



Building a More Efficient DC-DC Converter: Efficiency Evaluation and Loss Analysis of a 300 W Isolated DC-DC Converter

Efficiency plays a critical role in the design of DC-DC converters, and the power MOSFETs use significantly impacts this efficiency. A specific area with potential for improvement lies in the selection of MOSFETs for the synchronous rectifier on the secondary-side.

Introduction

This article focuses on determining the characteristics of the secondary-side MOSFET necessary for achieving higher efficiency. It studies the direct measurements using the evaluation circuit, as depicted in Figure 1, and, subsequently, compares them with results from a highly accurate simulation to determine the dominant source of losses.





Figure 1. Physical evaluation circuit used to investigate secondary-side losses on a 300 W DC-DC converter.

Chapter 1: Pursuing Enhanced Efficiency

The quest for higher efficiency dominates most power applications, including DC-DC converters. The definition of efficiency is:

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

Different design decisions impact efficiency and losses, with a predominant choice being the selection of the primary- and secondary-side MOSFETs, accounting for over 40 % of the losses within an isolated DC-DC converter circuit.

The results of the simulations are presented, followed by design recommendations based on those findings.

Reference links:

[DC/DC Converters: Devices for Converting to a Higher Voltage](#)

Chapter 2: Evaluation Board Design

A 300 W DC-DC converter evaluation board was built to gain insight into the losses involved. A simplified circuit diagram is shown in Figure 2.

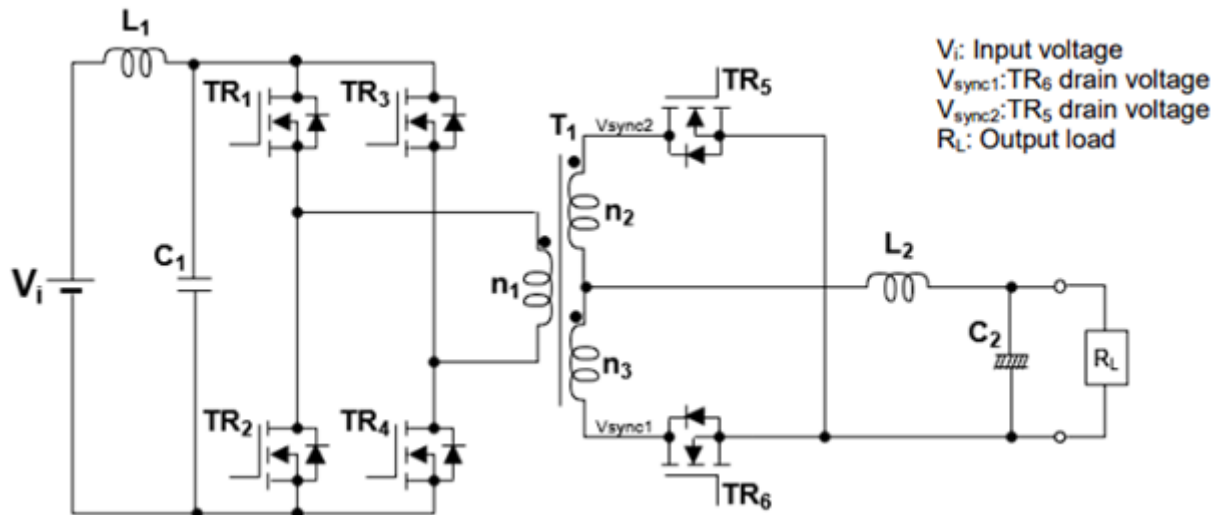


Figure 2. Simplified isolated DC-DC converter circuit.

In this circuit, the primary-side (input side) serves as the input and has two legs and four switching devices (TR₁, TR₂, TR₃, and TR₄). The secondary-side (output side) has two devices (TR₅ and TR₆). These are intended for synchronous rectification. Additionally included is an output smoothing filter with a capacitance of C₂ and an inductor of L₂. The input voltage is V_i, the output load is R_L, and V_{sync1} and V_{sync2} are the drain voltages for TR₆ and TR₅, respectively. Observe that TR₅ and TR₆ have two MOSFETs connected in parallel.

