

**Flyback DC-DC Power Supply
Basic Simulation Circuit
Reference Guide**

RD038-RGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

Most of the internal circuits in information and communication equipment, home appliances, and other electrical devices work on DC voltage. Since they cannot work on commercial power (AC voltage) directly, it is necessary to convert AC voltage to DC voltage. An AC-DC power supply is used for this purpose. It is necessary to convert DC voltage from an AC-DC power supply to the desired voltages according to the power supply specifications of each load in the system. An electronic circuit that converts one DC voltage level to another is called a DC-DC converter. Figure 1.1 shows an example of power supply lines to system loads. Multiple power supply lines deliver different DC voltages to different loads. In Figure 1.1, the DC voltage from an AC-DC power supply is directly supplied to one load whereas it is converted to different voltage levels before being supplied to the other loads.

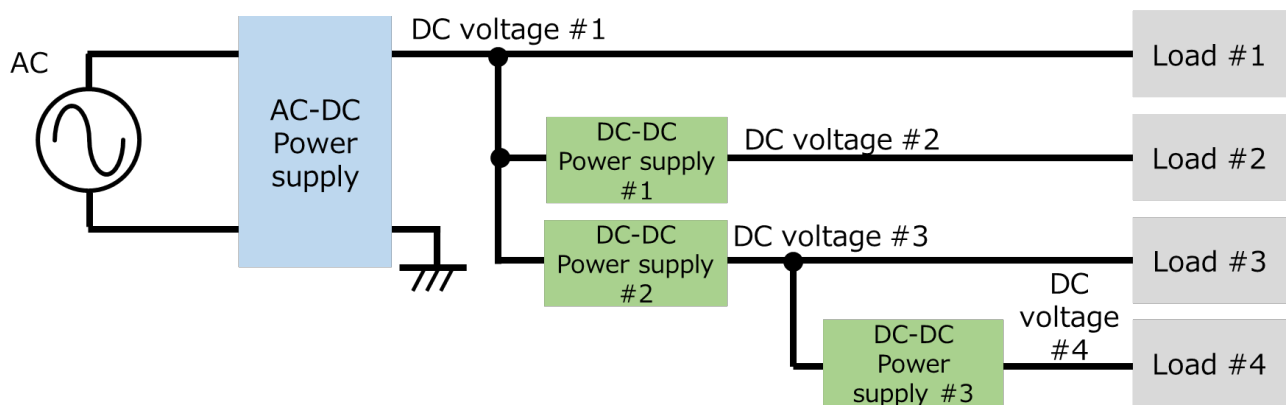


Figure 1.1 Power supply lines in a system

There are two major types of DC-DC converters: series regulators and switched-mode regulators. Switched-mode regulators, which are most commonly used for DC-DC power supplies, is discussed in this document.

Switched-mode regulators generate a desired voltage by controlling the on/off of switching devices. Therefore, switched-mode regulators require a more complex control circuit than series regulators, but generally cause less power loss. There are two types of switched-mode regulators: isolated DC-DC power supplies in which a transformer provides electrical isolation between the primary (input) and secondary (output) sides and non-isolated DC-DC power supplies in which the input and output sides are not isolated from each other. This reference guide focuses on isolated DC-DC power supplies.

In an isolated DC-DC power supply, switching devices are used to switch the input DC voltage at a frequency in the order of 10 to 200kHz. Energy charged in the primary side of the transformer is transferred to the secondary side before DC voltage is delivered to the output. The DC voltage level at the final stage is controlled by adjusting the on/off periods of switching devices.

Figure 1.2 shows the block diagram of an isolated switched-mode DC-DC power supply, which consists of 1) a DC-DC converter and 2) a feedback circuit. Each block is briefly explained below:

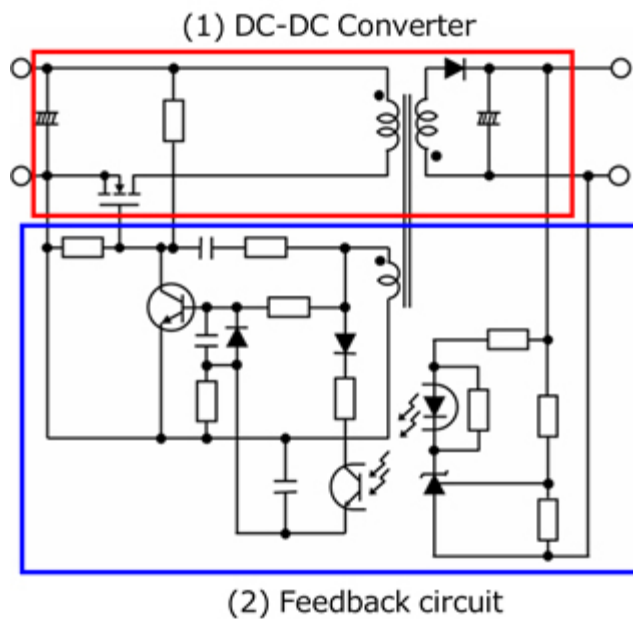


Figure 1.2 Example of a block diagram of an isolated switched-mode DC-DC power supply

(1) DC-DC converter

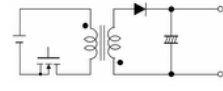
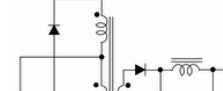
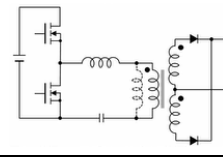
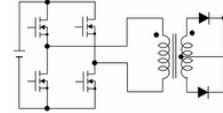
The input DC voltage is converted to the desired DC voltage.

(2) Feedback circuit

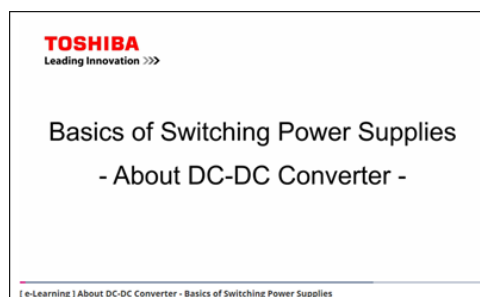
The on/off periods of the switching devices are controlled to generate a desired output voltage.

There are various topologies for transformer-based isolated switched-mode DC-DC converters. Table 1.1 shows the most common topologies and their characteristics.

Table 1.1 Commonly used DC-DC converter topologies and their characteristics

Topology	Power Level	Advantage	Disadvantage
Flyback 	< 120W	<ul style="list-style-type: none"> • Small parts count 	<ul style="list-style-type: none"> • Decrease in efficiency at high power • Large transformer
Forward 	100W~500W	<ul style="list-style-type: none"> • Higher efficiency than a flyback circuit 	<ul style="list-style-type: none"> • Requires a transformer reset circuit
Resonant half-bridge (LLC resonance) 	100W~1.6kW	<ul style="list-style-type: none"> • High efficiency • Low noise 	<ul style="list-style-type: none"> • Requires a custom-designed transformer • Difficult to control
Full-bridge 	> 1kW	<ul style="list-style-type: none"> • High efficiency • Capable of increasing the power capacity 	<ul style="list-style-type: none"> • Large parts count • Difficult to control

A [video](#) describing the basic operation of a DC-DC converter is available for viewing on Toshiba's website.



