PSIM

TUTORIAL

IGBT and MOSFET Loss Calculation in Thermal Module

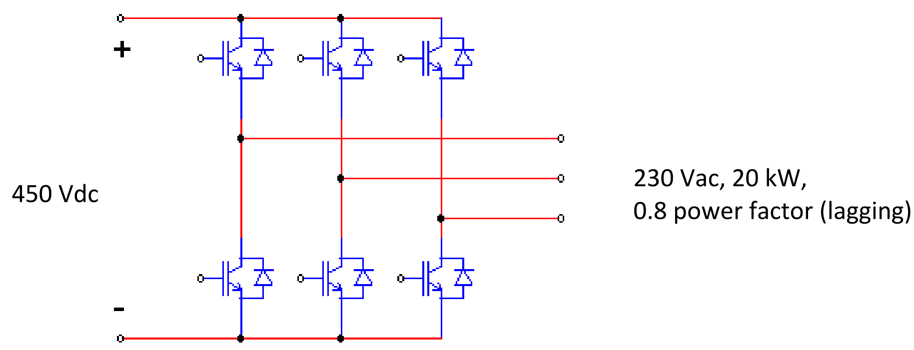
July, 2019

The Thermal Module is an add-on option to PSIM. Its purpose is to simulate the losses of semiconductor devices and inductors quickly from manufacturer device datasheets.

In this tutorial, the process of how to use the Thermal Module for power loss calculation of IGBT and MOSFET is described. The loss calculation of SiC and GaN devices is covered in the tutorial "Tutorial – SiC and GaN loss calculation and transient analysis.pdf", and the loss calculation of inductors is covered in another tutorial "Tutorial – Inductor loss calculation in the Thermal Module.pdf".

1. IGBT Loss Calculation

To illustrate how IGBT losses and junction temperature are calculated in PSIM's Thermal Module, the datasheet of Semikron's IGBT Module SEMiX151GD066HDs (600V, 150A) is used in a 3-phase voltage source inverter example, as shown below:



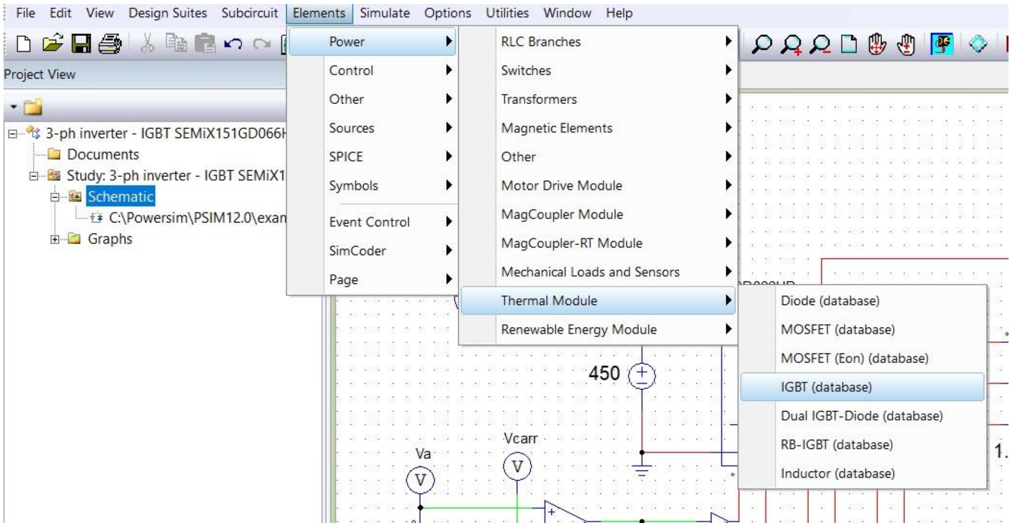
In this example, the inverter operating conditions are:

DC Bus Voltage: 450 Vdc
AC Output: 230 V (line-line, rms), 60 Hz, 20 kW, 0.8 power factor (lagging)
Switching Frequency: 8 kHz

