Air Conditioner Outdoor Unit Circuit

Design guide

RD219-DGUIDE-01

Toshiba Electronic Devices & Storage Corporation

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1. Introduction

This Design Guide (hereinafter referred to as this guide) describes the specifications and operation procedures of the Air Conditioner Outdoor Unit Circuit (hereinafter referred to as this design).

Recently, low power consumption has been required for outdoor air conditioner units. And brushless motors driven by inverters using high efficiency switching devices have become common for compressors and fans. In addition, sensorless vector control is being increasingly used for motor control, as equipment is required to have low cost, high efficiency, and low motor noise. In addition, the demand for smaller circuit boards in equipment is also increasing.

This design uses a low on-resistance power MOSFET TK20A60W5 for the compressor drive inverter to achieve a highly efficient compressor drive. In addition, a highly efficient and compact fan motor drive is achieved by using an intelligent power device TPD4204F with a built-in gate driver and inverter circuit for the fan motor drive. PFC inductors are also downsized by using IGBT device GT30J65MRB that has low switching losses and can operate at high switching frequencies in a switching PFC power supply circuit. Furthermore, by using the microcontroller TMPM4KLFYAUG equipped with a vector engine, sensorless vector control of the fan motor and the compressor as well as PFC power supply control are realized with a single microcontroller, which simplifies and reduces the size of the outdoor unit circuit.

In addition, a transistor array TBD62003AFG is used as a valve control driver, a photocoupler TLP785 is used as an insulating interface for communication between outdoor units and indoor units, a SiC Schottky barrier diode TRS24N65FB is used as a PFC diode, a TC75W59FU is used as an operational amplifier for signal amplification, and a TA75S393F is used as a comparator for detecting abnormalities.

2. Main Components Used

2.1. Microcontroller TMPM4KLFYAUG

This design uses a microcontroller TMPM4KLFYAUG of TXZ+™4A series for PFC and motor control. The main features of TMPM4KLFYAUG are as follows.

- Arm® Cortex®-M4 (with FPU)
- Operating frequency: 1 to 160 MHz, Operating voltage: 2.7 to 5.5 V
- 256 KB code flash, 32 KB data flash
- LQFP64 package
- Hardware IPs (A-VE+, 12 bit ADC, A-PMD) are provided for implementation of vector control and PFC control

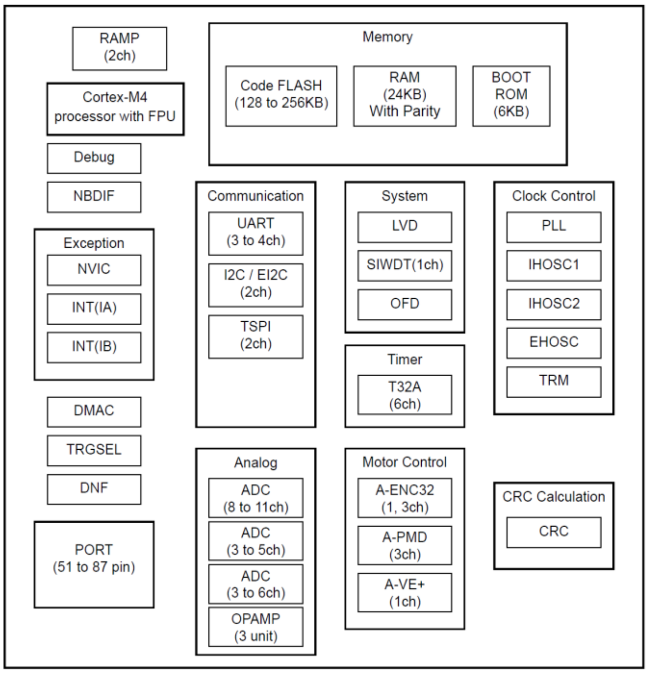


Fig. 2.1 TMPM4KLFYAUG Internal Block Diagram

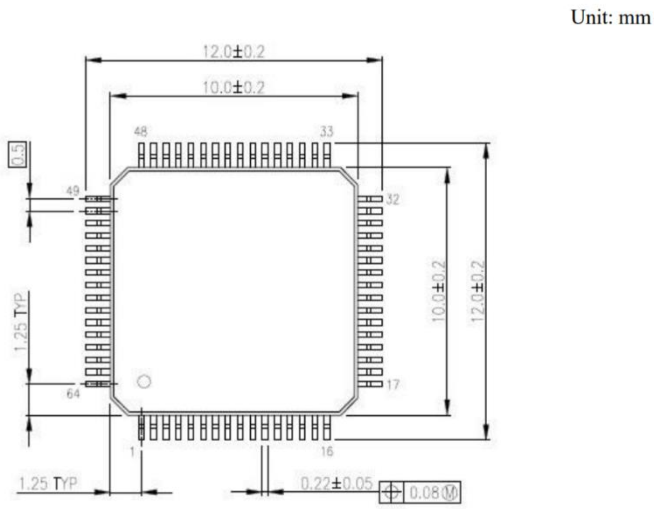


Fig. 2.2 TMPM4KLFYAUG Package
(LQFP64, 10 mm x 10 mm, 0.5 mm pitch)

2.2. Intelligent Power Device TPD4204F

This design uses an intelligent power device TPD4204F to drive fan motors. TPD4204F is a high voltage 3-phase brushless motor driver with a built-in powered MOSFET rated 600 V and supports 3 shunt resistor current sensing. The built-in level-shift high-side driver, low-side driver, overheat protection circuit, undervoltage protection circuit, overcurrent protection, shutdown (SD) function, and output signal MOSFET enable a 3-phase brushless motor to be driven directly by the control signal input from the microcontroller. The main features of TPD4204F are as follows.

- Power supply voltage V_{BB} 600 V (Max.)
- Output current I_{out} 2.5 A (Max.)
- SSOP30 package

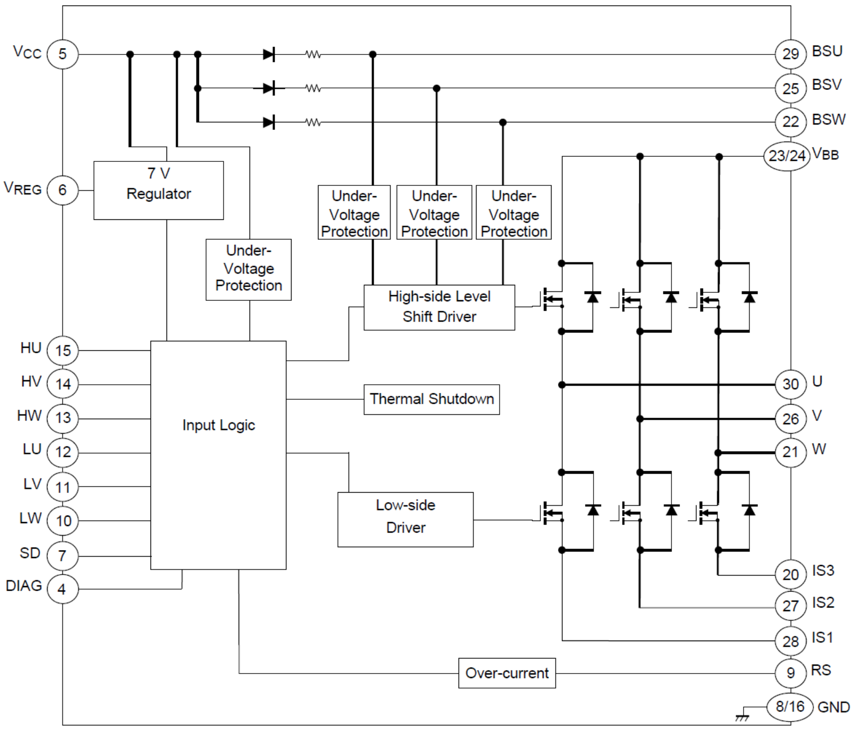


Fig. 2.3 TPD4204F Internal Block Diagram

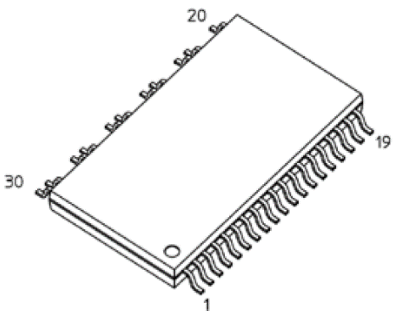


Fig. 2.4 TPD4204F Package (SSOP30)

2.3. IGBT GT30J65MRB

This design uses an IGBT GT30J65MRB as a switching element in PFC circuit. The main features of GT30J65MRB are as follows.

- Built-in FWD (Free wheeling Diode) in RC configuration
- Enhancement mode
- High-speed switching: t_f = 40 ns (Typ.) (I_C = 15 A, R_G = 56 Ω)
- Low saturation voltage: $V_{CE(sat)}$ = 1.40 V (Typ.) (I_C = 30 A)
- High junction temperature: T_j = 175 °C (Max.)

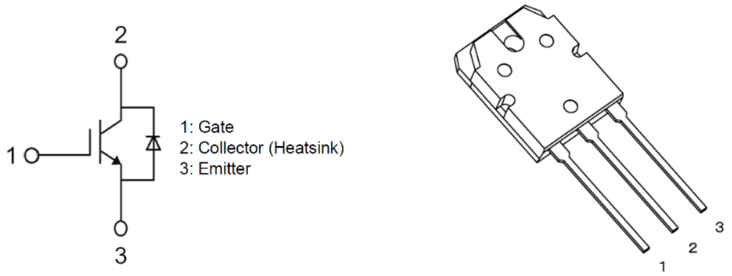


Fig. 2.5 GT30J65MRB Internal Circuit Configuration and Package (TO-3P(N))

2.4. Power MOSFET TK20A60W5

This design uses power MOSFETs TK20A60W5 as switching elements in the inverter circuit for driving a compressor. The main features of TK20A60W5 are as follows.

- Fast reverse recovery time: t_{rr} = 110 ns (Typ.)
- Low on-resistance due to the use of a super junction structure DTMOS: $R_{DS(ON)}$ = 0.15 Ω (Typ.)
- Easy to control gate switching
- Enhancement mode: V_{th} = 3 to 4.5 V (V_{DS} = 10 V, I_D = 1 mA)

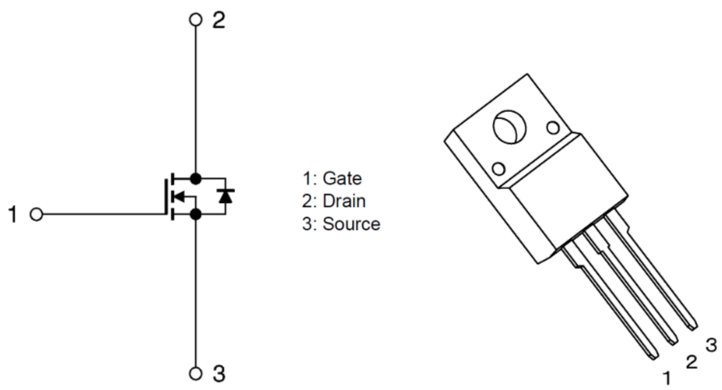
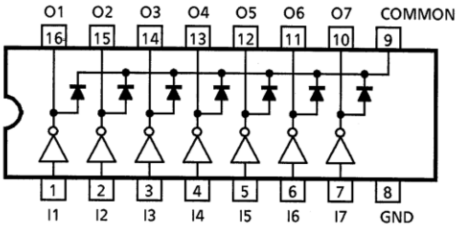


Fig. 2.6 TK20A60W5 Internal Circuit Configuration and Package (TO-220SIS)

2.5. Transistor Array TBD62003AFG

This design uses TBD62003AFG for air conditioner valve control. TBD62003AFG is a seven-circuit DMOS transistor array with a built-in output clamp diode that clamps the back EMF generated when driving inductive loads. The main features of TBD62003AFG are as follows.

- 7 built-in circuits
- High voltage: V_{OUT} = 50 V (Max.)
- High output current: I_{OUT} = 500 mA/ch (Max.)
- Input voltage (output on): 2.5 V (Min.)
- Input voltage (output off): 0.6 V (Max.)



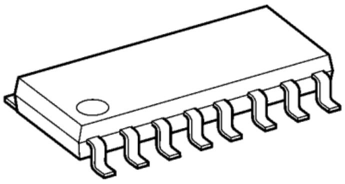
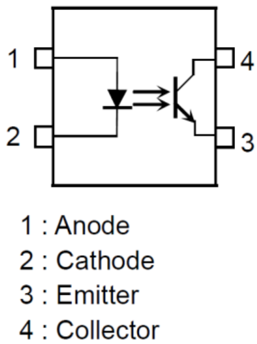


Fig. 2.7 TBD62003AFG Circuit Configuration and Package (SOP16-P-225-1.27)

2.6. Optical Photocoupler TLP785

This design uses TLP785 for communication with indoor unit of the air conditioner. TLP785 is a high dielectric strength photocoupler that combines an infrared light emitting diode and a silicon phototransistor. The main features of TLP785 are as follows.

- Collector emitter voltage: 80 V (Min.)
- Current transfer ratio: 50% (Min.) Rank GB: 100% (Min.)
- Isolation voltage: 5000 Vrms (Min.)
- UL recognized: UL 1577, File No.E67349
- cUL recognized: CSA Component Acceptance Service No.5A File No.E67349
- VDE approved: EN 60747-5-5
- CQC approved: GB4943.1, GB8898 China Factory
- SEMKO approved: EN 62368-1



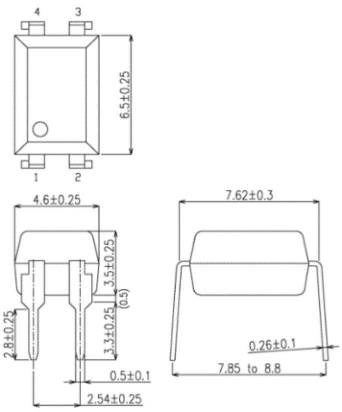


Fig. 2.8 TLP785 Circuit Configuration and Package (DIP4(TLP785))

3. Operation

3.1. Operation of the Air Conditioner

Fig. 3.1 and 3.2 show the operation of the air conditioner. The air conditioner uses the compression, condensation, expansion (decompression), and evaporation to absorb or release heat. These process are used to exchange the heat between the indoor unit and the outdoor unit to perform air conditioning.

The compressor compresses the refrigerant circulating between the outdoor unit and the heat exchanger of the indoor unit. The refrigerant becomes a high temperature and high pressure when compressed, and a low temperature and low pressure when expanded. When the high-temperature and high-pressure refrigerant compressed by the compressor is supplied to the heat exchanger of the outdoor unit, the indoor unit does cooling, and when it is supplied to the heat exchanger of the indoor unit, the indoor unit does heating. A fan is required to efficiently exchange heat from the heat exchanger with the surrounding atmosphere.

The compressors and fans are operated by motor drive, and motor drive using inverter has become common to increase energy efficiency. A PFC that efficiently converts incoming power into DC power and an inverter that efficiently drives 3-phase motors from DC power are critical functions in reducing power consumption in air conditioners.