The flyback DC-DC converter has the merit of realizing simple circuit, however the flyback topology has a lower efficiency and requires a larger transformer at high output power than other topologies. Therefore, flyback DC-DC converters suit power supplies with a relatively small power capacity. A basic simulation circuit of a flyback DC-DC converter for a switched-mode DC-DC power supply (RD038-SPICE-01) is available for download on Toshiba's website, which will help you understand its operation.

The Reference Guide provides an overview of this simulation circuit and shows how to simulate. OrCAD[®] Capture and PSpice[®] A/D from Cadence[®] are necessary to simulate this circuit. Both the simulation circuit and the Reference Guide are based on OrCAD[®] 17.2.

2. Overview of the DC-DC flyback power supply

The basic simulation circuit (RD038-SPICE-01) is a DC-DC converter of a 30W flyback DC-DC power supply.

2.1. Power supply specifications

The specifications of the flyback DC-DC power supply are as follows:

- Input voltage: 24V
- Output voltage: 5V
- Output current: 0 to 6A
- Operating frequency: 100kHz
- Flyback voltage: 9 V
- Primary-side peak current: 6 A
- Transformer primary-winding setting: 70 μ H
- Transformer secondary-winding setting: 24 μ H

2.2. Circuit configuration

Figure 2.1 shows the simulation circuit for OrCAD[®]. It is a flyback DC-DC power supply, which mainly consists of a power supply section (flyback circuit) and a PWM controller. The secondary side of the transformer in the flyback circuit is synchronous rectifier circuit using MOSFET. The PWM controller is a general-purpose controller with a MOSFET gate driver, which was prepared to create this flyback AC-DC power supply. The flyback circuit uses the TPN7R006PL and TPN2R304PL as switching MOSFETs.

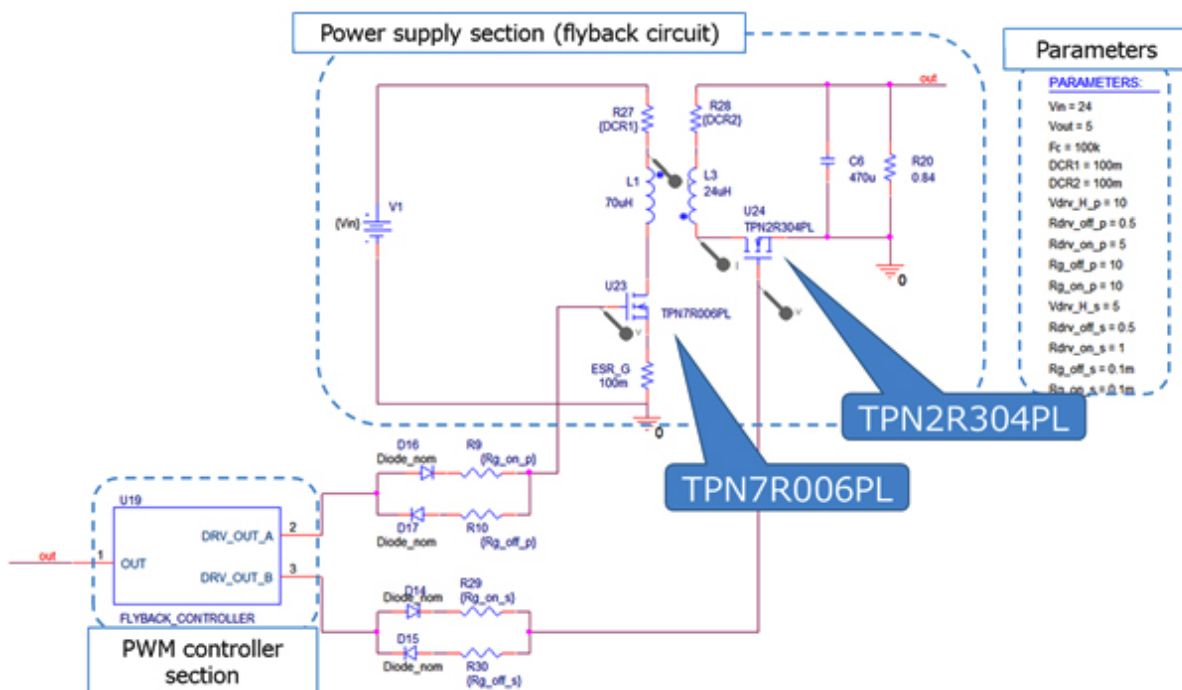


Figure 2.1 Simulation circuit of a 30W flyback DC-DC power supply

Selection of the primary-side MOSFET

The primary-side MOSFET (TPN7R006PL with a V_{DSS} of 60V and an I_D of 54A) was selected, taking the following into consideration:

1. Withstand voltage

Since the input voltage is 24V, the flyback voltage is 9V, and the voltage across the primary winding in the steady state is 33V, a MOSFET with a withstand voltage of 60V or higher must be selected for the primary-side MOSFET.

2. Current rating

The flyback DC-DC power supply has the maximum input current at the maximum output power. If the flyback DC-DC power supply has a conversion efficiency of 85% at the maximum output power of 30W, then the maximum input current is calculated to be 1.6Arms. The design value of the peak current of the primary winding is 6A. So a MOSFET with a peak current rating of 12A or higher must be selected for the primary-side MOSFET.

Selection of the secondary-side MOSFET

The secondary-side MOSFET (TPN2R304PL with a V_{DSS} of 40V and an I_D of 80A) was selected, taking the following into consideration:

1. Withstand voltage

The voltage across the secondary winding (V_s) in the steady state can be calculated as follows:

$$V_s = \frac{V_{out}}{V_{flyback}} \times V_{in} + V_{out}$$

Where, the input voltage (V_{in}) is 24V, the flyback voltage ($V_{flyback}$) is 9V, and the output voltage (V_{out}) is 5V. So V_s is calculated to be 18.3V. Thus a MOSFET with a withstand voltage of 40V or higher was selected for the secondary-side MOSFET.

2. Current rating

The flyback DC-DC power supply has the maximum output current at the maximum output power. Since the maximum output current is 6A_{rms} at the maximum output power of 30W, a MOSFET with a current rating of 12A or higher was selected for the secondary-side MOSFET.

Selection of a transformer

The following paragraphs explain how to select a transformer. The inductance of the transformer to be used in the simulation circuit can be calculated from the following power supply parameters:

- Input voltage: V_{in} (V)
- Output voltage: V_{out} (V)
- Flyback voltage: $V_{flyback}$ (V)
- Switching frequency: F_c (Hz)
- Power conversion efficiency: η (%)
- Output current: I_{out} (A)

The inductance of the primary winding of the transformer (L_p) can be calculated as follows:

$$L_p = \frac{V_{in}^2 \times \eta \times 0.01 \times \left(\frac{V_{flyback}}{V_{in} + V_{flyback}} \right)^2}{2 \times I_{out} \times V_{out} \times F_c}$$

The ratio (n) of the number of turns of the primary winding (N_p) to the number of turns of the secondary winding (N_s) can be calculated as follows:

$$n = \frac{N_p}{N_s} = \frac{V_{flyback}}{V_{out} + V_{flyback}}$$

The inductance of the secondary winding (L_s) can be calculated as follows from the inductance of the primary winding (L_p) and the turns ratio (n):

$$L_s = L_p \times \frac{1}{n^2}$$

From the power supply specifications of this simulation circuit model, it has the input voltage (V_{in}) is 24V, the output voltage (V_{out}) is 5V, the flyback voltage ($V_{flyback}$) is 9V, and the switching frequency (F_c) is 100kHz, and the power conversion efficiency (η) is 85%. Assuming that the flyback DC-DC converter operates in continuous-current mode at 10% load, it is necessary to calculate inductance at an output current (I_{out}) of 0.6A and set the inductance to a value higher than that. From the above equations, the inductance of the primary winding (L_p) is calculated to be 60.7 μ H, the turns ratio (n) to be 1.63, and the inductance of the secondary winding (L_s) to be 22.7 μ H. So we set L_p to 70 μ H, n to 1.7, and L_s to 24 μ H in the simulation model.

