RX23E-A Group

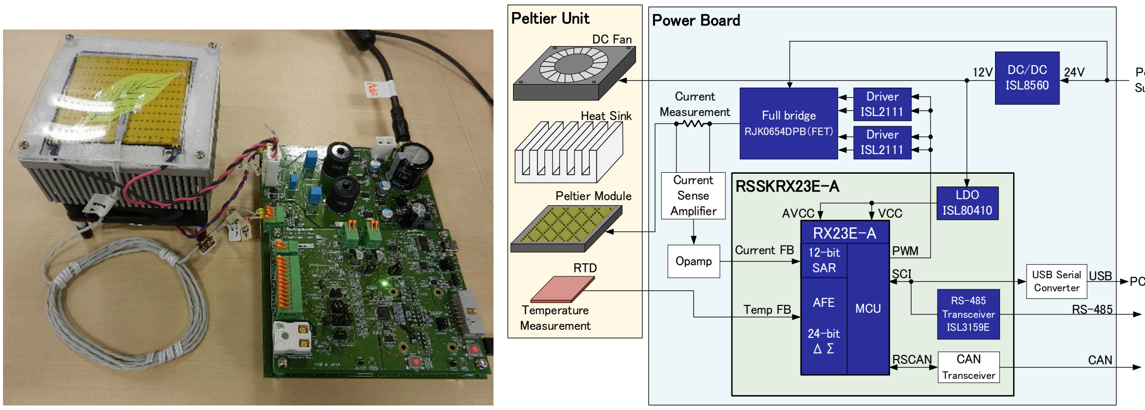
Example of Thermoelectric Peltier Controller

Summary

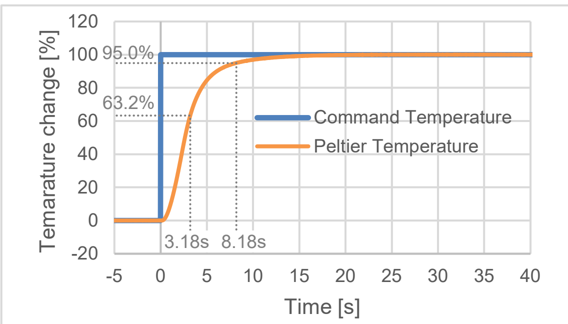
This document shows an example of how to control temperature of Peltier module using the Renesas microcontroller RX23E-A. Measurement, calculation, and control required for the Peltier Controller can be implemented with a single chip of RX23E-A, and the system can be configured easily.

The appearance and configuration overview of the Peltier Controller and its evaluation results are shown below.

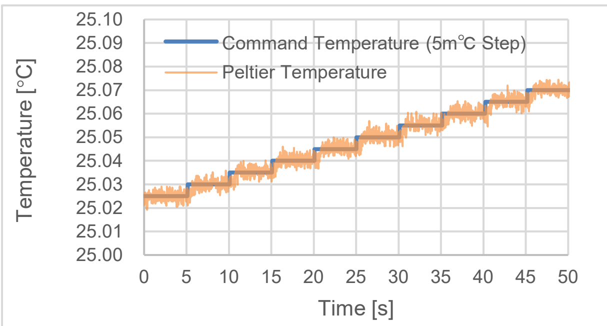
Based on the evaluation results of the step response characteristics, it is confirmed that the target value can be achieved in several seconds. In addition, it is confirmed that the Peltier Controller can be controlled in a resolution of 5m°C or less because it responds to changes in command values in steps of 5m°C.



Appearance and Configuration Overview of the Peltier Controller



Temperature Step Response (25°C → 35°C)



5m°C Control Resolution

Evaluation Results

Target Device

RX23E-A

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1. Overview

This document shows an example of how to control the Peltier temperature using the Renesas microcontroller RX23E-A. The Peltier Controller (hereafter called "this system") consists of the RSSKRX23E-A board with RX23E-A, the power board, and the Peltier unit.

In this system, temperature is controlled using the Peltier module as an example of implementing temperature control. Temperature control with the Peltier module is used to keep the characteristics of devices with high temperature dependency such as laser diodes constant.

This system implements temperature measurement using a resistance temperature detector, PID control operations, and communication with a single chip of RX23E-A.

1.1 Introduction of Renesas Electronics' Products

Table 1-1 lists the Renesas Electronics' products used in this system.

Table 1-1 List of Renesas Electronics' Products in This System

Part No.	Part name	Board	Quantity
R5F523E6ADFL (RX23E-A)	MCU	RSSKRX23E-A	1
ISL80410	LDO	RSSKRX23E-A	1
ISL3159E	RS-422/RS-485 driver	RSSKRX23E-A	1
ISL8560	Step-down DC/DC converter	Power board	1
ISL2111	Half bridge driver	Power board	2
RJK0654DPB	N-channel MOSFET	Power board	4
READ2302GSP	Operational amplifier	Power board	2

- RX23E-A

Table 1-2 shows an overview of the specifications of RX23E-A used in this system.

RX23E-A is mounted on the evaluation board for the RX23E-A "Renesas Solution Starter Kit for RX23E-A (RSSKRX23E-A)". RX23E-A has two channels of the low-noise 24-bit Δ-ΣA/D converter (DSAD) that allows high-precision measurement. DSAD has a programmable gain instrumentation amplifier (PGA) which gain is selectable from x1, x2, x4, x8, x16, x32, x64, and x128. It also has an analog front-end (AFE) circuit suitable for sensor measurement of thermocouples, resistance temperature detectors, and strain gauges. Up to 6 channels can be measured by switching the analog multiplexer (AMUX) built in the AFE. In addition, it has one channel of the successive approximation 12-bit A/D converter (S12AD).

For details about RX23E-A, refer to "RX23E-A Group User's Manual: Hardware". For details about RSSKRX23E-A, refer to "RSSKRX23E-A User's Manual: Board".

Table 1-2 Overview of the Specifications of RX23E-A

Item	Description
Product group	RX23E-A
Part No.	R5F523E6ADFL
CPU max. operating frequency	32 MHz
Bit count	32 bits
Package/pin count	LFQFP/48 pins
ROM	256 KB
RAM	32 KB
Operating temperature range	-40°C to +85°C
Storage temperature range	-55°C to +125°C

- ISL80410

ISL80410 is mounted on RSSKRX23E-A. ISL80410 is a low-noise LDO with a wide input voltage range of 6 V to 40 V, variable output voltage of 2.5 V to 10 V, and no-load current consumption of 16 uA. The output voltage of RSSKRX23E-A is set to 5 V.

- ISL8560

ISL8560 is mounted on the power board. ISL8560 is a step-down DC/DC converter with integrated FETs with a wide input voltage range of 9 V to 60 V, variable output voltage of 1.21 V to 55 V, and maximum output current of 2 A. The output voltage of the power board is set to 12.0 V.

- ISL2111

ISL2111 is mounted on the power board. ISL2111 is a half-bridge N-channel MOSFET driver with an on-chip bootstrap diode that operates at the power supply voltage of 8 V to 14 V and can drive the maximum rail voltage of 100 V. On the power board, two units of ISL2111 are used to drive the 24 V full bridge circuit for driving the Peltier module.

- RJK0654DPB

RJK0654DPB is mounted on the power board. RJK0654DPB is an N-channel power MOSFET with 60 V, 30 A, and on-resistance of 8.3 mΩ max. On the power board, four units of the full bridge circuit are used.

- READ2302GSP

READ2302GSP is mounted on the power board. READ2302GSP is a CMOS dual operational amplifier with a high driving capacity, high slew rate, and full-range input/output. It operates with the low voltage single power supply of 2.5 V to 5.5 V, and provided as a small sized 8-pin TSSOP.

2. Related Documents

- R01UH0801 RX23E-A Group User’s Manual: Hardware
- R20UT4542 RSSKRX23E-A User’s Manual
- R20AN0540 Application Notes RSSKRX23E-A PC Tool Program Operation Manual
- R01AN4788 Application Notes RX23E-A Group Temperature Measurement Examples Using Resistance Temperature Detectors

3. Environment for Operation Confirmation

The environment for operation confirmation is given in Table 3-1.

Table 3-1 Environment for Operation Confirmation

Item		Description
Power Board		Thermoelectric Controller Board
MCU Board		RSSKRX23E-A Board (RTK0ESXB10C00001BJ)
	MCU	RX23E-A (R5F523E6ADFL) Power supply voltages (VCC, AVCC0): 5 V Operating frequencies (ICLK): 32 MHz Peripheral operating frequency (PCLKA): 32 MHz (MTU3, MTU4) Peripheral operating frequency (PCLKB): 32 MHz (AFE, DSAD0, S12ADE, SCI5) DSAD operating frequency (f_{DR}): 4 MHz DSAD modulator clock frequency (f_{MOD}): 0.5 MHz
Peltier Unit		Peltier Unit
	Peltier Module	TAISEI CO.,Ltd. UT-7070KA-M
	3-wire resistance temperature detector	CHINO CORPORATION R060-33
IDE		Renesas e^2 studio 2020-07
Tool Chain		Renesas CC-RX V3.02.00
Emulator		E2 Emulator Lite

4. System Configuration

Figure 4-1 shows the Configuration of This System, and Figure 4-2 shows the Appearance of This System. This system consists of the Peltier unit to be controlled, the power board for driving the Peltier unit, and the RSSKRX23E-A board for temperature/current measurement, control operations, and communication.

In this system, temperature is controlled by controlling the current flowing into the Peltier module. Current control is implemented by using PWM control of the full bridge circuit. Current is measured by using the 12-bit successive approximation A/D converter (hereafter called S12ADC) built into RX23E-A. It is synchronized with current measurement by using the multi-function timer pulse unit (hereafter called MTU), and current is controlled using PWM output.

The Peltier module temperature is measured by using the 3-wire resistance temperature detector (hereafter called RTD). The resistance value of RTD is measured by using the 24-bit Δ-Σ A/D converter (hereafter called DSAD) built into RX23E-A. RTD measurement usually requires external circuits such as excitation current sources. However, the excitation current sources of AFE of RX23E-A can be used to perform high-precision temperature measurement without any external IC.

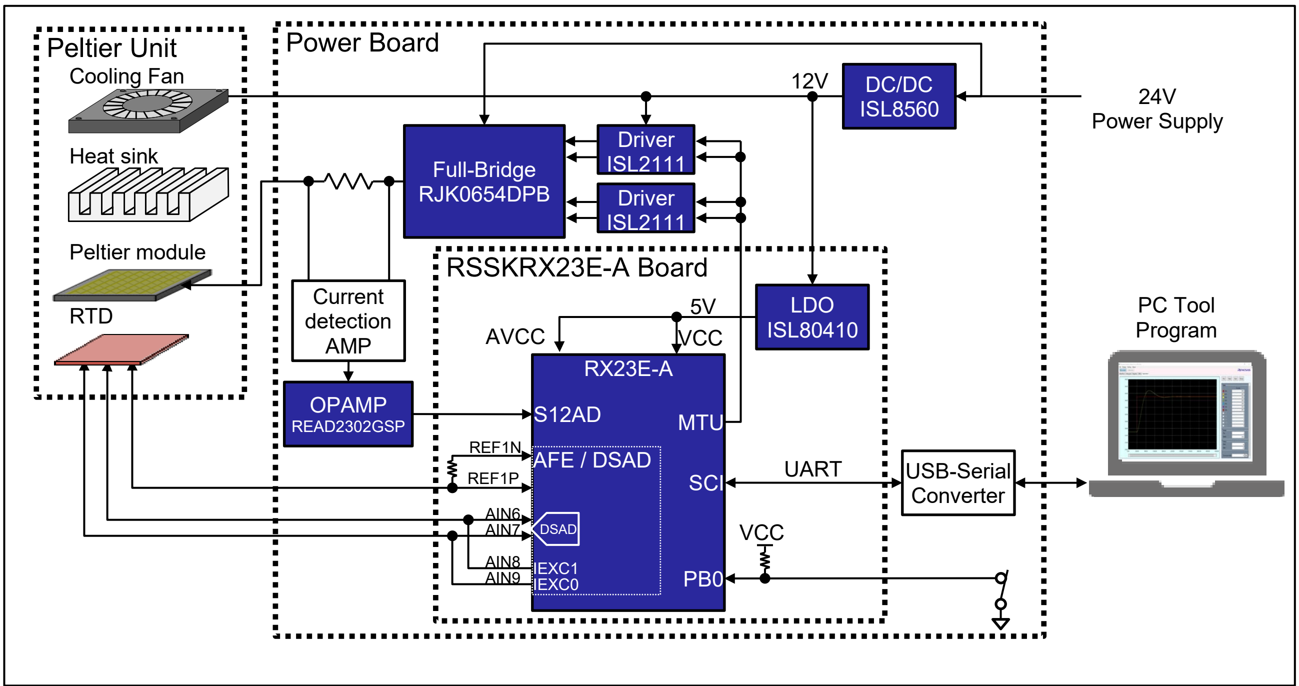


Figure 4-1 Configuration of This System

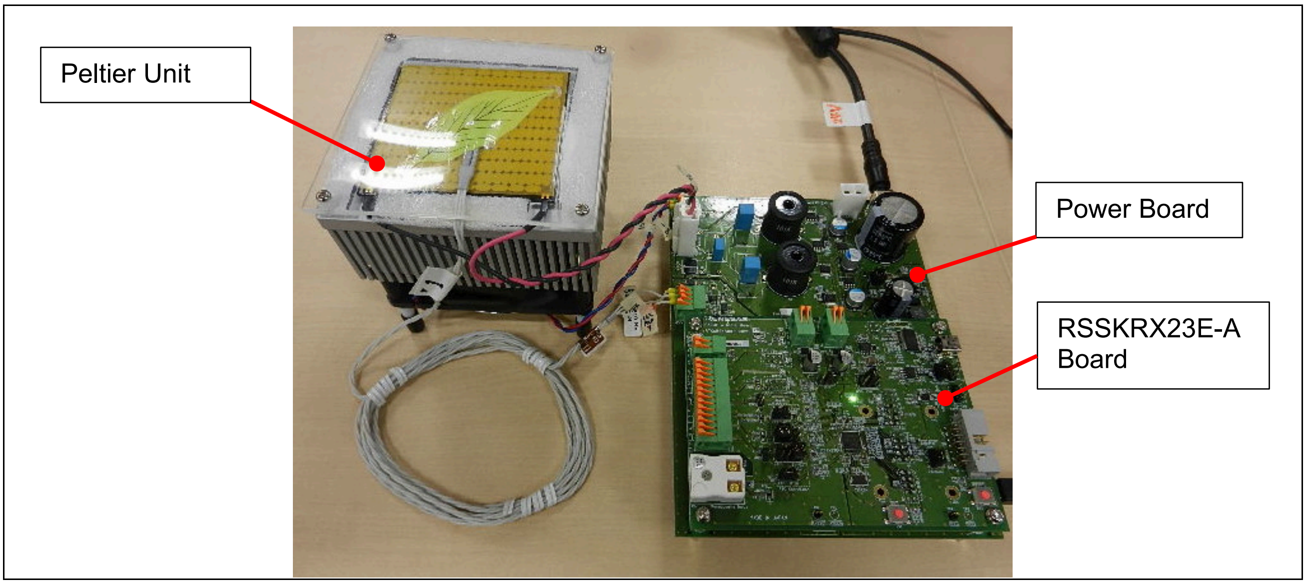


Figure 4-2 Appearance of This System

Transmission of temperature command values and temperature measurement can be performed by using the Application tab of the PC tool program (hereafter called the "PC tool") of RSSKRX23E-A, as shown in Figure 4-3. The demo operation that increases/decreases the temperature command value can be turned on/off with the slide switch.

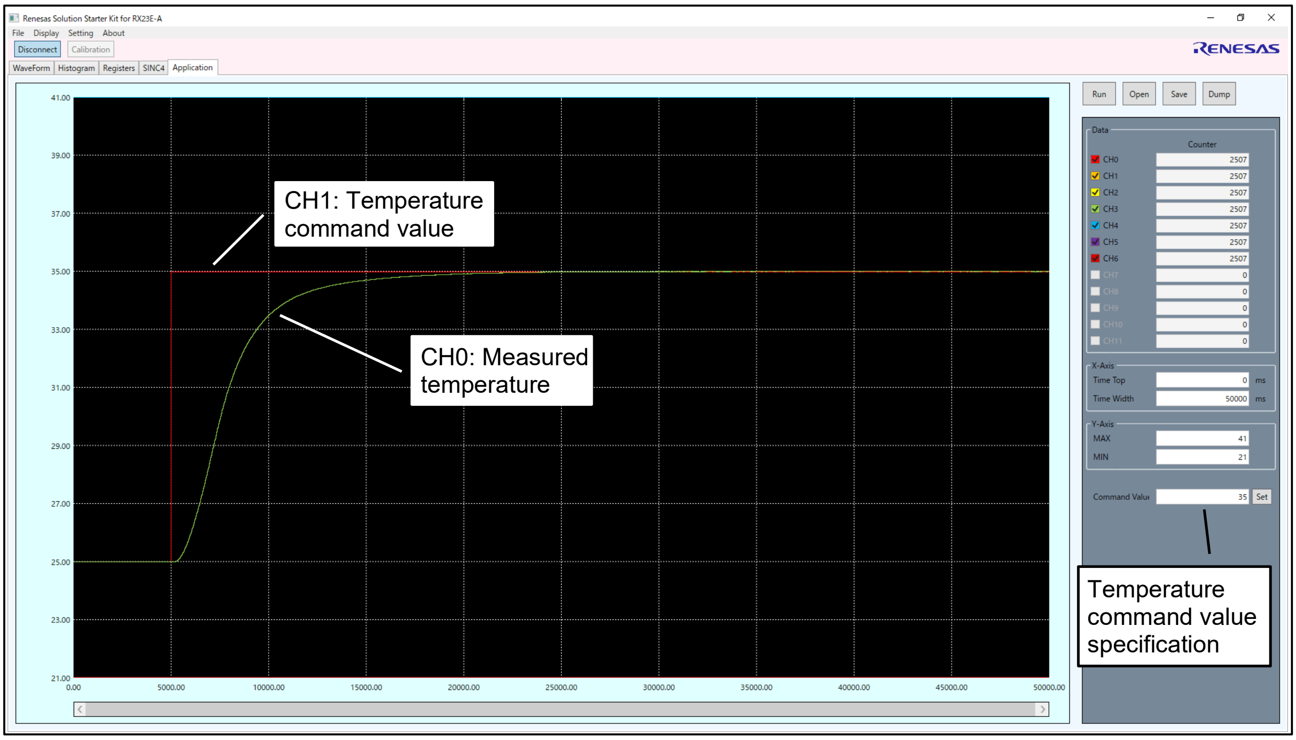


Figure 4-3 Display Example of the PC Tool Program

4.1 Hardware Configuration

4.1.1 Power Supply Configuration

Figure 4-4 shows the Power Supply Configuration of This System. Table 4-1 shows the Power Supply Specifications of This System.

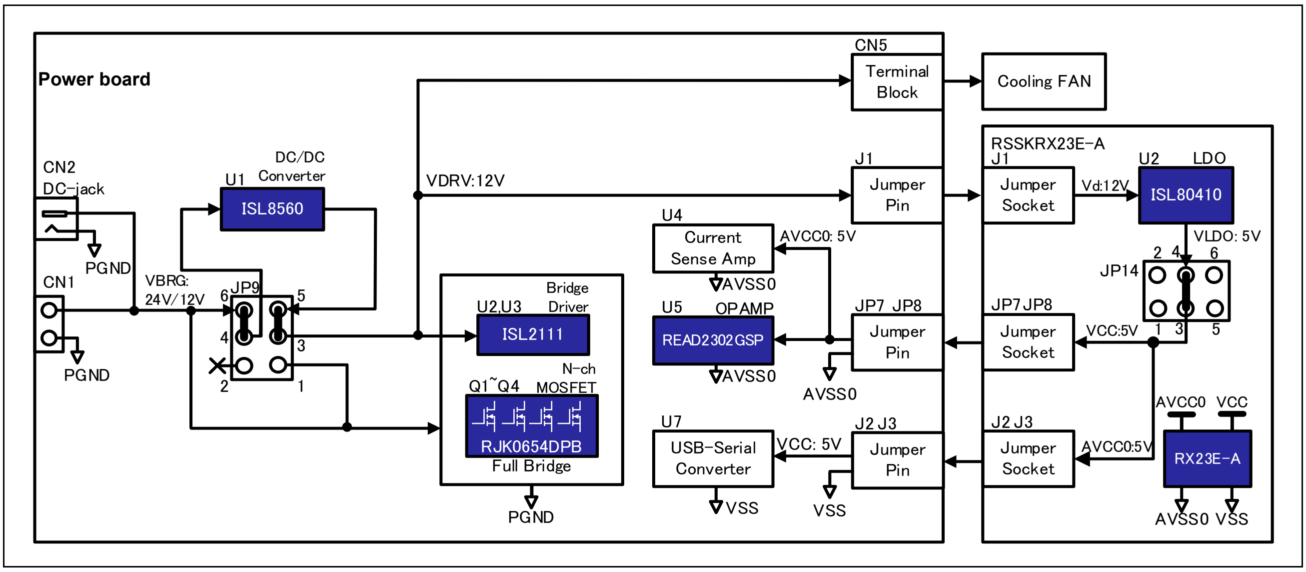


Figure 4-4 Power Supply Configuration of This System

Table 4-1 Power Supply Specifications of This System

Item	Symbol	Connector	Operating voltage	Remarks
System power supply	VBRG	CN1 Or CN2	24 V	Maximum load current: 5 A Pins 4-6 and Pins 3-5 of JP9 of the power board are connected.
			12 V	Maximum load current: 10 A Pins 2-4 and Pins 1-3 of JP9 of the power board are connected.
Bridge driver power supply	VDRV (Vd)	J1	12 V	Power supply for the bridge driver and air-cooling fan Input power supply of RSSKRX23E-A Pins 3-4 of JP14 of RSSKRX23E-A are connected.
Digital power supply	VCC	J2 J3	5 V	Output of U2 of RSSKRX23E-A
Analog power supply	AVCC0	JP7 JP8	5 V	Output of U2 of RSSKRX23E-A (Separated from the digital power supply by RSSKRX23E-A)

The power supply voltage of this system is 24 V or 12 V. The power is supplied from CN1 or CN2. For 24 V input, Pins 4-6 and Pins 3-5 of JP9 of the power board are connected.so that U1: DC/DC converter (ISL8560) generates 12 V power supply (VDRV) for the bridge driver, air-cooling fan, and RSSKRX23E-A. For 12 V input, Pins 2-4 and Pins 1-3 of JP of JP9 of the power board are connected so that the power is supplied directly to the bridge driver, air-cooling fan, and RSSKRX23E-A. . The 12 V power is supplied to RSSKRX23E-A via J1. The 5 V power supply is generated by U2: LDO (ISL80410) mounted on RSSKRX23E-A. VCC and AVCC0 are supplied to U4: Power Current detection amplifier, U5: Op-amp (READ2302GSP), and U7: USB serial conversion IC of the power board via U1: RX23E-A, J2, J3, JP7, and JP8. On RSSKRX23E-A, Pins 3-4 of JP14 are connected to use LDO.

In this document, the operation is checked using the input voltage of 24 V.

4.1.2 RSSKRX23E-A

(1) Configuration and Appearance

Figure 4-5 and Figure 4-6 show the system block diagram and appearance of RSSKRX23E-A.

