Automotive Buck-Boost DC-DC Converter for USB PD

Design guide

RD227-DGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

This Design Guide (hereafter referred to as this guide) describes the design of the Automotive Buck-Boost DC-DC Converter for USB PD (hereafter referred to as this power supply).

Recently, USB Power Delivery (hereafter referred to as USB PD) power supply (for recharging) has become popular for smart phones, tablets, laptop PC, etc. In response to the growing demand for power supply not only indoors but also inside vehicles, USB Type-C® connectors have been installed, and power supply by USB PD has become popular. Since the output voltage is determined by the power receiving device in USB PD, DC-DC converter for automotive USB PD requires a buck-boost converter to generate the output voltage from the vehicle battery voltage. This power supply is an H-bridge type buck-boost DC-DC converter with four switching elements. By using our small-package automotive MOSFETs as switching devices, we have realized an automotive buck-boost DC-DC converter that is highly efficient and has a small board mounting area.

We have prepared two types of automotive MOSFETs which are used in the H-bridge buck-boost DC-DC converter section of this power supply. Option 1 uses a XPN7R104NC, and Option 2 uses a SSM6K804R. In addition, our automotive MOSFET XPN3R804NC is used as a switching device in reverse-connection protection circuit and shield short-circuit protection circuit.

2. Components Used

This section introduces the components used in this power supply. We have an extensive lineup of automotive power semiconductor devices, including the components used this time.

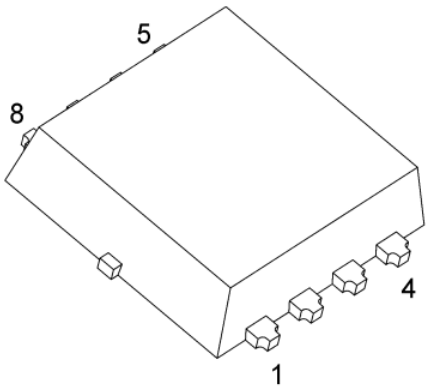
2.1. Automotive Power MOSFET XPN7R104NC

Option 1 of this power supply uses XPN7R104NC of V_{DSS} = 40 V (Max.), I_D = 20 A (Max.) for switching the buck-boost H-bridge.

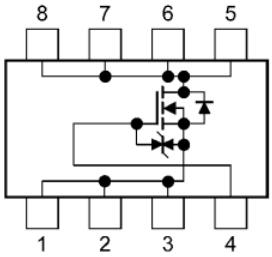
Features

- AEC-Q101 qualified
- Small size, low profile and small mounting area
- Low on-resistance: $R_{DS(ON)}$ = 5.6 mΩ (Typ.) (V_{GS} = 10 V)
- Low leakage current: I_{DSS} = 10 μA (Max.) (V_{DS} = 40 V)
- Easy-to-use enhancement type: V_{th} = 1.5 to 2.5 V (V_{DS} = 10 V, I_D = 0.2 mA)

Appearance and Terminal Layout



TSON Advance(WF)



1, 2, 3: Source
4: Gate
5, 6, 7, 8: Drain

2.2. Automotive Power MOSFET SSM6K804R

Option-2 of this power supply uses SSM6K804R of V_{DSS} = 40 V (Max.), I_D = 12 A (Max.) for switching the buck-boost H-bridge.

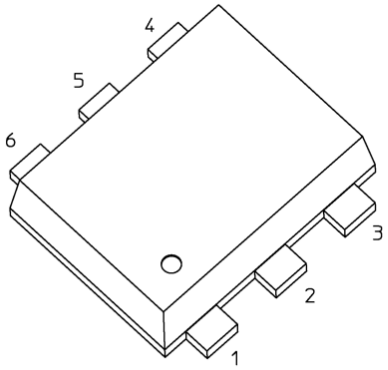
Features

- AEC-Q101 qualified
- MOSFET for 175 °C
- 4.5 V drive
- Low on-resistance

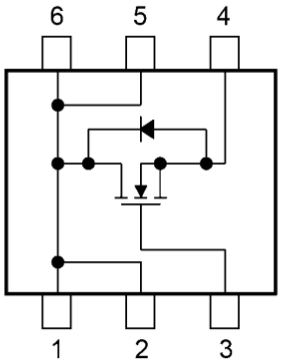
  $R_{DS(ON)}$ = 12 mΩ (Typ.) (@V_{GS} = 4.5 V)

  $R_{DS(ON)}$ = 9 mΩ (Typ.) (@V_{GS} = 10 V)

Appearance and Terminal Layout



TSOP6F



1: Drain
2: Drain
3: Gate
4: Source
5: Drain
6: Drain

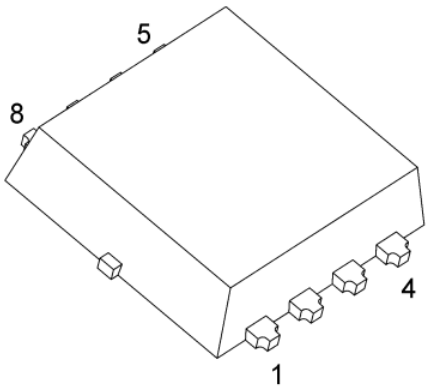
2.3. Automotive Power MOSFET XPN3R804NC

XPN3R804NC of V_{DSS} = 40 V(Max.), I_D = 40 A(Max.) is used as MOSFET for the power switch, reverse-connection protection, and shielded short-circuit protection of this power supply.

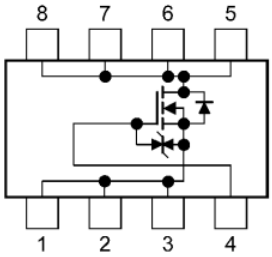
Features

- AEC-Q101 qualified
- Small size, low profile and small mounting area
- Low on-resistance: $R_{DS(ON)}$ = 3.0 mΩ (Typ.) (V_{GS} = 10 V)
- Low leakage current: I_{DSS} = 10 μA (Max.) (V_{DS} = 40 V)
- Easy-to-use enhancement type: V_{th} = 1.5 to 2.5 V (V_{DS} = 10 V, I_D = 0.3 mA)

Appearance and Terminal Layout



TSON Advance(WF)



1, 2, 3: Source
4: Gate
5, 6, 7, 8: Drain

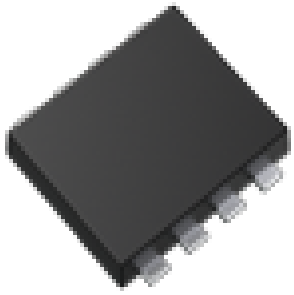
2.4. High-Side Gate Driver TPD7104AF

TPD7104AF is used as a gate driver for the power switch and the reverse-connection protection MOSFET in this power supply.