In actual design, the inductance values vary because of DC bias characteristics. Select a transformer that exhibits inductance values greater than the above results even when the inductance values decrease because of DC bias characteristics.

3. Simulation results

This section shows the simulation waveforms at the points (1) to (3) shown in Figure 3.1.

- (1) Basic operation of the flyback DC-DC power supply (current and voltage of the primary and secondary windings related to the flyback operation)
- (2) Synchronous rectification on the secondary side (gate voltage, drain-source voltage, and drain current of the MOSFETs related to synchronous rectification)
- (3) Output voltage and current from the flyback DC-DC power supply

The simulation circuit model also allows you to view other waveforms. See Section 5 for how to view waveforms.

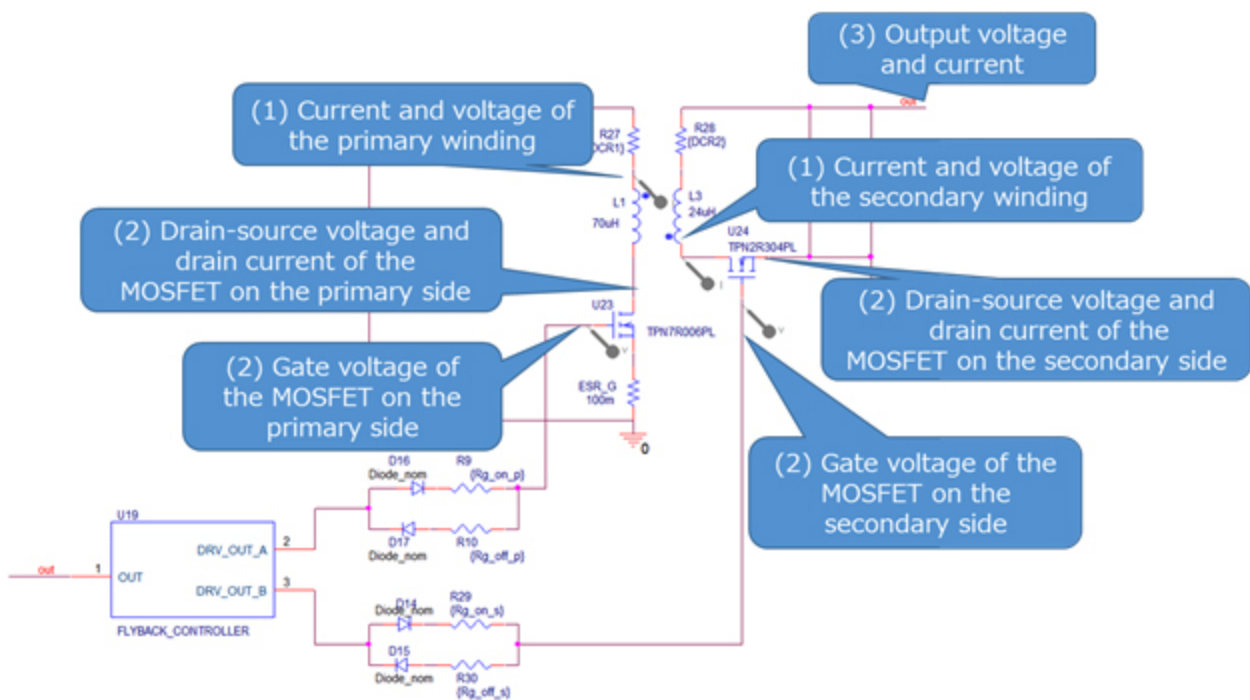


Figure 3.1 Current and voltage measurement points during simulation

(1) Basic operation of flyback DC-DC power supply

The following paragraphs explain the basic operation of the flyback DC-DC power supply, referring to the DC-DC converter shown in Figure 3.2.

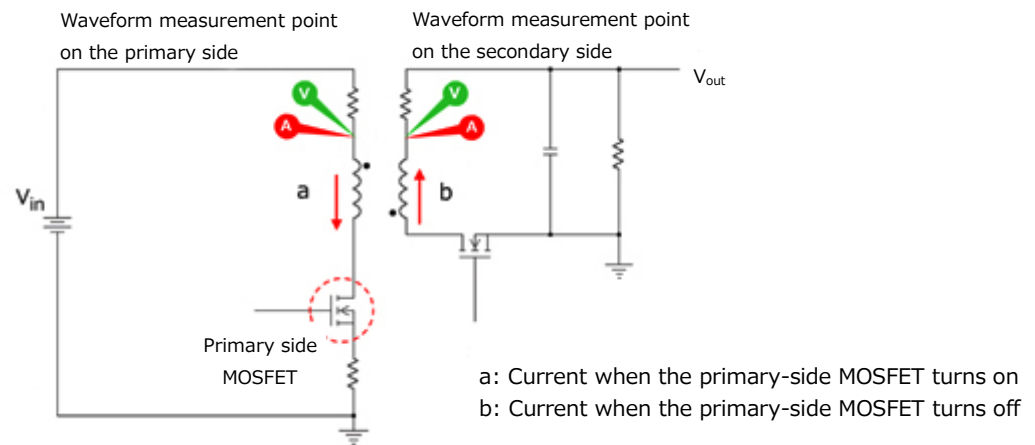


Figure 3.2 Points of measurement of flyback operation

a. The primary-side MOSFET turns on.

Current flows through the primary winding in the direction shown by the arrow.

At this time, the primary-winding voltage becomes equal to the input voltage (V_{in}). The voltage that appears across the secondary winding depends on the turns ratio: $N_s/N_p \times V_{in}$. If that the polarity marking on the secondary side indicates the positive terminal, then the voltage at the measurement point shown in Figure 3.2 is $-(N_s/N_p \times V_{in})$. The sum of V_{out} and $(N_s/N_p \times V_{in})$ is applied to the devices on the secondary side. So the devices on the secondary side must have a withstand voltage greater than $V_{out} + (N_s/N_p \times V_{in})$.

b. The primary-side MOSFET turns off.

The energy charged in the transformer is discharged to the output through the secondary winding.

At this time, the voltage across the secondary winding is equal to the output voltage (V_{out}). The voltage depending on the turns ratio, $N_p/N_s \times V_{out}$, appears across the primary winding as the polarity marking side is the negative terminal. This voltage is called the flyback voltage ($V_{flyback}$). The sum of V_{in} and $V_{flyback}$ is applied to the devices on the primary side. Therefore, the devices on the primary side must have a withstand voltage greater than $(V_{in} + V_{flyback})$.