The converter outputs 12 V using a phase-shifted full-bridge (PSFB) topology. The output voltage is regulated by phase-shifted operation between a leg of TR₁, TR₂, and the leg of TR₃, and TR₄ with a 50 % duty cycle. To prevent shoot-through in the dead time between the high side MOSFET and low side MOSFET, zero voltage switching (ZVS) is achieved to reduce the switching loss of the power converter.

Table 1 shows input and output characteristics of 300 W DC-DC converter.

Table 1. input and output characteristics of 300 W 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

Table 2 summarizes eight operating modes. Figures 3 and 4 illustrate the flow of current in each of these modes using blue and red dotted lines.

Table 2. Operating modes

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
TR1	TURN-ON	ON	ON	TURN-OFF	OFF	OFF	OFF	OFF
TR2	OFF	OFF	OFF	OFF	TURN-ON	ON	ON	TURN-OFF
TR3	OFF	OFF	TURN-ON	ON	ON	TURN-OFF	OFF	OFF
TR4	ON	TURN-OFF	OFF	OFF	OFF	OFF	TURN-ON	ON
TR5	OFF	OFF	TURN-ON	ON	ON	ON	ON	TURN-OFF
TR6	ON	ON	ON	TURN-OFF	OFF	OFF	TURN-ON	ON

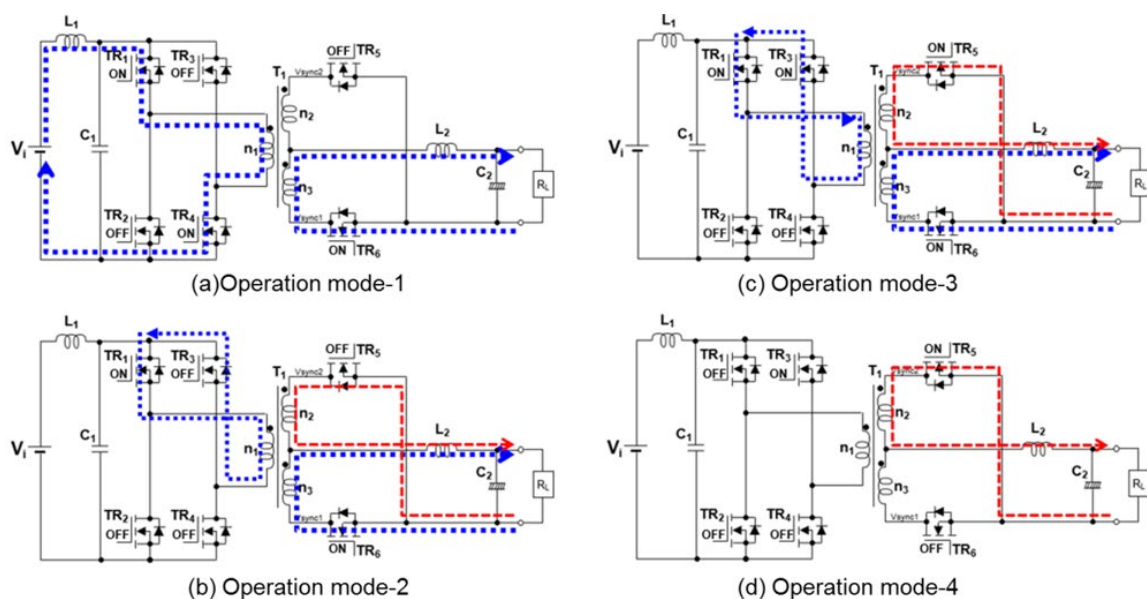


Figure 3. Operating modes 1 - 4.