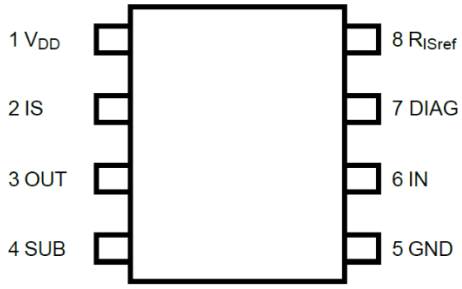
Features

- Built-in charge pump circuit
- Built-in load short (overcurrent detection) and power reverse connection protection function
- Compact with surface mount package (PS-8)

Appearance and Terminal Layout



PS-8



3. Buck-Boost DC-DC Converter

3.1. Outline of Operation

The configuration of the buck-boost DC-DC converter is shown in Fig. 3.1.

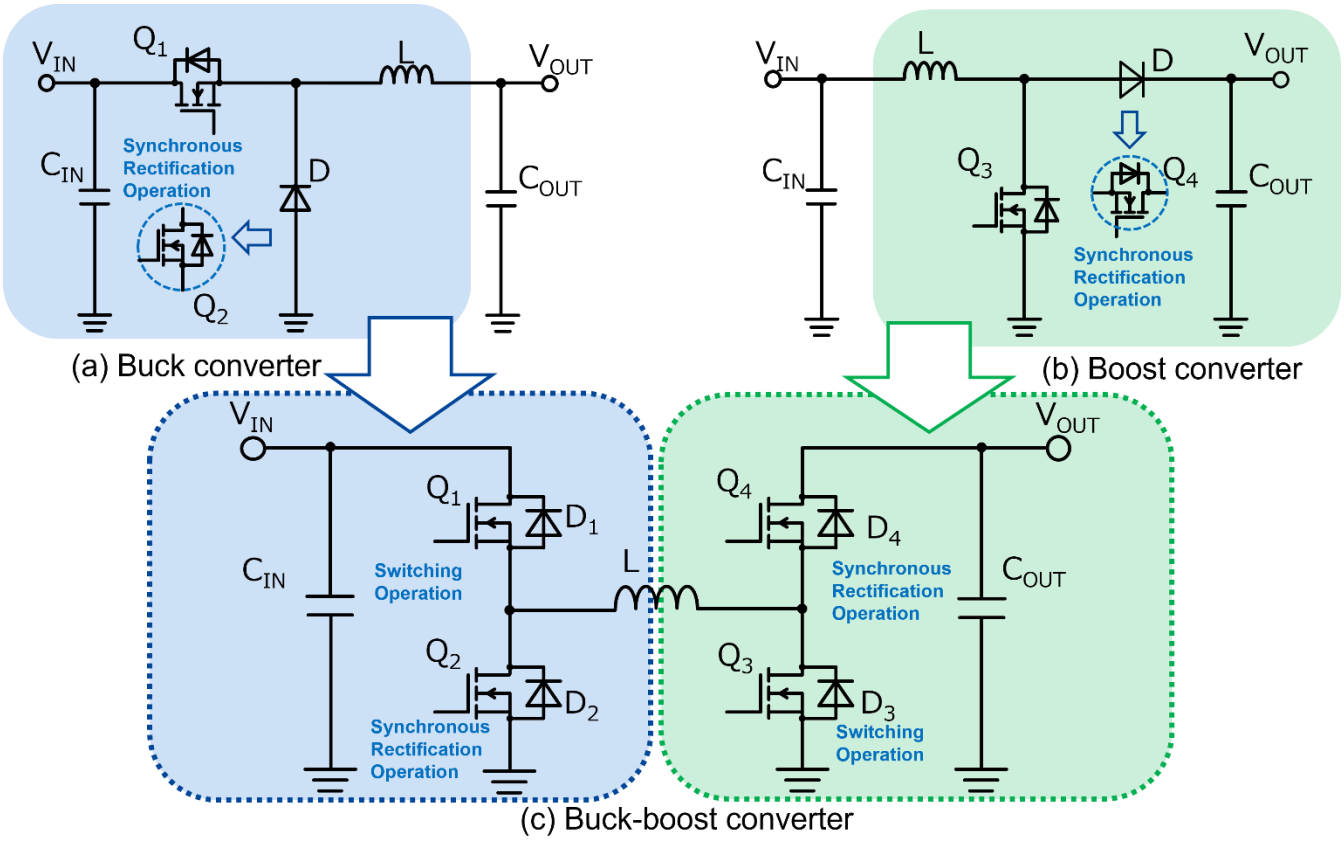


Fig. 3.1 Configuration of Buck-Boost DC-DC Converter

The non-inverting buck-boost DC-DC converter circuit, which combines a buck DC-DC converter circuit and a boost DC-DC converter circuit, can be more efficient by using synchronous rectification with MOSFET instead of the diodes as used in the buck DC-DC converter and the boost DC-DC converter. It contains four MOSFETs surrounding the inductor and is also called H-bridge buck-boost DC-DC converter. The buck-boost DC-DC converter is suitable for switching between step-up and step-down operation. It can output a constant voltage even when the input voltage fluctuates, such as with battery, and it can also change the output voltage depending on the output loads, such as in USB Power Delivery powered equipment. The buck-boost DC-DC converter has the following operating modes.

(1) Buck Mode (when the input voltage is sufficiently higher than the output voltage)

Switching Q_1 and Q_2 shown in Fig. 3.1 enables buck mode. Q_1 and Q_2 operate in a complementary fashion and Q_2 behave as a synchronous rectifier. At this time, Q_4 is fixed to on and Q_3 is fixed to off.

(2) Boost Mode (when the input voltage is sufficiently lower than the output voltage)

Switching Q_3 and Q_4 shown in Fig. 3.1 enables boost mode. Q_3 and Q_4 operate in a complementary fashion and Q_4 behave as a synchronous rectifier. At this time, Q_1 is fixed to on and Q_2 is fixed to off.

(3) Buck-Boost Mode (when input voltage ≈ output voltage)

If the input voltage ≈ output voltage, the output voltage fluctuation becomes large in the step-down mode or step-up mode. In the buck-boost mode, all Q_1 to Q_4 in Fig. 3.1 operate and correspond to the operation of the step-down mode and the step-up mode.

3.2. Operation of Each Mode

3.2.1. Buck Mode

Fig. 3.2 shows the current path in buck mode. In buck operation, Q_1 and Q_2 are switched to control the voltage of SW1. At this time in the boost circuit, Q_3 is fixed to off, and Q_4 is fixed to on. The voltage of SW2 is V_{OUT}. When Q_1 is on (Q_2 is off), the current rises in the path of V_{IN}-Q_1-Inductor L-Q_4-V_{OUT} to charge the L. When Q_1 is off (Q_2 is on), the stored energy in L is discharged along the path of GND-Q_2-Inductor L-Q_4-V_{OUT} and the current is reduced. The waveforms of the current flowing through inductor L and the voltage across inductor L are shown in Fig. 3.3.