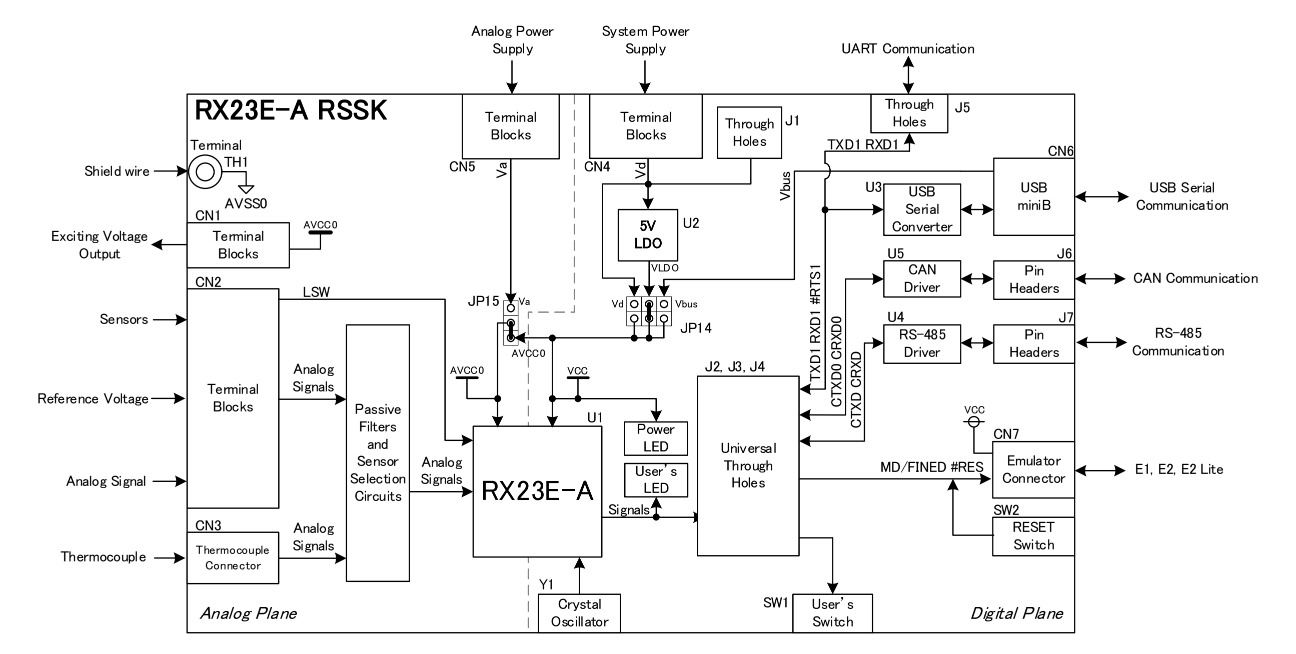


Figure 4-5 System Block Diagram of RSSKRX23E-A

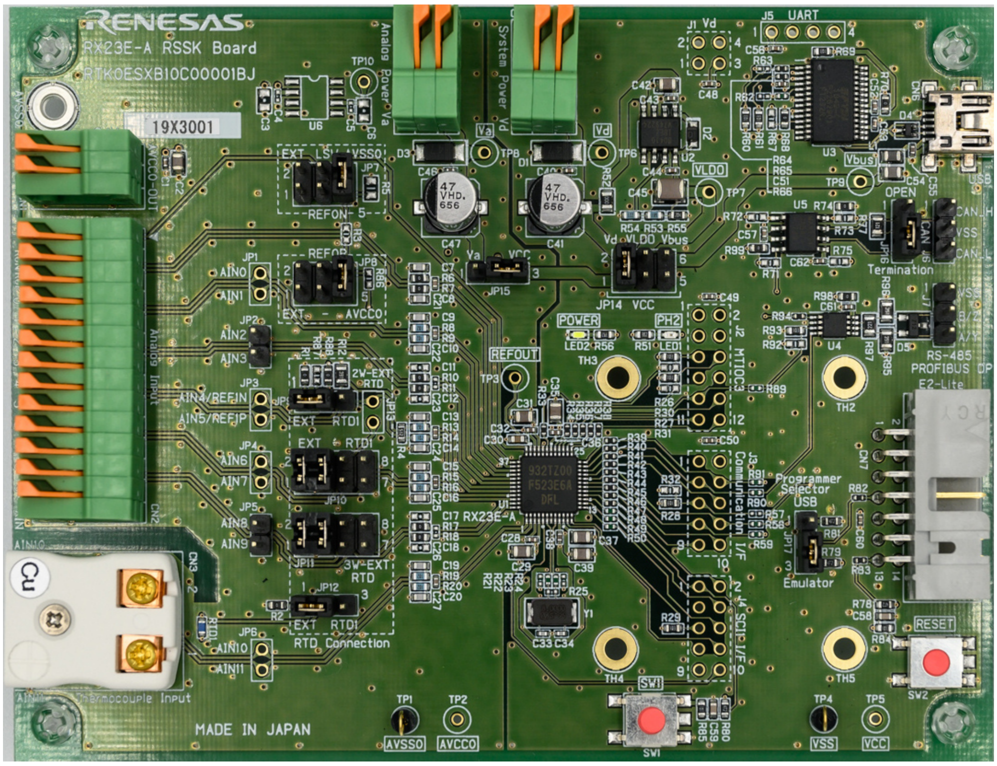


Figure 4-6 Appearance of RSSKRX23E-A

(2) Connections with the power board

Table 4-2 through Table 4-4 show the connections between RSSKRX23E-A and the power board. For the signal names of RSSKRX23E-A, refer to "Appendix 2. Circuit Diagram" in "RSSKRX23E-A User's Manual: Board". For the signal names of the power board, refer to "Appendix 2 Circuit Diagrams of the Power Board" in this document.

Table 4-2 Connection Between RSSKRX23E-A and the Power Board (Power Supply)

RSSKRX23E-A			Direction	Power board		
Signal name	Reference Designator	Pin number		Signal name	Reference Designator	Pin number
VSS	J1	1, 2	←	PGND	J1	1, 2
Vd	J1	3, 4	←	VDRV	J1	3, 4

Table 4-3 Connection Between RSSKRX23E-A and the Power Board (Digital)

RSSKRX23E-A			Direction	Power board		
Signal name	Reference Designator	Pin number		Signal name	Reference Designator	Pin number
VSS	J2	1, 3, 7, 8	→	VSS	J2	1, 3, 7, 8
PB0	J2	5	←	PB0/SW1	J2	5
PB1	J2	6	←	V_DET	J2	6
VCC	J2	2, 4	→	VCC	J2	2, 4
PC4/MTIOC3D	J2	9	←	CTS5#	J2	9
VSS	J3	1	→	VSS	J3	1
VCC	J3	2	→	VCC	J3	2
PH1/TXD5	J3	3	→	TXD5	J3	3
PH0/RXD5	J3	4	←	RXD5	J3	4
P27/IRQ3/SW1	J4	1	→	PWM-AH	J4	1
P26/TXD1	J4	2	→	PWM-AL	J4	2
VSS	J4	3	→	VSS	J4	3
P30/RXD1	J4	4	→	PWM-BH	J4	4
P31/CTS1#	J4	6	→	PWM-BL	J4	6

Table 4-4 Connection Between RSSKRX23E-A and the Power Board (Analog)

RSSKRX23E-A			Direction	Power board		
Signal name	Reference Designator	Pin number		Signal name	Reference Designator	Pin number
AIN5/REF1P	JP3	2	←	REF1P	JP3	2
AIN6	JP4	1	⇔	AIN6/IEXC1	JP4	1
AIN7	JP4	2	⇔	AIN7/IEXC0	JP4	2
AIN10	JP6	1	←	Ifb/AN004	JP6	1
AIN11	JP6	2	←	AVSS0	JP6	2
AVSS0	JP7	1, 2, 6	→	AVSS0	JP7	1, 2, 6
REF0N	JP7	3, 5	←	AVSS0	JP7	3, 5
LSW	JP7	4	←	AVSS0	JP7	4
AVSS0	JP8	1, 2	→	AVSS0	JP8	1, 2
REF0P	JP8	4, 6	←	AVCC0	JP8	4, 6
AVCC0	JP8	5	→	AVCC0	JP8	5

(3) Changes on RSSKRX23E-A

Table 4-5 shows the changes arranged for connecting RSSKRX23E-A to the power board.

Table 4-5 Changes on the RSSKRX23E-A Board

Circuit symbol	Before change		After change	
	Part No.	Mounting side	Part No.	Mounting side
J1	Not mounted	-	M20-7830246	Solder side
J2	Not mounted	-	PPTC062LFBN-RC	Solder side
J3, J4	Not mounted	-	M20-7830546	Solder side
JP3, JP4, JP6	Not mounted	-	M20-7820246	Solder side
JP7, JP8	M20-9980345	Component side	M20-7830346	Solder side
R48~R50	RK73Z1ETTP	Component side	RK73B1ETTP330J	Component side
R60, R61	RK73B1JTTD103J	Component side	Not mounted	-
R64, R65	RK73B1ETTP330J	Component side	Not mounted	-
R66, R89~R91	RK73Z1ETTP	Component side	Not mounted	-
R80	RK73B1JTTD472J	Component side	Not mounted	-
R85	RK73B1JTTD101J	Component side	Not mounted	-
C27	CGA2B3X7R1H104K050BB	Component side	Not mounted	-
C59	CGA3E2X7R1H102K080AA	Component side	Not mounted	-

4.1.3 Power Board

4.1.3.1 Configuration and Appearance View

Figure 4-7 shows the System Block Diagram of the Power Board, and Figure 4-8 shows the Appearance View of the Power Board. For the list of parts of the power board, refer to "Appendix 1 Parts List of the Power Board". For the circuit diagrams, refer to "Appendix 2 Circuit Diagrams of the Power Board".

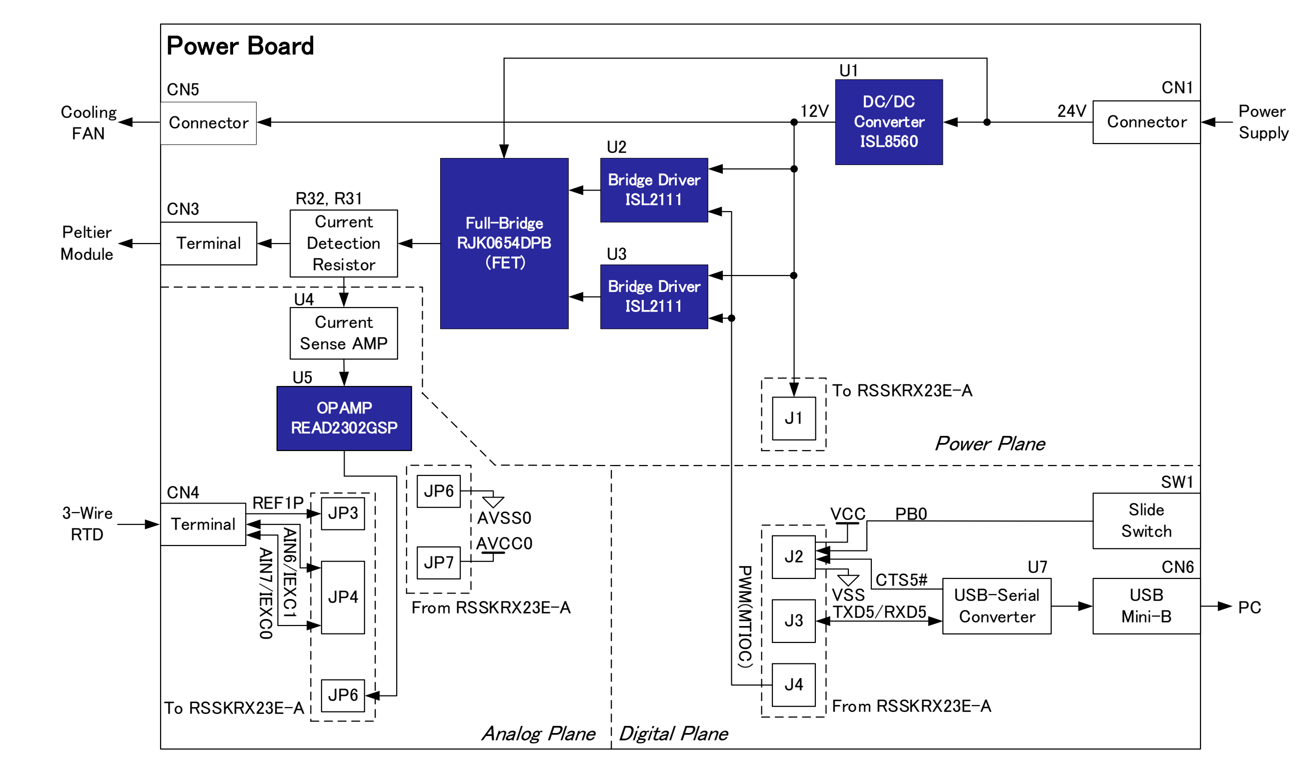


Figure 4-7 System Block Diagram of the Power Board

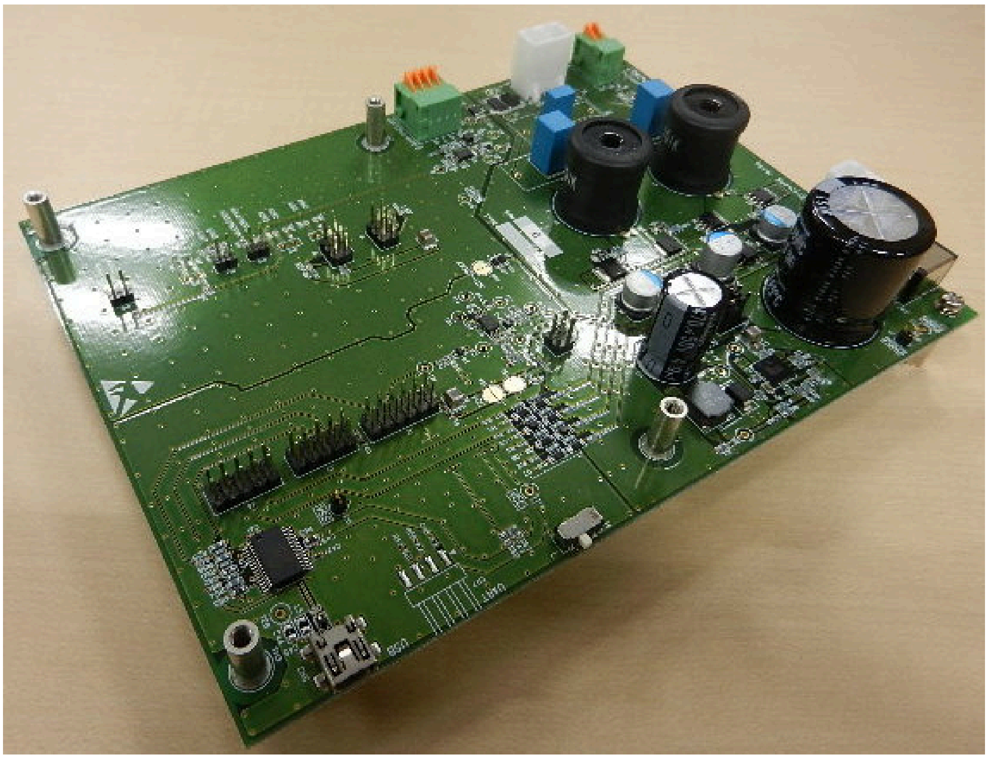


Figure 4-8 Appearance View of the Power Board

4.1.3.2 Descriptions of Circuits

(1) Power supply circuit

Figure 4-9 shows the DC/DC Converter Circuit of the power board.

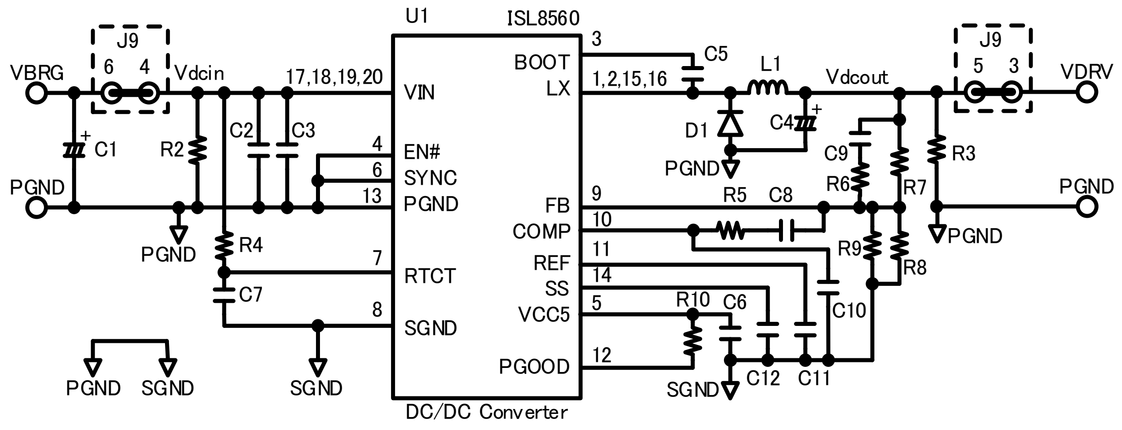


Figure 4-9 DC/DC Converter Circuit

The DC/DC converter ISL8560 is mounted on the power board. The DC/DC converter circuit is used when 24 V is supplied to the system power supply and outputs the 12 V power supply for the bridge driver, air-cooling fan, and RSSKRX23E-A. When the DC/DC converter is used, Pins 3 to 5 and Pins 4 to 6 of JP9 are connected.

(2) Full bridge circuit

Figure 4-10 shows the Full Bridge Circuit. Figure 4-11 shows the Operating Modes of the Full Bridge Circuit.

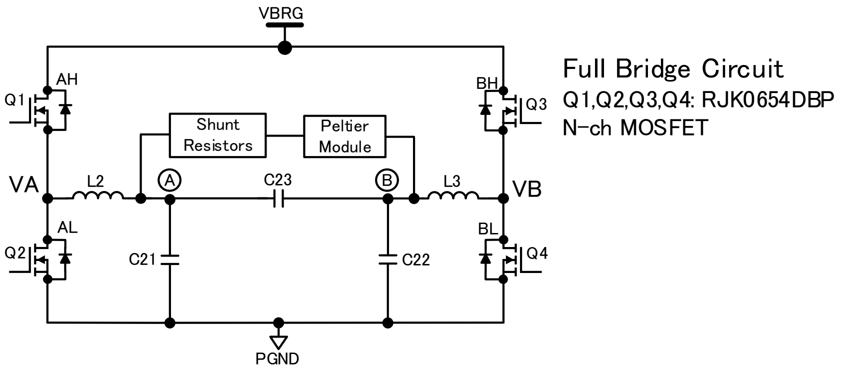
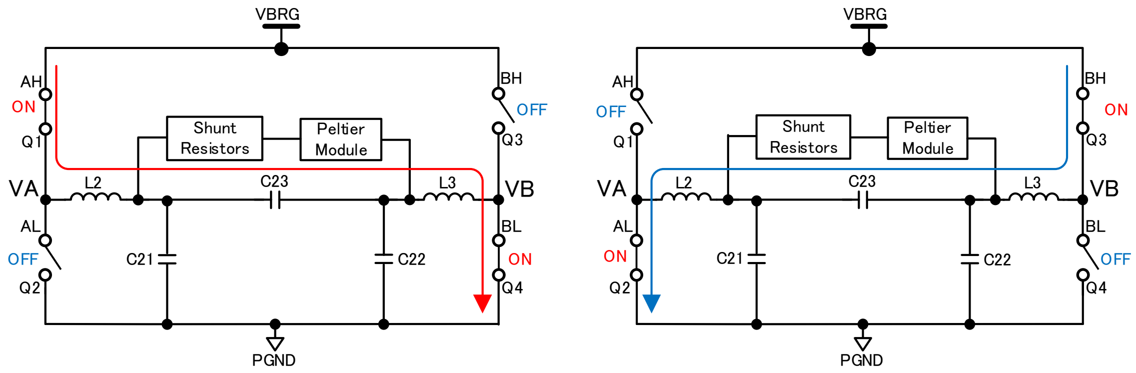


Figure 4-10 Full Bridge Circuit



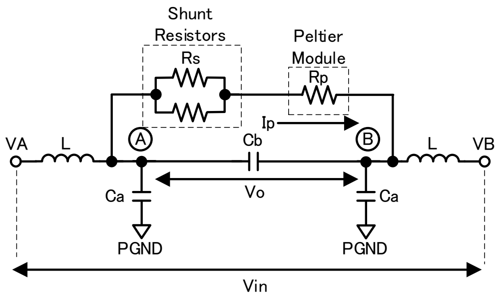
(a) Forward mode (positive side) (b) Reverse mode (negative side)

Figure 4-11 Operating Modes of the Full Bridge Circuit

In the Peltier Controller the current flowing into the Peltier module is controlled with the full bridge circuit using the N-channel MOSFET, Q1, Q2, Q3, and Q4. In (a) Forward mode, a positive current flows into the Peltier module when Q1 and Q4 are ON as shown in Figure 4-11. In (b) Reverse mode, a negative current flows into the Peltier module when Q2 and Q3 are ON. The amount of current is controlled by changing the ON duration of FET by pulse width modulation (PWM) control. The shunt resistors connected in series to the Peltier module are inserted to detect the current flowing into the Peltier module. For details about the current detection circuit, refer to "(4) Current Detection Circuit".

In this system, control is performed using complementary PWM control. In complementary PWM control, positive-phase PWM signals are applied to Q1 and Q4, and negative-phase PWM signals are applied to Q2 and Q3. As a result, complementary PWM controls the voltages VA and VB and accordingly controls the current flowing into the Peltier module based on the voltage difference between VA and VB. The operation around the current value of 0 can be switched successively by using complementary PWM.

Figure 4-12 shows the Filter Portion of the Full Bridge Circuit.



$R_s = R_{31} // R_{32} = 0.028[\Omega]$
$R_p = 4.0[\Omega]$*
$L_f = L_2 = L_3 = 100[\mu H]$
$C_a = C_{21} = C_{22} = 2.2[\mu F]$
$C_b = C_{23} = 1.0[\mu F]$
R_s: Shunt resistor
R_p: Peltier module on-chip resistor
* The resistance of the Peltier module on-chip resistor R_p changes depending on the temperature.

Figure 4-12 Filter Portion of the Full Bridge Circuit

When the input voltage of this filter circuit Vin is the difference between VA and VB and the voltage between Point A and Point B is Vo, Vin and Vo can be expressed by the following transfer function.

$$\frac{V_o}{V_{in}} = \frac{1}{L_f(C_a + 2C_b)s^2 + \frac{2L_f}{R_s + R_p}s + 1} \tag{1}$$

s indicates the Laplace variable
The relationship between the current flowing into the Peltier module Ip and Vin can be expressed as follows.

$$\frac{I_p}{V_{in}} = \frac{1}{R_s + R_p} \cdot \frac{1}{L_f(C_a + 2C_b)s^2 + \frac{2L_f}{R_s + R_p}s + 1} \tag{2}$$

The transfer function of (1) can be expressed as follows using the general expression for quadratic low-pass filter circuits.

$$\frac{V_o}{V_{in}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad \omega_n^2 = \frac{1}{L_f(C_a + 2C_b)}, \quad \zeta = \frac{1}{R_s + R_p}\sqrt{\frac{L_f}{C_a + 2c_b}} \tag{3}$$

Figure 4-13 shows the frequency characteristics of the filter portion of the full bridge circuit. In this system, the carrier frequency of PWM is set to 100 kHz. The 100 kHz component of the carrier frequency can be attenuated by -44.6 dB in the filter portion of the full bridge circuit.

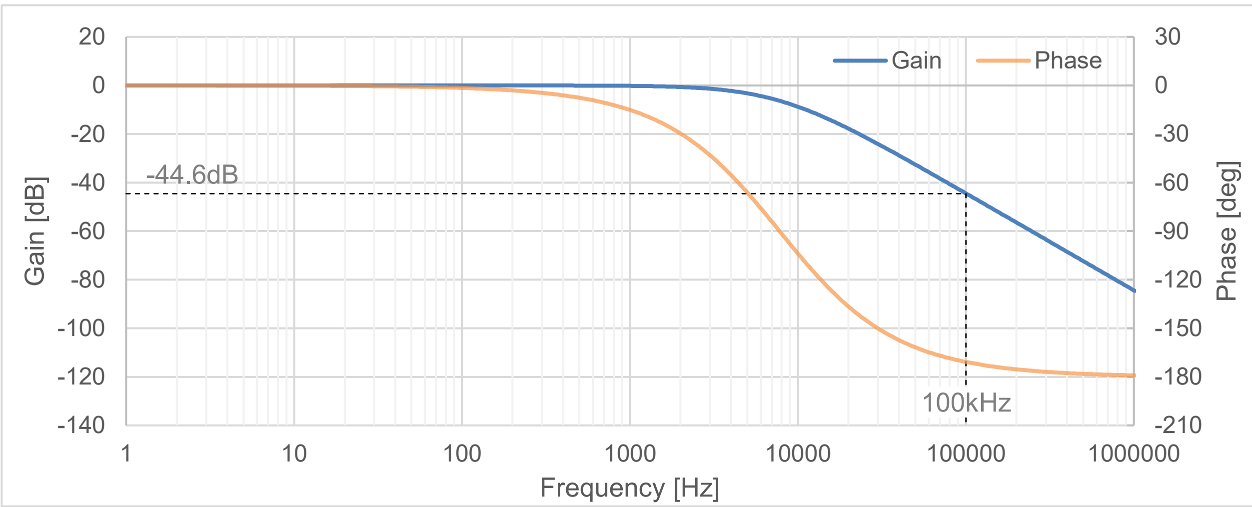


Figure 4-13 Frequency Characteristics of the Filter Portion of the Full Bridge Circuit

(3) PWM driver circuit

Figure 4-14 shows the PWM Driver Circuit.