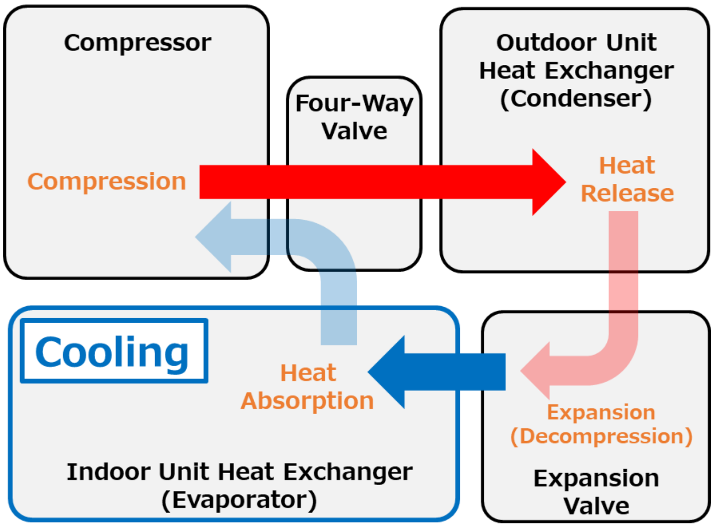


Fig. 3.1 Air Conditioner Operation When Cooling

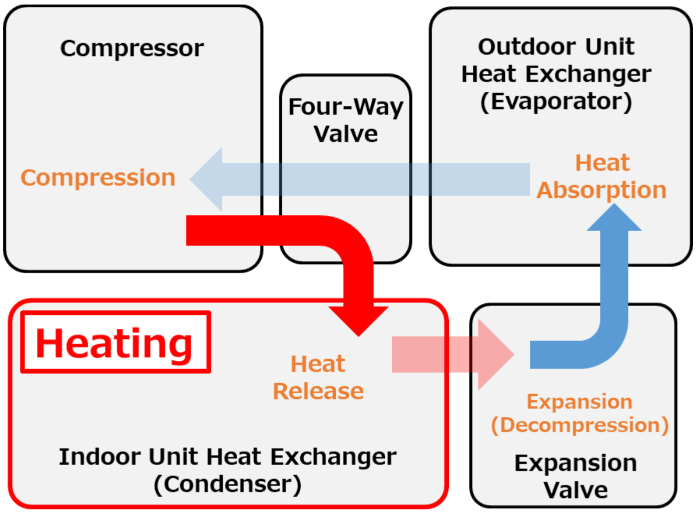


Fig. 3.2 Air Conditioner Operation When Heating

3.2. PFC (Power Factor Correction)

3.2.1. PFC Operation

Fig. 3.3 shows the relation between the input voltage, the output voltage, and the input current of the full-wave rectifier AC-DC circuit. (Although the actual input current is repeated with positive and negative currents, the change in absolute value is shown here.) In this circuit, AC input voltage is rectified by the rectifying element (diode bridge) and then smoothed by the capacitor C. The input current I_{in} flows only when AC input voltage is higher than the charge voltage of the capacitor C, and the input current deviates significantly from the sine wave, including many harmonic components, and the power factor (PF) drops significantly. PFC is required to bring this input current waveform closer to a sine wave, and improve the power factor.

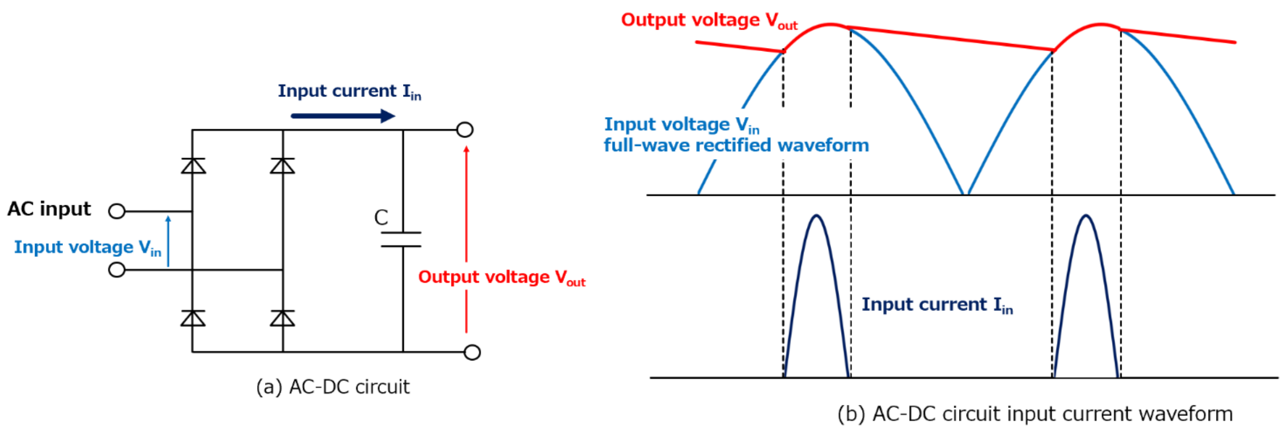


Fig. 3.3 Operation of Full-Wave Rectifier AC-DC Circuit

Fig. 3.4 shows the single phase PFC circuit and its operation. In recent years, single phase PFC circuit has been mainstream as a PFC circuit used in the air conditioner outdoor units. As shown in the diagram, when AC input is positive, (a) the energy is stored in inductor L when the IGBT is on, and (b) the energy stored in the inductor L is released when the IGBT is off and these two processes keep repeating. When AC input is negative, (c) the energy is stored in the inductor L when the IGBT is on, and (d) the energy stored in the inductor L is released when the IGBT is off and these two processes keep repeating.

By controlling the on/off of IGBT in this way, the input current is made closer to the sine wave, and the power factor is improved. The in-circuit C_{in} is a capacitor that reduces the high-frequency ripple current flowing through the inductor and the switching noise generated by switching IGBT, and C_{out} is a capacitor that smoothes the output voltage. The larger the capacitance of C_{in}, the smaller EMI filter can be, but care must be taken because the power factor will decrease because current distortion will occur.

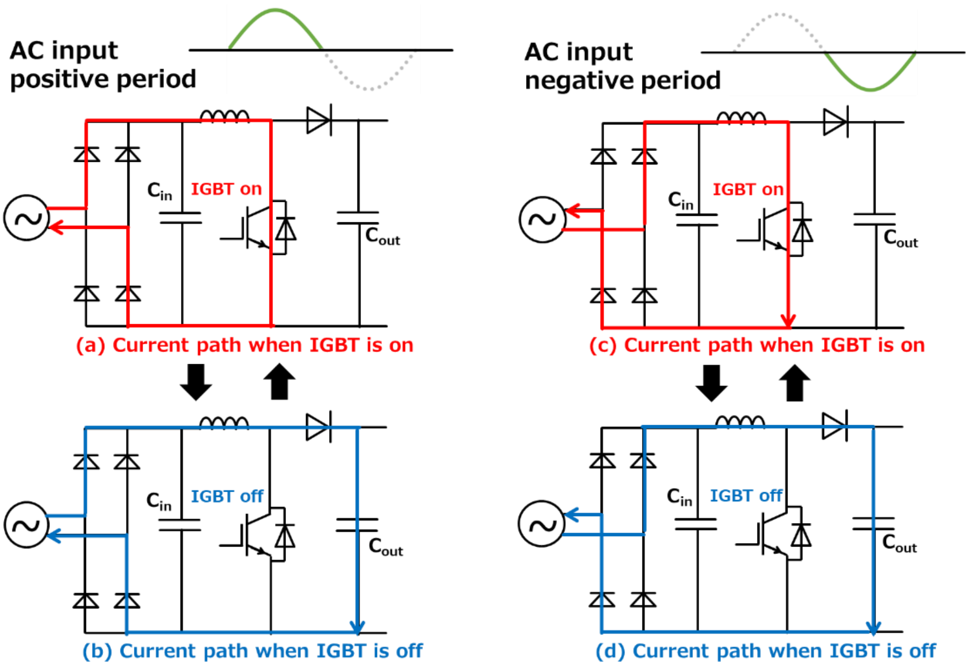


Fig. 3.4 Single Phase PFC Circuit Operation

3.2.2. PFC Conduction Mode

There are three conduction modes for the current control of a PFC inductor. The sample program in this design uses Continuous Conduction Mode (CCM). Table 3.1 compares the features of each PFC conduction mode, and Fig. 3.5 shows the example of inductor current waveforms in each PFC conduction mode.

Table 3.1 Feature Comparison of PFC Conduction Modes

Conduction Mode	Operation	Application Examples	Features
Continuous Conduction Mode (CCM)	Switching operation where PFC inductor current continues to flow	High power PFC Industrial power supply	･Low current ripple ･Small current peak ･Long reverse recovery t_{rr} of PFC diodes can lead to inefficiency and noise related problems.
Critical Conduction Mode (CRM)	Operation in which the IGBT turns on when the PFC inductor current becomes 0 A	Low wattage power supply Consumer power supply (LCD TV､PC)	･High current ripple ･Large current peak ･Low switching loss due to zero current switching
Discontinuous Conduction Mode (DCM)	Discontinuous switching operation in which the PFC inductor current becomes 0 A for some time.	Low wattage power supply (LED Lighting)	･High current ripple ･Large current peak ･Low switching loss due to zero current switching ･Valley oscillations must be considered

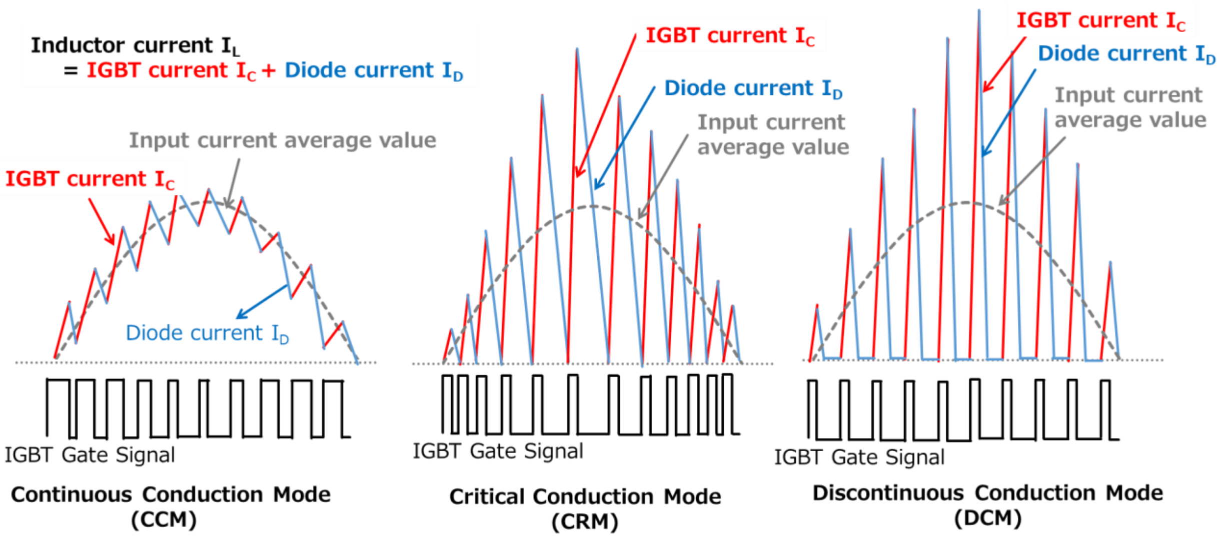


Fig. 3.5 Example of Inductor Current Waveforms in Each PFC Conduction Mode

CCM used in this design is the continous conduction mode, which is typical for high power PFC above 200 W. After IGBT is switched off, the IGBT is switched on before to the current flowing through PFC inductor becomes 0 A, therefore current keeps flowing continuously through the PFC inductor. The inductor current is software controlled in order to make the inductor current similar to a sine wave. This is done by PWM control method that changes the duty ratio of the on duration while the switching frequency remains fixed.

Fig. 3.6 shows an example of current in reverse recovery operation in CCM. While the current ripple can be designed to be smaller than the other two conduction modes (CRM, DCM), since the current flows through the PFC diode when the IGBT turns on, the reverse recovery current of this diode is superimposed on PFC inductor current, thus increasing the switching loss when the IGBT is turned on. High-speed diodes with short reverse recovery times are required to realize low-loss PFC and increase efficiency, and therefore SiC SBD can be used when high efficiency is required.

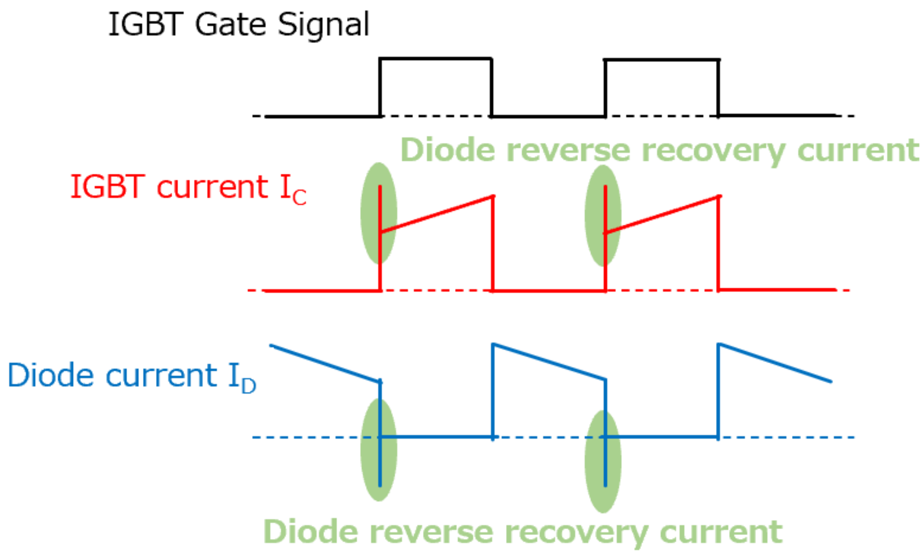


Fig. 3.6 Example of Current in Reverse Recovery Operation in Continuous Conduction Mode (CCM)

3.3. 3-Phase Inverter

3.3.1. 3-Phase Inverter Operation

Fig. 3.7 shows a 3-phase inverter circuit. 3-phase inverters convert direct current into 3-phase alternating current, and are used to drive many motors, such as air-conditioner compressors and electric vehicles. 3-phase inverters produce 3-phase alternating current from direct current, enabling control of output voltage and output frequency. The commutation method used to drive the motor with a 3-phase inverter includes square-wave drive (120° commutation) and sine-wave drive (180° commutation). The square-wave drive switches only 120° out of the half-wave 180° interval in the electrical angle, so the switching loss becomes smaller than the sine-wave drive, but the output current becomes a square-wave and the motor efficiency becomes lower than the sine-wave drive. The sine wave drive uses a sine wave commutation, which results in smooth rotation and low noise.

Fig. 3.8 shows the example of phase voltage waveforms in a 3-phase inverter. Sine-wave drive (180° commutation) converts the DC voltage to 3-phase AC voltage output with phase difference of 120° by PWM control of the upper and lower arm elements of each phase. This 3-phase alternating current drives brushless motors such as fan motors and compressor in the outdoor unit.

