Efficiency evaluation of Half-bridge DC-DC converter supporting 48V Bus system

Toshiba UMOS-Ⅸ-H Series Power MOSFET
Ideal for 48Vin-1.2Vout DC-DC converters

Description

With the rapid progress of information and communication technologies, the volume of information processed every day has been increasing at an explosive rate in recent years. In response to this trend, many data centers have been constructed and expanded, however, due to the huge rise in the total amount of power utilized by all the data center's activities, the reduction of power consumption becomes significant. In this document, we consider one of the ways to reduce a data center's power consumption using 48V bus voltage for server racks to improve its power supply efficiency, which is recommended by the Open Compute Project (OCP). The "open rack architecture" which is proposed by OCP uses 48V bus lines to be converted from the AC voltage while conventional server uses 12V bus lines to be converted from AC voltage. The power loss caused by a power line is calculated as I2R, where R is the power line resistance and I is the power line current, so the lower the current, the lower the power loss. Moreover, let us consider the power consumption when the same amount of power is supplied to server racks through 12V bus lines and 48V ones. The current that passes through a 48V bus line is one-fourth the current that passes through a 12V bus line. If the 48V bus lines and 12V ones have the same resistance with the bus lines, the 48V bus line solution has 1/16th less power consumption than the 12V one. To solve this problem, Toshiba offers a reference design for a Half-bridge DC-DC converter that efficiently steps down the 48V bus line voltage to 1.2V to improve total system power consumption. The switching devices mounted in the reference design uses our latest generation small surface mount power MOSFET, which is ideal for DC-DC converters, and achieves high efficiency (up to 91%) and minimization of a convertor size (160mm x 100mm).

This application note describes the basic operation of the Half-bridge DC-DC converter adopted for the reference design and the losses of the switching devices, and then verifies the effects on the efficiencies when the mounted switching devices are replaced.

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1. Half-bridge DC-DC Converter Supporting 48V Bus System

This application note shows the Half-bridge DC-DC converter supporting 48V bus voltage. Its input voltage range is compliant with the 48V bus for server applications as recommended by the Open Compute Project (OCP), which is specified to be in the range of 40VDC to 59.5VDC. This 1.2V/100A DC-DC converter can supply 1.2V directly from a 48V bus. Although the 1.2V/100A DC-DC converter is designed to supply power to the loads on a 48V server motherboard, it is well suited to various applications, including communication equipment with 48VDC lines and industrial systems powered by 48V batteries. The picture and main specifications of this DC-DC converter evaluation board are shown below(Fig.1.1, Table1.1). This section describes the basic operating principle of the Half-bridge DC-DC converter.

Fig. 1.1 Picture of Half-bridge DC-DC converter evaluation board supporting 48V Bus systems

Table 1.1 Input and output characteristics of Half-bridge DC-DC Converter

Parameter		Condition	Min.	Typ.	Max.	Unit
Input characteristics						
	Input voltage		40	54.5	59.5	V
	Input current	Vin = 54.5 V, Iout = 100 A			2.8	A
Output characteristics						
	Output voltage		1.18	1.2	1.22	V
	Output current	Vin = 48V			100	A
	Output power	Vin = 48V			120	W
	Ripple				10	mV
	Switching frequency			302		kHz

1.1. Schematic and Notes for Half-bridge DC-DC Converter Supporting 48V Bus System

Fig. 1.2 is a schematic diagram of the DC-DC converter used in this evaluation. With the transformer T_1 as the boundary, the input side (primary side) is composed of two capacitors C_1, C_2 which divides the DC input and two switching devices TR_1, TR_2. The output side (secondary side) is composed of two switching devices TR_3, TR_4 that is intended for synchronous rectification and output smoothing filter circuits consisting of inductance L1 and capacitor C_3. Half-bridge DC-DC converters have only one winding of the transformer, which makes it more efficient to use the transformer. In addition to the difficulty of direct current excitation due to C_1, C_2, these have the advantage of being able to use a low-voltage MOSFET on the switching device because the voltage on the transformer is only half that of the input voltage. Note, however, that the following points must be noted when driving a switching device.

- Because the source of the upper arm (TR_1) varies depending on the operation of the lower arm (TR_2), dedicated drive circuitry with separate V_i and low-side drive power supplies and reference potential must be used to drive the upper arm (TR_1).
- Need to set a dead time to avoid the turning on of the upper and lower arms simultaneously.

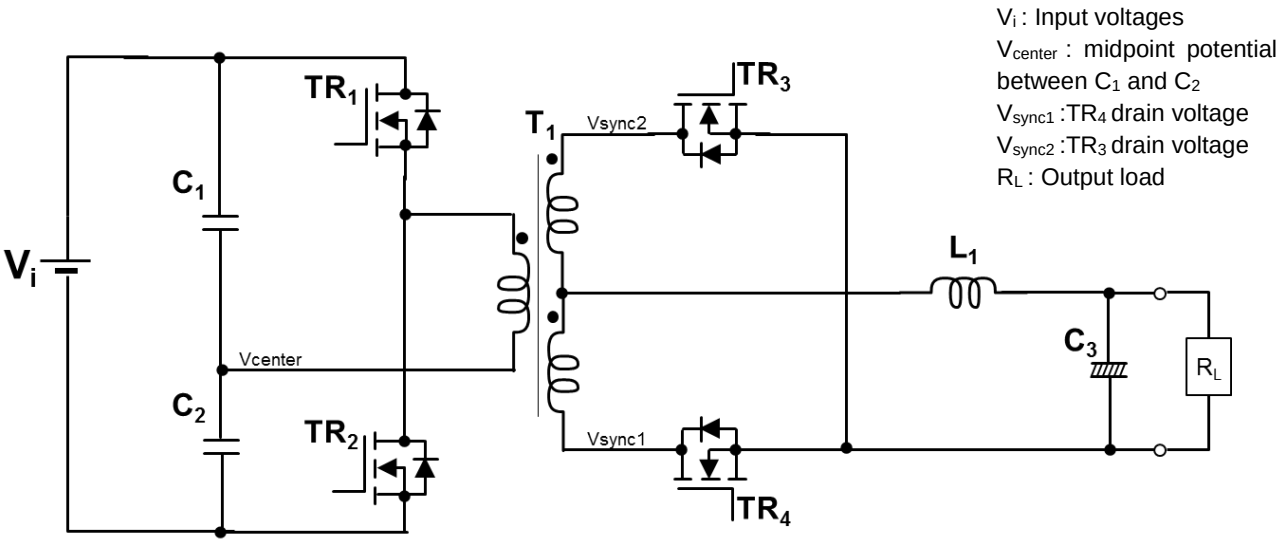


Fig. 1.2 Simplified schematic diagram of Half-bridge DC-DC converter

Fig. 1.3 shows a detailed circuit diagram of the secondary side MOSFET. Q5 and Q6 correspond to TR_3 in Fig. 1.2, and Q7 and Q8 correspond to TR_4.

