H-bridge Drive Circuit
for Automotive and Industrial
DC Motors

Reference Guide

RD177-RGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. 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.

In line with the low power consumption requirement of home appliances and increasing vehicle electrification, the importance of motors is growing dramatically. There are various kinds of motors. For example, brushed direct-current (DC) motors are commonly used in automotive applications, toy trains and so on. Nowadays, brushed DC motors are the most widely used due to their excellent controllability, high efficiency, ease of size reduction, and low price. Stepping motors, which are also in widespread use, are characterized by their high accuracy. For example, industrial precision machines require high positioning accuracy, which is enabled by stepping motors. In addition, stepping motors ensure repeatability of movement. The stepping motors found in air-conditioner louvers also feature long service life and quiet operation.

Brushed DC motors use brushes to send electric currents to coils. A motor's rotor has several coils, and a commutator is attached on the motor shaft. The commutator is a rotating electrical switch that reverses the current direction in the rotor coils periodically. The commutator is connected to the coils rotating inside magnetic fields. As a coil rotates, it makes contact with one brush on the power supply side. At this point, the commutator reverses the direction of current through the coil. The commutation sequence is controlled to produce an even torque.

In contrast, BLDC motors do not use any brush (i.e., mechanical contactor) or commutator to change the current direction. Instead, BLDC motors rely on sensors and electronic circuits (collectively called a "driver"). Current commutation using an electronic motor driver was enabled by the progress of semiconductor devices. Being similar in the principle of operation, brushed and BLDC motors have almost the same current-to-torque and voltage-to-rpm relationships. However, as the structure of BLDC motors is similar to that of alternating-current (AC) motors, BLDC motors provide the combined advantages of both DC and AC motors. BLDC motors are small, provide high output power, generate no internal spark or noise due to brushes, have a long service life being free from mechanical wear, and exhibit low energy loss. Therefore, BLDC motors are widely used for various applications including computers and home appliances.

TPD7212F/FN is a power MOSFET gate driver for a 3-phase full-bridge circuit with a charge pump method. Since the charge pump circuit for the high side drive is built-in for 3 phases, H bridge drive circuit for DC motor can be constituted by using 2 phases out of 3 phases.

Combined with an external discrete N-channel MOSFET, the H-bridge drive circuitry for DC motors can be easily configured with large currents.

It is also equipped with a load short (overcurrent) detection comparator and a power supply reverse connection protection function to protect the system and ensure safe operation even in abnormal situations such as load short circuits or incorrect connection of reverse polarity power supplies, which have a large impact on the system due to the large current system.

This reference guide describes the operation and application of the load short (overcurrent) detection function and the power supply reverse connection protection function, which are important to safely operate the system including the high-current load switch.

Refer to the datasheet for TPD7212F/FN and TPD7104AF functions and detailed information.

Download TPD7212F datasheet from here → Click Here

Download the new TPD7212FN data sheet here → Click Here

Download TPD7104AF datasheet from here → Click Here

Note) Regarding TPD7212F/FN, the F and FN types have the same function but different package. Therefore, the TPD7212F will be described below as a representative.

1.1. Target Application

- For automotive use: Door locks, sliding door, etc.
- For consumer and industrial use: OA equipment, home appliances, etc.

Circuit example

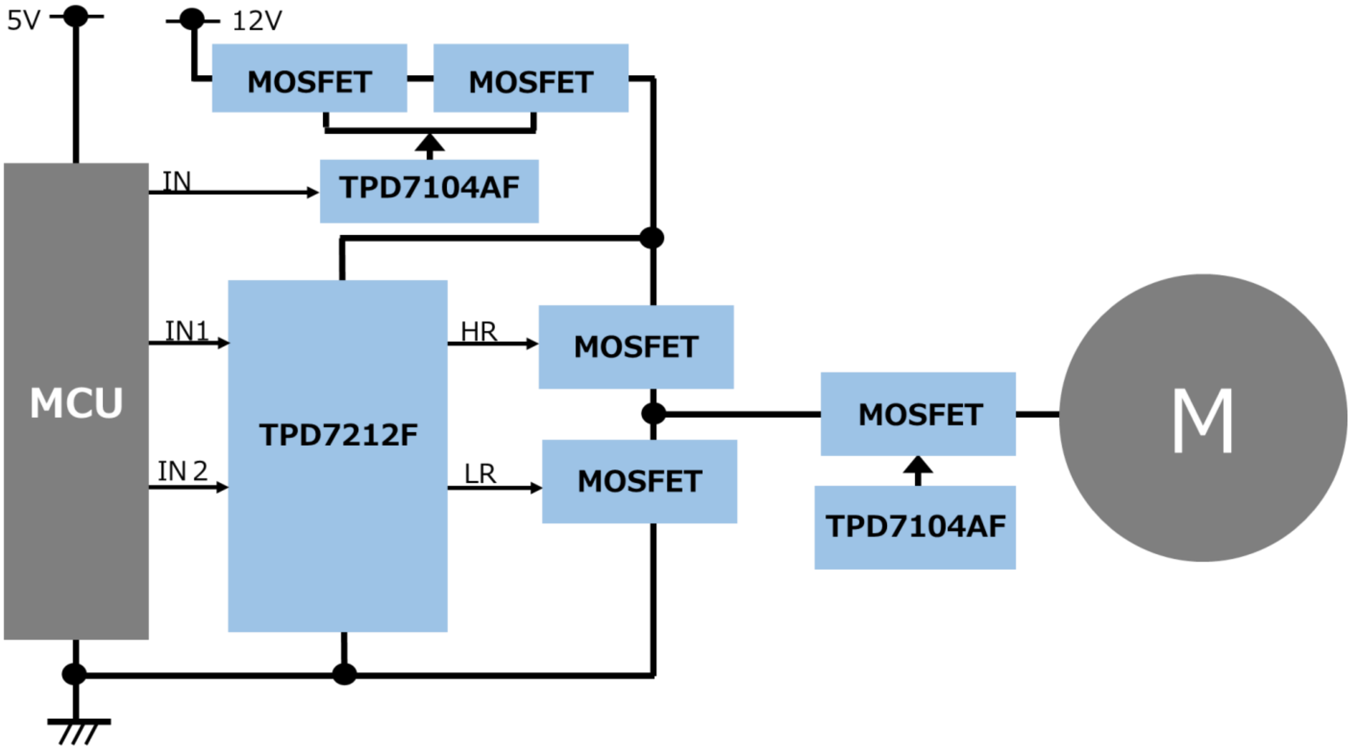


Fig. 1.1 Example of H-bridge Drive Circuit for DC Motor (R-Phase)

※ Fig. 1.1 shows an example of the R-phase, but the L-phase is the same.

※ A lineup of MOSFET suitable for the above applications.

For more information about MOSFET, go here to → Click Here

2. Application Circuit Block Diagram

Fig. 2.1 is a block diagram of an application circuit for H-bridge drive for DC motors. The functions (1) to (5) in the block diagram are described in detail in Chapter 4 "Application Circuit Design Guide," and should be checked together.

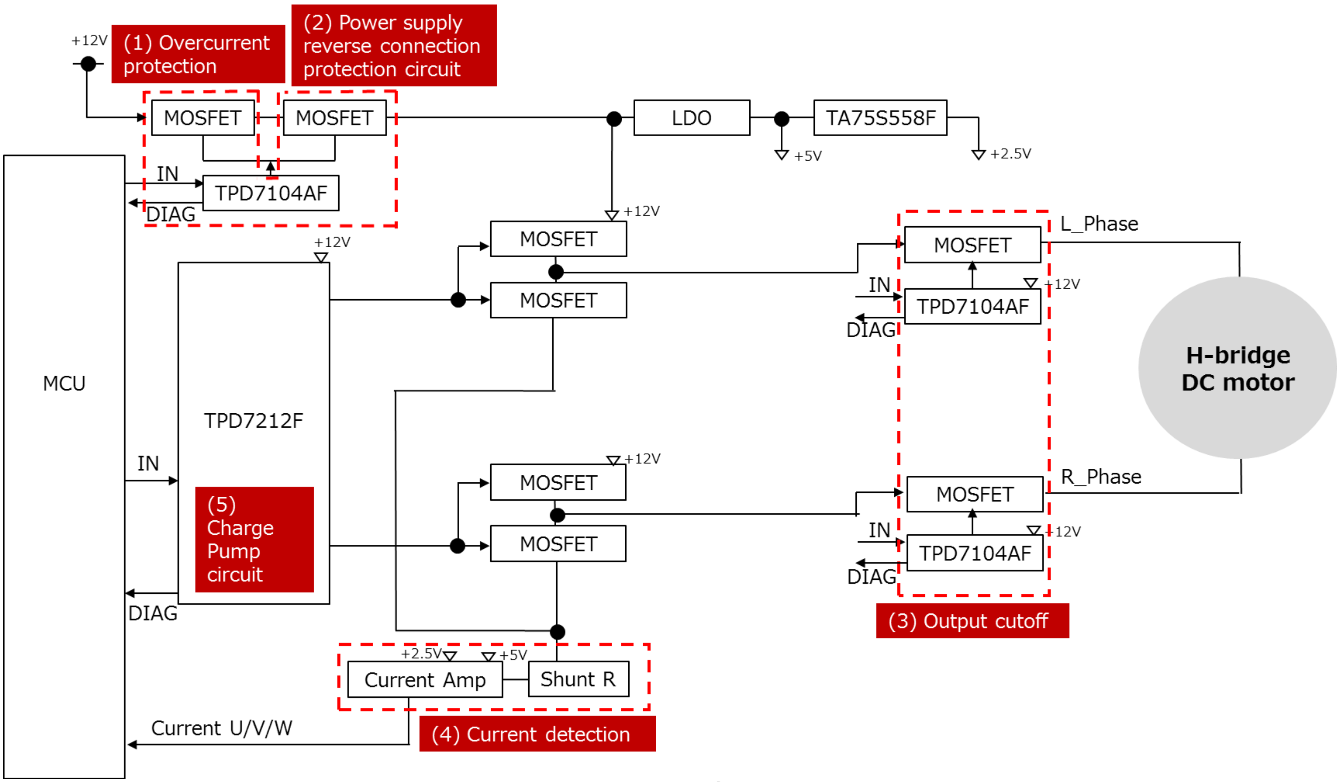


Fig. 2.1 H-bridge Drive Applications for 1 DC Motors Block Diagram

The N-channel MOSFET is TPW1R104PB (V_{DS}=40 V, $R_{DS(ON)}$=1.14 mohms (max)). A TPD7212F is for the gate drive of the H-bridge drive MOSFET for DC-motors. The gate driver of the output cutoff MOSFET is TPD7104AF to protect the power supply in the event of an error (1) overcurrent protection, (2) power supply reverse connection protection, and interruption of each phase current (3). PWM control signals, power supply, and phase current on/off control must be received from the MCU and other controller ICs. In addition, the (4) current detection using an op-amp and the diagnostic output of the gate driver are output to the controller IC. And also, TPD7212F drives an N-channel MOSFET on the high side, which requires a boost to bias the gate. (5) By adopting a charge pump circuit, 100% on-duty control is possible.