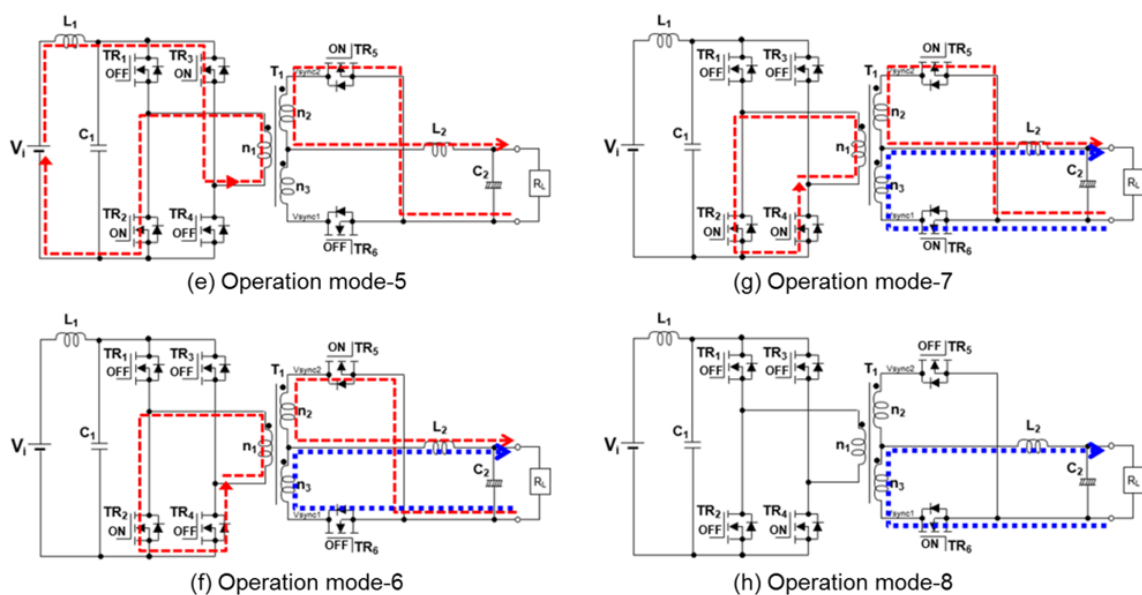


Figure 4. Operating modes 5 - 8.

A The waveforms associated with all eight operating modes are summarized in Figure 5. In these simplified waveforms, the following is depicted: gate voltage (V_G) and drain current (I_D) of the switching devices TR₁ to TR₆, drain-source voltage (V_{sync1} , V_{sync2}) of TR₅ and TR₆, and voltage between the terminals (V_{L2}) and the current (I_{L2}) of the inductor L₂. Recognize that the current through TR₅ and TR₆ are denoted as negative because current flows from the source to the drain.