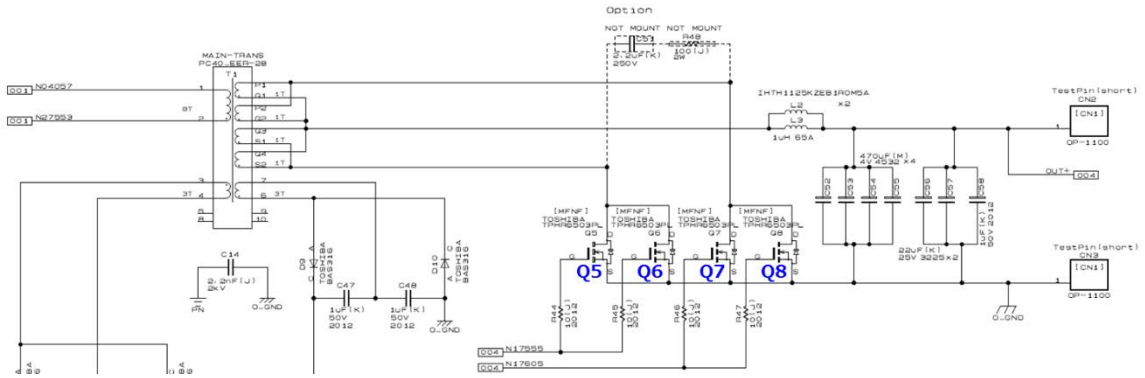


Fig. 1.3 Actual schematic diagram around the output side synchronous rectifying MOSFETs

1.2. Waveforms of The Half-bridge DC-DC Converter Supporting 48V Bus System

There are four modes of operation for TR_1, TR_2's on/off timing of the switching device and TR_3 and TR_4, which turn on/off synchronously with TR_1 and TR_2. Fig. 1.4 shows the current path in each operation mode, and Fig. 1.5 shows the waveforms of each switching device and L_1.

・Operating mode-1: TR_1 and TR_4 on, TR_2 and TR_3 off

As shown by the dotted arrow in Fig. 1.4(a), when TR_1 is on, current flows through TR_1 and then flows through the primary end of T_1 to charge C_2. Here, energy is propagated from the primary side to the secondary side through the transformer T_1, and C_3 is charged through the on TR_4 and L_1.

・Operating mode-2: TR_1, TR_2 off, TR_4 on, TR_3 off on

As shown in Fig 1.5, TR_3 is turned on when TR_1 is turned off. As shown in Fig. 1.4(b), the primary side does not allow the flow of current because both TR_1 and TR_2 are off, but the secondary side allows current to flow along the dotted arrow path through the energy stored in L_1.

・Operating mode-3: TR_2 and TR_3 on, TR_1 and TR_4 off

As shown by the dotted arrows in Fig. 1.4(c), current flows from C_1 through the primary side of T_1 through the ON state's TR_2. Energy propagates from the primary side to the secondary side through the trans T_1, but as opposed to operation mode-1, energy flows from the on TR_3 to the secondary side of the transformer through L_1 to charge C_3.

・Operating Mode-4: TR_1, TR_2 off, TR_3 on, TR_4 off on

As shown in Fig 1.5, TR_4 is turned on when TR_2 is turned off. As shown in Fig. 1.4(d), current does not flow on the primary side because both TR_1 and TR_2 are off, but the energy stored in L_1 on the secondary side causes the current to flow along the dotted arrow path.

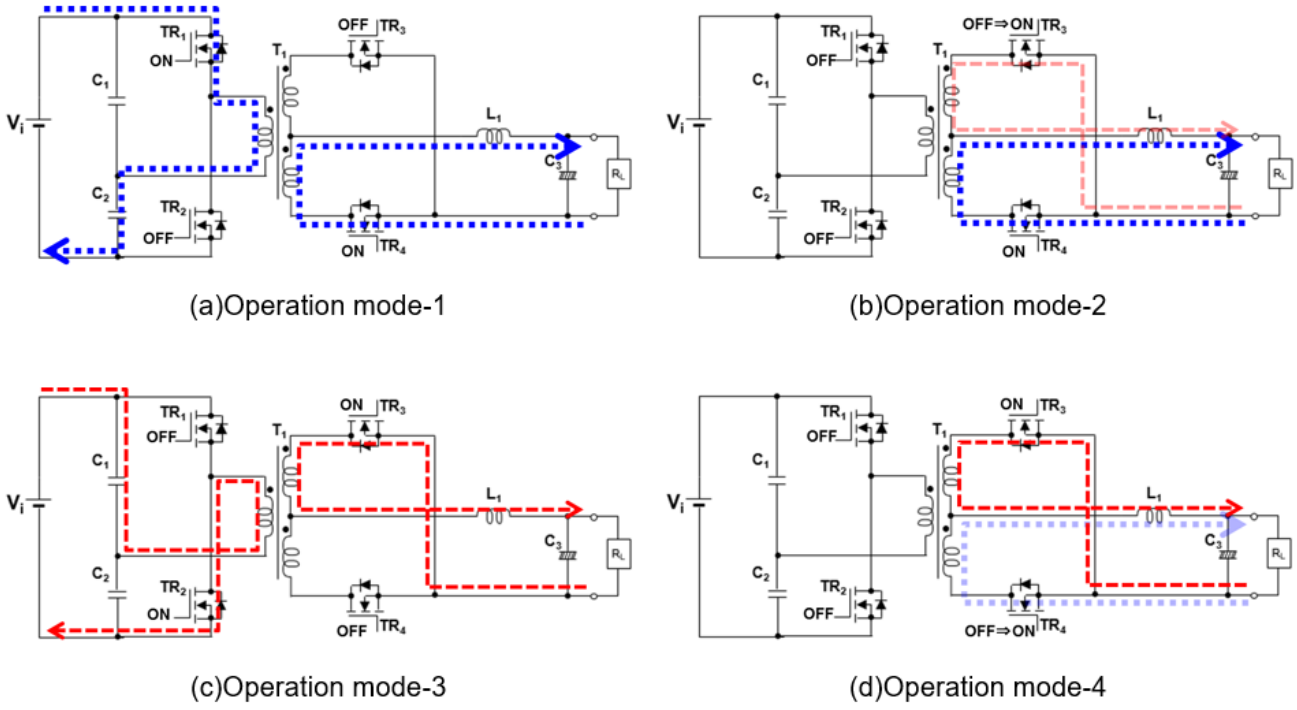


Fig. 1.4 Half-bridge DC-DC converter operation modes

The figure below shows the simplified operation waveforms of the half-bridge DC-DC converter. Fig. 1.4 shows the gate voltage (V_G) of the switching device TR_1-TR_4, the midpoint potential V_{center} between C_1 and C_2, the drain voltage V_{sync1} of TR_4, the drain voltage V_{sync2} of TR_3, the voltage VL_1 and current IL_1 of the inductance L_1, and the drain current (I_D) of TR_1-TR_4 for the operation modes-1 to 4. The current of TR_3 and TR_4 flows from the source to the drain so that current waveforms are represented as negative values.