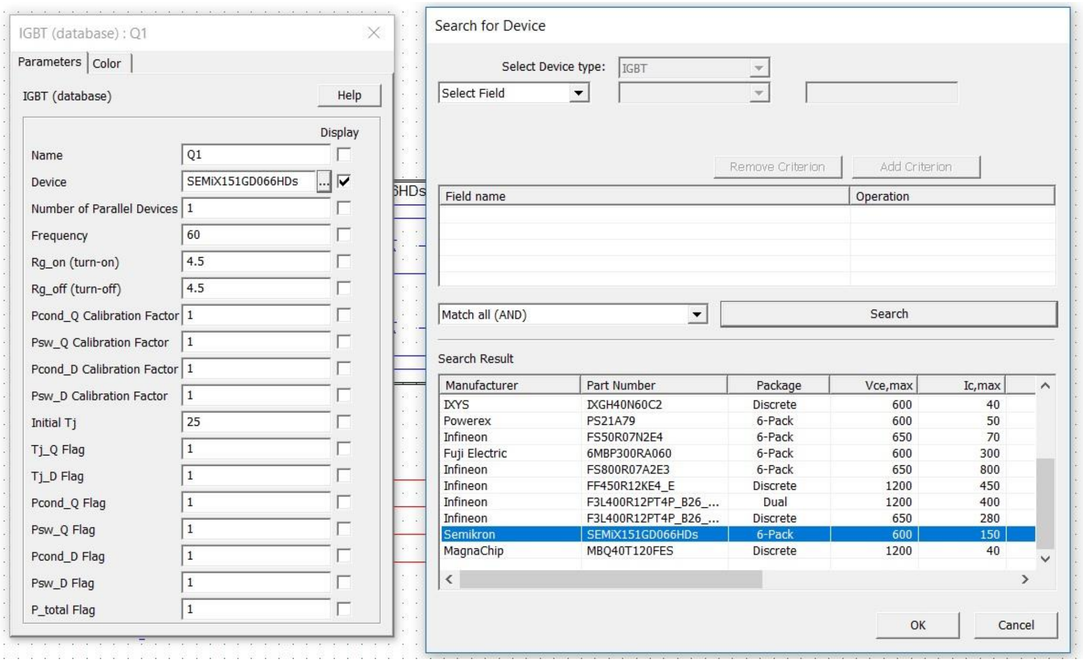
From the values above, the ac output current is calculated as: Io = 62.75 A.

1.1 Simulation of IGBT Losses in PSIM

Assuming the IGBT device is already available in PSIM's device database, it can be placed in a PSIM schematic for the calculation of losses. To choose this device, in PSIM, select **Elements** >> **Power** >> **Thermal Module** >> **IGBT (database)** as shown below:

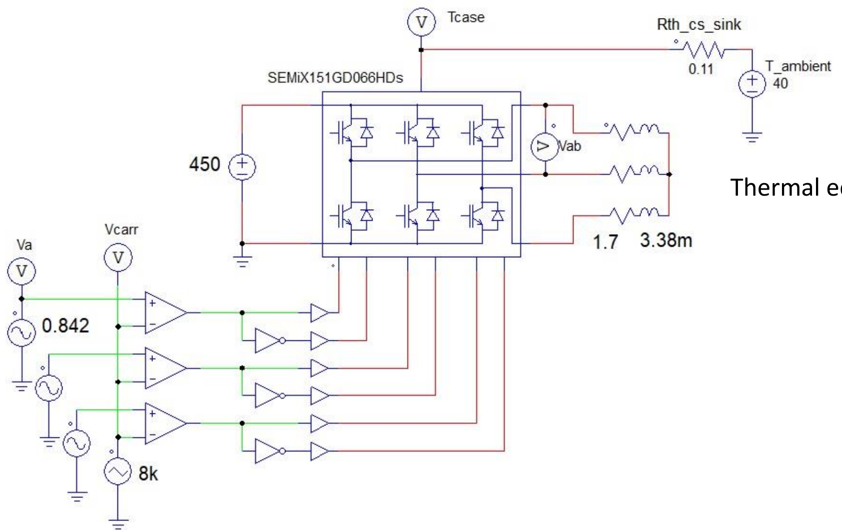


Place the discrete IGBT element on the schematic. Double click on the IGBT element to open the parameter dialog window. Click on the Browser button next to the “Device” input field, and choose the device “Semikron SEMiX151GD066HDs”.



The IGBT image will change to a 6-pack inverter bridge. Continue to build the rest of the circuit.

The circuit below shows the completed inverter circuit using the IGBT Module SEMiX151GD066HDs. The load resistances and inductances and the modulation index are selected such that the circuit operates under the specified conditions (output of 230 Vac, 20-kW, 0.8 power factor (lagging)).



