Application Circuit of TPD4207F for Small Compressor Motor Drive

Reference Guide

RD042-RGUIDE-02

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

Incorporating 250- to 600-V switching devices, Toshiba's intelligent power devices (IPDs) can directly drive a brushless DC (BLDC) motor. Toshiba offers various IPDs that meet a wide range of requirements, including a motor's output power, the control method (square wave vs sine wave), and the AC input voltage of the application.

For Toshiba's high-voltage IPDs → Click Here

Table 1.1 compares the applications of the TPD4152F, TPD4204F, and TPD4207F that incorporate a switching device with a maximum rated voltage of 600V. These IPDs can be used for applications with a 200 VAC input targeting countries or regions with an unstable power supply.

Table 1.1 Comparison of 600-V IPDs

Part number	TPD4152F	TPD4204F	TPD4207F
Maximum rating	600V / 0.7A	600V / 2.5A	600V / 5A
Applicable motor output	≤ 30W	≤ 60W	≤ 60W
Commutation	Square-wave	Sine-wave	Sine-wave
Recommended PWM controller	N/R	TB6634FNG	TMPM4K0FSADUG
Target applications	Fans	Fans	Compressors
Reference design	Click Here	Click Here	Click Here
Reference Guide	RD017-RGUIDE-02	RD018-RGUIDE-02	This document

As is the case of the TPD4204F, the TPD4207F supports sine-wave control. The TPD4207F achieves 5A current rating, which is higher than the TPD4204F, because TPD4207F has 0.44Ω (typ) on-resistance MOSFETs inside which are considerably lower than those of the TPD4204F. Because of the high current rating, the TPD4207F provides a motor with a higher startup current, making it suitable for compressor motor applications, which cannot be supported by the TPD4204F. Since the output stage of the TPD4207F has a maximum rated voltage of 600V, the TPD4207F is suitable for applications with a 200 VAC input targeting countries or regions with an unstable power supply.

This reference guide describes an example of the application of the TPD4207F to a compressor motor.

2. Overview

A motor is a generic name of machine designed to convert electric energy into mechanical energy. When an electric current flows through a motor's coil, magnetic fields are produced. The rotor of the motor spins as magnets in the rotor are attracted and repelled by the magnetic fields. The direction of motor rotation can be changed by controlling the direction of the electric current.

Brushed DC motors are the most widely used type of DC motors because they are highly controllable and physically small. However, a drawback of brushed DC motors is that contact wear reduces their lifespan because they control the direction of an electric current through mechanical contacts between a commutator and a brush. In contrast, brushless DC (BLDC) motors sense the rotor position without using a brush and a commutator, and control a current with an electronic control circuit based on the rotor position. Without mechanical contacts, BLDC motors have advantages of long service life and low conversion loss. They are widely used not only for industrial applications but also for information equipment and home appliances. Table 2.1 compares brushed and brushless DC motors.

Table 2.1 Brushed motors vs. BLDC motors

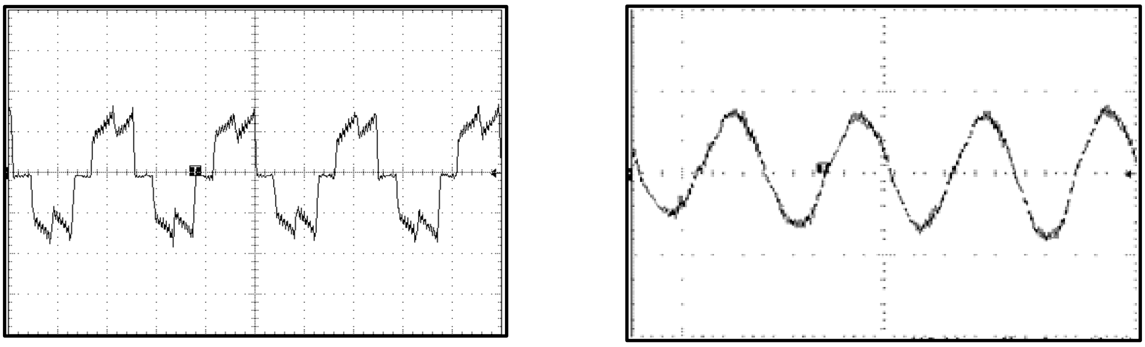
	Brushed DC motors	BLDC motors
Efficiency	60 to 80%	≥80%
Size	Small	Small
Electronic circuit	N/R	Required
Service life	Short	Long
Brushes	Y	N
Applications	Toys, small home appliances	Air conditioners, washing machines, refrigerators, small home appliances

As described above, the BLDC motor needs to sense the rotor position to control its rotation. There are two principal ways of sensing the rotor position: 1) using Hall-effect sensors incorporated in a motor to monitor the magnetic fields in the rotor and 2) detecting changes in the back-EMF voltage induced by the rotation of the rotor. The technique for sensing the rotor position based on the changes in the back-EMF voltage instead of using Hall-effect sensors is called sensorless drive. Sensorless drive eliminates the need to attach any sensor to a motor, making it possible to reduce its size. However, sensorless drive has its own drawback in that it does not lend itself to low-rpm operation because the back-EMF voltage induced at low rpm is too low to be measured. Table 2.2 shows major advantages and disadvantages of sensorless drive. Hall-effect sensors cannot be attached to a compressor motor since it is subject to high temperature. Therefore, a compressor motor needs sensorless drive.

Table 2.2 Advantages and disadvantages of sensorless BLDC motors

Advantages	Disadvantages
●The size and weight of a motor can be reduced because no sensor is required. ●The time taken to assemble and adjust a motor can be reduced because it is unnecessary to adjust the sensor positions relative to a rotor. ●Sensorless BLDC motors are inexpensive because the sensor wiring is unnecessary.	●Sensorless BLDC motors cannot be run at low rpm because the back-EMF voltage cannot be monitored at low rpm. ●Sensorless drive is less responsive than sensored drive because sensorless drive requires computation for rotor position detection.

As described above, BLDC motors can operate at high efficiency due to low energy conversion loss. In recent years, manufacturers of home appliances and other consumer products have been under pressure to further reduce their power consumption, driving the widespread use of efficient BLDC motors. For example, a three-phase BLDC motor is commutated using six switching devices. There are two major control techniques for three-phase BLDC motors: 120-degree square-wave control and 180-degree sine-wave control. A square-wave control technique generates square motor winding currents in such a manner as to energize each phase winding for 120 electrical degrees whereas a sine-wave control technique controls sine-wave currents to energize each phase winding for 180 electrical degrees. Figure 2.1 shows examples of phase currents for square- and sine-wave control.



(a) Square-wave control **(b) Sine-wave control**

Figure 2.1 Phase current examples

Table 2.3 summarizes the characteristics of 120-degree square-wave control and 180-degree sine-wave control.

Table 2.3 Characteristics of square-wave and sine-wave commutation

	Square-wave (120-degree) control	Sine-wave (180-degree) control
Noise/vibration	Moderate	Low
Efficiency	Moderate	Excellent
Ease of design	Simple control, small board area	Complicated control, large board area
Other	Configurable only with an IPD	Composed of a PWM controller and an IPD

The TPD4207F incorporates a level-shifting high-side driver, a low-side driver, and output power MOSFETs. The TPD4207F can directly drive a BLDC motor with an output power of 60 W or less using control signals from a PWM controller IC. The TPD4207F provides thermal shutdown, overcurrent protection, and undervoltage protection, which force its outputs to be shut down via an external signal in the event of a potentially damaging condition. These protection features help reduce design resource of peripheral circuits, reduce the system size, and improve the safety and reliability of an entire system. The built-in power MOSFETs with a maximum rated voltage of 600V have lower on-resistance than the 500-V MOSFETs in the TPD4206F. Therefore, the TPD4207F provides higher efficiency than the TPD4206F. Housed in the newly developed small SSOP30 surface-mount package, the TPD4207F helps reduce the size and thickness of a motor control board, providing greater design flexibility and reducing the size of motor applications.

The TMPM4K0FSADUG is a microcontroller suitable for vector control of a BLDC motor using sine-wave control. The TPD4207F and TMPM4K0FSADUG can be used in combination to realize sine-wave control of a BLDC motor. The TPD4207F-TMPM4K0FSADUG pair makes it possible to drive a BLDC motor with high efficiency, low acoustic noise, and low vibration through cycle-by-cycle vector control. In addition, it is possible to program protection functions and adjust rotation control and other parameters under software control.

To help obtain the best performance from the TPD4207F and TMPM4K0FSADUG, this reference guide discusses an application circuit and design considerations for sine-wave commutation of a BLDC motor.

For details of the TPD4207 and TMPM4K0FSADUG, see their datasheets.