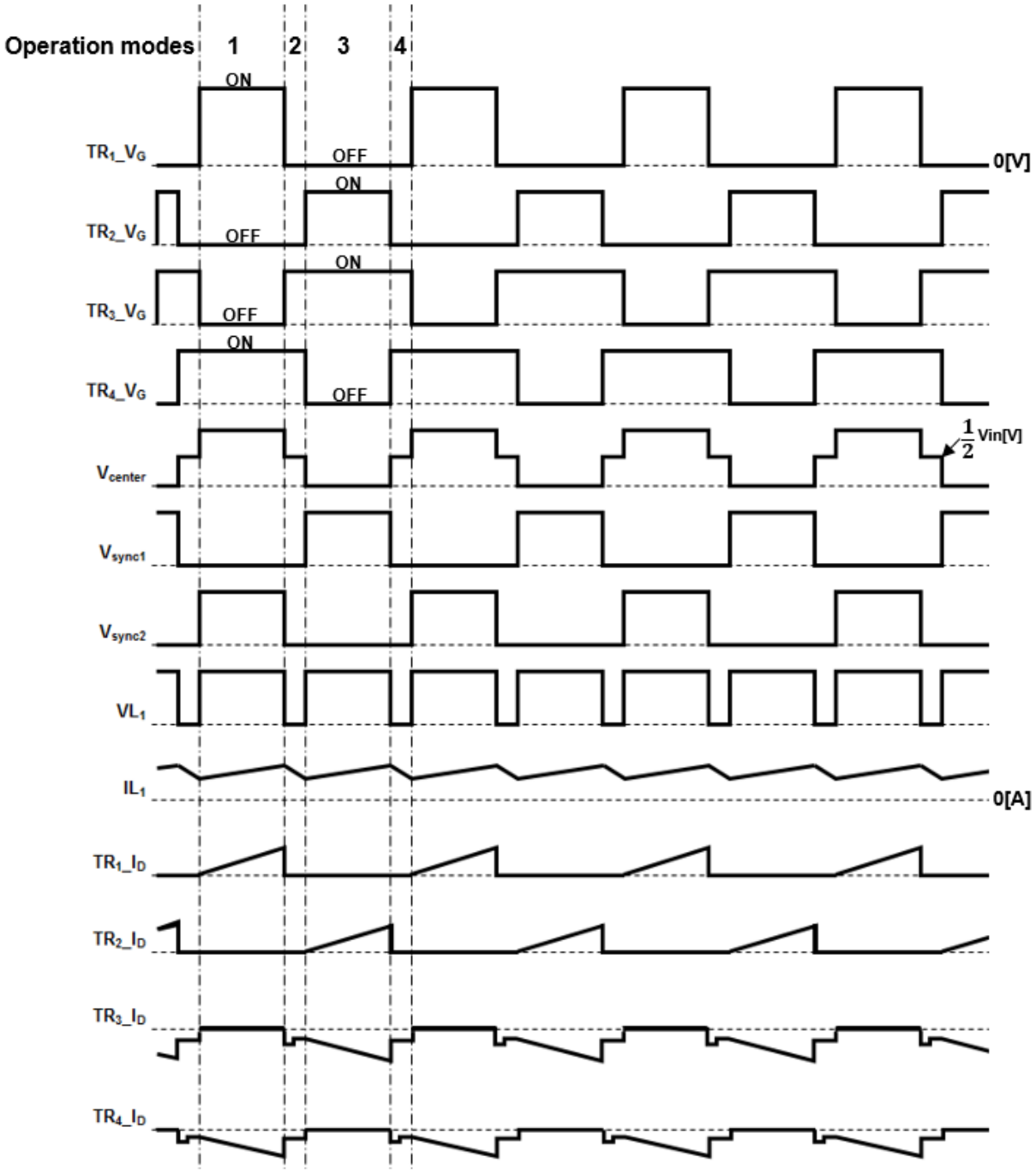


Fig. 1.5 Simplified waveforms of Half-bridge DC-DC converter

2. Power Losses of DC-DC Converters

Losses in step-down DC-DC converters occur in the path through which current flows. Among the losses that occur, generally the loss due to MOSFET's switching operation is the largest, followed by the loss generated by the inductance placed on the output side. With the transformer as the boundary shown in Fig. 1.2, the loss of TR_1, TR_2 of the input side (primary side), TR_3, TR_4 of the output side (secondary side) and inductance when designing DC-DC converter should be estimated. In MOSFETs, switching loss, gate drive loss, output capacitance loss, and diode reverse recovery loss are generated in addition to the loss due to steady-state current (conduction loss).

2.1. Loss Index and Loss Calculation Method of Switching Devices

To simplify the explanation, we will use a typical buck-type DC-DC converter consisting of two MOSFETs instead of a half-bridge type DC-DC converter. Fig. 2.1 and 2.2 show the schematic, main loss factors and the simplified MOSFET operation waveforms. To consider the loss of the Half-bridge type DC-DC converter, the High-side MOSFET in Fig. 2.1 corresponds to the primary MOSFET in Fig. 1.2, and Low-side MOSFET in Fig. 2.1 corresponds to the secondary MOSFET in Fig. 1.2.

Conduction (P_C) are calculated in t_{ON} section and t_{OFF} section. In this circuit, the Low-side MOSFET is turned off when the High-side MOSFET is turned on, and the losses are calculated from the drain current (I_{DS}) flowing through each MOSFET, the on-resistance ($R_{DS(ON)}$) of MOSFET and the conduction duty ratio of the switching operation (d.c = t_{ON}/T: d.c is duty cycle, T is one cycle of the switching operation). The conduction losses of the respective MOSFET are calculated by the following formula.

High-side MOSFET $P_{C\_H} = I_{DS}^2 \times R_{DS(ON)} \times d.c$ [W] Use t_{ON_H} and $T_{\_H}$ for d.c
Low-side MOSFET $P_{C\_L} = I_{DS}^2 \times R_{DS(ON)} \times d.c$ [W] Use t_{ON_L} and $T_{\_L}$ for d.c

The switching loss (P_{SW}) is calculated in t_r section and t_f section. Losses occur during transitions in which the MOSFET between High-side and Low-side alternately turns on and off. Since the formula for obtaining the area of the triangle is similar to the calculation of the power loss during the switching transition, it is calculated by approximating it with a simple figure calculation. Switching losses increase in proportion to the switching frequency (f_{SW}) and are calculated by multiplying the switching frequency, drain current (I_{DS}), drain source voltage (V_{DS}), and on period (t_{ON}) for one switching operation cycle. The switching loss of the High-side MOSFET can be calculated by the following equation. As for the Low-side MOSFET, the gate turns on while the body diode is conducting, and when the gate turns off, I_{DS} continues to flow through the body diode in the same direction, so the drain voltage remains low and the switching loss is very small.

High-side MOSFET $P_{SW\_H} = 1/2 \times I_{DS} \times V_{DS} \times (t_{r\_H} + t_{f\_H}) \times f_{SW}$[W]

Gate drive loss (P_G) is a power loss that results from charging the MOSFET's gates. This loss depends on High-side and Low-side MOSFET gate capacitances and it is calculated from the switching frequency (f_{SW}), Gate charge at V_{GS} (Q_g) and Gate voltage (V_{GS}). The gate drive loss is calculated by the following formula:

$P_G = (Q_{g\_H} + Q_{g\_L}) \times V_{GS} \times f_{SW}$ [W]
However, Q_{g_H} and Q_{g_L} indicate High-side MOSFET charge and Low-side MOSFET charge respectively.

