.
		CP_3_CURRENT_OMEGA	300.0f	Natural frequency of current control system [Hz]
		CP_3_CURRENT_ZETA	1.0f	Damping ratio of current control system
		CP_3_SPEED_OMEGA_1	3.0f	Natural frequency of speed control system [Hz]
		CP_3_SPEED_ZETA	1.0f	Damping ratio of speed control system
		CP_3_MIN_SPEED_RPM	0	Minimum speed (mechanical) [rpm]
		CP_3_E_OBS_OMEGA	1000.0f	Natural frequency of BEMF estimation system [Hz]
		CP_3_E_OBS_ZETA	1.0f	Damping ratio of BEMF estimation system
		CP_3_PLL_EST_OMEGA	20.0f	Natural frequency of position estimation system [Hz]
		CP_3_PLL_EST_ZETA	1.0f	Damping ratio of position estimation system
		CP_3_ID_DOWN_SPEED_RPM	600	Speed (mechanical) when start decreasing d-axis current reference [rpm]
		CP_3_ID_UP_SPEED_RPM	400	Speed (mechanical) when start increasing d-axis current reference [rpm]
		CP_3_MAX_SPEED_RPM	2650	Maximum speed (mechanical) [rpm]
		CP_3_OVERSPEED_LIMIT_RPM	3000	Speed limit value (mechanical)[rpm]
		CP_3_SPEED_RATE_LIMIT	0.5f	Limit on the rate of change in speed [rpm/ms]
		CP_3_OL_ID_REF	0.3f	d-axis current at low speed [A]

Table 3-10 List of Macro Definitions 'r_mtr_control_parameter.h' (4/4)

File name	Motor	Macro name	Definition value	Remarks
r_mtr_control_parameter.h	4	CP_4_INT_DECIMATION	0	Number of times the interrupt is skipped.
		CP_4_CURRENT_OMEGA	300.0f	Natural frequency of current control system [Hz]
		CP_4_CURRENT_ZETA	1.0f	Damping ratio of current control system
		CP_4_SPEED_OMEGA_1	3.0f	Natural frequency of speed control system [Hz]
		CP_4_SPEED_ZETA	1.0f	Damping ratio of speed control system
		CP_4_MIN_SPEED_RPM	0	Minimum speed (mechanical) [rpm]
		CP_4_E_OBS_OMEGA	1000.0f	Natural frequency of BEMF estimation system [Hz]
		CP_4_E_OBS_ZETA	1.0f	Damping ratio of BEMF estimation system
		CP_4_PLL_EST_OMEGA	20.0f	Natural frequency of position estimation system [Hz]
		CP_4_PLL_EST_ZETA	1.0f	Damping ratio of position estimation system
		CP_4_ID_DOWN_SPEED_RPM	600	Speed (mechanical) when start decreasing d-axis current reference [rpm]
		CP_4_ID_UP_SPEED_RPM	400	Speed (mechanical) when start increasing d-axis current reference [rpm]
		CP_4_MAX_SPEED_RPM	2650	Maximum speed (mechanical) [rpm]
		CP_4_OVERSPEED_LIMIT_RPM	3000	Speed limit value (mechanical)[rpm]
		CP_4_SPEED_RATE_LIMIT	0.5f	Limit on the rate of change in speed [rpm/ms]
		CP_4_OL_ID_REF	0.3f	d-axis current at low speed [A]

Table 3-11 List of Macro Definitions ‘r_mtr_inverter_parameter.h’

File name	Motor	Macro name	Definition value	Remarks
r_mtr_inverter_parameter.h	1	IP_1_DEADTIME	2.0f	Dead time [µs]
		IP_1_CURRENT_RANGE	25.0f	Current A/D conversion range [A] (peak-to-peak value)
		IP_1_VDC_RANGE	111.0f	Vdc A/D conversion range [V]
		IP_1_INPUT_V	24.0f	Input DC voltage [V]
		IP_1_CURRENT_LIMIT	10.0f	Over-current limit [A]*
		IP_1_OVERVOLTAGE_LIMIT	28.0f	High voltage limit [V]
		IP_1_UNDERVOLTAGE_LIMIT	14.0f	Low voltage limit [V]
	2	IP_2_DEADTIME	2.0f	Dead time [µs]
		IP_2_CURRENT_RANGE	25.0f	Current A/D conversion range [A] (peak-to-peak value)
		IP_2_VDC_RANGE	111.0f	Vdc A/D conversion range [V]
		IP_2_INPUT_V	24.0f	Input DC voltage [V]
		IP_2_CURRENT_LIMIT	10.0f	Over-current limit [A]*
		IP_2_OVERVOLTAGE_LIMIT	28.0f	High voltage limit [V]
		IP_2_UNDERVOLTAGE_LIMIT	14.0f	Low voltage limit [V]
	3	IP_3_DEADTIME	2.0f	Dead time [µs]
		IP_3_CURRENT_RANGE	25.0f	Current A/D conversion range [A] (peak-to-peak value)
		IP_3_VDC_RANGE	111.0f	Vdc A/D conversion range [V]
		IP_3_INPUT_V	24.0f	Input DC voltage [V]
		IP_3_CURRENT_LIMIT	10.0f	Over-current limit [A]*
		IP_3_OVERVOLTAGE_LIMIT	28.0f	High voltage limit [V]
		IP_3_UNDERVOLTAGE_LIMIT	14.0f	Low voltage limit [V]
	4	IP_4_DEADTIME	2.0f	Dead time [µs]
		IP_4_CURRENT_RANGE	25.0f	Current A/D conversion range [A] (peak-to-peak value)
		IP_4_VDC_RANGE	111.0f	Vdc A/D conversion range [V]
		IP_4_INPUT_V	24.0f	Input DC voltage [V]
		IP_4_CURRENT_LIMIT	10.0f	Over-current limit [A]*
		IP_4_OVERVOLTAGE_LIMIT	28.0f	High voltage limit [V]
		IP_4_UNDERVOLTAGE_LIMIT	14.0f	Low voltage limit [V]

Note: * This value is calculated from the rated power of the shunt resistance.