(1) Overcurrent protection → 4.1 "Overcurrent protection function"
(2) Power supply reverse connection protection → 4.2 Power supply reverse connection protection function
(3) Output Cutoff → 4.3 Output cutoff function
(4) Current detection → 4.4 Current detection method
(5) Charge Pump Circuit → 4.5 Design of the charge pump circuit

Please refer to (RD177-SCHEMATIC-01) for the schematic diagram of the H-bridge drive for DC-motors.

The overall schematic of the H-bridge drive for the DC-motor from here → Click Here

TPW1R104PB datasheet from here → Click Here

More information on MOSFET devices from here → Click Here

3. Bill of Materials

Table 3.1 is a bill of materials for the overall circuit diagram of the H-bridge drive for DC motors.

Table 3.1 Bill of materials for H-bridge DC Motor Drive Applied Circuits

No.	Ref.	Q'ty	Value	Part Number	Manufacturer	Description	Package Name	Standard Dimensions in mm (inches)
1	IC1,IC4,IC6	1	-	TPD7104AF	TOSHIBA	IPD	PS-8	2.9 x 2.8
2	IC3	1	-	NJW4107U2-05A-T1	JRC	LDO	SOT-89-5-2	4.5 x 4.5
3	IC5	1	-	TPD7212F	TOSHIBA	IPD	WQFN32	5.0 x 5.0
4	IC11	1	-	LTC2054HS5	TEXAS INSTRUMNTS	Opamp	TSOP-23	2.9 x 2.8
5	Q1	1	-	SSM3K17FU	TOSHIBA	MOSFET	USM	2.0 x 2.1
6	Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9	8	-	TPW1R104PB	TOSHIBA	MOSFET	DSOP	5.0 x 6.0
7	D1,D2,D4,D5,D10,D11,D12,D13,D14,D15,D16,D17,D18,D19	14	-	CRZ16	TOSHIBA	Zener diode	S-FLAT	1.6 x 3.5
8	D3,D6	2	-	CMZ27	TOSHIBA	Zener diode	M-FLAT	2.4 x 4.7
9	D7,D8,D9	3	-	CRH01	TOSHIBA	Diode	S-FLAT	1.6 x 3.5
10	R1,R2,R3,R8,R9,R10,R11,R15,R31,R32,R36,R37	12	10K			Carbon ±5%	1608	1.6 x 0.8 (0603)
11	R4,R6,R33,R38	4	200K			Carbon ±5%	1608	1.6 x 0.8 (0603)
12	R5,R34,R39	3	1K			Carbon ±5%	1608	1.6 x 0.8 (0603)
13	R12,R13,R17,R18	4	10			Carbon ±5%	1608	1.6 x 0.8 (0603)
14	R14	1	1K			Carbon ±１%	1608	1.6 x 0.8 (0603)
15	R16,R20,R23,R24	4	10			Carbon ±1%	3216	3.2 x 1.6 (1206)
16	R19,R26	2	10K			Carbon ±1%	1608	1.6 x 0.8 (0603)
17	R21,R22,R29,R30	4	22			Carbon ±5%	1608	1.6 x 0.8 (0603)
18	R25	1	1m	PSEDTE2L00F	KOA	Current detecting resistor,5W ±1%	6464	6.4 x 6.4
19	R27,R28	2	390			Carbon ±1%	1608	1.6 x 0.8 (0603)
20	C1,C8	2	330uF			Aluminum、50V,±20%	-	DIP
21	C2,C17,C18	3	100nF			Ceramic,50V,±10%	1608	1.6 x 0.8 (0603)
22	C3,C4,C6,C10,C11	5	2.2uF			Ceramic,50V,±２０%	1608	1.6 x 0.8 (0603)
23	C5,C7	2	4.7uF			Ceramic,50V,±10%	3216	3.2 x 1.6 (1206)
24	C12,C14	2	1nF			Ceramic,50V,±10%	1608	1.6 x 0.8 (0603)
25	C13,C16	2	100uF			Ceramic,50V,±２０%	-	DIP
26	C15	1	100nF			Ceramic,50V,±10%	1608	1.6 x 0.8 (0603)

4. Applied Circuit Design Guide

This chapter describes the five key points for designing "Overcurrent protection", "Power reverse connection protection function", "Output cutoff", "Current detection", and "Charge pump circuit" in chapters 4.1 to 4.5.

4.1 Overcurrent Protection Function

Overcurrent protection is a function that cuts off the power supply path when an overcurrent occurs due to a load short circuit or inverter error. Fig. 4.1 shows the overcurrent protection circuit.

※ Fig. 4.1 shows a circuit configuration that detects the current externally (Fig. 4.4 Current Detection Methods) and shuts off the current (turns off the MOSFET) by a signal from the MCU.

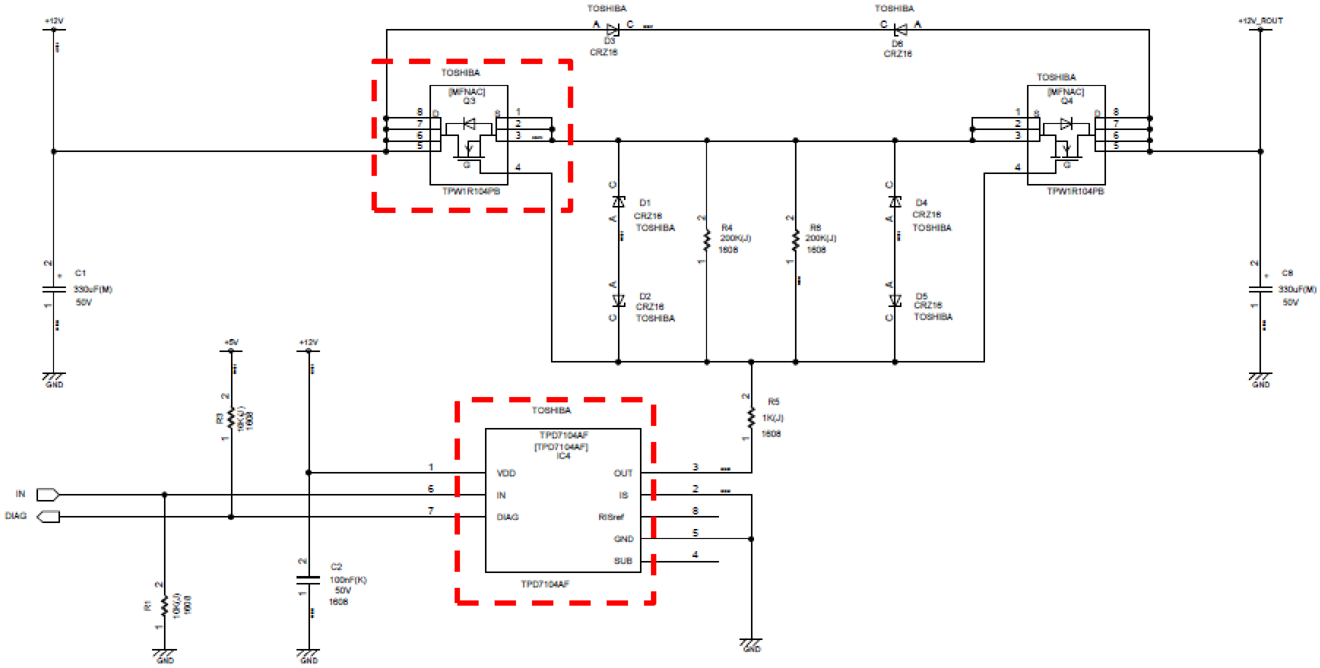


Fig. 4.1 Overcurrent Protection Circuit

Of the two MOSFET arranged in series in Fig. 4.1, Q_3 MOSFET is to shut off the overcurrent. In this circuit, the overcurrent protection function is realized by using IC4 (TPD7104AF). Refer to Reference Design (RD016-RGUIDE-01) for overcurrent protection function using TPD7104AF.

TPD7104AF reference design from here → Click Here

4.1.1 Simulation Verification

The overcurrent protection function is effective for MOSFET protection when the load is shorted. Table 4.1 lists the simulation conditions and procedures, and Fig. 4.2 shows the simulation circuit. Since MOSFET has a built-in parasitic diode called a body diode, a common-source pin like M14 and M15 in Fig. 4.2 is connected to cut off the current generated in both directions. Current interruption controls the VIN pin of TPD7104AF.

Table 4.1 Simulation Conditions and Procedures

1	VBB	12 V
2	U1	IN1=H state, IN5=PWM (20kHz)
3	M12、M13	Conducting state
4	Start of simulation	
5	U7VIN	L-state for 9 ms to 11 ms (M14, M15 off)