Steps a and b are repeated.

Figure 3.3 shows the voltage and current waveforms of the primary and secondary windings. As shown in Figure 3.3, voltage is alternately applied across the primary and secondary windings, and current flows through each winding while voltage is applied.

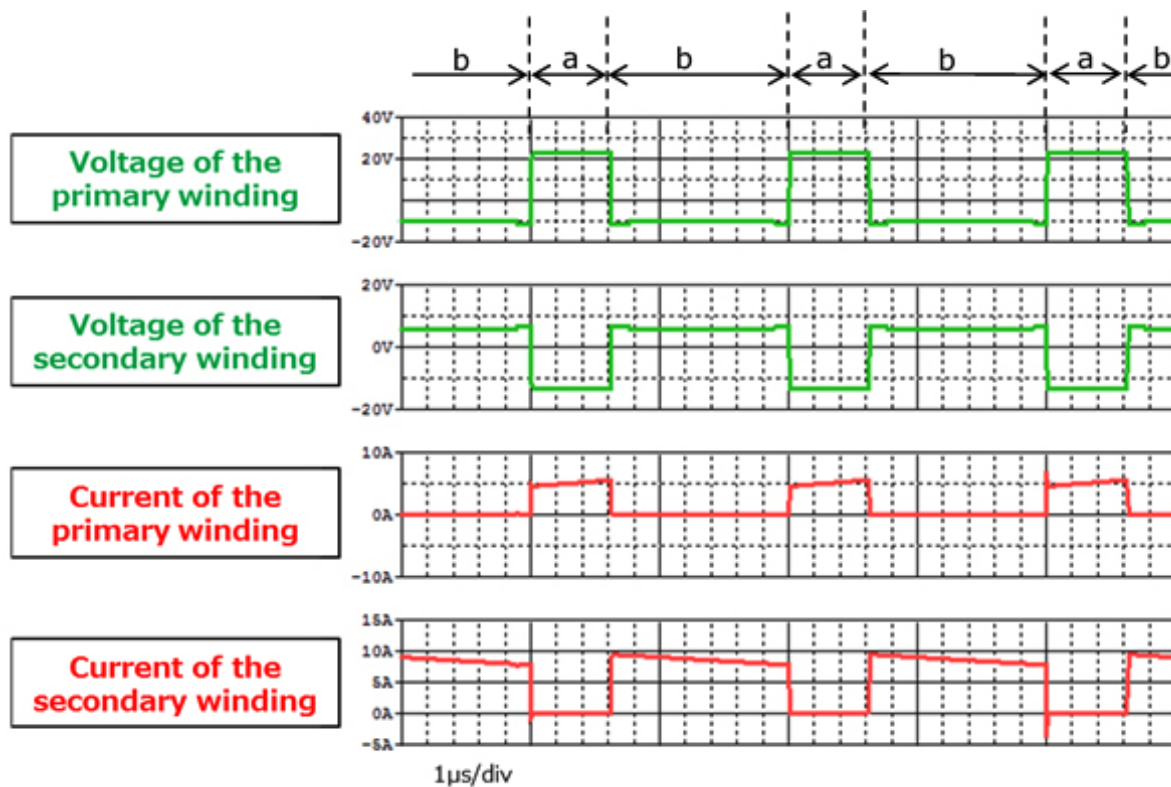


Figure 3.3 Voltage and current waveforms of the primary and secondary windings

(2) Synchronous rectification on the secondary side

The secondary side of the simulation circuit is a synchronous rectification circuit, in which a MOSFET is used instead of diodes. When the MOSFET on the primary side turns off, the transformer reverses the polarity of the secondary-winding voltage, releasing the charged energy to the output. This turns on the MOSFET on the secondary side, allowing current to flow through it. While current is flowing in the circuit on the secondary side of the transformer, a diode rectifier causes a loss proportional to the diode forward voltage, whereas the MOSFET rectifier causes a loss because of the MOSFET on-resistance. Since a voltage drop due to the MOSFET on-resistance is generally lower than the diode forward voltage, a MOSFET synchronous rectifier incurs less loss than a diode rectifier. However, a MOSFET synchronous rectifier requires a dedicated drive circuit to control the MOSFET on/off timing, which incurs a loss due to MOSFET drive.

Figure 3.4 shows a DC-DC converter. The following paragraphs describe the basic operation of synchronous rectification using this circuit.

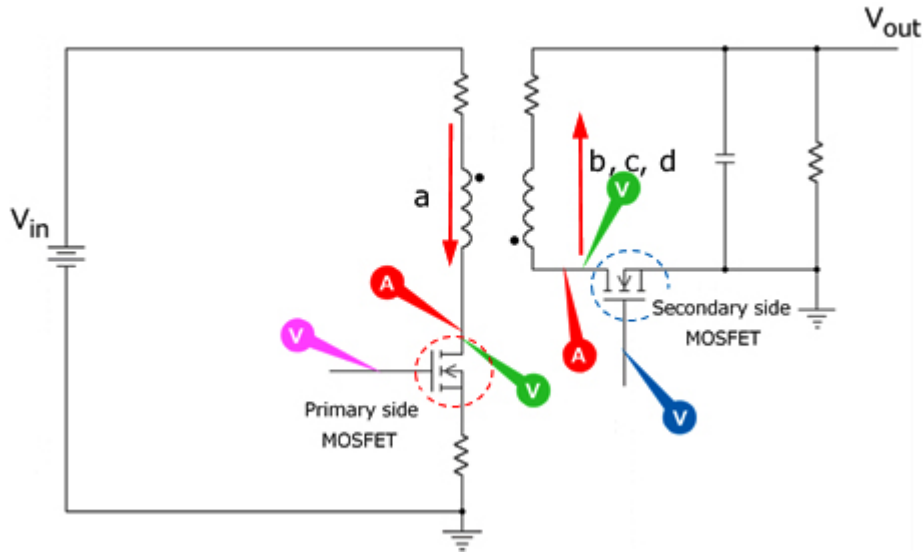


Figure 3.4 Points of measurement during synchronous rectification

- a. The primary-side MOSFET turns on, and the secondary-side MOSFET turns off.
As current flows through the primary winding, energy is charged in the transformer.
- b. The primary-side MOSFET turns off, and the secondary-side MOSFET remains off.
The polarity of the voltage across the secondary winding reverses. This induces a current in the secondary winding, causing the stored energy to be discharged. Since the secondary-side MOSFET is in the off state, this current flows through the parasitic diode of the MOSFET.
- c. The primary-side MOSFET remains off, and the secondary-side MOSFET turns on.
The polarity of the voltage across the secondary winding reverses. Then, the secondary-side MOSFET turns on, allowing a current to flow through it.
- d. The primary-side MOSFET remains off, and the secondary-side MOSFET turns off.
The secondary-side MOSFET turns off before the primary-side MOSFET turns on.
Since the transformer is still discharging the charged energy, the current on the secondary side flows through the parasitic diode of the MOSFET.

Steps a to d are repeated.

Figure 3.5 shows the gate voltage, drain-source voltage, and drain current of the primary- and secondary-side MOSFETs. As shown in Figure 3.5, these MOSFETs turn on and off alternately with dead-time periods (b and d) inserted (during which both MOSFETs are off).