Table 3-12 List of Macro Definitions ‘r_mtr_config.h’

File name	Macro name	Definition value	Remarks
r_mtr_config.h	RX72T_MRSSK	—	MCU select macro
	IP_MRSSK	—	Inverter select macro
	MP_TG55L	—	Motor select macro
	CP_TG55L	—	
	CONFIG_DEFAULT_UI	BOARD_UI	Default UI selection ICS_UI: Use Analyzer UI BOARD_UI: Board UI
	FUNC_ON	1	Enable
	FUNC_OFF	0	Disable
	DEFAULT_LESS_SWITCH	FUNC_ON	Sensorless switching control
	DEFAULT_FLUX_WEAKENING	FUNC_OFF	Flux weakening control
	DEFAULT_VOLT_ERR_COMP	FUNC_ON	Voltage error compensation
	DEFAULT_OPENLOOP_DAMPING	FUNC_ON	Open-loop damping control
	GAIN_MODE	MTR_GAIN_DESIGN_MODE	Gain mode MTR_GAIN_DESIGN_MODE: PI gain design mode MTR_GAIN_DIRECT_MODE: PI gain direct input mode
	MOD_METHOD	MOD_METHOD_SVPWM	Modulation method MOD_METHOD_SPWM: Sinusoidal PWM MOD_METHOD_SVPWM: Space Vector PWM

Table 3-13 List of Macro Definitions ‘r_mtr_common.h’

File name	Macro name	Definition value	Remarks
r_mtr_common.h	MTR_TFU_OPTIMIZE	1	1: Use TFU code 0: Use Standard library code