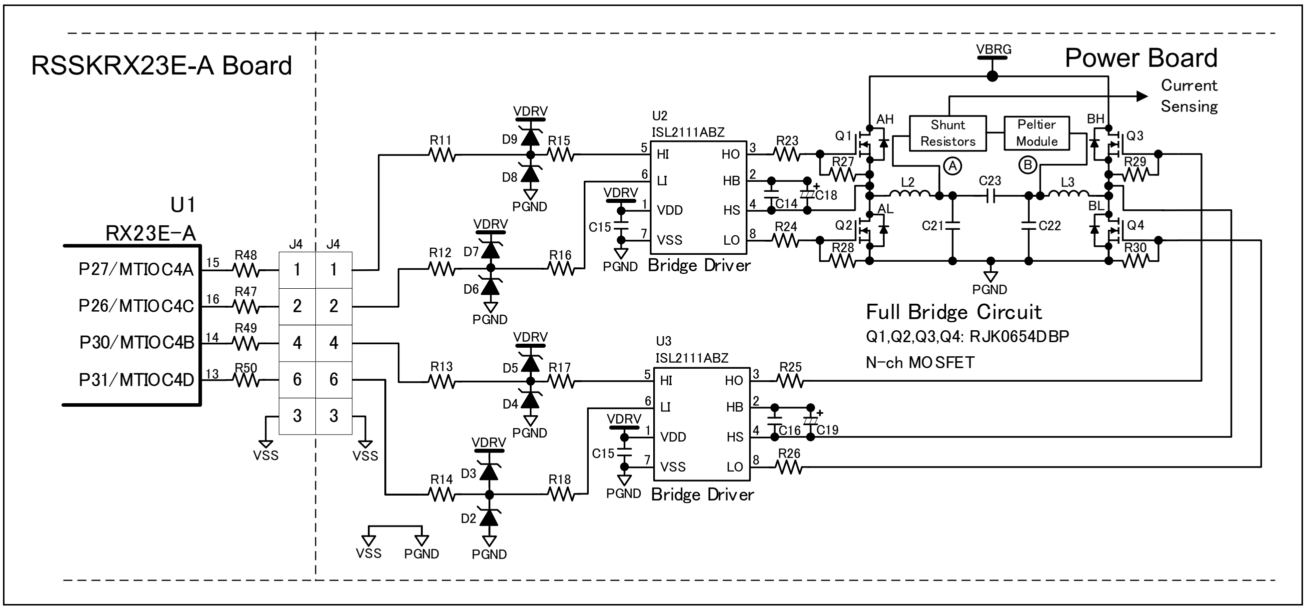


Figure 4-14 PWM Driver Circuit

The PWM signal is output using MTIOC4 of RX23E-A. MTIOC4 is input to the half bridge driver ISL2111. ISL2111 drives the N-channel MOSFET Q1, Q2, Q3, and Q4 of the full bridge circuit.

(4) Current Detection Circuit

Figure 4-15 shows the Peltier Module Current Detection Circuit.

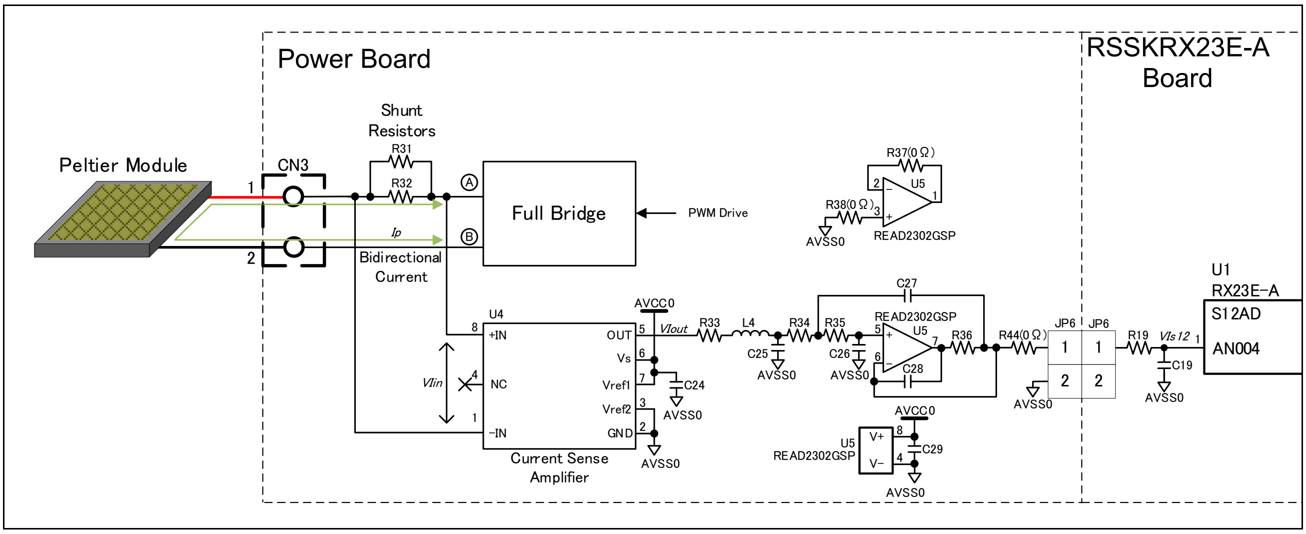


Figure 4-15 Peltier Module Current Detection Circuit

The current I_p flowing into the Peltier module is converted to the voltage V_{Iin} with the shunt resistors (R31 and R32) and input to the current detection amplifier U4. V_{Iin} is amplified by 20 times inside U4, and then output to Pin 5 as the voltage V_{Iout} which has range from 0 V to AVCC0, using a half of AVCC0 as the middle point voltage. The operational amplifier of U5 constitutes a quadratic low-pass filter circuit with a cutoff frequency of 442 Hz. The output of U5 is connected to Pin 1 of RX23E-A via JP6. Pin 1 of RX23E-A is used as S12AD (AN004). R19 and C19 in series with S12AD are sampling filters for S12AD. S12AD uses AVCC0 as the positive side reference voltage and AVSS0 as the negative side reference voltage.

The steady-state relational expressions for each of I_p, V_{Iin}, V_{Iout}, input voltage to S12AD V_{Is12}, and A/D conversion value of S12AD $ADdata_{S12}$ are shown below.

The relationship between the current flowing into the Peltier module I_p and the input voltage to the current detection amplifier V_{Iin} is expressed as follows:

$$V_{Iin} = I_p \cdot R_s, \qquad R_s = \frac{R_{31}R_{32}}{R_{31} + R_{32}} \tag{4}$$

The output voltage of the current detection amplifier V_{Iout} is expressed as follows:

$$V_{Iout} = 20 \cdot V_{Iin} + \frac{AVCC0}{2} \tag{5}$$

Because U5 and the filter with R19 and C19 have a DC amplification factor of 1, the input voltage to S12AD V_{Is12} is expressed as follows:

$V_{Is12} = V_{Iout}$ (DC value)

The AD value obtained by S12AD $ADdata_{S12}$ is expressed as follows:

$$ADdata_{s12} = \frac{V_{Is12}}{AVCC0} \cdot 2^{12} = \left(\frac{20 \cdot I_p \cdot R_s}{AVCC0} + \frac{1}{2}\right) \cdot 2^{12} \tag{6}$$

Therefore, the conversion formula from $ADdata_{S12}$ to I_p is determined as follows:

$$I_p = \frac{AVCC0}{20 \cdot R_s} \cdot \frac{ADdata_{s12} - 2^{11}}{2^{12}} \tag{7}$$

(5) 3-wire RTD measurement circuit

Figure 4-16 shows the 3-Wire RTD Measurement Circuit.

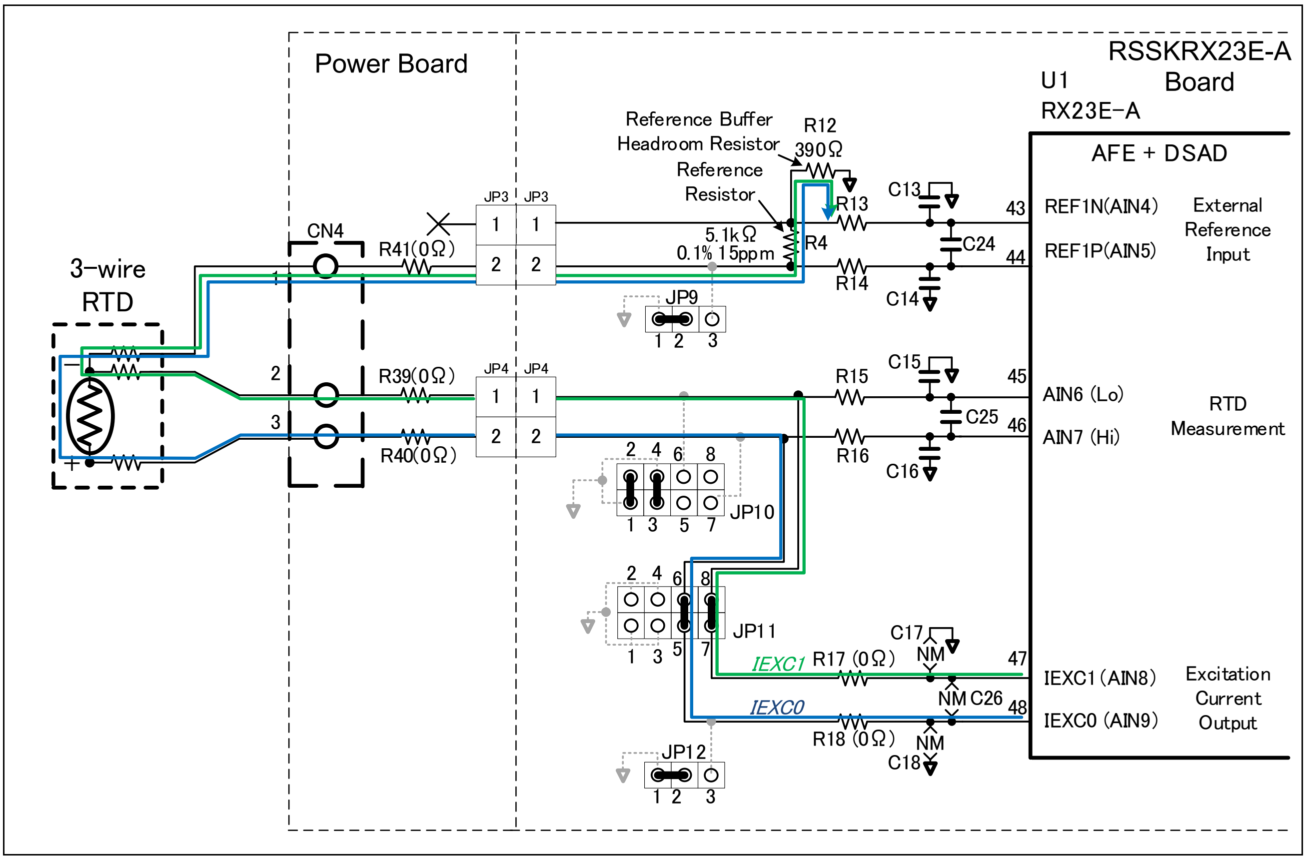


Figure 4-16 3-Wire RTD Measurement Circuit

The 3-wire RTD is connected to CN4 of the power board. From CN4, it is connected to RSSKRX23E-A via JP3 and JP4. In the measurement with the 3-wire RTD, the excitation current sources IEXC0 and IEXC1 are output from AIN8 and AIN9. The ratio of the voltage between AIN6 and AIN7 and the voltage between REF1P and REF1N is measured, and the resistance value of the 3-wire RTD is calculated in the MCU. The calculated resistance value is converted to temperature using the temperature conversion table.

For details about the measurement circuit, refer to "RSSKRX23E-A User's Manual: Board". For temperature measurement examples using RTD, refer to "Application Notes RX23E-A Group Temperature Measurement Examples Using Resistance Temperature Detectors".

(6) USB serial conversion circuit

Figure 4-17 shows the USB serial conversion circuit of this board. In this system, the SCI5 interface of RX23E-A is used for UART communication. A UART signal is converted to USB by the UART-USB conversion IC in U3 and then connected to the PC. The USB communication is used to receive command values from the PC and transmit temperature measurement results to the PC.

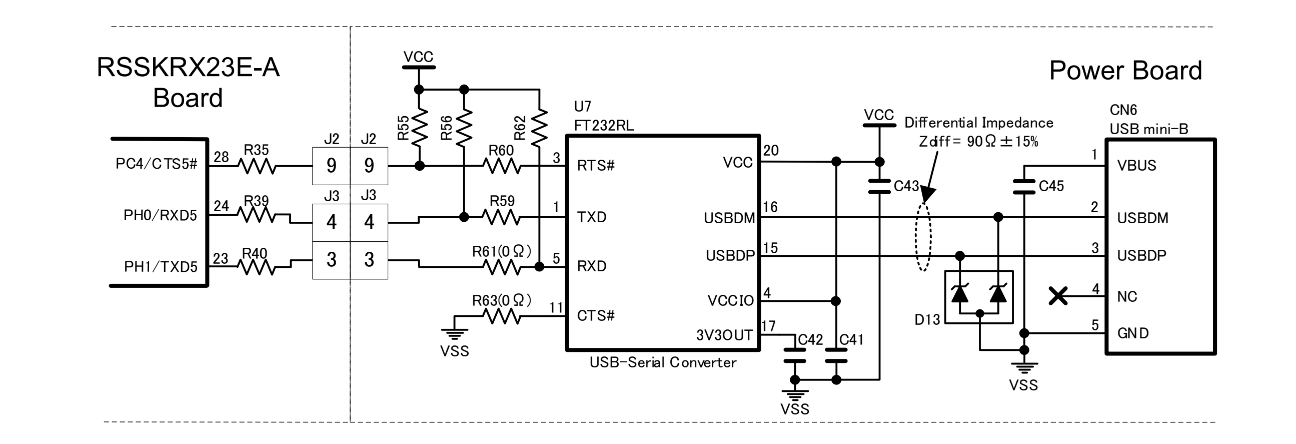


Figure 4-17 USB Serial Communication Circuit

4.1.4 Peltier Unit

Figure 4-18 shows the Structure of the Peltier Unit. Table 4-6 lists the major parts of the Peltier unit.

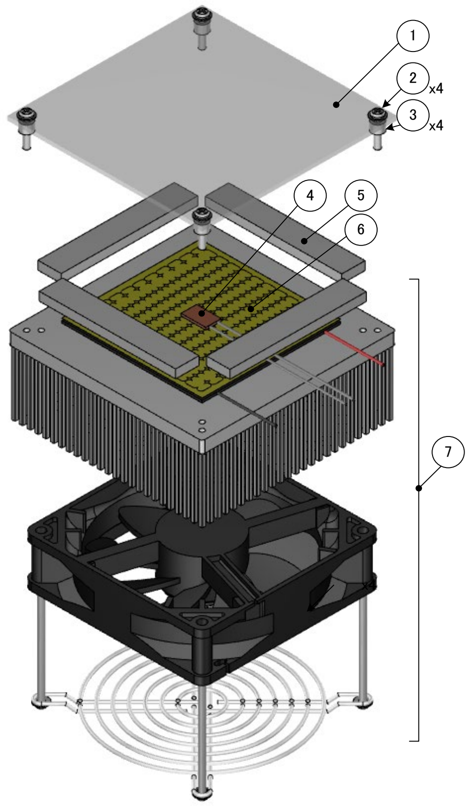


Figure 4-18 Structure of the Peltier Unit

Table 4-6 List of Major Parts of the Peltier Unit

No.	Part	Part No.	Quantity	Manufacturer
1	Acrylic cover	–	1	SUMITOMO CHEMICAL COMPANY, LIMITED
2	Sems screw	B-0318	4	Hirosugi-Keiki Co.,Ltd.
3	Spacer	C-303.5	4	
4	3-wire RTD	R060-33	1	CHINO CORPORATION
5	Moisture-proof cover	–	4	–
6	Peltier module	UT-7070KA-M	1	TAISEI CO.,Ltd.
7	Active heat sink	FS10040WM-0D5 (Custom)	1	ALPHA CO., LTD.

4.2 Control Configuration

4.2.1 Principle of Operation

Figure 4-19 shows the control block diagram of this system. In this system, control is performed with dual loops of temperature PID control and current PI control to improve the control responsiveness and stability.

Temperature control of this system operates as described below.

- The current command value is calculated from the deviation between the temperature command value specified by the PC tool and Peltier temperature by using the temperature PID operation.
- The output voltage is calculated from the deviation between the current command value and Peltier current by using the current PI operation.
- The output voltage is converted to the PWM duty ratio for driving the full bridge circuit.
- The full bridge circuit is driven by PWM control to control the Peltier current.
- The Peltier current flows into the Peltier module, changing its temperature.

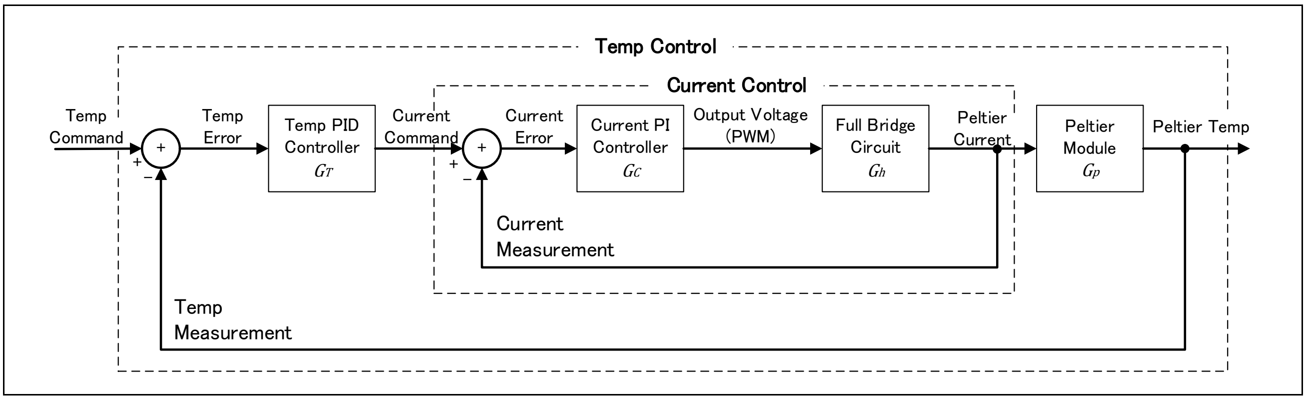


Figure 4-19 Control Block Diagram of This System

4.2.2 PID Control

This system consists of the current controller based on PI control and the temperature controller based on PID control. Figure 4-20 shows the block diagram of the current controller, and Figure 4-21 shows the block diagram of the temperature controller.

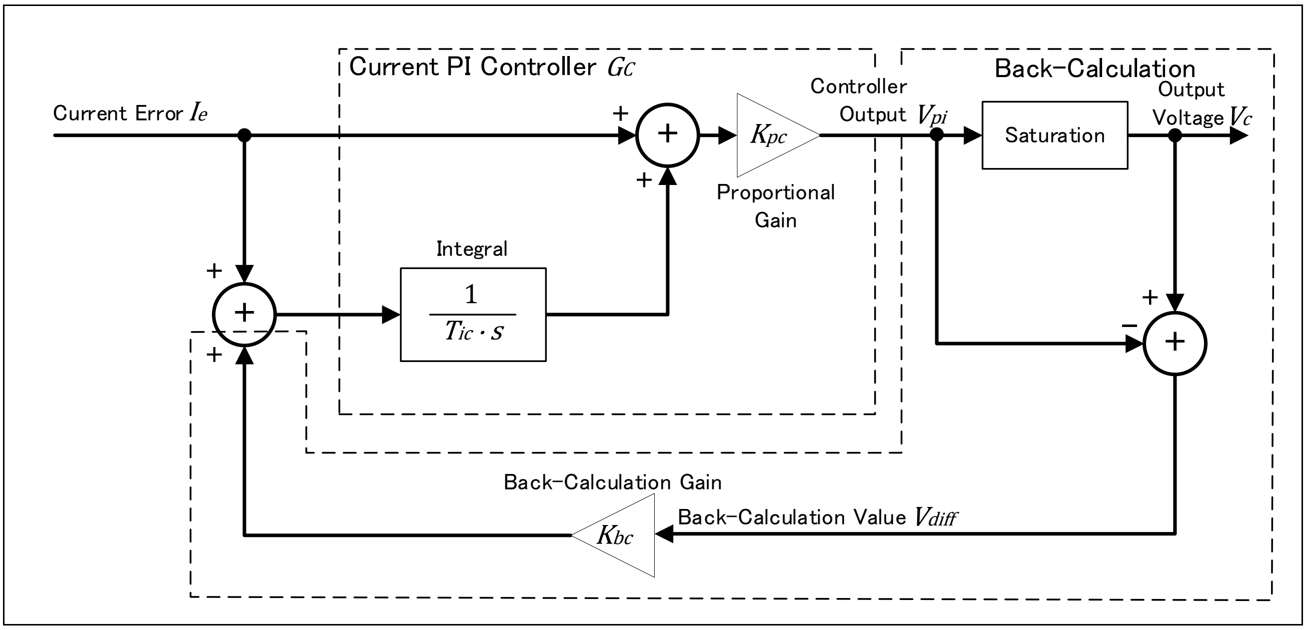


Figure 4-20 Current PI Controller

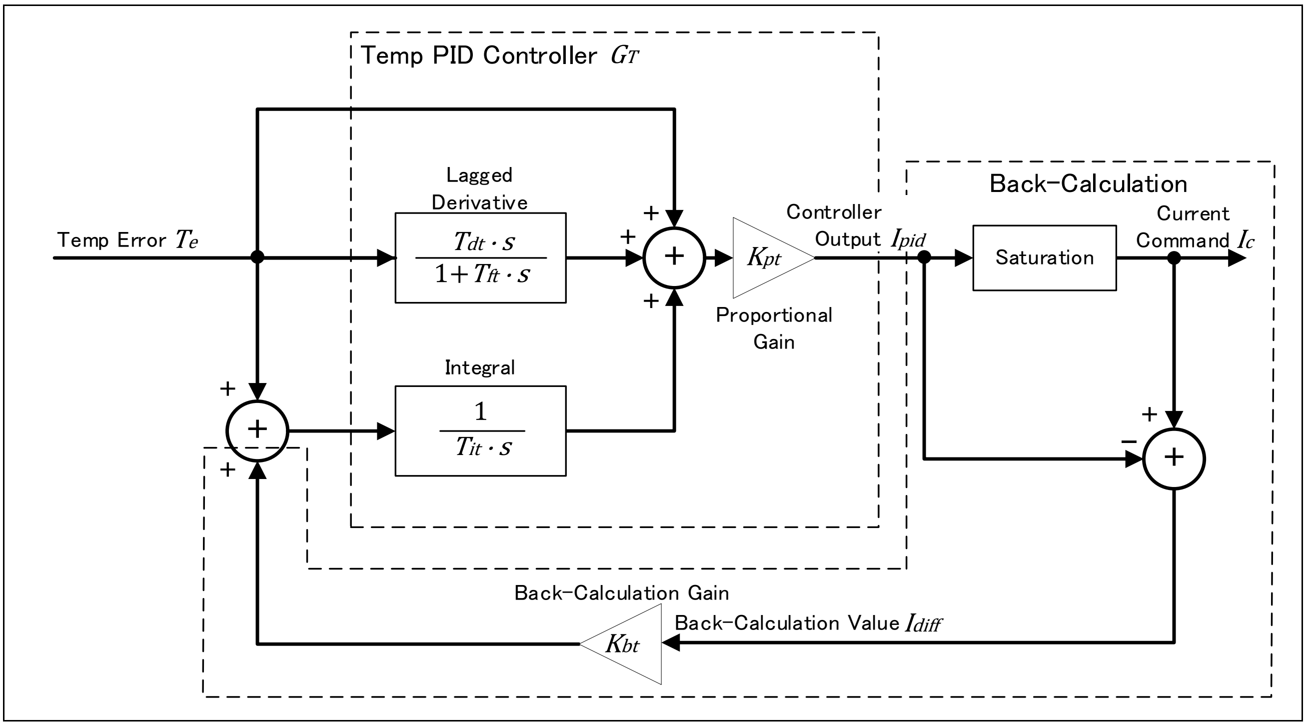


Figure 4-21 Temperature PID Controller

(1) Control operation formulas

When V_{diff} = 0, the operation of the current PI controller can be expressed by the following transfer function.

$$G_C = \frac{V_{pi}}{I_e} = K_{pc}\left(1 + \frac{1}{T_{ic} \cdot s}\right) \tag{8}$$

When I_{diff} = 0, the operation of the temperature PID controller can be expressed by the following transfer function.

$$G_T = \frac{I_{pid}}{T_e} = K_{pt}\left(1 + \frac{1}{T_{it} \cdot s} + \frac{T_{dt} \cdot s}{1 + T_{ft} \cdot s}\right) \tag{9}$$

Where;

s: Laplace variables

T_{ic}: Current PI controller integral time

T_{it}: Temperature PID controller integral time

T_{dt}: Temperature PID controller derivative time

T_{ft}: Temperature PID controller lagged derivative filter time

(2) Derivative element

The derivative element used in temperature control contributes to the improvement in the responsiveness of the Peltier module. The lagged derivative filter limits bandwidth to suppress amplification of unnecessary noise,

(3) Anti-reset windup

In both current control and temperature control, the output of the controller is limited by a limiter, and the difference between the controller outputs before and after the limiter is fed back to the integrator to prevent deterioration in responsiveness due to integration saturation. As a result, input to the integrator is reduced when the output of the controller exceeds the limit value to prevent the integrator output from keeping increasing.

The output of each controller when it is limited by anti-reset windup is as follows.