To download the datasheet for the TPD4207F → Click Here

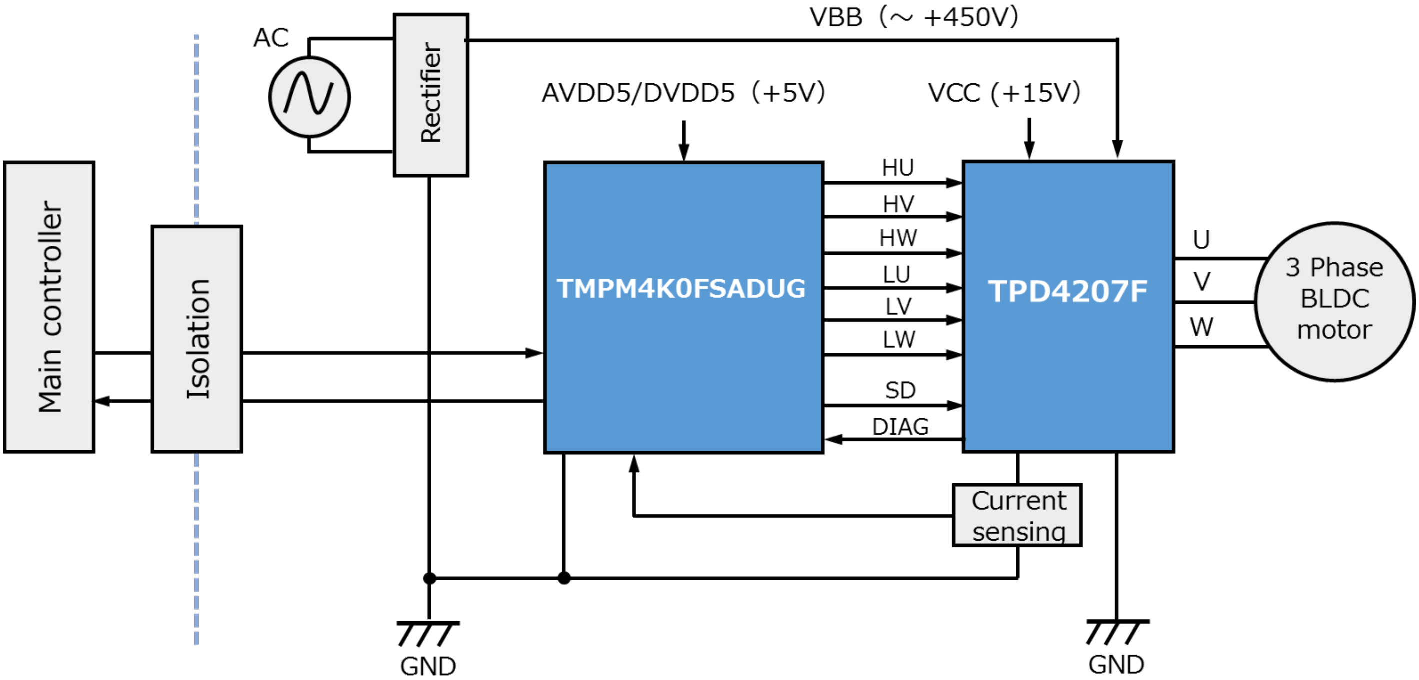
To download the datasheet for the TMPM4K0FSADUG → Click Here

Target applications :

Applications using a small compressor motor with an output power of 60W or less

- Refrigerators
- Water purifiers
- Dehumidifiers and other equipment

Circuit Example:



3. Application circuit example and the bill of materials

3.1. Application circuit example

Figure 3.1 shows a control circuit for a compressor motor.

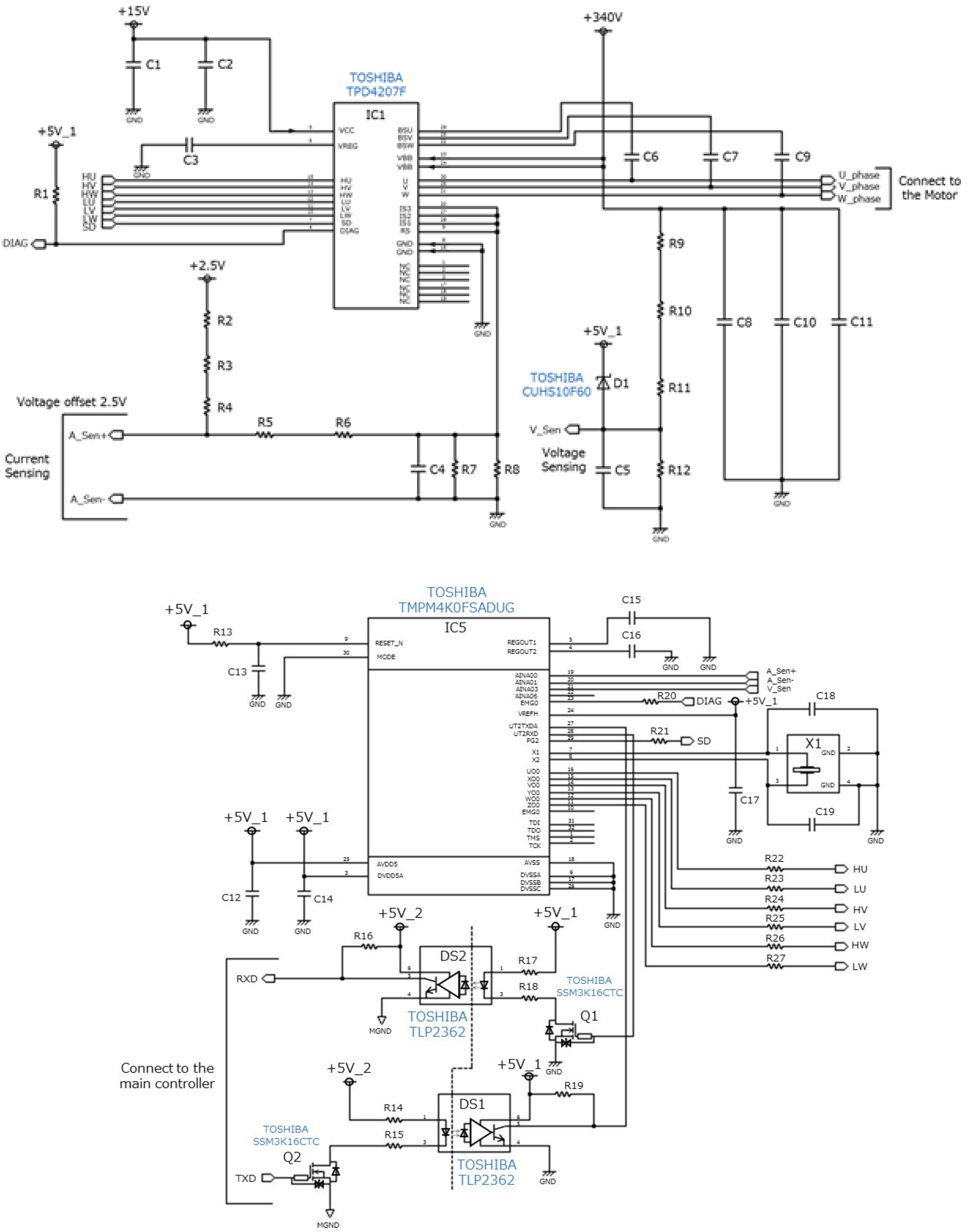


Figure 3.1 Application circuit for controlling a compressor motor

3.2. Bill of materials

Table 3.1 Bill of materials

No.	Ref.	Qty	Value	Part Number	Manufacturer	Description	Packaging	Typical Dimensions in mm (inches)
1	IC1	1	-	TPD4207F	TOSHIBA	IPD 600V	SSOP30	20.0 x 14.2
2	IC5	1	-	TMPM4K0FSADUG	TOSHIBA	TXZ4 Microcomputer	LQFP32	7.0 x 7.0
3	Q1、Q2	2	-	SSM3K16CTC	TOSHIBA	Small-signal MOSFET	CST3C	0.8 x 0.6
4	D1	1	-	CUHS10F60	TOSHIBA	Schottky barrier diode	US2H	2.5 x 1.4
5	DS1、DS2	2	-	TLP2362	TOSHIBA	Photocoupler (IC output)	SO6	3.7 x 7.0
6	X1	1	10MHz	FCX-04C	River Eletec	X'tal oscillator	-	3.2 x 2.5
7	R1、R13	2	10kΩ	-	-	Carbon, ±5%	-	1.0 x 0.5 (0402)
8	R2、R6	2	150Ω	-	-	Carbon, ±1%	-	1.0 x 0.5 (0402)
9	R3	1	100Ω	-	-	Carbon, ±1%	-	1.0 x 0.5 (0402)
10	R4	1	11kΩ	-	-	Carbon, ±1%	-	1.0 x 0.5 (0402)
11	R5	1	3.6kΩ	-	-	Carbon, ±1%	-	1.0 x 0.5 (0402)
12	R7、R8	2	240mΩ	SL1TTER240F	KOA	Current detecting resistor, 1W, ±1%	-	6.3 x 3.2 (2512)
13	R9、R10、R11	3	180kΩ	-	-	Carbon, ±1%	-	1.6 x 0.8 (0603)
14	R12	1	3.3kΩ	-	-	Carbon, ±1%	-	1.6 x 0.8 (0603)
15	R14、R15、R17、R18	4	180Ω	-	-	Carbon, ±1%	-	1.0 x 0.5 (0402)
16	R16、R19	2	2.7kΩ	-	-	Carbon, ±5%	-	1.0 x 0.5 (0402)
17	R20、R21、R22、R23、R24、R25、R26、R27	8	100Ω	-	-	Carbon, ±5%	-	1.0 x 0.5 (0402)
18	C1、C2、C3	3	4.7μF	-	-	Ceramic, 25V, ±10%	-	2.0 x 1.2 (0805)
19	C6、C7、C9	3	2.2μF	-	-	Ceramic, 25V,±10%	-	2.0 x 1.2 (0805)
20	C4、C5	2	10nF	-	-	Ceramic, 25V, ±10%	-	3.2 x 1.6 (1206)
21	C8、C10	2	1μF	-	-	Polypropylene Film, 650V, ±10 %	DIP	-
22	C11	1	1nF	-	-	Polypropylene Film, 650V, ±10 %	DIP	-
23	C12、C14	2	2.2μF	-	-	Ceramic, 10V, ±10%	-	1.0 x 0.5 (0402)
24	C13、C17	2	100nF	-	-	Ceramic, 25V, ±10%	-	1.0 x 0.5 (0402)
25	C15、C16	2	4.7μF	-	-	Ceramic, 10V, ±10%	-	1.0 x 0.5 (0402)
26	C18、C19	2	5pF	-	-	Ceramic, 50V, ±5%	-	1.0 x 0.5 (0402)

4. Circuit design

This section describes the key considerations for the design of the application circuit shown in the previous section.