3.4 Control Flowcharts

3.4.1 Main Process

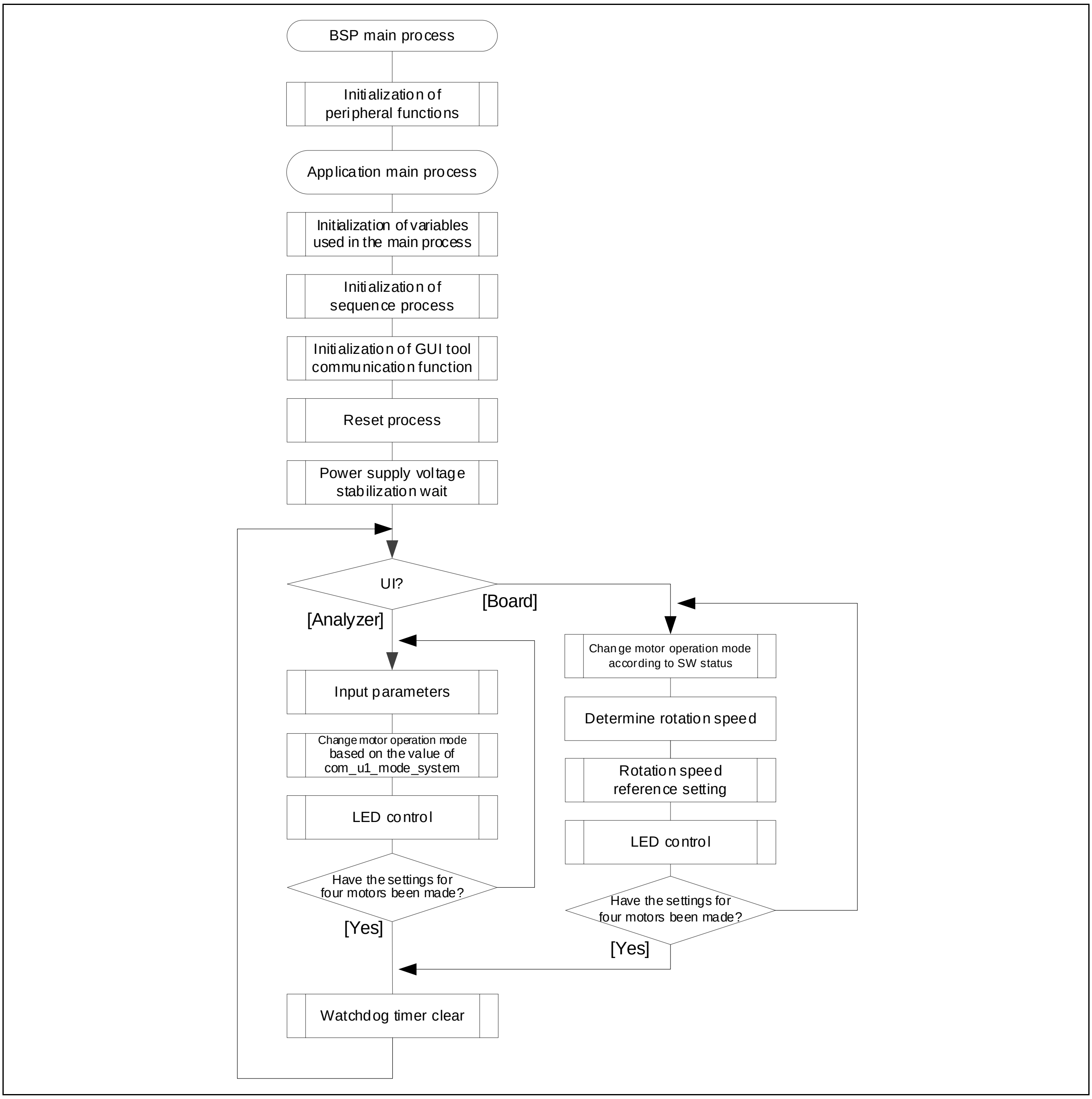


Figure 3-7 Main Process Flowchart

3.4.2 50 [μs] Period Interrupt (Carrier Interrupt) Process

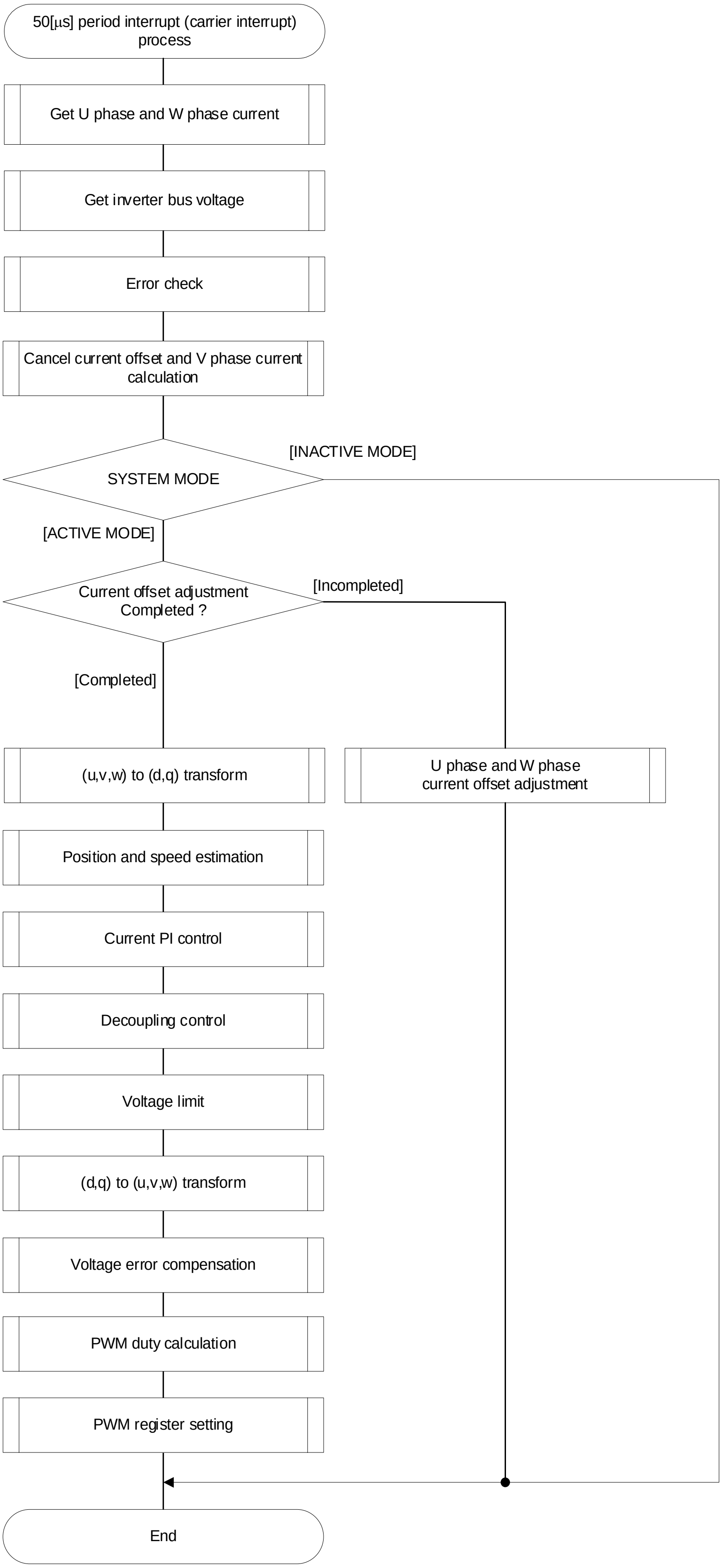


Figure 3-8 50 [μs] Period Interrupt (Carrier Interrupt) Process Flowchart

3.4.3 500 [μs] Period Interrupt Process

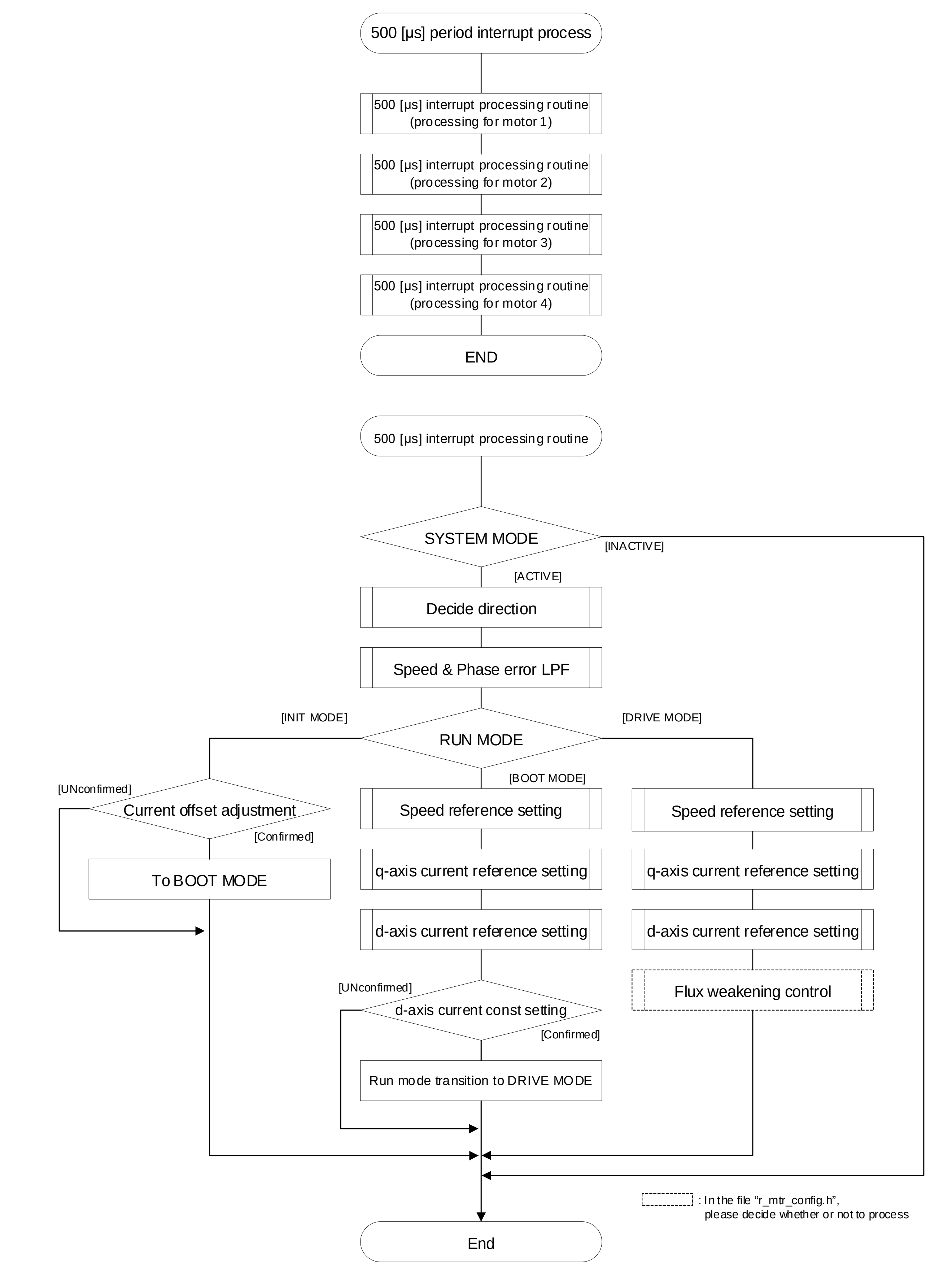


Figure 3-9 500 [μs] Period Interrupt Process Flowchart

3.4.4 Over-Current Detection Interrupt Process

The over-current detection interrupt occurs when POE# pin detects falling-edge or when output levels of the MTU complementary PWM output pins are compared and simultaneous active-level output continues for one cycle or more. Therefore, when this interrupt process is executed, PWM output pins are already in high-impedance state and the output to the motor is stopped.

Table 3-14 shows the correspondence between the motors and POE# pins.