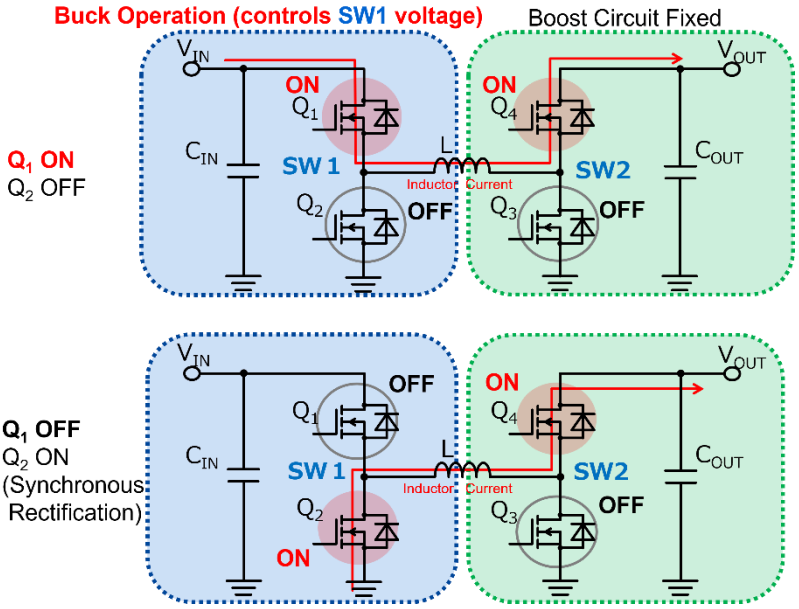


Fig. 3.2 Current Path in Buck Mode

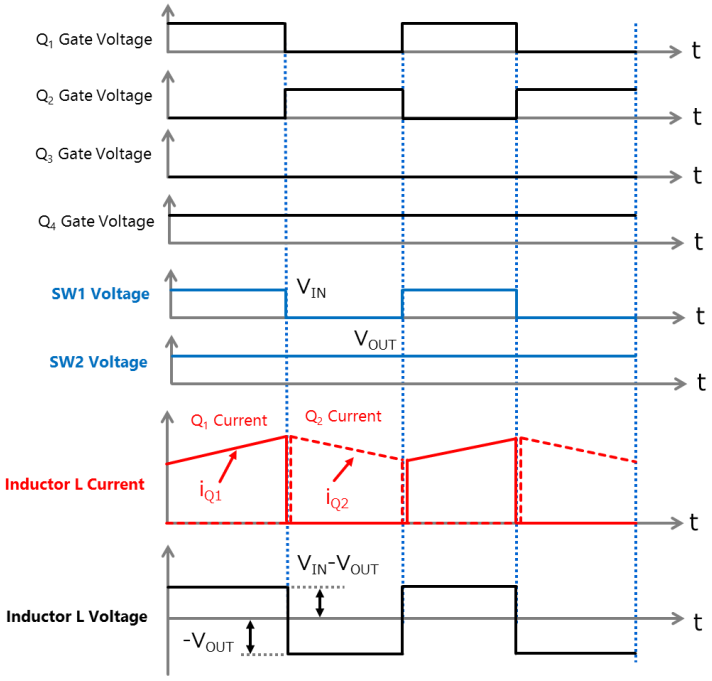


Fig. 3.3 Operation Waveforms in Buck Mode

The relationship between the input voltage and the output voltage is derived from the fact that the stored energy and the released energy of the inductor L are equal in Fig. 3.3. The following equation holds between the energy ΔU_1 accumulated in the inductor during Q_1 on (Q_2 off) period and the energy ΔU_2 (<0) released from the inductor during Q_1 off (Q_2 on) period:

$$\Delta U_1 + \Delta U_2 = 0$$

ΔU_1, ΔU_2 calculation is as follows; when the energy is accumulated in the inductor the current increases by Δi_{Q1}, and when the energy is released the current decreases by Δi_{Q2}, Q_1 on time is T_{on}, and the off time is T_{off}. (V_{IN}-V_{OUT} is applied when Q_1 is ON and -V_{OUT} is applied when Q_1 is OFF)

$$\Delta U_1 = (V_{IN} - V_{OUT}) \cdot \Delta i_{Q1} \cdot T_{on}$$

$$\Delta U_2 = -V_{OUT} \cdot \Delta i_{Q2} \cdot T_{off}$$

From the above

$$(V_{IN} - V_{OUT}) \cdot \Delta i_{Q1} \cdot T_{on} - V_{OUT} \cdot \Delta i_{Q2} \cdot T_{off} = 0$$

When a constant current is applied to the inductor,

$$\Delta i_{Q1} = \Delta i_{Q2}$$

Thus, it becomes

$$V_{OUT} = \frac{T_{on}}{T_{on} + T_{off}} V_{IN} = \frac{T_{on}}{T} V_{IN}$$

Assuming that the ratio of T_{on} in the switching period T of Q_1 is duty D,

$$V_{OUT} = D \cdot V_{IN}$$

If the switching frequency is f_{sw}, D is expressed by the following equation.

$$D = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on} + T_{off}} = T_{on} \times f_{sw}$$

3.2.2. Boost Mode

Fig. 3.4 shows the current path in boost mode. In boost operation, Q_3 and Q_4 are switched to control the voltage of SW2. At this time in the buck circuit, Q_1 is fixed to on and Q_2 is fixed to off. Thus, the voltage of SW1 is V_{IN}. When Q_3 is on (Q_4 is off), the current rises along the path of V_{IN}-Q_1-Inductor L-Q_3-GND to charge the Inductor L. When Q_3 is off (Q_4 is on), current flows through the path of V_{IN}-Q_1-inductor L-Q_4-V_{OUT} based on the stored energy in the inductor L. The difference between the input voltage and the output voltage is applied to inductor L. The waveforms of the current flowing through inductor L and the voltage across inductor L are shown in Fig. 3.5.