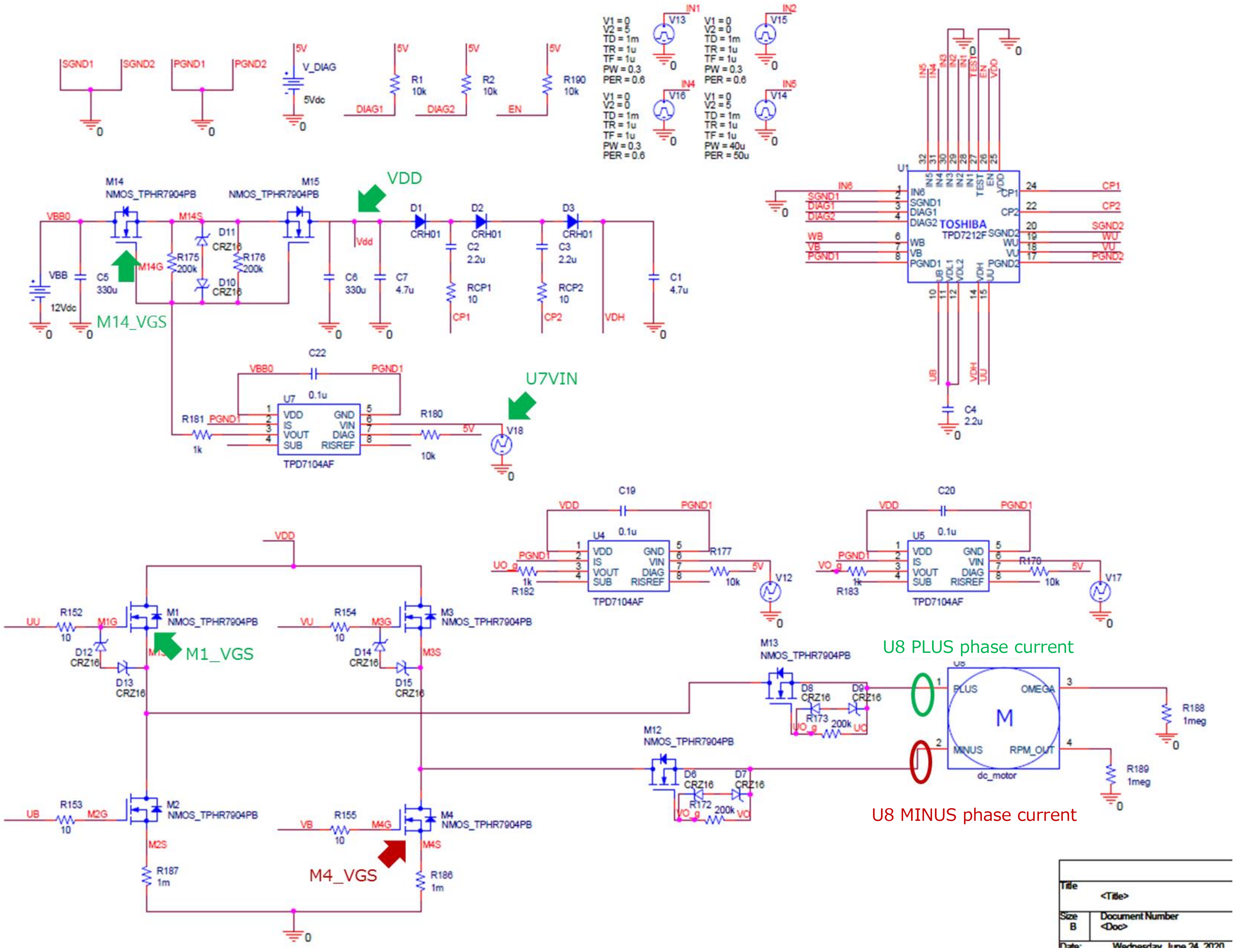


Fig. 4.2 Overcurrent Protection Simulation Circuit

Fig. 4.3 shows the simulation waveform when the power line is shut off. The simulated step is to set the VIN pin of the U7 to the L-state and turn off MOSFET M14 and M15 during the normal operation period from 9 ms to 11 ms. Consequently, no power is supplied from VBB0 pin and the phase current of the motor is interrupted.

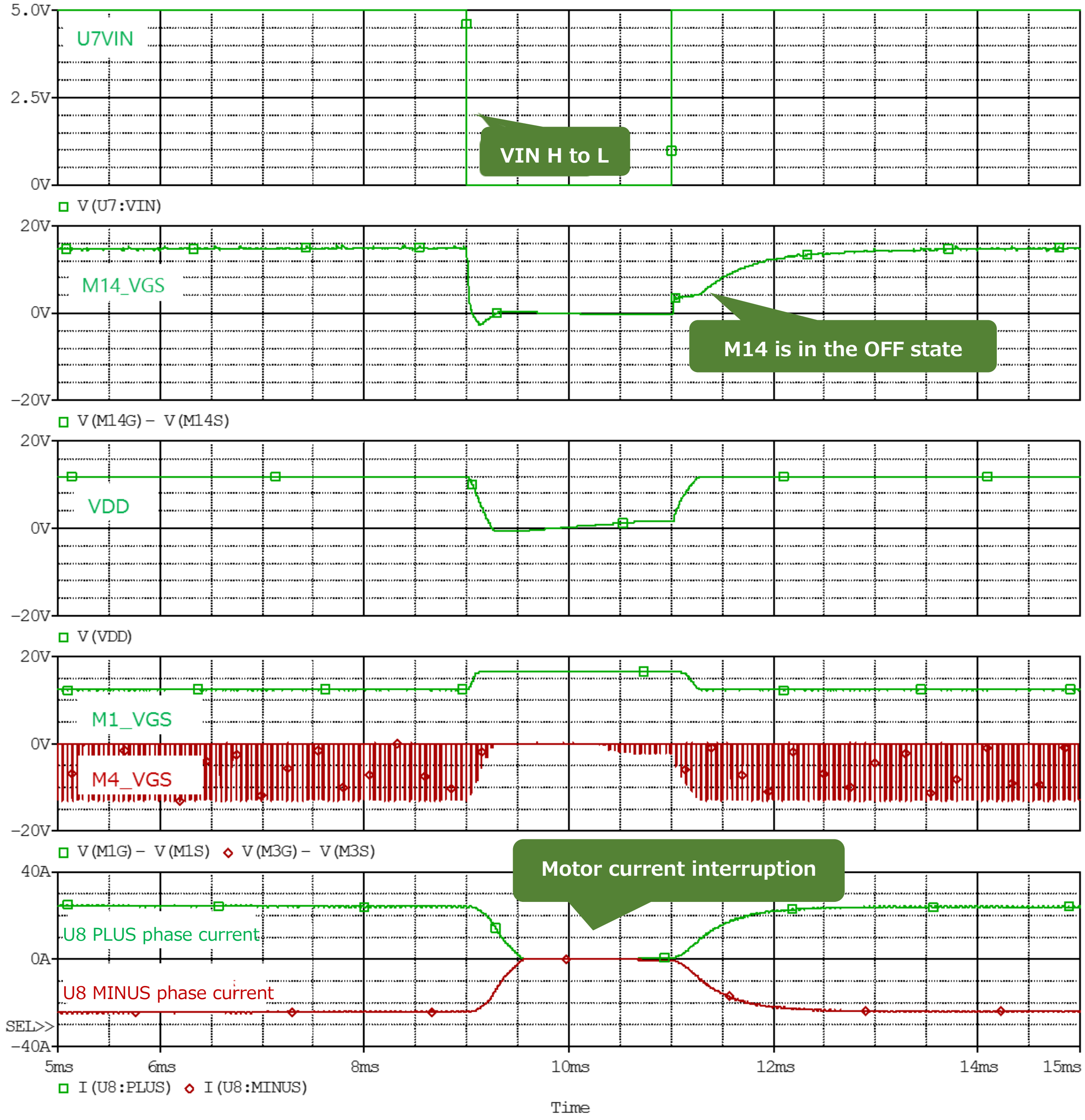


Fig. 4.3 Simulation Waveform for Overcurrent Protection

4.2 Power Supply Reverse Connection Protection Function

Power supply reverse connection protection is a function that suppresses current to prevent damage to the control unit if the battery is accidentally connected in reverse. Fig. 4.4 shows the power supply reverse connection protection circuit. Of the two MOSFET arranged in series in Fig. 4.4, Q_4 is MOSFET for protecting the power supply from reverse connection. Q_4 must be kept off reliably when the power supply is reversed. IC4 (TPD7104AF) enables the power supply reverse-connection protection function by opening the SUB pin.

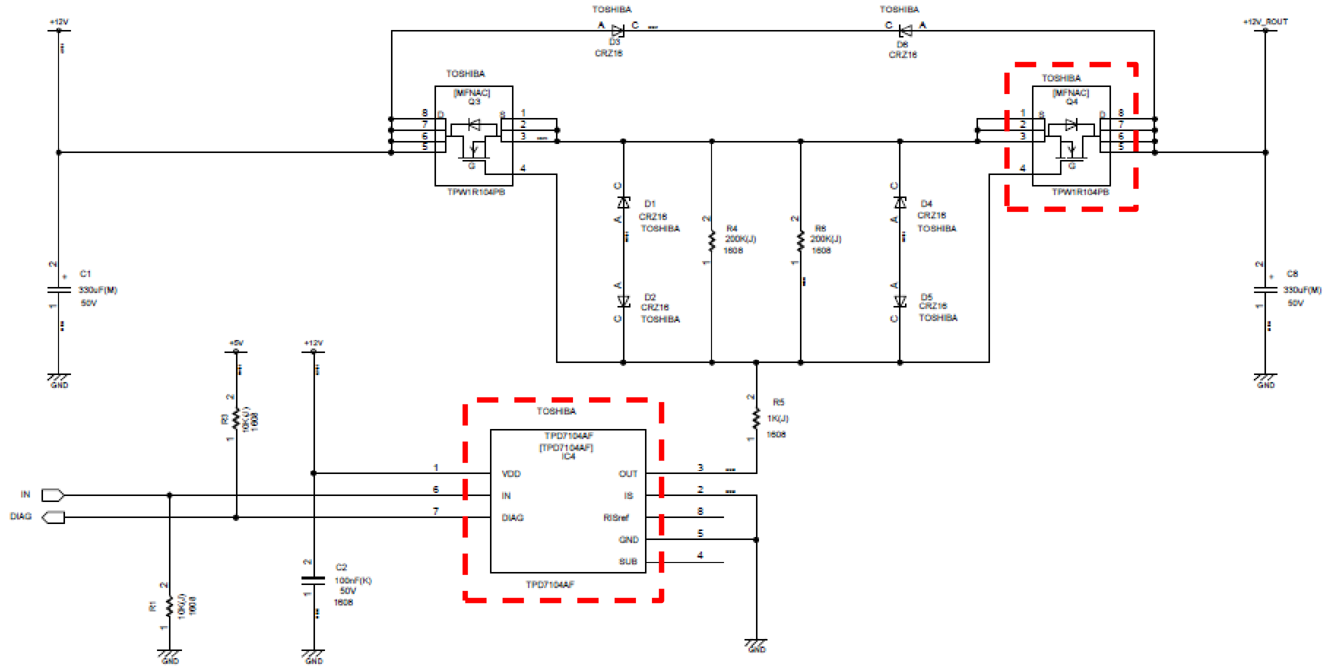


Fig. 4.4 Power Supply Reverse Connection Protection Circuit

4.2.1 Simulation Verification

Table 4.2 lists the simulation conditions and procedures, and Fig. 4.5 shows the simulation circuit. The power supply is reversed by setting VBB0 pin to-12 V. M15 V_{GS} and drain current are monitored. Fig. 4.6 shows the simulation waveform. It can be seen that the drain current M15_I_D is held down to several tens of μA and the reverse current is suppressed.