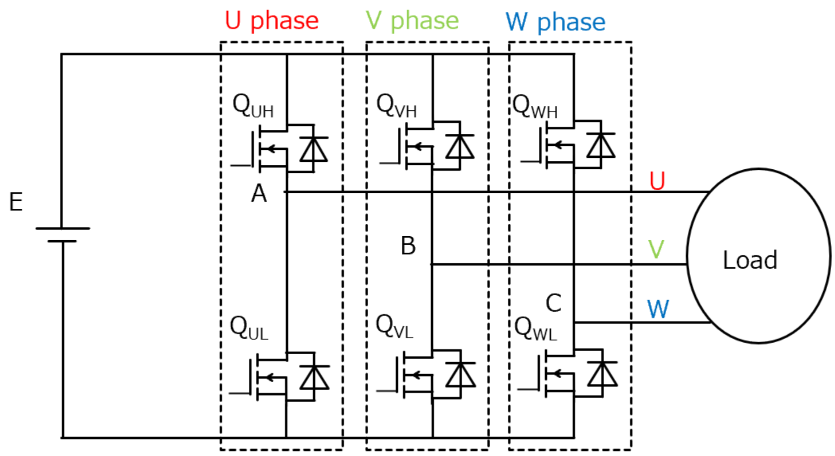


Fig. 3.7 3-Phase Inverter Circuit

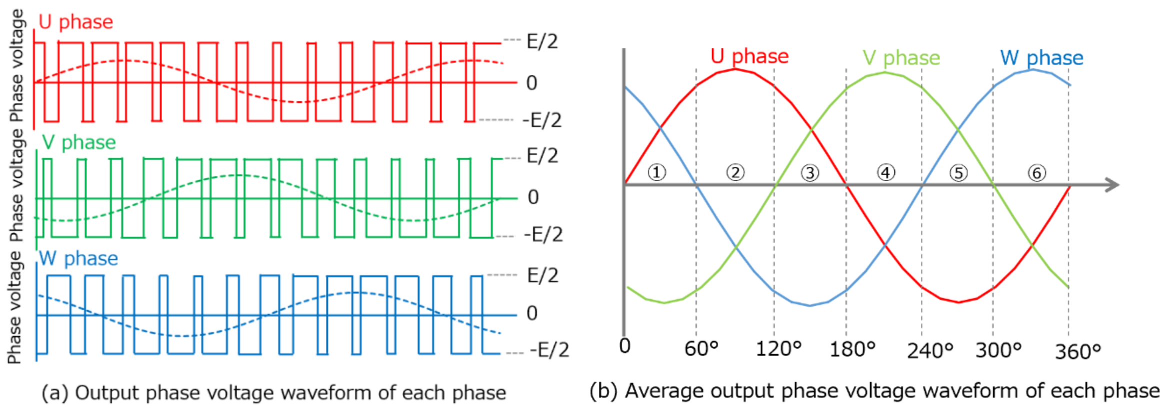


Fig. 3.8 Example of Phase Voltage Waveforms in a 3-phase Inverter

In sinusoidal drive, PWM (Pulse Width Modulation) control is used to switch the MOSFETs of the upper and lower arms of each phase in a complementarily manner. PWM control is the method of controlling by changing the duty of the pulse-width of the input signal while keeping the time period constant. The voltage and frequency of the output can be controlled by changing the duty of the pulse width. When the duty of the pulse width of the switching element is large, the output voltage and output current become large.

Fig. 3.9 shows the example of sine wave PWM signal generation. The voltage of the sinusoidal signal wave shown by the red line is compared with the voltage of the triangular carrier signal. When the sinusoidal signal voltage is higher than the carrier signal voltage, PWM control signal output becomes 1 and the inverter switch element is turned on. Otherwise, PWM control signal output becomes 0 and the inverter switch element is turned off. PWM control signal of the switching element of the lower arm uses a signal obtained by inverting PWM control signal of the switching element of the upper arm.

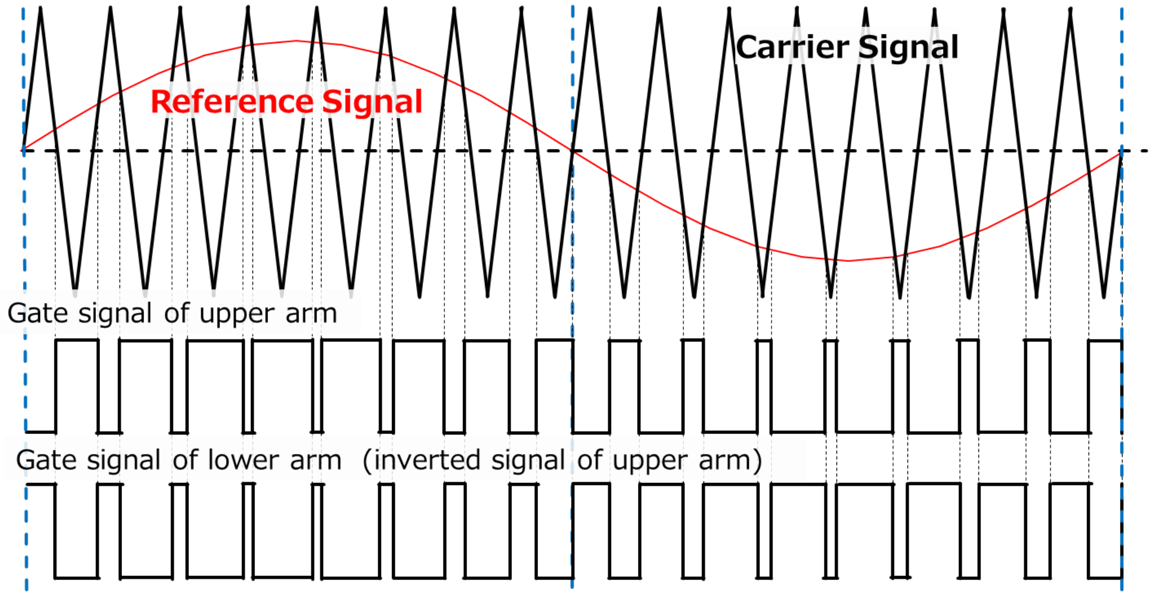


Fig. 3.9 Example of Sine Wave PWM Signal Generation

3.3.2. Sensorless Vector Control

Fig. 3.10 shows the example of the sensorless vector control block diagram. Vector control, which can efficiently process motor rotation control from low speed to high speed, has become widely used in motor control in recent years. Motor rotation angle detection is required for vector control. Previously, rotation angle Hall sensors and encoders were used, however in this design a technique to estimate the rotation angle by detecting the motor current is used and thus eleminating the requirement of these external elements.

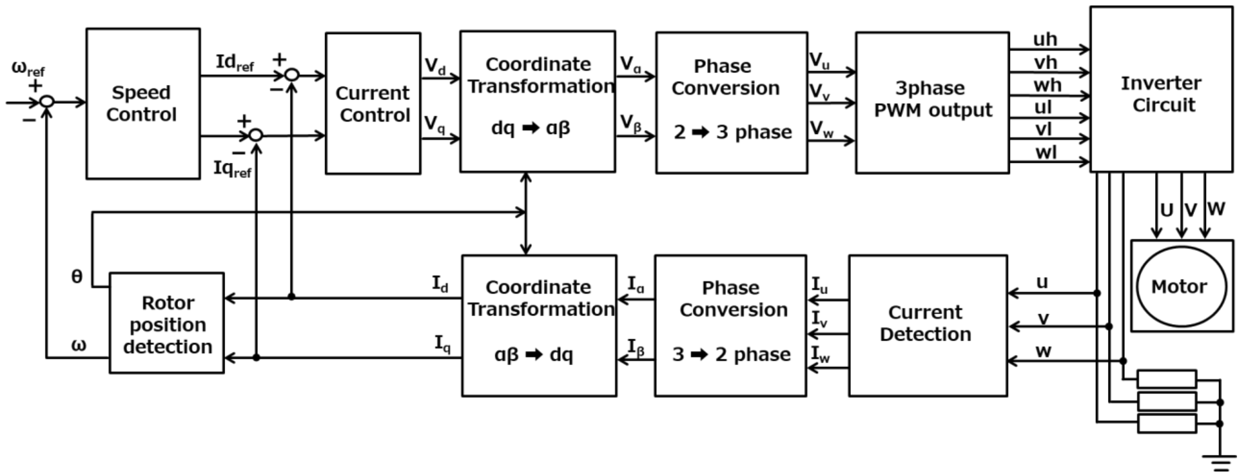


Fig. 3.10 Example of Sensorless Vector Control Block Diagram

This design uses sensorless vector control for fan motor drive and compressor drive. Note that the 1 shunt method, which is the easiest to configure, is used as the motor current detection method.

4. Circuit Design

4.1. Overall Block Diagram

Fig. 4.1 shows the block diagram of this design. The main functions of the air conditioner outdoor unit are power supply PFC switching control, sensorless vector control of the compressor, and sensorless vector control of the fan motor. And these are handled by a single microcontroller (MCU).

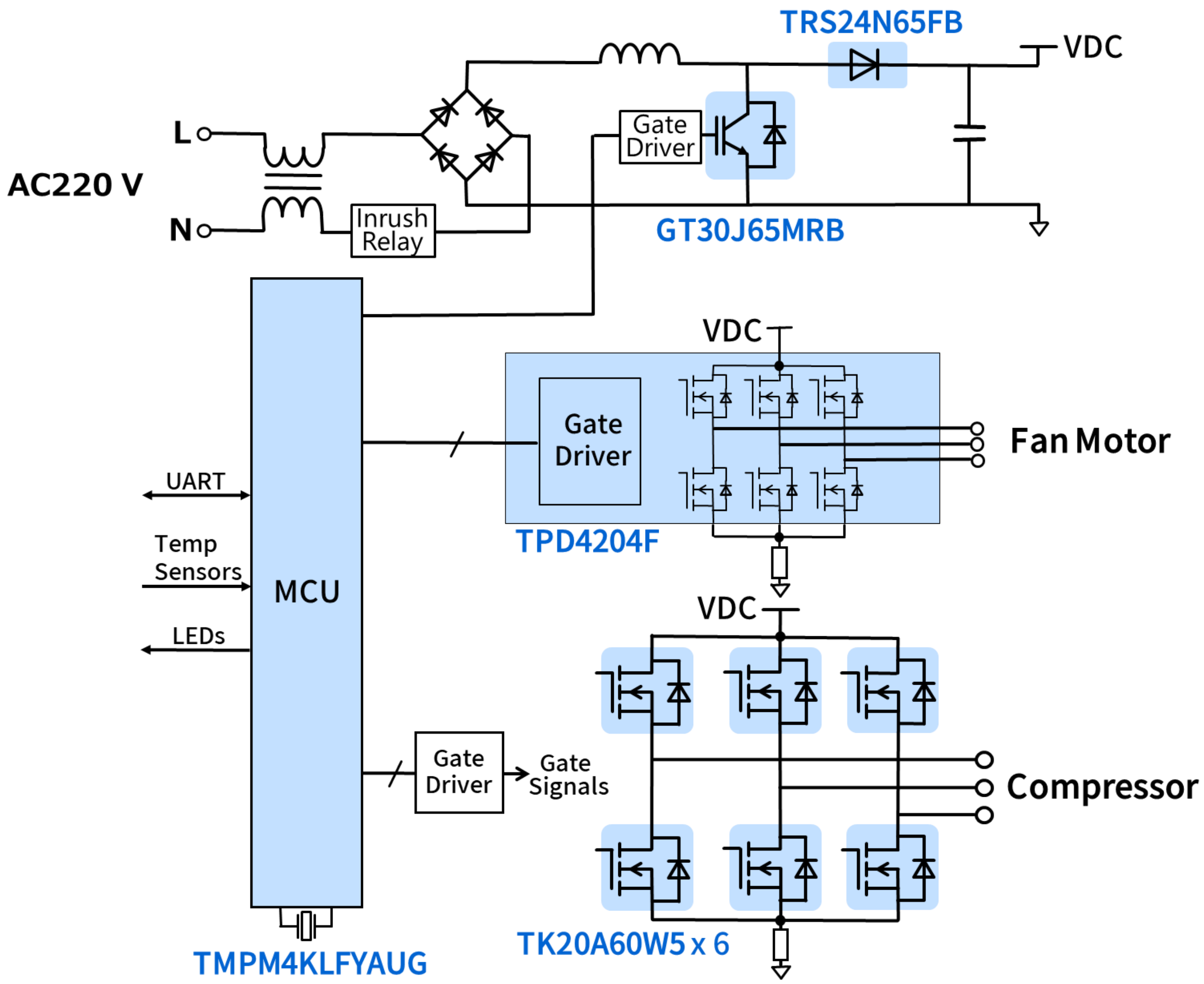


Fig. 4.1 Block diagram of Air Conditioner Outdoor Unit Circuit

4.2. MCU Peripheral Circuit

Fig. 4.2 shows MCU peripheral circuit. TMPM4KLFYAUG of TXZ+™4A series used as a MCU in this design has a built-in Arm Cortex-M4 (with FPU function) as a processor core and can operate at maximum frequency of 160 MHz.

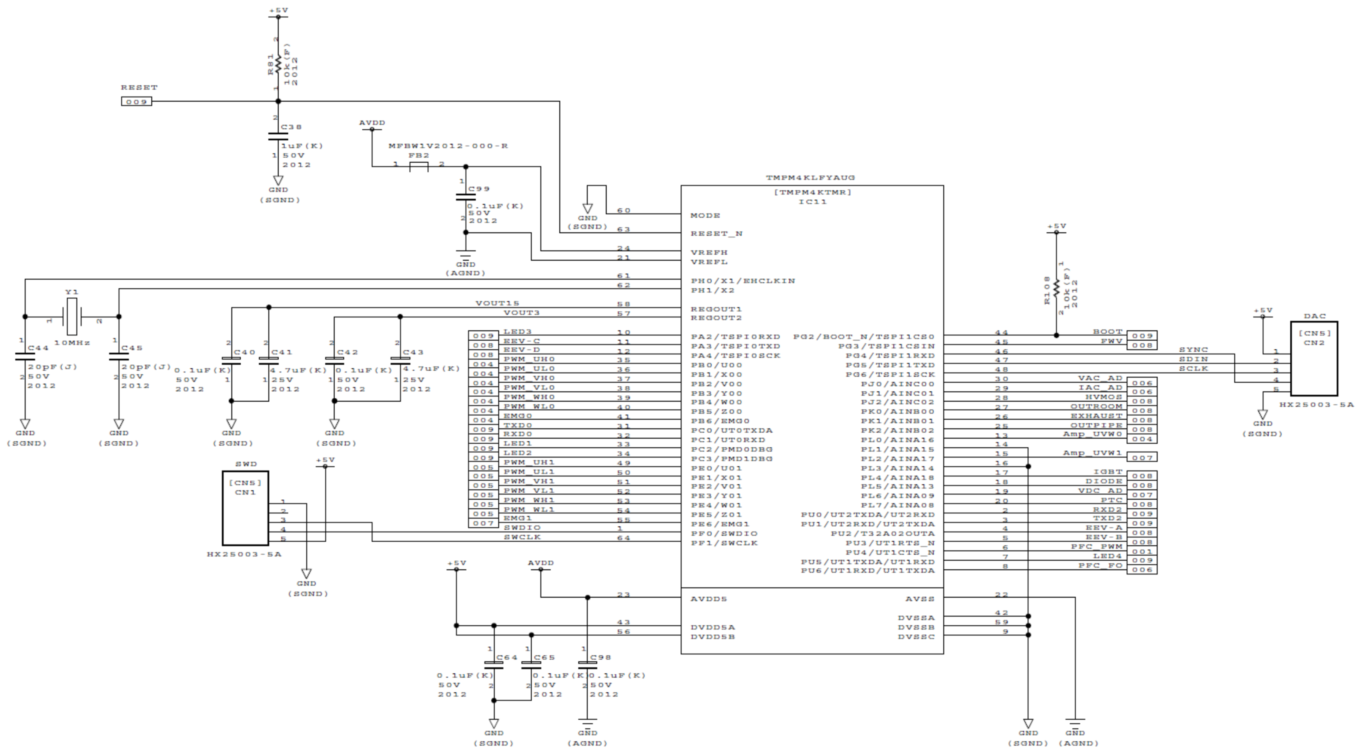


Fig. 4.2 MCU peripheral circuit

MCU can operate with a power supply of 2.7 V to 5.5 V, however in this design 5 V is provided for both the digital power pins (DVDD5A and DVDD5B) and the analog power pin (AVDD5). Bypass capacitors (C64, C65, C98) must be placed in the vicinity of each power supply pin. In addition, for stabilizing the power supply, ceramic capacitors of same capacitance must be placed in the vicinity of the capacitor connecting pins (REGOUT1, REGOUT2) for the built-in regulator. This design uses 4.7 µF (C41, C43) and 0.1 µF (C40, C42) ceramic capacitors. Connect a low-noise power supply to the analogue reference voltage pin (VREFH, VREFL) used in ADC. 5 V analogue supply (AVDD) provides the analogue reference via a ferrite bead (FB2) and a bypass capacitor (C90).