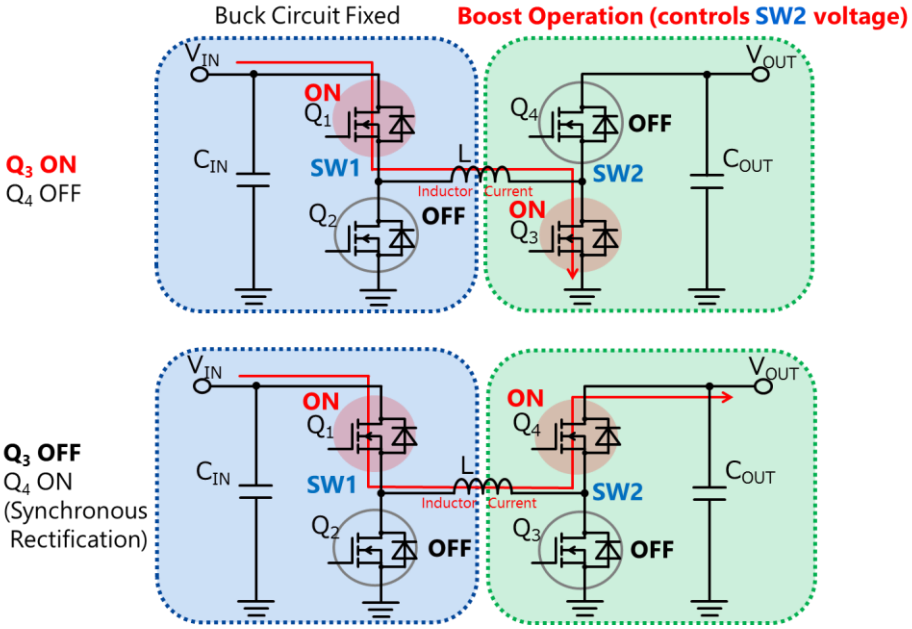


Fig. 3.4 Current Path in Boost Mode

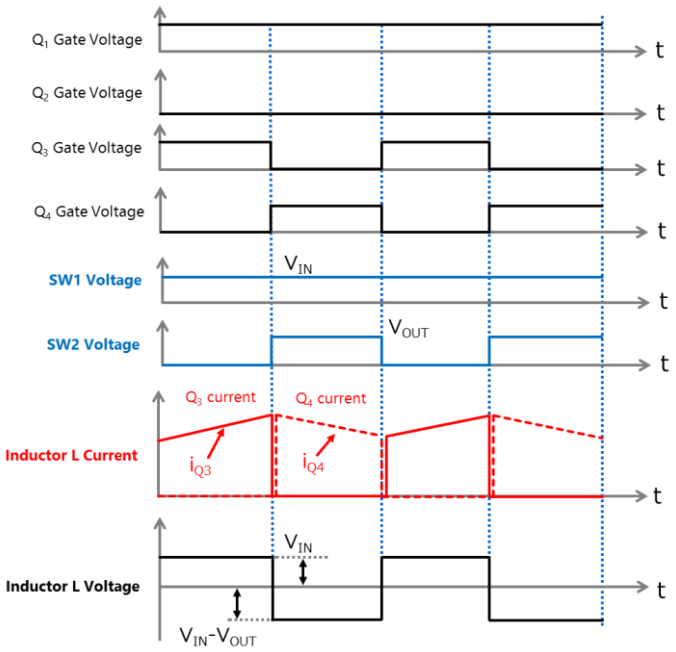


Fig. 3.5 Operation Waveforms in Boost Mode

The relationship between the input voltage and the output voltage is derived from the fact that the stored energy and the released energy of the inductor L are equal in Fig. 3.5. The following equation holds between the energy ΔU_3 accumulated in the inductor during Q_3 on (Q_4 off) period and the energy ΔU_4 (<0) released from the inductor during Q_3 off (Q_4 on) period:

$$\Delta U_3 + \Delta U_4 = 0$$

ΔU_3, ΔU_4 are calculated as follows; when the energy is accumulated in the inductor the current increase is Δi_{Q3}, and when the energy is released from the inductor the current decrease is Δi_{Q4}, Q_3 on time is T_{on}', and the off time is T_{off}'. (V_{IN} is applied when Q_3 is ON and V_{IN}-V_{OUT} is applied when Q_3 is OFF)

$$\Delta U_3 = V_{IN} \cdot \Delta i_{Q3} \cdot T_{on}'$$
$$\Delta U_4 = (V_{IN} - V_{OUT}) \cdot \Delta i_{Q4} \cdot T_{off}'$$

From the above

$$V_{IN} \cdot \Delta i_{Q3} \cdot T_{on}' + (V_{IN} - V_{OUT}) \cdot \Delta i_{Q4} \cdot T_{off}' = 0$$

When a constant current is applied to the inductor,

$$\Delta i_{Q3} = \Delta i_{Q4}$$

Thus, it becomes

$$V_{OUT} = \frac{T_{on}' + T_{off}'}{T_{off}'} V_{IN} = \frac{T}{T_{off}'} V_{IN}$$

Assuming that the duty D' is the ratio of T_{on}' in Q_3 switching period T

$$V_{OUT} = \frac{1}{1 - D'} V_{IN}$$

If the switching frequency is f_{sw}, D is expressed by the following equation.

$$D' = \frac{T_{on}'}{T} = \frac{T_{on}'}{T_{on}' + T_{off}'} = T_{on}' \times f_{sw}$$

3.2.3. Buck-Boost Mode

In order to achieve the input voltage ≈ output voltage, particularly the voltage ratio 1 in the buck mode and boost mode, in buck mode from the I/O voltage relation expression $V_{OUT} = D \cdot V_{IN}$, Q_1 duty needs to be D=1, and in the boost mode from the I/O voltage relation expression $V_{OUT}=1/(1-D') V_{IN}$, Q_3 duty needs to be D'=0. However, since such switching is not realistic, the IC operates in the buck-boost mode when input voltage ≈ output voltage.

As described above, the relationship between the input voltage and the output voltage in the buck mode is as follows.

$$V_{OUT} = \frac{T_{on}}{T_{on} + T_{off}} V_{IN}$$
$$= \frac{T_{on}}{T} V_{IN}$$

(T_{on}: Buck switch Q_1 on time, T_{off}: Buck switch Q_1 off time)

The relationship between the input voltage and the output voltage in boost mode is shown below.

$$V_{OUT} = \frac{T}{T_{off}'} V_{IN}$$

(T_{on}': Boost switch Q_3 on time, T_{off}': Boost switch Q_3 off time)

In the buck-boost mode, the operation is such that the output on the buck circuit side becomes the input of the boost circuit side. Therefore, the relationship between the input voltage and the output voltage is expressed by the following equation.

$$V_{OUT} = V_{IN} \frac{T_{on}}{T} \times \frac{T}{T_{off}'}$$

When V_{IN}, V_{OUT} or T (switching period) is determined for the buck mode or boost mode, the requirements of the switching elements are determined in one way. However, even if V_{IN} and V_{OUT} are determined, both the switching element Q_1 on the buck side and the switching element Q_3 on the boost side can be operated in various ways. There may also be cases where T (switching period) differs between the buck circuit side and the boost circuit side, or where the switching period fluctuates.

4. Circuit Design

This section describes the gist of the circuit design. This power supply uses a MAX25432 (hereafter referred to as this controller) manufactured by Analog Devices as a controller IC. Refer to MAX25432 data sheet and related documentation for detailed information on component circuit design.

Refer to RD227-SCHEMATIC1 (Option 1) or RD227-SCHEMATIC2 (Option 2) for schematic diagrams and to RD227-BOM1 (Option 1) or RD227-BOM2 (Option 2) for bill of materials. Fig. 4.1 shows the block diagram of this power supply.