Table 4.2 Simulation Conditions and Procedures

1	VBB0	-12 V

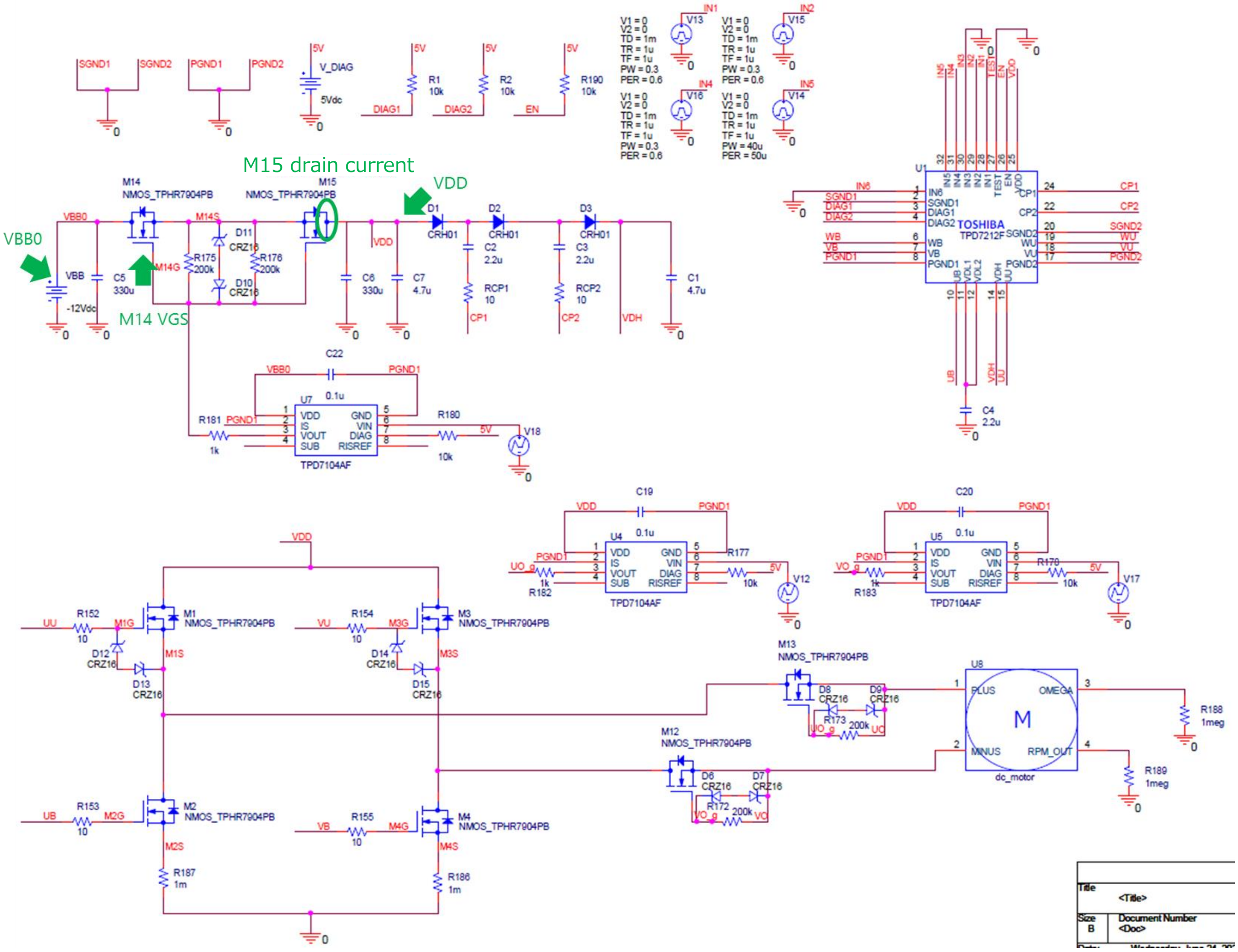


Fig. 4.5 Power Supply Reverse Connection Protection Simulation Circuit

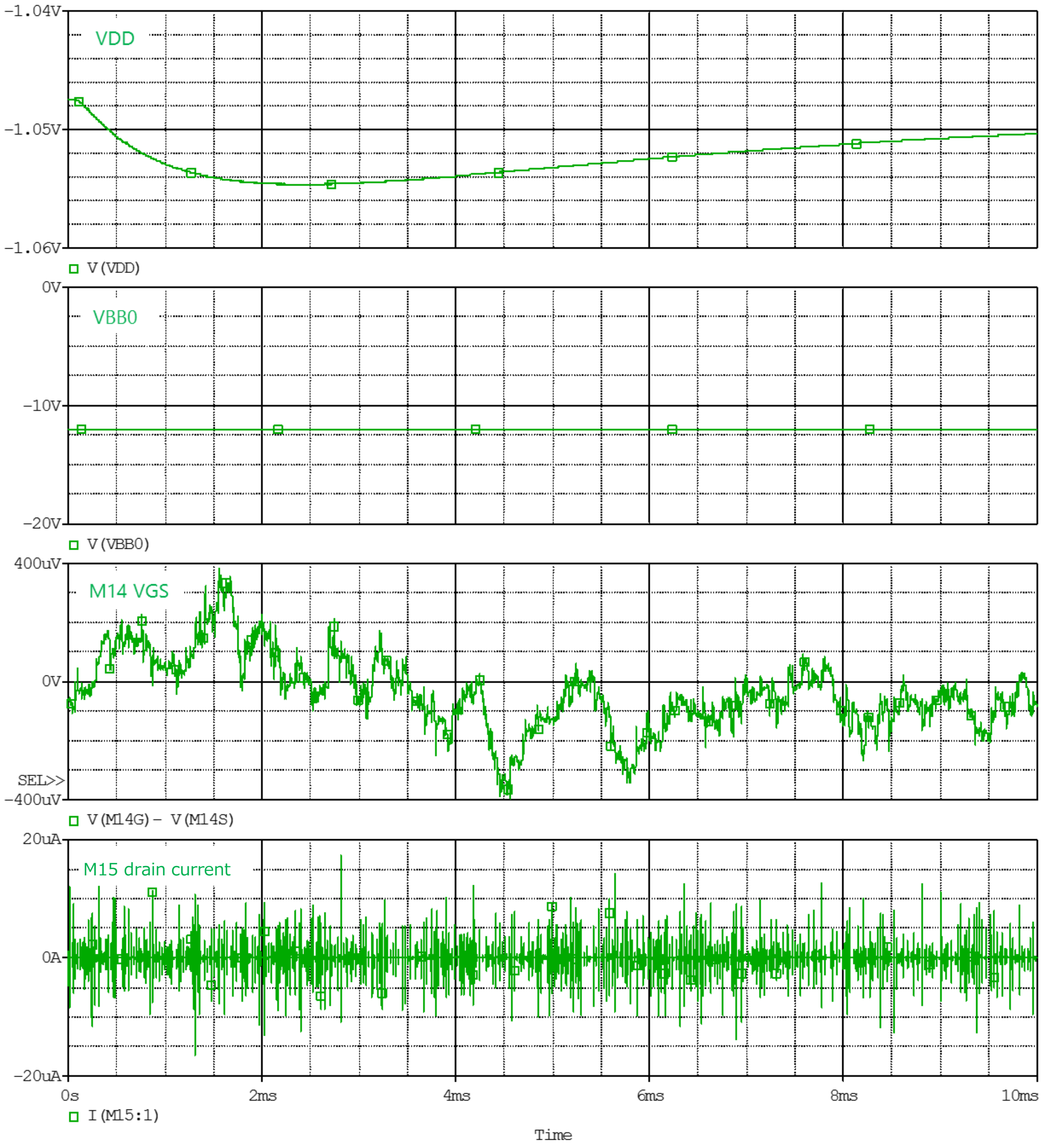


Fig. 4.6 Power Supply Reverse Connection Protection Simulation Waveform

4.3 Output Cutoff Function

In this circuit, the output cutoff function is realized by using IC6 (TPD7104AF). By inputting the signal from the controller to the IN of TPD7104AF as shown in Fig. 4.7, the output can be controlled by MOSFET connected to the OUT. If an error is detected on the controller, output cutoff control can be performed.

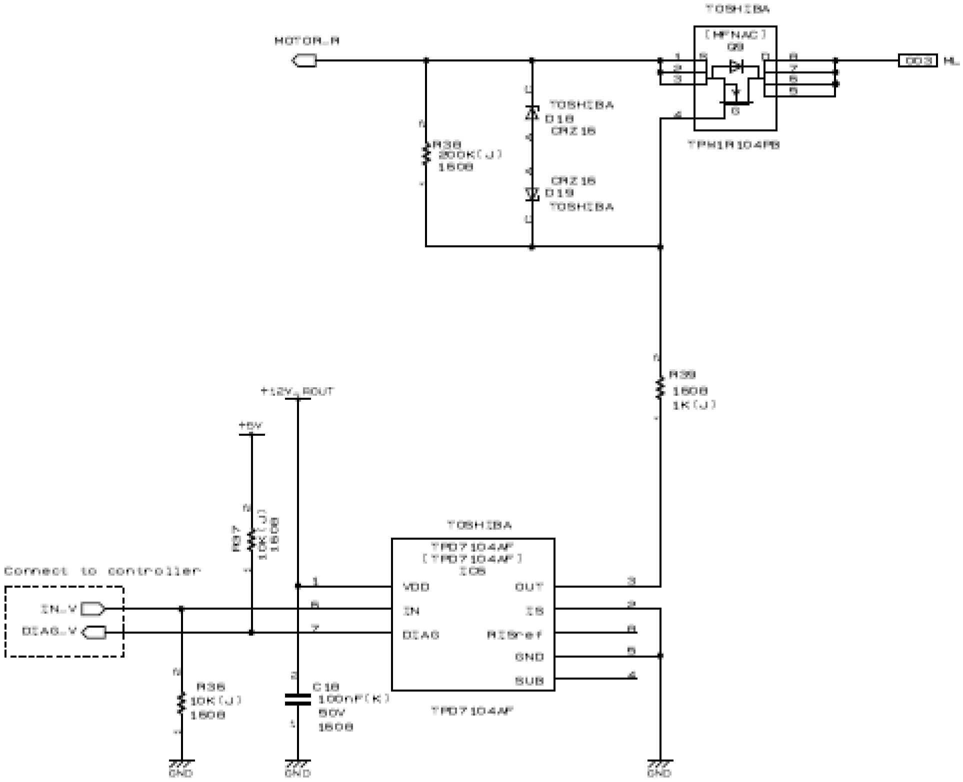


Fig. 4.7 Output Cutoff Circuit (R-phase)

※ Fig. 4.7 shows an example of the R-phase, but the L-phase is the same.

4.3.1 Simulation Verification

The output cutoff function stops the output current of each phase of the motor. Table 4.3 lists the simulation conditions and procedures, and Fig. 4.8 shows the simulation circuit. Motor control for electric power steering for automotive applications requires a function to disconnect the current path of each phase in order to avoid locking due to abnormal motor operation. This action is simulated. MOSFET and gate driver IC TPD7104AF (U4, U5) are used for continuity and interruption of phase current of DC motor. To cut off the phase current when abnormal operation such as overcurrent occurs, control the VIN pin of TPD7104AF.