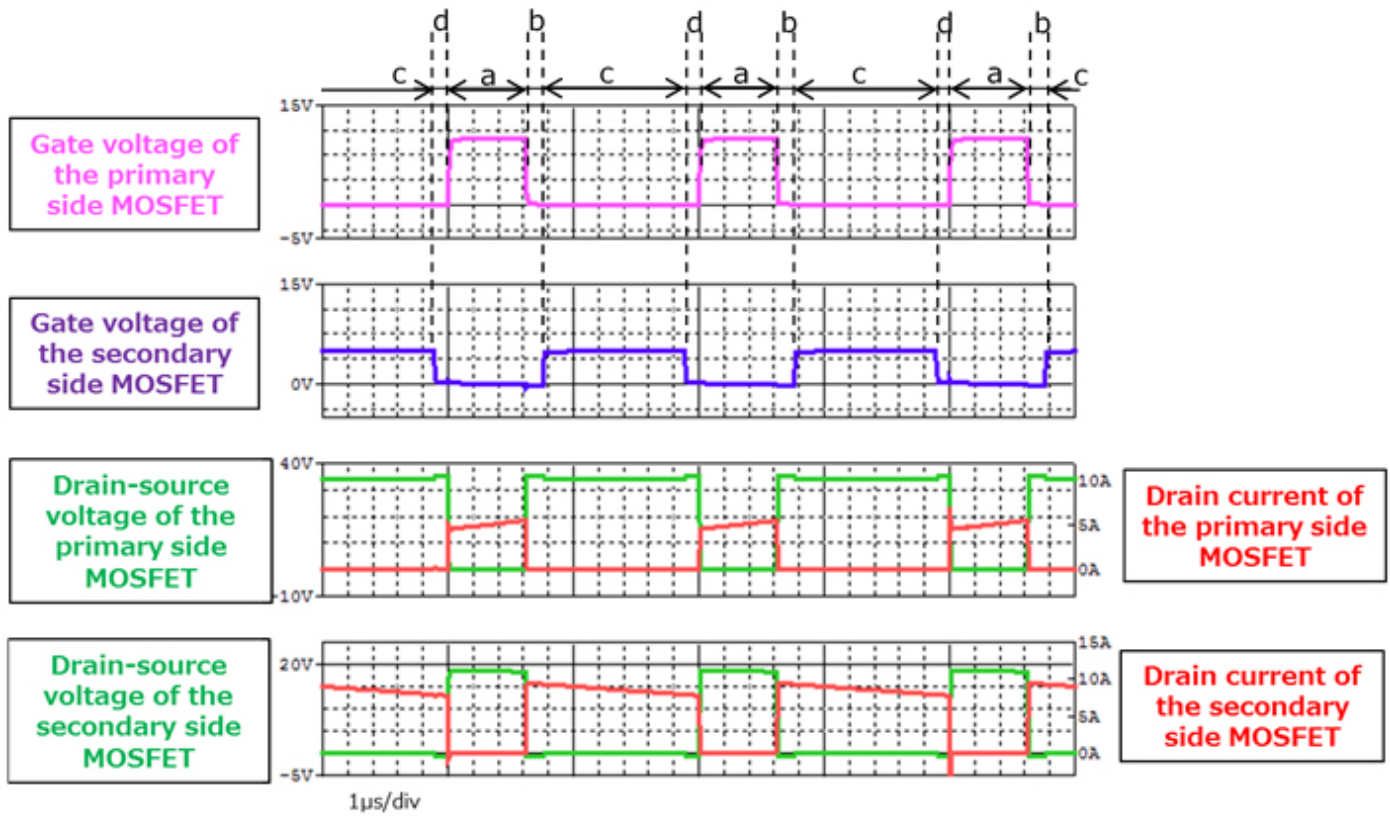


Figure 3.5 Gate voltage, drain-source voltage, drain current waveforms of the primary- and secondary-side MOSFETs

Figure 3.6 shows the gate voltage, drain-source voltage, and drain current of the secondary-side MOSFET during turn-on (b-to-c transition) and turn-off (c-to-d transition). The I_D waveform shows that a current flows during a period from the beginning of b (prior to turn-on) to the end of d (after turn-off). $|V_{DS}|$ during the period of c (in which the MOSFET is on) is lower than $|V_{DS}|$ during the periods of b and d (in which a current flows through a parasitic diode in the MOSFET). This indicates that a synchronous rectification circuit helps reduce power loss.

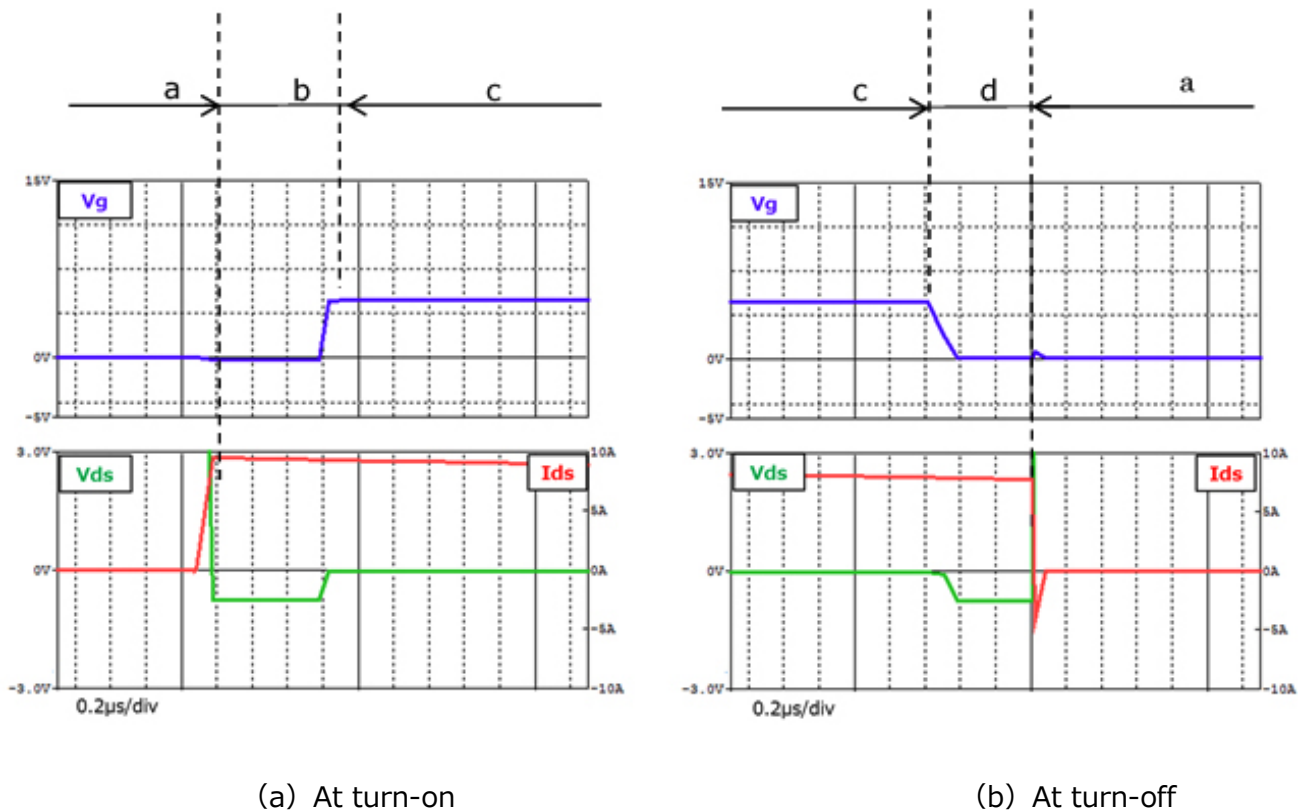


Figure 3.6 Gate voltage, drain-source voltage, and drain current waveforms of the secondary-side MOSFET

(3) Output voltage and current from the flyback DC-DC power supply

Figure 3.7 shows the output voltage and current waveforms of the flyback DC-DC power supply. As shown, the output voltage and current remain stable at the desired values.