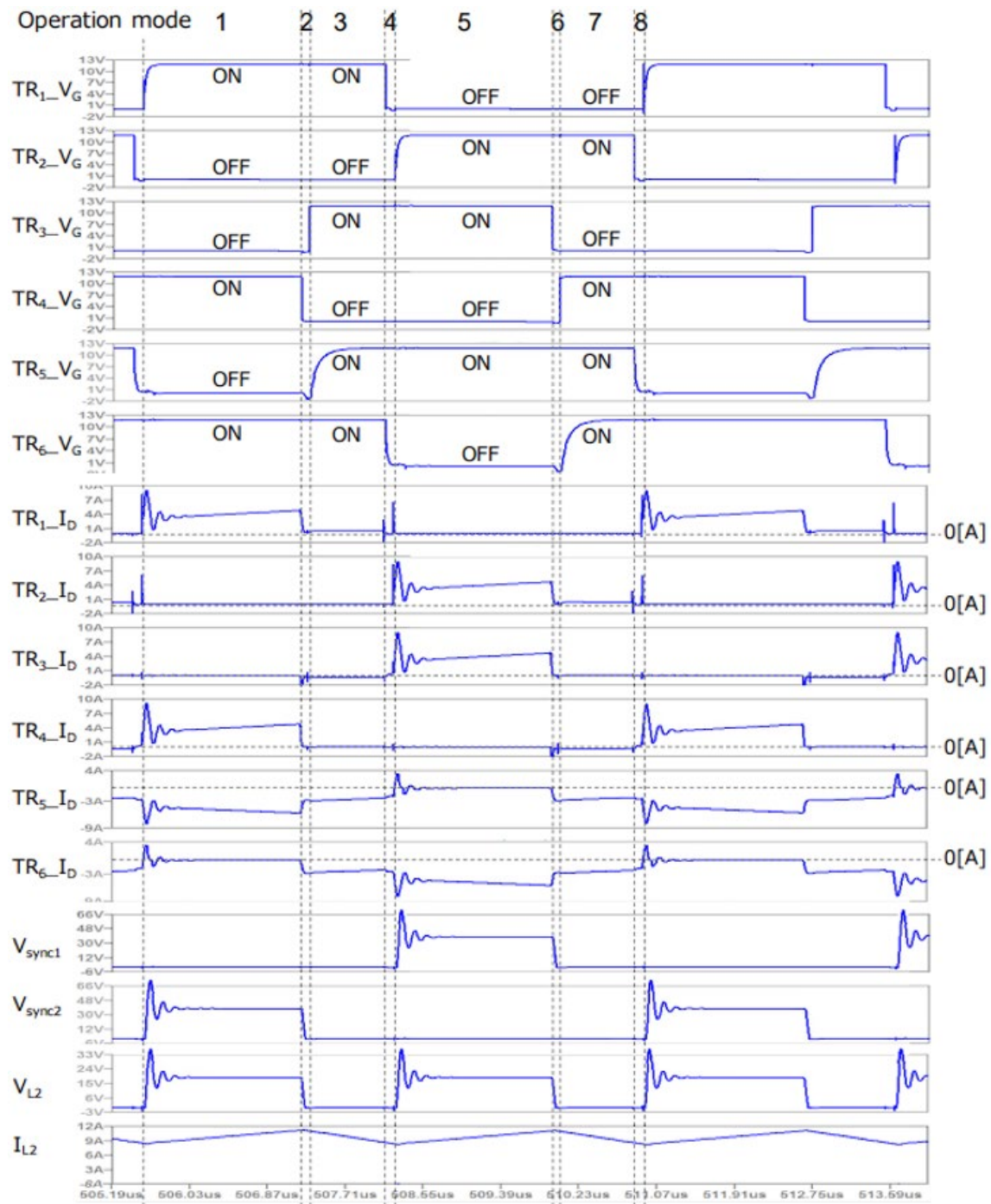


Figure 5. Waveforms associated with all eight operating modes.

Chapter 3: Efficiency Evaluation and Loss Analysis

The formula used to calculate efficiency is:

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

Figure 6 displays the setup for evaluating the efficiency of the 300 W isolated DC-DC converter circuit. V_{in} , I_{in} , V_{out} and I_{out} were measured for two patterns of switching device combinations under these conditions: $V_{\text{in}} = 48 \text{ V}$, $V_{\text{out}} = 12 \text{ V}$, and T_{a} (ambient temperature) = 25 °C with I_{out} at 1 A, 3 A, 5 A, 7 A, 10 A, 14 A, 16 A, 18 A, 20 A, and 25 A. The DC-DC converter circuit board is forcibly air-cooled using a cooling fan located near the circuit board.

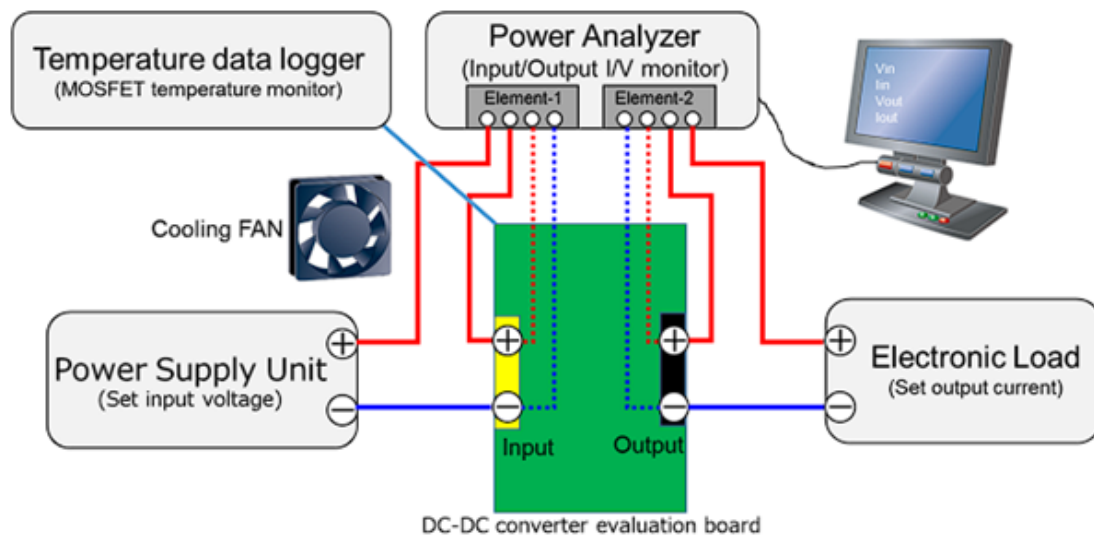


Figure 6. Setup used for efficiency measurement.