Output Capacitance Loss (P_{QOSS}) is a loss of charge for High-side and Low-side MOSFET output capacitance (C_{OSS}) during MOSFET switching operations. The switching frequency (f_{SW}), charge between drain sources (Q_{OSS}), and drain-source voltage (V_{DS}) are used for approximation by a simple figure calculation, and are calculated by the following formula:

$P_{QOSS} = (Q_{OSS\_H} + Q_{OSS\_L}) \times V_{DS} \times f_{SW}$ [W]

However, Q_{OSS_H} indicates the amount of charge between drain sources in High-side MOSFET, and Q_{OSS_L} indicates the amount of charge between drain sources in Low-side MOSFET. Q_{OSS} can be calculated by the following equation, where C(v) is a function of the output capacitance C_{OSS} with V_{DS} dependency.

$$Q_{OSS}=\int_0^{VDS} C(v)dv$$

When the High-side MOSFET is turned on, the forward-biased Low-side MOSFET body diodes are reverse-biased. During this transition, residual carriers in the body diodes are swept out and the reverse-biased condition is restored, resulting in reverse-recovery-loss (P_{DIODE}). This loss is calculated from the switching frequency (f_{SW}), drain-source voltage (V_{DS}), diode reverse recovery current (I_{rr}), and reverse recovery time (t_{rr}), and is given by the following equation:

$$P_{DIODE} = 1/2 \times V_{DS} \times I_{rr} \times t_{rr} \times f_{SW} \text{ [W]}$$

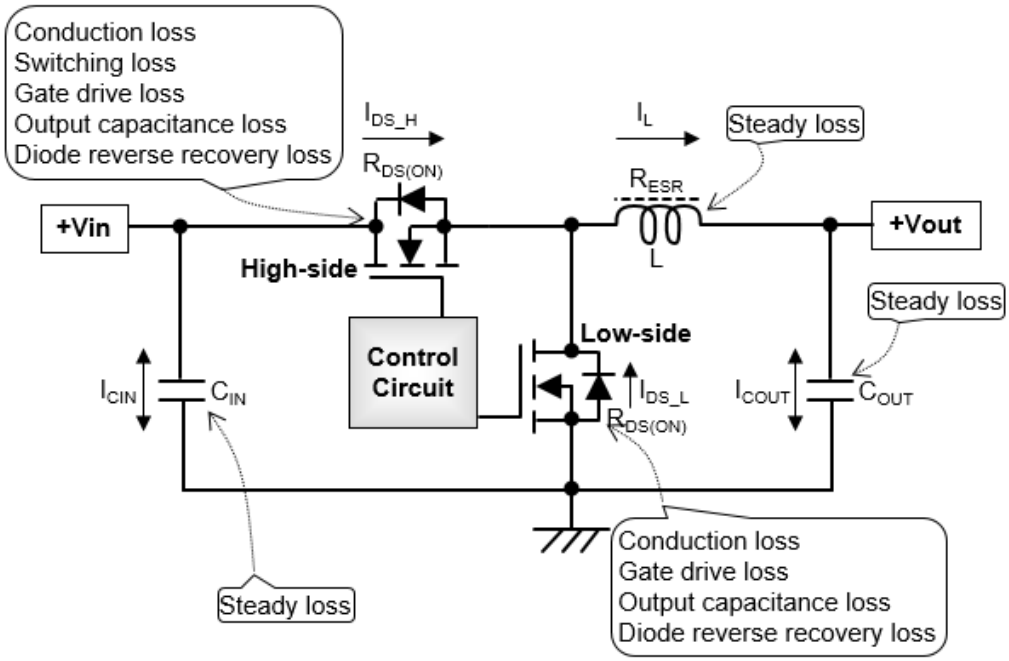


Fig. 2.1 Schematic diagram of step-down DC-DC converter and main loss factors

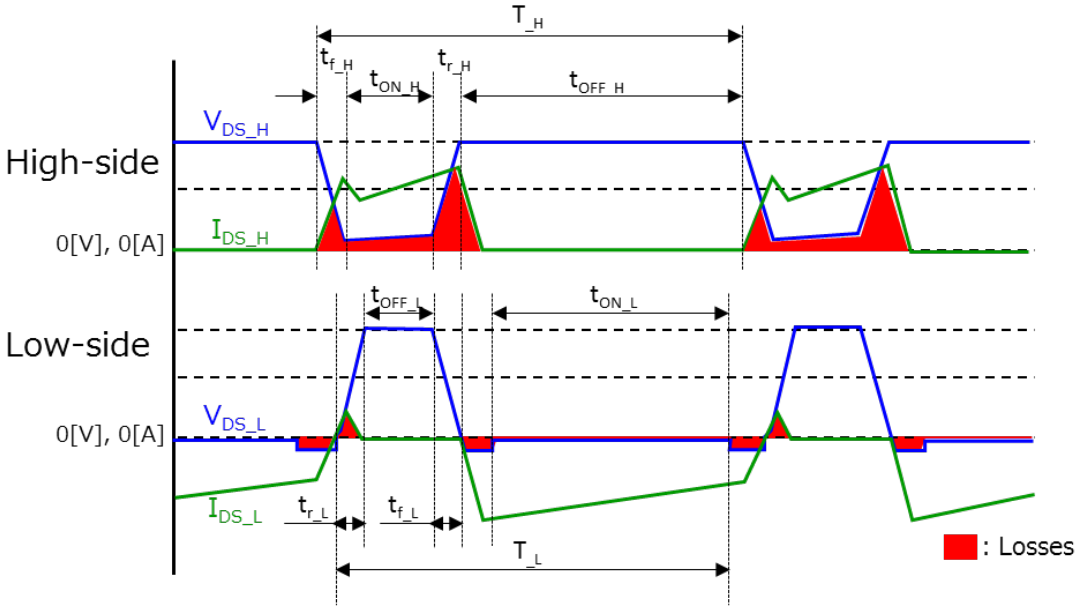


Fig. 2.2 MOSFET operation waveform of step-down DC-DC converter

2.2. Power Losses Depending on Output Load

Switching-type DC-DC converters generally consist of PWM (abbreviated as Pulse Width Modulation) control combined with negative feedback amplifiers. PWM control is a method of controlling an object by changing the pulse width ratio (duty ratio) between the on and off times of a pulse train. For the half-bridge type DC-DC converter shown in Fig. 1.2, the output power is controlled by alternately turning on and off the two primary MOSFETs and changing its duty ratio by the output of a control IC called a PWM controller.

Fig. 2.3(a) shows the basic configuration of the PWM control circuit. The node of a sensing resistor (R_1, R_2) that monitors the change in the power supply outputs and the node of reference voltage (V_{ref}) are connected to the input end of the error amplifier (A_1). For example, if the output load increases and the output voltage decreases, the input voltage of the error amplifier (A_1) becomes lower compared to the reference voltage (V_{ref}), so the output voltage of A_1 rises. A_2, on the other hand, is a voltage-comparator. If a triangular wave with a frequency sufficiently higher than the frequency of the input signal from A_1 is applied to the negative terminal of the input, and the output voltage of A_1 is connected to the positive terminal, a pulse-modulated signal that repeatedly turns on and off within a certain period can be obtained as shown in Fig. 2.3 (b). The output pulse width and duty cycle vary depending on the magnitude of the input signal from A_1. When the output voltage of A_1 increases, the duty cycle of the PWM output increases. The MOSFET is driven by a gate signal that varies the ratio of the on-off time generated by the PWM control circuit, and the constant voltage control of DC-DC converter is performed.