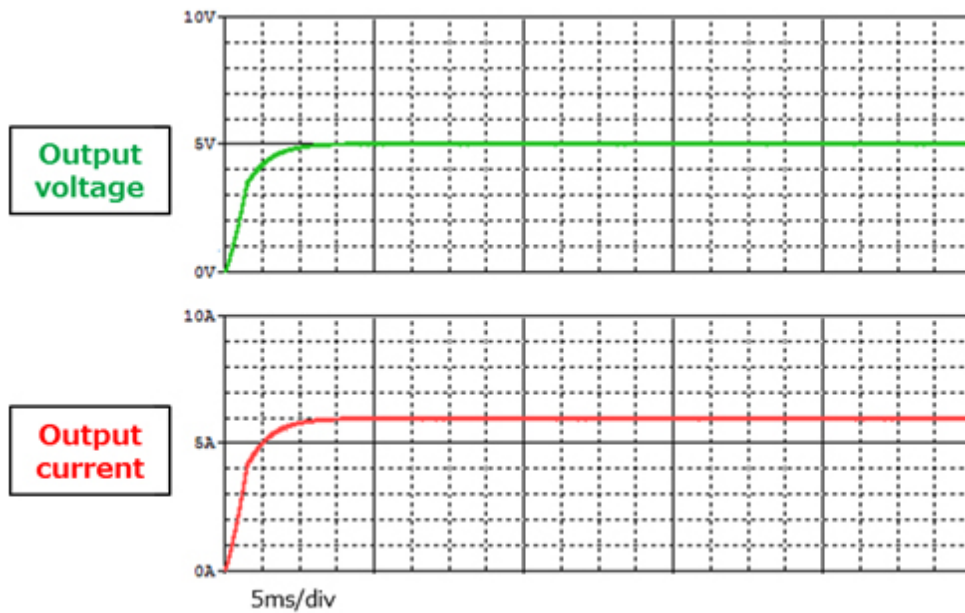


Figure 3.7 Output voltage and current waveforms

4. Product Overview

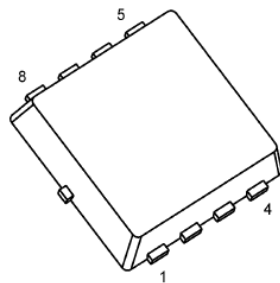
This section provides an overview of Toshiba’s devices used as PSpice® models in the simulation circuit.

4.1. TPN7R006PL

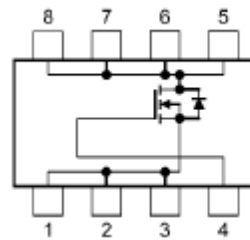
Characteristics

- $V_{DSS} = 60V, I_D = 54A$
- Fast switching
- Low gate charge: $Q_{SW} = 6.8nC$ (typical)
- Low output charge: $Q_{OSS} = 20nC$ (typical)
- Low on-resistance: $R_{DS(ON)} = 5.4m\Omega$ (typical) ($V_{GS} = 10V$)
- Low leakage current: $I_{DSS} = 10\mu A$ (maximum) ($V_{DS}=60V$)
- Easy-to-use enhanced-mode MOSFET: $V_{th}=1.5$ to $2.5V$ ($V_{DS}=10V, I_D=0.2mA$)

External view and pin assignment



TSON Advance



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

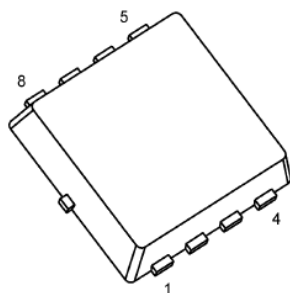
3.3 (W) × 3.3 (L) × 0.85 (H) (mm)

4.2. TPN2R304PL

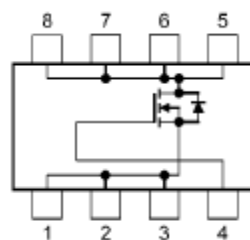
Characteristics

- $V_{DSS} = 40V, I_D = 80A$
- Fast switching
- Low gate charge: $Q_{SW} = 10.8nC$ (typical)
- Low output charge: $Q_{OSS} = 27nC$ (typical)
- Low on-resistance: $R_{DS(ON)} = 1.8m\Omega$ (typical) ($V_{GS} = 10V$)
- Low-leakage current: $I_{DSS} = 10\mu A$ (maximum) ($V_{DS} = 40V$)
- Easy-to-use enhanced-mode MOSFET: $V_{th} = 1.4$ to $2.4V$ ($V_{DS} = 10V, I_D = 0.3mA$)

External view and pin assignment



TSON Advance



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

3.3 (W) × 3.3 (L) × 0.85 (H) (mm)

5. Using the simulation circuit

You can freely change various parameters with OrCAD Capture to verify the circuit operation according to the actual power supply specifications and evaluate how these parameters affect the circuit operation. This section shows how to set simulation parameters and verify the circuit operation.

Parameter settings

Table 5.1 shows the parameters you can set for the simulation circuit. Double-click a parameter name in the PARAMETERS section, then the Display Properties dialog box appears as shown in Figure 5.1. Change the value in the Value field.

Table 5.1 Parameters that can be modified in the Parameters section

Parameter name	Unit	Description
Vin	V	Input voltage
Vout	V	Output voltage
DCR1	Ω	Parasitic resistance of the primary winding of the transformer
DCR2	Ω	Parasitic resistance of the secondary winding of the transformer
Fc	Hz	Switching frequency
Rg_on_p	Ω	External turn-on gate resistor for the primary-side MOSFET
Rg_off_p	Ω	External turn-off gate resistor for the primary-side MOSFET
Rdrv_on_p	Ω	Internal resistance of the turn-on gate driver for the primary-side MOSFET
Rdrv_off_p	Ω	Internal resistance of the turn-off gate driver for the primary-side MOSFET
Rg_on_s	Ω	External turn-on gate resistor for the secondary-side MOSFET
Rg_off_s	Ω	External turn-off gate resistor for the secondary-side MOSFET
Rdrv_on_s	Ω	Internal resistance of the turn-on gate driver for the secondary-side MOSFET
Rdrv_off_s	Ω	Internal resistance of the turn-off gate driver for the secondary-side MOSFET
Vdrv_H_p	V	Supply voltage for the primary-side gate driver
Vdrv_H_s	V	Supply voltage for the secondary-side gate driver