4.1. TPD4207F

The TPD4207F incorporates six MOSFETs at the output stage, which are turned on and off according to three-phase PWM signals (UVWXYZ) to control a BLDC motor. The following subsections describe key considerations for using the TPD4207F.

4.1.1. Overcurrent protection

Overcurrent protection protects the TPD4207F from excessive current that is applied to the output MOSFETs in the event of rotor lock or other abnormal conditions. The TPD4207F monitors the RS terminal voltage derived from a current-sensing resistor. When the RS terminal voltage exceeds the threshold for current limiting (V_R=0.5V typical), the TPD4207F turns off all the output MOSFETs irrespective of the input signal states after a current limiting delay (Dt=3µs typical) in order to limit an increase in current. The TPD4207F recovers from overcurrent protection when all the input signals are set to the Low level. The DIAG output inverts when the TPD4207F enters and recovers from the overcurrent protection mode.

In the application circuit, the overcurrent protection threshold becomes the minimum when V_R is the minimum (=0.46V) and the current-sensing resistor has the maximum variation within its tolerance (R_S(max)). Suppose that the overcurrent protection threshold is 3.6A. Then,

$$R_S = 0.46 \div 3.6 = 0.128\ (\Omega)$$

R_S(max) is calculated to be 128mΩ as shown above. When a resistor with a tolerance of ±1% is used as the current-sensing resistor, Rs(typ) is calculated to be 126.7mΩ. Therefore, a resistor with a typical value of 120mΩ should be selected for Rs. (In the application circuit, R4 and R5 with 240mΩ are connected in parallel.) Now, let's recalculate the overcurrent protection threshold with R_S(typ)=120mΩ.

Typical overcurrent protection threshold: $I_{limit}(typ)$

$$I_{limit}(typ) = V_R(typ) \div R_S(typ)$$

Hence,

$$I_{limit}(typ) = 0.5 \div 0.12 = 4.17\ (A)$$

Maximum overcurrent protection threshold: $I_{limit}(max)$

$$I_{limit}(max) = V_R(max) \div R_S(min)$$

Hence,

$$I_{limit}(max) = 0.54 \div 0.1188 = 4.55\ (A)$$

Minimum overcurrent protection threshold: $I_{limit}(min)$

$$I_{limit}(min) = V_R(min) \div R_S(max)$$

Hence,

$$I_{limit}(min) = 0.46 \div 0.1212 = 3.80\ (A)$$

The overcurrent protection threshold falls between the maximum current of 3.6A and the maximum rated current of 5A of the TPD4207F. It was confirmed that the selection of R4=240mΩ and R5=240mΩ is appropriate.

4.1.2. Thermal shutdown (TSD)

Thermal shutdown protects the TPD4207F from excessive temperature caused by an external factor or the heat generated by the internal output MOSFETs. When the temperature at the internal temperature sensor has reached the thermal shutdown threshold (T_{SD}=135°C minimum and 185°C maximum), the TPD4207F turns off all the output MOSFETs irrespective of the input signal states. Thermal shutdown has a typical hysteresis (ΔT_{SD}) of 50°C. When the temperature falls below TSD-ΔTSD, the TPD4207F recovers from thermal shutdown and resumes operation according to the input signals. Depending on the positions of, and the distance between, a heat source and the temperature sensor, the temperature at the heat source might exceed the thermal shutdown threshold before thermal shutdown is tripped. The DIAG output inverts when the TPD4207F enters and recovers from the thermal shutdown mode.

4.1.3. Undervoltage protection

The output MOSFETs in the TPD4207F cannot turn on sufficiently if the V_{CC} or V_{BS} voltage drops. Undervoltage protection protects the TPD4207F from such abnormal conditions. When the V_{CC} voltage drops to the V_{CC} undervoltage protection threshold ($V_{CC}UVD$=11V typical), the TPD4207F turns off all the output MOSFETs irrespective of the input signal states. The V_{CC} undervoltage protection function has a hysteresis. When the V_{CC} voltage reaches the V_{CC} undervoltage protection recovery voltage ($V_{CC}UVR$=11.5V typical), the TPD4207F resumes operation according to the input signals. The DIAG output inverts when the TPD4207F enters and recovers from the V_{CC} undervoltage protection mode. However, the DIAG output might not invert if the V_{CC} voltage is lower than 7V. When the V_{BS} voltage drops to the V_{BS} undervoltage protection threshold ($V_{BS}UVD$=10V typical), the TPD4207F turns off all the output MOSFETs irrespective of the input signal states. The V_{BS} undervoltage protection function also has a hysteresis. When the V_{BSC} voltage reaches the V_{BS} undervoltage protection recovery voltage ($V_{BS}UVR$=10.5V typical), the TPD4207F resumes operation according to the input signals. The V_{BS} undervoltage protection does not cause the DIAG output to invert.

4.1.4. Timing chart and truth table

Figure 4.1 shows the timing chart of the PWM input signals of the TPD4207F. Table 4.1 shows its truth table.