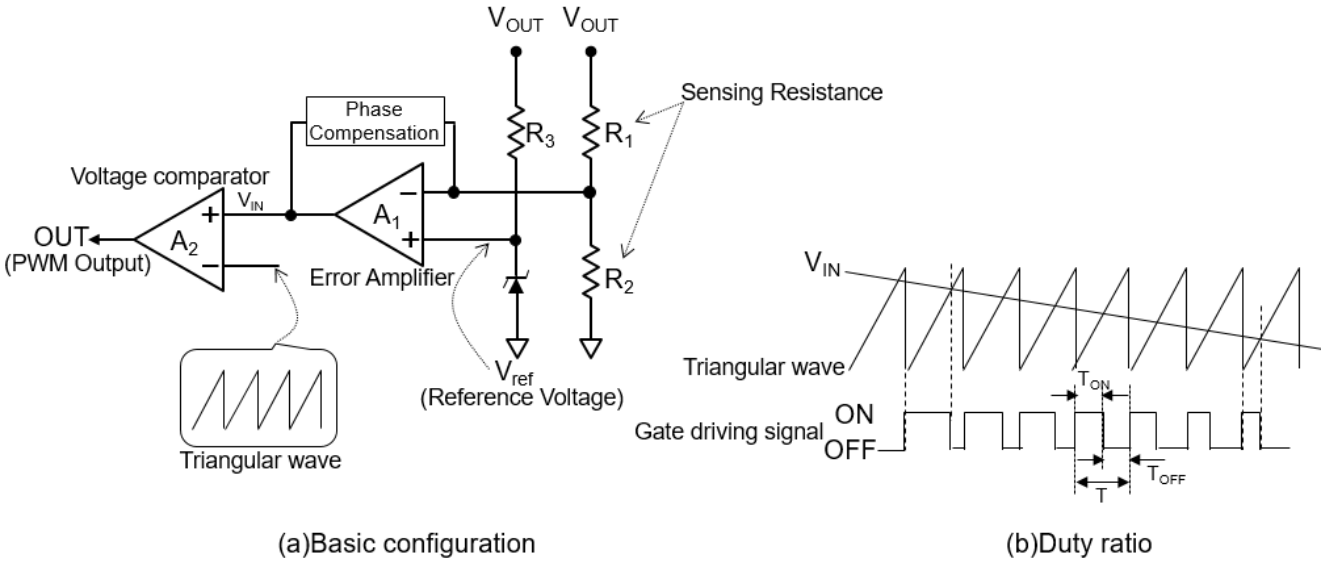


Fig. 2.3 PWM control basic configuration and duty-ratio control operation principles

Fig. 2.4 shows the duty ratio of the primary MOSFET when the output load of the half-bridge type DC-DC converter changes as shown in Fig. 1.2. It can be seen that the duty cycle of a MOSFET is varied by PWM control. When the output load is light, the duration when a MOSFET is turned on in one period is short, and the loss is mainly dominated by the switching loss. On the other hand, when the output is heavy load, the duration when a MOSFET is on becomes long and conduction losses are dominant.

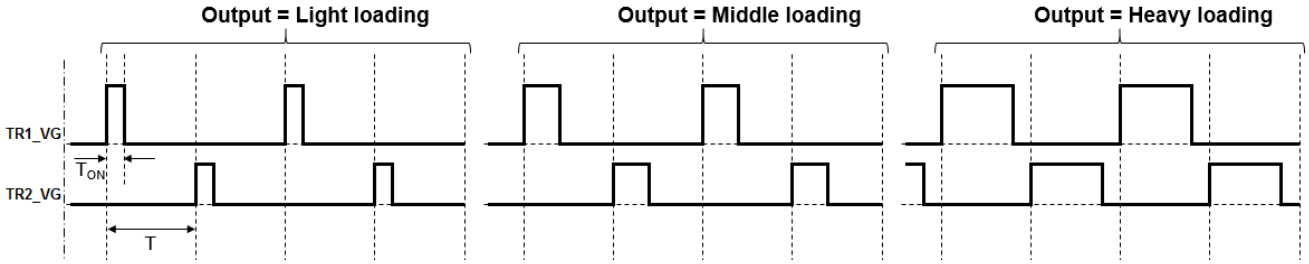


Fig. 2.4 Output load dependency of primary MOSFET switching timing of step-down DC-DC converter

3. Power MOSFETs Lineup for Efficiency Evaluation

Toshiba offers the U-MOSⅧ-H, U-MOSⅨ-H and U-MOSⅩ-H low-voltage MOSFET series which suits primary (main switch) and secondary (synchronous rectification) sides of DC-DC converters. Toshiba provides MOSFETs with wide range of V_{DSS} from 30V to 250V and various on-resistance types in each V_{DSS} class so you can find proper MOSFETs when designing a DC-DC converter, according to its circuit topology, input and output voltages, output specification, and the locations of MOSFETs on circuit (primary or secondary side). Figure 3 shows the lineup of the U-MOSⅧ-H, U-MOSⅨ-H and U-MOSⅩ-H MOSFET series.

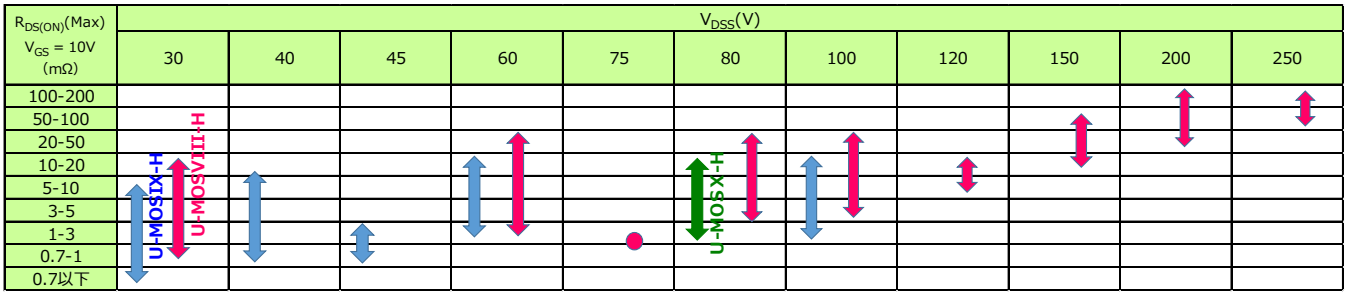


Fig. 3.1 Product lineup of the U-MOSⅧ-H, U-MOSⅨ-H and UMOSⅩ-H MOSFET series

3.1. List of Switching Devices to be compared

Table 3.1 shows the main specifications of MOSFETs used in this evaluation. The primary side is a product with 100V withstand voltage. Three types of MOSFETs are prepared which differ in on-resistance between drain and source and in input capacitance. In particular, since switching loss is considered to dominate on the primary side, the light-load dependence of the input capacitance is confirmed by including Company B devices, which clearly have a smaller input capacitance compared to the other two devices. Subsequently, four types of MOSFET with different drain-to-source on-resistance and input-capacitance on the secondary side were also prepared, however TPHR6503PL was selected, which is a drain-to-source on-resistance approximately half the size of the other MOSFETs considering that conduction loss will dominate over the primary side. The impact on efficiency during heavy loads with other products was then compared.