A 10 MHz crystal resonator (Y1) and 22 pF external capacitors (C45, C46) can be connected to the MCU on the circuit diagram of this design. However, in this design the sample software is configured to use MCU's built-in high-speed oscillator (IHOSC1), so MCU operates without using these components, and thus reducing component cost. Since IHOSC1 is a 10 MHz oscillator with an output frequency error of ±1 %, UART can be connected to an external device without any problems with the communication rate. 160 MHz of the system clock is generated by the internal PLL based on the clock output from IHOSC1.

Many of the pins in MCU are multiplexed, and the post startup software configuration determines the pin assignment. Table 4.1 shows the pin assignments in the sample software operation of this design. The pin functions used in this design are indicated in orange. The boot mode is set according to the level of BOOT_N pin (pin 44) when RESET_N pin (pin 63) becomes High. In this design in order to use single chip mode, this BOOT_N pin is pulled up by R108. MODE pin (pin 60) must be connected to the L level (GND) at all times.

Table 4.1 Pin-Function Assignments in MCU

Pin Number	Functions									Direction	Description
1	PF0	UT2TXDA	UT2RXD	T32A05INA0	T32A05INC0	SWDIO				In/Out	SWD-SWDIO
2	PU0	INT12	UT2TXDA	UT2RXD	I2C1SDA	T32A02INB1	UO2	E12C1SDA		In	UART-RXD2 (For indoor communication)
3	PU1	INT07a	UT2RXD	UT2TXDA	I2C1SCL	T32A02INA0	T3202INC0	XO2	EI2C1SCL	Out	UART-TXD2 (For indoor communication)
4	PU2	INT07b	T32A02OUTA	T32A02OUTC	VO2					Out	GPIO-EEV ch.A
5	PU3	INT08a	UT1RTS_N	T32A02INB0	ENC2A	YO2				Out	GPIO-EEV ch.B
6	PU4	INT08b	UT1CTS_N	T32A02OUTB	T32A02INC1	WO2				Out	PFC IGBT gate control
7	PU5	INT13	UT1TXDA	UT1RXD	T32A02INA1	ENC2B	ZO2			Out	GPIO-LED4
8	PU6	INT09	UT1RXD	UTITXDA	ENC2Z	EMG2				In	EMG2-PFC Over Current
9	DVSSC									-	Digital GND
10	PA2	INT00	TSPI0RXD	T32A00INA0	T32A00INC0	PMD2DBG	TRGIN0			Out	GPIO-LED3/PMD2DBG
11	PA3	INT01b	TSPI0TXD	T32A00OUTA	T32A00OUTC	TRGIN1				Out	GPIO-EEV ch.C
12	PA4	INT01a	TSPI0SCK	T3200OUTB	TRGIN2					Out	GPIO-EEV ch.D
13	PL0	AINA16								Analog In	Fan Motor Current Sense (OP-AMP+)
14	PL1	AINA15								Analog In	Fan Motor Current Sense (OP-AMP-)
15	PL2	AINA17								Analog In	Compressor Current Sense (OP-AMP+)
16	PL3	AINA14								Analog In	Compressor Current Sense (OP-AMP-)
17	PL4	AINA18								Analog In	Temparature Sense ch.3 (PFC IGBT)
18	PL5	AINA13								Analog In	Temparature Sense ch.4 (PFC Diode)
19	PL6	AINA09								Analog In	Bus Voltage Sense
20	PL7	AINA08								Out	GPIO-Inrush relay control
21	VREFL									-	Analog Reference GND
22	AVSS									-	Analog GND
23	AVDD5									-	Analog 5 V
24	VREFH									-	Analog Reference 5V
25	PK2	AINB02								Analog In	Temparature Sense ch.1 (Out Pipe)
26	PK1	AINB01								Analog In	Temparature Sense ch.0 (Exhaust)
27	PK0	AINB00								Analog In	Temparature Sense ch.2 (Out Room)
28	PJ2	AINC02								Analog In	Temparature Sense ch.5 (MOSFET)
29	PJ1	AINC01								Analog In	PFC Current Sense
30	PJ0	AINC00								Analog In	PFC Voltage Sense
31	PC0	UT0TXDA	UT0RXD	EI2C0SDA	I2C0SDA	T32A02INA0	T3202INC0			Out	UART-TXD0
32	PC1	INT02a	UT0RXD	UT0TXDA	EI2C0SCL	I2C0SCL	T3202OUTA	T3202OUTC		In	UART-RXD0
33	PC2	INT10	TSPI0CS0	T32A03OUTA	T32A03OUTC	PMD0DBG				Out	GPIO-LED1/PMD0DBG
34	PC3	INT03a	TSPI0RXD	T32A03OUTB	PMD1DBG					Out	GPIO-LED2/PMD1DBG
35	PB0	UO0								Out	FAN Motor-PWM U Phase High Side
36	PB1	XO0								Out	FAN Motor-PWM U Phase Low Side
37	PB2	VO0								Out	FAN Motor-PWM V Phase High Side
38	PB3	YO0								Out	FAN Motor-PWM V Phase Low Side
39	PB4	WO0								Out	FAN Motor-PWM W Phase High Side
40	PB5	ZO0								Out	FAN Motor-PWM W Phase Low Side
41	PB6	EMG0								In	EMG0-Fan Motor Exception
42	DVSSA									-	GND pin for digital
43	DVDD5A									-	Power supply pin for digital
44	PG2	BOOT_N	TSPI1CS0	T32A04OUTA	T32A04OUTC					In	BOOT mode (Single Chip Mode when "H" level)
45	PG3	INT21	TSPI1CSIN	T32A04OUTB						Out	GPIO-4-way valve relay control
46	PG4	TSPI1RXD	T32A04INB0							Out	SYNC for external DAC
47	PG5	TSPI1TXD	T32A04INB1							Out	SDIN for external DAC
48	PG6	TSPI1SCK								Out	SCLK for external DAC
49	PE0	UO1								Out	Compressor U phase high side output
50	PE1	INT04b	T32A03INA0	T32A03INC0	XO1					Out	Compressor U phase low side output
51	PE2	T32A03OUTA	T32A03OUTC	VO1						Out	Compressor V phase high side output
52	PE3	INT04a	T32A03INA1	T32A03INC1	YO1					Out	Compressor V phase low side output
53	PE4	INT11a	T32A03INB0	WO1						Out	Compressor W phase high side output
54	PE5	INT05a	INT11b	T32A03INB1	ZO1					Out	Compressor W phase low side output
55	PE6	INT05b	T32A03OUTB	EMG1						In	EMG1-Compressor Over Current
56	DVDD5B									-	Digial 5 V
57	REGOUT2									-	Capacitor for a 3.3 V regulator
58	REGOUT1									-	Capacitor for a 1.5 V regulator
59	DVSSB									-	Digital GND
60	MODE									In	Mode Pin (must be fixed to "Low" level)
61	PH0	X1	EHCLKIN							-	External Cristal (not used)
62	PH1	X2								-	External Cristal (not used)
63	RESET_N									In	Reset
64	PF1	INT06a	UT2RXD	UT2TXDA	T32A05OUTA	T32A05OUTC	SWCLK			Out	SWD-SWCLK

Fig. 4.3 shows the motor control related built-in hardware of the MCU. Dedicated hardware for motor control and PFC control, such as the Vector Engine (A-VE+) and the Programmable Motor Control Circuit (A-PMD) are built-in. These features can reduce the processing load of the processor cores.

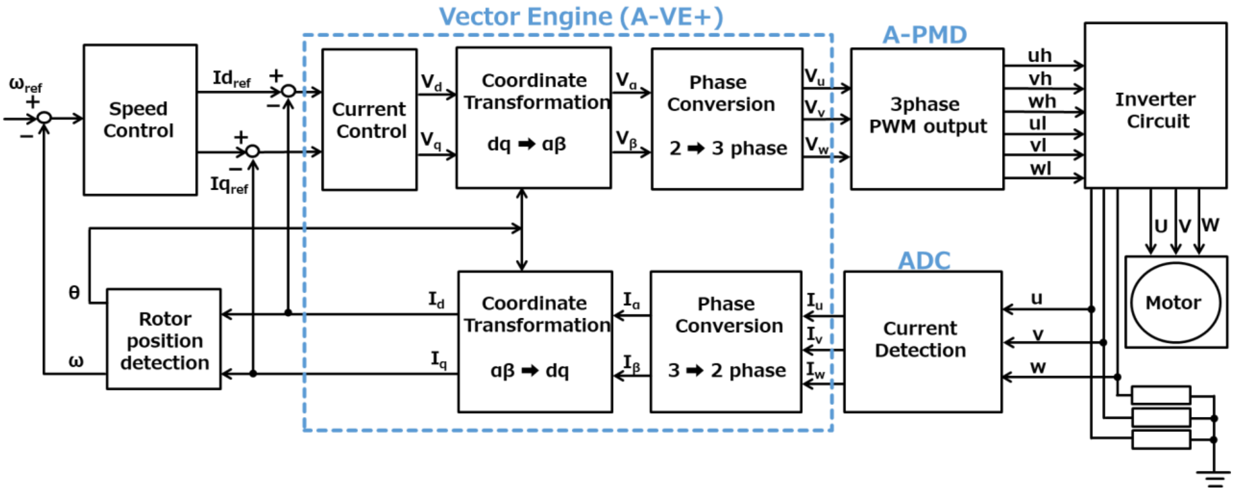


Fig. 4.3 Motor Control Related Hardware in the MCU(TMPM4KLFYAUG)

4.3. PFC Circuit

4.3.1. AC Power Supply Input Circuit and PFC Circuit

Fig. 4.4 shows AC power supply input circuit and PFC circuit.

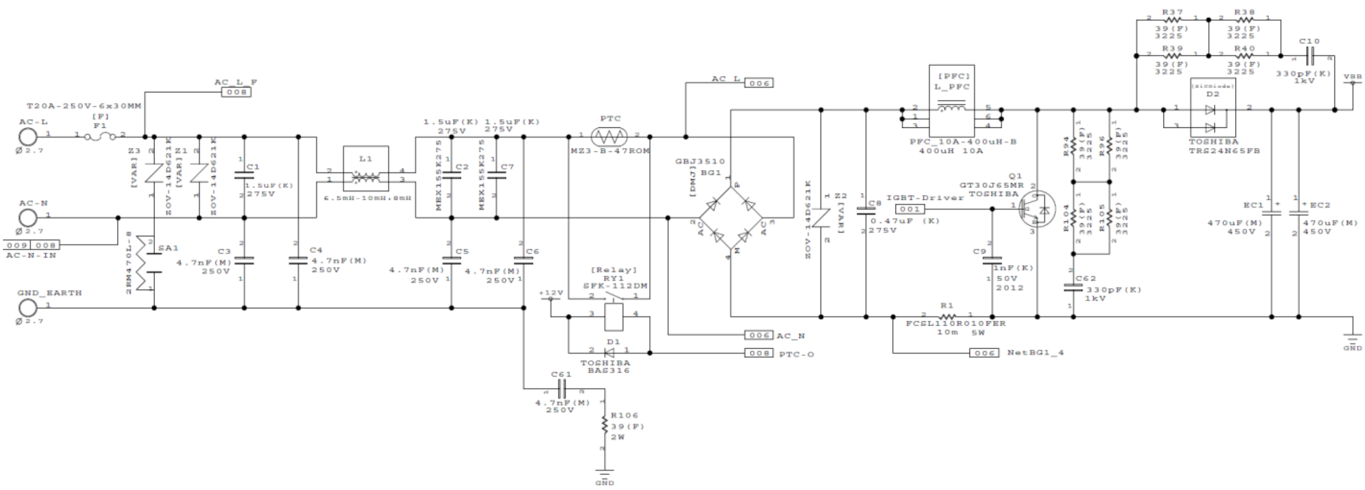


Fig. 4.4 AC Power Supply Input Circuit and PFC Circuit

AC power input (AC-L, AC-N) is rectified by a diode-bridge (BG1) after passing through a varistor, an X capacitor, a Y capacitor, a common-mode choke, and an inrush prevention relay. It is then input to PFC circuit. PFC circuit is a single phase PFC circuit and consists of a PFC inductor (L_PFC), an IGBT (Q1) for PFC switching, a PFC diode (D2), and output cpapcitors (EC1, EC2).

PFC circuit of this design operates in current continuous mode (CCM), which is often used in air conditioners, etc. In air conditioners IGBTs are generally used as switches for PFC, and the typical switching frequency has been around 20 to 40 kHz, but in recent years high switching frequency operation is increasing in demand to reduce the size of components such as PFC inductors.

Increasing the switching frequency increases the switching loss, but this design can operate at a higher switching frequency of 60 kHz because of low switching loss due to IGBT GT30J65MRB which has the maximum collector emitter voltage of 650 V and the maximum collector current of 30 A.

When operating in CCM, the reverse recovery current of the diode is superimposed on the current when IGBT is turned on. Therefore, the reverse recovery current characteristic of the diode greatly affects the switching loss. This design uses a SiC Schottky barrier diode TRS24N65FB which has a good reverse recovery performance as a PFC diode. It has the maximum repetitive peak reverse voltage of 650 V and the maximum forward current of 24 A.

4.3.1.1. IGBT

This design uses GT30J65MRB which has low loss even at high switching frequencies. It is a reverse-conducting IGBT (RC-IGBT) consisting of a reverse-diode (FWD, Free wheeling Diode) embedded into a single chip. Although FWD is not required in PFC circuit of this design, care should be taken if there is no FWD, the energy might get applied between emitter and collector and the voltage might get generated between emitter and collector.

4.3.1.2. PFC Inductor

The inductance L of PFC inductor (L_PFC) should be selected considering the ripple ratio of the inductor current. The ripple ratio is generally set to less than 30 %.

Generally, PFC inductance L is as shown in the following equation. Here, input voltage: V_{IN}, output voltage: V_{OUT}, output power: P_{OUT}, f_{SW}: switching frequency, ht: PFC efficiency, and M: ripple ratio.

$$L = \frac{\left(\left(V_{OUT} - \sqrt{2} \times V_{IN}\right) \times \eta \times {V_{IN}}^2\right)}{f_{sw} \times M \times P_{OUT} \times V_{OUT}}$$

If V_{IN} = 220 (V), V_{OUT} = 350 (V), P_{OUT} = 2000 (W), fSW = 60×10^3 (Hz), η = 0.9, M = 0.3

$$L = \frac{\left(\left(350 - \sqrt{2} \times 220\right) \times 0.9 \ \times 220^2\right)}{60 \times 10^3 \times 0.3 \times 2000 \times 350} ≒ 134 \times 10^{-6}$$

Therefore, inductance L of 134 μH or more is required. This design uses an inductor (rated 10 A) with inductance of 400 μH as PFC inductor (L_PFC).

4.3.2. IGBT Gate Drive Circuit

Fig. 4.5 shows the IGBT gate drive circuit. The gate drive of IGBT uses a gate driver IC (IC7). The 2 channels of the gate driver are used in parallel to enhance the drive capacity. The gate drive voltage is 15 V that is the supply voltage (VDD) of the gate driver. This design allows the user to change the gate-resistance when IGBT is on and off. The gate-resistor R_G setting can be changed. When IGBT is turned on, the gate resistance $R_{G(ON)}$ is set by R43, and when IGBT is turned off, the gate resistance $R_{G(OFF)}$ becomes the parallel resistance between R43 and R44. In the initial state of this design, D11 and R44 are not mounted and the on and off gate resistors are $R_{G(ON)} = R_{G(OFF)} = 22\ \Omega$. When designing an actual set, implement an appropriate gate resistance confirmed by system evaluation, etc.