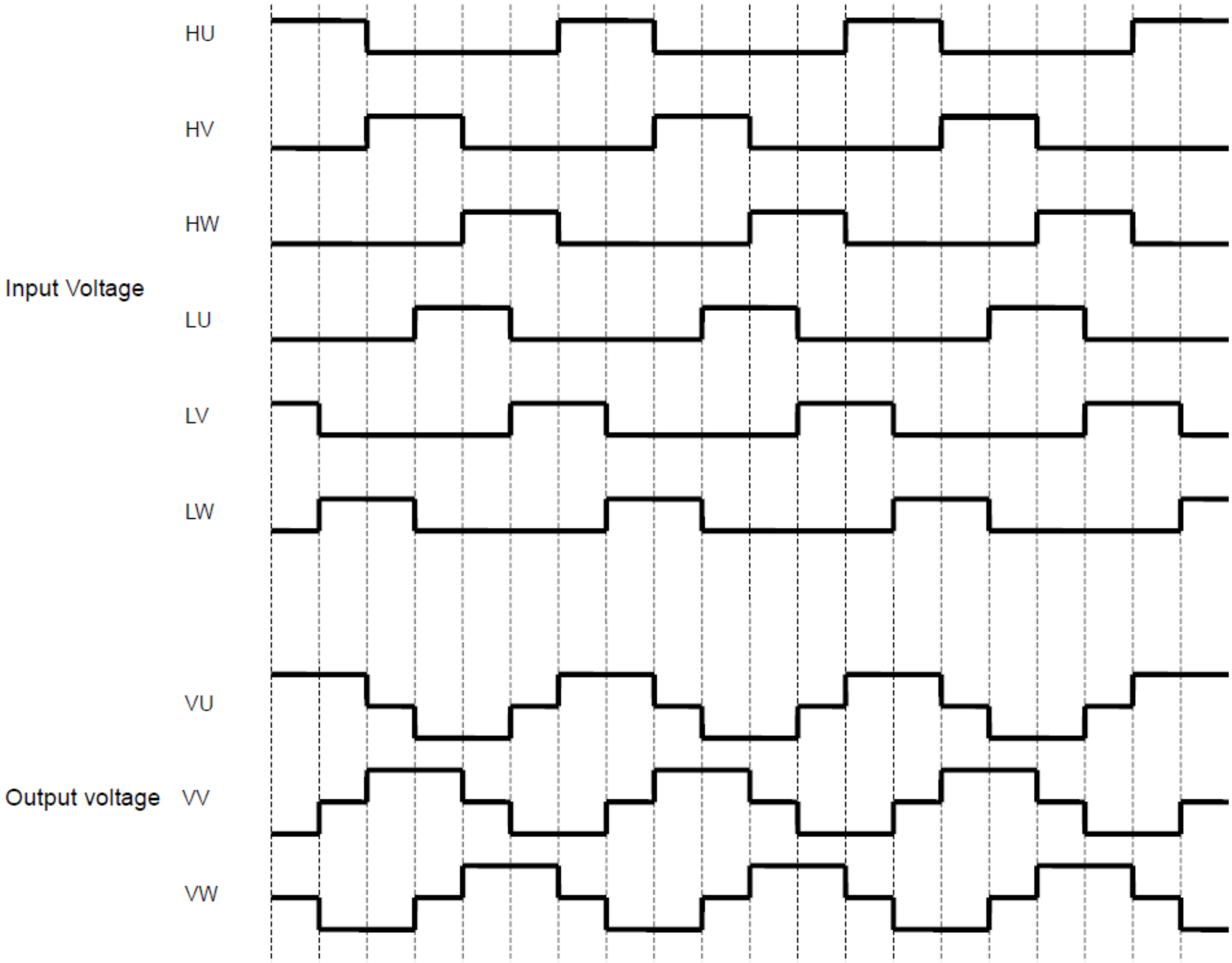


Figure 4.1 Timing chart of the TPD4207F

Table 4.2 Truth table of the TPD4207F

	Input							High side			Low side			DIAG
Mode	HU	HV	HW	LU	LV	LW	SD	U phase	V phase	W phase	U phase	V phase	W phase	
Normal	H	L	L	L	H	L	H	ON	OFF	OFF	OFF	ON	OFF	OFF
	H	L	L	L	L	H	H	ON	OFF	OFF	OFF	OFF	ON	OFF
	L	H	L	L	L	H	H	OFF	ON	OFF	OFF	OFF	ON	OFF
	L	H	L	H	L	L	H	OFF	ON	OFF	ON	OFF	OFF	OFF
	L	L	H	H	L	L	H	OFF	OFF	ON	ON	OFF	OFF	OFF
	L	L	H	L	H	L	H	OFF	OFF	ON	OFF	ON	OFF	OFF
Over-current	H	L	L	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	H	L	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
Thermal shutdown	H	L	L	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	H	L	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
V_{CC} Under-voltage	H	L	L	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	H	L	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	H	L	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
	L	L	H	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	ON
V_{BS} Under-voltage	H	L	L	L	H	L	H	OFF	OFF	OFF	OFF	ON	OFF	OFF
	H	L	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	ON	OFF
	L	H	L	L	L	H	H	OFF	OFF	OFF	OFF	OFF	ON	OFF
	L	H	L	H	L	L	H	OFF	OFF	OFF	ON	OFF	OFF	OFF
	L	L	H	H	L	L	H	OFF	OFF	OFF	ON	OFF	OFF	OFF
	L	L	H	L	H	L	H	OFF	OFF	OFF	OFF	ON	OFF	OFF
Irregular (Note)	H	L	L	H	L	L	H	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	L	H	L	L	H	L	H	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	L	L	H	L	L	H	H	OFF	OFF	OFF	OFF	OFF	OFF	OFF
SD	X	X	X	X	X	X	L	OFF	OFF	OFF	OFF	OFF	OFF	ON

X: Don't care

Note: The output of the input logic is OFF if the high side input and low side input are ON at the same time

4.1.5. Other design considerations

- The absolute maximum ratings of a semiconductor device are a set of ratings that must not be exceeded, even instantaneously. None of the absolute maximum ratings must be exceeded. Exposure to conditions exceeding the absolute maximum ratings may damage or degrade a device, or cause personal injury due to explosion or ignition.

- Use an appropriate power supply fuse to ensure that an excessive current does not continuously flow in the event of an overcurrent or a device failure. The device may be permanently damaged if it is used under conditions exceeding its absolute maximum ratings or if it is wired incorrectly or exposed to abnormal pulse noise induced by wires and a load. An excessive current, if left to flow continuously, might cause smoke or fire. The capacity, fusing time, and location of a fuse should be considered to minimize the impact of an excessive current flowing into or out of the device in the event of self-damage.

- For applications with a motor coil or other inductive load, add a protection circuit to prevent malfunction or destruction of the device due to an inrush current at power-on or a negative current generated by back-EMF at power-off. Device destruction might cause personal injury, smoke, or fire. Use a regulated power supply for the device with protection features. If the power supply is unstable, the protection features might not work properly, leading to device destruction and causing personal injury, smoke, or fire.

- Control the input signals while the V_{CC} voltage is stable. (The order of V_{BB} and V_{CC} is insignificant.) When V_{CC} and V_{BB} are powered down, the device might be permanently damaged if the V_{BB} line is disconnected by a relay or other means while the motor is running because this blocks a current recirculation path to V_{BB}.

- If a motor is allowed to stop or slow to low rpm quickly, a current recirculates to the motor power supply due to the effect of a motor’s back-EMF. This might cause a rise in supply voltage. Therefore, care should be exercised in reducing the motor speed. It is advisable to reduce the motor speed slowly so as not to damage power devices due to a rise in supply voltage. Experiment with your application to determine the rate of deceleration.

4.2. TMPM4K0FSADUG

To drive a compressor motor, the following functions are required for a microcontroller to be used in combination with the TPD4207F.

- Capability to generate three-phase PWM signals (UVWXYZ)
- Capability to monitor the DIAG output from the TPD4207F and turn off the PWM outputs in the event of an abnormal condition
- Sensorless drive using vector control (because Hall-effect sensors cannot be attached to a compressor motor for rotor position sensing)
- Capability to adjust various parameters to be able to drive various types of compressor motors
- Communication function to receive the rpm command from the main microcontroller
- Floating-point arithmetic for vector control
- AD converter with four or more channels

The TMPM4K0FSADUG used in the application circuit satisfies all these requirements. The following subsections discuss vector control and other functions specifically required to drive a compressor motor.

4.2.1. Vector control

To drive a BLDC motor with sine-wave control, it is necessary to sense the rotor position using Hall-effect sensors or other devices. However, Hall-effect sensors cannot be attached to a compressor motor because it is subject to high temperature. Instead, sensorless vector control drive is used to control a compressor motor. Since vector control requires heavy and frequent mathematical computations as well as parameter adjustment for each motor, a microcontroller with a floating-point arithmetic unit is generally used.

Vector control is a motor control method to achieve the optimal control of the motor according to the rotor position. It monitors three-phase motor currents (U, V, and W) and converts them into two orthogonal components that define the torque and magnetic flux of the motor. There are two techniques for the monitoring of three-phase currents. One technique called three-shunt current sensing adds a shunt resistor to each phase to directly monitor each phase current. The other technique called single-shunt current sensing alternately monitors three-phase currents with a single shunt resistor, which is located between GND and the point that source terminals of lower-arm MOSFET of 3 phases are combined. The application circuit shown in this reference guide uses single-shunt current sensing. Because of a fast torque response, vector control generally provides high efficiency, low vibration, and low acoustic noise.

4.2.2. Stages of vector control from startup to a steady state

To estimate the rotor position, vector control calculates the back-EMF voltage based on the output voltage, input current, motor inductance, and other parameters. However, the back-EMF voltage is too low to be measured at low rpm. To address this issue, a technique called forced commutation is used to start a motor before it is switched to normal control.

Vector control consists of the following five stages from the Stop stage to the Steady stage.

Stop stage

At this stage, there is no output to the motor. The motor may be running owing to an external load.

Positioning (DC excitation) stage

Electric currents are applied to the motor coils to generate magnetic flux in the iron core and thereby lock the rotor at an arbitrary position so that control can smoothly transition to forced commutation. After a rotor positioning time, control moves to the forced commutation (Force) stage.

Force stage

With sensorless control, the rotor position is estimated based on the back-EMF voltage from the motor. Since the back-EMF voltage is too low to be measured at zero to low rpm, the motor rpm is forced to increase so that a sufficient back-EMF voltage is generated.

Change-up stage (transition from forced commutation to a steady state)

At this stage, control transitions from forced commutation to the steady (sensorless) state. After a transition time, control moves to the Steady stage.

Steady stage

The motor runs according to the estimated rotor position. In addition, the duty cycles of the three-phase PWM signals are controlled to achieve the target rpm.

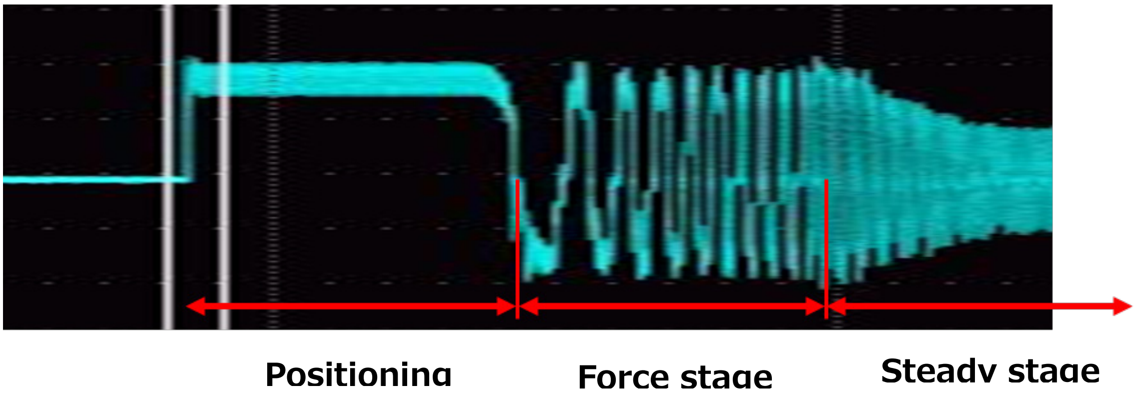


Figure 4.2 Motor current waveform at startup

4.2.3. Advanced Vector Engine Plus (A-VE+)

The TMPM4K0FSADUG incorporates a peripheral unit called Advanced Vector Engine Plus (A-VE+) that performs part of vector control computations. Because vector control requires a series of complicated computations, it would substantially increase the CPU workload if all the computations were performed by CPU software. To solve this problem, A-VE+ performs part of vector control, greatly offloading the CPU.