Table 3.1 Main specifications of evaluation MOSFETs

Characteristics	Symbol	Unit	Primary Side			Secondary Side			
			TPN1200APL	Company A	Company B	TPHR6503PL	TPHR9203PL	Company A	Company C
Gate leakage current (Max)	I_{GSS}	μA	10	0.1	0.1	0.1	0.1	0.1	0.1
Drain cut-off current (Max)	I_{DSS}	μA	10	1	1	10	10	1	1
Drain-source breakdown voltage (Min)	$V_{(BR)DSS}$	V	100	100	100	30	30	30	30
Gate threshold voltage (Max)	V_{th}	V	2.5	2.3	2.9	2.1	2.1	2	2
Drain-source on-resistance (Typ)	$R_{DS(ON)}$	mΩ	9.8	8.2	11.2	0.41	0.91	0.9	0.75
Input capacitance (Typ)	C_{iss}	pF	1425	1600	968	7700	5800	4700	7036
Reverse transfer capacitance (Typ)	C_{rss}	pF	15	12	11	220	190	220	353
Output capacitance (Typ)	C_{oss}	pF	205	250	241	2720	1750	1500	2778
Gate resistance (Typ)	r_g	Ω	2.1	1.2	0.6	0.6	0.5	0.6	1.1
Switching time (rise time) (Typ)	t_r	ns	6	4.6	3.6	12	8	8.8	12.8
Switching time (turn-on time) (Typ)	t_{on}	ns	19	5.7	9.7	36	20	6.7	12.3
Switching time (fall time) (Typ)	t_f	ns	6	5.3	3.4	10	18	6.2	28.8
Switching time (turn-off time) (Typ)	t_{off}	ns	34	21	16	100	71	37	68.5
Total gate charge (Typ)	Q_g	nC	24	12	15	110	81	36	107
Gate-drain charge(Typ)	Q_{gd}	nC	4.9	4.1	3.5	16	11	10.3	21.4
Gate switch charge(Typ)	Q_{SW}	nC	7.5	6.3	4.4	30	19	14	---
Output charge(Typ)	Q_{oss}	nC	24	30	---	81.3	51	40	---

4. Efficiency Evaluation Results

In this evaluation, we verified the basic characteristics and efficiencies of DC-DC converters with the products listed in Table 3.1 using our 48V bus-voltage compatible half-bridge DC-DC converter boards. In the efficiency evaluation, 12 patterns of combinations of three types of switching devices of primary side and four types of switching device on the secondary side were measured and the results were compared. The switching frequency is set to 302 kHz. (This can be set by connecting a 20kΩ resistor to the RT terminal of the control IC.)

Efficiency is one of the most important characteristics of DC-DC converters. Efficiency is the ratio of the power output to the power input of DC-DC converter and it is calculated by the following formula.

$$\text{Efficiency} = (V_{out} \times I_{out})/(V_{in} \times I_{in}) \times 100\ [\%]$$

In this evaluation, we measured V_{in}, I_{in}, V_{out} and I_{out} for 12 patterns of switching device combinations under the following conditions, calculated the efficiency and compared the trends of each pattern. Fig. 4.1 shows the connection diagram for efficiency measurement. DC-DC converter circuit board is installed in a temperature chamber so that the entire circuit board is uniformly heated, and that the air from the fan in the chamber constantly blows the circuit board.

Input Voltage (V_{in}) = 40V, 54.5V, 59.5V
Outside temperature (T_a) = 25℃
Output Load Current (I_{out}) = 0A, 10A - 100A (10A increments, V_{in}=40V up to 50A)

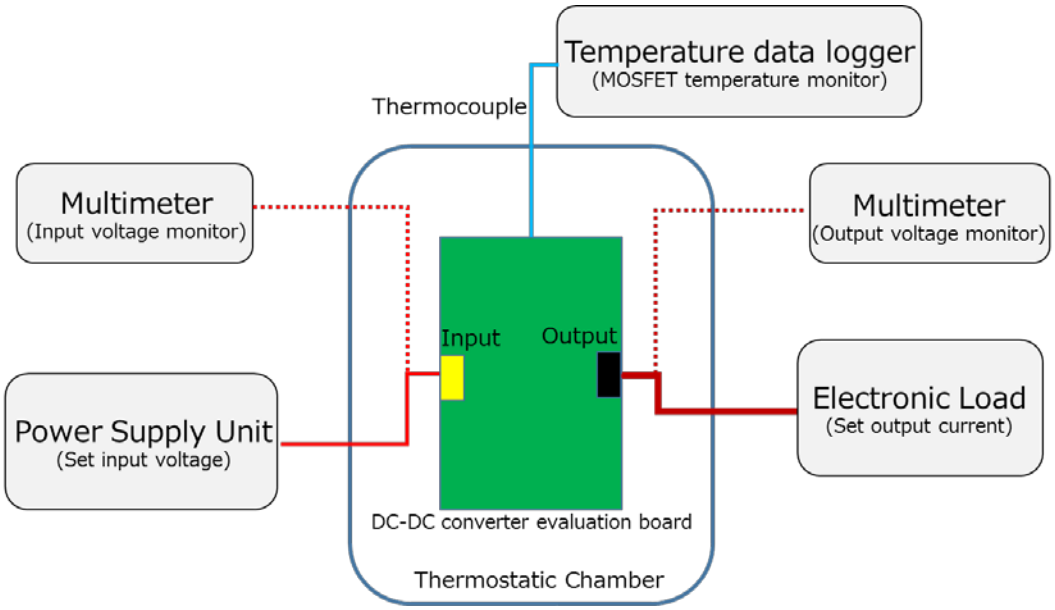


Fig. 4.1 Connection between evaluation board and each equipment for efficiency measurement

4.1. Input/Output Characteristics of Half-bridge DC-DC Converter Evaluation Board

Fig. 4.2(a) - (f) show the basic characteristics of DC-DC converter. Ripples on the input side are caused by pulsating currents flowing through the internal oscillator and should be small because they can interfere with other parts of the circuit through parasitic inductances and capacitances on the PCB (Printed circuit board) wiring, leads and connections. On the output side, the ripple voltage is generated by the current flowing through the ESR (series equivalent resistance) of the capacitor when the coil current due to switching or the current energy stored in the coil is opened to the load capacitor. This ripple voltage is the main output fluctuation factor of the switching power supply, and it is desirable that the ripple voltage generated on the input side is as small as possible like the ripple current. In this evaluation board, the input ripple current is about 190mA (p-p) and the output voltage ripple is about 340mV (p-p). Fig. (e) The dynamic response of output voltage indicates the stability of the output voltage when the output load fluctuates. Fig. (f) shows the efficiency of this evaluation board with respect to the output load current, achieving a maximum efficiency of 87.5% when the input voltage is 40V and the load current is 30A. The measurement conditions in Fig. 4.2(a) - (e) are T_a=25℃, V_{in}=54.5V, I_{out}=100A (however, the load response is between 25A and 75A).