Table 4.3 Simulation Conditions and Procedures

1	VBB0	12 V
2	U7	H state (on state)
3	U1	IN1=H state, IN5=PWM (20kHz)
4	Start of simulation	
5	U4_VIN	L-state for 9 ms to 11 ms (M13 off)

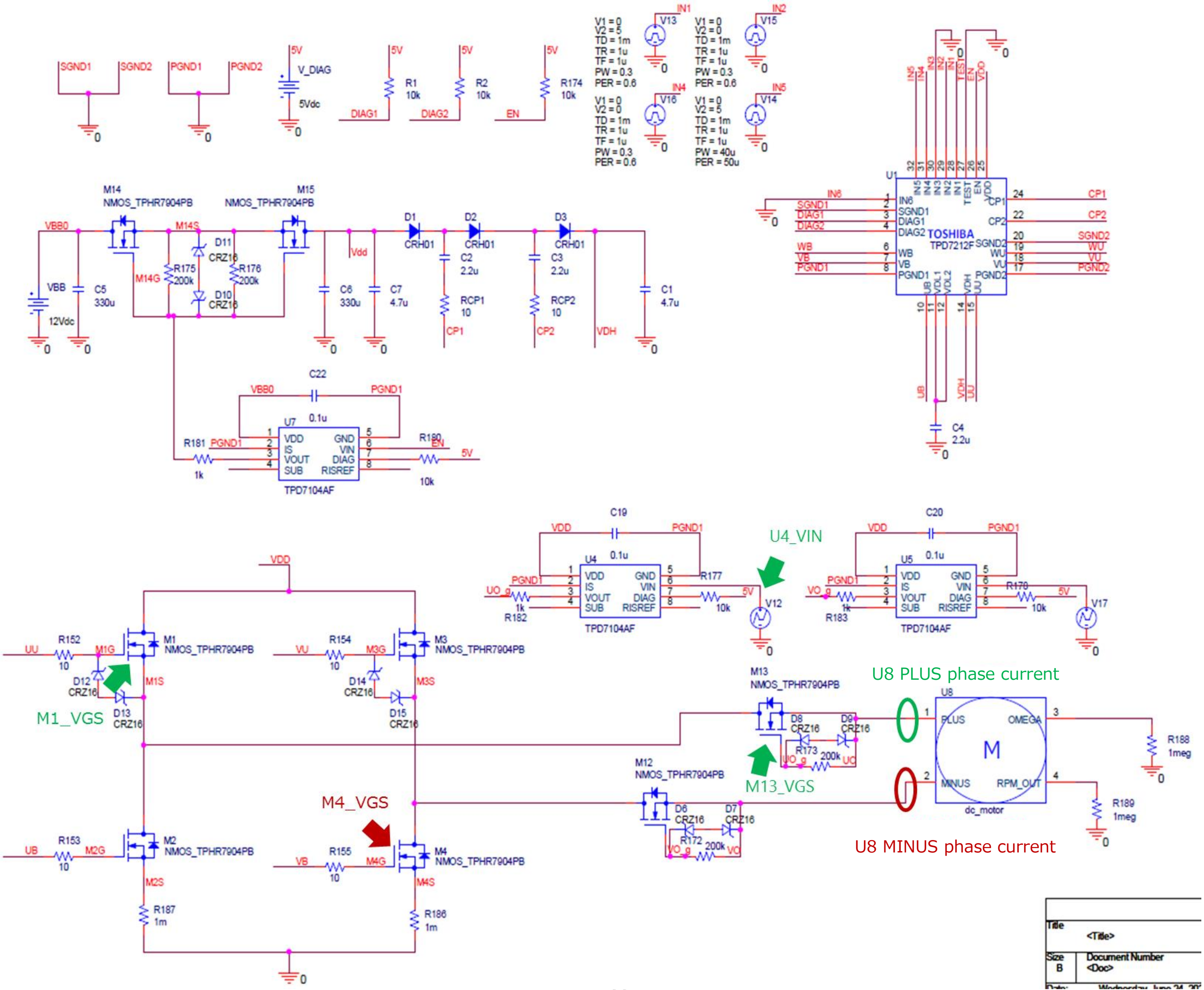


Fig. 4.8 Output Cutoff Simulation Circuit

Fig. 4.9 shows the simulation waveforms when the phase current is interrupted. PLUS phase current is interrupted asynchronously during normal operation. It can be confirmed that the motor current is stopped by shutting off MOSFET M13 connected to the phase. When the current has the opposite polarity, control U5 and M12 to interrupt the current. V_{GS} of MOSFET (M12, M13) when the phase is energized is approximately 16 V. This means that it is clamped by the zener diode CRZ16.

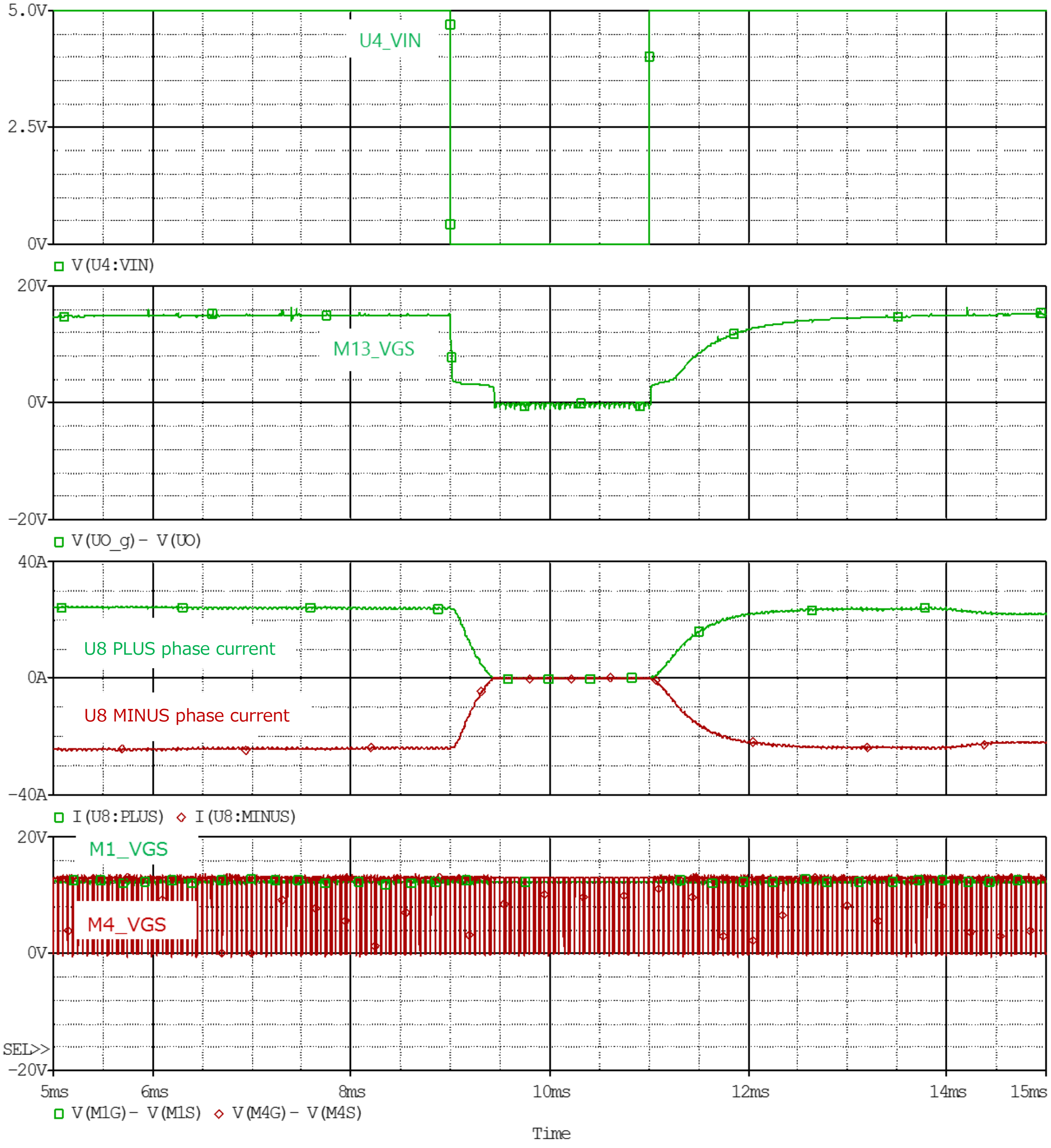


Fig. 4.9 Output Cutoff Simulation Waveform

4.4 Current Detection Method (Low side)

Fig. 4.10 shows the current detection circuit for detecting abnormal current. The current of each phase is detected by the voltage generated across the current detection resistor (R25) placed between the low-side FET and GND of the H bridge.

Fig. 4.10 The current detection circuit uses 1 mΩ.

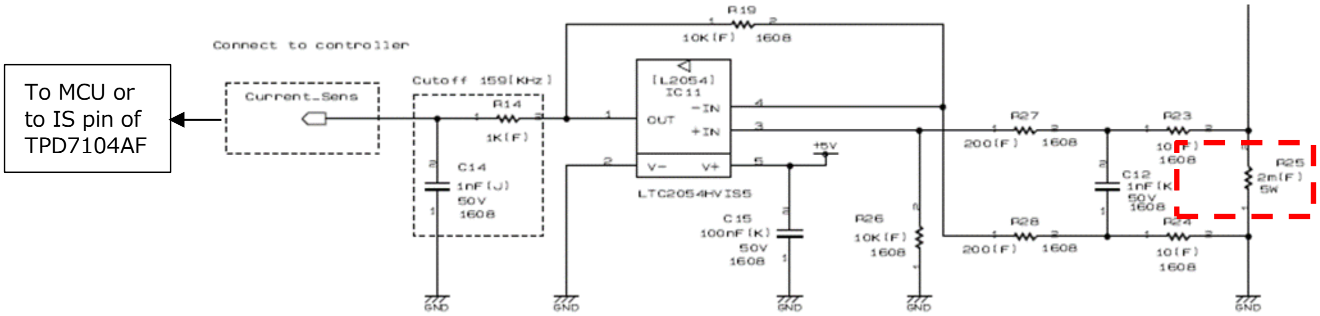


Fig. 4.10 Current Detection Circuit

As shown in Fig. 4.11, the general method of motor control using the H-bridge is that the current direction flowing through the motor is a single direction of the current detection resistor, so the level is not shifted to the positive side in the offset circuit as in the case of a three-phase brushless motor.

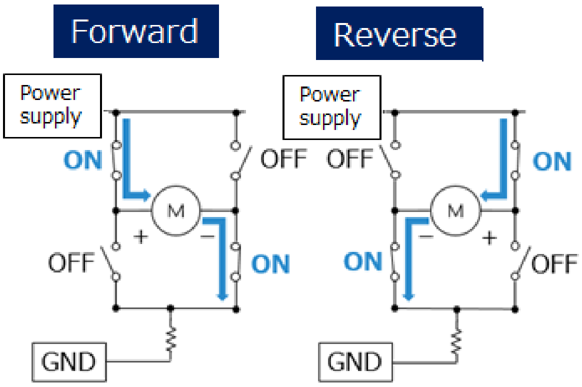


Fig. 4.11 Current Detection Method

In this circuit configuration, the voltage drop of the current detection resistor (R25 in Fig. 4.10) is amplified by the differential operational amplifier and measured by the controller's ADC. The formula for calculating the gain of the op-amp in this circuit configuration is as follows.

$$R19=R26=RA$$
$$R27=R28=RB$$

$$Gain=RA/RB=50.0\ [V/V]$$

The gain of the operational amplifier should be adjusted while taking into account the voltage input range and resolution of the controller and the amount of load current in the application, making actual measurements.

In this circuit configuration, the maximum detected current to the motor is set to 100 A, and the gain of the op-amp is set to approximately 50 V/V with an external resistor.

・4.5 Design of the Charge Pump Circuit

Fig. 4.12 shows the peripheral circuitry required to use TPD7212F charge pump circuitry.