This evaluation was performed using the TPN1200APL as the primary-side MOSFET and two different secondary-side MOSFETs (TR_5 and TR_6): Toshiba TPH2R408QM and an equivalent MOSFET from Company A. All specification details are found on page 9 in the Application Note. The TPH2R408QM MOSFET was selected due to its lower drain-source on-resistance ($1.9\text{ m}\Omega$) and lower reverse recovery charge (74 nC) compared to other equivalent products.

Reference links:

[Efficiency Evaluation and Loss Analysis of 300W isolated DC-DC converter \(PDF:2.3MB\)](#)



[**TPN1200APL**](#)



[**TPH2R408QM**](#)

Chapter 4: Secondary-Side Switching Effect on Power Conversion Efficiency

Figure 7 (a) to (c) compares the efficiency curves using the TPH2R408QM and Company A's MOSFET. As expected, the TPH2R408QM exhibits the highest efficiency level for medium and heavy loads because conduction loss is the main element of loss in such loads. In addition to this, the TPH2R408QM has a smaller drain-source on-resistance. The maximum efficiency is 94.83 % at 16 A of output load and 94.12 % at 25 A of full load.

In contrast, the drain-source on-resistance of Company A's MOSFET is approximately 16 % larger than the TPH2R408QM, with efficiencies of 94.65 % at 16 A of output load and 93.89 % at 25 A of full load.

Figure 8 illustrates the relationship between device temperature and output current for both types of MOSFETs. Notably, the TPH2R408QM exhibits temperatures consistently lower than 45 °C, indicating less heat generation than the MOSFET manufactured by Company A. the larger chassis, where airflow will not be as constrained.

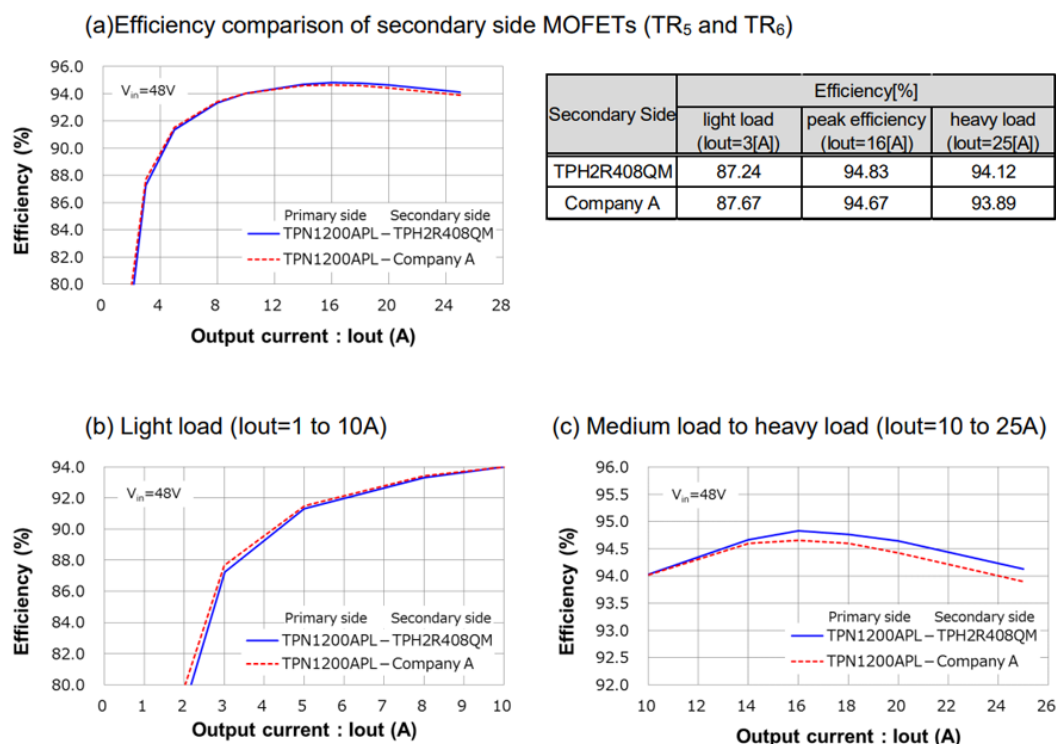


Figure 7. Efficiency curves.