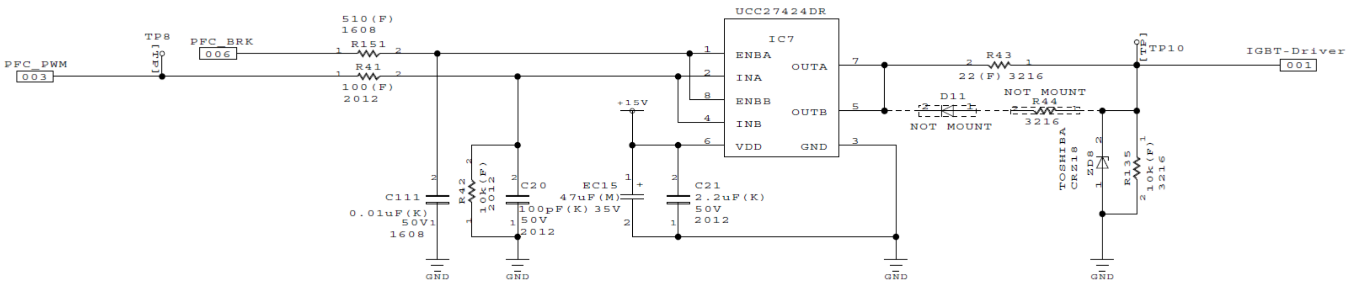


Fig. 4.5 IGBT Gate Drive Circuit

A PFC control PWM (PFC_PWM) from MCU is connected to the gate inputs (INA and INB pins) of the gate driver. An error detection output signal (PFC_BRK) of PFC overcurrent detection circuit is input to the enable input (ENBA pin and ENBB pin), and therefore the gate signal output is forcibly turned off when an overcurrent error is detected (PFC_BRK = L level).

4.3.3. Snubber Circuit

Fig. 4.6 shows the snubber circuit used in the PFC circuit. It is connected in parallel to the IGBT switch and PFC diode. RC snubber circuit constitutes of R (2 parallel × 2 series) = 39 Ω, and C = 330 pF. Although there is a slight decrease in efficiency and temperature rise due to the loss at the snubber circuit itself, the device can be operated safely because of the expected improvement in the ringing and the voltage surge during the switching by the snubber circuit.

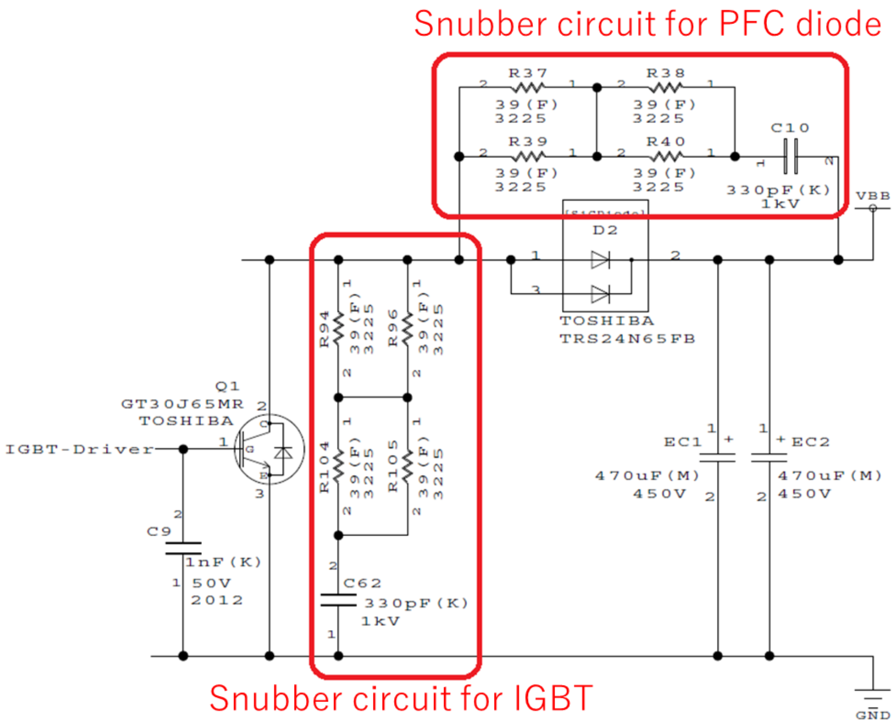


Fig. 4.6 Snubber Circuit

Fig. 4.7 shows the example of IGBT turn-on waveforms with and without a snubber circuit. In the figure, V_{CE} is IGBT collector emitter voltage, and I_C is the collector current I_C. If there is no snubber circuit, ringing can be seen in I_C, but application of the snubber circuit suppresses ringing of I_C.

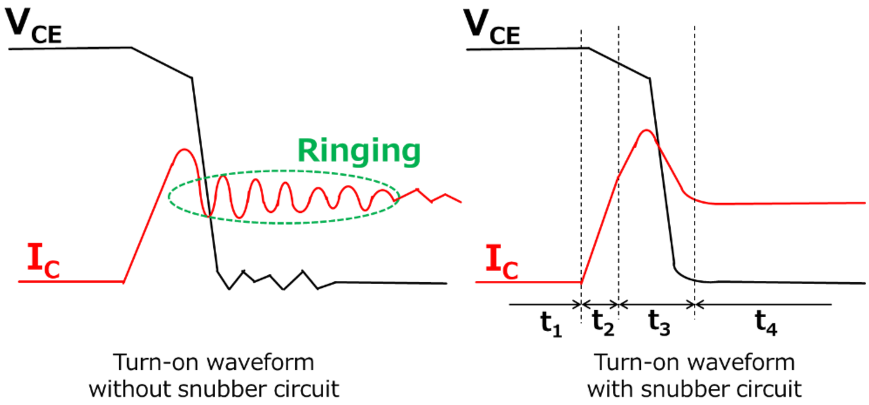


Fig. 4.7 Example of IGBT Turn-On Waveforms With and Without a Snubber Circuit

Fig. 4.8 shows the example of IGBT turn-off waveforms with and without a snubber circuit. When there is no snubber circuit, surge voltage or ringing occurs in V_{CE} due to the sharp rise of V_{CE} (dv/dt), but using the snubber circuit suppresses these.

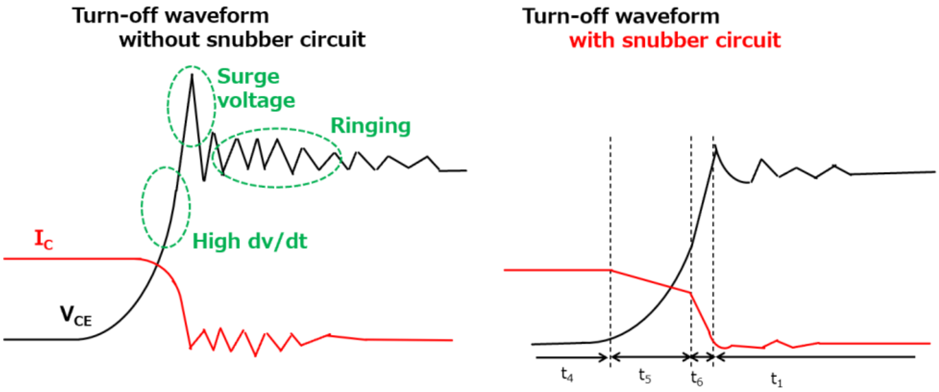


Fig. 4.8 Example of IGBT Turn-Off Waveforms With and Without a Snubber Circuit

4.3.4. PFC Current Sensor Circuit

Fig. 4.9 shows the PFC current sensor circuit. The current flowing through the PFC circuit generates a voltage across 0.01 Ω shunt resistor (R1). This shunt resistor voltage (IAC_SHUNT) is amplified by the current sensor circuit. And, then it is converted from analog to digital by the ADC of the MCU to be used for PFC control, etc.

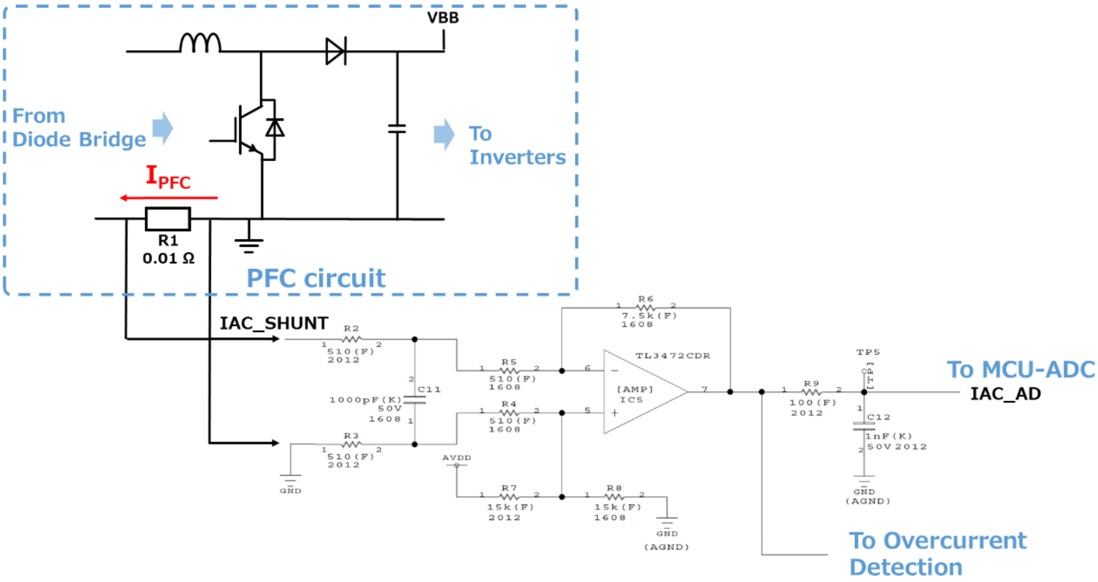


Fig. 4.9 PFC Current Sensor Circuit

Fig. 4.10 shows an example of a differential amplifier circuit using an operational amplifier.

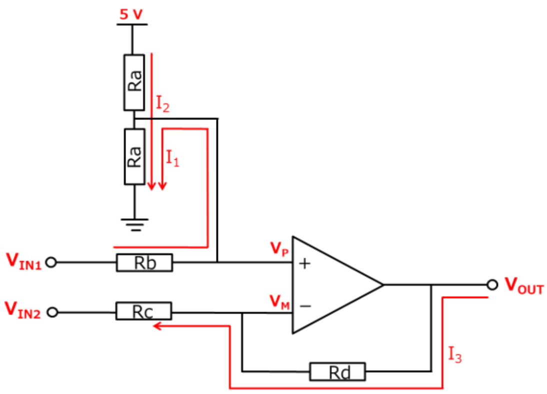


Fig. 4.10 Example of Differential Amplifier Circuit

When V_{IN1}, V_{IN2} is input and V_{OUT} is output, the relation of current, voltage, etc. in the circuit is as follows

$$I_1 = \frac{V_{IN1} - V_P}{Rb}$$

$$I_2 = \frac{5 - V_P}{Ra}$$

$$I_1 + I_2 = \frac{V_P}{Ra}$$

$$V_M = V_{IN2} + \frac{Rc}{Rc + Rd} \cdot (V_{OUT} - V_{IN2})$$

Because of virtual short circuit during op amp negative feedback

$$V_P = V_M$$

If applied, the resulting V_{OUT} will be

$$\boldsymbol{V_{OUT} = \frac{Rc + Rd}{(Ra + 2Rb) \cdot Rc} \cdot (5Rb + Ra \cdot V_{IN1}) - \frac{Rd}{Rc} \cdot V_{IN2}} \quad (4.1)$$

If following values are used in the differential amplifier circuit described by the above equation(4.1),

Ra = R7 and R8 = 15 (kΩ)
Rb = R3+R4 = 1.02 (kΩ)
Rc = R2+R5 = 1.02 (kΩ)
Rd = R6 = 7.5 (kΩ)
V_{IN1} = 0 (V)

the voltage output of the current sensor circuit becomes

$$V_{OUT} \fallingdotseq 2.5 - 7.353 \times V_{IN2}$$

If the direct current of the PFC is I_{PFC} (A),

$$V_{IN2} = -I_{PFC} \cdot 0.01$$

then the current sensor voltage (IAC_AD) applied to the ADC of the MCU becomes

$$\boldsymbol{IAC_{AD} = 2.5 + 0.07353 \cdot I_{PFC} \quad (V)} \quad (4.2)$$

4.3.5. PFC Overcurrent Detection Circuit

Fig. 4.11 shows the PFC overcurrent detection circuit.

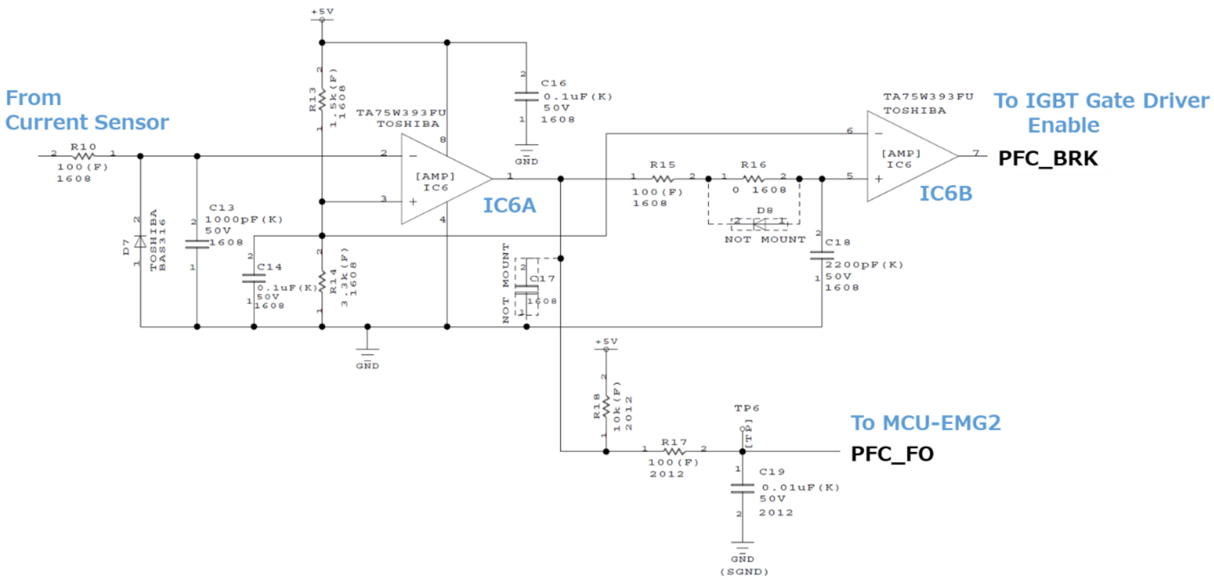


Fig. 4.11 PFC Overcurrent Detection Circuit

The voltage output (IAC_AD) from the current sensor circuit is compared with the reference voltage by the dual-comparator TA75W393FU (with open-collector output) to detect overcurrent. The reference voltage V_{REF} of the two comparators is obtained by dividing 5 V by R13 (1.5 kΩ) and R14 (3.3 kΩ).

$$V_{REF} = 5 \cdot \frac{3.3 \times 10^3}{1.5 \times 10^3 + 3.3 \times 10^3} \fallingdotseq 3.44\ (\mathrm{V})$$

IC6A comparator has the V_{REF} connected to IN(+) pin, so when IN(-) pin input voltage > V_{REF}, OUT pin output (PFC_FO signal) is L level. PFC current for which this signal is L level is calculated from the equation (4.2).

$$\boldsymbol{I_{PFC} > \frac{V_{REF} - 2.5}{0.07353} \fallingdotseq 13\ (A)} \tag{4.3}$$

When I_{PFC} exceeds 13 A, the PFC_FO signal output from the comparator going to the MCU's EMG2 pin becomes L level and therefore the MCU enters the hardware exception state. Resistor R18 (10 kΩ) is used as the pull up resistor required by the open collector output to pull it up to 5 V.

IC6B comparator has the V_{REF} connected to IN(-) pin, so when IN(+) pin input voltage falls below V_{REF}, OUT pin output (PFC_BRK signal) becomes L level. Here, IN(+) pin input voltage is IC6A's OUT pin output voltage. Normally it is 5 V and becomes 0 V during overcurrent abnormality, therefore if I_{PFC} exceeds 13 A, IC6A's OUT pin output voltage becomes L level, and the ENB signal of IGBT gate driver (IC7) becomes L level and thus stopping the gate drive of IGBT (Q1). The internal pull up of the IGBT gate driver is used as the pull up required by the open collector output.