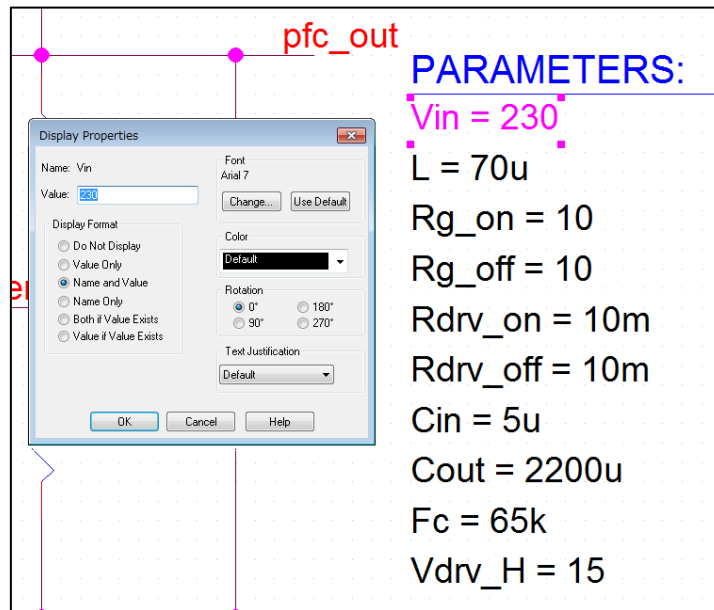


Figure 5.1 Display Properties dialog box

Setting analysis parameters

The following describes how to run a simulation on the simulation circuit.

1. From the menu bar of OrCAD Capture, select **PSpice - New Simulation Profile**. Then, the New Simulation dialog box shown in Figure 5.2 appears. Enter an arbitrary profile name and click **Create**.

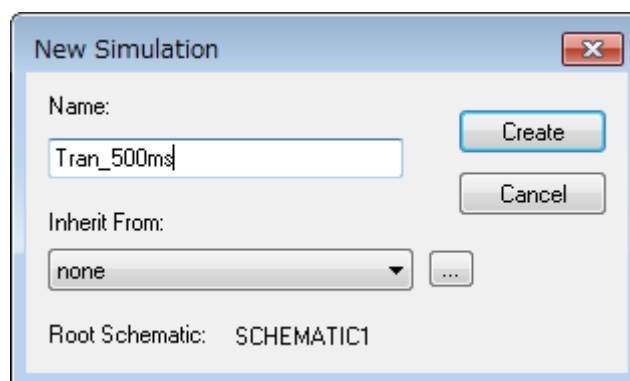


Figure 5.2 New Simulation dialog box

- Then, the Simulation Settings dialog box shown in Figure 5.3 appears. In this dialog box, you can set parameters for various types of analysis. First, click the **Analysis** tab. Select **Time Domain (Transient)** from the **Analysis Type** drop-down list. Enter the simulation end time in the **Run To Time** field and the maximum step size in the **Maximum Step Size** field.

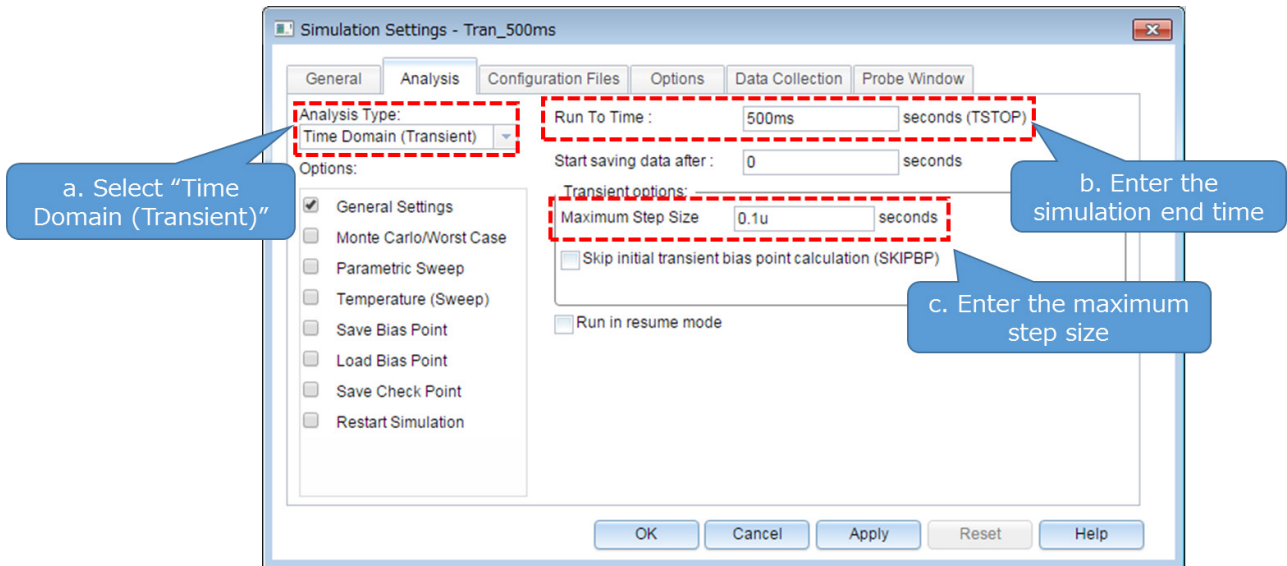


Figure 5.3 Simulation Settings - Analysis dialog box

- Click the **Options** tab to choose analysis options. For the simulation of our model, it is recommended to check **Analog Simulation - Auto Converge - AutoConverge** as shown in Figure 5.4 to enable the automatic convergence feature.

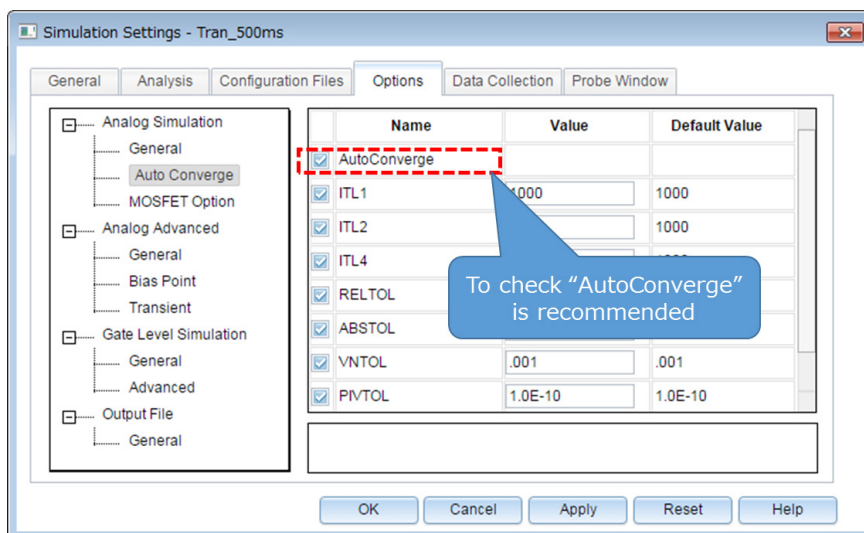


Figure 5.4 Simulation Settings - Options dialog box

- Click **OK** to close the Simulation Settings dialog box.
- To run a simulation, select **PSpice - Run** from the menu bar of OrCAD Capture. Then, PSpice A/D starts automatically and runs a simulation.