Thermal equivalent circuit

The IGBT Module image shows 2 dc bus terminals on the left, 3 ac output terminals on the right, 6 gating signal nodes at the bottom, and one extra nodes on the top. This node is for the monitoring of the device's thermal effects:

- The voltage at this node is the module's case temperature, can be monitored with a Voltmeter.
- The current flowing out of this node is the total power losses of the whole module (all 6 devices), can be monitored with an Ammeter.

This node should be connected to a voltage source representing the ambient temperature or grounded via a network representing the dynamic thermal impedance between the case of the module and the ambient. In this example, the resistor **Rth_cs_sink** is the sum of the thermal resistances between the case and heat sink, and between the heat sink and the ambient.

The parameters of the IGBT (database) are defined as below:

The parameter ***Frequency*** defines the interval under which the losses are calculated. For example, if the frequency is 60 Hz, the losses results are the average value for an interval of 16.67 ms. If the frequency is set to be the same as the switching frequency, the losses in each switching cycle are obtained.

The parameters ***Rg_on*** and ***Rg_off*** are the gate resistances at turn-on and turn-off. Note that they must be defined correctly to reflect the actual operating conditions.

The ***Calibration Factors*** are used to scale the calculation results against experimental results. For example, for a specific device, if the datasheet losses are 10 W, but the measured losses from the experiments are 12 W, the calibration factor should be set to 1.2.

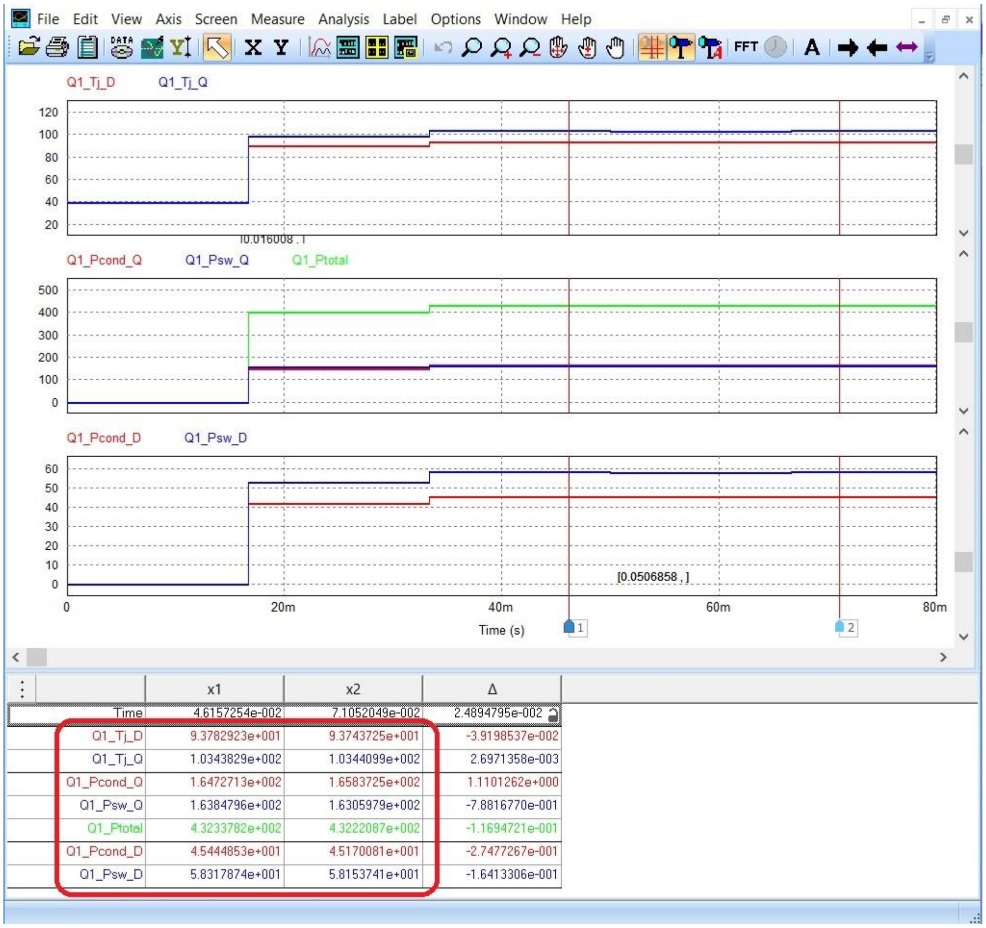
If the ***flags*** are for the monitoring of the device's thermal behaviour. When the flags are set, the following thermal related characteristics can be monitored:

- transistor junction temperature Tj_Q
- diode junction temperature Tj_D
- transistor conduction loss Pcond_Q,

- transistor switching loss Psw_Q,
- diode conduction loss Pcond_D, and
- diode switching loss Psw_D.

