Efficiency Evaluation and Loss Analysis of 300W isolated DC-DC converter

Toshiba U-MOSⅩ-H Series Power MOSFET
Ideal for 48Vin, 12Vout DC-DC converters

Description

This application note first describes the basic operation of the 300W isolated DC-DC converter adopted for the reference design (Note1). After that, the efficiency evaluation results are explained. Furthermore, the loss of the switching devices is analyzed using a high accuracy electric circuit model that simulates this reference design. The device model (SPICE model) of the switching devices for the loss simulation uses a sub-circuit model originally developed by Toshiba (hereinafter referred to as the G2 model). The G2 model is a SPICE model that expresses the nonlinearity of the capacitance of a power device and is suitable for transient simulations of power devices.

(Note1) Reference design refers to the data information about application design listed at the Reference Design Center on the Toshiba Device & Storage website. The reference design includes schematics, board data, BOM information, reference guides and design guides.

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1. 300W Isolated DC-DC Converter

This converter operates over an input voltage range of 36 to 75VDC and provides 300W power at 12VDC output. This converter is suitable for various applications, including telecommunication equipment with 48VDC lines and industrial systems powered by 48V batteries. This reference design provides various design information, which can help reduce the time and effort in designing a DC-DC converter according to actual required specifications. This converter uses Toshiba's latest small surface-mount power MOSFETs (TPN1200APL, TPH2R408QM) as switching devices on both the primary and secondary sides and small surface-mount components for other types of devices. Consequently, despite the use of a general-purpose winding transformer, small PCB size (82mm x 82mm x 24mm) and high efficiency (94%) are achieved.

Fig. 1.1 300W DC-DC converter evaluation board

Table 1.1 Input and output characteristics of 300W DC-DC converter

Parameter	Condition	Min.	Typ.	Max.	Unit
Input characteristics					
Input voltage		36		75	V
Input current	Vin = 48 V, Iout = 25 A			12	A
Output characteristics					
Output voltage		11.4	12.0	12.6	V
Output current				25	A
Output power				300	W
Ripple				200	mV
Switching frequency			185		kHz

1.1. Schematic diagram of 300W isolated DC-DC converter

Fig.1.2 is a schematic diagram of DC-DC converter used in this evaluation. With the transformer T_1 as the boundary, the primary side (input side) is composed of four switching devices TR_1 to TR_4 consisting of two arms, the secondary side (output side) is composed of two devices TR_5, TR_6 that is intended for synchronous rectification and output smoothing filter circuits consisting of inductance L_2 and capacitor C_2. Fig. 1.3 shows a detailed schematic diagram of the secondary side MOSFET. TR_5 and TR_6 have two MOSFETs connected in parallel. This converter generates 12V output voltage by phase-shifted full-bridge (PSFB) topology. The output voltage is regulated by phase-shifted operation between an arm of TR_1, TR_2 and the other arm of TR_3, TR_4 with a 50% duty cycle. In the dead time between the high side MOSFET and low side MOSFET to prevent shoot-through, zero voltage switching(ZVS) is achieved and reduces the switching loss of the power converter.