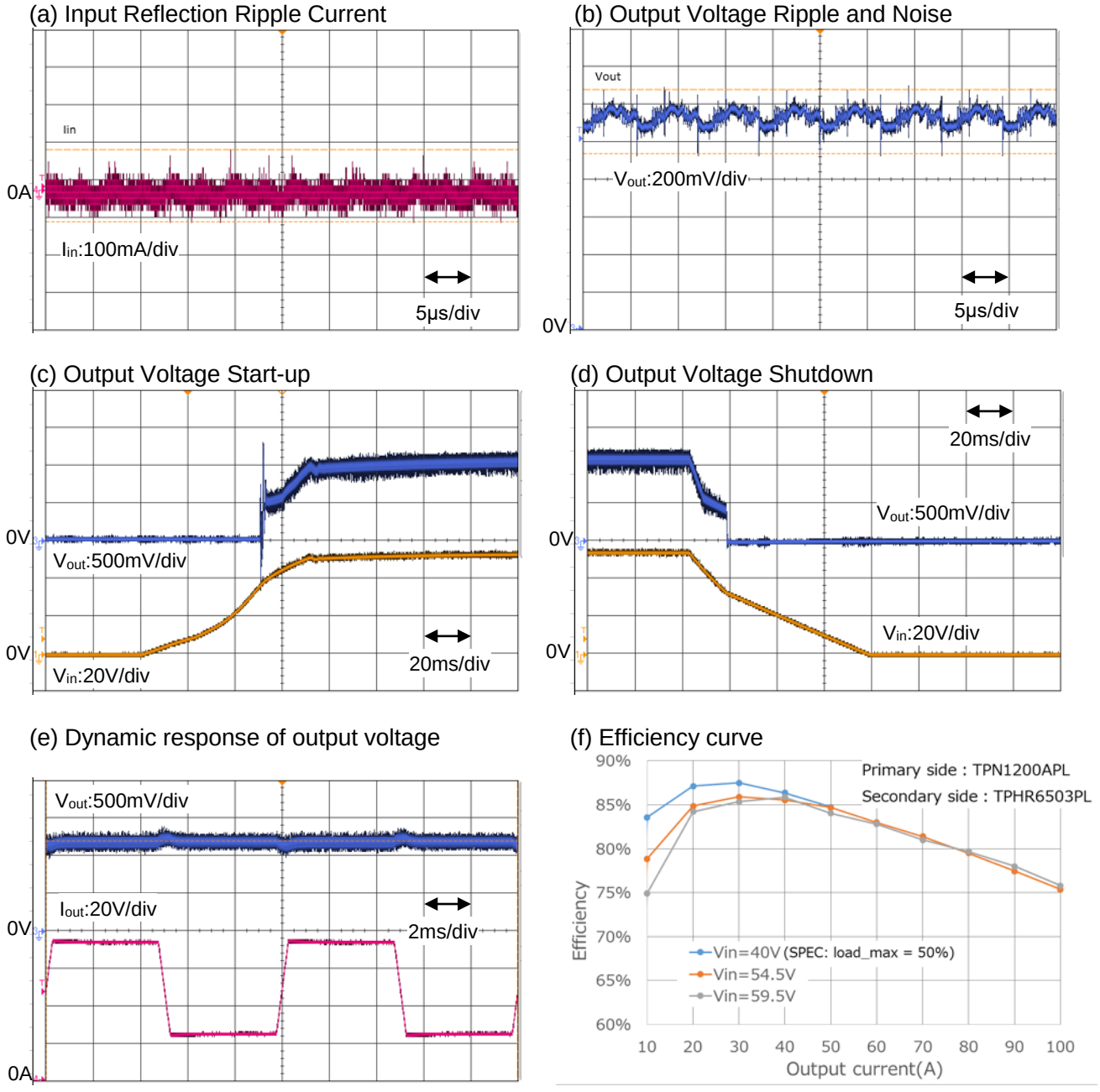
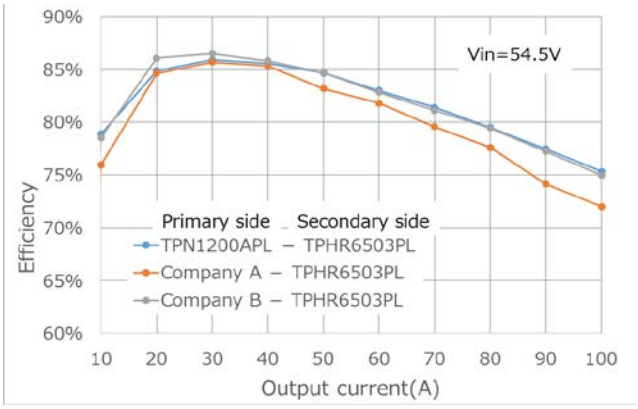


Fig. 4.2 Basic characteristics of DC-DC converter input/output

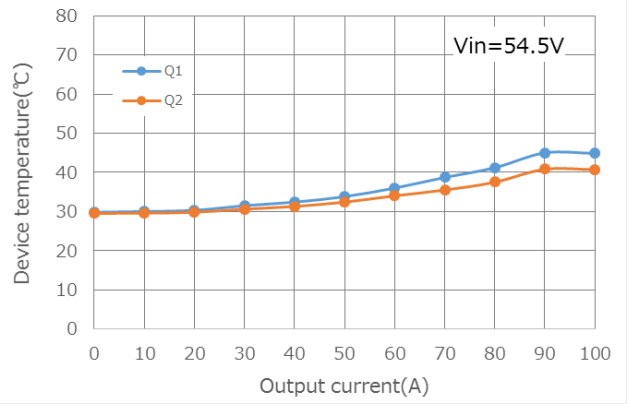
4.2. Effect of Primary Switching Device on Power Conversion Efficiency

Fig. 4.3(a) shows the efficiency curve when the secondary side MOSFET is fixed to TPHR6503PL and the primary side MOSFET is changed to TPN1200APL, Company A or Company B device. Since switching loss dominates at light loads (10-30 A), Company B device with the smallest input capacitance achieves the highest efficiency of 87%. However, TPN1200APL has an advantage in medium to heavy loads (40-100A). This is because of the fact that the input capacitance is 1435 pF, which is the second smallest compared to that of Company B device, as well as the drain-to-source on resistance of 9.8 mΩ which is about 12.5% smaller than that of Company B's 11.2 mΩ. Fig. 4.3 (b) - (d) show the results of measuring the temperatures of MOSFET devices on the primary sides when a respective MOSFET is used on the primary side. When A Company device which shows the lowest efficiency result is used on the primary side (Fig.(a)), it is clear that the device temperature is higher at all output current and the loss is larger than that of other products (Fig.(c)). As shown in Table 3.1, it is presumed that the gate drive loss and the output capacitance loss are large because the input capacitance is 12% and the output charge is 25% or more larger than the TPN1200APL. Q1 and Q2 in Fig. 4.3 are TR_1 and TR_2 in Fig. 1.2.

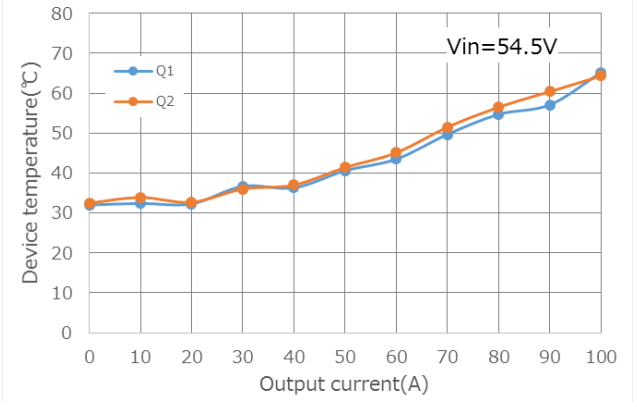
(a) Efficiency comparison of primary-side MOSFET



(b) primary device: TPN1200APL and its temp.



(c) Primary device: Company A and its temp.



(d) Primary device: Company B and its temp.