4.3.6. AC Voltage Sensor Circuit

Fig. 4.12 shows the AC voltage sensor circuit. The differential amplifier circuit of AC voltage sensor circuit converts the voltage level between AC-L and AC-N of the single phase AC power supply, and after that it is converted from analog to digital by the ADC of the MCU, and then used in PFC control, etc. by the software.

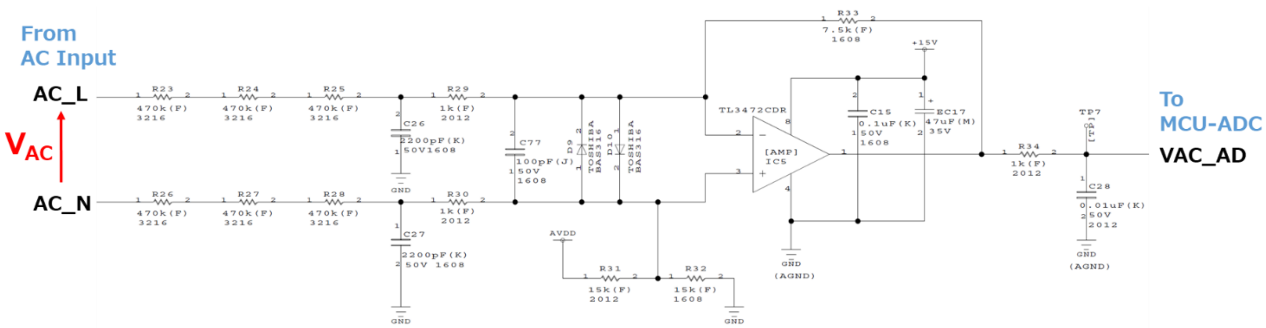


Fig. 4.12 AC Voltage Sensor Circuit

If in the differential amplifier circuit expressed by the equation(4.1)

Ra = R31 and R32 = 15 (kΩ)

Rb = R26+R27+R28+R30 = 1411 (kΩ)

Rc = R23+R24+R25+R29 = 1411 (kΩ)

Rd = R33 = 7.5 (kΩ)

the voltage out of AC voltage sensor circuit becomes

$$V_{OUT} \fallingdotseq 2.5 + 5.32 \times 10^{-3} \cdot (V_{IN1} - V_{IN2})$$

If AC_L potential (V_{IN2}) in reference to AC_N potential (V_{IN1}) is V_{AC} (V)

$$V_{AC} = V_{IN2} - V_{IN1}$$

Therefore, AC voltage sensor output voltage (VAC_AD) applied to the ADC of the MCU becomes:

$$\boldsymbol{VAC_{AD} = 2.5 - 5.32 \times 10^{-3} \cdot V_{AC} \quad (V)} \qquad (4.4)$$

4.3.7. DC Voltage Sensor Circuit

Fig. 4.13 shows the DC voltage sensor circuit.

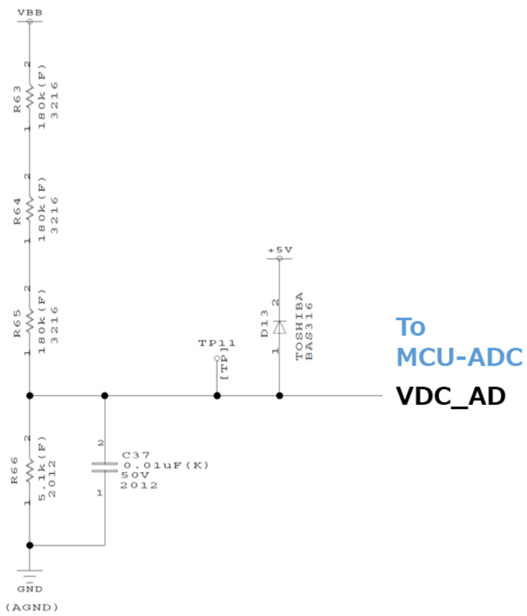


Fig. 4.13 DC Voltage Sensor Circuit

DC voltage (V_{BB}) output from PFC circuit is monitored by the MCU, so voltage divider resistors (R63, R64, R65, and R66) are used as the output of the sensor. Therefore, the DC voltage sensor output (VDC_AD) applied to the ADC of the MCU becomes

$$\boldsymbol{VDC_{AD} = \frac{5.1\ (k\Omega)}{180\ (k\Omega) + 180\ (k\Omega) + 180\ (k\Omega) + 5.1\ (k\Omega)} \cdot V_{BB}}$$

$$\boldsymbol{\fallingdotseq 9.36 \times 10^{-3} \cdot V_{BB}\ (V)} \qquad (4.5)$$

4.4. Fan Motor Drive Circuit

4.4.1. Fan Motor Drive Inverter Circuit

Fig. 4.14 shows the inverter circuit used for driving the fan motor.

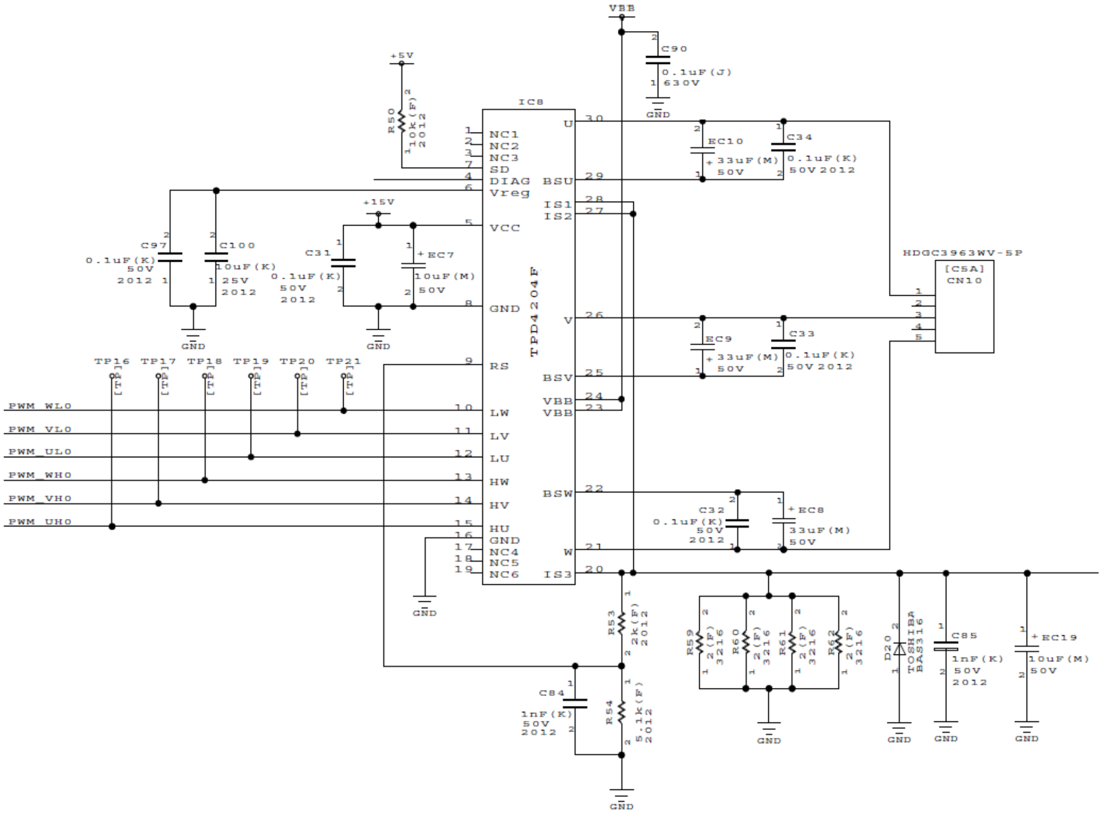


Fig. 4.14 Fan Motor Drive Inverter Circuit

The Intelligent Power Device TPD4204F (IC8) features a three-phase inverter consisting of MOSFETs (with a maximum rated voltage of 600 V), a level-shift type gate driver, an overheat protection function, a voltage reduction protection function, and an overcurrent protection function in one package.

MCU's 5 V inverter control PWM signals (PWM_UH0, PWM_VH0, PWM_WH0, PWM_UL0, PWM_VL0, PWM_WL0) can be directly connected to TPD4204F's HU pin, HV pin, HW pin, LU pin, LV pin, and LW pin. Inverter output from U pin, V pin and W pin is output to the fan motor connector (CN10).

Inverter bus power supply VBB is supplied to the VBB pin. The source of each low-side MOSFET of the internal-inverter phase is connected to IS1, IS2, and IS3 pins. Shunt resistors can be connected to these pins, however in this design, all sources are combined and connected to the GND via a single-shunt configuration. R59, R60, R61 and R62 are shunt resistors which are 2 Ω resistors connected in parallel and thus operate as a single 0.5 Ω shunt resistor. Strictly speaking, the overall shunt resistance is little less than 0.5 Ω because of the effect of parallelly connected resistance (of R53 and R54) used for overcurrent detection, however, the effect is negligible due to the higher resistance of R53, R54.

For level shifting the high-side gate driver, TPD4204F has a built-in bootstrap diode and requires bootstrapped capacitors (EC10, C34, EC9, C33, EC8, C32) to be connected between U pin and BSU pin, V pin and BSV pin, and W pin and BSW pin.

TPD4204F also has a built-in regulator that provides 7 V output to VREG pin. This is not used in this design. Regardless of the use of the built-in regulator output, connect a power supply stabilization capacitor (C100, 100 μF) and a surge-absorbing capacitor (C97, 0.1 μF) to VREG pin of U1.

SD pin is the input for the shutdown control signal. When L level is input, all the inverter outputs are shut off. In this design, it is pulled up to VDD (5 V) via R50 (10 kΩ).

4.4.2. Fan Motor Drive Error Detection Circuit

Fig. 4.15 shows the error detection circuit used in the fan motor drive.

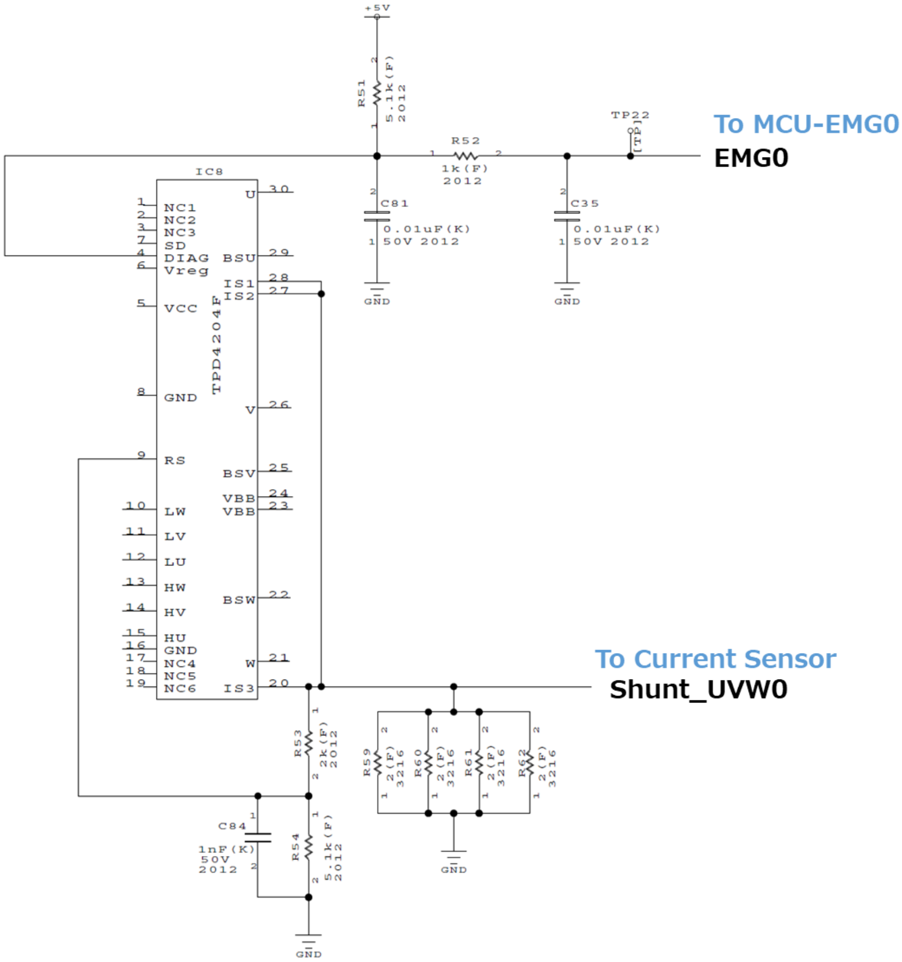


Fig. 4.15 Fan Motor Drive Error Detection Circuit

Fan motor drive error is detected by TPD4204F. The voltage generated across the by the shunt resistor (totaling 0.5 Ω in R59, R60, R61, R62) is divided by R53 (2 kΩ) and R54 (5.1 kΩ) and is applied to RS pin. In TPD4204F, overcurrent is detected when RS pin voltage exceeds 0.5 V(Typ.) When the current flowing through the shunt resistor is OC_{FAN}, the overcurrent is detected.

$$OC_{FAN}\ (\mathrm{A}) \times 0.5\ (\Omega) \times \frac{5.1\ (k\Omega)}{5.1\ (k\Omega) +\ 2\ (k\Omega)} >\ 0.5\ (\mathrm{V})$$

$$\boldsymbol{OC_{FAN}} >\ \mathbf{1.392\ (A)} \tag{4.6}$$

Therefore, when the current flowing through the shunt resistor exceeds approximately 1.4 A, TPD4204F detects the overcurrent. In addition to this overcurrent, when TPD4204F detects a power supply voltage drop or overheating, the DIAG pin (open drain) output going to the MCU’s EMG0 pin becomes L level, causing the MCU to enter the hardware exception state. R51 (5.1 kΩ) is used as the pull-up required for the open-drain output.

4.4.3. Fan Motor Current Sensor Circuit

Fig. 4.16 shows the fan motor current sensor circuit. The bus current flowing through the inverter of the fan motor generates a voltage in the shunt resistance (combination of R59, R60, R61, R62) with effective resistance of 0.5 Ω. This shunt resistance voltage (Shunt_UVW0) is amplified by a current sensor circuit that includes a built-in op-amp (AMPA) of the MCU, and is then converted from analog to digital via ADC of the MCU and after that it is used for fan motor control. This eliminates the need for an external op-amp, which reduces the number of components on the board.