For details about vector control and the vector engine, visit our website.

For descriptions of vector control and the vector engine → Click Here

4.2.4. DC voltage sensing circuit

The TMPM4K0FSADUG determines the voltage to be applied to a motor. To output a DC voltage as a PWM signal, it is necessary to monitor the V_{BB} voltage at a duty cycle of 100%. The least costly way to do this is to use a resistor divider. Therefore, the application circuit shown in this reference guide uses a resistor divider.

The DC voltage sensing circuit is designed to sense a motor supply voltage in the range of 100 to 600V. Suppose that the V_{BB} voltage is divided by R9, R10, R11, and R12, and let the input voltage to the TMPM4K0FSADUG be V_{sen} and the gain of the on-chip operational amplifier be VGAIN_VBB. Then,

$$V_{sen} = V_{BB} \times \left(\frac{R12}{R9 + R10 + R11}\right) \times VGAIN\_VBB$$

Figure 4.3 shows the relationship between V_{sen} and V_{BB} when the Op-Amp Control Register is programmed to 0000 to set VGAIN_VBB to 2.

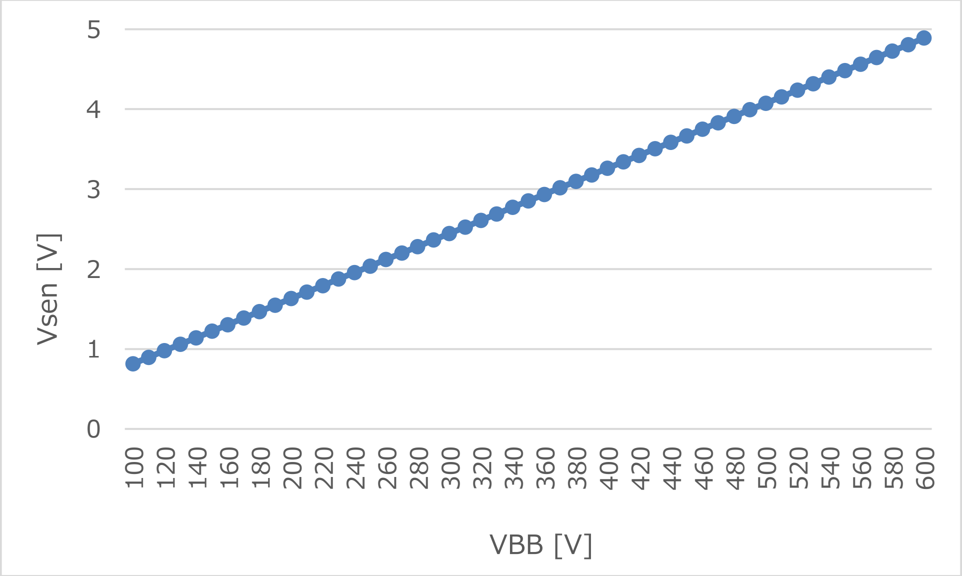


Figure 4.3 Motor supply voltage (V_{BB}) vs. V_{sen}

The safety of a system can be improved by shutting it down in the event of an overvoltage condition being detected by the TMPM4K0FSADUG. An overvoltage threshold should be set according to the application requirement. In practice, it is necessary to consider the tolerance of each component and reduce noise on V_{BB} if it is not negligible.

4.2.5. Current-sensing circuit

To calculate the parameters necessary for motor drive such as the rpm and rotation direction, it is necessary to sense the motor current with the TMPM4K0FSADUG. Accurate current sensing is important to control a motor efficiently. Although the least costly way to do this is to use current-sensing resistors, current clamping or other techniques may be used, depending on the application requirements and the restrictions on the placement of components. A current-sensing technique suitable for each application should be selected. Current-sensing resistors are used in the circuit shown below.

The gain (VGAIN_I) of the operational amplifier incorporated in the TMPM4K0FSADUG can be calculated as follows:

$$VGAIN\_I = R2'/R1'$$

where, R1′ and R2′ are gain-setting registers.

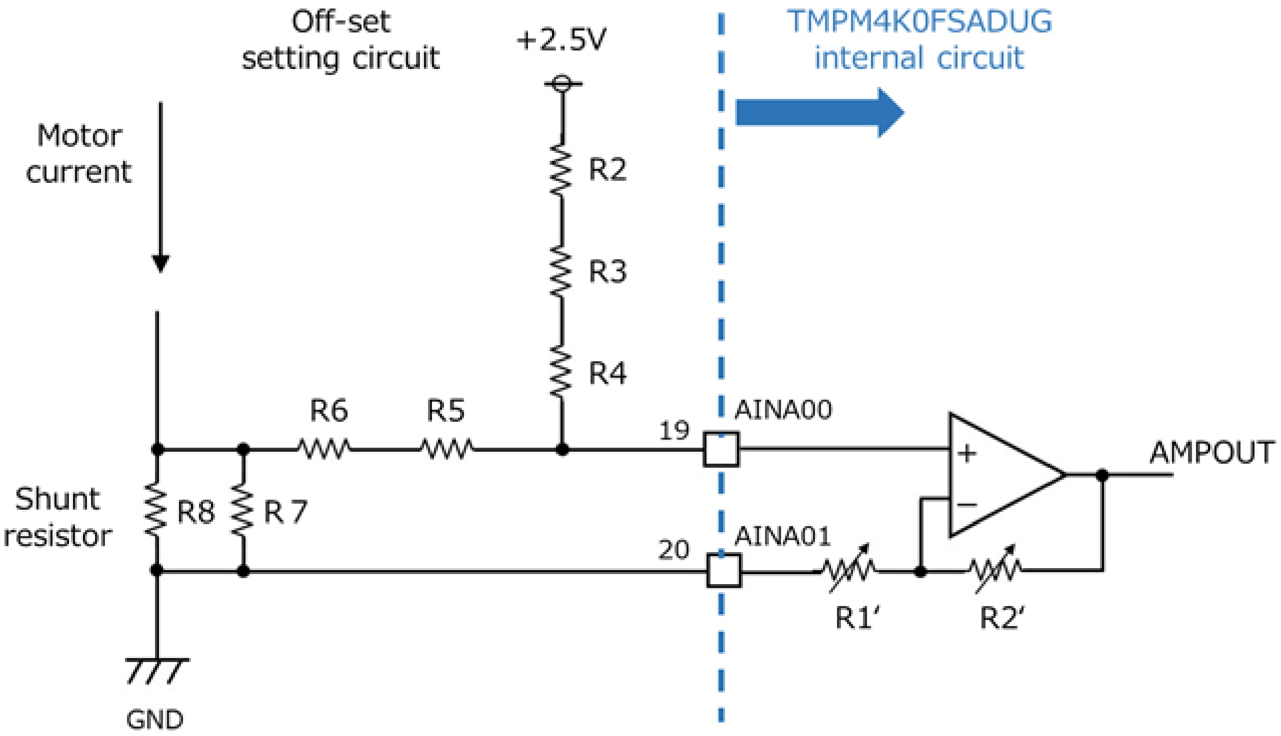


Figure 4.4 Current-sensing circuit (internal schematic of the TMPM4K0FSADUG)

Table 4.2 shows the settings of R1′ and R2′ in the TMPM4K0FSADUG.

* Resistors should be programmed so that R1′=R2+R3+R4 and R2′=R5+R6.

Table 4.2 Gain vs. R1′ and R2′

Gain	R1′ (Ω)	R2′ (Ω)
1	7500	7500
1.5	6000	9000
2	5000	10000
2.5	4286	10714
3	3750	11250
3.5	3333	11667
5	2500	12500
6	2143	12857
7	1875	13125
9	1500	13500
11	1250	13750
14	1000	14000

* R1′ and R2′ are typical values.

The current-sensing circuit is designed, assuming that the maximum motor current is 5A. V_{ref} is designed to be 2.5V so that 0A=V_{ref}.

The current-sensing circuit senses the voltage across the shunt resistors R7 and R8 (V_{Isen}). Suppose that the gain (VGAIN_I) of the operational amplifier in the TMPM4K0FSADUG is programmed to be 3. Then, the current-sensing level is calculated as follows:

$$V_{Isen} = \left((A\_Sen+) - (A\_Sen-)\right) \times VGAIN\_I + V_{ref}$$

$$VGAIN\_I = 3$$

The relationship between V_{Isen} and the motor current (I_{motor}) is graphically shown in Figure 4.5.