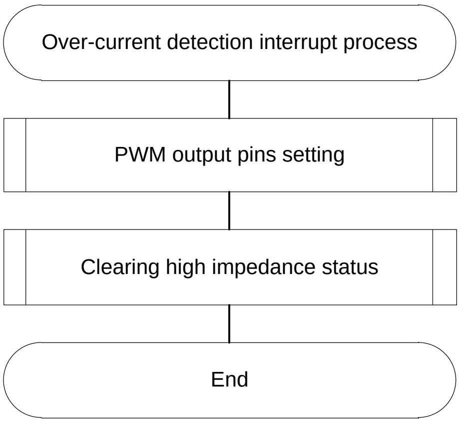


Figure 3-10 Over-Current Detection Interrupt Process Flowchart

Table 3-14 Correspondence between the Motors and POE# Pins

Motor	POE# pin	Interrupt Source
1	POE0#	OEI1
2	POE4#	OEI2
3	POE12#	OEI5 * The ICSR7.POE12F flag is used to judge whether the target pin is POE12# or POE14#.
4	POE14#	OEI5 The ICSR10.POE14F flag is used to judge whether the target pin is POE12# or POE14#.

4. Motor Control Development Support Tool ‘Renesas Motor Workbench’

4.1 Overview

‘Renesas Motor Workbench’ is support tool for development of motor control system. ‘Renesas Motor Workbench’ can be used with target software of this application note to analyze the control performance. The user interfaces of ‘Renesas Motor Workbench’ provide functions like rotating/stop command, setting rotation speed reference, etc... Please refer to ‘Renesas Motor Workbench User’s Manual’ for usage and more details. ‘Renesas Motor Workbench’ can be downloaded from Renesas Electronics Corporation website.

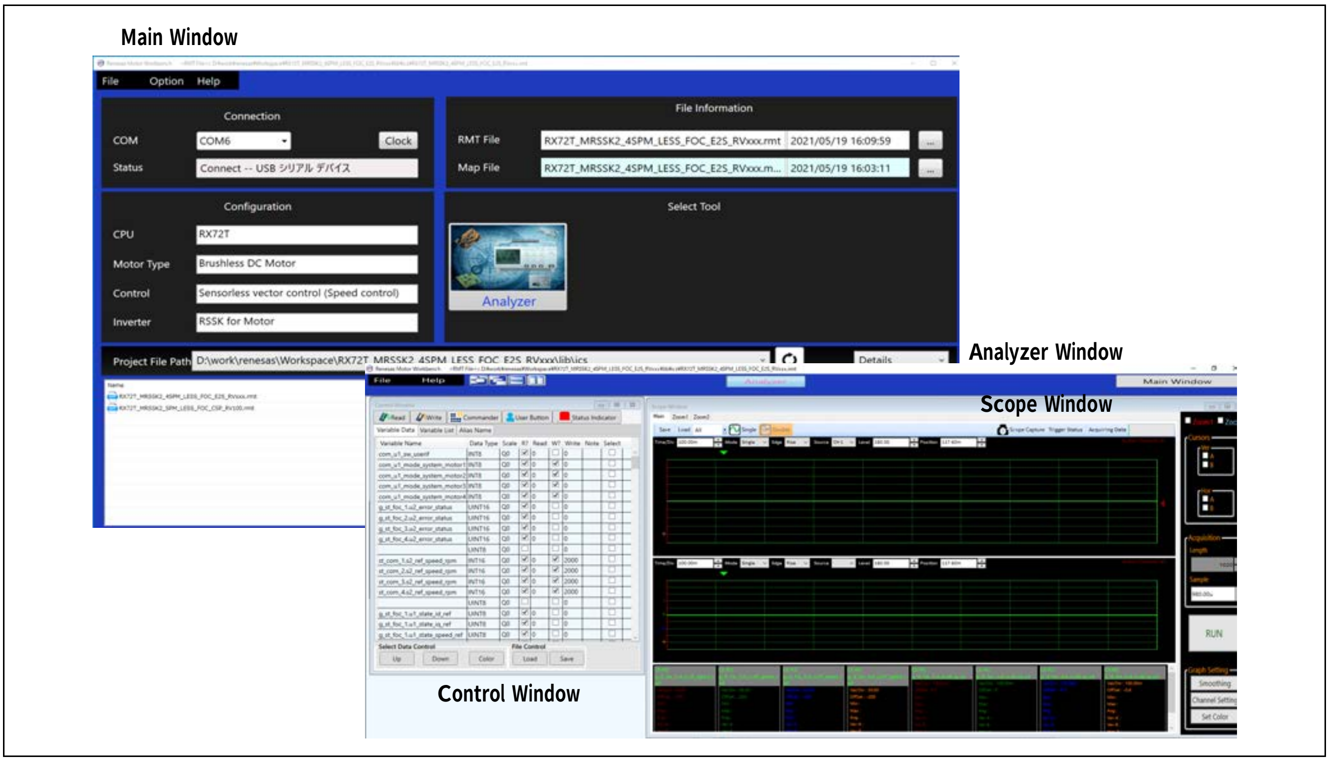


Figure 4-1 Renesas Motor Workbench – Appearance

<u>Set up for ‘Renesas Motor Workbench’</u>

(1) Start ‘Renesas Motor Workbench’ by clicking this icon. 

(2) Click on [File] and select [Open RMT File(O)] from drop down Menu.
Select the RMT file from following location of e2studio/CS+ project folder.
‘[Project Folder]/ application/user_interface/ics/’
(3) Use the ‘Connection’ [COM] select menu to choose the COM port.
(4) Click on the ‘Analyzer’ icon of Select Tool panel to open Analyzer function window.
(5) Please refer to ‘4.3 Operation Example for Analyzer’ for motor driving operation.

4.2 List of Variables for Analyzer function

Table 4-1 is a list of variables for Analyzer. When the same value as g_u1_enable_write is written to u1_enable_write, a member of the com_if_t structure, the values input to these variables are reflected in the corresponding variables in the middle layer and then used for control over the motors. However, note that variables with (*) do not depend on com_u1_enable_write. For details on how to set the variables, refer to section 4.3.

Table 4-1 List of Variables for Analyzer

Variable name	Type	Content
com_u1_sw_userif (*)	uint8_t	User interface switch 0: ICS user interface use (default) 1: Board user interface use
st_com_1	com_if_t	Function input structure for motor 1
st_com_2	com_if_t	Function input structure for motor 2
st_com_3	com_if_t	Function input structure for motor 3
st_com_4	com_if_t	Function input structure for motor 4
com_u1_mode_system_motor1	uint8_t	State management for motor 1 0: Stop mode 1: Run mode 3: Reset
com_u1_mode_system_motor2	uint8_t	State management for motor 2 0: Stop mode 1: Run mode 3: Reset
com_u1_mode_system_motor3	uint8_t	State management for motor 3 0: Stop mode 1: Run mode 3: Reset
com_u1_mode_system_motor4	uint8_t	State management for motor 4 0: Stop mode 1: Run mode 3: Reset

Table 4-2 List of main members of com_if_t structure (1/2)