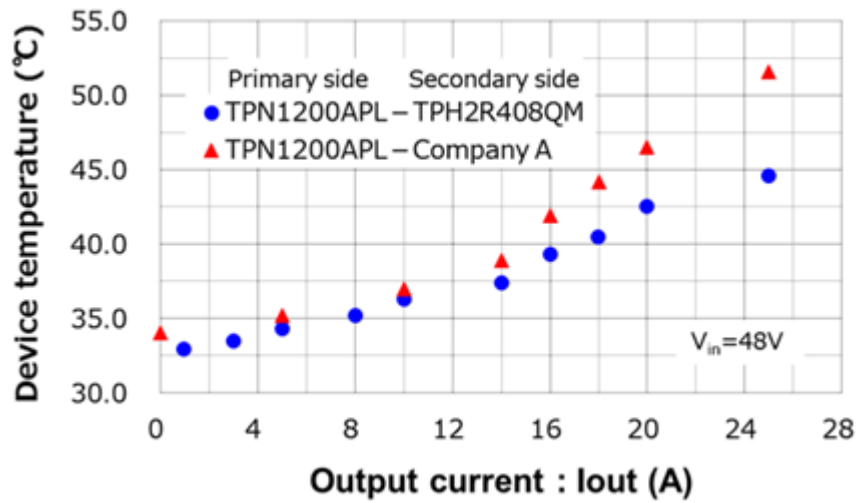


Figure 8. Temperature comparisons.

Chapter 5: Loss Analysis Simulation

Loss analysis was performed using a simulator circuit with a high-accuracy device model specifically designed for loss analysis. The evaluation board 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. The simulation circuit is found in Figure 9. The transformer and reactors are based on measurement results. Additional details on simulation design are found in the Application Note.