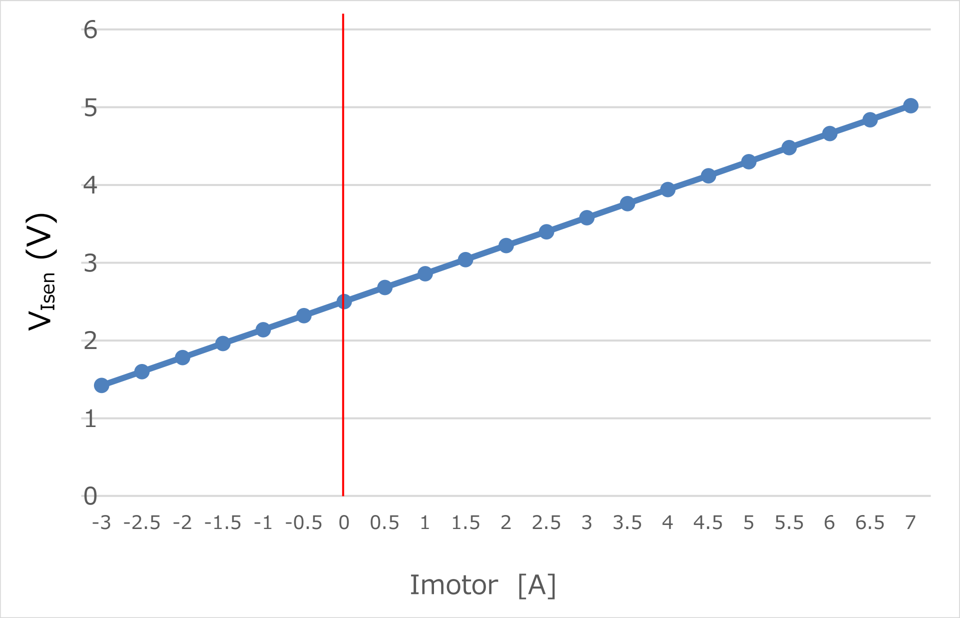


Figure 4.5 Motor current vs. V_{Isen}

4.2.6. Other design considerations

- Upon power-on, the internal nodes of the TMPM4K0FSADUG are in unknown states. The I/O pins also assume unknown states until the power supply voltage reaches the level at which the power-on reset becomes valid. The motor operation should be started after all the I/O pins assume known values as a result of a power-on reset.

4.3. TLP2362

The TLP2362 photocoupler is used to transfer electronic signals between the TMPM4K0FSADUG and the main controller. R14, R15, R17, and R18 around the TLP2362 should be selected. It is necessary to meet the recommended operating conditions shown in Table 4.3.

Table 4.3 Recommended operating conditions of the TLP2362

Characteristics	Symbol	Note	Min	Typ.	Max	Unit
Input on-state current	$I_{F(ON)}$	(Note 1)	7.5	—	14	mA
Input off-state voltage	$V_{F(OFF)}$		0	—	0.8	V
Supply voltage	V_{CC}	(Note 2)	2.7	3.3/5.0	5.5	
Operating temperature	T_{opr}	(Note 2)	-40	—	125	°C

Since the LED sides of the RXD and TXD circuits have the same configuration, R_{IN} (=R14+R15=R17+R18) is calculated as follows:

$$R_{IN} = \frac{V_{CC} - V_F - V_{OL1}}{I_F}$$

$$V_{CC} = V5R0 = V5R0\_CON$$

R_{IN} will be minimum at $V_{CC(min)}$, $V_{F(max)}$ and $V_{OL1(max)}$. Let’s assume that an LDO regulator is used to regulate V_{CC} at 5V ± 3%. Hence,

$$V_{CC}(min) = 5V \times 0.97 = 4.85V$$

Select R_{IN} to meet that the LED input current is higher than the minimum Input on-state current, 7.5mA. The maximum V_F value at Ta = 25˚C is 1.7V. The condition when V_F value is the maximum is at the minimum temperature (Tj = -40 ˚C), since V_F has a temperature coefficient of -2mV/˚C, the maximum V_F value is 1.83V. $R_{IN(max)}$ at this condition is calculated as follows:

$$R_{IN}(max) = \frac{V_{CC1} - V_F}{I_F} = \frac{(4.85 - 1.83)V}{0.0075A} = 402\ \Omega$$

So, R_{IN} of 360kΩ is selected at this time. Now, let's check the typical and maximum currents. Assuming that V_{CC1} (typ.) =5V, V_F (typ.) =1.6V, and V_{OL1} (typ.) =0V, the typical current is calculated as follows:

$$I_F(typ) == \ 9.44\ mA$$

Assuming that V_{CC1} (max) =5.15V and V_F (min) = 1 .25V, the maximum current value is calculated as follows:

$$I_F(typ) = \frac{(5.15 - 1.25)V}{360\Omega} = \ 10.83mA$$

5. Overview of the devices used

5.1. TPD4207F

5.1.1. Overview

The TPD4207F in the 30-pin SSOP package is a high-voltage BLDC motor driver with 600-V power MOSFETs that supports current sensing using three shunt resistors. The TPD4207F incorporates a level-shifting high-side driver, a low-side driver, a thermal shutdown circuit, an undervoltage protection circuit, an overcurrent protection circuit, an output shutdown (SD) function, and output power MOSFETs. The TPD4207F provides direct variable-speed control of a BLDC motor based on control signals from a microcontroller.

- Isolates high-voltage, high-current pins and control pins on the opposite sides of the package
- Supports current sensing using three shunt resistors
- Incorporates a bootstrap circuit, eliminating the need for a power supply for the high-side driver
- Incorporates bootstrap diodes
- Ideal for sine-wave control due to a dead time that can be set to as short as 1.4μs
- Incorporates a three-phase bridge composed of power MOSFETs
- Incorporates overcurrent protection, thermal shutdown, output shutdown (SD), and undervoltage protection functions
- Incorporates a 7-V regulator (typical)
- Package: SSOP30 (20.2 mm x 14.5 mm x 2.2 mm (maximum))

5.1.2. External view and pin assignment

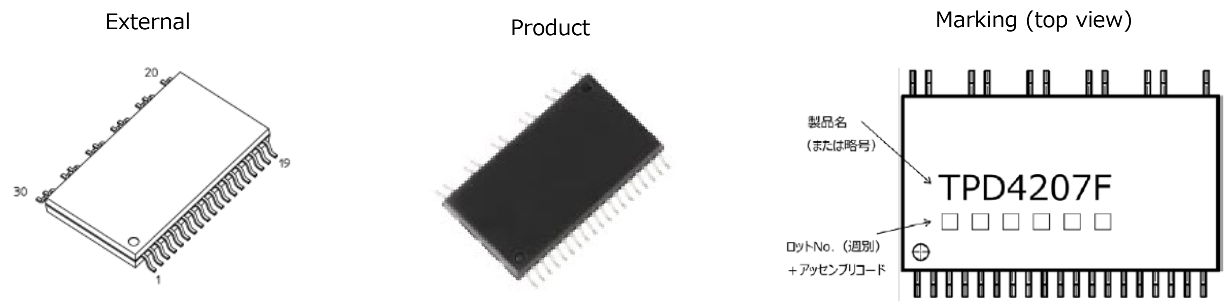

External
Product
Marking (top view)