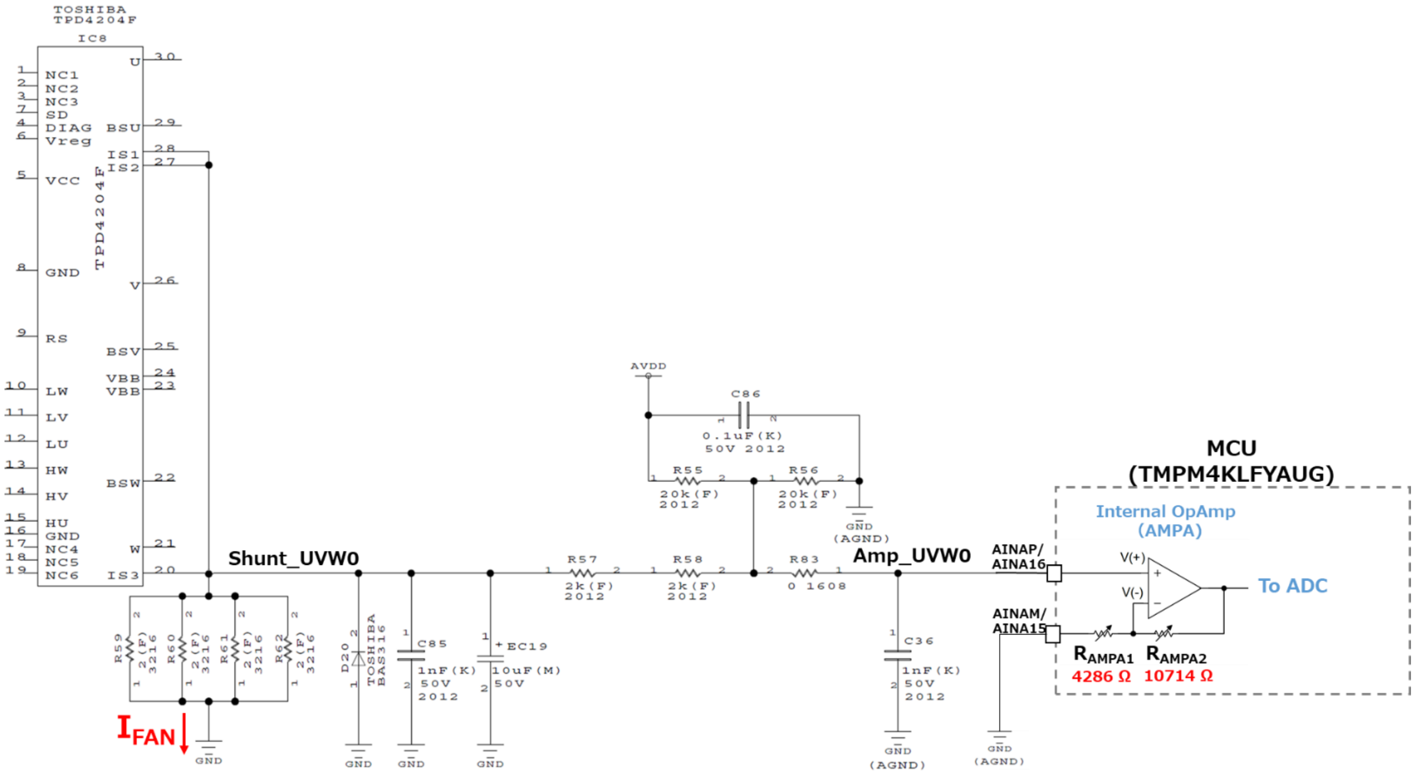


Fig. 4.16 Fan Motor Current Sensor Circuit

Resistor R_{AMPA1} and R_{AMPA2} connected to the MCU's internal operational amplifier (AMPA) can be set in MCU's operational amplifier control register, and the example software in this design sets R_{AMPA1}= 4286 Ω, R_{AMPA2} = 10714 Ω.

If in the differential amplifier circuit expressed by equation(4.1)

Ra = R55 and R56 = 20 (kΩ)

Rb = R57+R58 = 4 (kΩ)

Rc = R_{AMPA1} = 4.286 (kΩ)

Rd = R_{AMPA2} = 10.714 (kΩ)

V_{IN2} = 0 (V)

the voltage output of the current sensor circuit becomes

$$V_{OUT} \fallingdotseq 2.49983 + 2.49983 \cdot V_{IN1}$$

$$\fallingdotseq 2.5 + 2.5 \cdot V_{IN1}$$

If the bus current of the fan motor drive circuit is I_{FAN} (A)

$$V_{IN1} = I_{FAN} \cdot 0.5$$

then the current sensor voltage (ADC_UVW0) going into ADC becomes

$$\boldsymbol{ADC_{UVW0} = 2.5 + 1.25 \cdot I_{FAN} \quad (V)} \tag{4.7}$$

4.5. Compressor Drive Circuit

4.5.1. Compressor Drive Inverter Circuit

Fig. 4.17 shows the inverter circuit used in compressor drive.

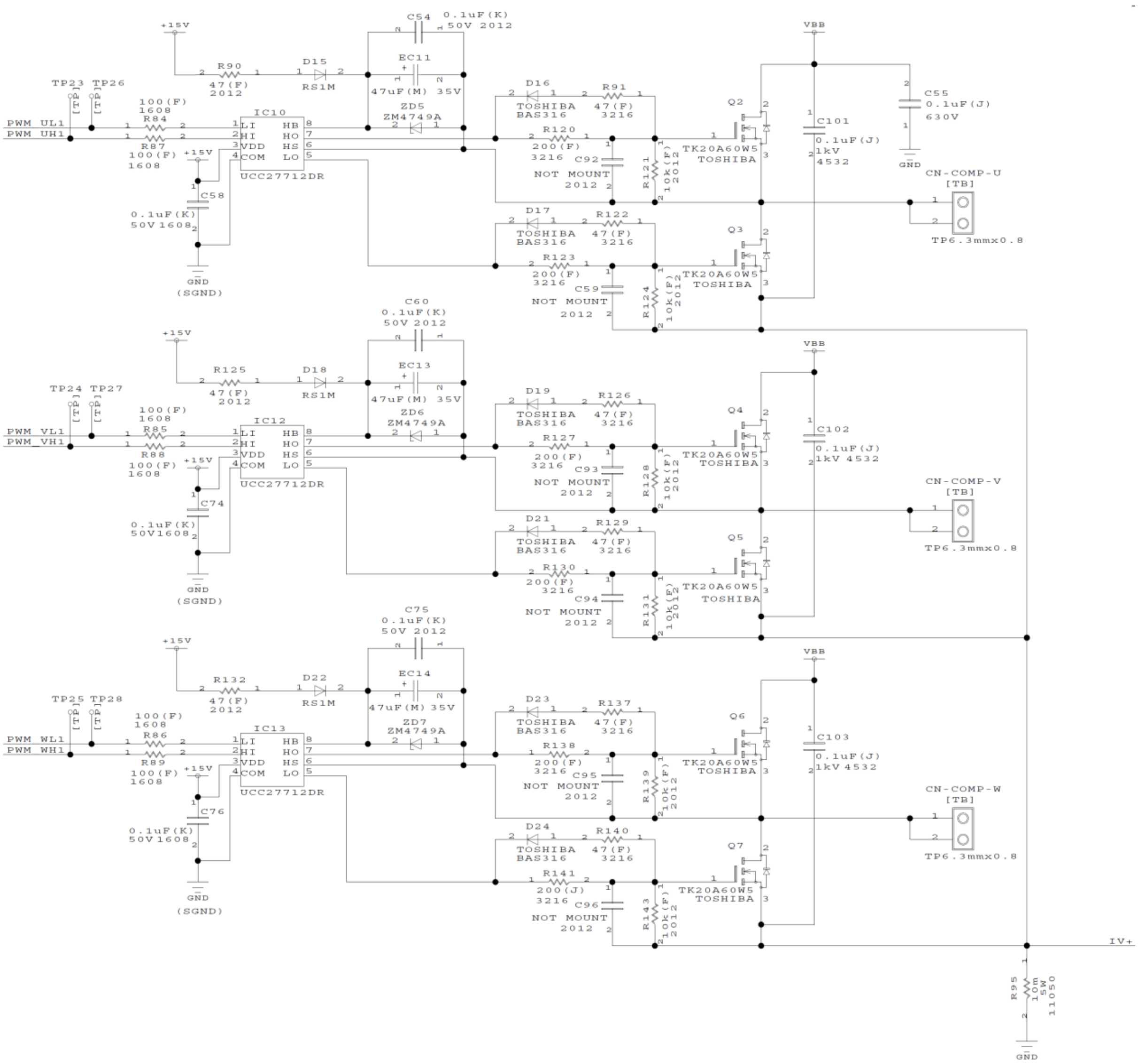
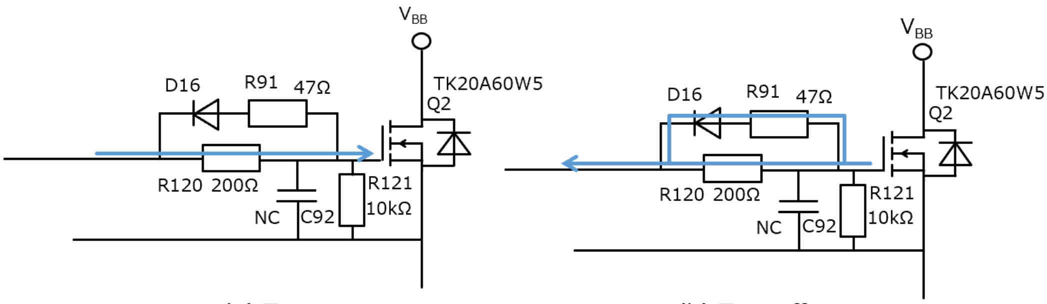


Fig. 4.17 Inverter Circuit for Compressor Drive

Six TK20A60W5 power MOSFETs with the maximum drain current of 20 A and the maximum drain-source voltage of 600 V, are used to form (Q2, Q3, Q4, Q5, Q6, Q7) a 3-phase inverter. TK20A60W5 MOSFET has a built-in high speed reverse recovery diode with the reverse recovery time t_{rr} = 110 ns(Typ.) , which can reduce losses due to reverse recovery currents that occur during switching in the inverter. A snubber capacitor (C101, C102, C103) of 0.1 μF with rated voltage of 1 kV is connected to each arm of the inverter. The output of each phase of the inverter is output to the corresponding compressor connector (CN-CMP-U, CN-CMP-V, CN-CMP-W).

5 V PWM signals (PWM_UH1, PWM_UL1, PWM_VH1, PWM_VL1, PWM_WH1, PWM_WL1) for controlling the inverter are output from the MCU and are connected to the gate driver ICs (IC10, IC12, IC13) which in turn generate the gate signals for the MOSFETs.

Fig. 4.18 shows the circuit around the gate resistors.



(a) Turn on (b) Turn off

Fig. 4.18 Circuit Around the Gate Resistors

The gate drive voltage of the MOSFET is the supply voltage of the gate driver IC (VDD) on the low-side, and the bootstrapped supply voltage between HB and HS pins of the gate driver IC on the high-side, each of which is approximately 15 V. This design allows the user to change the gate-resistance when MOSFET turns on and turns off. In this design, the default gate resistance setting for the low-side and the high-side of the inverter, when the MOSFET turns on is $R_{G(ON)}$ which is 200 Ω, and when the MOSFET turns off is $R_{G(OFF)}$ which is the parallel resistance of 200 Ω and 47 Ω i.e. approximately 38 Ω. When designing an actual set, an appropriate gate resistance confirmed by system evaluation, etc can be implemented.

4.5.2. Compressor Current Sensor Circuit

Fig. 4.19 shows the compressor current sensor circuit. The the voltage (IV+) is generated across the 10 mΩ shunt resistor (R95) as the bus current flowing through the compressor inverter passes through it. This shunt resistor voltage (IV+) is amplified by the current sensor circuit consisting of MCU's built-in op amp (AMPB), and is then converted from analog to digital by the ADC of the MCU and after that it is used for compressor control. This eliminates the need for an external op-amp and thus reduces the number of components on the board.

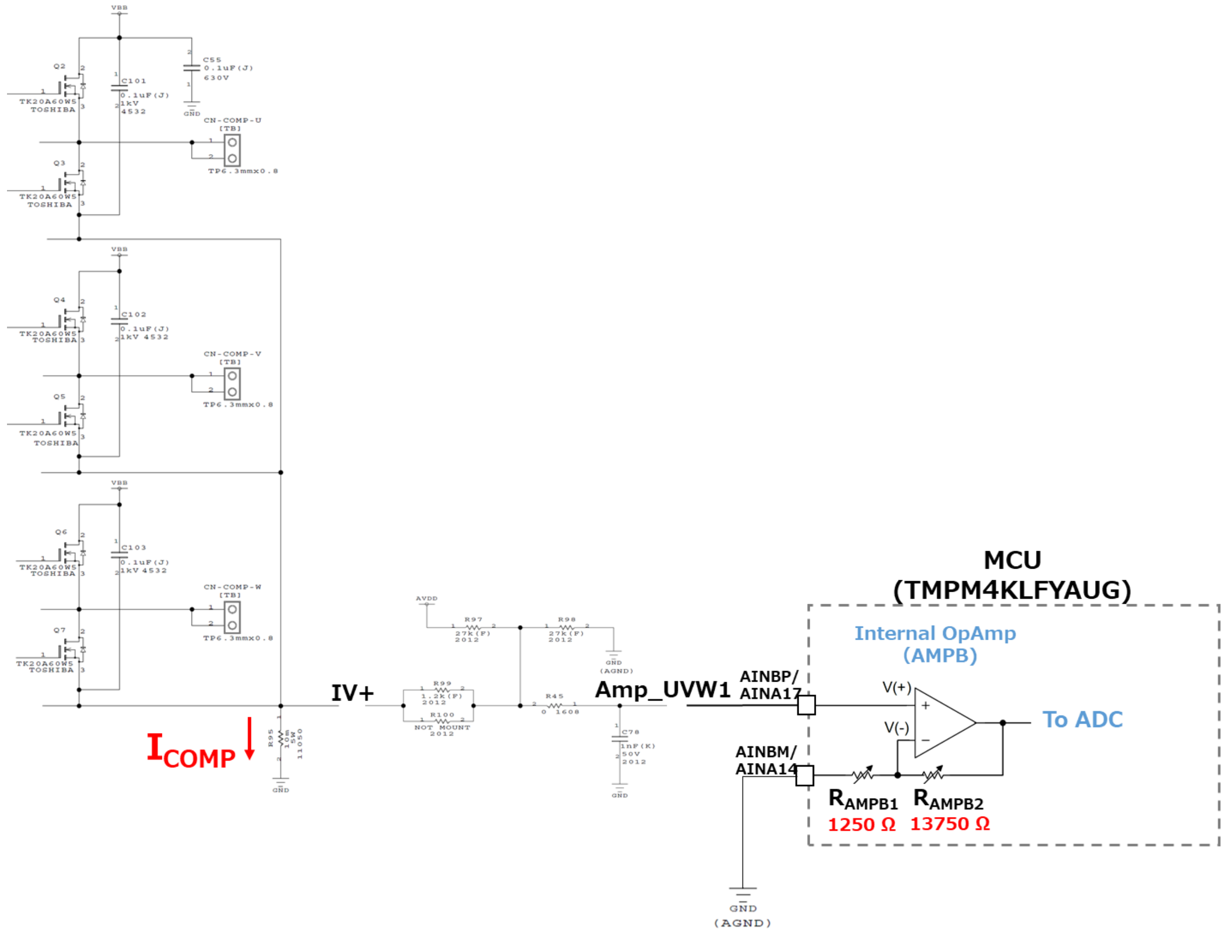


Fig. 4.19 Compressor Current Sensor Circuit

Resistor R_{AMPB1} and R_{AMPB2} connected to MCU's internal operational amplifier (AMPB) can be set in MCU's operational amplifier control register, and the example software in this design sets R_{AMPB1}= 4286 Ω, R_{AMPB2} = 10714 Ω.

If in the differential amplifier circuit described by the equation(4.1)

Ra = R97 and R98 = 27 (kΩ)

Rb = R99 = 1.2 (kΩ)

Rc = R_{AMPB1} = 1.25 (kΩ)

Rd = R_{AMPB2} = 13.75 (kΩ)

V_{IN2} = 0 (V)

the voltage output of the current sensor circuit becomes

$$V_{OUT} \fallingdotseq 2.45 + 11 \cdot V_{IN1}$$

If the bus current of the compressor drive is I_{COMP} (A)

$$V_{IN1} = I_{COMP} \cdot 0.01$$

the current sensor voltage (ADC_UVW1) applied to ADC becomes

$$\boldsymbol{ADC_{UVW1} = 2.45 + 0.11 \cdot I_{COMP} \ \ (V)} \tag{4.8}$$

4.5.3. Compressor Overcurrent Detection Circuit

Fig. 4.20 shows the overcurrent detection circuit for the compressor.