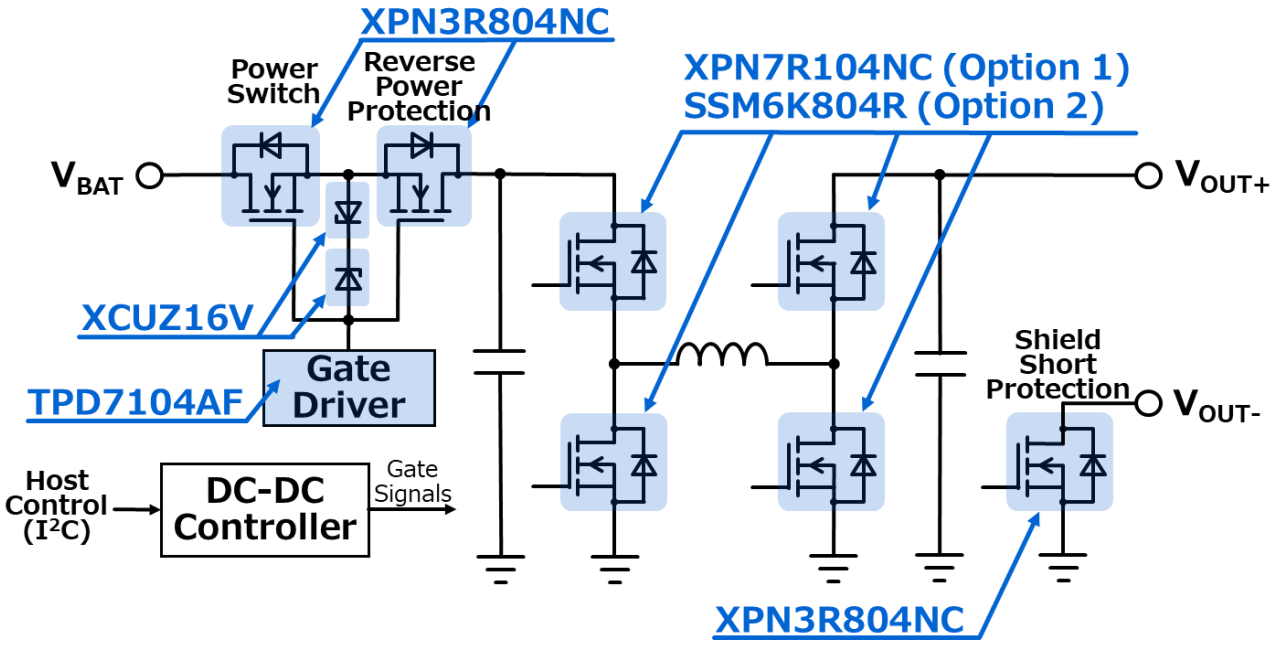


Fig. 4.1 Block Diagram of Automotive Buck-Boost DC-DC Converter for USB PD

4.1. Buck-Boost DC-DC Converter

Fig. 4.2 shows the basic circuit of the buck-boost DC-DC converter.

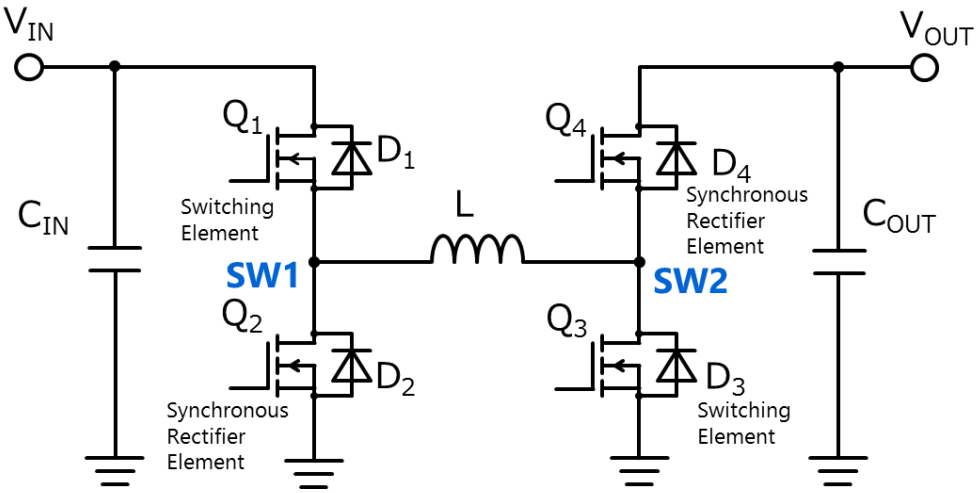


Fig. 4.2 Basic Circuit of Buck-Boost DC-DC converter

4.1.1. Bootstrap Circuit

The high-side MOSFET of the buck-boost H-bridge, Q_1 and Q_4 gate-drive supplies are generated by a capacitor-diode bootstrap. Fig. 4.3 shows the bootstrap circuit. The capacitor C_1 is MOSFET Q_1 gate drive power supply (BST1) and the capacitor C_2 is MOSFET Q_4 gate drive power (BST2). When Q_2 is on, C_1 is charged via V_{CC}-D_{B1}-C_1-Q_2 path relative to Q_1 source (LX1). Similarly, when Q_3 is on, C_2 is charged via V_{CC}-D_{B2}-C_2-Q_3 path relative to LX2 of Q_4 source (LX2).