Figure 5.1 External view and marking of the TPD4207F

5.1.3. Internal block diagram

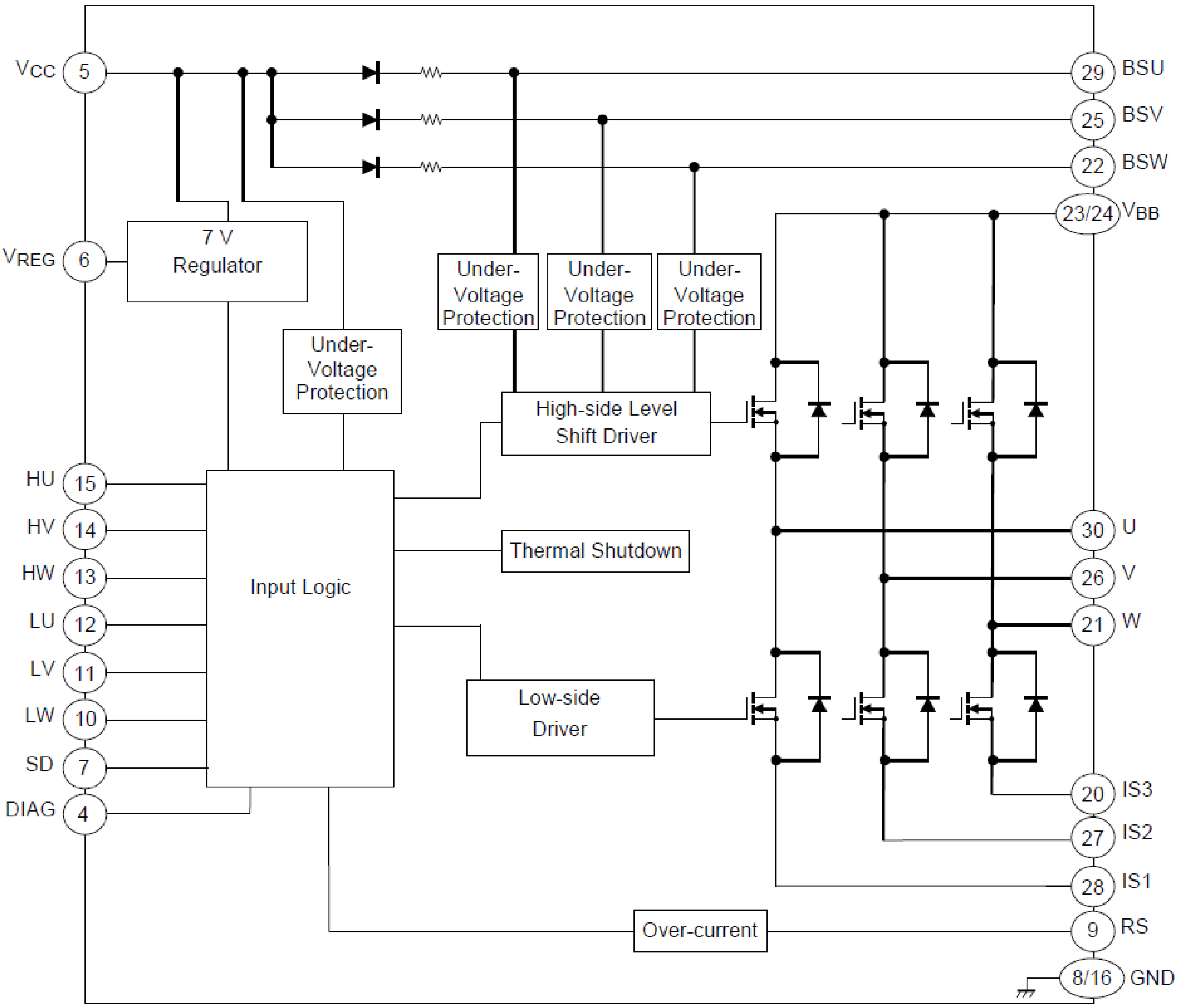


Figure 5.2. Internal block diagram of the TPD4207F

5.1.4. Pin description

Table 5.1. Pins of the TPD4207F

Pin no.	Symbol	Description
1	NC	No-connect pin, which is not connected to the internal chip
2	NC	No-connect pin, which is not connected to the internal chip
3	NC	No-connect pin, which is not connected to the internal chip
4	DIAG	Open-drain diagnostic output. Connect a pull-up resistor to the DIAG pin. The DIAG output is set to on in the event of a faulty condition.
5	V_{CC}	Control power supply pin. 15V (typ.)
6	V_{REG}	7-V regulator output pin
7	SD	External protection input (Active-Low, no hysteresis)
8	GND	Ground pin
9	RS	Overcurrent detection pin
10	LW	Control pin for the low-side Phase-W MOSFET. The MOSFET turns off when LW ≤ 1.5V and turns on when LW ≥ 2.5V.
11	LV	Control pin for the low-side Phase-V MOSFET. The MOSFET turns off when LV ≤ 1.5V and turns on when LV ≥ 2.5V.
12	LU	Control pin for the low-side Phase-U MOSFET. The MOSFET turns off when LU ≤ 1.5V and turns on when LU ≥ 2.5V.
13	HW	Control pin for the high-side Phase-W MOSFET. The MOSFET turns off when HW ≤ 1.5V and turns on when HW ≥ 2.5V.
14	HV	Control pin for the high-side Phase-V MOSFET. The MOSFET turns off when HV ≤ 1.5V and turns on when HV ≥ 2.5V.
15	HU	Control pin for the high-side Phase-U MOSFET. The MOSFET turns off when HU ≤ 1.5V and turns on when HU ≥ 2.5V.
16	GND	Ground pin
17	NC	No-connect pin, which is not connected to the internal chip
18	NC	No-connect pin, which is not connected to the internal chip
19	NC	No-connect pin, which is not connected to the internal chip
20	IS3	Source pin for the Phase-W MOSFET
21	W	Phase-W output pin
22	BSW	Phase-W bootstrap capacitor connection pin
23	V_{BB}	High-voltage power supply pin
24	V_{BB}	High-voltage power supply pin
25	BSV	Phase-V bootstrap capacitor connection pin
26	V	Phase-V output pin
27	IS2	Source pin for the Phase-V MOSFET
28	IS1	Source pin for the Phase-U MOSFET
29	BSU	Phase-U bootstrap capacitor connection pin
30	U	Phase-U output pin

5.2. TMPM4K0FSADUG

5.2.1. Overview

The TMPM4K0FSADUG is one of the motor microcontrollers of the TMPM4K Group (1) in a 32-pin package. The TMPM4K0FSADUG incorporates an 80-MHz, 32-bit Arm® Cortex™-M4 CPU core with an FPU. It also has a 64-KB flash ROM and a set of hardware units (A-VE+, 12-bit ADC, and A-PMD) for vector control and power factor correction (PFC), making it suitable for a wide range of applications, including motors, motor-driven home appliances, and industrial equipment.

- High-speed Arm® Cortex™-M4 (with an FPU)
- Incorporates functions suitable for motor control
    - AD converter (ADC), programmable motor driver (PMD), vector engine, encoder
- 5-V operation suitable for motor control