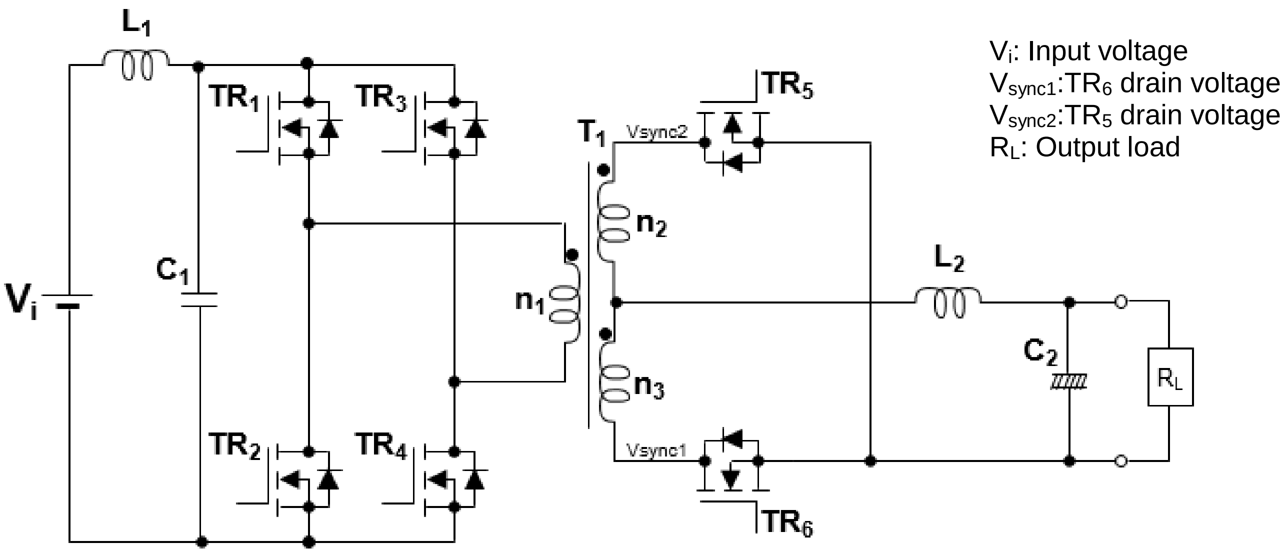


Fig. 1.2 Simplified schematic diagram of 300W DC-DC converter

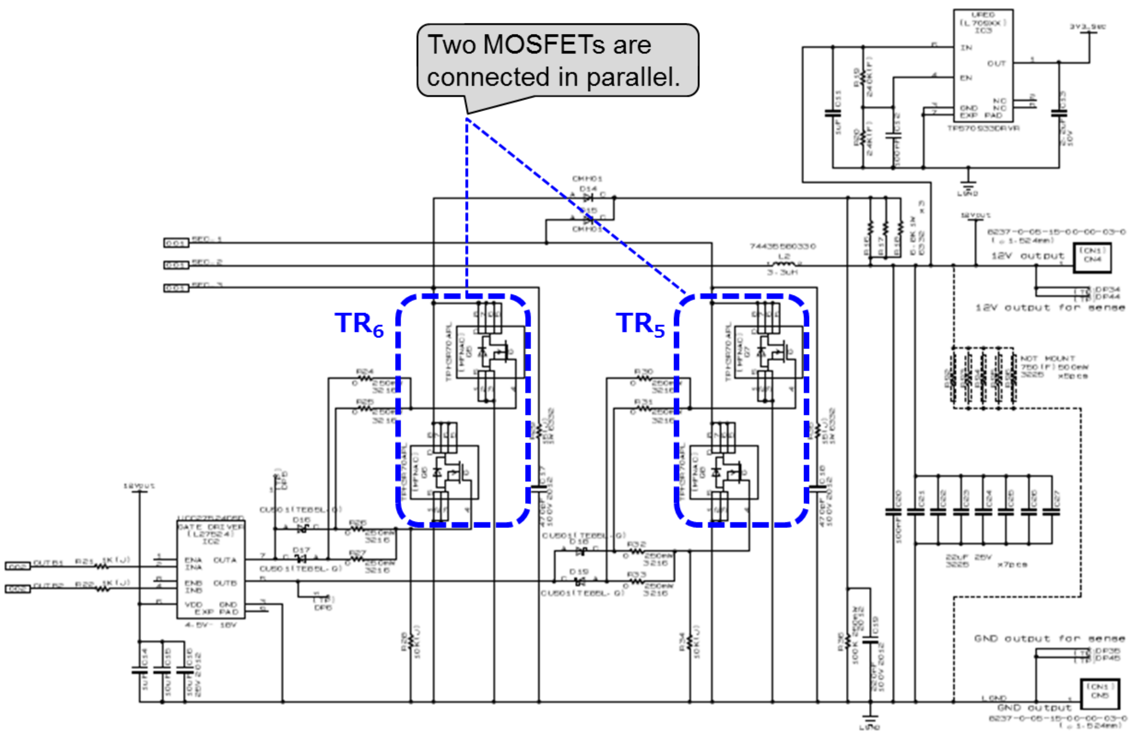


Fig. 1.3 Actual schematic diagram around the output side synchronous rectifying MOSFETs

1.2. Operating waveforms of the 300W isolated DC-DC converter

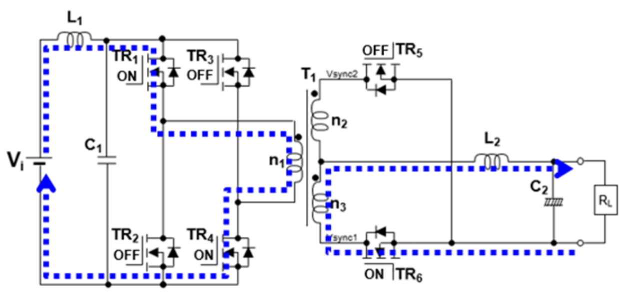
This chapter introduces the principle of switching operation by describing the eight different modes. Fig.1.4 and Fig.1.5 show the current path in each operation mode, and Fig.1.6 shows the waveforms of each switching device and L_2.

・Operation mode-1:TR_1 and TR_4 are ON state, TR_2, TR_3 and TR_5 are OFF state
As shown by the dotted arrows in Fig.1.4(a), while TR_1 and TR_4 are ON state, current flows through TR_1 and then flows through the primary end of T_1, and then flows through TR_4. Here, the energy is transferred from the primary side(n_1) to the secondary side(n_3) through the transformer T_1, and C_2 is charged through TR_6 and L_2.

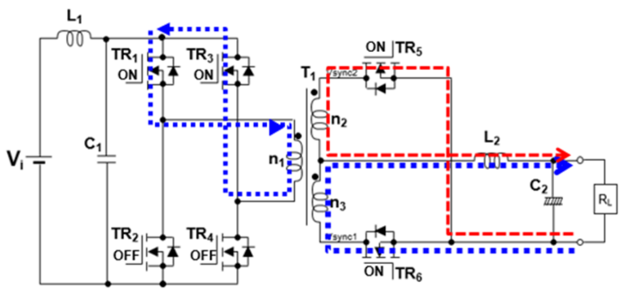
・Operation mode-2:TR_1 and TR_6 are ON state, TR_2, TR_3 and TR_5 are OFF state, TR_4 is turn-off
When TR_4 turns off, the current that flows on the primary side causes a freewheeling operation through the body-diode of TR_3 after charging the output capacitance C_{oss} of TR_2 and TR_4 as shown by the dotted arrows in Fig. 1.4(b). Because of the freewheeling operation, energy is not transferred from the primary side (n_1) to the secondary side (n_3) through the transformer T_1, but on the secondary side, the current that flows along the path of the blue dotted arrow comes from L_2 due to energy stored. In addition, the current also flows along the red dashed arrow through body diode of TR_5.

・Operation mode-3:TR_1 and TR_6 are ON state, TR_2 and TR_4 are OFF state, TR_3 and TR_5 is turn-on
When TR_3 turns on, the freewheeling current in TR_3 flows through the transistors rather than through the body diodes. In addition, when TR_5 turns on, current in TR_5 flows through the transistors rather than through the body diode along the red dashed arrows.

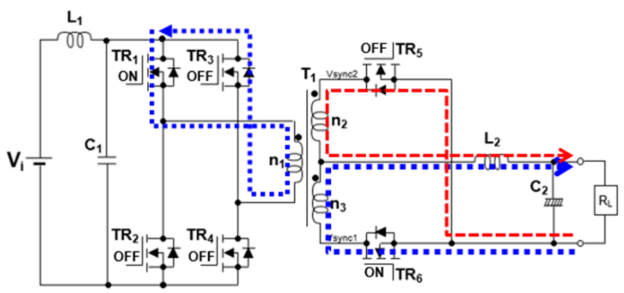
・Operation mode-4:TR_3 and TR_5 are ON state, TR_2 and TR_4 are OFF state, TR_1 and TR_6 are turn-off
When TR_1 turns off, the freewheeling operation stops and no current flows at the primary. However, on the secondary, the current flows along the red dashed arrow through the on-state TR_5 from L_2 due to energy stored.



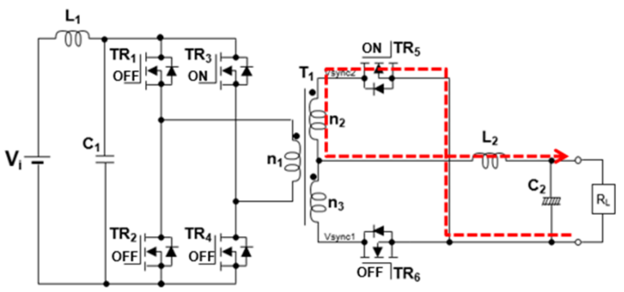
(a)Operation mode-1



(c) Operation mode-3



(b) Operation mode-2



(d) Operation mode-4

Fig. 1.4 300W DC-DC converter operation mode 1~4

・Operation mode-5:TR_2, TR_3 and TR_5 are ON state, TR_1, TR_4 and TR_6 are OFF state
As shown by the dotted arrows in Fig.1.5(a), while TR_2 and TR_3 are ON state, the current flows through TR_3 and then flows through the primary(n_1) of T_1, and then flows through TR_2. Here, the energy is transferred from the primary side(n_1) to the secondary side(n_2) through the transformer T_1, and C_2 is charged through TR_5 and L_2.