Main members of com_if_t structure	Type	Content
u1_direction	uint8_t	Rotation direction 0: CW 1: CCW
s2_ref_speed_rpm	uint16_t	Speed reference (Mechanical) [rpm]
u2_mtr_pp	uint16_t	Number of pole pairs
f4_mtr_r	float	Resistance [Ω]
f4_mtr_ld	float	d-axis inductance [H]
f4_mtr_lq	float	q-axis inductance [H]
f4_mtr_m	float	Flux [Wb]
f4_mtr_j	float	Rotor inertia [kgm^2]
u2_offset_calc_time	uint16_t	Current offset value calculation time [ms]
f4_speed_rate_limit	float	Speed limit change rate (Electrical) [krpm/s]
u2_max_speed_rpm	uint16_t	Maximum speed value (Mechanical) [rpm]
u2_id_up_speed_rpm	uint16_t	Speed (mechanical) when start increasing d-axis current reference [rpm]
f4_id_up_time	float	Decreasing time of d-axis current reference [ms]
f4_ol_ref_id	float	d-axis current reference in open loop mode [A]
u2_id_down_speed_rpm	uint16_t	Speed (mechanical) when start decreasing d-axis current reference [rpm]
f4_id_down_time	float	Decreasing time of d-axis current reference [ms]
f4_speed_omega_1	float	Natural frequency of speed control system [Hz]
f4_speed_omega_2	float	Natural frequency of speed control system [Hz]
f4_speed_zeta	float	Damping ratio of speed control system
f4_current_omega	float	Natural frequency of current control system [Hz]

Table 4-2 List of main members of com_if_t structure (2/2)

Main members of com_if_t structure	Type	Content
f4_current_zeta	float	Damping ratio of current control system
f4_e_obs_omega	float	Natural frequency of BEMF estimation system [Hz]
f4_e_obs_zeta	float	Damping ratio of BEMF estimation system
f4_pll_est_omega	float	Natural frequency of position estimation system [Hz]
f4_pll_est_zeta	float	Damping ratio of position estimation system
f4_id_kp	float	d-axis current PI control proportional gain
f4_id_ki	float	d-axis current PI control Integral gain
f4_iq_kp	float	q-axis current PI control proportional gain
f4_iq_ki	float	q-axis current PI control Integral gain
f4_speed_kp	float	Speed PI control proportional gain
f4_speed_ki	float	Speed PI control Integral gain
u2_speed_limit_rpm	uint16_t	Over-speed limit value (Mechanical) [rpm]
f4_nominal_current_rms	float	Nominal current [A(rms)]
f4_switch_phase_err_deg	float	Phase error enabled switching to sensorless control (Electrical) [deg]
f4_opl2less_sw_time	float	Process time of sensorless switching control [s]
f4_ed_hpf_omega	float	d-axis BEMF HPF cut-off frequency [Hz]
f4_ol_damping_zeta	float	Damping ratio of open-loop damping control
f4_ol_damping_fb_limit_rate	float	Feedback limit of open-loop damping control
f4_phase_err_lpf_cut_freq	float	Phase error LPF cut-off frequency [Hz]
u1_less_switch	uint8_t	Sensorless switching control 0: Enable 1: Disable
u1_flux_weakening	uint8_t	Flux weakening control 0: Enable 1: Disable
u1_volt_err_comp	uint8_t	Voltage error compensation 0: Enable 1: Disable
u1_openloop_damping	uint8_t	Open-loop damping control 0: Enable 1: Disable
u1_enable_write	uint8_t	Enable to rewriting variables (when the same values as of g_u1_enable_write is written)

Next, the structures that are frequently monitored during motor driving evaluation under sensorless vector control are listed in Table 4-3. In addition, the primary variables of the structures are listed in Table 4-4. Please refer when using Analyzer function. Regarding variables not listed in Table 4-2, refer to source codes.

Table 4-3 List of sensorless vector control structures

Structure name	Type	Content
g_st_foc_1	mtr_foc_control_t	Speed control structure for motor 1
g_st_foc_2	mtr_foc_control_t	Speed control structure for motor 2
g_st_foc_3	mtr_foc_control_t	Speed control structure for motor 3
g_st_foc_4	mtr_foc_control_t	Speed control structure for motor 4

Table 4-4 List of main members of mtr_foc_control_t structure

Main members of mtr_foc_control_t structure	Type	Content
st_cc.f4_id_ref	float	d-axis current reference [A]
st_cc.f4_id_ad	float	d-axis current [A]
st_cc.f4_iq_ref	float	q-axis current reference [A]
st_cc.f4_iq_ad	float	q-axis current [A]
f4_iu_ad	float	U phase current A/D conversion value [A]
f4_iv_ad	float	V phase current A/D conversion value [A]
f4_iw_ad	float	W phase current A/D conversion value [A]
st_cc.f4_vd_ref	float	d-axis output voltage reference [V]
st_cc.f4_vq_ref	float	q-axis output voltage reference [V]
f4_refu	float	U phase voltage reference [V]
f4_refv	float	V phase voltage reference [V]
f4_refw	float	W phase voltage reference [V]
f4_modu	float	U phase modulation factor
f4_modv	float	V phase modulation factor
f4_modw	float	W phase modulation factor
f4_ed	float	Estimated d-axis BEMF [V]
f4_eq	float	Estimated q-axis BEMF [V]
st_rotor_angle.f4_rotor_angle_rad	float	Estimated position (Electrical) [rad]
st_sc.f4_ref_speed_rad_ctrl	float	Speed reference (Electrical) [rad/s]
st_sc.f4_speed_rad	float	Estimated speed (Electrical) [rad/s]
f4_phase_err_rad	float	Phase error (Electrical) [rad]
u2_error_status	uint16_t	Error status

4.3 Operation Example for Analyzer

The section shows an example below for motor driving operation using Analyzer. Operation is using 'Control Window' of Analyzer. Regarding specification of 'Control Window', refer to 'Renesas Motor Workbench User's Manual'.

- Driving the motor (The steps below apply in the case of motor 1.)
  (1) Confirm the check-boxes of column [W?] for 'com_u1_mode_system_motor1', 'st_com_1.s2_ref_speed_rpm', 'st_com_1.u1_enable_write' marks.
  (2) Input a reference speed value in the [Write] box of 'st_com1.s2_ref_speed_rpm'.
  (3) Click the 'Write' button.
  (4) Click the 'Read' button. Confirm the [Read] box of 'st_com1.s2_ref_speed_rpm', 'g_u1_enable_write'.
  (5) Set a same value of 'g_u1_enable_write' in the [Write] box of 'st_com1.u1_enable_write'.
  (6) Write '1' in the [Write] box of 'com_u1_mode_system_motor1'.
  (7) Click the 'Write' button.