5.2.2. Pin assignment

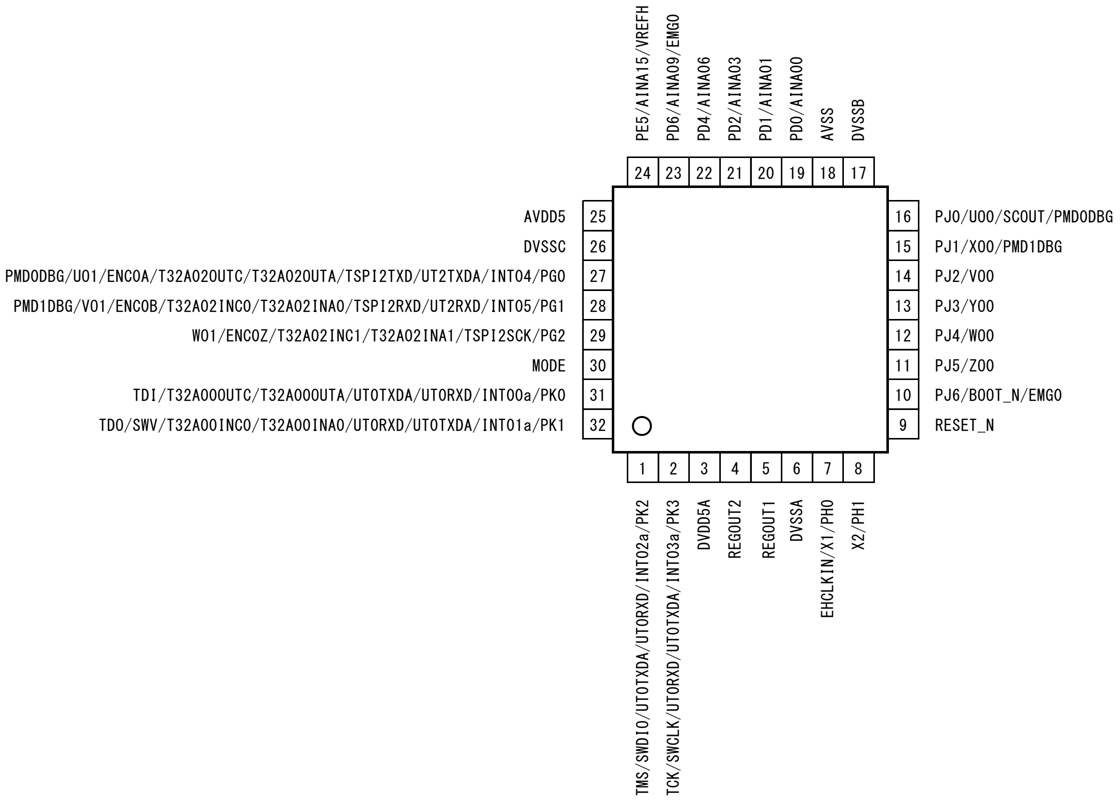


Figure 5.3 Pin assignment of the TMPM4K0FSADUG

5.2.3. Internal block diagram

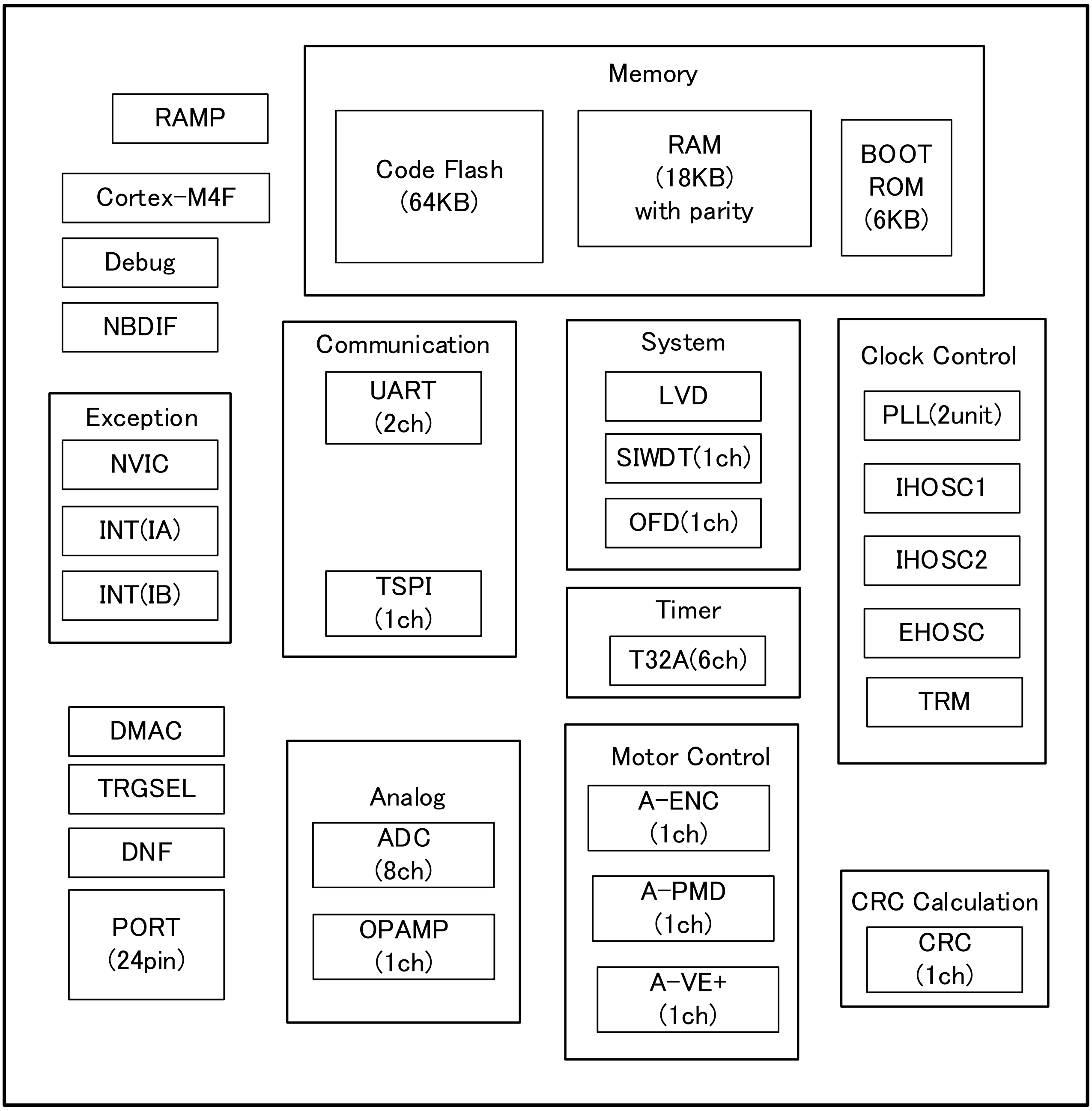


Figure 5.4 Internal block diagram of the TMPM4K0FSADUG

5.2.4. Pin description

Table 5.2 Pins of the TMPM4K0FSADUG

Pin No.	Peripheral function	Pin name	Input Output Power GND	Function
1	JTAG	TMS	Input	JTAG test mode selection pin (not used in this circuit)
2	JTAG	TCK	Input	JTAG serial clock input pin (not used in this circuit)
3	Power Supply	DVDD5A	Power	Power supply pin for digital （5V)
4	Power Supply	REGOUT2	Input	Connection pin with a capacitor for a regulator （4.7uF)
5	Power Supply	REGOUT1	Input	Connection pin with a capacitor for a regulator （4.7uF)
6	Power Supply	DVSSA	GND	GND pin for digital
7	Control pin	X1	Input	Connection pin with high a speed oscillator
8	Control pin	X2	Output	Connection pin with high a speed oscillator
9	Control pin	RESET_N	Input	Reset signal input pin
10	Advanced Programmable Motor control circuit (A-PMD)	EMG0	Input	Emergency state detection input pin (not used in this circuit)
11		ZO0	Output	Z phase output pin
12		WO0	Output	W phase output pin
13		YO0	Output	Y phase output pin
14		VO0	Output	V phase output pin
15		XO0	Output	X phase output pin
16		UO0	Output	U phase output pin
17	Power Supply	DVSSB	GND	GND pin for digital
18	Power Supply	AVSS	GND	GND pin for analog, reference GND pin for analog
19	Analog to Digital Converter (ADC)	AINA00	Input	Analog input pin
20		AINA01	Input	Analog input pin
21		AINA03	Input	Analog input pin
22		AINA06	Input	Analog input pin （not used in this circuit)
23	Advanced Programmable Motor control circuit (A-PMD)	EMG0	Input	Emergency state detection input pin
24	Power Supply	VREFH	Input	Reference pin for analog
25	Power Supply	AVDD5	Power	Power supply pin for analog, reference pin for analog
26	Power Supply	DVSSC	GND	GND for digital
27	UART	UT2TXDA	Output	Asynchronous serial communication data output pin TXD
28		UT2RXD	Input	Asynchronous serial communication data input pin RXD
29	I/O	PG2	Output	Shut down output oin
30	Control pin	MODE	Input	Mode pin (must be fixed to "Low" level)
31	JTAG	TDI	Input	JTAG serial data input pin (not used in this circuit)
32	JTAG	TDO	Output	JTAG serial data output pin (not used in this circuit)

Note 1: Apply an equal voltage to DVDD5A, DVDD5B, and DVDD5C when these pins are available.

Note 2: Apply an equal voltage to DVSSA, DVSSB, and DVSSC when these pins are available.

Note 3: Do not short-circuit REGOUT1 and REGOUT2 to DVDD5A, DVDD5B, DVDD5C, DVSSA, DVSSB, or DVSSC.

Note 4: See the Electrical Characteristics table for capacitor values.

Note 5: Apply an equal voltage to DVDD5 and AVDD5.

5.3. TLP2362

5.3.1. Overview

The TLP2362 is a photocoupler in the SO6 package that consists of a GaAlAs infrared light-emitting diode (LED) with high light output optically coupled with a high-gain, high-speed photosensor IC chip. The TLP2362 is guaranteed for proper operation over an ambient temperature range of -40 to 125°C and a supply voltage range of 2.7 to 5.5V. Its output has an open-collector configuration. The photosensor has a galvanic shield to provide an instantaneous common-mode rejection voltage of ±20kV/μs and thereby an excellent noise immunity between input and output pins.

- Inverting output (open-collector output)
- Operating temperature range: -40 to 125°C
- Voltage supply range: 2.7V to 5.5V
- Data transfer rate: 10MBd (NRZ)
- Threshold input current: 5.0mA (maximum)
- Supply current: 4mA (maximum)
- Instantaneous common-mode rejection voltage: ±20kV/μs (minimum)
- Isolation voltage: 3750Vrms (minimum)
- Package: SO6 (3.7mm x 4.55mm x 2.1mm (typical))

5.3.2. External view and pin assignment

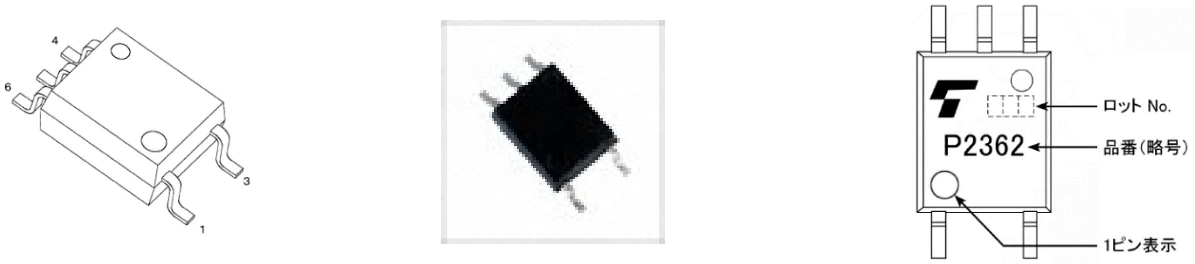
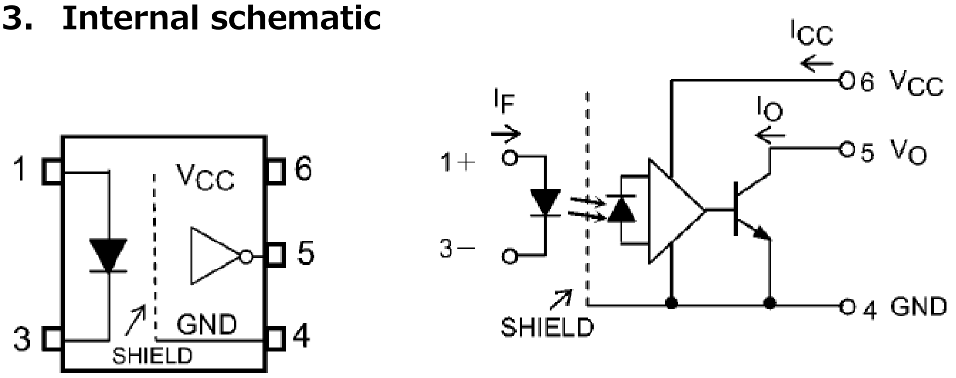

External
Product
Marking (top view)

Figure 5.5 External view and marking of the TLP2362

5.3.3. Internal schematic



1: Anode
3: Cathode
4: GND
5: V_O (output)
6: V_{CC}

Figure 5.6 Internal block diagram of the TLP2362

5.3.4. Description

Table 5.3 Truth table

Input	LED	Output
H	ON	L
L	OFF	H

Table 5.4 Physical parameters

Parameter	Min	Unit
Creepage distance	5.0	mm
Clearance distance	5.0	
Distance through insulation	0.4	

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