The temperatures are in ^oC. The losses are for the whole IGBT module (all 6 IGBT switches).

The simulation result displayed in SimView is as below:



The following thermal results are obtained from the PSIM simulation of this example:

Diode Junction Temperature (^oC):	93.28
Transistor Junction Temperature (^oC):	103.3
Transistor Conduction Loss (W):	165.8
Transistor Switching Loss (W):	163.1
Diode Conduction Loss (W):	45.2
Diode Switching Loss (W):	58.2
Total Loss per Module (W):	432.2

1.2 Adding an IGBT Device into the Device Database

The above example shows how to run a thermal simulation in PSIM when the device is already available in the database. However, in many cases, a device is no available in the database.

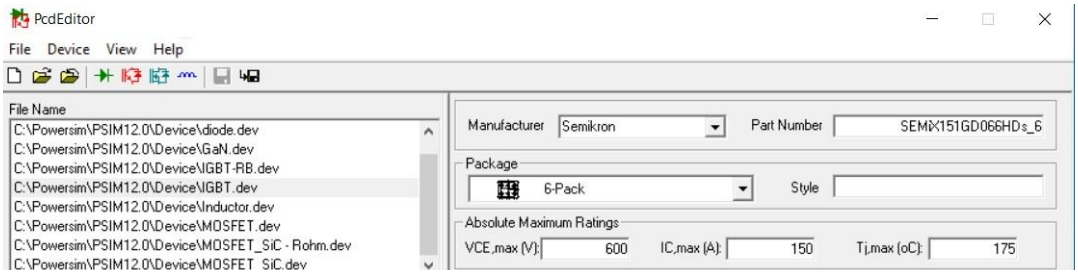
Therefore, it has to be entered into the database before it can be used in a PSIM schematic for thermal simulation.

Here, the IGBT Module SEMiX151GD066HDs is used as the example to illustrate the procedure of entering a device into PSIM's device database. Below is the procedure to add this device as a new IGBT device into the device database file “IGBT.dev”.

Step 1. In PSIM, go to **Utilities** >> **Device Database Editor** to launch the **PcdEditor**.

Step 2. Highlight the device file “IGBT.dev” in the **File Name** list box. Select **Device** >> **New IGBT**, and confirm that you want to save the new device to “IGBT.dev”.

Step 3. Enter basic device information from manufacturer’s datasheet into PSIM’s Device Database. To avoid destroying the device information in PSIM’s original database, the new device is be named as “SEMiX151GD066HDs_6” instead.



Step 4. Use PSIM’s Curve Capture Tool to enter the transistor Electrical Characteristics from the graphs provided in manufacturer’s datasheet.

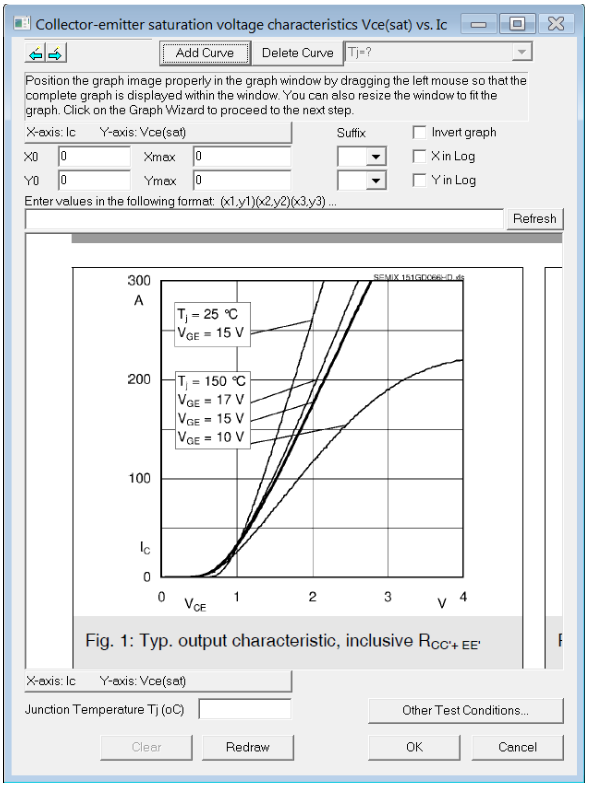
The forward conduction characteristic **Vce(sat) vs. Ic** is used as the example.