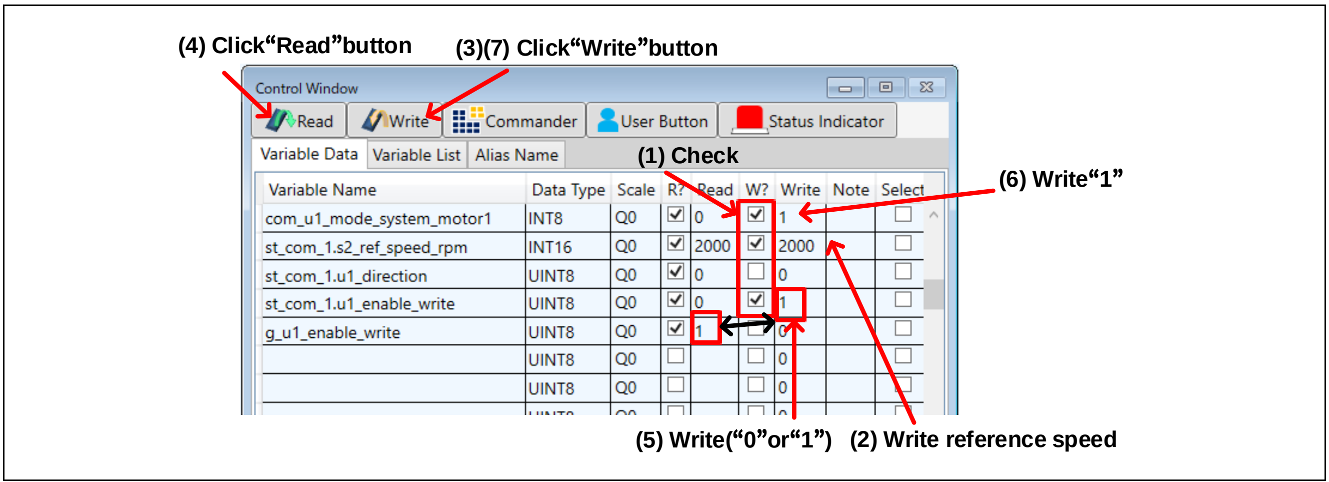


Figure 4-2 Procedure – Driving the Motor

The table below lists the respective variables for use with motors 1 to 4.

Table 4-5 Variables for Use with Each Motor

Motor 1	Motor 2	Motor 3	Motor 4
com_u1_mode_system_motor1	com_u1_mode_system_motor2	com_u1_mode_system_motor3	com_u1_mode_system_motor4
st_com_1.s2_ref_speed_rpm	st_com_2.s2_ref_speed_rpm	st_com_3.s2_ref_speed_rpm	st_com_4.s2_ref_speed_rpm
st_com_1.u1_enable_write	st_com_2.u1_enable_write	st_com_3.u1_enable_write	st_com_4.u1_enable_write
g_u1_enable_write	←	←	←

- Stopping the motor (The steps below apply in the case of motor 1.)
  (1) Write ‘0’ in the [Write] box of ‘com_u1_mode_system_motor1’
  (2) Click the ‘Write’ button.

* com_u1_mode_system_motor1 is replaced by com_u1_mode_system_motor2, com_u1_mode_system_motor3, and com_u1_mode_system_motor4 in the cases of motors 2, 3, and 4, respectively.

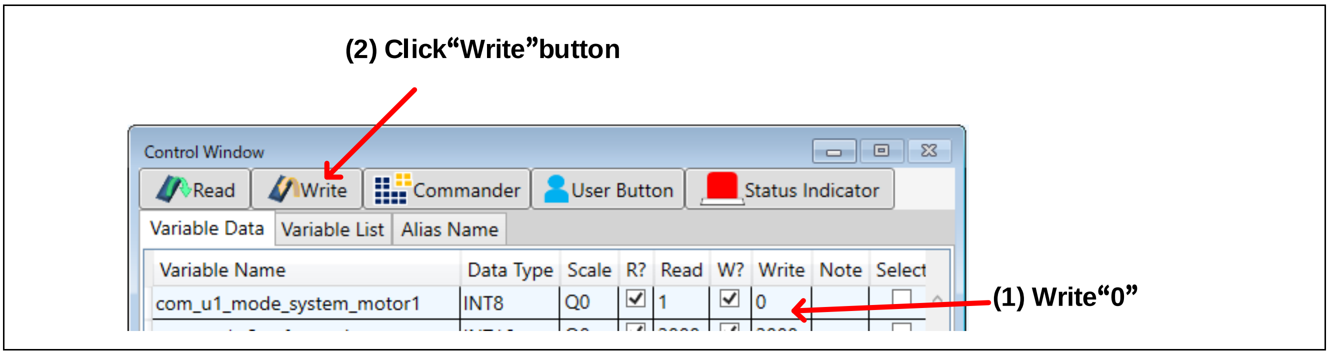


Figure 4-3 Procedure – Stop the Motor

- Error cancel operation (The steps below apply in the case of motor 1.)
  (1) Write ‘3’ in the [Write] box of ‘com_u1_mode_system_motor1’
  (2) Click the ‘Write’ button.

* com_u1_mode_system_motor1 is replaced by com_u1_mode_system_motor2, com_u1_mode_system_motor3, and com_u1_mode_system_motor4 in the cases of motors 2, 3, and 4, respectively.

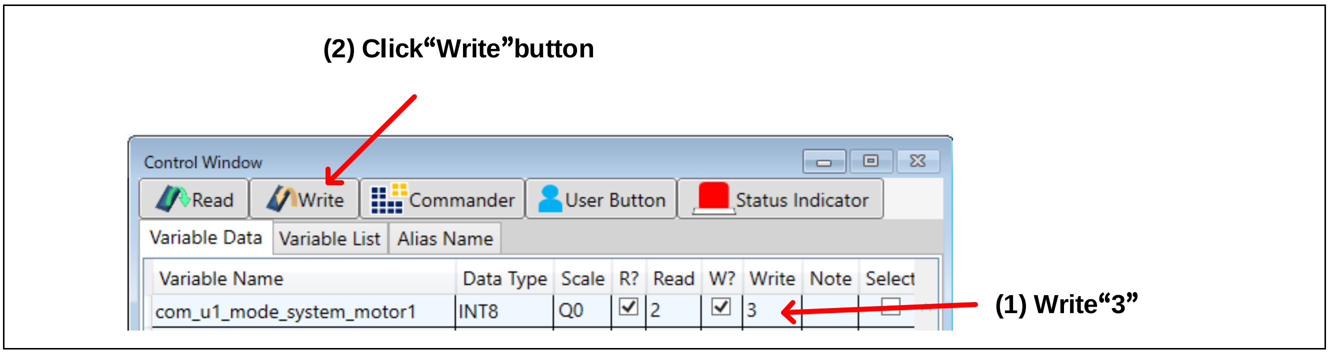


Figure 4-4 Procedure – Error Cancel Operation

4.4 Operation Example for User Button

The section shows an example below for motor driving operation using User Button.

- Driving or stopping the motor

By setting as shown in Figure 4-5, driving and stopping change each time the button is pressed.