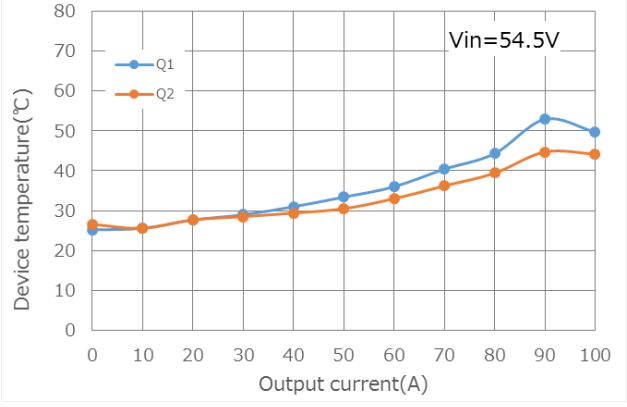


Fig. 4.3 Efficiency influence by primary side MOSFETs, and its temperatures depending on output load

4.3. Effect of Secondary Switching Device on Power Conversion Efficiency

Fig. 4.4(a) shows the efficiency curve when the primary side MOSFET is fixed to TPN1200APL and the secondary side MOSFET is changed to TPHR6503PL, TPHR9203PL, Company A or Company C device. In Table 3.1, when we confirm Q_{OSS} that affects the efficiency at light load (10-40 A), TPHR9203PL or Company A's device are small and achieve the highest efficiency of 87%. However, for medium to heavy loads (50 to 100A), conduction losses are dominant, so TPHR6503PL with the smallest on-resistance between the drain and source has an advantage, and then followed by TPHR9203PL. Fig. 4.4 (b) - (e) show the results of measuring MOSFET device temperatures on the secondary sides when each MOSFET is used on the secondary side (TPN1200APL is used for the primary side MOSFET). Focusing on the highly efficient TPHR6503PL (Fig. (b)) on the heavy-load side, Q7 exceeds 75°C, but the other MOSFET is below 75°C, confirming that heat generation is relatively lower than other MOSFET.

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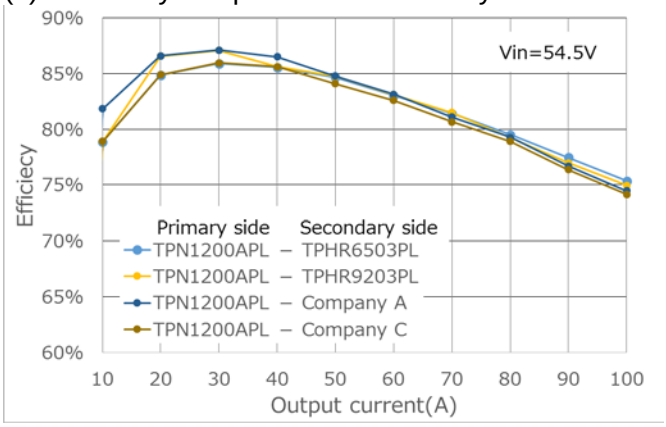
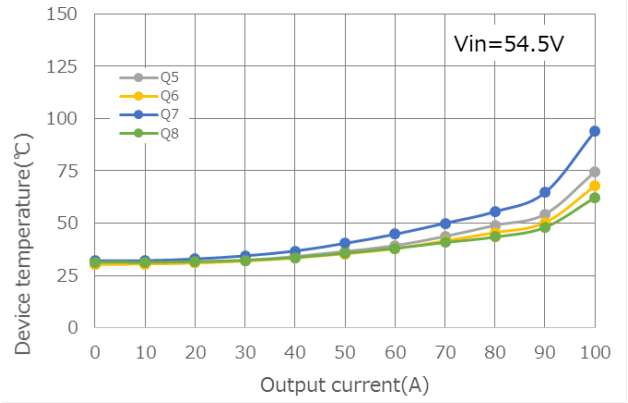
(a) Efficiency comparison of secondary-side MOSFET

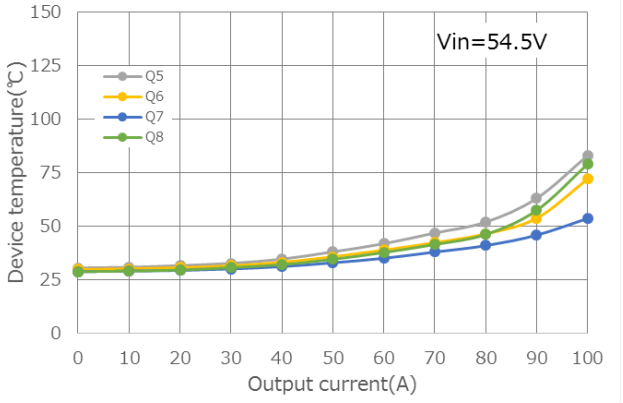


Q5 and Q6 in Fig. 4.4 correspond to TR_3 in Fig. 1.2, and Q7 and Q8 correspond to TR_4. Refer to Fig. 1.3 for detailed wiring of Q5 to Q8.

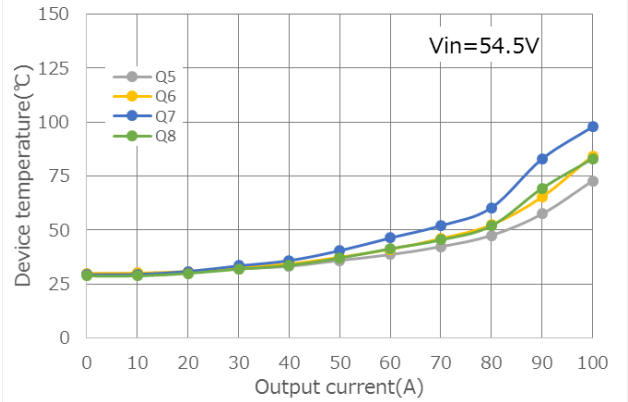
(b) Secondary device: TPHR6503PL and its temp.



(c) Secondary device: TPHR9203PL and its temp.



(d) Secondary device: Company A and its temp.



(e) Secondary device: Company C and its temp.

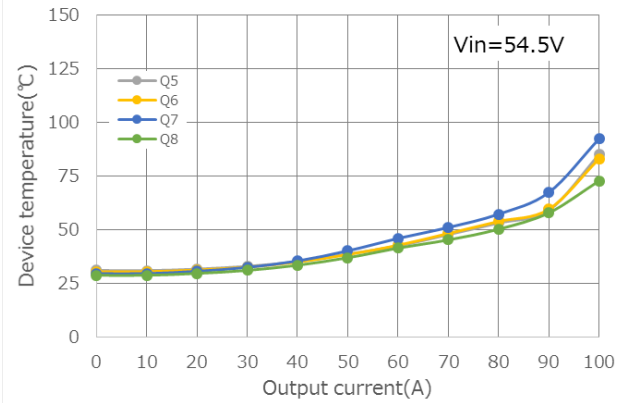


Fig. 4.4 Efficiency influence by secondary side MOSFETs, and its temperatures depending on output load

4.4. Conclusion

Since the primary side is dominated by the effect of switching losses, MOSFET products with small input capacitance are superior, and high efficiencies have been achieved in TPN1200APL for medium to heavy loads (40 to 100A). The reason for this is that the input capacitance is small and the on-resistance is also as small as 9.8mΩ. On the secondary side, the built-in diodes operate before the MOSFET is turned on, so conduction losses are predominant. Therefore, it is advisable to select a MOSFET with a small on-resistance. In the efficiency evaluation when the MOSFET shown in Table 3.1 is applied to the secondary side, TPHR6503PL with the smallest on-resistance exhibited high efficiency from medium load to heavy load. Finally, we were able to confirm from this evaluation that using TPN1200APL for the primary side and TPHR6503PL for the secondary side is the most efficient combination.

5. Application support

Detailed information on the reference designs adopted for this application note can be found at the following URL:
https://toshiba.semicon-storage.com/us/semiconductor/design-development/referencedesign/articles/12v-100a-output-dc-dc_power_supply_rd040.html

Notes on Contents

1. **Block Diagrams**
   Some of the functional blocks, circuits, or constants in the block diagram may be omitted or simplified for explanatory purposes.

2. **Equivalent Circuits**
   The equivalent circuit diagrams may be simplified or some parts of them may be omitted for explanatory purposes.

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