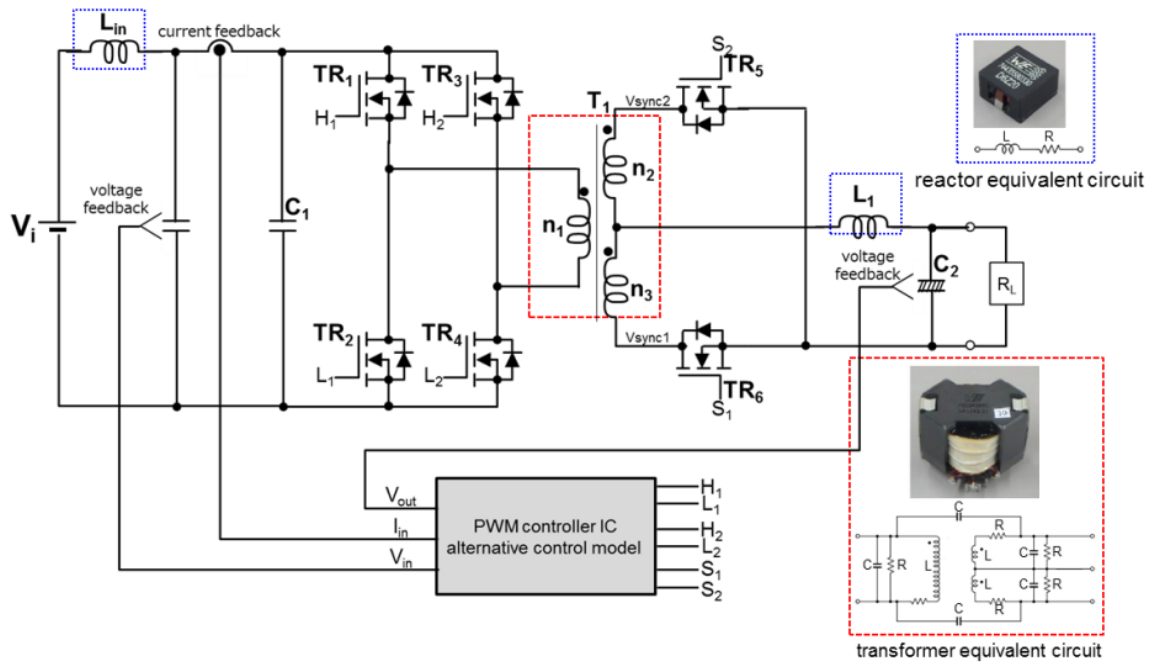


Figure 9. Loss analysis circuit.

After the simulation was verified, results related to loss definition of the secondary MOSFETs were performed. Figure 10 shows how I and V are defined, the timing chart of the secondary MOSFET, and how each form of loss is calculated based on the timing chart. Each loss section is based on a segment of time and six types of losses were calculated.

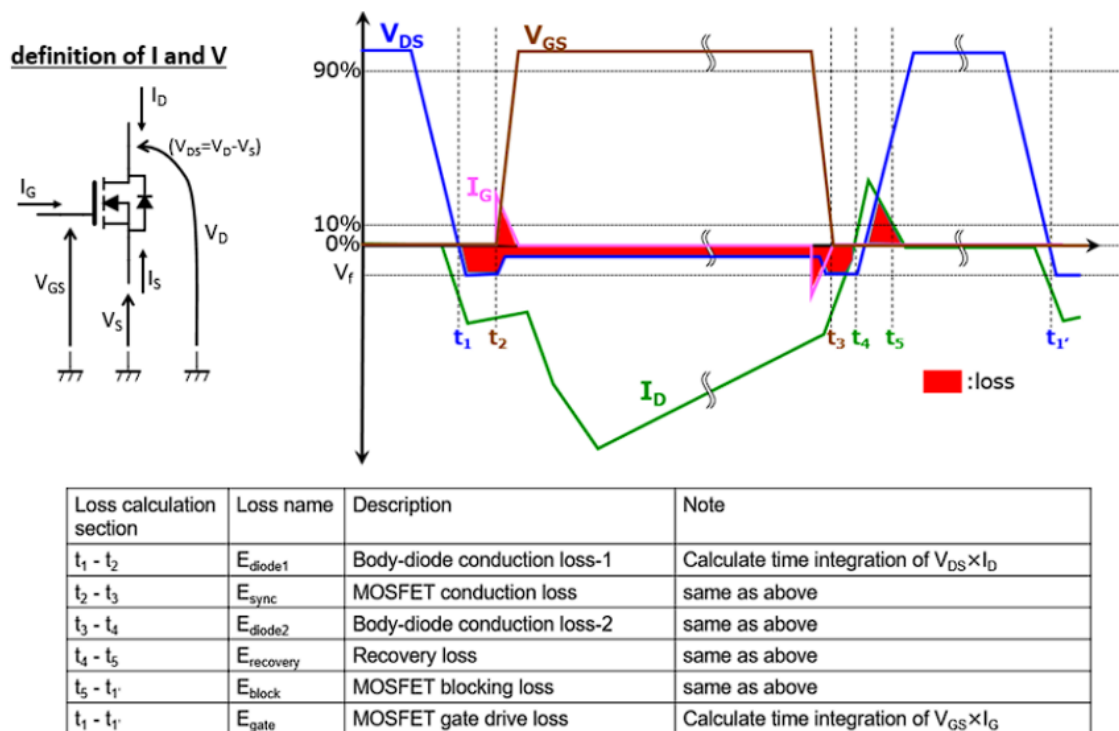


Figure 10. Timing chart for loss calculation.

Reference links:

[Efficiency Evaluation and Loss Analysis of 300W isolated DC-DC converter \(PDF:2.3MB\)](#)

Chapter 6: Which MOSFET Is Best?

The results of loss analysis for the secondary MOSFETs, in the case of TPH2R408QM, are plotted in Figure 11. The dominant form of loss is the recovery loss of the body diodes (which is not sensitive to current) and the conduction loss (E_{sync}), which increases with output current. This indicates that a MOSFET with a low recovery charge and low drain-source on-resistance is the most efficient choice.