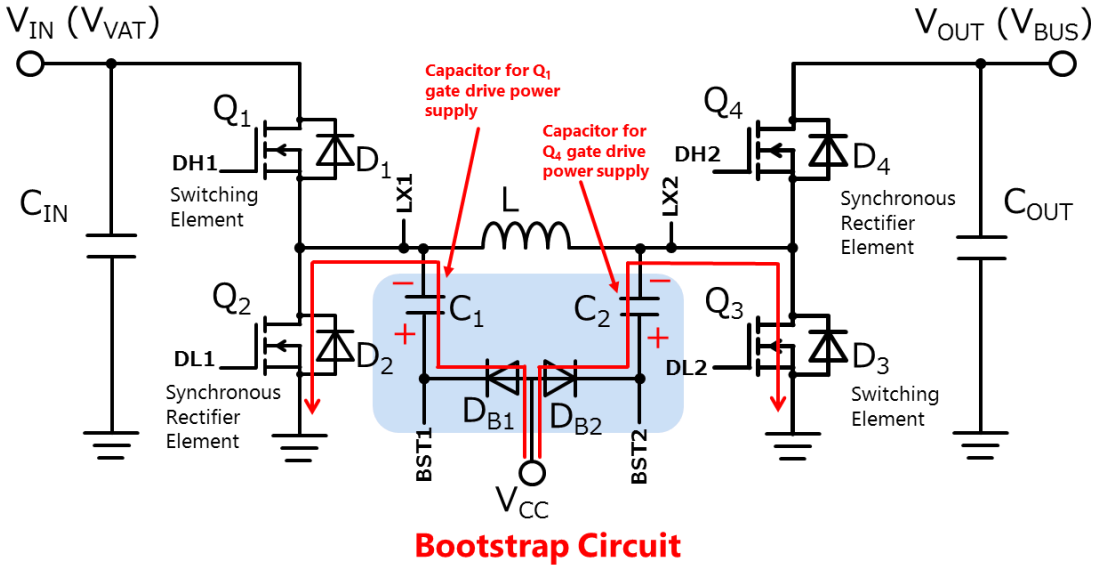


Fig. 4.3 Bootstrap Circuit

4.1.2. Buck Mode Operation

In Fig. 4.2, Q_1 and Q_2 are switched to perform the buck-mode operation. Q_1 and Q_2 operate in a complementary fashion, and Q_2 performs synchronous rectification. Q_4 of the boost circuit is fixed to ON, and Q_3 is fixed to OFF, so the operation is the same as that of the buck DC-DC converter circuit. Fig. 4.4 shows Q_1 to Q_4 gate signal control in buck-mode operation.

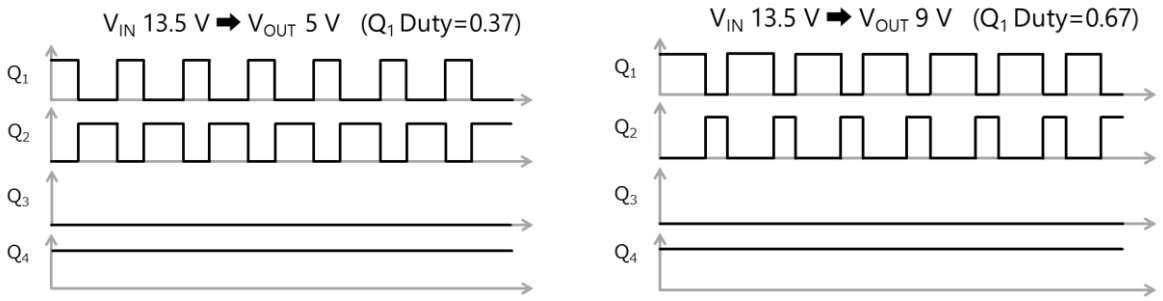


Fig. 4.4 Gate Signal Control Example in Buck Mode Operation

If Q_1 on time is T_{on} and the off time is T_{off}, the input voltage V_{IN} and output voltage V_{OUT} are related as follows.

$$V_{OUT} = \frac{T_{on}}{T_{on} + T_{off}} V_{IN}$$
$$= \frac{T_{on}}{T} V_{IN}$$
$$= D \cdot V_{IN}$$

(T: Q_1, Q_2 switching period, D: On duty of Q_1)

4.1.3. Boost Mode Operation

In Fig. 4.2, Q_3 and Q_4 can be switched for boost mode operation. Q_3 and Q_4 operate in a complementary fashion and Q_4 behave as a synchronous rectifier. Q_1 of the buck circuit is fixed to on, and Q_2 is fixed to off. This operation is similar to that of the boost DC-DC converter circuit. Fig. 4.5 shows Q_1 to Q_4 gate signal control in boost mode.

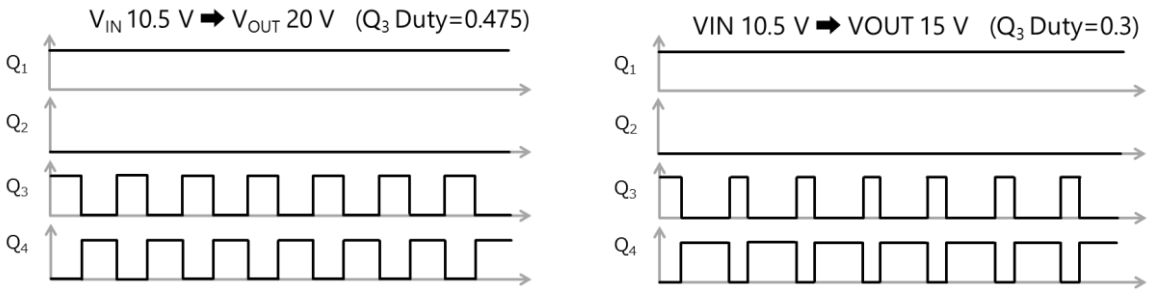


Fig. 4.5 Gate Signal Control Example in Boost Mode Operation

When Q_3 on time is T_{on}' and the off time is T_{off}', the input voltage V_{IN} and output voltage V_{OUT} are related as follows.

$$V_{OUT} = \frac{T_{on}' + T_{off}'}{T_{off}'} V_{IN}$$

$$= \frac{T}{T_{off}'} V_{IN}$$

$$= \frac{1}{1 - D'} V_{IN}$$

(T: Q_3, Q_4 switching period, D': On duty of Q_3)

4.1.4. Buck-Boost Mode Operation

When the input voltage V_{IN} ≈ output voltage V_{OUT}, buck-boost mode operation is performed, and boost mode operation and buck mode operation are alternately performed to stabilize the output voltage. Fig. 4.6 shows Q_1 to Q_4 gate-signal control in Buck-Boost mode. In the Fig. 4.6, when Q_3 is off and Q_4 is on, Q_1 and Q_2 are switched, and when, Q_1 is on and Q_2 is off, Q_3 and Q_4 are switched.