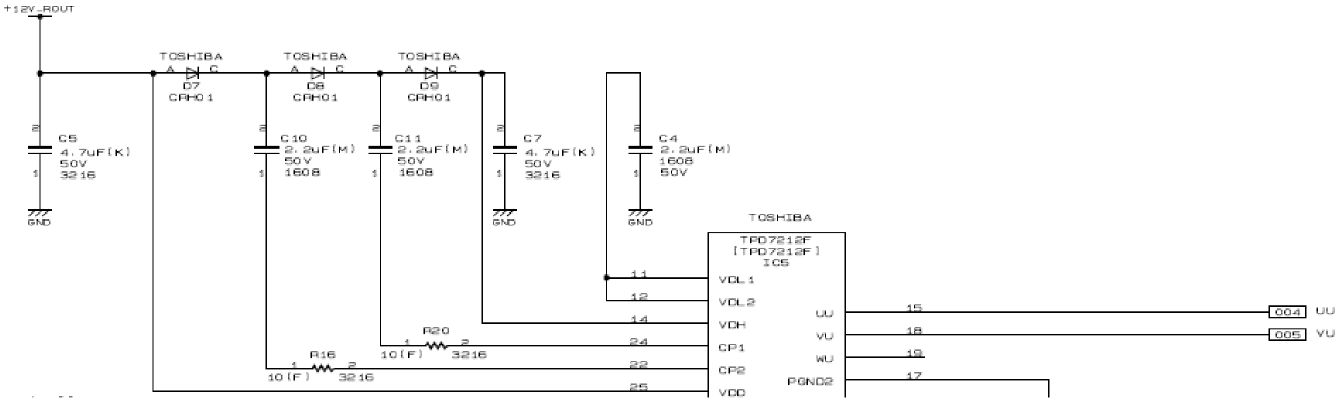


Fig. 4.12 Charge Pump Circuit

Commonly used as non-isolated high-side gate drivers are the bootstrap method or the charge pump method. The bootstrap method requires periodic recharging of the bootstrapped capacitor, so operation close to 100 % duty is not possible. Therefore, the bootstrap method cannot be used for systems requiring high-duty operation, such as systems with low input voltages and high loads.

TPD7212F employs a charge pump system capable of 100% duty operation, so it can also be used for systems requiring high duty.

The currents required for the charge pump circuit can be obtained from the driving MOSFET, VDD pin voltage of TPD7212F, power supply voltage, and drive frequency. Table 4.4. shows conditoins of this circuit.

Table 4.4 Requirements for Charge Pump Circuits

MOSFET	TPW1R104PB
VDD pin voltage of TPD7212F	12 V
Power supply voltage	12 V
Drive Frequency (F_{sw})	20 kHz

The dynamic input/output characteristics of MOSFET (TPW1R104PB) shown in Fig. 4.16 calculate the amount of gate-input charges required to drive MOSFET 1 piece.

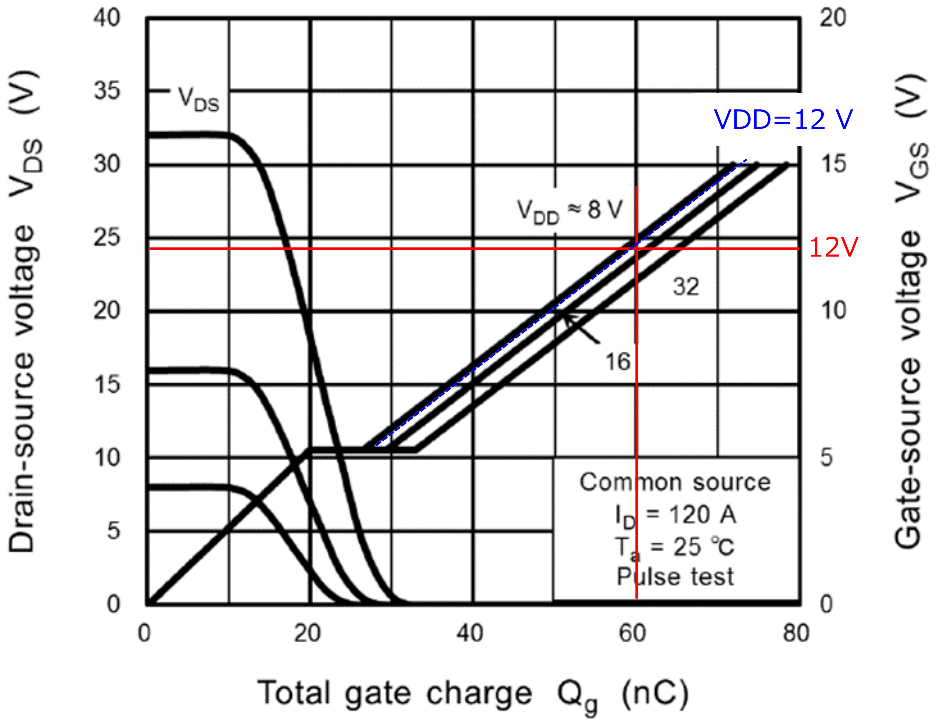


Fig. 4.13 TPW1R104PB Dynamic Input/Output Characteristics

For the high-side MOSFET, VDD is the system power supply voltage (12 V) and V_{GS} is the gate drive voltage 12 V, so the gate-input charge is approximately 60 nC. In this circuit, the high-side MOSFET is driven at the drive frequency (F_{sw}) =20 kHz. Therefore, the output current of the charge pump circuit is calculated as follows.

$$I_{average} = Q_g \times F_{SW} = 60\ (nC) \times 20\ (kHz) = 1.2\ (mA)$$

The supply voltage of low-side driver in TPD7212F is stepped down voltage from the charge pump voltage by the internal regulator. The number of channels that turn on per around PWM 1cycle varies depending on the energization method. However, since the H-bridge operates on two channels, the output current is approximately 2.4 (mA). The capacitance value is estimated in the simulation environment described in the next section, taking into account the effects of pull-down resistors and IC internal impedance. If external diodes are also changed, it is recommended that the element model be changed for simulation.

4.5.1 Simulation Verification

In this section, the output characteristics of the charge pump circuit are verified by simulation. Table 4.5 lists the simulation conditions and procedures, and Fig. 4.13 shows the simulation circuit.

Table 4.5 Simulation Conditions and Procedures

1	VBB0	12 V
2	V_DIAG	5 V
3	I load	1m to 300mA (1ms span.)
4	C2,C3	0.1μF to 2.2μF

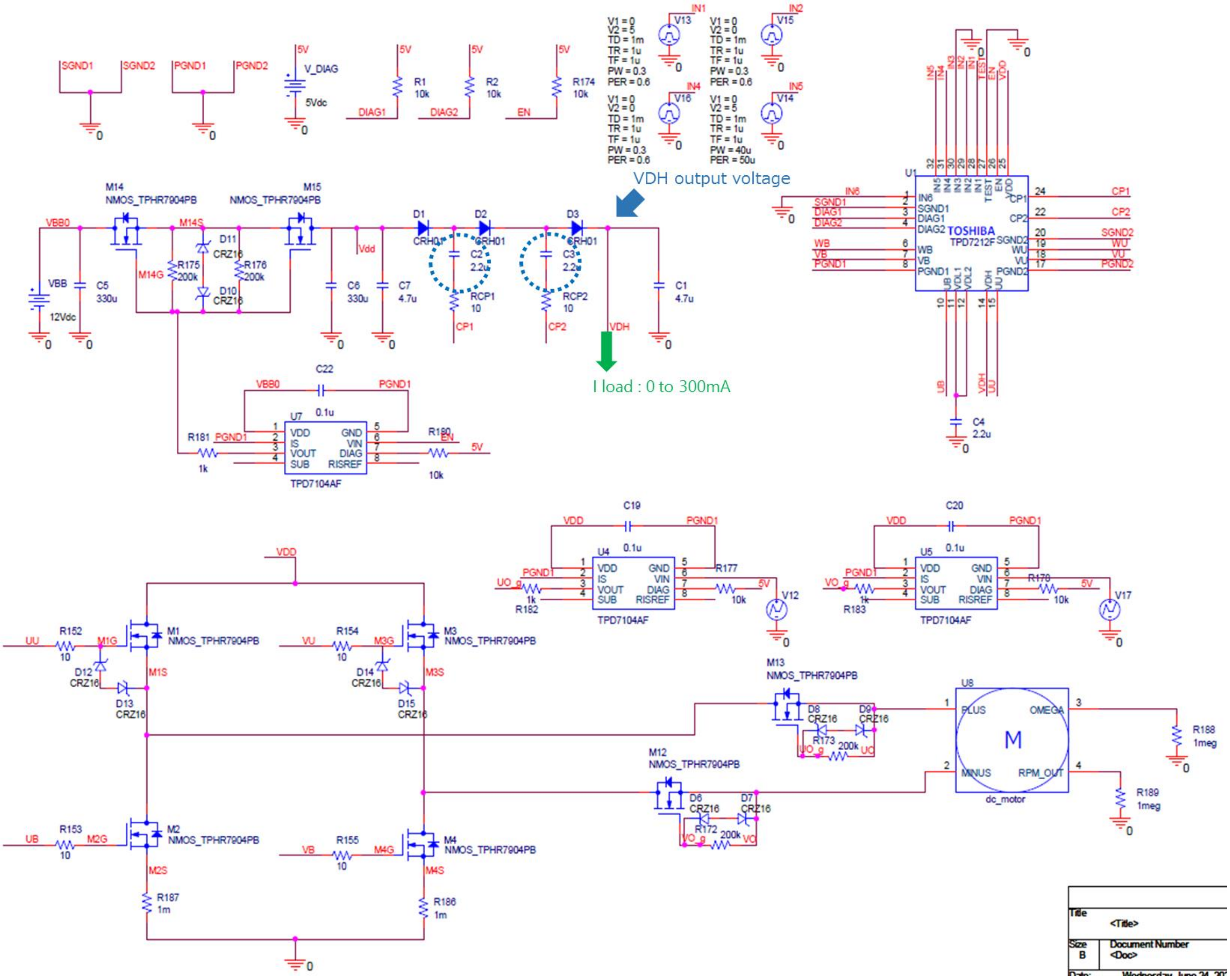


Fig. 4.14 Charge Pump Output Characteristics Simulation Circuit

Fig. 4.15 shows an example of a simulation circuit for checking the charge pump output characteristics. Check that the boosted VDH pin voltage does not drop with respect to the load current caused by the external MOSFET calculated in the previous section. Turning EN 0V stops the output of U1, and only the charge pump circuit operates. Connect a constant current source I load and set the load current to be increased every 1ms. Since the charge pump includes an oscillator circuit, DC analysis cannot be performed. Therefore, the above simulation checks the output characteristics with transient analysis. Fig. 4.14 shows the simulation results. Depending on the nature of MOSFET, V_{GS} typically requires at least 10V. Therefore, the area where the VDH pin voltage is 22V or less becomes an unstable area with bias application. The results also show that the output characteristics vary depending on the charge pump capacities C2 and C3. It is possible to estimate the selectable capacity value from this result. However, environmental temperatures, power supply voltage conditions, and characteristics of peripheral components such as diodes will also affect the product. Therefore, we recommend that you conduct actual measurements. 2.2µF is selected for this circuit in consideration of sufficient margin for design. In addition, the capacitors in the charge pump circuitry of TPD7212F are supplied with voltages typically 12 V higher than the incoming voltage, so care must be taken when withstanding the voltage of the capacitors. In this circuit, the voltage at the VDH pin is boosted to 24 V for an input voltage of 12 V. Therefore, a 50 V withstanding voltage product is selected.