Output of current PI controller V_{pi}

$$V_{pi} = K_{pc}\left\{\left(1 + \frac{1}{T_{ic} \cdot s}\right) I_e + \frac{1}{T_{ic} \cdot s} \cdot K_{bc} \cdot V_{diff}\right\} \tag{10}$$

Output of temperature PID controller I_{pid}

$$I_{pid} = K_{pt}\left\{\left(1 + \frac{1}{T_{it} \cdot s} + \frac{T_{dt} \cdot s}{1 + T_{ft} \cdot s}\right) T_e + \frac{1}{T_{it} \cdot s} \cdot K_{bt} \cdot I_{diff}\right\} \tag{11}$$

4.2.3 Temperature Control Design

The transfer functions of the blocks in Figure 4-19 are shown in Table 4-7. The constants related to control are shown in Table 4-8.

Table 4-7 Transfer Functions

Item	Transfer function	Unit
Current PI controller	$G_C = K_{pc}\left(1+\frac{1}{T_{ic}\cdot s}\right)$	V/A
Temperature PID controller	$G_T = K_{pt}\left(1+\frac{1}{T_{it}\cdot s}+\frac{T_{dt}\cdot s}{1+T_{ft}\cdot s}\right)$	A/°C
Full bridge circuit transfer function	$G_h = \frac{1}{R_s+R_p}\cdot\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$	A/V
Peltier module transfer function*	$G_p = \frac{K_{pel}}{1+T_p s}$	°C/A

Note: For the Peltier module transfer function, the temperature response when a current step is input to the Peltier module is measured, and an approximate value is obtained from the measurement result.

Table 4-8 Constants Related to Control

Symbol	Description	Value	Unit
K_{pc}	Current controller proportional gain	1.2	V/A
T_{ic}	Current controller integral time	1.2×10^{-3}	s
K_{bc}	Current controller inverted integral gain	0.8	A/V
K_{pt}	Temperature controller proportional gain	3.0	A/°C
T_{it}	Temperature controller integral time	5.0	s
T_{dt}	Temperature controller derivative time	1.0	s
T_{ft}	Temperature controller lagged derivative filter time	0.1	s
K_{bt}	Temperature controller inverted integral gain	0.8	°C/A
ω_n	Full bridge circuit natural angular frequency $\omega_n^2=\frac{1}{L_f(C_a+2C_b)}$	48795.0	rad/s
ζ	Full bridge circuit attenuation constant $\zeta=\frac{1}{R_s+R_p}\sqrt{\frac{L_f}{C_a+2C_b}}$	1.2	-
L_f	Full bridge circuit filter inductance	100×10^{-6}	H
C_a	Capacitance between both terminals of the Peltier module	1.0×10^{-6}	F
C_b	Full bridge circuit capacitance	2.2×10^{-6}	F
R_p	Peltier element internal resistance	4.0	Ω
R_s	Current detection resistance	0.028	Ω
K_{pel}	Peltier temperature gain	15.3	°C/A
T_p	Peltier filter time	28	s

Table 4-9 shows the open loop transfer functions and closed loop transfer functions of current control and temperature control of this system. Figure 4-22 shows the current control frequency characteristics, and Figure 4-23 shows the temperature control frequency characteristics.

Table 4-9 Transfer function of the Temperature Control Loop and Current Control Loop

Item	Open loop transfer function	Closed loop transfer function
Current control	$L_C = G_C \cdot G_h$	$\omega_C = \dfrac{L_C}{1 + L_C}$
Temperature control	$L_T = G_T \cdot \omega_C \cdot G_p$	$\omega_T = \dfrac{L_T}{1 + L_T}$

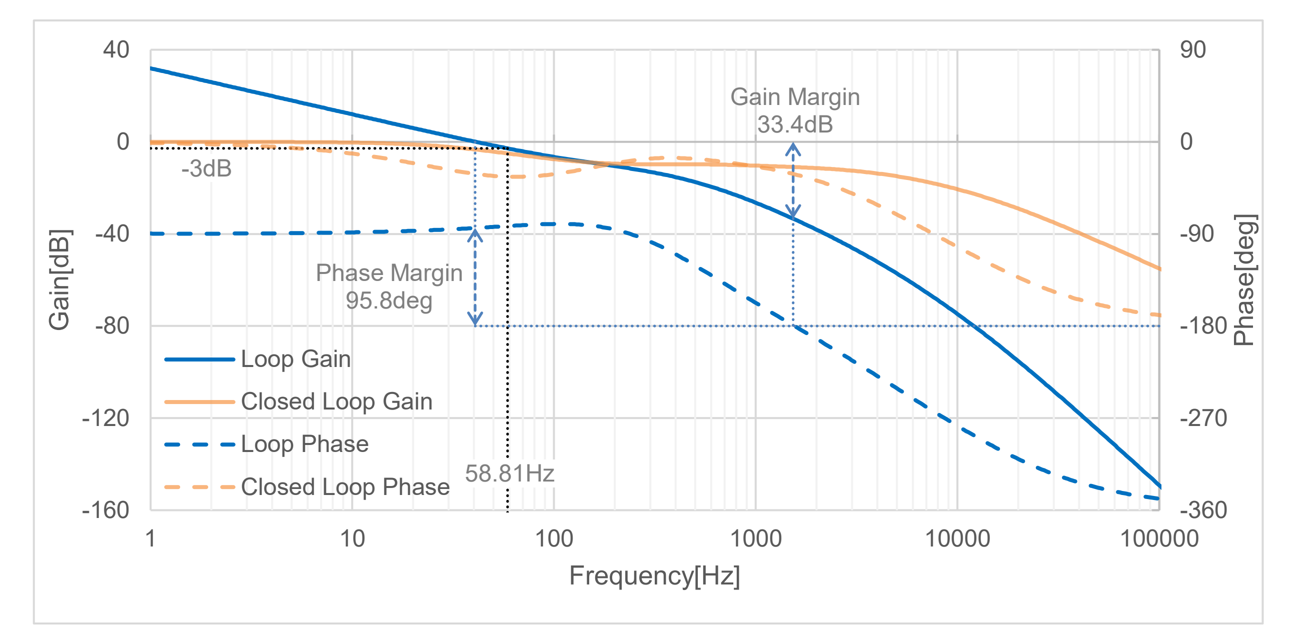


Figure 4-22 Current Control Frequency Characteristics

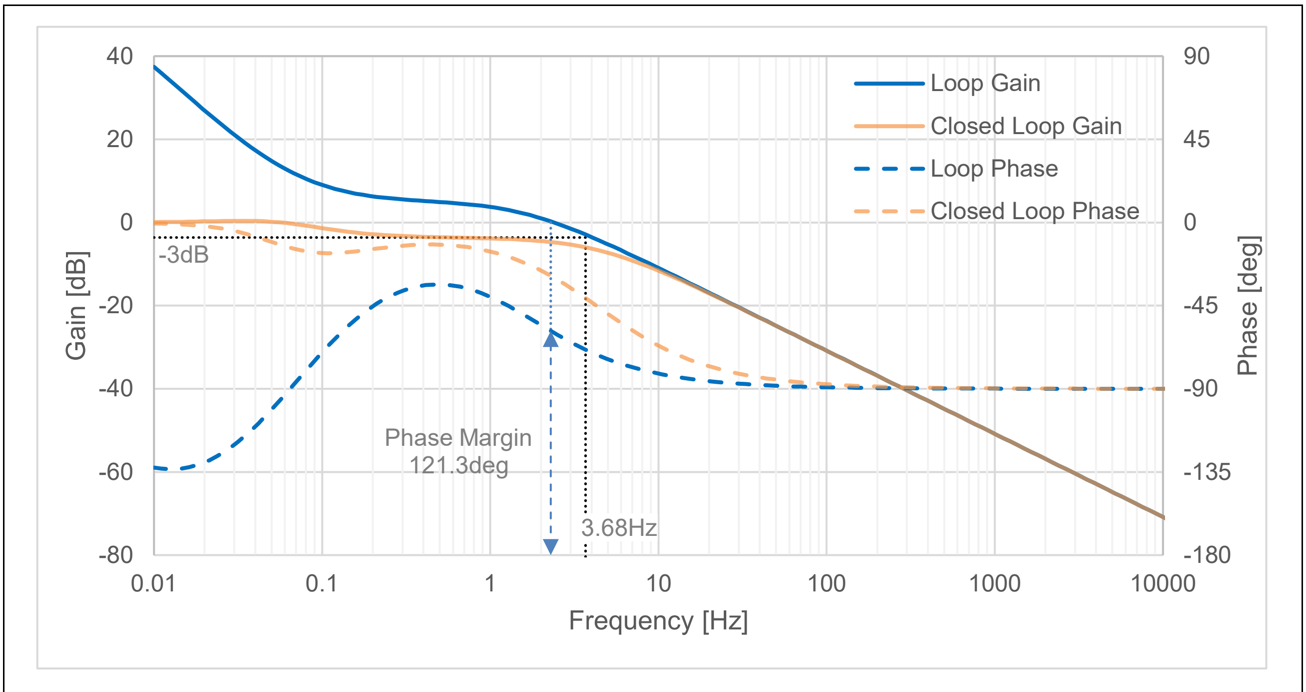


Figure 4-23 Temperature Control Frequency Characteristics

4.2.4 Implementation of Temperature Control Operations

Measurement and control operations in temperature control can be performed with RX23E-A. Figure 4-24 shows the control block diagram using RX23E-A.

(1) Current control loop

Current measurement is performed with the successive approximation A/D converter S12AD. Current is sampled on the A/D conversion start request from MTU in cycles of 10 μs synchronized with PWM.
The mean value is calculated from 50 current measurements and set as the measured current value.
Next, the measured current value and current command value are compared to calculate the current deviation, and then a PI operation is performed. The result of the current PI operation is set as the output voltage value, which is reflected to the PWM duty ratio.

(2) Temperature control loop

For temperature measurement, the voltage across the 3-wire RTD is measured with DSAD of RX23E-A. Using 2 channels of the excitation current source of AFE, The resistance of RTD is measured from the ratio of the RTD voltage to the reference register located between the external reference input pins of RX23E-A. Using the resistance value of RTD, table data is created based on the reference resistance value for PT100 in IEC60751, and converted to temperature. Temperature sampling is set to 976.563SPS (oversampling ratio: 512). The mean value of temperature measurement is obtained for every 40 times of current control (500 us cycle), i.e. in cycles of 20 ms, and set as the measured temperature value. Because temperature sampling and current sampling are not synchronized, the number of measured temperature value used for averaging changes based on the timing, which is 19 or 20. The measured temperature value and temperature command value are compared to calculate the temperature deviation, and then a PID operation is performed. The result of the temperature PID operation is set as the current command value for current PI.

For details about temperature measurement using RTDs, refer to "Application Notes RX23E-A Group Temperature Measurement Examples Using Resistance Temperature Detectors".

(3) Method of implementation of the control operations

Current PI operation and temperature PID operation are designed as continuous systems. Discretization is performed by bilinear Z - transform, and implemented as difference equations.

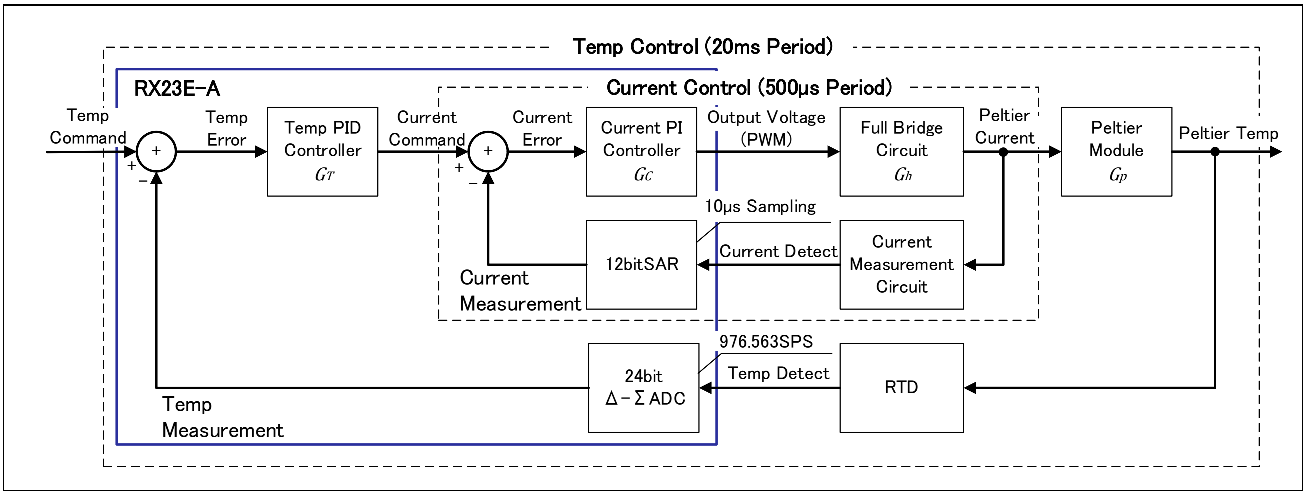


Figure 4-24 Temperature Control Block Diagram Using RX23E-A

5. Sample Program

5.1 Overview of Operation

Figure 5-1 shows the process flow of this sample program.

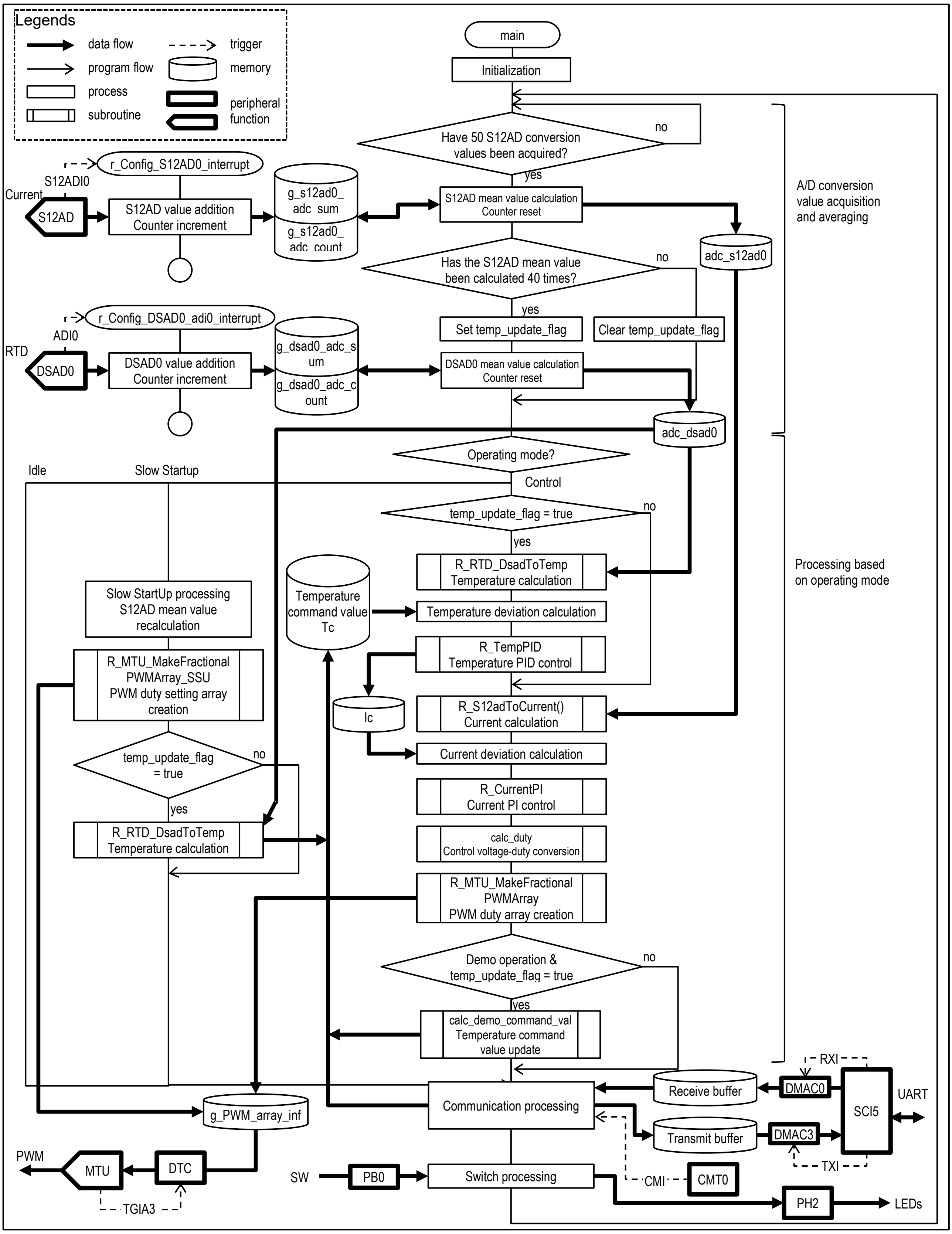


Figure 5-1 Temperature Control Process Flow

The following provides an overview of each process.

- Initialization
  The following are performed.
  - Initialization of the communication transmit/receive buffers and start of SCI5 operation
  - Acquisition of the switch status and setting of demo operation
  - Start of A/D conversion of S12AD and DSAD0
  - Start of PWM output. For details, refer to 5.4.
- A/D conversion value acquisition and averaging
  A/D conversion values of S12AD and DSAD0 are obtained by using the respective interrupt processing function, and the number of times of acquisition is incremented and A/D conversion values are added. In the main routine, averaging of the A/D conversion values is performed. Averaging is performed when 50 A/D conversion values of S12AD are obtained. A/D conversion values of DSAD0 are averaged when averaging of A/D conversion values of S12AD is performed 40 times, and then the temperature update flag is set.
- Processing depending on the operating mode
  Slow startup processing or temperature control processing is performed depending on the operating mode.
  - Slow startup processing is performed at startup, and a transition is made to temperature control processing.
  - The temperature control is performed based on temperature command values. Temperature command values are given using the PC tool. During the demo operation, command values are updated after temperature control processing.

For details about slow startup processing, refer to 5.5. For details about temperature control processing, refer to 5.3. For details about the demo operation, refer to 5.6.

- Communication control
  Communication with the PC tool program is processed. For details, refer to 5.7.
- Switch processing
  The status of the slide switch is acquired, and demo operation is switched on/off.

  Port PB0 is High for On and Low for Off.

Figure 5-2 shows the timing chart of control processing, and Table 5-1 shows the priority levels of the interrupts used.

After startup, the operation starts when a connection with the PC tool is established. Processing is performed for every 50 A/D conversions of S12AD. Slow startup is performed first, followed by temperature control operation.

In temperature control operation, current PI control operation is performed by calculating control current from the mean value of 50 A/D conversion values of S12AD, and then the duty of PWM output is set. In addition, the current command value is updated by temperature PID control operation using both measured temperature which the mean of DSAD conversion values of every 40 current control cycles, and command value of temperature.

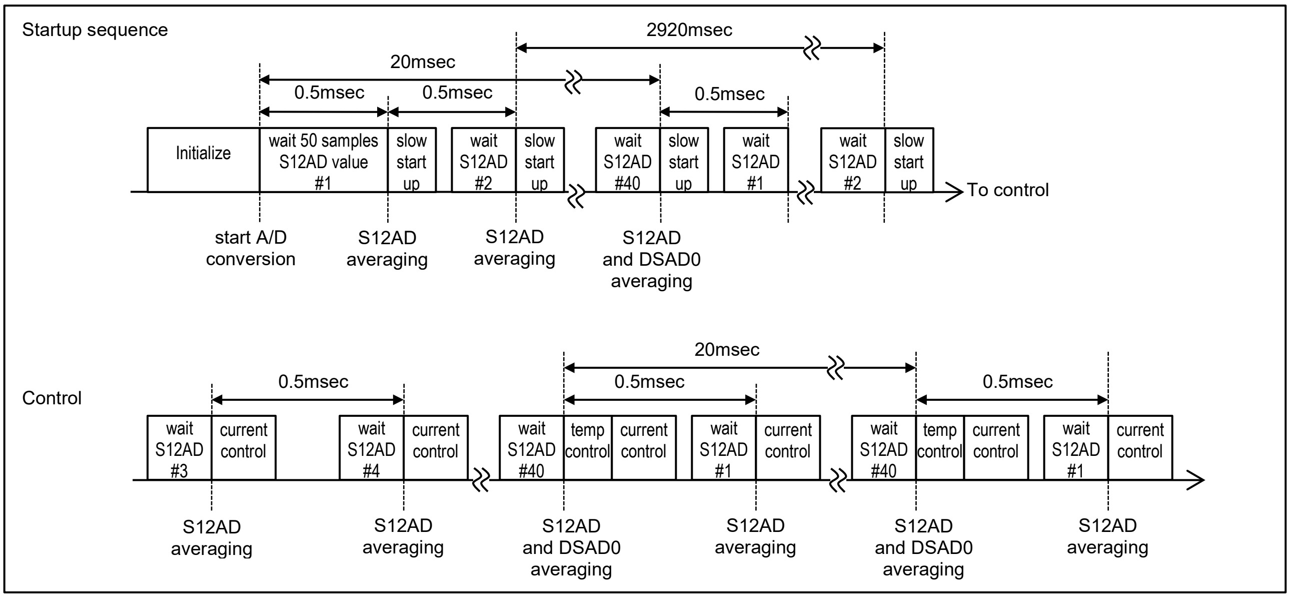


Figure 5-2 Control Processing Timing Chart

Table 5-1 Interrupt Priority Levels

Priority level	Peripheral function	Cause	Reception	Processing
15	SCI5	RXI5	DMAC0	Receive data transfer
15	SCI5	TXI5	DMAC3	Transmit data transfer
12	MTU3	TGIA3	DTC, program	
10	S12AD	S12ADI0	Program	S12AD conversion value acquisition
8	DSAD0	ADI0	Program	DSAD0 conversion value acquisition

5.2 Peripheral Functions and Pins Used

The peripheral functions used in this sample program are listed in Table 5-2. The pins used are listed in Table 5-3. The unused pins and their handling are listed in Table 5-4. The conditions for setting each peripheral function are described together.

The settings for peripheral functions are generated by using the code generation function of Smart Configurator (hereafter called SC).

Table 5-2 Peripheral Functions Used

Peripheral function	Use
AFE, DSAD0	Measurement of Peltier module temperature via RTD and A/D conversion
AFE, S12ADE	Measurement of Peltier module current and A/D conversion
MTU3,4	PWM control of voltage applied to the Peltier module
DTC	Duty value setting with a compare match interrupt of MTU3 as a trigger
SCI5	UART communication with the PC tool program
DMAC0	Data transfer with a receive data full interrupt of SCI5 as a trigger
DMAC3	Data transfer with a transmit data empty interrupt of SCI5 as a trigger
CMT0	Detection of a communication timeout of SCI5
Port PB0	Slide switch (between normal mode and demo mode, High for On and Low for Off)
Port PH2	LED, demo operation when it is ON

Table 5-3 Pins Used

Pin No.	Pin name	Input/Output	Use
1	AIN10/AN004	Input	Current measurement with S12ADE
6	P37/XTAL	Output	8 MHz crystal oscillator
8	P36/EXTAL	Input	8 MHz crystal oscillator
13	P31/MTIOC4D	Output	PWM output, Peltier current control (B-L) initial value Low output
14	P30/MTIOC4B	Output	PWM output, Peltier current control (B-H) initial value Low output
15	P27/MTIOC4A	Output	PWM output, Peltier current control (A-H) initial value Low output
16	P26/MTIOC4C	Output	PWM output, Peltier current control (A-L) initial value Low output
22	PH2	Output	LED1 ON (demo operation), OFF (not demo operation)
23	PH1/TXD5	Output	SCI5 UART transmission
24	PH0/RXD5	Input	SCI5 UART reception
28	PC4/CTS5#	Input	SCI5 CTS input
31	PB0	Input	Slide switch (between normal mode and demo operation)
43	AIN4/REF1N	Input	DSAD0 negative (-) side reference voltage
44	AIN5/REF1P	Input	DSAD0 positive (+) side reference voltage
45	AIN6	Input	DSAD0 negative (-) side input
46	AIN7	Input	DSAD0 positive (+) side input
47	AIN8/IEXC1	Output	Excitation current output
48	AIN9/IEXC0	Output	Excitation current output

Table 5-4 Unused Pins and Their Handlings

Pin No.	Pin name	Input/Output	Handling of Unused Pin
2	AIN11/AN005	Input	Connect to GND
12	P35/NMI	Input	Pull up to VCC
17	P17	Output	Low-level output
18	P16	Output	Low-level output
19	P15/CRXD0	Input	Input (reserved for CAN driver)
20	P14/CTXD0	Input	Input (reserved for CAN driver)
21	PH3	Input	Pull up to VCC (reserved for CAN driver)
25	PC7	Output	Low-level output
26	PC6	Output	Low-level output
27	PC5	Output	Low-level output
29	PB1	Input	Monitoring of voltage applied to full bridge driver
37	REF0N	Input	Connect to AVSS0 (JP7)
38	REF0P	Input	Connect to AVCC0 (JP8)
39	AIN0	Input	Connect to AVSS0
40	AIN1	Input	Connect to AVSS0
41	AIN2	Input	Connect to AVSS0
42	AIN3	Input	Connect to AVSS0

5.2.1 AFE and DSAD0

AFE and DSAD0 are used for measurement of Peltier module temperature via RTD. The settings of AFE and DSAD0 are shown in Table 5-5 and Table 5-6.