・Operation mode-6:TR_2 and TR_5 are ON state, TR_1, TR_4 and TR_6 are OFF state, TR_3 turn off
When TR_3 turns off, the current flows on the primary side causes a freewheeling operation through body-diode of TR_4 after charging the output capacitance C_{oss} of TR_1 and TR_3 as shown by the dotted arrows in Fig. 1.5(b). Because of the freewheeling operation, energy is not transferred from the primary side (n_1) to the secondary side (n_2) through the transformer T_1, but on the secondary side, the current that flows along the path of the blue dotted arrow comes from L_2 due to energy stored. In addition, the current also flows along the red dashed arrow through body diode of TR_6.

・Operation mode-7:TR_2 and TR_5 are ON state, TR_1 and TR_3 are OFF state, TR_4 and TR_6 are turn-off
When TR_4 turns on, the freewheeling current in TR_4 flows through the transistors rather than through the body diodes. In addition, when TR_6 turns on, current flows in TR_6 through the transistors rather than through the body diode along the red dashed arrows.

・Operation mode-8:TR_4 and TR_6 are ON state, TR_1 and TR_3 are Off state, TR_2 and TR_5 are turn-off
When TR_2 turns off, the freewheeling operation stops and no current flows at the primary. However, on the secondary, the current flows along the red dashed arrow through the on-state TR_6 from L_2 due to energy stored.

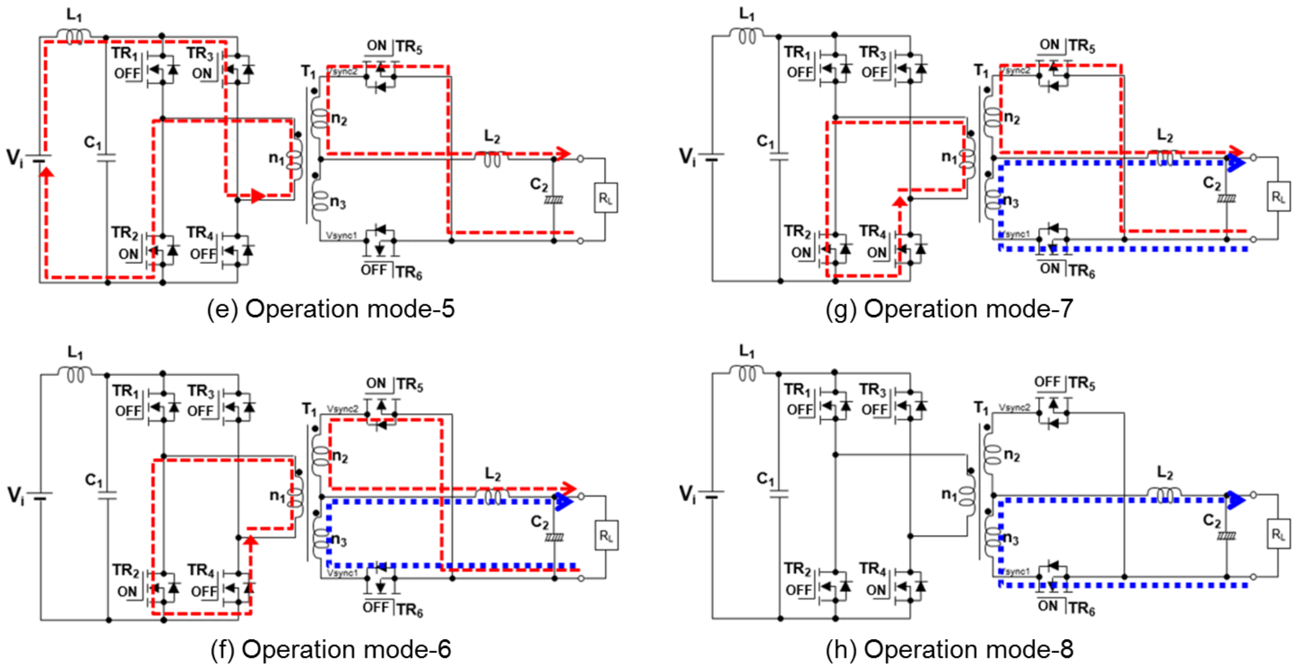


Fig. 1.5 300W DC-DC converter operation mode 5~8

Fig.1.6 shows the simplified operating waveforms of 300W isolated DC-DC converter. For the operation modes-1 to 8 shown in Fig.1.4 and Fig.1.5, the gate voltage (V_G) and drain current (I_D) of the switching devices TR_1 to TR_6, drain-source voltage (V_{sync1}, V_{sync2}) of TR_5 and TR_6, and the inductance voltage (V_{L2}) and current (I_{L2}) of L_2 are described. The current through TR_5 and TR_6 are denoted by a negative value because the current flows from the source to the drain.