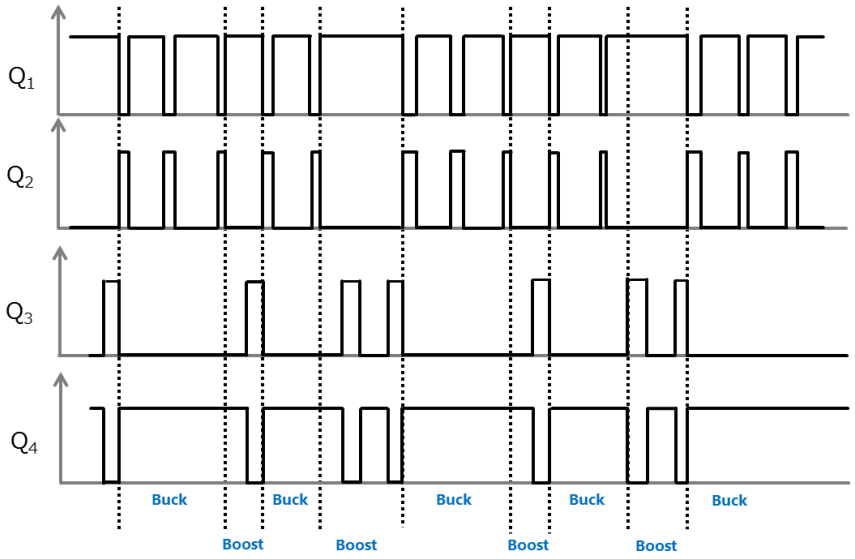


Fig. 4.6 Gate Signal Control Example in Buck-Boost Mode Operation

4.2. Power Switch and Reverse Connection Protection Circuit

Fig. 4.7 shows the power switch and reverse connection protection circuit. In the power supply input section, two MOSFETs with their sources connected in common are connected in two stages (back-to-back connection), the first stage acts as a power switch and the second stage acts as a reverse connection protection switch. These MOSFETs are driven by the high-side gate driver TPD7104AF, and when the power is normally supplied, the gates are driven and these two MOSFET are turned on to supply the power to the buck-boost DC-DC converter circuit. However, in case of reverse connection of power supply, the gates of these two MOSFETs are not turned on, and since the body diodes of these two MOSFETs are connected in reverse (because of back-to-back connection), the overall switch is turned off, thus protecting the buck-boost DC-DC converter circuit from the reverse voltage.

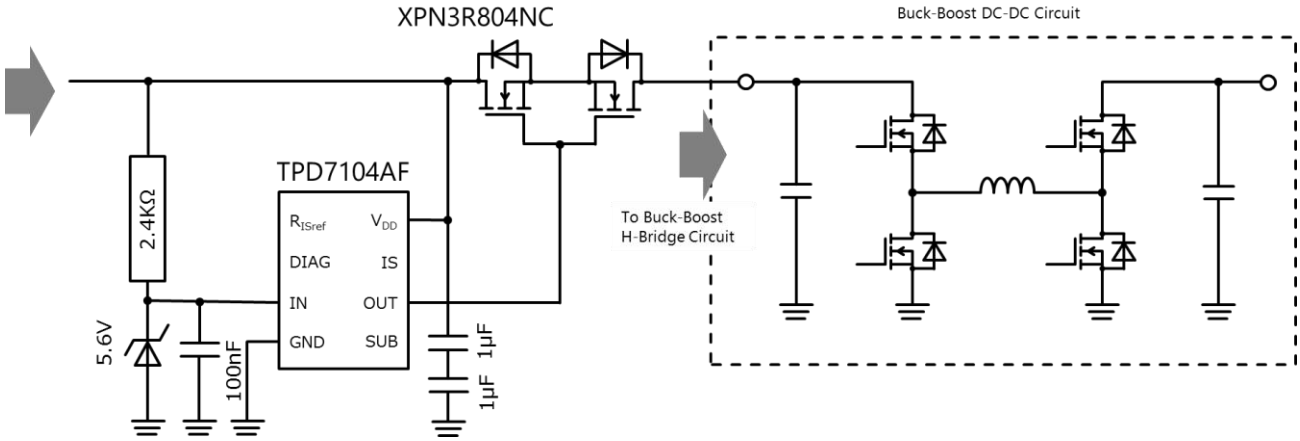


Fig. 4.7 Power Switch and Reverse Connection Protection Circuit

4.3. Shield Short Circuit Protection Circuit

The battery shield short protection circuit is shown in Fig. 4.8. It protects the circuit from short-circuit of the shield and battery power supply if the shield at the end of USB Type-C® cable touches the cigarette lighter socket. As shown in Fig. 4.8, the negative terminal of the Power Out connector is connected via a shielded short-circuit protective MOSFET rather than directly to ground within the power supply. The negative terminal (shield potential) of the power connector is monitored by the SHLD_SNS (shield sense) pin of this controller. When the voltage at the connector shield is detected, the shield short-circuit protective MOSFET is turned off by GDRV signal. This prevents a short circuit between the shield and the battery.

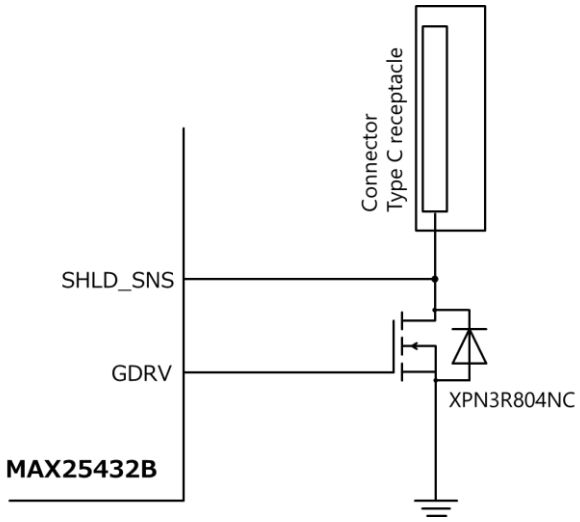


Fig. 4.8 Shield Short Circuit Protection Circuit

5. Performance

5.1. Switching MOSFET Characteristics

MOSFET used in the buck-boost DC-DC converter circuit of Option 1 and Option 2 of this power supply are shown in Table 5.1.

Table 5.1 Characteristics of Switching MOSFET Used in Each Option

		Option 1	Option 2
Equipped MOSFET		XPN7R104NC	SSM6K804R
Package	Name	TSON Advance(WF)	TSOP6F
	Size	3.1 x 3.6 mm	2.9 x 2.8 mm
Characteristics	Rated drain–source voltage	40 V	40 V
	Rated channel temperature	175 ℃	175 ℃
	Drain-source on-resistance (Max.)	14.2 mΩ @V_{GS} = 4.5 V	18 mΩ @V_{GS} = 4.5 V
	Total gate charge (Typ.)	10 nC @V_{DD} = 32 V V_{GS} = 4.5 V I_D = 20 A	7.5 nC @V_{DD} = 20 V V_{GS} = 4.5 V I_D = 12 A

5.2. Power Supply Efficiency

The power supply efficiency varies depending on the load conditions and I/O voltage conditions. Fig. 5.1 shows the example of measured efficiency curves under each I/O voltage condition.

Generally, in the light load region (output current is small), the conduction loss of the switching element is small, and the percentage of the switching loss of each element is high. In the light load region, Option 2 tends to be more efficient than Option 1 because it uses a smaller-gate-input-charge MOSFET. On the other hand, in the heavy load region (where the output current is large), the conduction loss in proportion to the current due to the on-resistance of the switching element accounts for a large percentage of the total loss. Therefore, under heavy loads, Option 1 tends to be more efficient as it uses a MOSFET with a smaller on-resistance.

