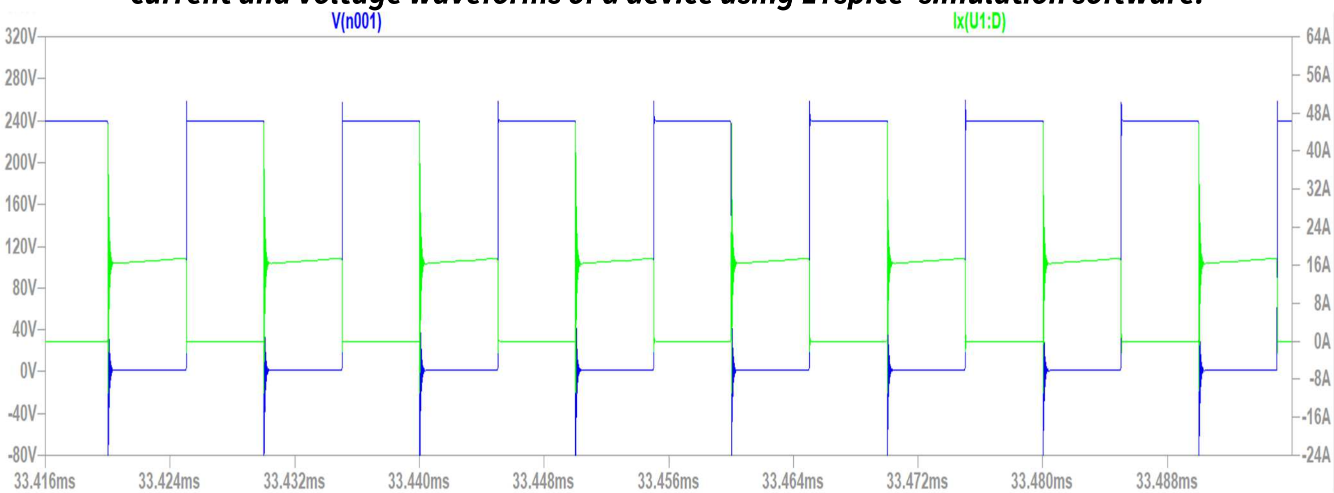
Application Note **PRD-03043**

Measuring Switching and Conduction Losses in LTspice® Simulation Software

This application note helps users to measure the switching and conduction power losses from the current and voltage waveforms of a device using LTspice® simulation software.



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Contents

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1. Introduction

The total power loss in a device can be divided into two significant components - the switching losses P_{sw} and the conduction losses P_{cond} as seen in Equation 1 [1]. These components can be measured by observing the waveform of voltage across the device and the current through the device in steady-state. Figure 1 marks the measurement area of the waveforms in steady-state that provide the most accuracy in estimation.

$$P_{tot} = P_{sw} + P_{cond} \qquad \text{Eq. 1}$$

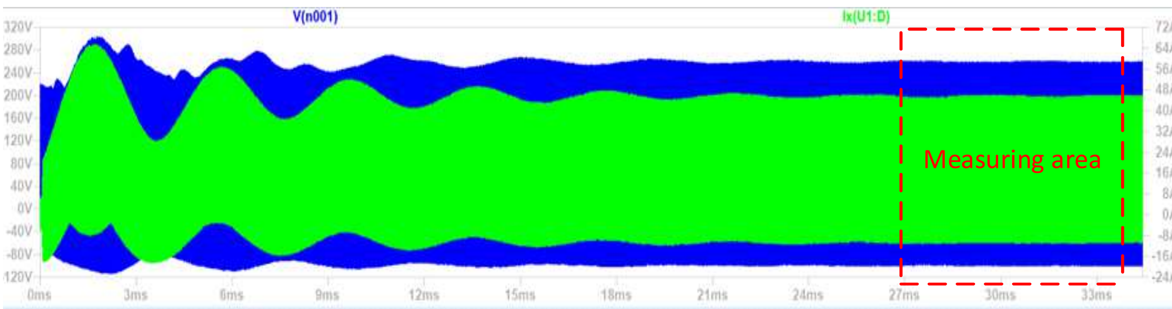

Figure 1: Measurement area for the voltage and current waveform

This application note will consider a 2kW Boost Converter Model, as shown in Figure 2. It is a DC-DC power converter used to step-up the input voltage to a desired output voltage by modifying the duty cycle of the PWM signal given to the gate of the MOSFET. Duty cycle is defined as the ratio of the pulse width to the total pulse period of the PWM signal.