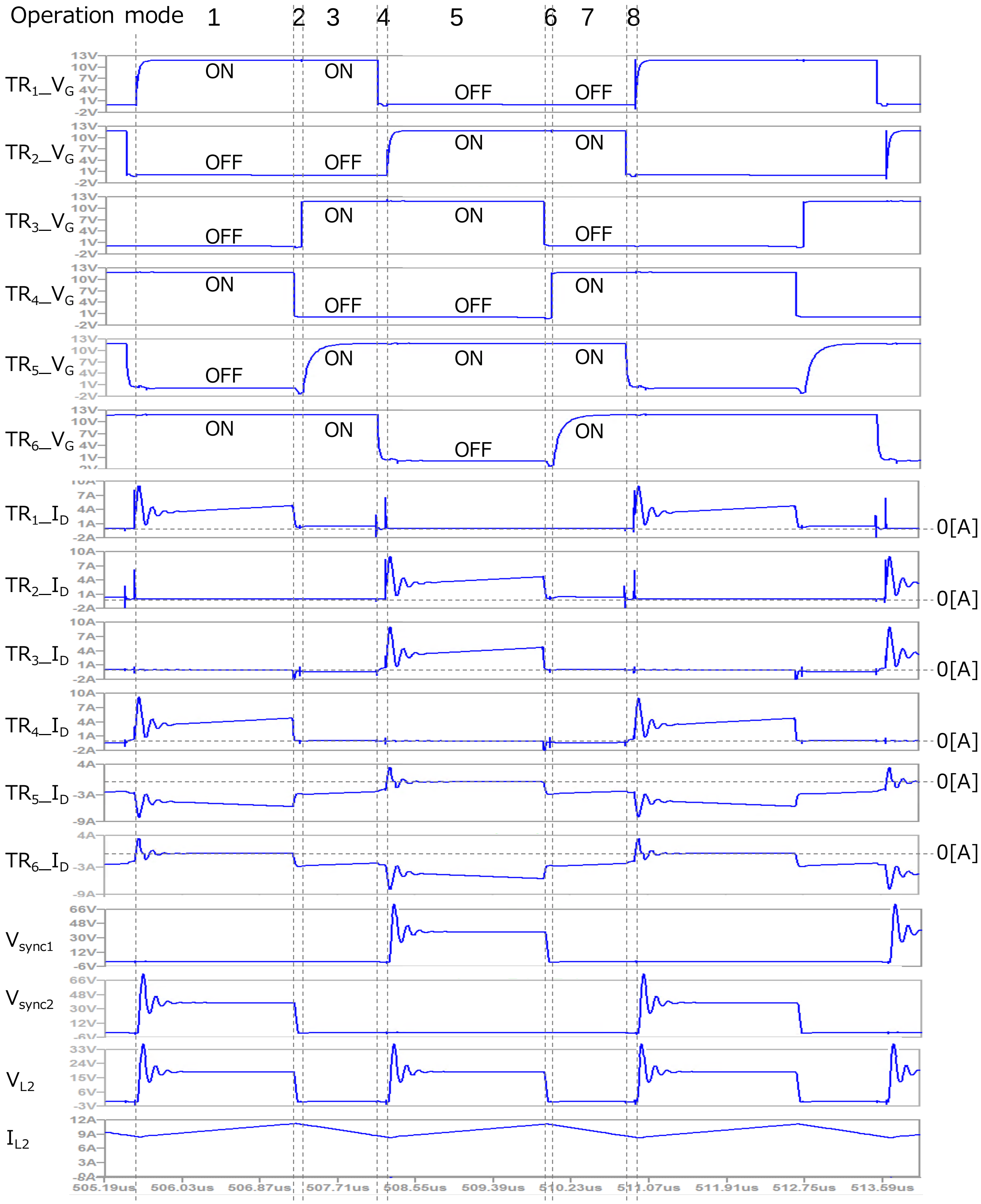


Fig. 1.6 Simplified operating waveforms of 300W DC-DC converter

2. Power MOSFETs lineup for efficiency evaluation device

Toshiba offers the U-MOSⅧ-H, U-MOSⅨ-H and U-MOSⅩ-H low-voltage MOSFET series which suits the primary (main switch) and secondary (synchronous rectification) sides of DC-DC converters. Toshiba provides MOSFETs with a wide range of VDSS from 30V to 250V and various on-resistance types in each VDSS class so it is easy to find proper MOSFETs when designing a DC-DC converter, according to the desired circuit topology, input and output voltages, output current, and the locations of MOSFETs on the circuit (primary or secondary side). Fig. 2.1 shows the lineup of the U-MOSⅧ-H, U-MOSⅨ-H and U-MOSⅩ-H MOSFET series.

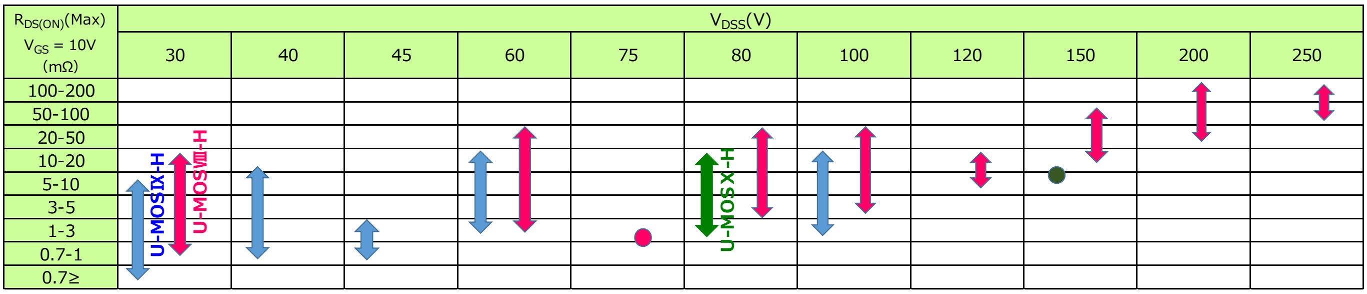


Fig. 2.1 Product lineup of the U-MOSⅧ-H, U-MOSⅨ-H, and U-MOSⅩ-H MOSFET series

2.1. List of Switching devices to be compared

Table2.1 shows the main specifications of MOSFETs used in this evaluation. The dominant losses on secondary MOSFET are conduction loss and reverse recovery loss in general, therefore the better efficiency especially on mid-load to heavy load is expected on the latest generation U-MOSX-H 80V product TPH2R408QM which has a lower on-resistance($R_{DS(ON)}$) and a smaller reverse recovery charge(Q_{rr}) compared with other products.

Table 2.1 Main specifications of evaluation MOSFETs

Characteristics	Symbol	Unit	Primary Side	Secondary Side	
			TPN1200APL	TPH2R408QM	Company A
Drain-source breakdown voltage (Min)	$V_{(BR)DSS}$	V	100	80	80
Gate threshold voltage (Max)	V_{th}	V	2.5	3.5	3.0
Drain-source on-resistance (Typ)	$R_{DS(ON)}$	mΩ	9.8	1.9	2.2
Input capacitance (Typ)	C_{iss}	pF	1425	5870	5200
Reverse transfer capacitance (Typ)	C_{rss}	pF	15	60	38
Output capacitance (Typ)	C_{oss}	pF	205	1340	840
Gate resistance (Typ)	r_g	Ω	2.1	1.9	1.9
Switching time (rise time) (Typ)	t_r	ns	6	10.8	14
Switching time (turn-on time) (Typ)	t_{on}	ns	19	29	18
Switching time (fall time) (Typ)	t_f	ns	6	26	16
Switching time (turn-off time) (Typ)	t_{off}	ns	34	123	47
Total gate charge (Typ)	Q_g	nC	24	87	74
Gate-drain charge(Typ)	Q_{gd}	nC	4.9	19	16
Gate switch charge(Typ)	Q_{SW}	nC	7.5	28	25
Output charge(Typ)	Q_{oss}	nC	24	90	88
Reverse recovery charge(Typ)	Q_{rr}	nC	47	74	92

3. Efficiency evaluation results of actual device

In this evaluation, we verified the efficiencies of our 300W isolated DC-DC converter using the products listed in Table 2.1. The switching frequency of PSFB circuit is set by an external resistor connected to the RT terminal of the PWM controller. In this evaluation, the external resistor is set to 27kΩ and PSFB switching frequency is set to 370kHz. The PWM controller switches MOSFET (TR_1, TR_2 and TR_3, TR_4) of the left and right arms of the primary bridge at 1/2 of PSFB switching frequency (185kHz).

Efficiency is one of the most important characteristics of DC-DC converters. Efficiency is the ratio of the output power to the input power to 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 2 patterns of switching device combinations under the following conditions, then calculated and compared the efficiency. Fig.3.1 shows the connection diagram for efficiency measurement. DC-DC converter circuit board is forcibly air-cooled by cooling –fan located nearby.