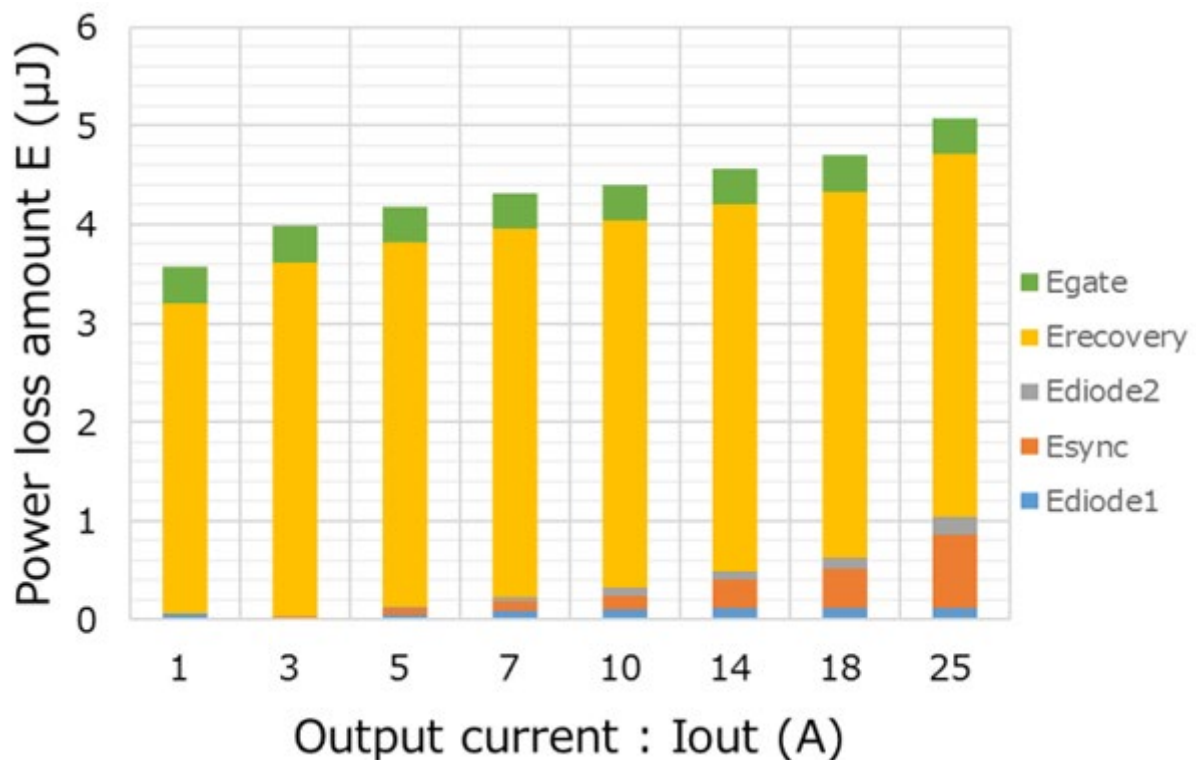


Figure 11. Secondary-side MOSFET loss analysis results grouped by type of loss.

Chapter 7: Optimize Efficiency: Explore Secondary-Side MOSFETs

The selection of secondary-side MOSFET for isolated DC-DC converter circuits is vital to overall efficiency. Toshiba offers a robust lineup of power MOSFETs, encompassing a wide range of V_{DS} from 30 V to 250 V and various drain-source on-resistance types within each V_{DS} class. Learn more about designing high-efficiency DC-DC converters with Toshiba's low recovery charge and low drain-source on-resistance MOSFETs with the Reference Design Materials guide.

Reference links:

[robust lineup of power MOSFETs](#)

[300W Isolated DC-DC Converter](#)

Restrictions On Product Use

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as "TOSHIBA".

Hardware, software and systems described in this document are collectively referred to as "Product".

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA's written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product's quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. **TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS' PRODUCT DESIGN OR APPLICATIONS.**
- **PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE").** Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signalling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. **IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT.** For details, please contact your TOSHIBA sales representative or contact us via our website.
- Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.
- **ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.**

- Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.
- Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. **TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.**