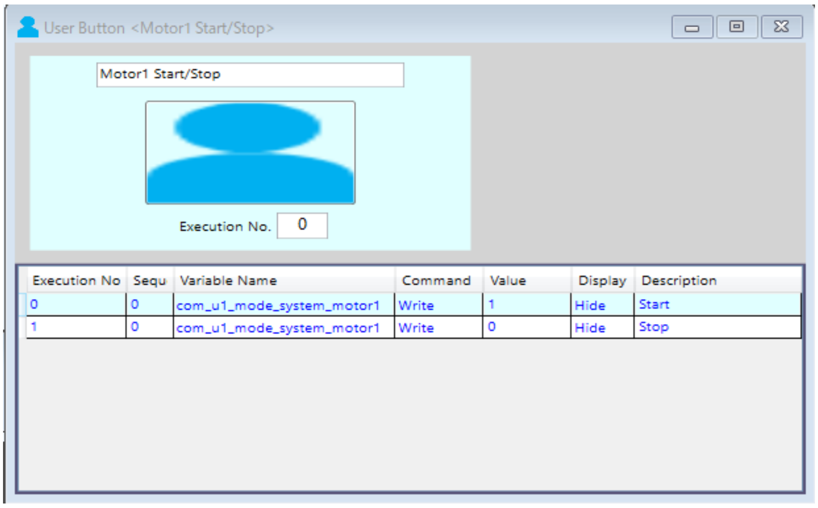


Figure 4-5 Driving or Stop the Motor

* com_u1_mode_system_motor1 in the figure above is for the case of motor 1. It is replaced by com_u1_mode_system_motor2, com_u1_mode_system_motor3, and com_u1_mode_system_motor4 in the cases of motors 2, 3, and 4, respectively.

- Change to speed

By setting as shown in Figure 4-6, enter the command speed and press the button to change the speed.

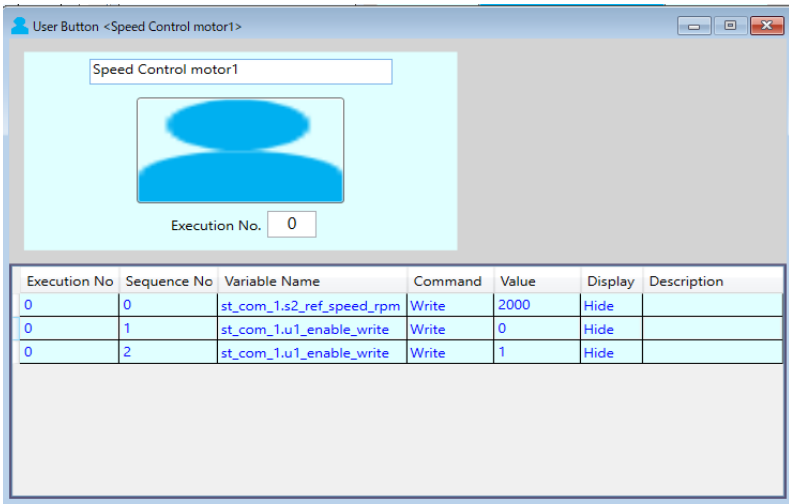


Figure 4-6 Change speed

The table below lists the respective variables for use with motors 1 to 4.

Table 4-6 Variables for Use with Each Motor

Motor 1	Motor 2	Motor 3	Motor 4
st_com_1.u2_ref_speed_rpm	st_com_2.u2_ref_speed_rpm	st_com_3.u2_ref_speed_rpm	st_com_4.u2_ref_speed_rpm
st_com_1.u1_enable_write	st_com_2.u1_enable_write	st_com_3.u1_enable_write	st_com_4.u1_enable_write

5. Data to be Measured

5.1 Driving Waveform

The figure below shows the waveforms in the simultaneous driving of four motors in terms of the speed and q-axis current information as an example of the operation. The driving waveforms at start-up, in the steady state, and during the transitional period between start-up and the steady state are given in order for reference below and on the following pages.

Figure 5-1 Driving Waveforms When Motors 1 to 4 are Starting up (1/3)

Figure 5-2 Driving Waveforms When Motors 1 and 2 are Starting up (2/3)

Figure 5-3 Driving Waveforms When Motors 3 and 4 are Starting up (3/3)

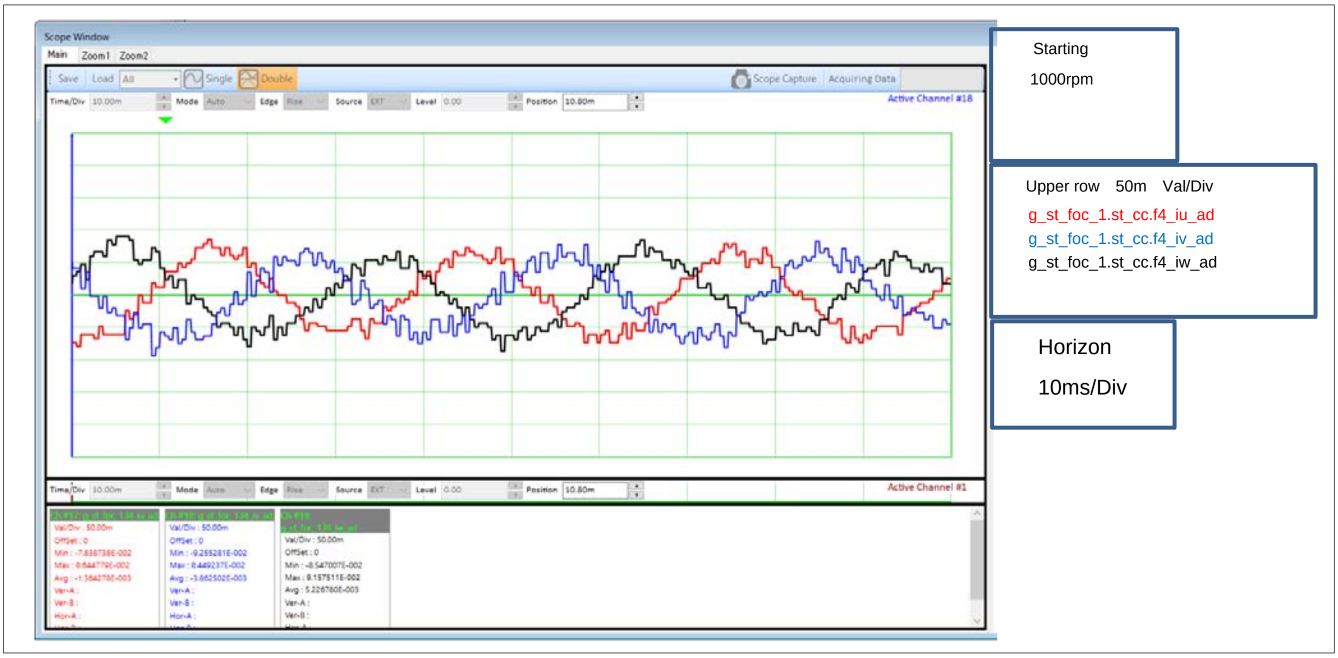


Figure 5-4 Driving Waveforms of Motor 1 in the Steady State

Figure 5-5 Driving Waveforms of Motors 1 and 2 during the Transitional Period between Start-up and the Steady State (1/2)