Input voltage (V_{in}) = 48V
Output voltage (V_{out}) = 12V
Ambient temperature (T_a) = 25℃
Output-load current (I_{out}) = 1A, 3A, 5A, 7A, 10A, 14A, 16A, 18A, 20A, 25A

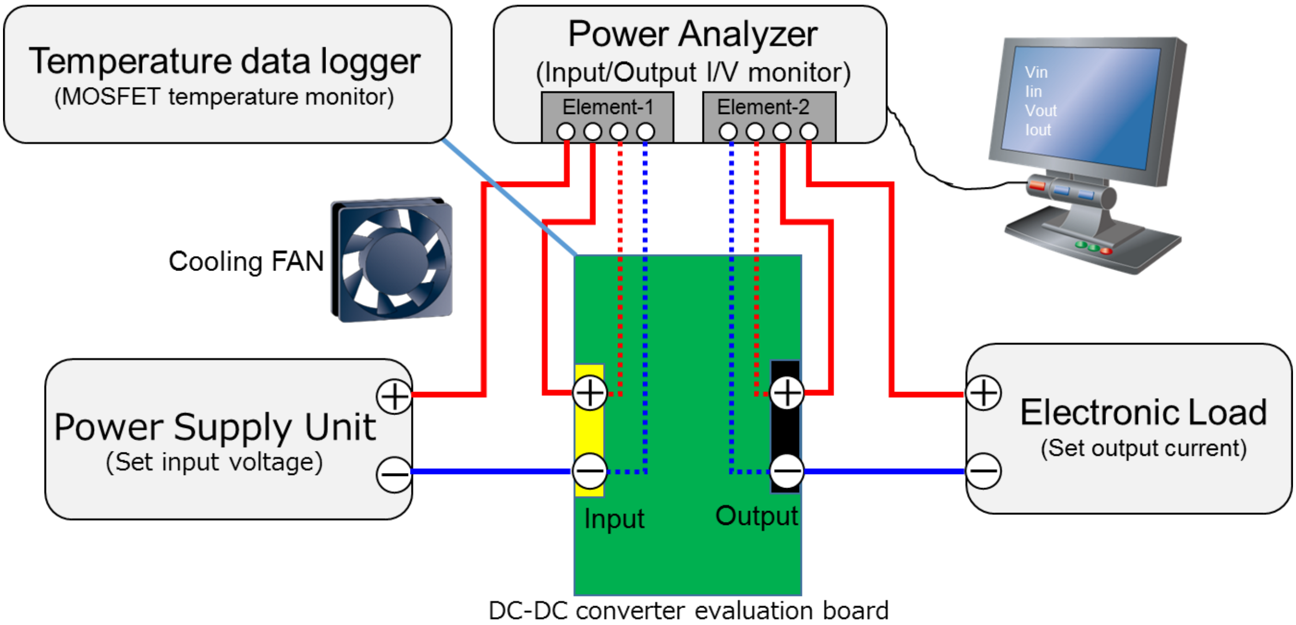
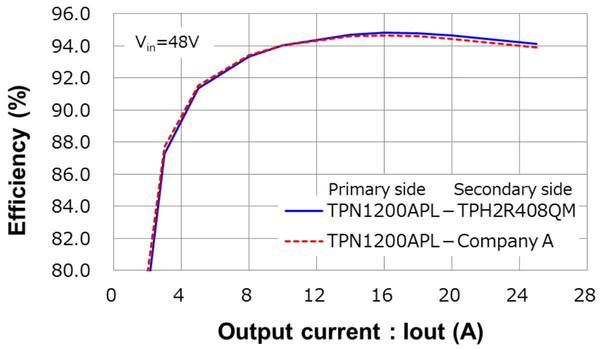


Fig. 3.1 Connection between evaluation board and each equipment for efficiency measurement

3.1. Effect of secondary-side switching device on power conversion efficiency

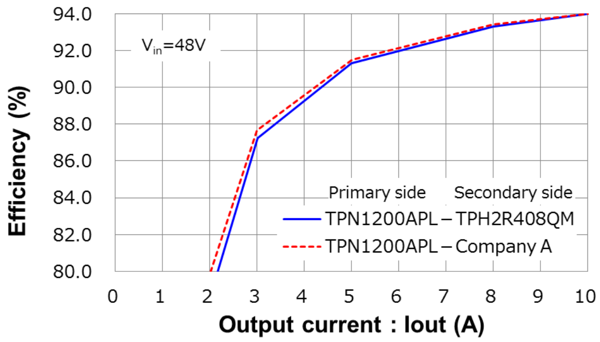
Figures 3.2 (a) to (c) show the efficiency curves when TPN1200APL is chosen as the primary MOSFET and TPH2R408QM or Company A's MOSFET is chosen as the secondary side MOSFET. Since conduction loss is dominant in medium to heavy loads, TPH2R408QM with the smallest drain-source on-resistance is superior. The maximum efficiency is 94.83% at 16A of output load and 94.12% at 25A of full load. On the other hand, the on-resistance of Company A is about 16% larger than that of TPH2R408QM, resulting in 94.65% at 16A of output load and 93.89% at 25A of full load. Fig.3.2 (d) shows the results of measuring MOSFET device temperatures of the secondary side. Even under heavy loads, TPH2R408QM has a temperature lower than 45°C, which indicates that it generates less heat than MOSFET produced by Company A.

(a)Efficiency comparison of secondary side MOFETs (TR_5 and TR_6)

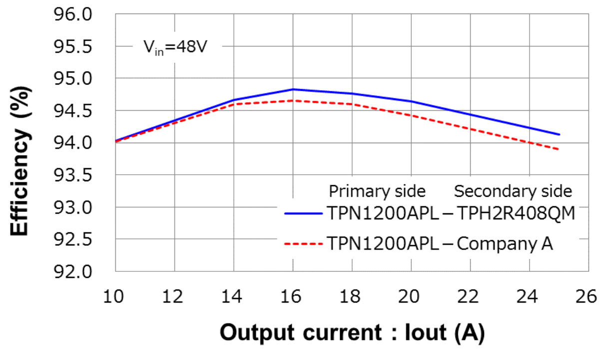


Secondary Side	Efficiency[%]		
	light load (Iout=3[A])	peak efficiency (Iout=16[A])	heavy load (Iout=25[A])
TPH2R408QM	87.24	94.83	94.12
Company A	87.67	94.67	93.89

(b) Light load (Iout=1 to 10A)



(c) Medium load to heavy load (Iout=10 to 25A)



(d) Device temperature of the secondary side MOSFETs (TR_5 and TR_6)