Table 5-5 AFE Settings

Item		Setting
Bias output setting		Not used
Excitation current output setting	Operation mode	2-channel output mode
	Excitation current	250 μA
	IEXC0 output pin	AIN9
	IEXC0 disconnect detection assist	Not used
	IEXC1 output pin	AIN8
	IEXC1 disconnect detection assist	Not used
Low level voltage detection setting		Not used
Low-side switch control setting		Not used

Table 5-6 DSAD0 Settings

Item		Setting
Analog input channel setting		Channel 0: Enable Channels 1 to 5: Disable
ΔΣ A/D Converter operation voltage setting		3.6 V to 5.5 V (High precision)
ΔΣ A/D Converter operation mode setting		Normal mode
Operation clock setting		PCLKB/8 (4 MHz)
Conversion start trigger setting		Software trigger
Interrupt setting	Enable ΔΣ A/D conversion completion interrupt (ADI0)	Enable
	Priority	8
	Enable ΔΣ A/D conversion scan completion interrupt (SCANENDI0)	Not used
Inter-unit synchronized start setting		Not used
Voltage fault and disconnection detection setting		Not used
Channel setting		Channel 0
Analog input setting	Positive input signal	AIN7
	Negative input signal	AIN6
	Reference input	REF1P/REF1N
	Positive reference voltage buffer	Enable
	Negative reference voltage buffer	Enable
Amplifier setting	Amplifier selection	PGA
	PGA gain setting	x32
ΔΣ A/D conversion setting	A/D conversion mode	Normal operation
	Data format	Two's complement
	A/D conversion number	Immediate value mode, 1
	Oversampling ratio	512 (976.5625 SPS)
	Set offset calibration value	Not used (device default)
	Set gain calibration value	Not used (device default)
	Enable averaging data	Not used
Disconnect detection assist setting		Not used

5.2.2 S12ADE

S12ADE is used for measurement of Peltier module current. The settings of S12ADE are shown in Table 5-7.

Table 5-7 AFE and S12ADE Settings

Item		**Setting**
Analog input mode setting		Not used
Analog input channel setting		AN004: Enable Others: Disable
Conversion start trigger setting		Compare match between MUT4.TADCORA and MTU4.TCNT
Interrupt setting	Enable AD conversion end interrupt (S12ADI0)	Enable
	Priority	10
Add/Average AD value setting		Not used
A/D conversion select		High-speed
High-Potential reference voltage setting		AVCC0
Low-Potential reference voltage setting		AVSS0
Self diagnosis setting		Not used
Disconnection detection assist setting		Not used
Data registers setting	Data placement	Right-alignment
	Automatic clearing	Disable automatic clearing
	Addition/Average mode select	Addition mode
	Addition count	1-time
Data storage buffer setting		Disable
Window function setting		Disable
Window A/B operation setting		Not used
Input sampling time setting	AN004	0.406 [μs]
Event link control setting		On completion of all scans

5.2.3 MTU3, MTU4, and DTC

MTU3 and MTU4 are used in Complementary PWM mode 2 for PWM control of voltage applied to the Peltier module. The conversion start trigger of S12AD is issued during counting-up of MTU, and the PWM duty ratio is updated during the trough of counting down. The PWM counter is set using DTC.

The settings of MTU3 and MTU4 are shown in Table 5-8, and the settings of DTC are shown in Table 5-9.

Table 5-8 Settings of MTU3 and MTU4

Item		Setting
Synchronous mode setting		Not used
TCNT3 counter setting	Counter clear source	Disabled counter clear
	Counter clock selection	PCLK
PWM output setting	Timer operation period	10 μs
	Enable dead time	Enable, 0.5 μs
	MTU3.TGRB register value	100
	MTU4.TGRA register value	16
	MTU4.TGRB register value	16
Brushless DC motor control setting		Not used
Output setting	Enable MTIOC3A toggle output	Not used
	Buffer transfer timing of PWM output level setting	Does not transfer data from the buffer register
	V phase: initial output level of MTIOC4A pin (positive-phase)	Active level: H
	V phase: initial output level of MTIOC4C pin (negative-phase)	Active level: H
	W phase: initial output level of MTIOC4B pin (positive-phase)	Active level: H
	W phase: initial output level of MTIOC4D pin (negative-phase)	Active level: H
Interrupt setting	Enable MTU3/TGRA compare match interrupt (TGIA3)	Enable
	Interrupt skipping count	Disable interrupt skip
	Priority	Level 12
	Enable MTU3/TGRB compare match interrupt (TGIB3)	Not used
	Enable MTU4/TGRA compare match interrupt (TGIA4)	
	Enable MTU4/TGRB compare match interrupt (TGIB4)	
	Enable MTU4 underflow interrupt (TGIV4)	
Buffer register and synchronous clearing operation setting		Not used
A/D conversion start trigger setting	Enable A/D conversion start request on matching of the counter and cycle register value (trigger signal of MTU4 TRG4ABN)	Enable
	Enable A/D conversion start request on matching of the counter and cycle set register A value	Enable
	A/D trigger request output	On matching of counting up
	Initial value of A/D conversion start request cycle set register A	16
	Initial value of cycle set buffer register A	16

Table 5-9 DTC Settings

Item		Setting
Activation source setting	Activation source	MTU3 (TGIA3)
	Chain transfer	Not used
Transfer mode setting		Block mode
Transfer data size setting		16 bits
Interrupt setting		An interrupt request to the CPU is generated when specified data transfer is completed
Block/Repeat area setting		Transfer destination
Transfer address and count setting	Source address	0x00000000 (specified by program), Address incremented
	Destination address	0x000D0A28 (MTU4.TGRC), Address incremented
	Count	1 (specified by program)
	Block size	2

5.2.4 SCI5, DMAC0, DMAC3, and CMT0

For communication with the PC tool program, SCI5 is used in asynchronous mode. DMAC0 is used to obtain receive data, and DMAC3 is used to set transmit data. CMT0 is used to detect a communication timeout.

The conditions for setting each peripheral function are listed below.

Table 5-10 SCI5 Settings

Item		Setting
Start bit edge detection setting		Low level on RXD5 pin
Data length setting		8 bits
Parity setting		None
Stop bit length setting		1 bit
Transfer direction setting		LSB-first
Transfer rate setting	Transfer clock	Internal clock
	Bit rate	3000000 (3 Mbps)
	Enable modulation duty correction	Enable
	SCK5 pin function	SCK5 is not used
Noise filter setting		Not used
Hardware flow control setting		CTS5#
Data handling setting	Transmit data handling	Data handling by DMAC (DMAC3)
	Receive data handling	Data handling by DMAC (DMAC0)
Interrupt setting	Enable reception error interrupt (ERI5)	Not used
	TXI5, RXI5, TEI5, ERI5 priority	Level 15 (highest)
Callback function setting		Not used

Table 5-11 DMAC Settings

<table>
<tr><th colspan="2" rowspan="2">Item</th><th colspan="2">Setting</th></tr>
<tr><th>DMAC0</th><th>DMAC3</th></tr>
<tr><td colspan="2">Activation Source</td><td>SCI5 (RXI5)</td><td>SCI5 (TXI5)</td></tr>
<tr><td colspan="2">Activation source flag control</td><td colspan="2">Clear interrupt flag of the activation source</td></tr>
<tr><td colspan="2">Transfer mode</td><td>free running mode</td><td>Normal mode</td></tr>
<tr><td colspan="2">Transfer data size</td><td colspan="2">8 bits</td></tr>
<tr><td colspan="2">Block / Repeat area setting</td><td>-</td><td>1 (specified by program)</td></tr>
<tr><td rowspan="3">Source address setting</td><td>Source address</td><td>0008 A0A5h(SCI5.RDR)
Fixed</td><td>(specified by program)
Incremented</td></tr>
<tr><td>Specify the transfer source as extended repeat area</td><td rowspan="2">-</td><td>Enable</td></tr>
<tr><td>Extended repeat area</td><td>Lower 8 bits of the address (256 bytes)</td></tr>
<tr><td rowspan="3">Destination address setting</td><td>Destination address</td><td>(specified by program)
Incremented</td><td>0008 A0A3h(SCI5.TDR)
Fixed</td></tr>
<tr><td>Specify the transfer destination as extended repeat area</td><td>Enable</td><td rowspan="2">-</td></tr>
<tr><td>Extended repeat area</td><td>Lower 8 bits of the address (256 bytes)</td></tr>
<tr><td colspan="2">Interrupt setting</td><td colspan="2">Not used</td></tr>
</table>

Table 5-12 CMT0 Settings

Item		Setting
Count clock setting		PCLKB/512
Compare match setting	interval value	1,000 ms
	Compare match interrupt (CMI0)	Enable
	Priority	Level 0 (disabled)

5.2.5 Ports

Port PB0 and Port PH2 are used. The unused ports shown in Table 5-4 are set to Low output.

Port PB0 is used to read the slide switch. Port PH2 is used to turn ON/OFF the LED.

The settings of Ports PB0 and PH2 are shown in Table 5-13.

Table 5-13 PB0 and PH2 Settings

Port Selection	PORTB	PORTH
Port	PB0	PH2
settings	In Pull-up: Disable	Out CMOS output Output 1: Enable (for LED off)

5.3 Temperature Control

Temperature control consists of temperature PID control and current PI control.

5.3.1 Temperature PID Control

In temperature PID control, the current command value corresponding to current PI control is calculated from the difference between the temperature command value and present temperature measured by the RTD. The signal flow of temperature PID control is shown in Figure 5-3.

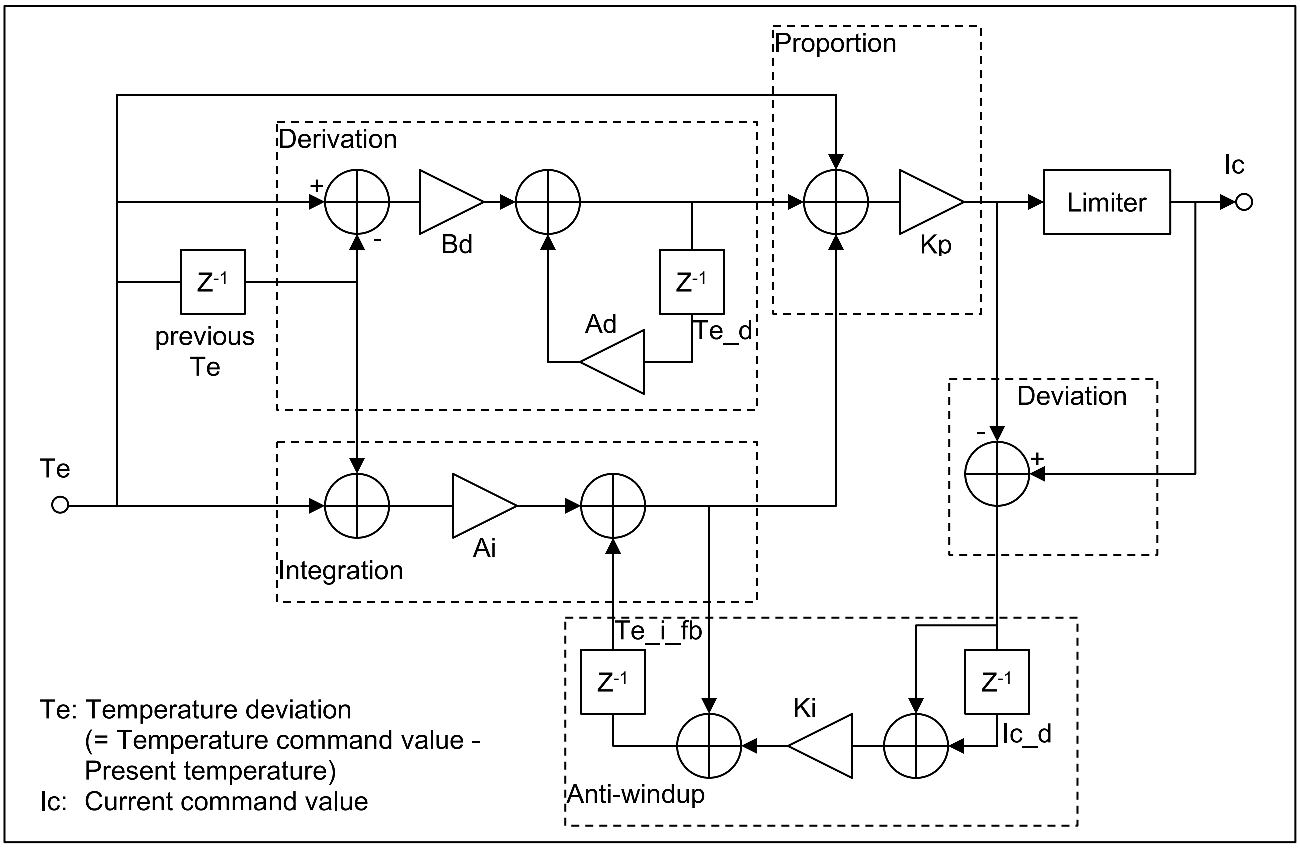


Figure 5-3 Temperature PID Control Signal Flow

5.3.2 Current PI Control

In current PI control, voltage applied to the Peltier module is calculated from the difference between the current command value and present current value. The calculated voltage is converted to a PWM duty value, and set as the PWM output duty. The signal flow of current PI control is shown in Figure 5-4.

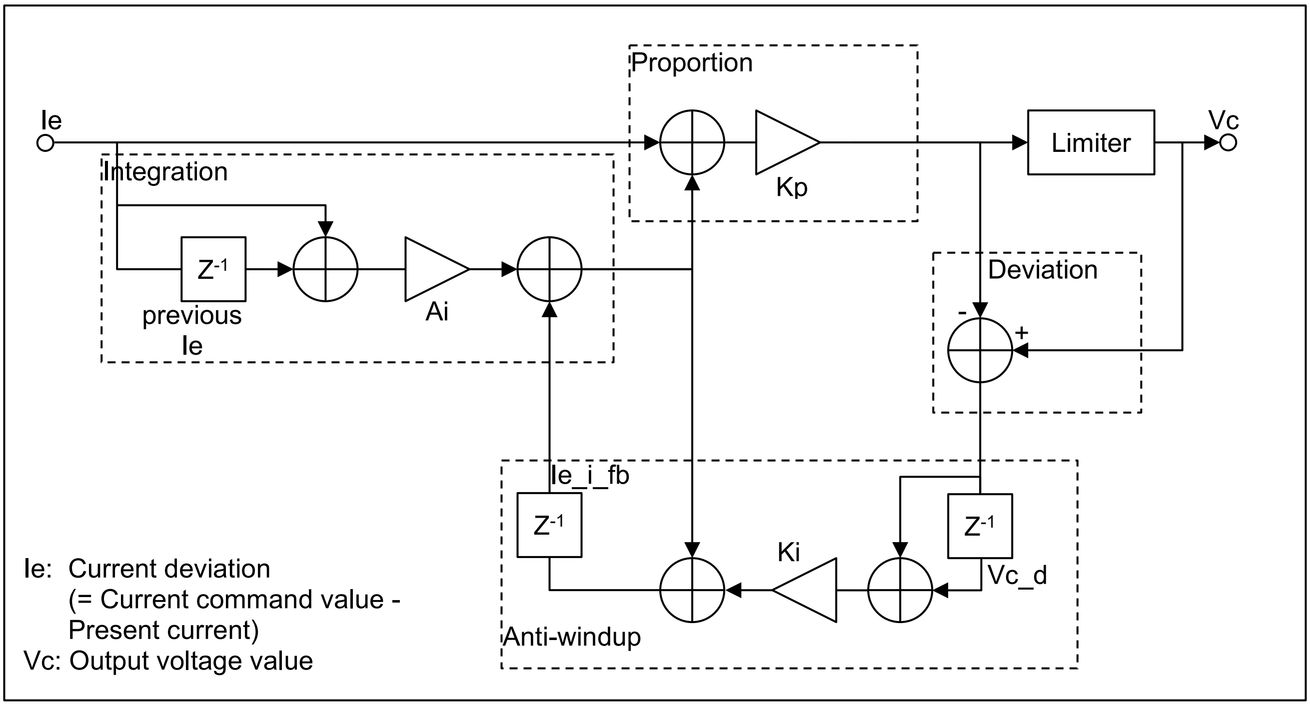


Figure 5-4 Current PI Control Signal Flow

The PWM duty value is obtained as the ratio of the voltage applied to the Peltier module V_C to the system power supply voltage V_{BRG}, as shown in the formula below.

$$PWM\ duty = \frac{V_C}{V_{BRG}}$$

If the calculated PWM duty value exceeds the available setting range, it is set as the upper or lower limit value.

For the upper and lower limits of PWM duty values, refer to the macro definitions in Table 5-17.

5.4 PWM Control

In this program, current control is performed with complementary PWM output using MTU as described in "4.1.3.2(2)Full bridge circuit".

Compared to the PWM duty value calculated in current PI control, resolution of the values set to MTU is lower. To improve precision, an array of MTU setting values including MTU setting values +1 or -1 is created so that the mean value of MTU setting values at current control cycles is the target duty value of PWM, and applied at each cycle of updating MTU setting values. Variations in PWM output duty are averaged by the low-pass filter effect of the hardware, approximated to the value calculated in current control. In this program, a 1/50 improvement of precision is expected in theory because the number of MTU setting value update cycles corresponding to the current control cycle is 50.

Figure 5-5 shows the timing chart of the PWM control operation.

The start of A/D conversion of S12AD is in synchronization with the PWM output cycles of MTU. MTU setting values are written from the MTU setting value array using DTC as triggered by a compare match of MTU.

Current PI control processing is performed for every 50 A/D conversions of S12AD. For the calculated PWM duty value, 50 MTU setting values are stored in the array. There are two MTU setting value arrays. The program stores 50 setting values in the array not used for DTC transfer.

To reserve the processing time required between the detection of completion of 50 A/D conversions of S12AD and the storage of setting values in the MTU setting value array, the size of the PWM setting value array is increased at MCU startup to delay the DTC transfer completion timing. In this program, the time required for processing is reserved by delaying it for 3 cycles of PWM output.

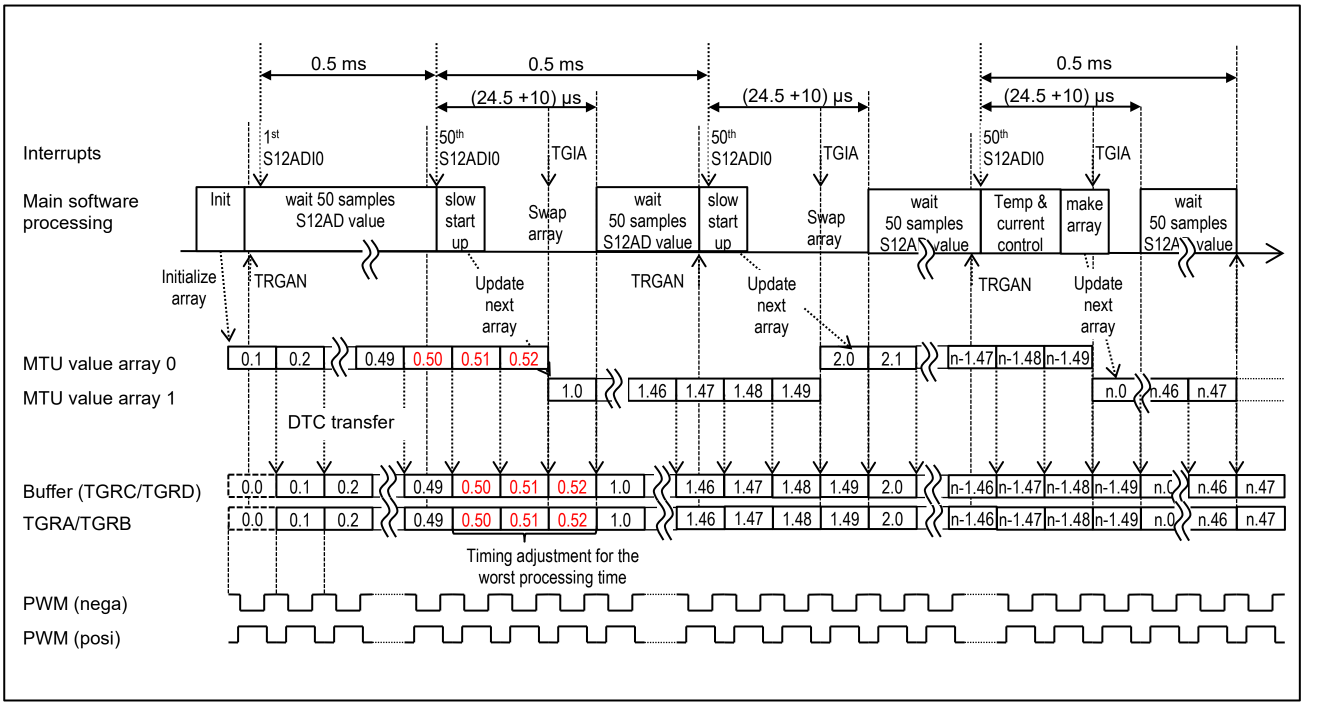


Figure 5-5 PWM Control Operation Timing Chart

5.5 Slow Startup Control

Slow startup is performed to start the full bridge circuit as shown in "4.1.3.2(2) Full bridge circuit" at system startup. In slow startup control, the PWM output duty is changed in the steps shown in Table 5-14 so that the current applied to the Peltier module becomes 0 A. The PWM output duty is changed at 1%/20 msec.

Table 5-14 Slow Startup Sequence

Sequence	PWM output duty setting				Voltage	
	MTIOC4A	MTIOC4B	MTIOC4C	MTIOC4D	Va	Vb
0: Initialization	0%				12 V	
1:	0%		5% to 95%		12 V to 0 V	
2:	5% to 50%		95% to 50%		0 V to 12 V	

5.6 Demo Operation

The demo operation starts when the slide switch is set to high. In the demo operation, the temperature command value is changed in specified steps between the upper limit and lower limit temperatures specified using macros. During the demo operation, no temperature command value is accepted from the PC tool. For the settings of the demo operation, refer to the macro definitions in Table 5-17.

5.7 Communication Control

Based on the communication specifications Rev.2.0 of RSSKRX23E-A, the processing with the PC tool program is performed.

A flow of the communication processing is shown in Figure 5-6.

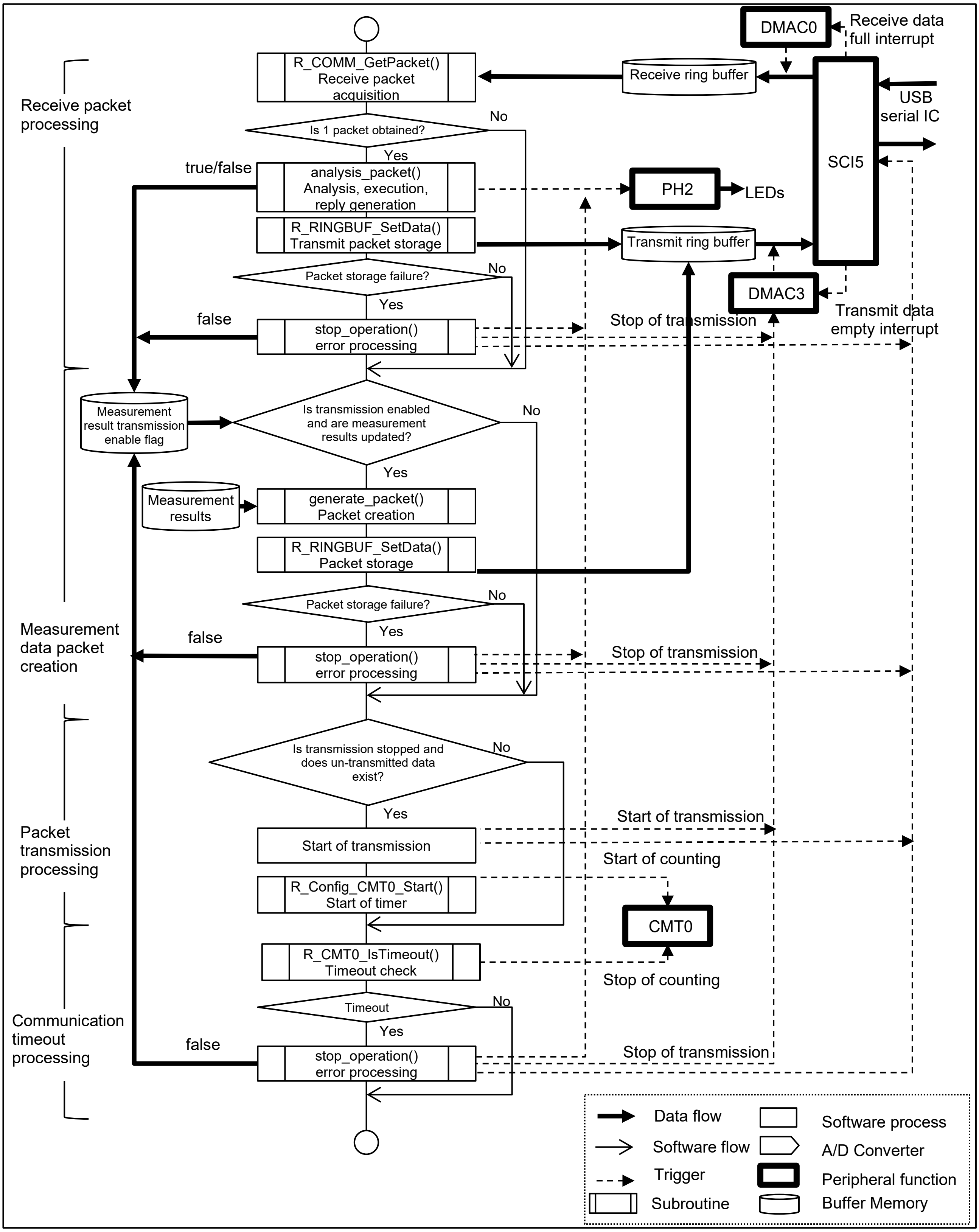


Figure 5-6 Communication Processing Flow

The following provides an overview of each process.