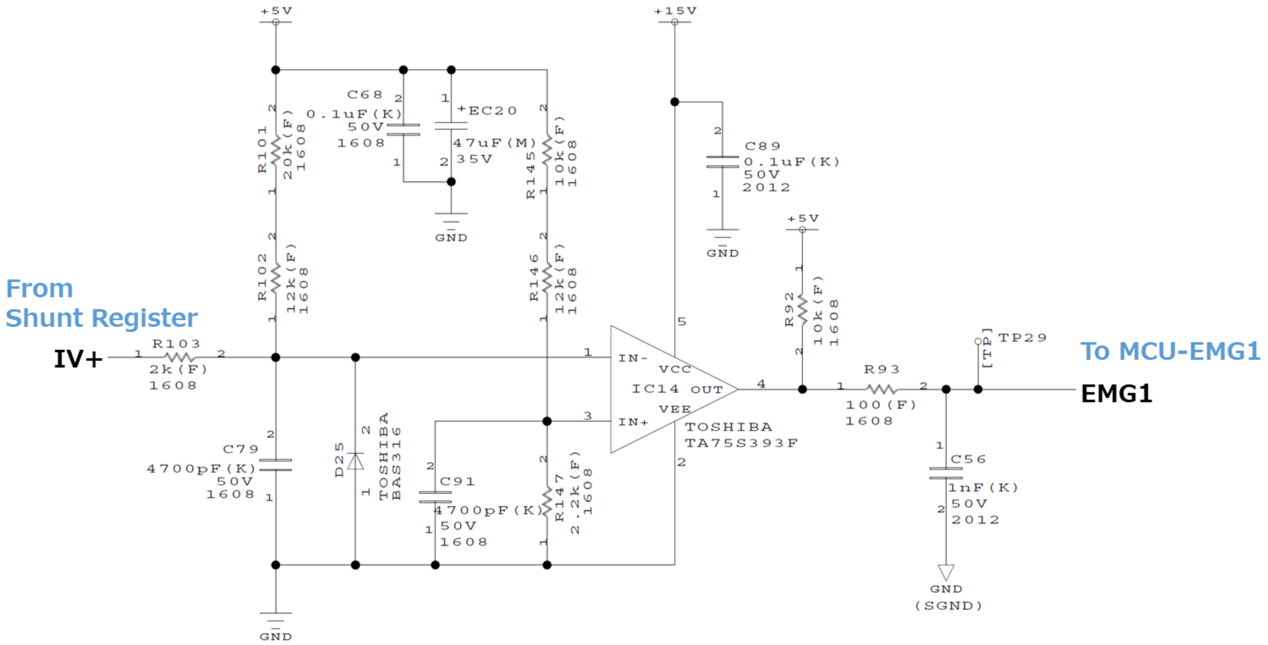


Fig. 4.20 Compressor Overcurrent Detection Circuit

The voltage generated by the shunt resistor (IV+) is divided using the voltage divider circuit (R101, R102, R103). The comparator TA75S393FU (IC14) detects overcurrent by comparing this voltage divider circuit output with the comparator reference voltage. The reference V_{ref} applied to IN (+) of the comparator is obtained by dividing 5 V using series resistors R145 (10 kΩ), R146 (12 kΩ) and R147 (2.2 kΩ). Therefore V_{ref} becomes

$$V_{ref} = \frac{2.2\ (k\Omega)}{10\ (k\Omega) + 12\ (k\Omega) + 2.2\ (k\Omega)} \cdot 5\ (V)$$
$$\fallingdotseq\ 0.455\ (V)$$

On the other hand, the comparison voltage applied to IN (-) pin of the comparator is obtained using the shunt resistor voltage (IV+) and the voltage divider circuit (R101, R102, R103). If the voltage of the comparator IN (-) is V_{IN-} and the shunt resistor voltage is V_{IV+}

$$V_{IN-} = V_{IV+} + \frac{2\ (k\Omega)}{20\ (k\Omega) + 12\ (k\Omega) + 2\ (k\Omega)} \cdot (5 - V_{IV+})$$

Actually, the current flowing through this divider resistor also flows to the shunt resistor, but the change in the voltage generated by the shunt resistor caused by this can be ignored.

When IN(+) voltage < IN(-) voltage, an error is detected and a L level signal is output from the open collector.

Therefore

$$V_{ref} < V_{IV+} + \frac{2\ (k\Omega)}{20\ (k\Omega) + 12\ (k\Omega) + 2\ (k\Omega)} \cdot (5 - V_{IV+})$$

$$V_{IV+} > 0.170$$

If the bus current of the compressor drive is I_{COMP} (A)

$$V_{IV+} = I_{COMP} \cdot 0.01$$

Therefore

$$\boldsymbol{I_{COMP} > 17.0\ (A)} \tag{4.9}$$

When the bus current of the compressor drive circuit exceeds 17 A, the EMG1 signal output from the comparator going to the MCU's EMG1 pin becomes L level and therefore causing the MCU to enter the hardware exception state.

4.6. Other Circuits

4.6.1. Temperature Sensor Circuit

Fig. 4.21 shows the temperature detection circuit.

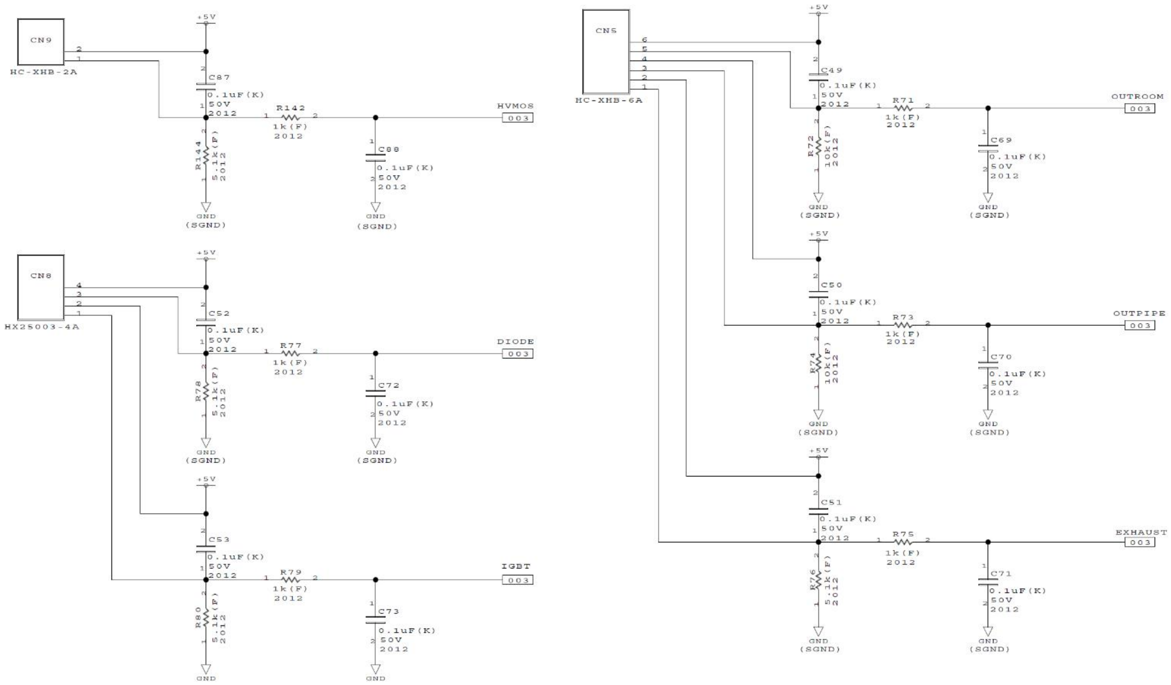


Fig. 4.21 Temperature Sensor Circuit

The thermistors (NTC) are used for sensing temperature and these are connected to the temperature sensor connectors (CN5, CN8, CN9). For measuring temperature, 5 V is divided by a voltage divider circuit consisting of a thermistor and a fixed resistor, and then this voltage is converted from analog to digital via the ADC of the MCU. A total of 6 channels of temperature measurement are supported.

4.6.2. Valve Control Circuit

Fig. 4.22 shows the valve control circuit.

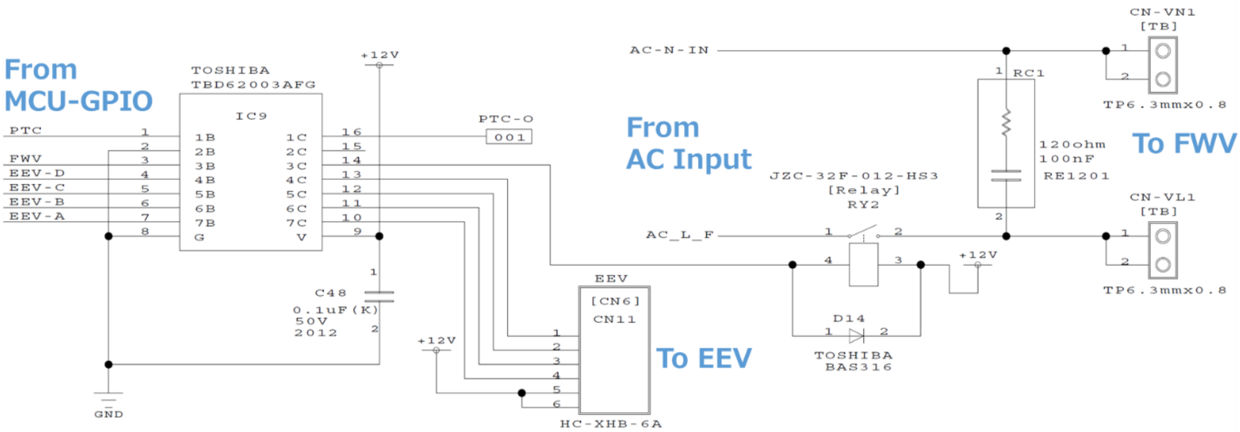


Fig. 4.22 Valve Control Circuit

DMOS transistor array TBD62003AFG is used to drive the valves. TBD62003AFG is a 7-channel transistor array that can be used as a low-side switch because when the input level is L the output is open, and when the input level is H the output is connected to GND. Since the maximum input L level voltage is 0.6 V, and the minimum input H voltage is 2.5 V, therefore a 5 V GPIO from the MCU can be directly connected.

The four-way valve (FWB) connected to the four-way valve connectors (CN-VN1, CN-VL1) is generally AC driven. The AC_L AC power supply is turned on/off by driving the mechanical relay (RY2). This product incorporates an output clamp diode that clamps the back electromotive force generated when driving inductive loads such as relays. The electric expansion valve (EEV) connected to the electric expansion valve connector (CN6) supports four channels of drive. When the control signal from MCU is ON (TBD62003AFG input is H level), 12 V is applied between the 12 V power supply (CN6-5 pin and CN6-6 pin) and EEV channels.

4.6.3. Internal Power Supply Circuits

Fig. 4.23 shows the circuit of the internal 15 V power supply.

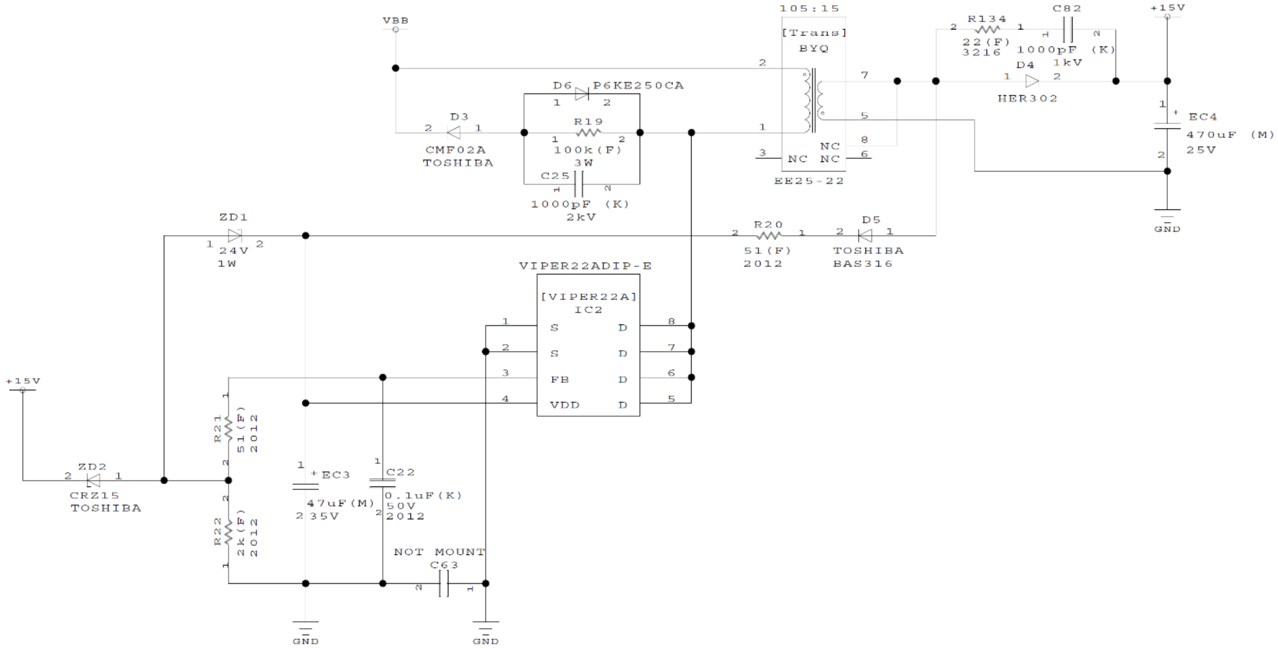


Fig. 4.23 Internal 15 V Power Supply

The flyback DC-DC converter converts the DC voltage (V_{BB}, approx. 350 V) output from PFC circuit to 15 V. The flyback transformer (BYQ) consist of a ferrite core EE25/10/6F (Anci), a primary side winding with 105 turns using a 0.3 mm diameter wire, and secondary side windings with 15 turns using two 0.3 mm diameter wires in parallel. At this time, the primary side inductance is approximately 2900 μH and the secondary side inductance is approximately 60 μH.

Fig. 4.24 shows the circuit of the internal 12 V power supply and internal 5 V power supply. The internal 15 V power supply is converted to 12 V power supply using a linear regulator IC (IC4), and then this 12 V power supply is converted to 5 V power supply using another linear regulator IC (IC3).

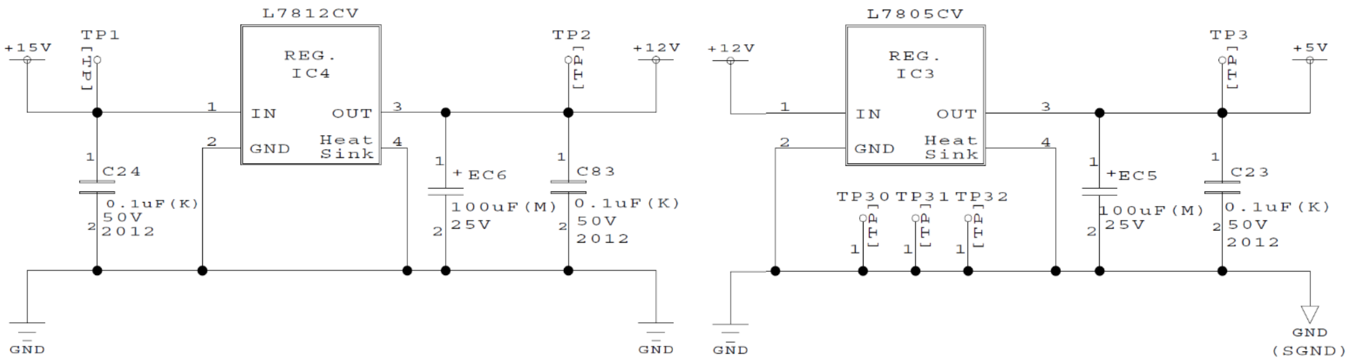


Fig. 4.24 Internal 12 V Power Supply and Internal 5 V Power Supply

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