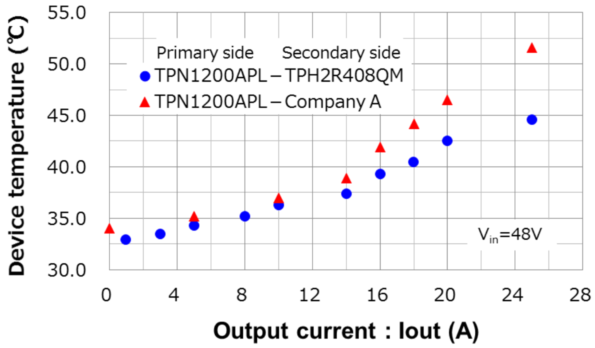
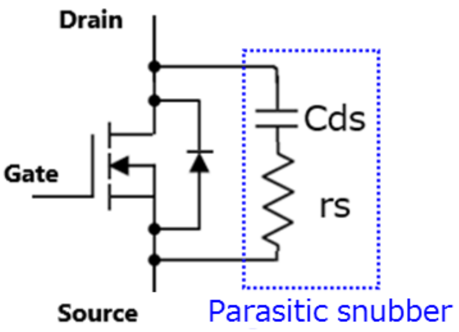


Fig. 3.2 Output load dependency of secondary MOSFET efficiencies and temperatures

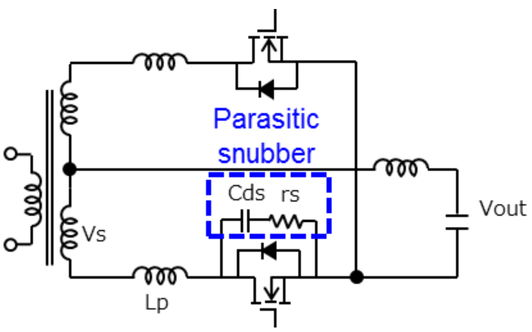
4. Spike voltage

Low-spike performance is one of the advantages of TPH2R408QM used on the secondary side. TPH2R408QM adopts a new structure in the gate trench. As shown in Fig. 4.1, parasitic capacitance and parasitic resistance exist between the drain and source, and a CR-snubber circuit is constructed, thereby suppressing the spike voltage. This effect is explained in this chapter using the secondary synchronous rectifier of DC-DC converter with the parasitic inductances Lp of the circuit boards shown in Fig.4.2. The damping coefficient (ζ) of this circuit is expressed by Equation (1). Since the numerator has rs and Cds, the larger each value, the larger the damping coefficient, the faster the damping speed, and the faster the ringing converges. Also, since the spike voltage (VCds) expressed by Equation (2) has rs and Cds in the denominator, it can be understood that the larger the value, the smaller the value of the spike voltage. The spike voltage reduction reduces noise and ringing concern and enables easier to design power supply circuit such as voltage safety margins. Fig.4.3 shows the R-load switching evaluation board circuit and TPH2R408QM and Company A's turn-off waveform (V_{DS}). TPH2R408QM has a V_{DS} spike voltage of 50.91V and a ringing time of 48ns. On the other hand, V_{DS} spike voltage of Company A is 56.61V and the ringing time is 71ns, indicating that TPH2R408QM is superior in both V_{DS} spike voltage and the ringing time.



Cds: Drain-source capacitance of MOSFET
rs: Embedded source-wire resistor for MOSFET

Fig. 4.1 Parasitic snubber circuit



Damping coefficient $\zeta = \frac{rs}{2} \times \sqrt{\frac{Cds}{Lp}}$ … equation(1)

Spike voltage $VCds = \frac{1}{rs} \times \frac{Vs}{\omega 0 \times Cds}$ … equation(2)

Lp: Substrate parasitic inductance
ω0: Angular frequency of the LCR series resonant circuit
Vs: Secondary voltage

Fig. 4.2 Synchronous rectifier circuit of DC-DC converter secondary side

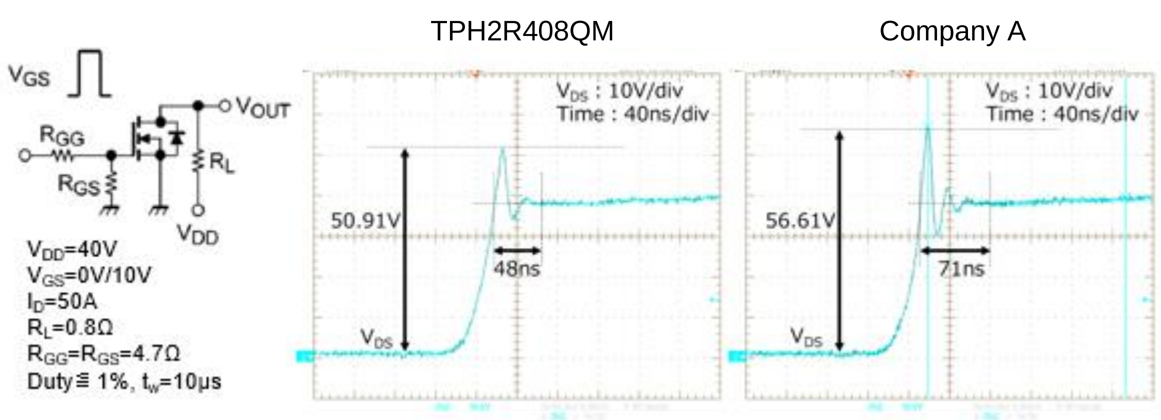


Fig. 4.3 R-load switching circuit diagram and turn off waveform comparison of V_{DS}

5. Loss Analysis using the high accuracy simulator circuit (Note2)

Fig.5.1 is a schematic diagram of the simulation circuit. The reference model uses a phase-shifted full-bridge PWM controller IC, but this simulation circuit uses the alternative control model making feedback according to the voltage and current sensing. All sensing points are connected to the control model, and primary or secondary side's MOSFET are controlled by this control model to regulate the output voltage. The transformer and reactors which greatly affect the simulation accuracy use equivalent circuit models created based on actual measurement results. *(Note2) The high* accuracy simulation circuit is originally developed for loss analysis.