- Receive packet processing

Obtains a received packet from the receive ring buffer, and performs processing corresponding to a command analysis in the packet, then creates and stores a reply packet in the transmit ring buffer. Table 5-15 lists the commands supported by this program and the processes corresponding to the commands. For an unsupported command, a NACK is returned.

If the reply packet cannot be stored in the transmit ring buffer, communication error processing is performed.

Table 5-15 Packets and Actions

Command	Processing
Negotiation	Return the software status with a reply packet
Read	Return the read value of the specified register with a reply packet
Run	Set the measurement result transmission enable flag
Stop	Clear the measurement result transmission enable flag
Command Value	Update the temperature command value to the received value (not during the demo operation)
Extra Information	Return the output data rate with a reply packet

- Measurement data packet creation
  If the measurement result transmission enable flag is set and the temperature measurement values are updated, a reply packet with the temperature command value and temperature measurement values is created and stored in the transmit ring buffer.

  If the reply packet cannot be stored in the transmit ring buffer, communication error processing is performed.
- Packet transmission processing
  If data is not being transmitted and the transmit ring buffer contains un-transmitted data, transmission starts with DMAC3 and 1-second counting starts with CMT0 for timeout detection.
- Communication timeout processing
  If transmission is completed, CMT0 for timeout detection is stopped.

  If transmission is in progress, the timer is checked for a compare match, and if a compare match has occurred, this is judged as a timeout. If it is judged as a timeout, communication error processing is performed.
- Communication error processing
  If the transmit packet cannot be stored in the transmit ring buffer or a communication timeout occurs, communication is stopped, and the following processes are performed to make a reconnection possible.
  - Stop SCI5 and DMAC3, which are used for transmission
  - Clear the transmit buffer and the temperature data transmission enable flag

Each ring buffer used for transmission and reception is for DMAC transmission, therefore, their address is arranged in the alignment adjusted for each buffer size. In this program, section name is declared as “B_DMAC_REPEAT_AREA” and arrangement is set based on the largest buffer size.

5.8 Program Configuration

5.8.1 File Configuration

Table 5-16 File Configuration

Folder name, file name	Description
src	
├ smc_gen	Smart Configurator generation
│├ Config_AFE	
│├ Config_CMT0	
│├ Config_DMAC0	
│├ Config_DMAC3	
│├ Config_DSAD0	
│├ Config_DTC	
│├ Config_MTU3_MTU4	
│├ Config_PORT	
│├ Config_S12AD0	
│├ Config_SCI5	
│├ general	
│├ r_bsp	
│├ r_config	
│└ r_pincfg	
├ main.c	Main processing
├ r_calc_api.c	General-purpose operation program
├ r_calc_api.h	General-purpose operation API definition
├ r_communication_control_api.c	Communication control program
├ r_communication_control_api.h	Communication control API definition
├ r_current_api.c	Current measurement-related program
├ r_current_api.h	Current measurement-related API definition
├ r_current_pi.c	Current PI control operation program
├ r_current_pi.h	Current PI control operation API definition
├ r_ring_buffer_control_api.c	Ring buffer control program
├ r_ring_buffer_control_api.h	Ring buffer control API definition
├ r_rtd_api.c	Resistance temperature detector measurement calculation program, temperature vs. resistance value table
├ r_rtd_api.h	Resistance temperature detector measurement calculation API definition
├ r_temp_pid.c	Temperature PID control operation program
└ r_temp_pid.h	Temperature PID control operation API definition

5.8.2 Macro Definitions

Table 5-17 main.c Definitions

Definition name	Value	Description
D_PRV_PC_TOOL_USE	1	Communication with the PC tool program is 0: Not used 1: Used
D_TIME_BASE	10U	S12AD conversion cycle 10 us
D_COUNT_S12AD	50U	Number of S12AD conversion value averaging 50
D_COUNT_TEMP	40U	Number of DSAD conversion value averaging cycle based on S12AD cycles
D_TIME_TEMP	D_TIME_BASE * D_COUNT_S12AD * D_COUNT_TEMP /1000	Temperature update cycle [ms]
D_VBRG	24.0F	Bridge circuit voltage [V]
D_DUTY_MIN	-0.9F	PWM duty lower limit value
D_DUTY_MAX	0.9F	PWM duty upper limit value
D_PWM_DELAY_NUM	3	Number of delays of PWM setting update in PWM update cycles
D_DEMO_CYCLE	300U / D_TIME_TEMP	Temperature command value update cycle during demo operation, numerical part [ms]
D_DEMO_STEP	0.1F	Temperature command value step during demo operation [°C]
D_DEMO_TC_MIN	31.0F	Temperature command value lower limit during demo operation [°C]
D_DEMO_TC_MAX	15.0F	Temperature command value upper limit during demo operation [°C]
D_CMD_TC_MIN	10.0F	Temperature command value lower limit of the PC tool [°C]
D_CMD_TC_MAX	50.0F	Temperature command value upper limit of the PC tool [°C]
D_CMD_TC_INIT	25.0F	Temperature command initial value [°C]
D_CMD_IC_MIN	-1.0F	Current command value lower limit [A]
D_CMD_IC_MAX	1.0F	Current command value upper limit [A]
D_CMD_IC_INIT	0.0F	Current command initial value [A]
D_SLOW_DIVISOR	100.0F	Percentage conversion parameter
D_SLOW_POINT_0	0.0F / D_SLOW_DIVISOR	Slow startup duty initial value, numerical part [%]
D_SLOW_POINT_1	95.0F / D_SLOW_DIVISOR	Slow startup step 1 duty completion value, numerical part [%]
D_SLOW_POINT_2	45.0F / D_SLOW_DIVISOR	Slow startup step 2 duty completion value, numerical part [%]
D_SLOW_UPDATE	1.0F / D_SLOW_DIVISOR / (float) D_COUNT_TEMP	Slow startup duty change, numerical part [%]

Table 5-18 r_current_pi.h Definitions

Definition name	Value	Description
D_TS_CURRENT	0.0005F	Control cycle [sec]
D_KP_CURRENT	1.2F	Proportional gain [V/A]
D_TI_CURRENT	0.0012F	Integral time [sec]
D_KB_CURRENT	0.8F	Inverted integral gain [A/V]
D_VC_MIN	-21.0F	Output voltage lower limit [V]
D_VC_MAX	21.0F	Output voltage upper limit [V]

Table 5-19 r_temp_pid.h Definitions

Definition name	Value	Description
D_TS_TEMP	0.02F	Control cycle [sec]
D_KP_TEMP	3.0F	Proportional gain [A/°C]
D_TI_TEMP	5.0F	Integral time [sec]
D_TD_TEMP	1.0F	Derivative time [sec]
D_TF_TEMP	0.1F	Derivative filter time [sec]
D_KB_TEMP	0.8F	Inverted integral gain [°C/A]

Table 5-20 r_rtd_api.h Definitions

Definition name	Type	Value	Description
D_RTD_RREF	float	5100.0F	R_{REF} resistance value [Ω]
D_RTD_PGA_GAIN	float	32.0F	Gain of PGA for RTD measurement G_{PGA} [x]
D_RTD_CODE_FS	uint32_t	16777216	2^{24}
D_RTD_DF_GAIN	float	1.0F	Digital filter gain G_{DF}
D_RTD_GAIN	float	D_RTD_RREF * 4 / (D_RTD_CODE_FS * D_RTD_PGA_GAIN * D_RTD_DF_GAIN)	Coefficient for conversion from A/D value to RTD resistance value [Ω] $\frac{4R_{REF}}{2^{24} \cdot G_{PGA} \cdot G_{DF}}$
D_RTD_OFFSET	float	0.0F	RTD resistance value offset [Ω]
D_RTD_TABLE_SIZE	uint16_t	302	Number of table elements
D_RTD_TABLE_TOP_TEMPARATURE	float	-50.0F	Top temperature in the table [°C]

5.8.3 Structures and Unions

Table 5-21 main.c Structures

Structure type name	st_flag_t		
Description	Variables manipulated by the communication receive data analysis function		
Member variable	**Type**	**Name**	**Description**
	bool	demo_mode	Demo operation On/Off true: On, false: Off
	bool	tx_run	Measurement value transmission enabled true: Enabled, false: Disabled
	float	demo_range	Demo operation temperature range

Table 5-22 r_current_pi Structures

Structure type name	st_current_pi_coef_t		
Description	Current PI control coefficient		
Member variable	**Type**	**Name**	**Description**
	float	Kp	Proportionality coefficient
	float	Ai	Integral coefficient
	float	Ki	Inverted integral coefficient
	float	vc_min	Voltage value lower limit [V]
	float	vc_max	Voltage value upper limit [V]
Structure type name	st_current_pi_data_t		
Description	Current PI control internal data		
Member variable	float	Ie	Previous current deviation value
	float	Vc_d	Previous voltage limitation deviation value
	float	Ie_i_fb	Previous inverted integral value

Table 5-23 r_temp_pid Structures

Structure type name	st_temp_pid_coef_t		
Description	Temperature PID control coefficient		
Member variable	**Type**	**Name**	**Description**
	float	Kp	Proportionality coefficient
	float	Ad	Derivative coefficient
	float	Bd	Derivative coefficient
	float	Ai	Integral coefficient
	float	Ki	Inverted integral coefficient
	float	ic_min	Current command value lower limit [A]
	float	ic_max	Current command value upper limit [A]
Structure type name	st_temp_pid_data_t		
Description	Temperature PID control internal data		
Member variable	float	Te	Previous temperature deviation value
	float	Te_d	Previous derivative output value
	float	Te_i_fb	Previous temperature inversion value
	float	Ic_d	Previous current limitation deviation value

Table 5-24 r_ring_buffer_control_api Structures

Structure type name	st_ring_buf_t		
Description	Ring buffer information		
Member	**Type**	**Name**	**Description**
	uint8_t *	p_buf	Pointer to the ring buffer
	size_t	length	Ring buffer length
	uint32_t	r_index	Read index
	uint32_t	w_index	Write index

Table 5-25 Config_MTU3_MTU4 Structures/Unions

Union type name	u_mtu_duty_t		
Description	PWM duty setting value of MTU		
Member	**Type**	**Name**	**Description**
	uint32_t	**both**	**32-bit value**
	uint16_t	each.neg	Negative phase 16-bit value
	uint16_t	each.pos	Positive phase 16-bit value
Structure type name	st_mtu_isr_inf_t		
Description	Shared variable structure with the MTU interrupt function		
Member	u_mtu_duty_t *	p_ptr	Pointer to the PWM duty setting value array for MTU
	uint32_t	num	Number of array elements

5.8.4 Functions

Table 5-26 main.c Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
main main function	void	-	-	void	-	-
stop_operation Stops DMAC/SCI, initializes the ring buffer	void	-	I	st_ring_buf_t *	ary	Pointer to the ring buffer
generate_packet Creates measurement value packets	size_t	Packet length	I	uint8_t	send_pkt[]	Packet storage array
			I	float	txdata_ch[]	Transmit data array
			I	uint16_t	tx_flag	Transmit channel specification (bit allocation)
analysis_pakect According to the receive packet, executes the command and stores a reply packet. For the Run/Stop commands, updates the measurement result transmission enable flag.	size_t	Reply packet length	I	uint8_t const	rcv_pck[]	Receive packet storage array
			O	uint8_t	send_pck[]	Reply packet storage array
			O	float *	p_cmd_value	Pointer to the temperature command value variable
			O	st_flag_t *	p_flag	Pointer to the flag structure variable manipulated by this function
			O	uint8_t *	p_mode	Pointer to the operating mode variable
calc_duty Calculates the PWM duty corresponding to the voltage value	float	Duty value (-0.90 to +0.90)	I	float	Vc	Voltage value
			I	float	Vbrg	Bridge circuit voltage
calc_demo_command_val Calculates the demo temperature command value	float	New temperature command value	I	float	temp	Present temperature command value
calc_temp_to_demo_command_val Calculates the demo temperature command initial value from the specified temperature	float	Temperature command initial value	I	float	temp	Temperature

Table 5-27 r_calc_api Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_CALC_BinarySearch Does a binary search from the search table, and returns the index of a recent value that does not exceed the data to search for	uint16_t	Index value	I	const float *	p_data_table	Pointer to the search table (ascending order)
			I	uint16_t	table_size	Number of elements in the search table
			I	float	data	Data to search for
R_CALC_Lerp Determines y corresponding to x in the straight line passing two points (x0,y0) and (x1,y1)	float	Linear interpolation results	I	float	x0	x0 value
			I	float	y0	y0 value
			I	float	x1	x1 value
			I	float	y1	y1 value
			I	float	x	x value
R_CALC_Limit Limits the value of val to the range between min and max	float	Control result	I	float	val	Target value
			I	float	min	Lower limit value
			I	float	max	Upper limit value

Table 5-28 r_communication_control_api Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_COMM_GetPacket Reads a single packet from the receive ring buffer	size_t	Packet length [Bytes]	I	st_ring_buf_t *	r_buf	Pointer to the receive ring buffer
			O	uint8_t	r_packet[]	Receive packet storage array

Table 5-29 r_current_api Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_S12adToCurrent Calculates the current from the A/D conversion value	float	Current [A]	I	float	s12ad	S12AD conversion value

Table 5-30 r_current_pi Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_CurrentPI Current PI control operation	float	Voltage value [V]	I	float	Ie	Current deviation [A]
			I	st_current_pi_coef_t *	p_coef	Pointer to the current PI control coefficient structure variable
			I/O	st_current_pi_data_t *	p_data	Pointer to the current PI control internal data structure variable

Table 5-31 r_temp_pid Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_TempPID Temperature PID control operation	float	Current command value [A]	I	float	Te	Temperature deviation [°C]
			I	st_temp_pid_coef_t *	p_coef	Pointer to the temperature PID control coefficient structure variable
			I/O	st_temp_pid_data_t *	p_data	Pointer to the temperature PID control internal data structure variable

Table 5-32 r_ring_buffer_control_api Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_RINGBUF_GetData Reads a specified number of bytes from the ring buffer	size_t	Number of bytes to read	I	st_ring_buf_t *	ary	Pointer to the ring buffer
			O	uint8_t	data[]	Data storage array
			I	size_t	len	Number of bytes to read
			I	bool	index_update	Index update flag true: Update false: Not update
R_RINGBUF_SetData Writes a specified number of bytes to the ring buffer	size_t	Number of bytes to write	O	st_ring_buf_t *	ary	Pointer to the ring buffer
			I	uint8_t	data[]	Data storage array
			I	size_t	len	Number of bytes to write
R_RINGBUF_GetDataLength Reads a specified number of bytes stored in the ring buffer	size_t	Number of bytes stored	I	st_ring_buf_t *	ary	Pointer to the ring buffer
R_RINGBUF_SetDataIndex Updates the index of the ring buffer	uint32_t	Index value	O	st_ring_buf_t *	ary	Pointer to the ring buffer
			I	uint16_t	value	Index value
			I	uint8_t	select	Target index 0:Read, 1:Write

Table 5-33 r_rtd_api.c Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_RTD_DsadToTemp Calculates the temperature from the DSAD conversion value	float	Temperature [C]	I	float	dsad	DSAD conversion value

Table 5-34 Config_CMT0 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_CMT0_IsTimeout Returns information as to whether a timeout has occurred	bool	false: Counting true: Timeout	I	bool	flag	Stop of counting false: Continuation true: Stop
R_CMT0_CntClear Clears the compare match timer/counter of CMT0	void	-	-	void	-	-

Table 5-35 Config_DMAC0 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_DMAC0_SetDestAddr Sets the DMDAR of DMAC0	void	-	I	void *	p_addr	destination address
R_DMAC0_GetDestAddr Returns the DMDAR of DMAC0 (macro function)	void *	DMDAR value	-	void	-	-

Table 5-36 Config_DMAC3 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_DMAC3_SetSrcAddr Sets the DMSAR of DMAC3	void	-	I	void *	p_addr	source address
R_DMAC3_SetTxCnt Sets the DMCRA of DMAC3	void	-	I	uint32_t	cnt	transfer count

Table 5-37 Config_DSAD0 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
r_Config_DSAD0_adi0_interrupt ADI0 interrupt handler of DSAD Obtains the DSAD conversion value, calculates the cumulative sum, and increments the cumulative number	void	-	-	void	-	

Table 5-38 Config_DTC User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_Config_DTC_SetParam DTC transfer setting of the PWM duty setting value of MTU	void	-	I	void *	addr	Beginning address of the setting value array
			I	uint16_t	num	Number of elements to be transferred

Table 5-39 Config_MTU3_MTU4 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
r_Config_MTU3_MTU4_tgia3_interrupt TGIA3 interrupt handler of MTU Starts the next DTC transfer setting and transfer	void	-	-	void	-	
R_MTU_SetPort Sets the PWM output port	void	-	I	uint8_t	config	Port setting - 0: Positive Phase/Negative Phase, fixed at Low - 1: Positive Phase, fixed at Low, Negative Phase enabled - 2: Positive Phase/Negative Phase enabled
R_MTU_FillPWMArray Fills the setting value array with posi and nega	void	-	O	u_mtu_duty_t *	array	Pointer to setting value array of MTU
			I	uint16_t	posi	Positive phase duty setting value
			I	uint16_t	nega	Negative phase duty setting value
			I	size_t	num	Number of array elements
R_MTU_MakeFractionalPWMArray Stores the PWM duty setting values of MTU corresponding to duty in the array	void	-	I	float	duty	PWM duty specification value
			O	u_mtu_duty_t *	array	Pointer to setting value array of MTU
			I	size_t	num	Number of array elements
R_MTU_MakeFractionalPWMArraySSU Stores the PWM duty setting values of MTU corresponding to duty during slow startup in the array	void	-	I	float	duty	PWM duty specification value
			O	u_mtu_duty_t *	array	Pointer to setting value array of MTU
			I	size_t	num	Number of array elements

Table 5-40 Config_PORT User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_LED1_On Turns LED1 ON (macro function)	void	-	-	void	-	
R_LED1_Off Turns LED1 OFF (macro function)	void	-	-	void	-	
R_SWITCH_Get Obtains the switch status (macro function)	uint8_t	Switch status (0/1)	-	void	-	
R_PORT_KeyScan Obtains the switch status after chattering absorption	uint16_t	Switch status (0/1)		uint16_t	key_current	Previous switch status

Table 5-41 Config_S12AD0 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
r_Config_S12AD0_interrupt S12ADI0 interrupt handler of S12AD Obtains the S12AD conversion value, calculates the cumulative sum, and increments the cumulative number	void	-	-	void	-	-

Table 5-42 Config_SCI5 User Defined Functions

Function name/Overview	Return value		Argument			
	Type	Value	I/O	Type	Variable name	Description
R_SCI5_IsTransferEnd Obtains the transmission status	bool	false: Transmission is in progress true: Transmission is completed	-	void	-	
R_SCI5_SendStart Instructs to start transmission	MD_STATUS	MD_OK	-	void	-	
R_SCI5_SendStop Instructs to stop transmission	MD_STATUS	MD_OK	-	void	-	
R_SCI5_ReceiveStart Instructs to start reception	MD_STATUS	MD_OK	-	void	-	

6. Importing a Project

After importing the sample project, make sure to confirm build and debugger setting.

6.1 Importing a Project into e² studio

Follow the steps below to import your project into e² studio. Pictures may be different depending on the version of e² studio to be used.

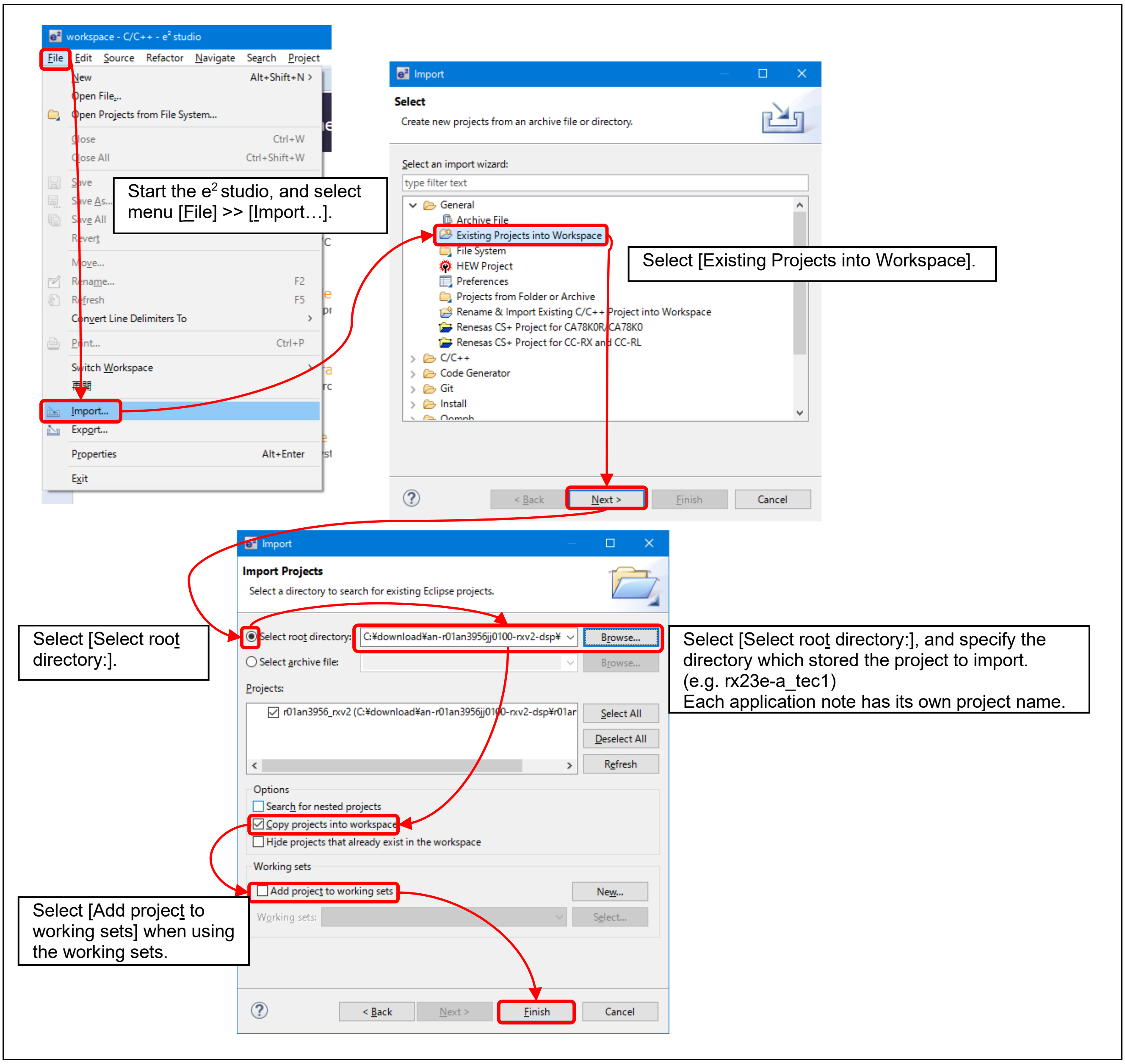


Figure 6-1 Importing a Project into e² studio

6.2 Importing a Project into CS+

Follow the steps below to import your project into CS+. Pictures may be different depending on the version of CS+ to be used.