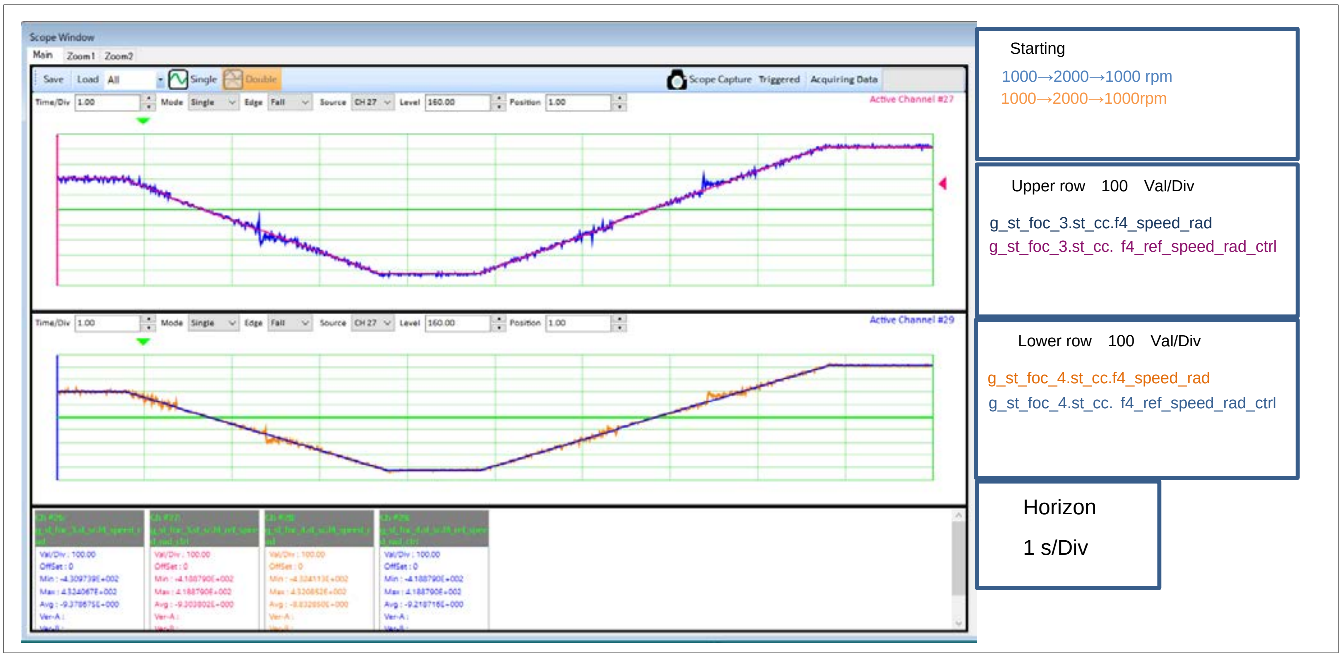


Figure 5-6 Driving Waveforms of Motors 3 and 4 during the Transitional Period between Start-up and the Steady State (2/2)

5.2 Loads Imposed on the CPU

The table below shows the CPU load factors during execution of this system. The values in the table were obtained under the following conditions.

- CPU clock frequency: 200 MHz
- PWM carrier frequency: 20 kHz

Table 5-1 Loads Imposed on the CPU

	Processing Time [μs]	Load Factor [%]
500 [μs] period interrupt	21.2*1	1.32*2
PWM periodic interrupt for motor 1	8.36	16.72
PWM periodic interrupt for motor 2	7.36	14.72
PWM periodic interrupt for motor 3	7.26	14.52
PWM periodic interrupt for motor 4	7.24	14.48
CPU load factor		61.76

Notes: 1. This includes the PWM periodic interrupts (multiple interrupts).
2. This is obtained by calculation from the processing time with the multiple interrupts taken into account.

5.3 Amounts of ROM and RAM Used by This System

The amounts of ROM and RAM used by this system are as follows.

Table 5-2 Amounts of ROM and RAM Used by This System

	Size
ROM	33.8 KB
RAM	13.5 KB

Revision History

Rev.	Date	Description	
		Page	Summary
1.00	Sep.06.21	—	First edition issued

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. Precaution against Electrostatic Discharge (ESD)

   A strong electrical field, when exposed to a CMOS device, can cause destruction of the gate oxide and ultimately degrade the device operation. Steps must be taken to stop the generation of static electricity as much as possible, and quickly dissipate it when it occurs. Environmental control must be adequate. When it is dry, a humidifier should be used. This is recommended to avoid using insulators that can easily build up static electricity. Semiconductor devices must be stored and transported in an anti-static container, static shielding bag or conductive material. All test and measurement tools including work benches and floors must be grounded. The operator must also be grounded using a wrist strap. Semiconductor devices must not be touched with bare hands. Similar precautions must be taken for printed circuit boards with mounted semiconductor devices.
2. Processing at power-on

   The state of the product is undefined at the time 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 time 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 time 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 time when power is supplied until the power reaches the level at which resetting is specified.
3. Input of signal during power-off state

   Do not input signals or an I/O pull-up power supply while the device is powered off. The current injection that results from input of such a signal or I/O pull-up power supply may cause malfunction and the abnormal current that passes in the device at this time may cause degradation of internal elements. Follow the guideline for input signal during power-off state as described in your product documentation.
4. 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 the 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.
5. Clock signals

   After applying a reset, only release the reset line after the operating clock signal becomes stable. When switching the clock signal during program execution, wait until the target clock signal is 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. Additionally, 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.
6. Voltage application waveform at input pin

   Waveform distortion due to input noise or a reflected wave may cause malfunction. If the input of the CMOS device stays in the area between V_{IL} (Max.) and V_{IH} (Min.) due to noise, for example, the device may malfunction. Take care to prevent chattering noise from entering the device when the input level is fixed, and also in the transition period when the input level passes through the area between V_{IL} (Max.) and V_{IH} (Min.).
7. Prohibition of access to reserved addresses

   Access to reserved addresses is prohibited. The reserved addresses are provided for possible future expansion of functions. Do not access these addresses as the correct operation of the LSI is not guaranteed.
8. Differences between products

   Before changing from one product to another, for example to a product with a different part number, confirm that the change will not lead to problems. The characteristics of a microprocessing unit or microcontroller unit products in the same group but having a different part number might differ in terms of 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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