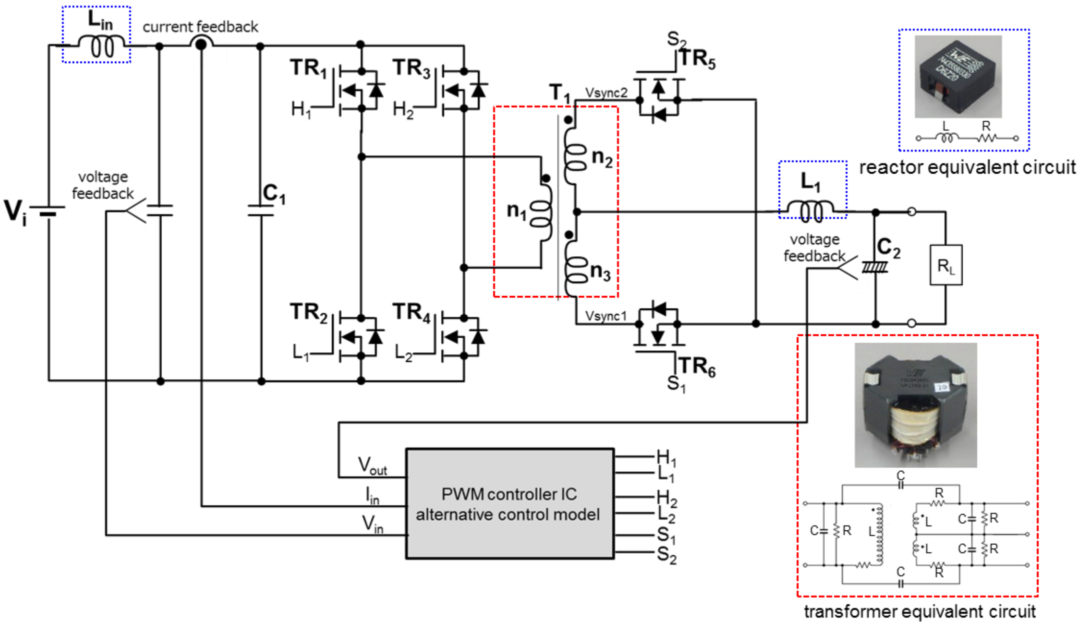


Fig. 5.1 Simulation circuit

In addition, this simulator uses a high-accuracy device model (G2 model) that enhances the reproducibility of the high-current-domain characteristics of I_D-V_{DS} curve and the voltage-dependent characteristics of the parasitic capacitance, and allows closer switching simulations to actual measurements. Fig.5.2 (a) to (d) show the comparison results between actual measurements and simulations of the main characteristics (I-V and C-V). Fig. (e) and (f) show turn off characteristics of R-load switching using this device model. The simulated waveform (Fig.(e)) is accurately reproduced the actual measured waveform(Fig.(f)).

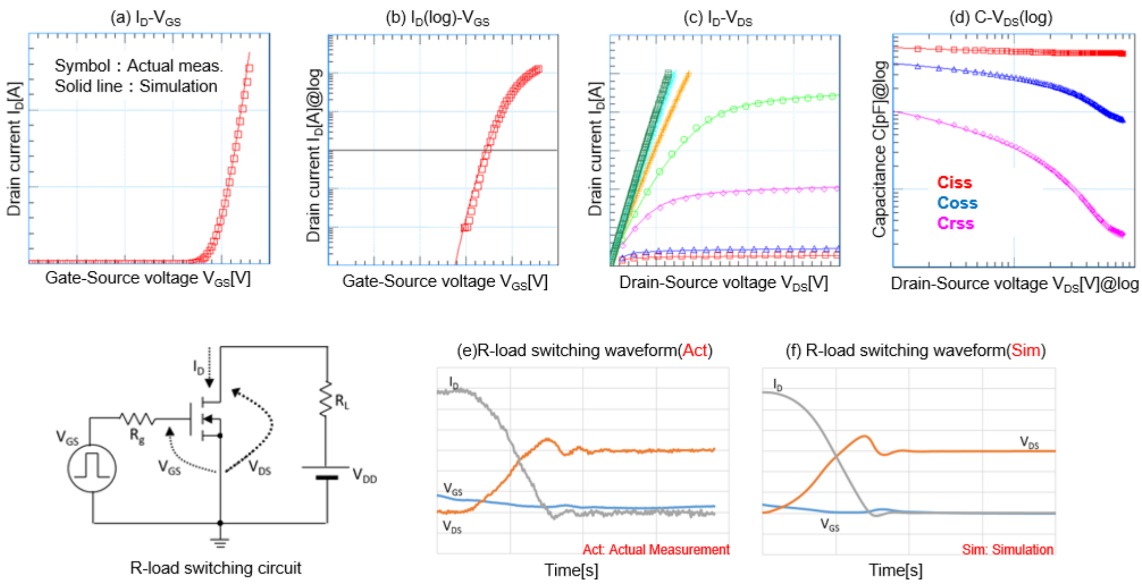
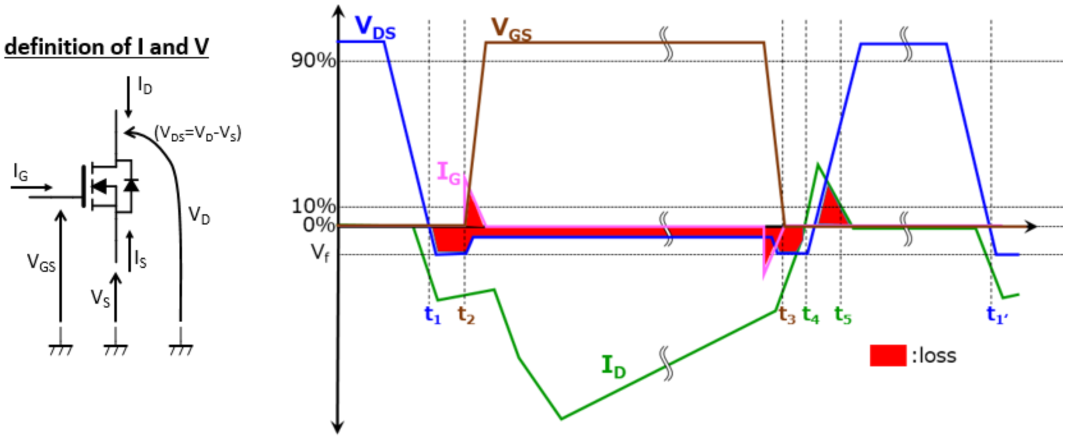


Fig. 5.2 Comparison of actual measurement and simulation characteristics of device model

5.1. Loss definition of secondary MOSFET

Figure 5.3 shows the timing chart of the secondary MOSFET that operate as synchronous rectification and each loss calculation section defined as E_{diode1}, E_{sync}, E_{diode2}, $E_{recovery}$, E_{block}, and E_{gate}. Each loss is defined with the conduction state in mind, and E_{diode1}, E_{sync}, E_{diode2}, $E_{recovery}$ and E_{block} are calculated by the time integration of the product of the drain-to-source voltage V_{DS} and the drain current I_D. On the other hand, E_{gate} is calculated by time integration of the product of gate-to-source voltage V_{GS} and gate current I_G.



Loss calculation section	Loss name	Description	Note
t_1 - t_2	E_{diode1}	Body-diode conduction loss-1	Calculate time integration of $V_{DS}\times I_D$
t_2 - t_3	E_{sync}	MOSFET conduction loss	same as above
t_3 - t_4	E_{diode2}	Body-diode conduction loss-2	same as above
t_4 - t_5	$E_{recovery}$	Recovery loss	same as above
t_5 - $t_{1'}$	E_{block}	MOSFET blocking loss	same as above
t_1 - $t_{1'}$	E_{gate}	MOSFET gate drive loss	Calculate time integration of $V_{GS}\times I_G$

Fig. 5.3 Timing chart of loss calculation for secondary MOSFET

5.2. Comparative analysis of efficiency between actual evaluation board and simulation

Fig. 5.4 shows the Efficiency-Output current(load) dependency of the evaluation board and the simulated circuit when TPN1200APL is chosen as the primary MOSFET and TPH2R408QM or Company A's MOSFET is chosen as the secondary side MOSFET. The efficiency difference between the evaluation board and the simulation result from medium load to heavy load region is 1 % or less. The main reason for this difference is the loss not considered in this simulation circuit such as the loss of the controller and the change in characteristics caused by the heat generated by each component constituting the circuit. However, since there is no discrepancy on relative merits between TPH2R408QM and Company A's MOSFET in the evaluation with evaluation board and simulation, it can be said that the operation of this simulation circuit can almost simulate the actual evaluation board. In the next section, we use this simulator to analyze the loss of components mounted on the evaluation board including the secondary MOSFET for one cycle.