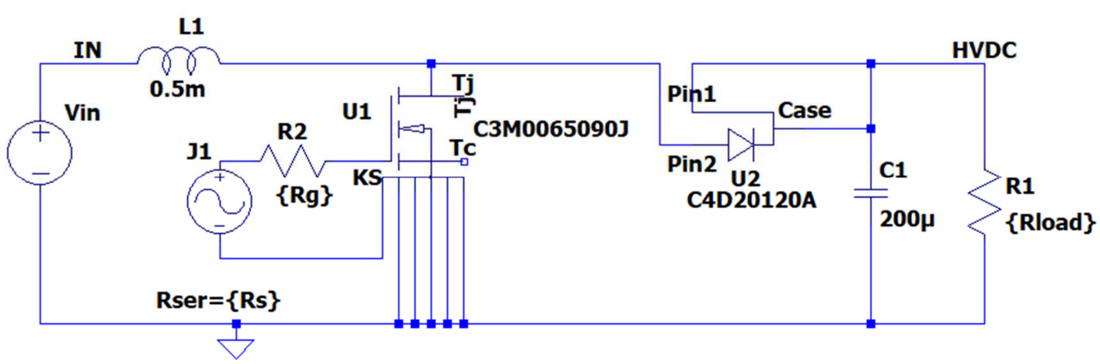

Figure 2: 2 kW boost converter model

2. Switching Losses

The switching losses of the device can be divided into two parts - the power loss when the device is turned on ($P_{sw,on}$) and the power loss when the device is turned off ($P_{sw,off}$). The general expression for the total switching loss Psw can be given by Equation 2 [1]:

$$P_{sw} = P_{sw,on} + P_{sw,off} = \frac{1}{2} t_{sw,on} V_{in} I_{on} f_{sw} + \frac{1}{2} t_{sw,off} V_{in} I_{on} f_{sw} \qquad \text{Eq. 2}$$

Where V_{in} is the voltage across the device, I_{on} is the current through the device, $t_{sw,on}$ and $t_{sw,off}$ are the switching turn-on time and switching turn-off time respectively, and f_{sw} is the switching frequency. In simple terms, it represents the power lost during switching. Total switching loss can be measured directly using LTspice® simulation software by zooming into the measuring area specified in Figure 1. The turn-on and turn-off transients are used to measure the $P_{sw,on}$ and $P_{sw,off}$ as shown in Figure 3.

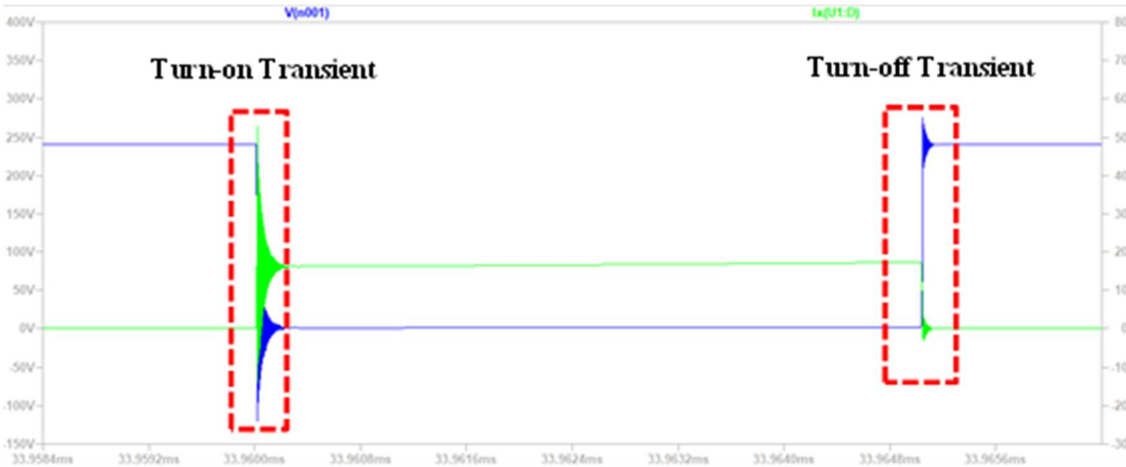

Figure 3: Turn-on and turn-off transients for measuring switching losses

A user can display the instantaneous power plot for the device by following these steps:

- Hold down the *Alt* key and hover the cursor over the device to be measured until  this symbol appears, and click on it.
- This will add a power trace to the plot. Modify the power expression by right-clicking on the power trace title and change it to the voltage and current product as seen in Figure 4.
- Right-click anywhere on the plot and choose the selection "Add a plot pane." Click on the power trace title and drag the power curve to that plot pane. The final window will look like Figure 5.