Viewing simulation results

The following describes how to view the simulation results. You can display the waveforms of the simulation results in two ways.

Method 1: Selecting traces

1. Right-click outside the graph area and select **Add Trace** as shown in Figure 5.5.
2. Then, the Add Traces dialog box shown in Figure 5.6 appears. Select traces to be added to a selected plot. To view a voltage waveform, select $V(\text{trace_name})$. To view a current waveform, select $I(\text{device_name})$. See Figure 5.6.
3. Click **OK**. Then, the selected waveform appears as shown in Figure 5.7.

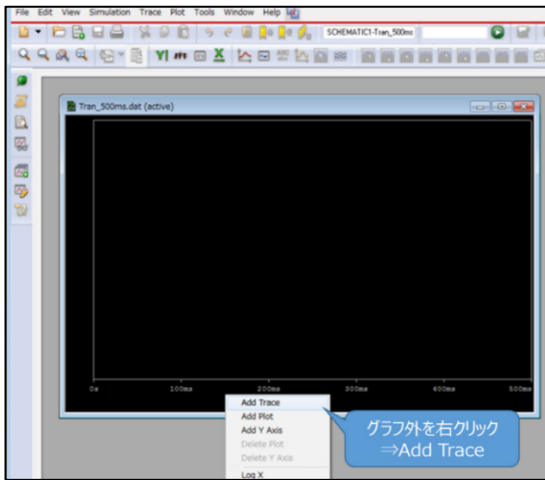


Figure 5.5 Graph window

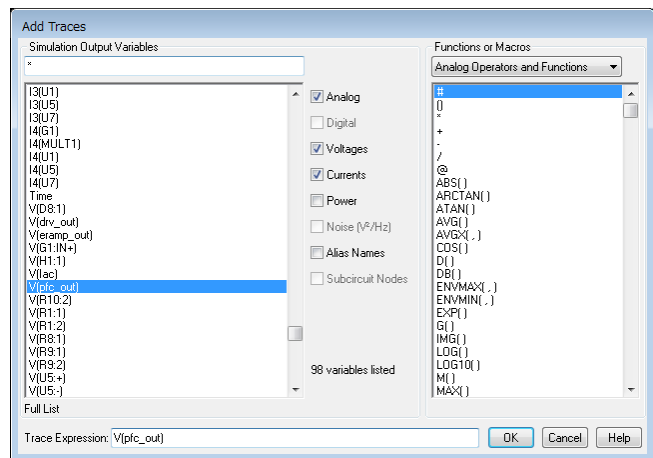


Figure 5.6 Add Traces dialog box

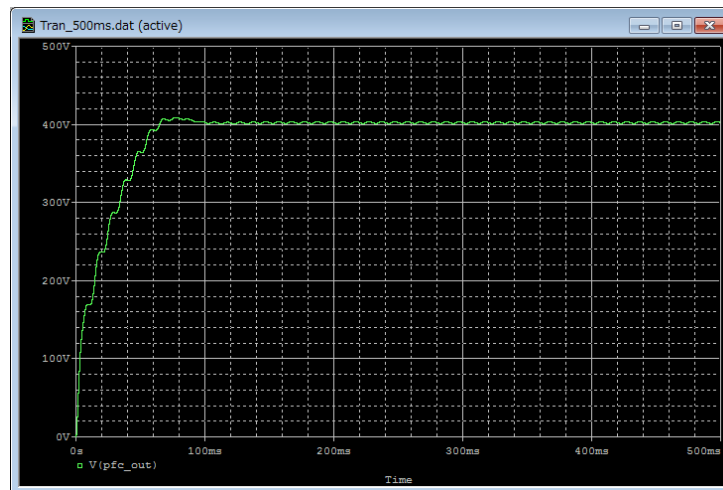


Figure 5.7 Simulation waveform view (Example: PFC output voltage waveform)

Method 2: Adding markers

1. From the menu bar of OrCAD Capture, select **PSpice - Markers** and then a type of marker as shown in Figure 5.8.
2. Place the selected marker on the desired node in the simulation circuit as shown in Figure 5.9.
3. Then, its waveform appears in the graph window of PSpice A/D as shown in Figure 5.10.

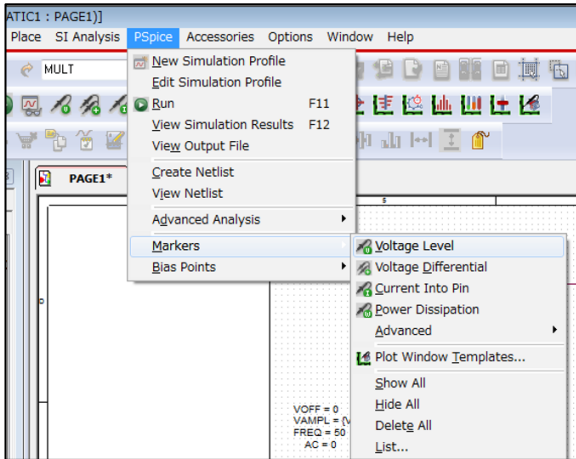


Figure 5.8 Selecting a marker type

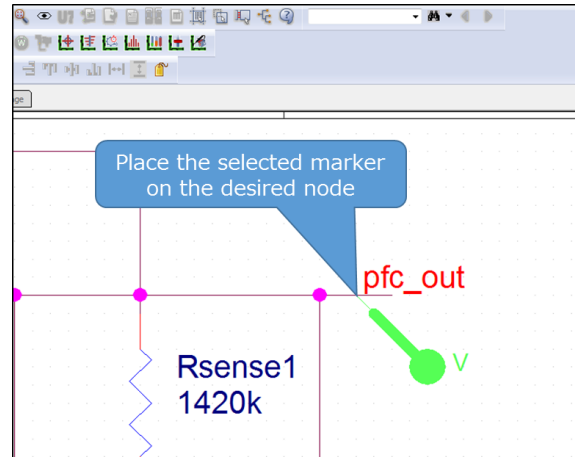


Figure 5.9 Placing a marker in the circuit

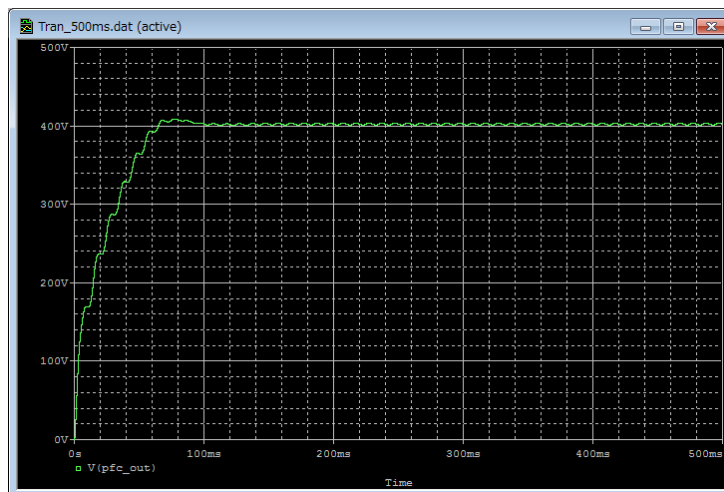


Figure 5.10 Simulation waveform view (Example: Output voltage waveform)

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