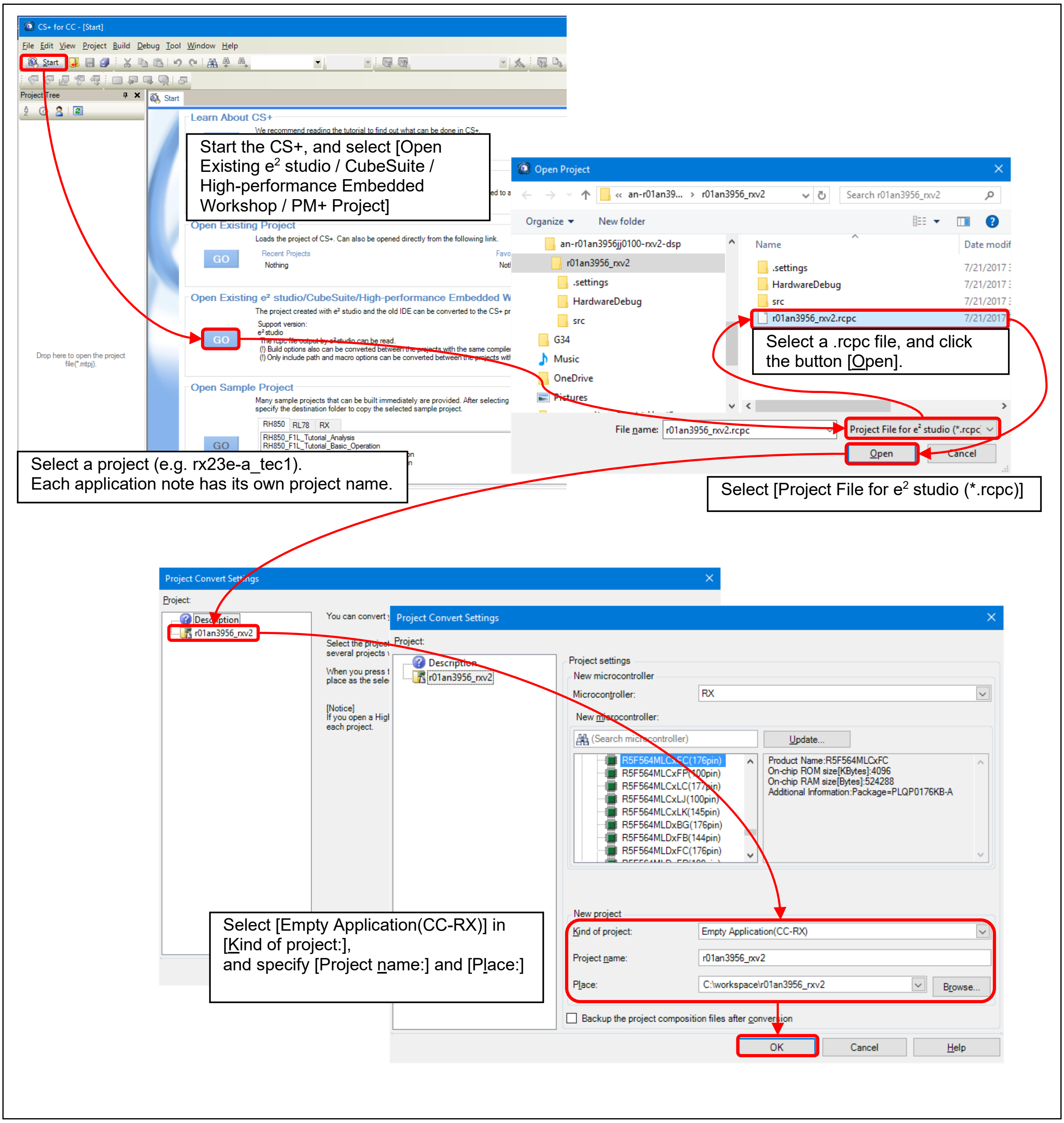


Figure 6-2 Importing a Project into CS+

7. Operations Results with the Sample Program

7.1 Memory Usage and Number of Execution Cycle

7.1.1 Build Conditions

The build conditions of the sample program are shown in Table 7-1. This setting is default setting when project is generated except for memory allocation to support the PC tool.

Table 7-1 Build Conditions

Item		Setting
Compiler		-isa=rxv2 -define=D_PC_TOOL_USE=1 -utf8 -nomessage -output=obj -debug -outcode=utf8 -nologo
Linker		-noprelink -output="rx23ea_tec1.abs" -form=absolute -nomessage -vect=_undefined_interrupt_source_isr -list=rx23ea_tec1.map -nooptimize -rom=D=R,D_1=R_1,D_2=R_2 -nologo
	Additional section	-start=B_DMAC_REPEAT_AREA_1/02000

7.1.2 Memory Usage

The amount of memory usage of sample program is shown in Table 7-2.

Table 7-2 Amount of Memory Usage

Item		Size [byte]	Remarks
ROM		12898	
	Code	9760	
	Data	3138	
RAM		8287 (3295)	Note:
	Data	3167	
	Stack	5120 (128)	Note:

Note: RAM usage for stack is shown in “()”.

7.1.3 Number of Execution Cycles

The number of execution cycles and processing load for each block in “Figure 5-1 Temperature Control Process Flow” is shown in Table 7-3.

Table 7-3 Number of Execution Cycles, Execution Time, and Processing Load

ICLK=32MHz

Item		Maximum number of execution cycles (Execution time)	Processing load [%]	Condition
Temperature Control	S12A/D averaging to temperature PID control/current PI control	567 cycles (17.72 µsec)	3.55	Including one interrupt each for S12A/D and DSAD
	PWM duty setting array creation	338 cycles (10.56 µsec)	2.12	
	S12AD conversion completion interrupt processing	46 cycles (1.44 µsec)	8.89	Processing load of 49 interrupts
	DSAD conversion completion interrupt processing	47 cycles (1.47 µsec)	0.94	1 interrupt
	Total	934 cycles (29.19 µsec)	5.84	Maximum load of temperature control Up to current PI control + Duty array creation
System	Demo operation processing	45 cycles (1.41 µsec)	0.29	
	Communication control	543 cycles (16.97 µsec)	3.40	Measurement value packet creation STOP command reception
	Switch processing	63 cycles (1.97 µsec)	1.97	
	Total	2977 cycles (93.04 µsec)	18.61	When temperature control is included in demo operation

7.2 Operation Examples

7.2.1 Step Response

Step response when the temperature command value is changed from 25°C to 35°C and change in temperature when a current of 0.5 A is flowed to the Peltier module without temperature control are shown in Figure 7-1.

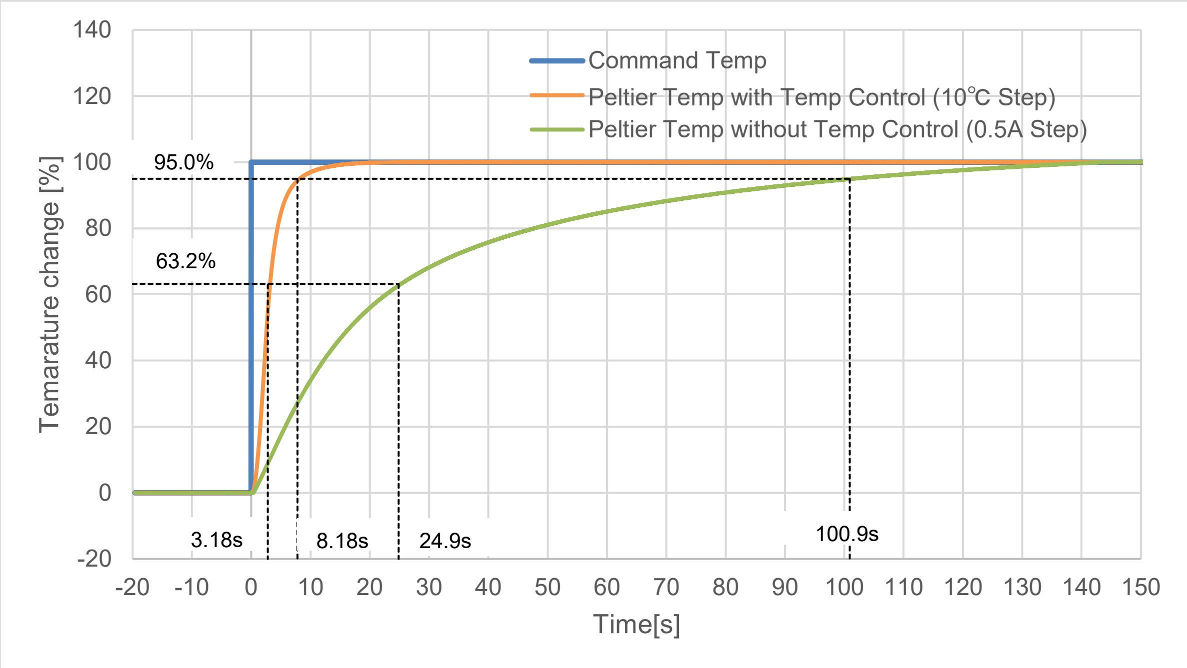


Figure 7-1 Temperature Step Response

Table 7-4 Summary of Temperature Step Response

Item	Temperature control measurement result	Peltier module response (Without temperature control)
63.2% time	3.18 [s]	24.9 [s]
Overshoot	None	None
±5% settling time	8.18 [s]	100.9 [s]

Based on Figure 7-1 and Table 7-4, the temperature response of the Peltier module with temperature control shortened the time to reach the final value of 63.2% from 24.9 sec to 3.18 sec compared to the response without temperature control, indicating a significant improvement in responsiveness.

7.2.2 Control Resolution

The temperature control response when temperature command values are entered to this system in 5m°C steps is shown in Figure 7-2. This system can perform high-precision temperature measurements with DSAD. Based on the measurement results, it is confirmed that fine temperature control in 5 m°C steps can be achieved.

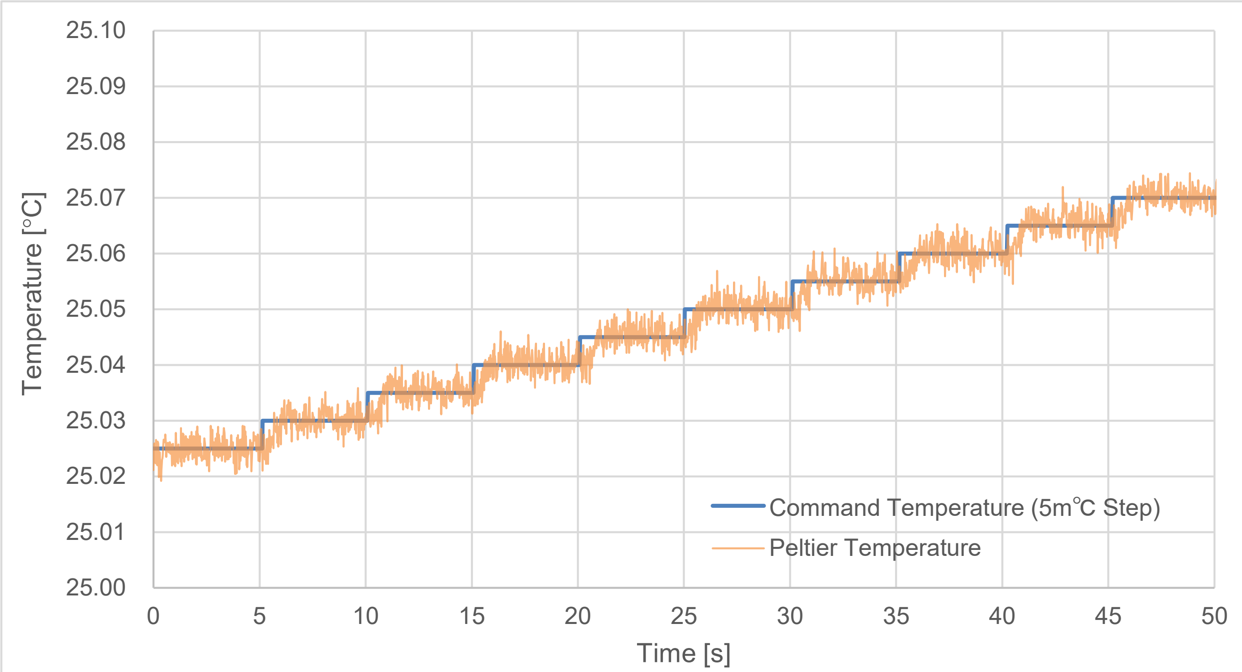


Figure 7-2 Temperature Control Response (5m°C Steps)

The histogram of deviations from the mean value of 1000 temperature measurement samples when the temperature is controlled to 25°C in a room temperature environment (25°C) is shown in Figure **7-3**. The RMS value of temperature deviation is 1.94m°C (P-P value: 12.0m°C). Assuming that the sensitivity of the RTD Pt100 is 385mΩ/°C and the excitation current is 250 uA, the temperature sensitivity for input voltage to RX23E-A is 96.25 uV/°C. Therefore, the input conversion voltage is 186.3 nVrms, 1157.9 nV peak to peak. The effective resolution and noise free resolution of temperature control calculated from the input conversion voltage are shown below.

Effective resolution:	1.94m°C (19.71 bits, equivalent to 186.3 nV)
Noise free resolution:	12.0m°C (17.07 bits, equivalent to 1157.9 nV)

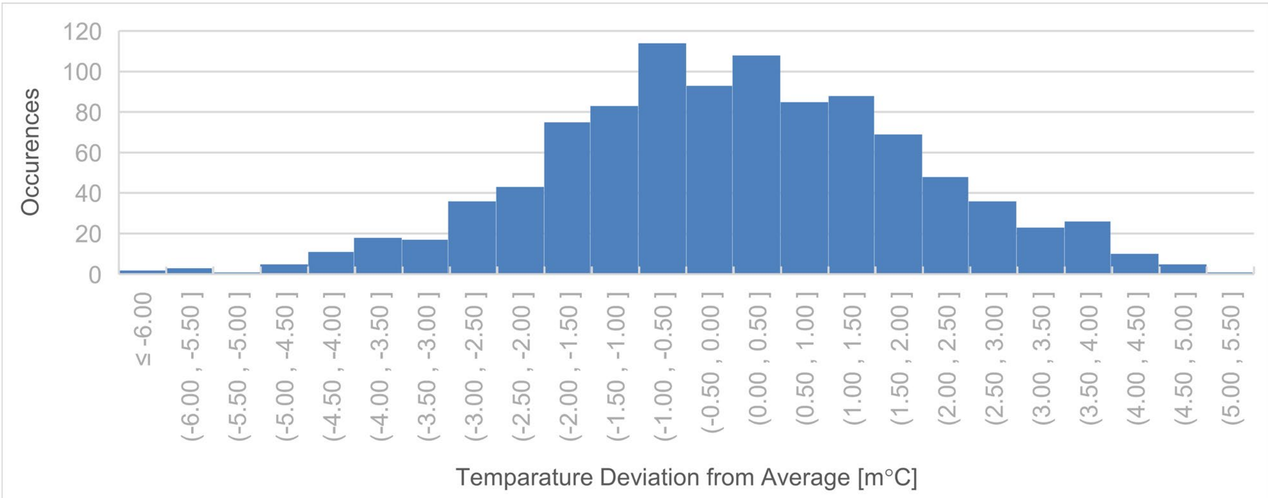
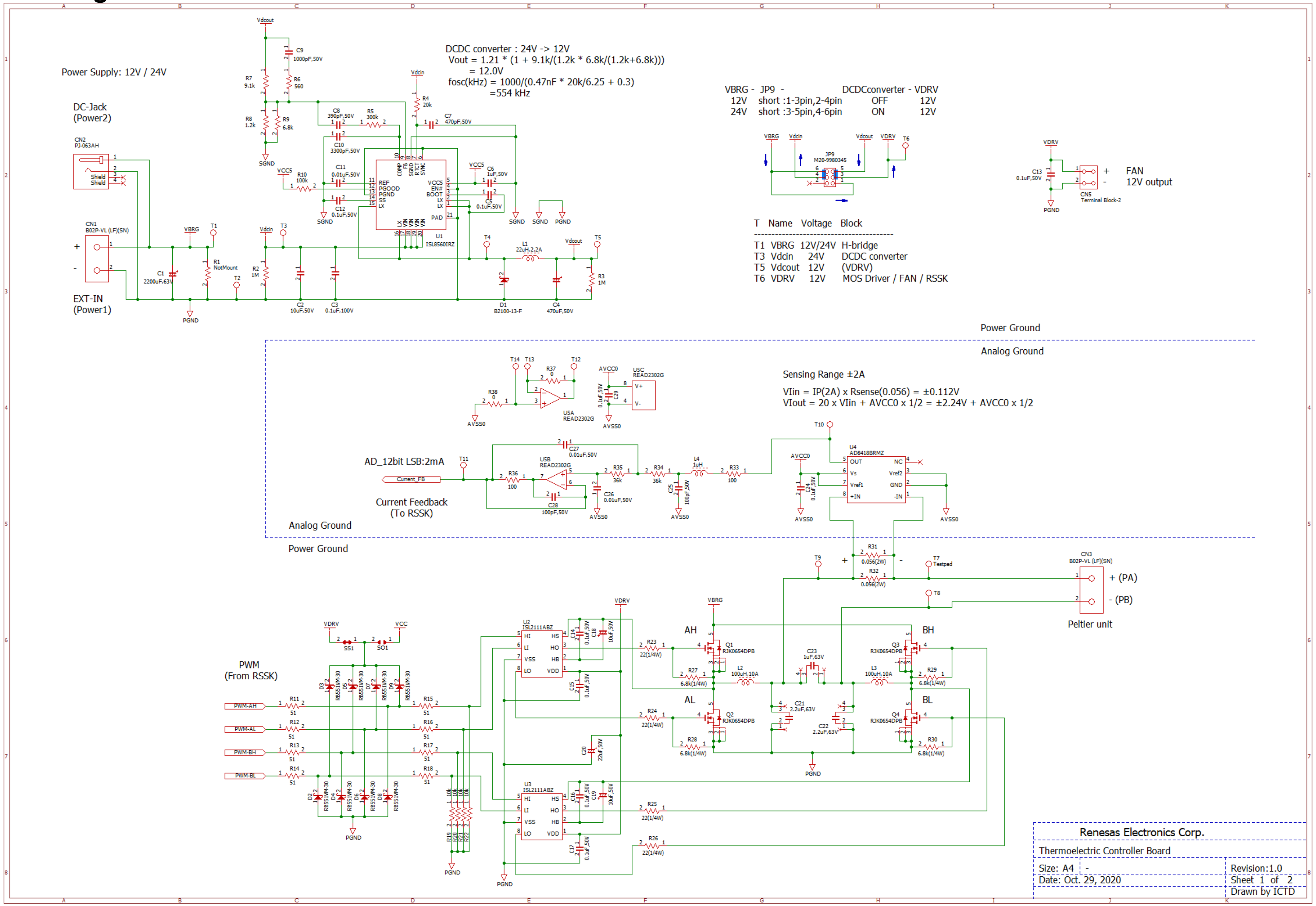


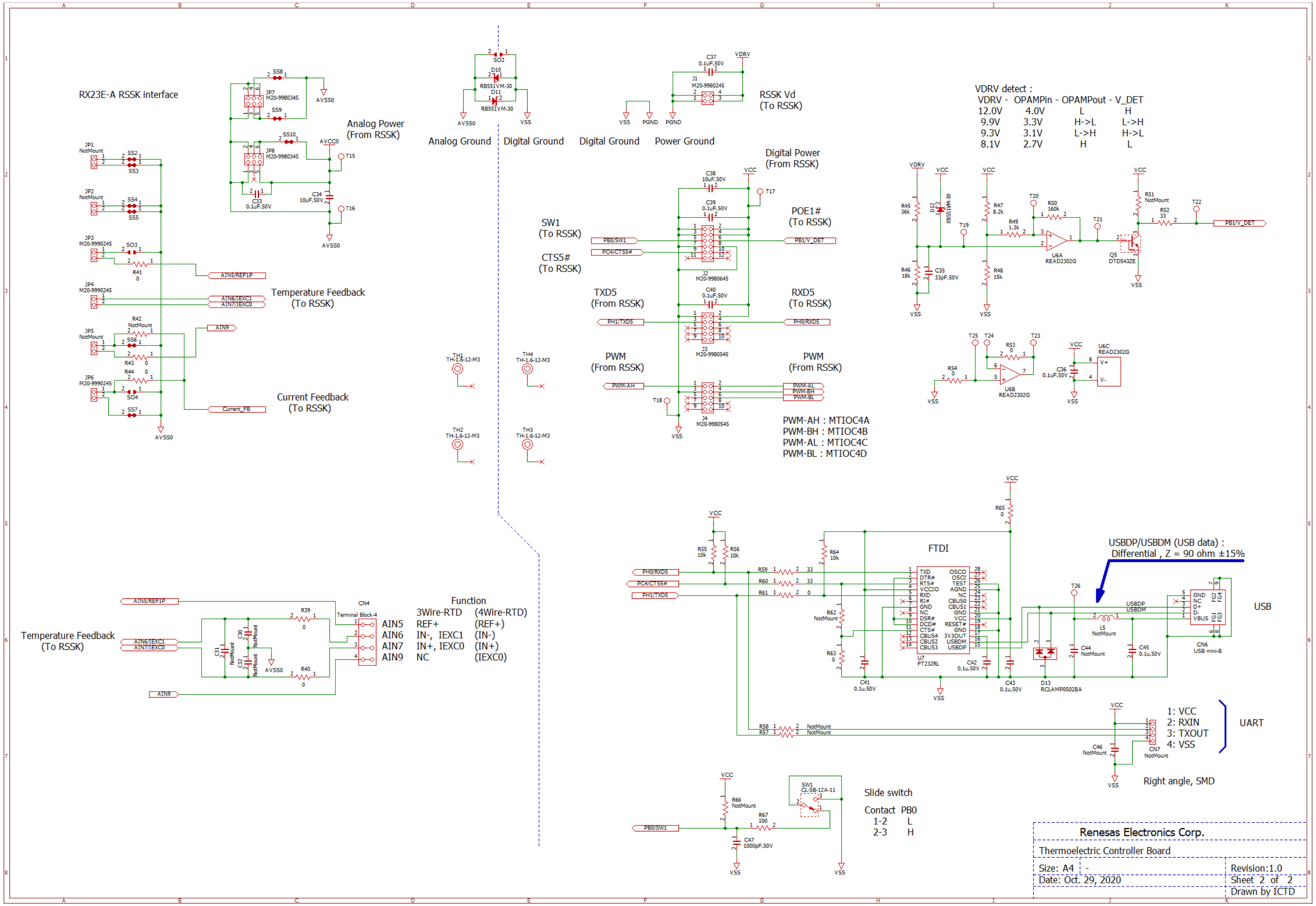
Figure 7-3 Temperature Control Deviations in a Room Temperature Environment