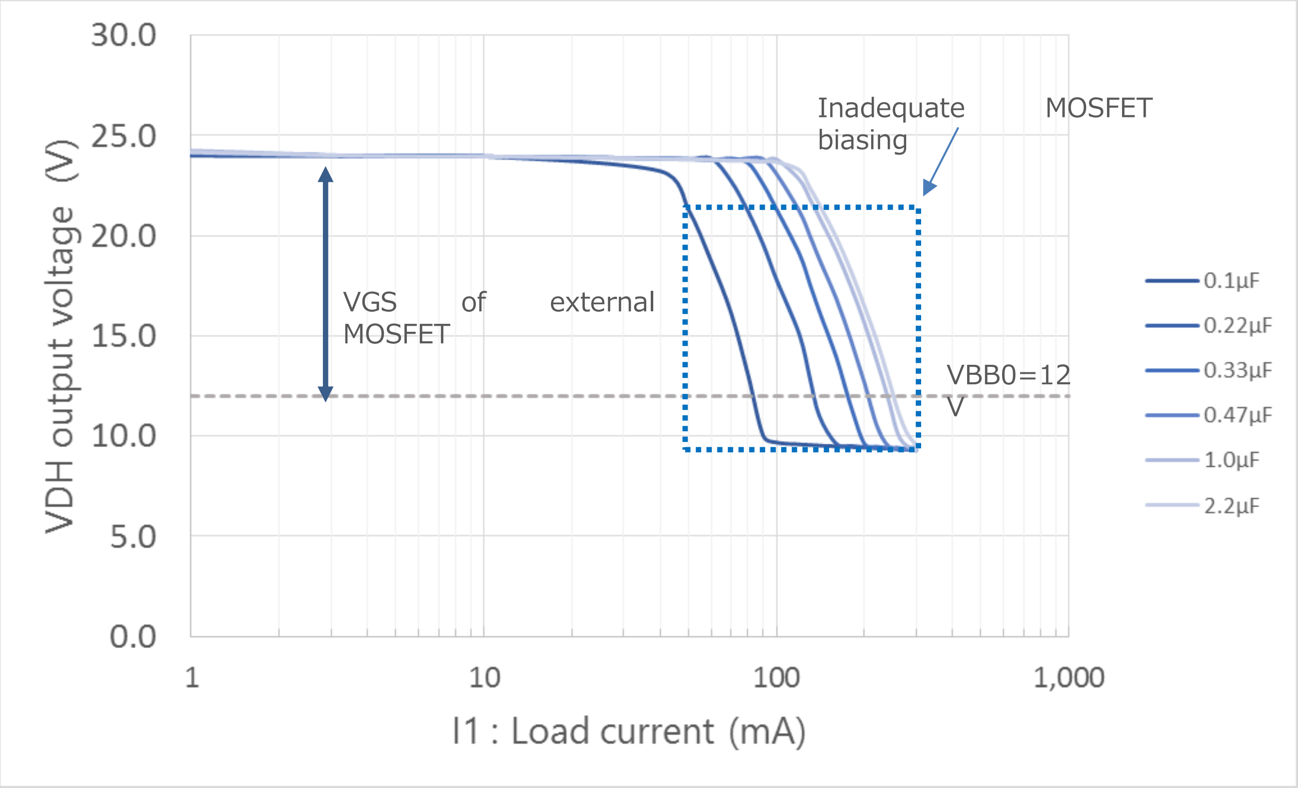


Fig. 4.15 Simulation Results of Charge Pump Output Characteristics

4.6 Surge Protection Function

In this circuit, the zener diode of D3, D6 (CMZ27) shown in Fig. 4.1 is inserted to constitute a protection function intended for clamping when surge voltages of 27 V (typical) or higher are generated, such as load dump surges for automotive applications. The clamping voltage must be designed not to exceed the withstand voltage of MOSFET and gate driver ICs.

Download CMZ27 datasheet from here → Click Here

4.7 H-bridge DC Motor Drive by TPD7212F

TPD7212F can be used for H-bridge DC motor drive. Pull down the input pin to open the output corresponding to the input. Table 4.6 lists the simulation conditions and procedures, and Fig. 4.16 shows the simulation circuit.

Table 4.6 Simulation Conditions and Procedures

1	VBB0	12 V
2	U7	H state (on state)
3	U1	IN1=H state, IN5=PWM (20kHz)
4	Start of simulation	

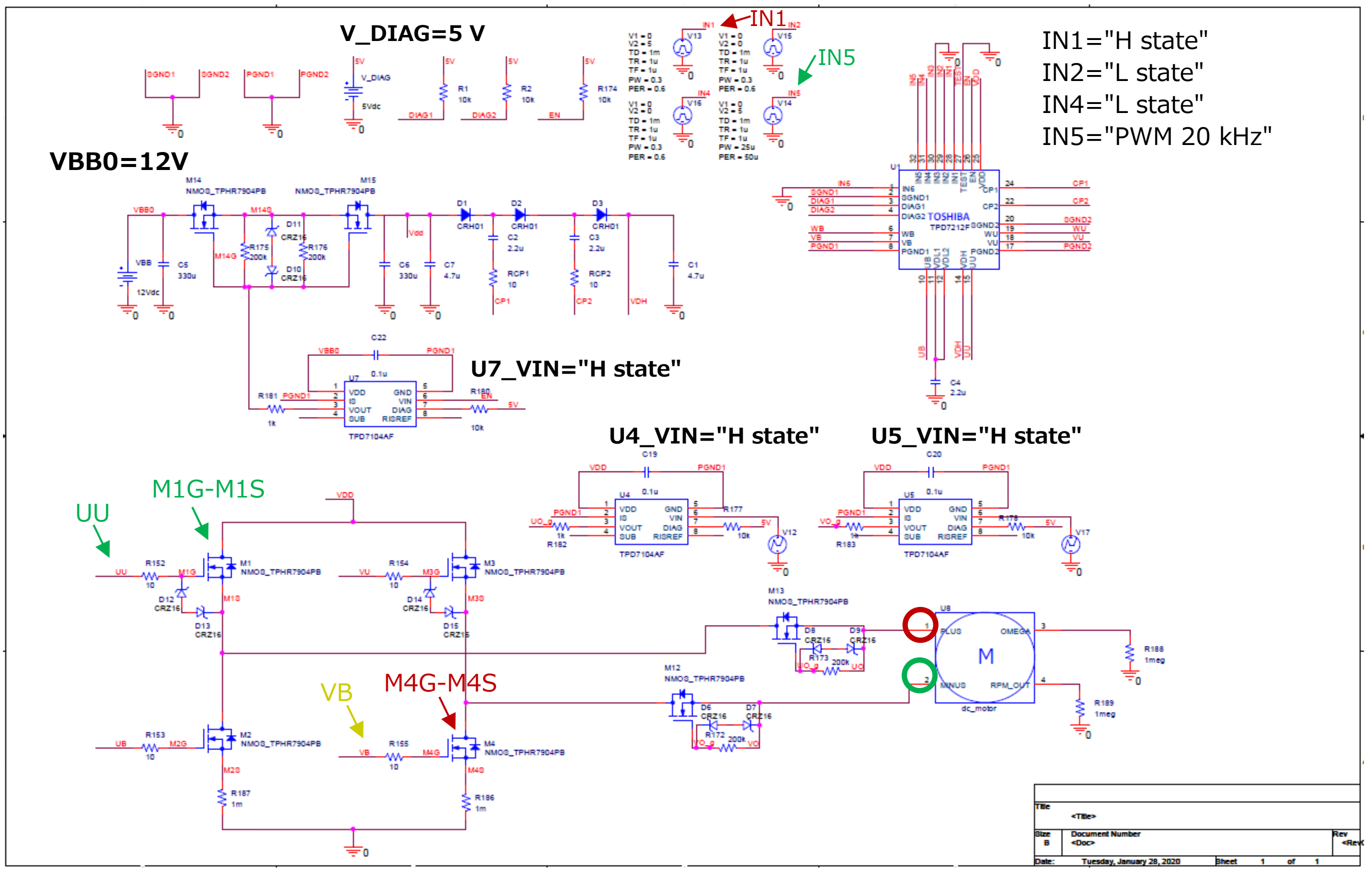


Fig. 4.16 H-bridge DC motor drive simulation circuit

Fig. 4.17 shows the simulation waveforms. IN3 and IN6 pins are grounded and the WU and WB pins are open. The high-side MOSFETM1 is turned on and the M4 is switched to 20kHz. Under these conditions, it can be confirmed that a current of approximately 15 A is generated in the motor U8.