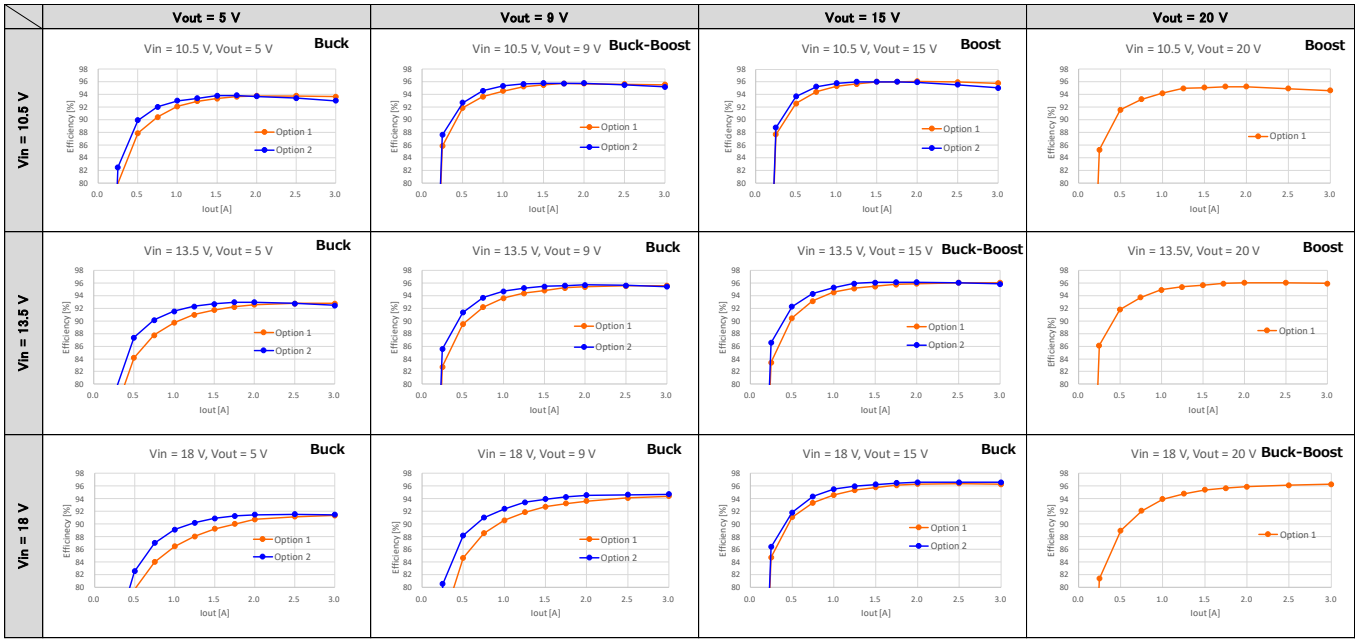


Fig. 5.1 Power Supply Efficiency Example in Each Condition

5.3. Temperature Rise

Fig. 5.2 shows the measurement results of MOSFET surface temperature rise ΔT under various input/output voltage conditions.

The maximum rated MOSFET channel temperature is 175 °C, and after derating it by 80% it becomes 140 °C. Considering the maximum ambient temperature of 85 °C, the allowable temperature rise becomes 55 °C (140 °C - 85 °C). The measured temperature rise shown in Fig. 5.2 has a considerable margin compared to the 55 °C.

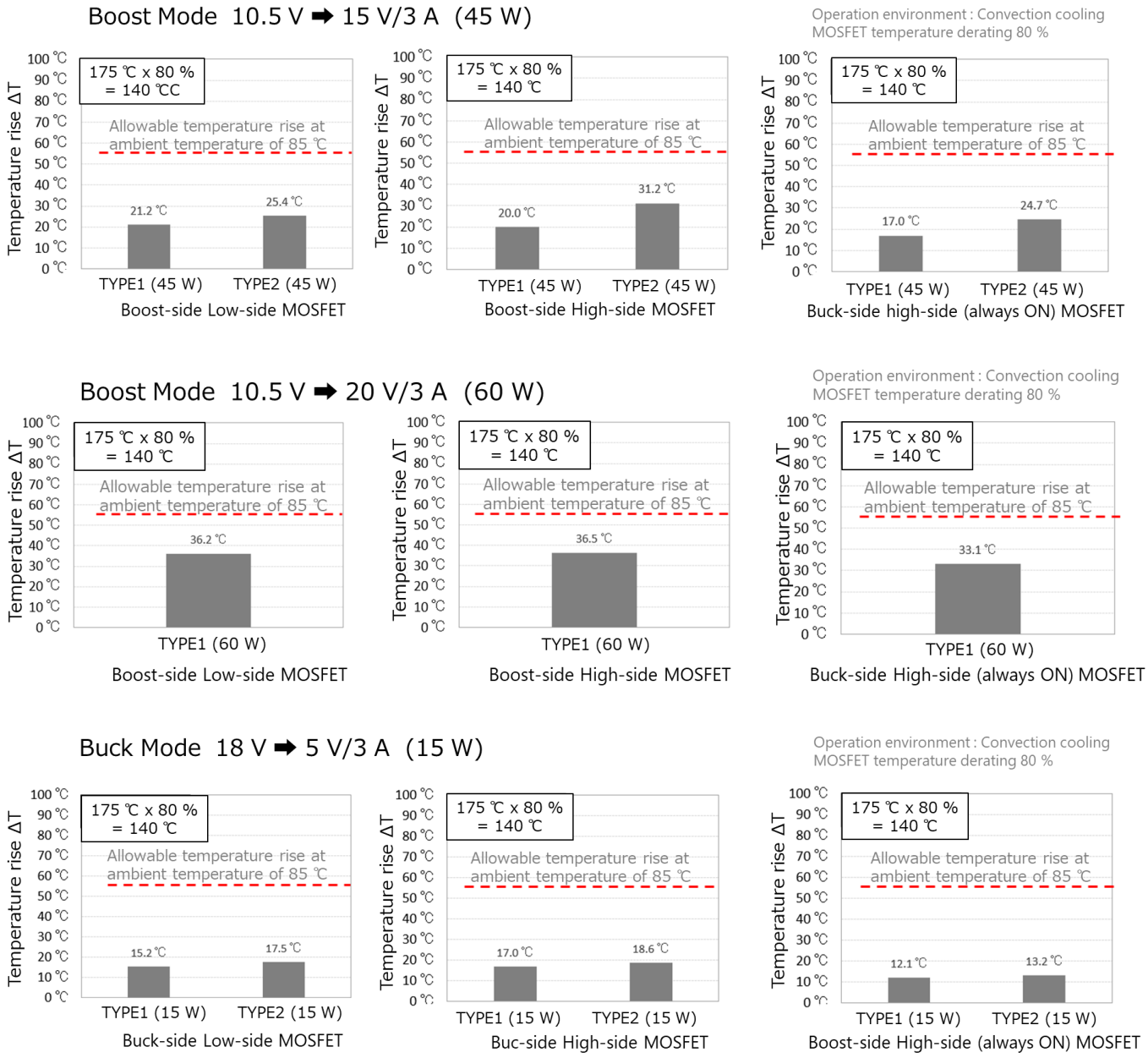


Fig. 5.2 MOSFET Temperature Rise

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