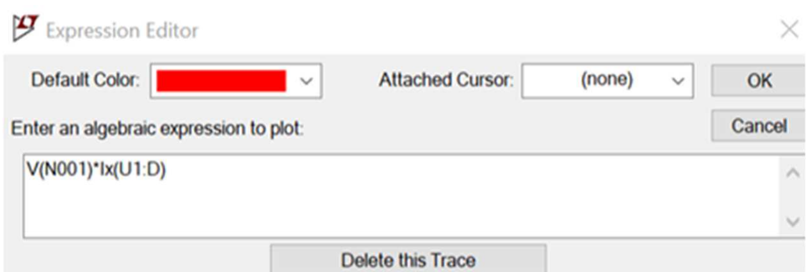

Figure 4: Modify expression for power

Figure 5: Final window to display power plot

As a rule of thumb, turn-on switching losses are measured as a function of energy loss $E_{sw,on}$ during the turn-on transient time. The turn-on transient is the period of time between the moment when the current increases to 10% of its final value and the moment when the voltage falls to 10% of its initial value, as shown in Figure 6. Similarly, turn-off switching losses are measured as a function of the energy loss $E_{sw,off}$ during the turn-off transient time. The turn-off transient is the period of time between the moment when the voltage increases to 10% of its final value and the moment when the current falls to 10% of its initial value, as shown in Figure 6.

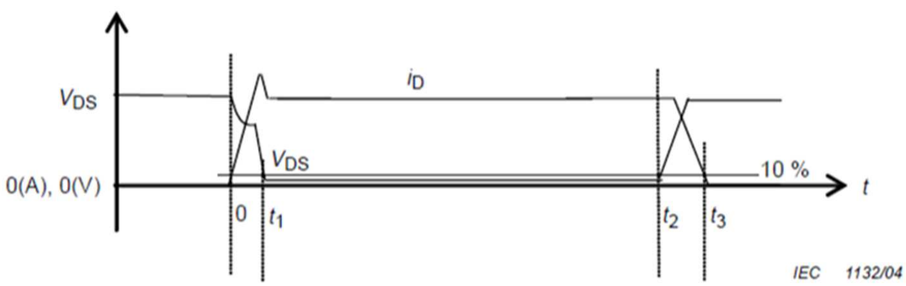

Figure 6: Integral times for $E_{sw,on}$ and $E_{sw,off}$ [3]

2.1 Turn-on Loss ($P_{sw,on}$)

Using the explained rule of thumb in Figure 6, the turn-on loss is measured during the period of time between the moment when the voltage reaches 10% of its initial value (as in the example shown in Figure 7, where the initial value was 240 V and the cursor 1 is placed at roughly 10% of that initial value, at 25.4V) and the moment when the current reaches 10% of its final value after the ringing (as shown in Figure 7, where the final value is 17.2 A and cursor 2 is placed at 1.76 A).

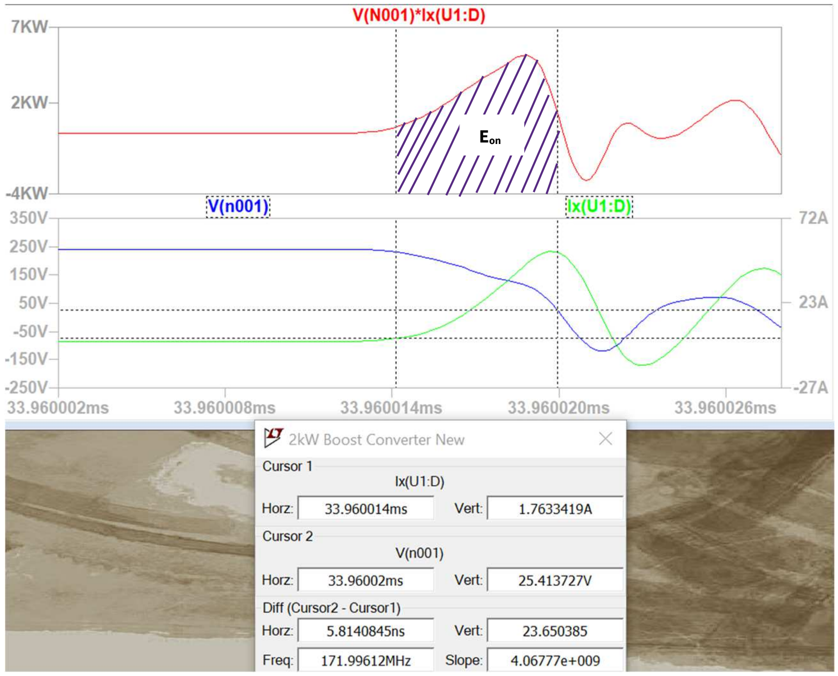

Figure 7: Placement of cursors to observe the turn-on loss

To observe the switching loss, right-click on the time scale on the plot to bring up the window shown in Figure 7. Enter the time values of the cursors from Figure 7 into the window shown in Figure 8 to set the limits of the horizontal axis. This will scale the time axis to show the turn-on period. Hold down the *Ctrl* key and click on the trace title for the power plot. A window with the integral should appear as seen in Figure 9. In this example, the $P_{sw,on}$ can be calculated as in Equation 3:

$$P_{sw,on} = E_{sw,on} f_{sw} \quad \text{Eq. 3}$$

$$P_{sw,on} = 17.162\mu J \times 100\ kHz = 1.716\ W$$

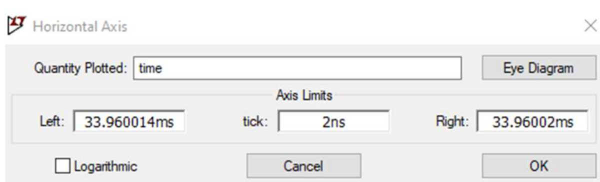

Figure 8: Changing the time-scale

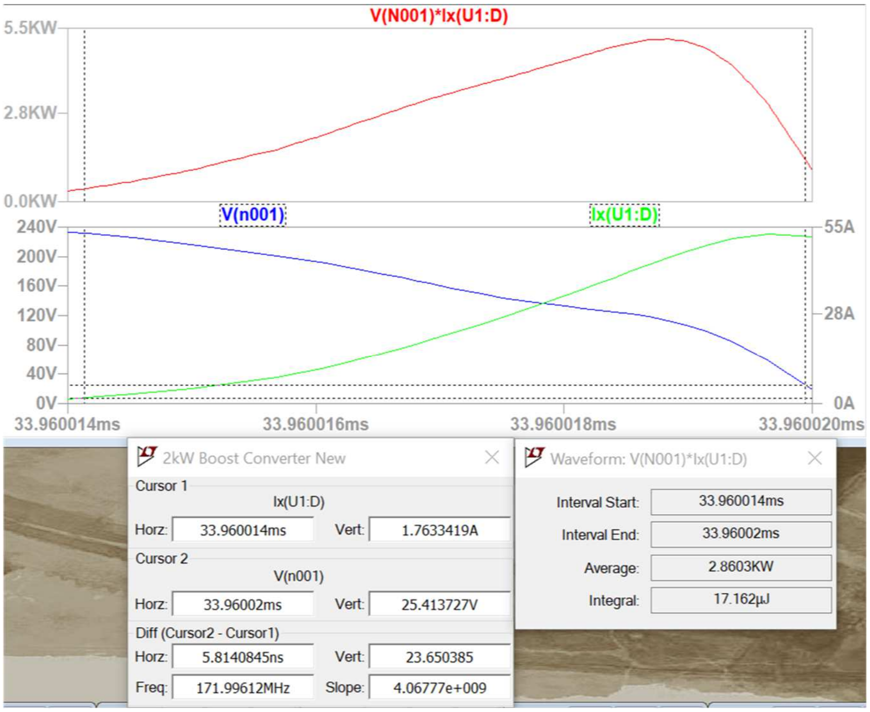

Figure 9: Window displaying turn-on energy loss

2.2 Turn-off Loss ($P_{sw,on}$)

As with measuring turn-on loss, the rule of thumb to measure turn-off loss is to measure during the period of time between the moment when the voltage increases to 10% of its final value (which is 240 V in this example, so cursor 1 is placed at 24V as seen in Figure 10) and the moment when the current reduces to 10% of its initial value (which is 17.2 A in this example, so cursor 2 is placed at 1.73 A). To observe the switching loss, right-click on the time scale on the plot to bring up a window similar to the one shown in Figure 7 on pg. 7. Enter the time values of the cursors from Figure 10 into the window shown in Figure 8 on pg. 8 to set the limits of the horizontal axis. This will scale the time axis to show the turn-off period. Hold down the *Ctrl* key and click on the trace title for the power plot. A window with the integral should appear as seen in Figure 10. The $E_{sw,off}$ can be obtained, which is used to calculate $P_{sw,off}$ in this example as shown in Equation 4:

$$P_{sw,off} = E_{sw,off} f_{sw} \quad \text{Eq. 4}$$

$$4.7822\mu J \times 100\ kHz = 0.478\ W$$

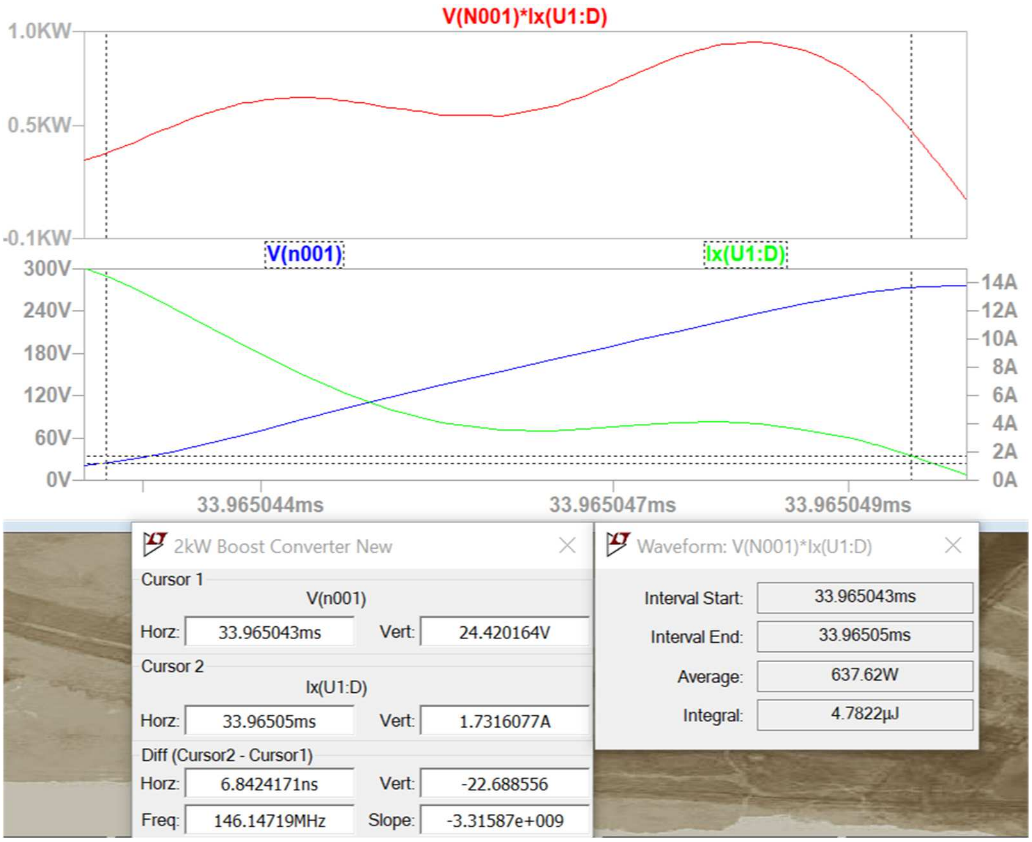

Figure 10: Window displaying turn-off energy loss

The total switching losses can be calculated using Equation 2 as:

$$P_{sw} = P_{sw,on} + P_{sw,off} = 1.716\,W + 0.478\,W = 2.194\,W$$

3. Conduction Losses

Conduction losses are measured between the switching transients. The conduction losses when the switch is on ($P_{cond,on}$) contribute to the total conduction losses. The general expression for conduction loss is given by Equation 5 [2]:

$$P_{cond,on} = E_{cond,on} f_{sw} \qquad \text{Eq. 5}$$

Where $E_{cond,on}$ is the energy lost in the device when the device is in the on-state and f_{sw} is the switching frequency of the device.

The on-state conduction losses are measured during the period of time between the moment when the voltage first decreases to 10% of its initial value during the switch-on transient and the moment when the voltage first increases to 10% of its final value during the switch-off transient. The cursor placement can be seen in Figure 11 where cursor 1 is a little over 24V at 24.97V, 10% of its initial value of 240V, and cursor 2 is at 24V, 10% of the final value of 240V. The scale on the time axis is adjusted to exactly match the cursor placement. The energy integral obtained following the first steps is 120.43 µJ. This must be multiplied with the switching frequency of the device, which is 100 kHz in the example.

$$P_{cond,on} = 102.21\,\mu J \times 100\,kHz = 10.22W$$

Figure 11: Window displaying average power loss and cursor placement during on-state

4. References

[1] George Lakkas “MOSFET power losses and how they affect power-supply efficiency”

[2] Akshay Mehta “DC/DC converter datasheets - Calculate system losses”

[3] International Standard IEC 60747-8-4, First Edition

5. Revision History

Date	Revision	Changes
June 2021	1	1st issue
January 2024	2	Branding and formatting updates