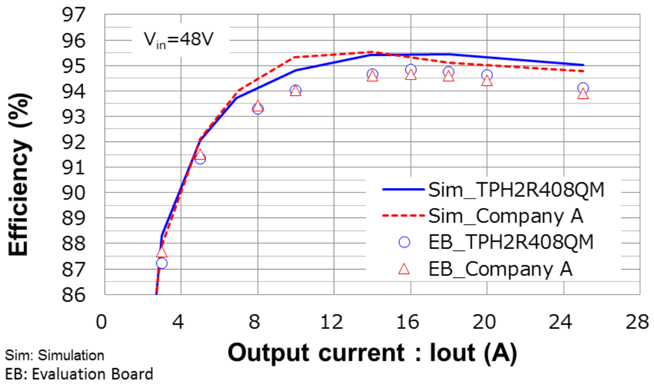


Fig. 5.4 Load dependent characteristics comparison (Reference model and Simulation circuit)

5.3. Loss analysis

Fig. 5.5 shows the results of loss-simulation for a 300W isolated DC-DC converter using TPN1200APL for the primary MOSFET and TPH2R408QM for the secondary MOSFET on the high-accuracy simulation circuits. The loss ratios of the components at the output current of 25 [A] are 24.9% for the primary MOSFET (Pri_Side), 17.7% for the secondary MOSFET (Sec_Side), 20.2% for the transformer (Transformer), 15.2% for the reactor (Reactor), 6.1% for the snubber (Snubber), and 15.9% for the rest (others), indicating that approximately 43% of the loss is generated by MOSFET on the primary and secondary sides. The rate of MOSFET loss increases as the output current decreases. This shows that it is crucial to reduce MOSFET losses to improve the efficiency of DC-DC converter. Fig. 5.6 shows the power loss amount for one cycle of TPH2R408QM used on the secondary side. Recovery loss ($E_{recovery}$) of the body diodes is dominant, but the increment is not sensitive to the output current. On the other hand, looking at the conduction loss (E_{sync}), it increases greatly as the output current increases. Therefore, for secondary MOSFET, it is desirable to select products with low recovery charge (Q_{rr}) associated with recovery loss and low drain-to-source on-resistance ($R_{DS(ON)}$).

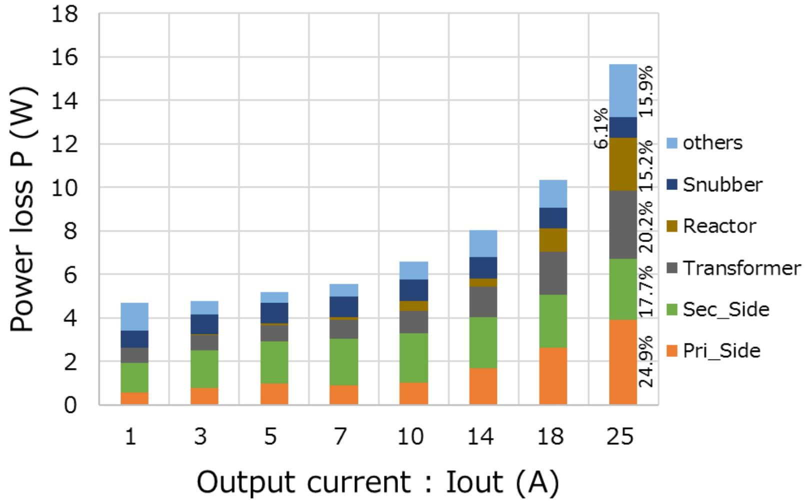


Fig. 5.5 Results of loss analysis for each mounted component

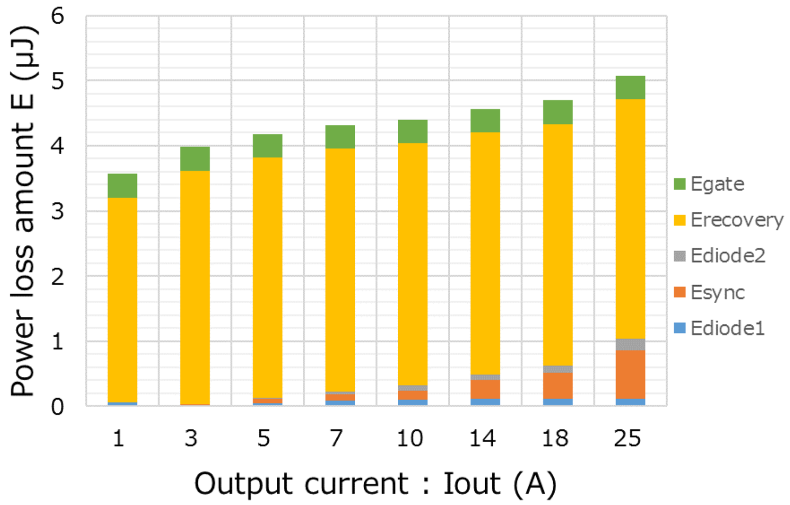


Fig. 5.6 Secondary MOSFET loss analysis results

6. Conclusion

The loss of the secondary MOSFET of the 300W isolated DC-DC converter is dominated by conduction and recovery losses as shown in Fig. 5.6. Therefore, it is recommended to select a MOSFET with low drain-source on-resistance and low reverse-recovery charge. Finally, it was confirmed in this evaluation that using TPH2R408QM on the secondary side resulted in the highest efficiency this time.

7. 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/ap-en/semiconductor/design-development/referencedesign/articles/300w-Isolated-dc-dc_powermanagement_rd024.html

8. Device Model (SPICE Model) Support

The SPICE models used in this application note are available at the following URLs.

Primary switching MOSFET : TPN1200APL
https://toshiba.semicon-storage.com/ap-en/semiconductor/product/mosfets/12v-300v-mosfets/detail.TPN1200APL.html

Secondary switching MOSFET : TPH2R408QM
https://toshiba.semicon-storage.com/ap-en/semiconductor/product/mosfets/12v-300v-mosfets/detail.TPH2R408QM.html

Description of grade notation for device models (SPICE models).
https://toshiba.semicon-storage.com/info/docget.jsp?did=139481

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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