This characteristic is provided in Fig. 1 of the datasheet. Fig. 1 provides one curve at Tj=25 ^oC for VGE=15V, but it provides three curves at Tj=150 ^oC for VGE=10, 15, and 17V. We will select the curves corresponding to VGE=15V since curves of the energy losses Eon and Eoff vs. Ic are for VGE=-8/+15V.

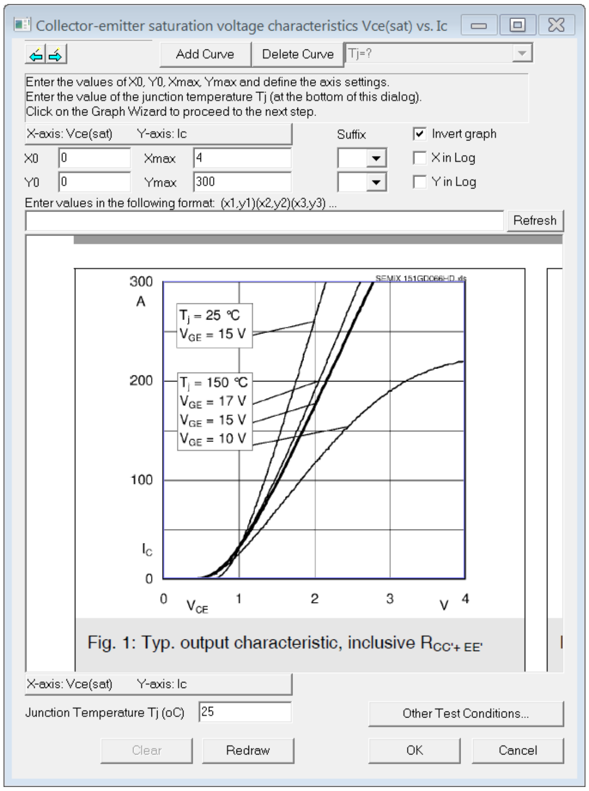
To capture the curve from Fig. 1 of the datasheet, click on the **Edit** button of the “Vce(sat) vs. Ic” characteristics. A window for the Curve Capture Tool will open.

In the dialog window, click on **Add Curve**. We will use the Graph Wizard button  at the upper left corner to capture the 25^{o}C curve. Follow the directions as displayed in the text window. The steps are:

- Display the graph of Fig. 1 on the screen. Click on the Print Screen key (PrtSc) to copy the screen to the clipboard.
- Click on the forward green arrow of the Graph Wizard. The image in the clipboard will be copied into the dialog window, as shown below.