Appendix 1 Parts List of the Power Board

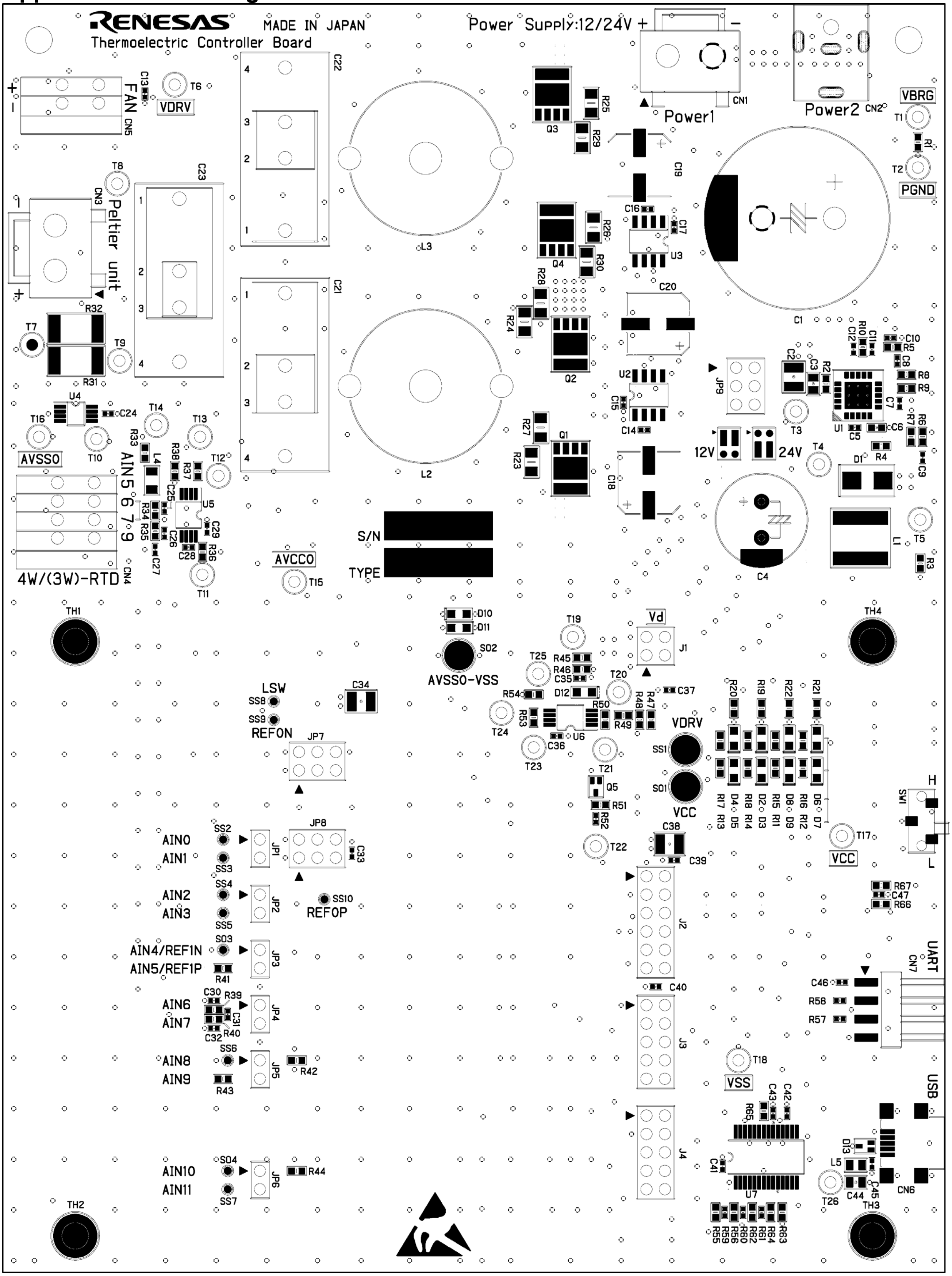
No.	Quantity (Mounted)	Reference Designator (Mounted)	Reference Designator (Not Mounted)	Description	Part Name	Manufacturer Part Name(*)	Manufacturer
1	1	U1		DCDC converter,2A	IC	ISL8560IRZ	Renesas
2	2	U2,U3		MOS driver	IC	ISL2111ABZ	Renesas
3	1	U4		Current sense	IC	AD8418BRMZ	ADI
4	2	U5,U6		OPAMP	IC	READ2302G	Renesas
5	1	U7		USB to UART interface	IC	FT232RL	FTDI
6	4	Q1,Q2,Q3,Q4		60V,30A	MOS-FET	RJK0654DPB	Renesas
7	1	Q5		12V,500mA	Digital Transistor	DTD543ZE	Rohm
8	2	CN1,CN3		2-pin	Connector	B02P-VL(LF)(SN)	JST
9	1	CN2		DC-Jack,24VDC,8A	Connector	PJ-063AH	CUI
10	1	CN4		Terminal Block-4	Connector	FFKDSA1/H-2,54-4	Phoenix Contact
11	1	CN5		Terminal Block-2	Connector	FFKDSA1/H-2,54-2	Phoenix contact
12	1	CN6		USB mini-B	Connector	UB-M5BR-G14-4S	JST
13	2	R31,R32		56mohm(2W)	Resistor	TLRH3AWTTE56L0F	KOA
14	4	R23,R24,R25,R26		22(1/4W)	Resistor	CRCW120622R0FKEAC	Vishay / Dale
15	11	R37,R38,R39,R40,R41,R43 R44,R53,R54,R63,R65		0	Resistor	RK73Z1JTTD	KOA
16	8	R11,R12,R13,R14 R15,R16,R17,R18		51	Resistor	RK73H1JTTD51R0F	KOA
17	3	R33,R36,R67		100	Resistor	RK73H1JTTD1000F	KOA
18	1	R6		560	Resistor	RK73H1JTTD5600F	KOA
19	1	R8		1.2k	Resistor	RK73H1JTTD1201F	KOA
20	1	R49		1.3k	Resistor	RK73H1JTTD1301F	KOA
21	1	R9		6.8k	Resistor	RK73H1JTTD6801F	KOA
22	1	R47		8.2k	Resistor	RK73H1JTTD8201F	KOA
23	1	R7		9.1k	Resistor	RK73H1JTTD9101F	KOA
24	1	R48		15k	Resistor	RK73H1JTTD1502F	KOA
25	1	R46		18k	Resistor	RK73H1JTTD1802F	KOA
26	7	R19,R20,R21,R22, R55,R56,R64		10k	Resistor	RK73H1JTTD1002F	KOA
27	1	R4		20k	Resistor	RK73H1JTTD2002F	KOA
28	3	R34,R35,R45		36k	Resistor	RK73H1JTTD3602F	KOA
29	1	R10		100k	Resistor	RK73H1JTTD1003F	KOA
30	1	R50		160k	Resistor	RK73H1JTTD1603F	KOA
31	1	R5		300k	Resistor	RK73H1JTTD3003F	KOA
32	2	R2,R3		1M	Resistor	RK73H1JTTD1004F	KOA
33	1	R61		0	Resistor	RK73Z1ETTP	KOA
34	3	R52,R59,R60		33	Resistor	RK73H1ETTP33R0F	KOA
35	4	R27,R28,R29,R30		6.8k(1/4W)	Resistor	RK73H2BTTD6801F	KOA
36	1	C35		33pF,50V	Ceramic capacitor	GCQ1555C1H330JB01D	Murata
37	2	C25,C28		100pF,50V	Ceramic capacitor	GCM1555C1H101JA16D	Murata
38	1	C7		470pF,50V	Ceramic capacitor	GCM1555C1H471JA16D	Murata
39	1	C8		390pF,50V	Ceramic capacitor	GCM1555C1H391FA16D	Murata
40	2	C9,C47	C30,C32	1000pF,50V	Ceramic capacitor	GRM1555C1H102JA01D	Murata
41	1	C10		3300pF,50V	Ceramic capacitor	GCM155R71H332KA37J	Murata
42	3	C11,C26,C27	C31	0.01uF,50V	Ceramic capacitor	GCM155R71H103KA55D	Murata
43	18	C5,C12,C13,C14,C15,C16 C17,C24,C29,C33,C36,C37 C39,C40,C41,C42,C43,C45	C46	0.1uF,50V	Ceramic capacitor	CGA2B3X7R1H104K050BB	TDK
44	1	C3		0.1uF,100V	Ceramic capacitor	C2012JB2A104K125AA	TDK
45	1	C6		1uF,50V	Ceramic capacitor	GRT188R61H105KE13D	Murata
46	3	C2,C34,C38		10uF,50V	Ceramic capacitor	GCM32EC71H106KA03K	Murata
47	2	C18,C19		10uF,50V	Electrolytic capacitor	PCX1H100MCL1GS	Nichicon
48	1	C20		22uF,50V	Electrolytic capacitor	PCX1H220MCL6GS	Nichicon
49	1	C4		470uF,50V	Electrolytic capacitor	UHD1H471MHD	Nichicon
50	1	C1		2200uF,63V	Electrolytic capacitor	LLS1J222MELA	Nichicon
51	2	C21,C22		2.2uF,63V	Film capacitor	B32529D0225J	TDK
52	1	C23		1uF,63V	Film capacitor	B32529C0105J	TDK
53	1	L4		1uH,455mA	Coil	NLFV25T-1R0M-EF	TDK
54	1	L1		22uH,2.2A	Coil	NRS8040T220MJGJ	TAIYO YUDEN
55	2	L2,L3		100uH,10A	Coil	AIRD-02-101K	Abracon
56	11	D2,D3,D4,D5,D6,D7 D8,D9,D10,D11,D12		30V,500mA	Diode	RB551VM-30	Rohm
57	1	D1		100V,2A	Diode	B2100-13-F	Diodes
58	1	D13		ESD protection	Diode	RCLAMP0502BA	Semtech
59	1	J1		HEADER 2X2	Pin header	M20-9980245	Harwin
60	1	J2		HEADER 6X2	Pin header	M20-9980645	Harwin
61	2	J3,J4		HEADER 5X2	Pin header	M20-9980545	Harwin
62	3	JP3,JP4,JP6	JP1,JP2,JP5	HEADER 2	Pin header	M20-9990245	Harwin
63	3	JP7,JP8,JP9		HEADER 3X2	Pin header	M20-9980345	Harwin
64	1	SW1		1 pole,2 positions	Slide switch	CL-SB-12A-11	NIDEC COPAL
65	4	TH1,TH2,TH3,TH4		M3,12mm	Through hole tap	TH-1.6-12-M3	MAC8
66	0		CN7	NotMount (HEADER 4,SMD,right angle)	Pin header	M20-8890445	Harwin
67	0		R1,R42,R51,R62,R66	NotMounted 1608	Resistor	-	
68	0		R57,R58	NotMounted 1005	Resistor	-	
69	0		C44	NotMounted 4.7uF,50V	Ceramic capacitor	GRM21BC71H475KE11L	Murata
70	0		L5	NotMounted EMI filter	Ferrite bead	MI0805K400R-10	Laird
M1	2			Brass, both-sides female spacer	Spacer	ASB-315E	Hirosugi
M2	2			Brass, M3 6mm	Screw	B-0306-S1	Hirosugi
M3	4			Brass, male-female spacer	Spacer	BSB-315E	Hirosugi
M4	1			4 position, 2.54mm pitch consolidated	Jumper socket	JS-42060-02	Hirosugi

Appendix 2 Circuit Diagrams of the Power Board

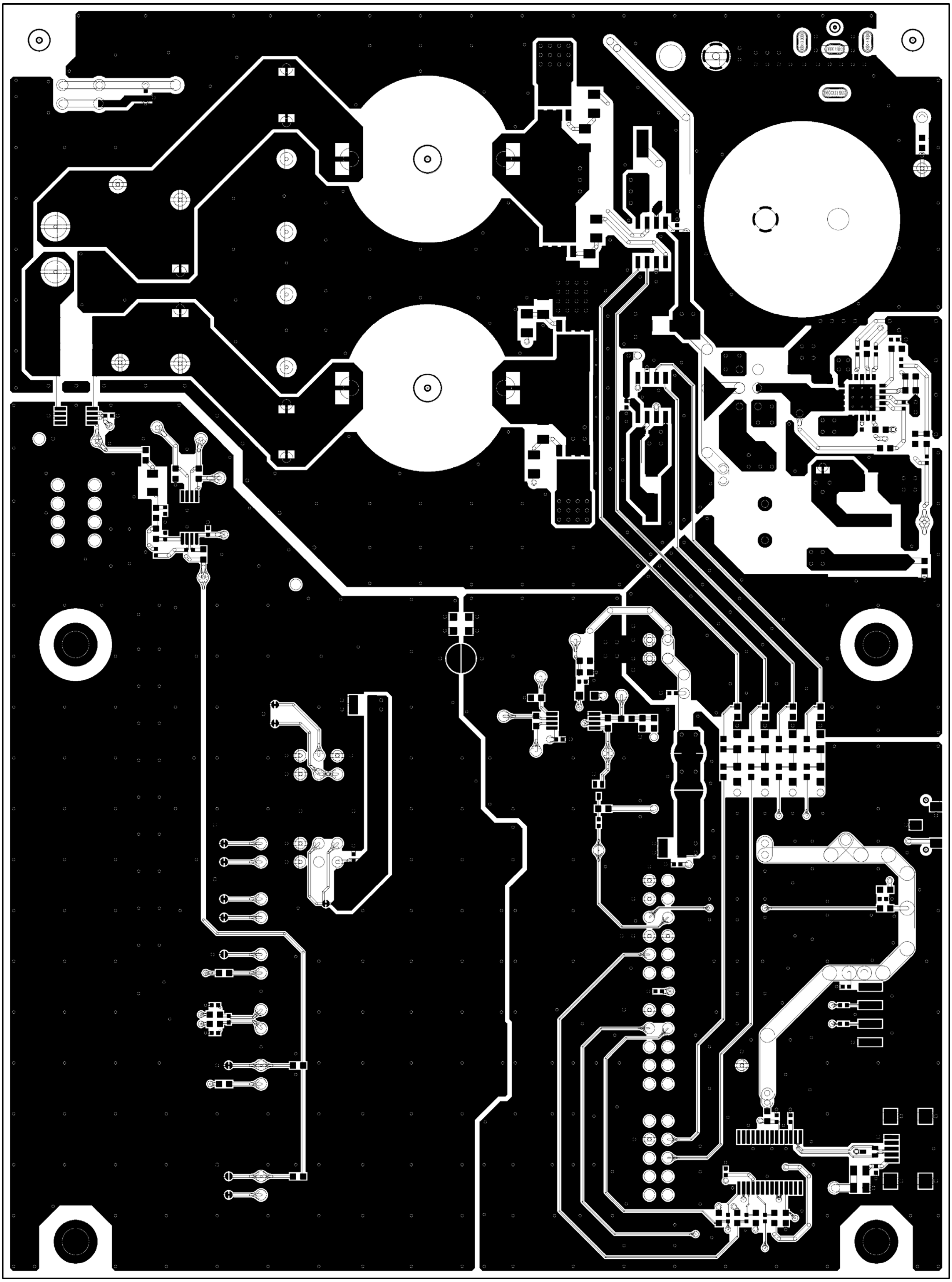



RX23E-A RSSK interface
Analog Power
(From RSSK)
Analog Ground
Digital Ground
Digital Ground
Power Ground
RSSK Vd
(To RSSK)
Digital Power
(From RSSK)
VDRV detect :
VDRV - OPAMPin - OPAMPout - V_DET
12.0V 4.0V L H
9.9V 3.3V H->L L->H
9.3V 3.1V L->H H->L
8.1V 2.7V H L
SW1
(To RSSK)
POE1#
(To RSSK)
CTS5#
(To RSSK)
Temperature Feedback
(To RSSK)
TXD5
(From RSSK)
RXD5
(To RSSK)
PWM
(From RSSK)
PWM
(From RSSK)
Current Feedback
(To RSSK)
PWM-AH : MTIOC4A
PWM-BH : MTIOC4B
PWM-AL : MTIOC4C
PWM-BL : MTIOC4D
FTDI
USBDP/USBDM (USB data) :
Differential , Z = 90 ohm ±15%
USB
Function
3Wire-RTD (4Wire-RTD)
AIN5 REF+ (REF+)
AIN6 IN-, IEXC1 (IN-)
AIN7 IN+, IEXC0 (IN+)
AIN9 NC (IEXC0)
Temperature Feedback
(To RSSK)
1: VCC
2: RXIN
3: TXOUT
4: VSS
UART
Right angle, SMD
Slide switch
Contact PB0
1-2 L
2-3 H
Renesas Electronics Corp.
Thermoelectric Controller Board
Size: A4
Date: Oct. 29, 2020
Revision:1.0
Sheet 2 of 2
Drawn by ICTD

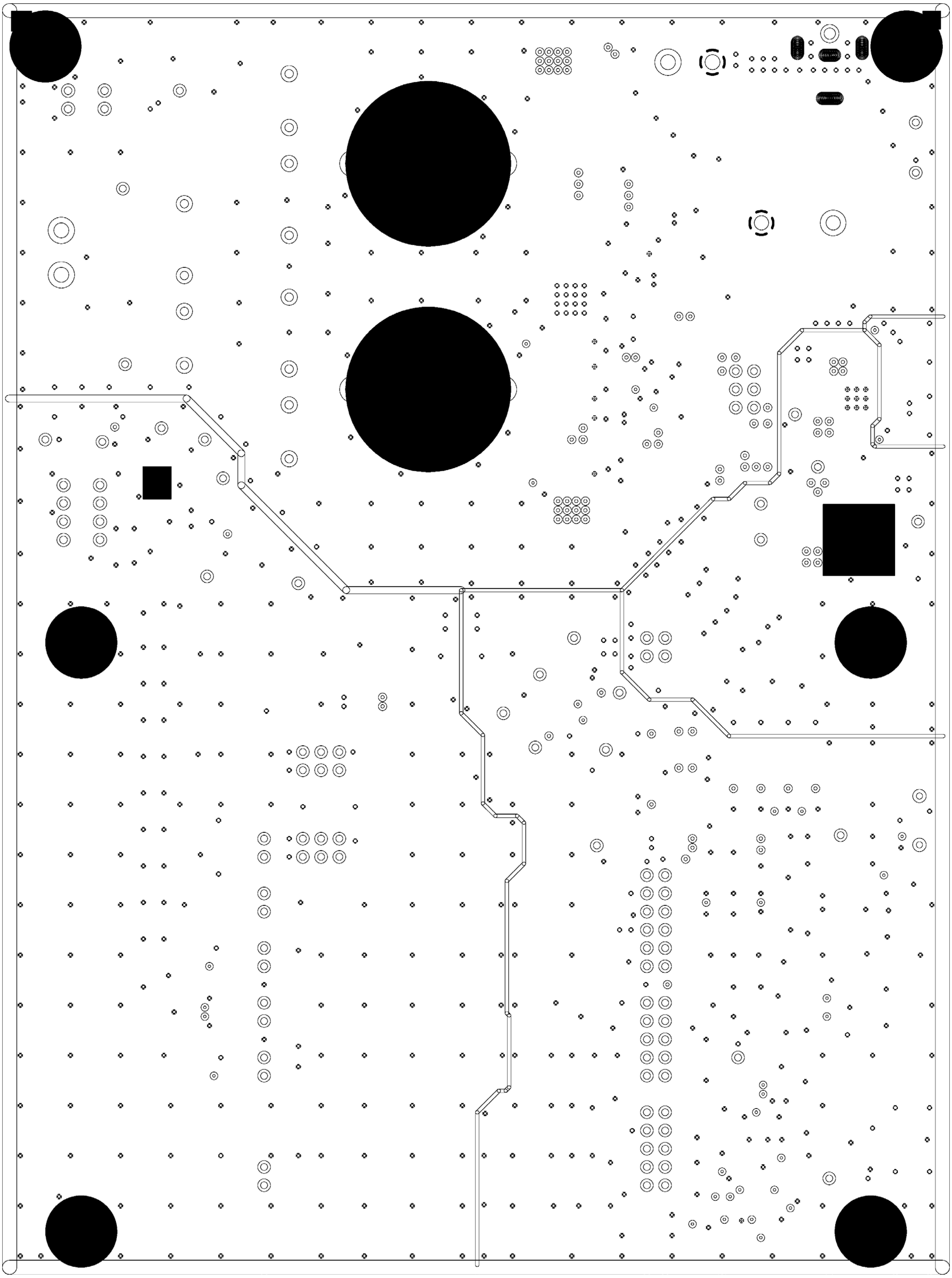
Appendix 3 Board Diagrams of the Power Board



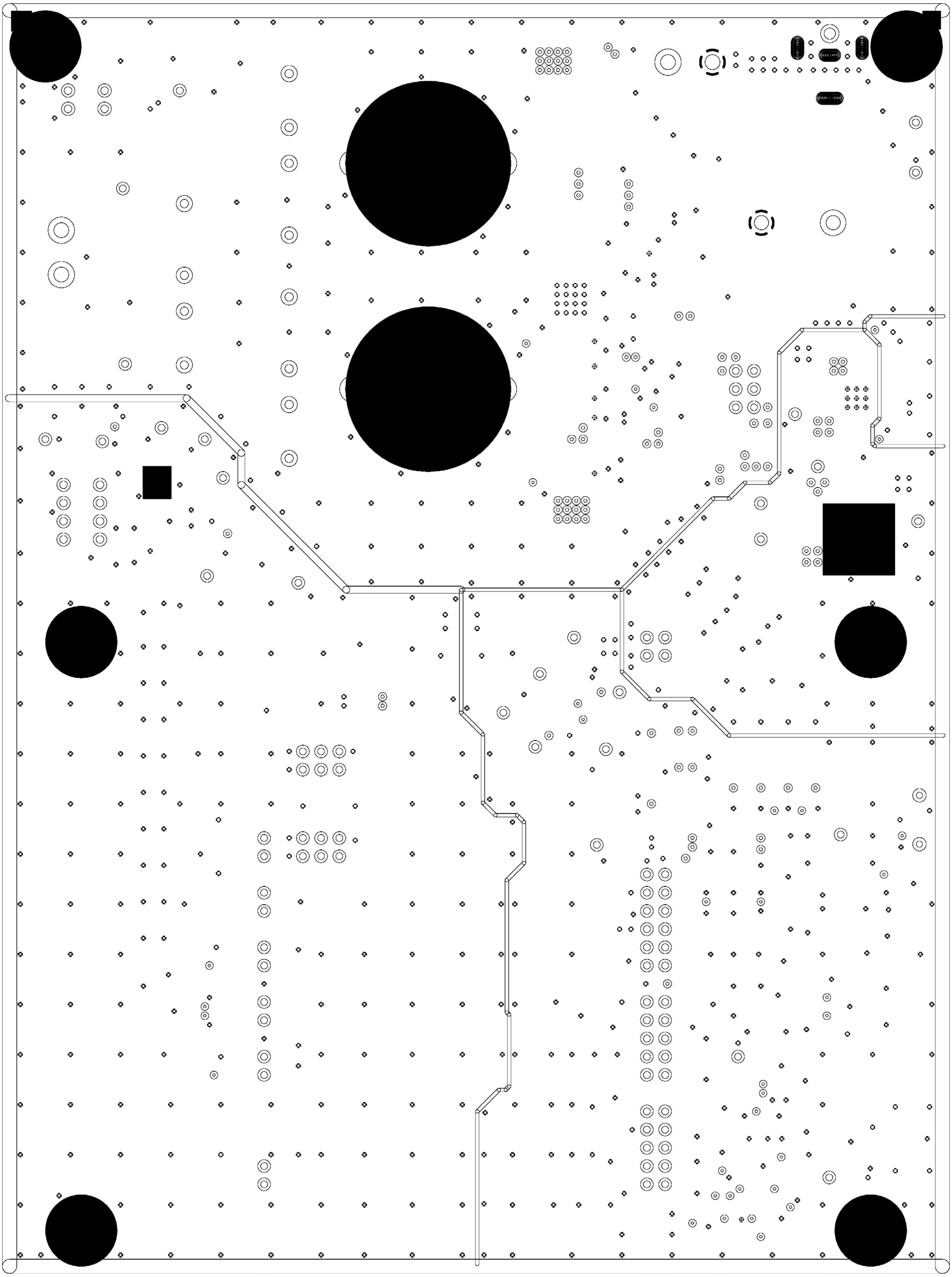
Silkscreen on the Component (Top) Side



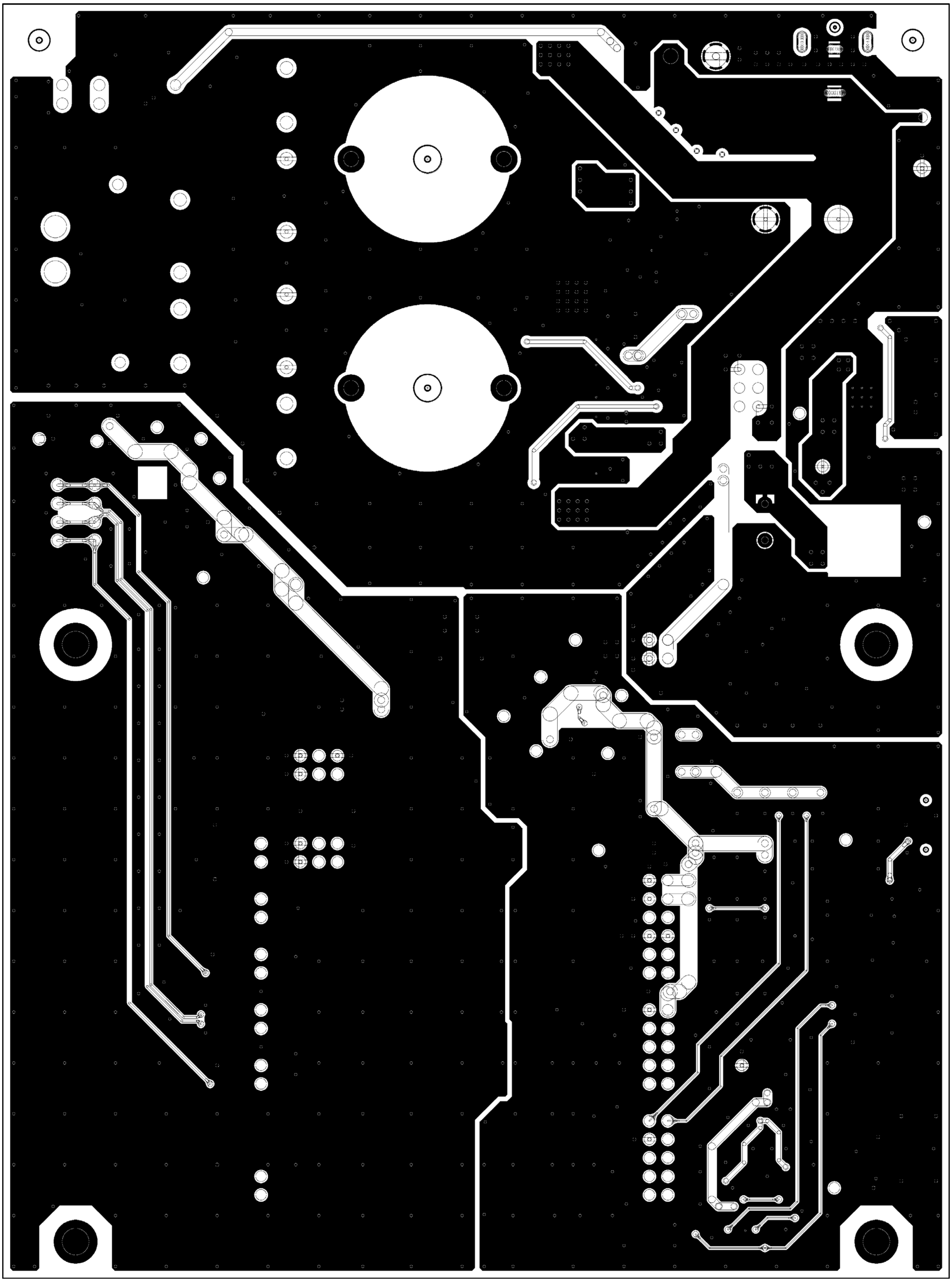
Layer 1: Top Side Layer



Layer 2: Ground Plane



Layer 3: Ground Plane



Layer 4: Bottom Side Layer (Viewed from the Component Side)

Revision History

Rev.	Date	Description	
		Page	Summary
1.00	Dec.25.20	-	-

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.

Corporate Headquarters

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Contact information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
www.renesas.com/contact/.