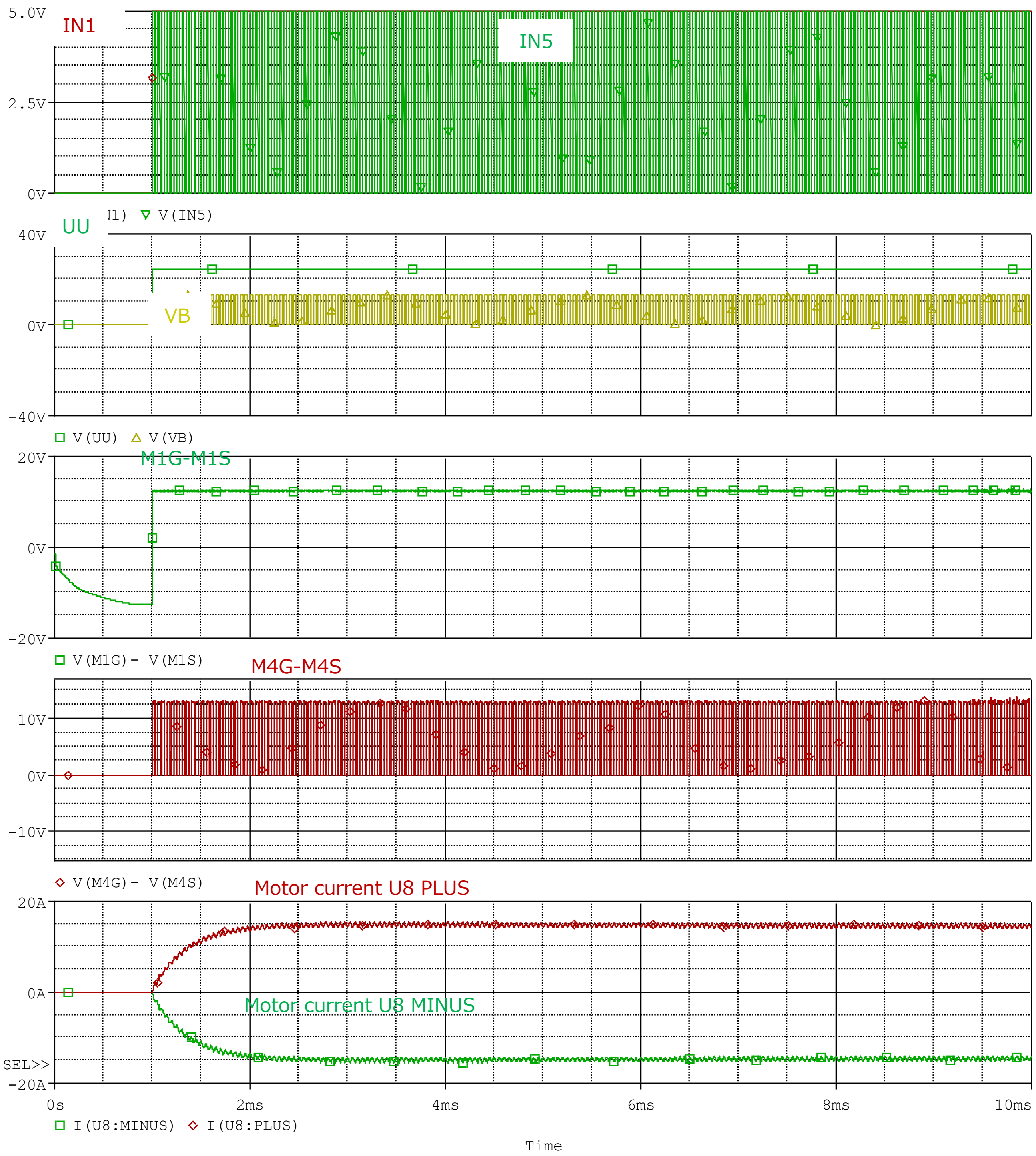


Fig. 4.17 H-bridge DC motor drive simulation waveforms

5. Product Overview

5.1. TPD7212F/FN

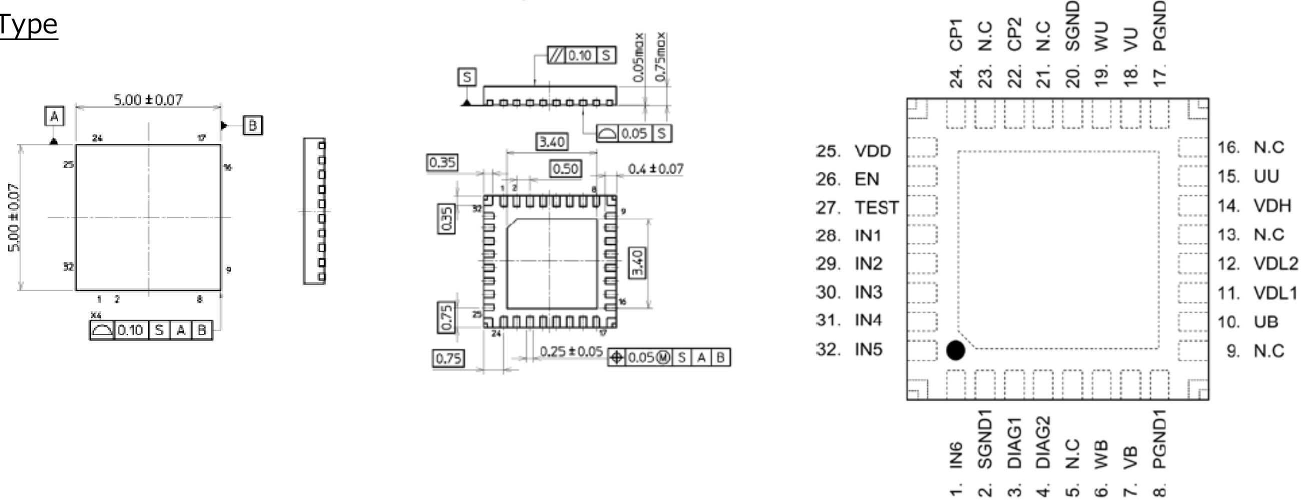
5.1.1. Overview

TPD7212F/FN is a power MOSFET gate driver for 3-phase full-bridge circuit with the charge-pump method by the BiCD process. The built-in charge pump circuit for the high side drive makes it easy to configure a 3-phase full-bridge circuit. It can also be used as an H-bridge circuit for DC motors by making one of the 3 phases unused.

- AEC-Q100 qualified
- Power MOSFET gate drivers for 3-phase DC motors and H-bridge DC motors
- Built-in diagnostic output function for driver power supply voltage and output voltage
- Built-in charge pump circuit
- WQFN32 package: TPD7212F
- SSOP30 package: TPD7212FN

5.1.2. Appearance and Pin Assignment

F Type



FN Type

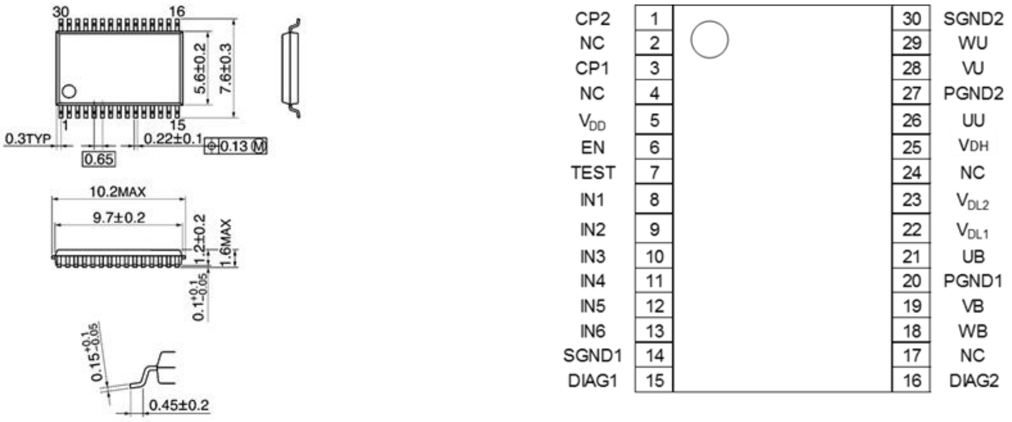


Fig. 5.1.2 External view and pin arrangement5.1.2

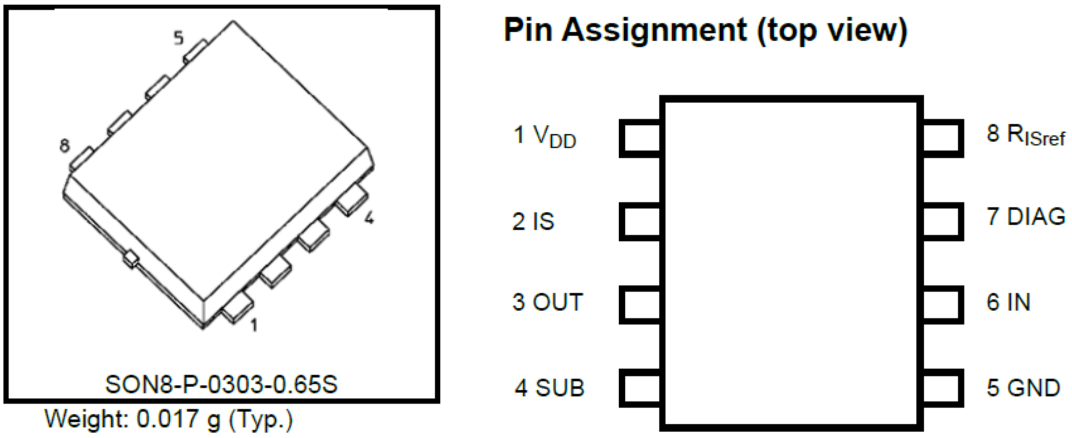
6.2 TPD7104AF

6.2.1 Overview

TPD7104AF is an N-channel power MOSFET gate driver for a 1channel output high-side switch. Built-in charge pump circuit allows easy configuration of high-side switches for high-current applications.

- AEC-Q100 qualified
- Built-in charge pump circuit
- Built-in load short-circuit (overcurrent) detection and power supply reverse connection protection function
- PS-8 package

6.2.2 Appearance and Pin Assignment



SON8-P-0303-0.65S

Weight: 0.017 g (Typ.)

Pin Assignment (top view)

Fig. 6.2 External View and Pin Layout

6.3 TPW1R104PB

6.3.1 Overview

TPW1R104PB is fabricated with our latest low-voltage MOSFET processing U-MOSIX-H to achieve low on-resistance and high current rating.

- AEC-Q101 qualified
- Compact, thin and small mounting area
- Low on resistor: $R_{DS(ON)}$=0.95 mΩ (Typ.) (@V_{GS}=10 V)
- Lower leakage current: I_{DSS} = 10 μA (Max) (V_{DS} = 40 V)
- Easy-to-use enhancement types: V_{th} = 2.0-3.0 V (V_{DS} = 10 V, I_D = 0.5 mA)
- Maximum current rating :I_D=120 A (DC)
- Maximum voltage rating: V_{DSS} = 40 V

6.3.2 Appearance and Pin Assignment

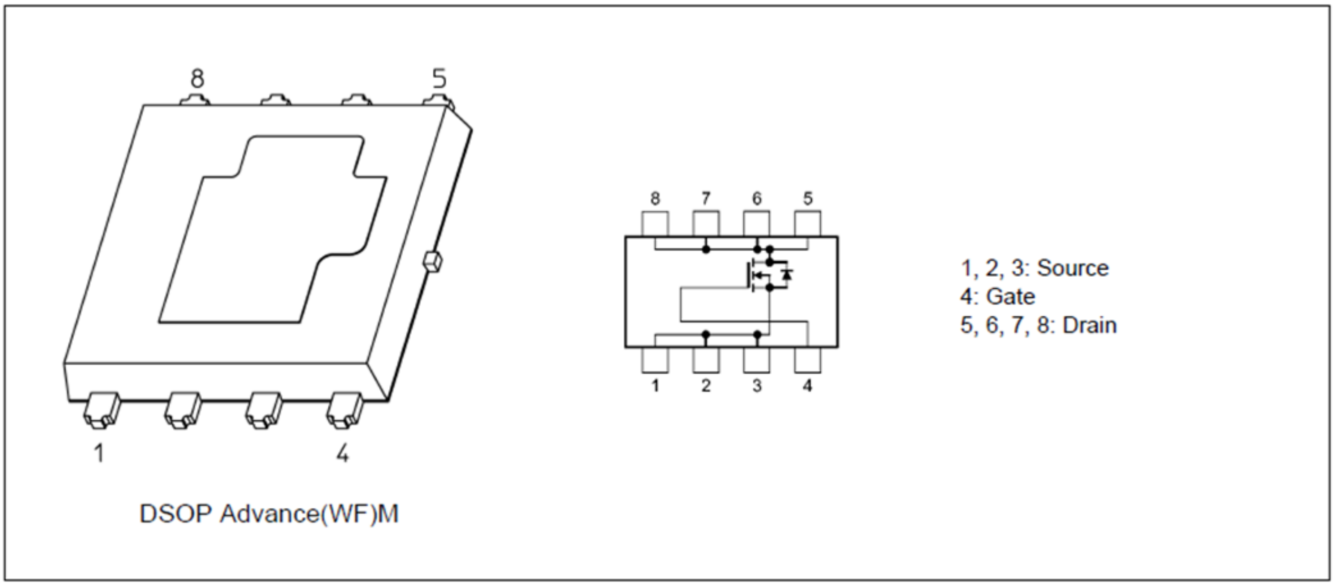


Fig. 6.3 Appearance and Pin Assignment

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