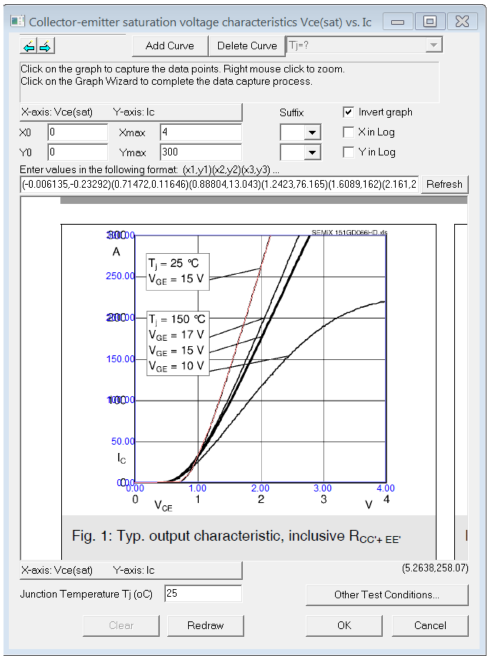


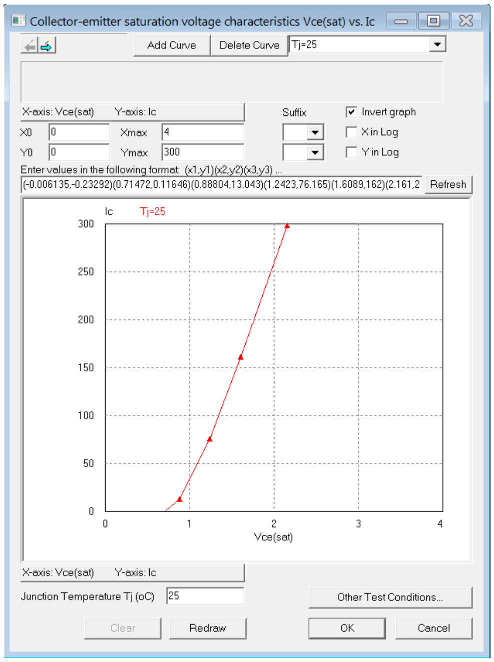
- Position the image properly within the window so that the complete graph is in full view. Click on the forward arrow. Define the border of the graph by left clicking on the graph's origin (lower left corner), and then move the cursor to the opposite corner (upper right corner) and left click. Right click to zoom in for easier cursor placement. After this, a blue frame will be superimposed on top of the original graph frame.
- Click on the forward arrow. Check if the x-axis and y-axis definitions are correct. By default, the x-axis is Ic and the y-axis is Vce(sat). But the x-axis is Vce(sat) and the y-axis is Ic in the datasheet. To match the datasheet, check the box **Invert graph**. Then define the axis settings X0, Xmax, Y0, Ymax. In this case, enter X0=0, Xmax=4, Y0=0, Ymax=300. Enter the junction temperature Tj as 25 for the 25^{o}C curve. The dialog window will look as follows:



- Click on the forward arrow. Starting from the origin, left click on top of the 25^{o}C curve to capture the data point. Right click to zoom in for easier cursor placement. As you click along the curve, a red curve will be drawn indicating the data points captured. The dialog window is shown below on the left.
- Click on the forward arrow. The capture process will be completed, and the captured curve will be shown below on the right.

You can edit the captured values directly in the input field on the left of the Refresh button. For example, you can round off the first two points from (-0.006135,-0.23292) (0.71472,0.11646) to (0,0) (0.71,0.12). But avoid having sudden jump between two points, for example, (0,0) (0.71,0). PSIM uses interpolation between two points. When there is sudden jump, interpolation may not give desired result.

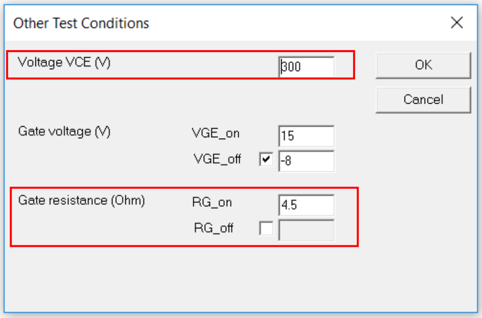




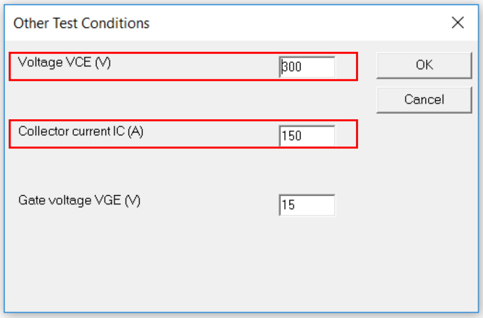
- Repeat the same process to capture the 150 ^oC curve.
- Enter the transistor switching energy losses characteristics **Eon and Eoff vs. Ic** from the curves in Fig. 3 of the datasheet. Use the Graph Wizard and the same process as described above to capture these curves.
- Enter the transistor switching energy losses characteristics **Eon and Eoff vs. RG** from the curves in Fig. 4 of the datasheet. Use the same process to capture these curves.

When entering these curves, be sure to click on **Other Test Conditions** and enter the test conditions as obtained from Fig. 3 and Fig. 4 of the datasheet. The test condition dialogs are shown as follows:

Eon/Eoff vs. Ic



Eon/Eoff vs. RG



While values of the gate voltages are not used in the loss calculation, values of the voltage VCE, collector current Ic, and the gate resistances are used in the calculation. Make sure to enter them correctly.

Step 5. Use PSIM's Curve Capture Tool to enter the diode Electrical Characteristics from the graphs provided in manufacturer's datasheet.

- Enter the diode forward conduction characteristic **Vd vs. IF**.

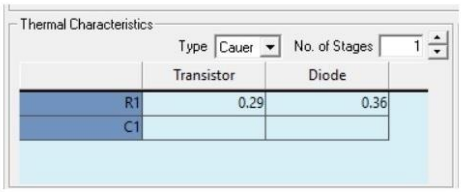
The diode forward conduction characteristics are provided in Fig. 11 in the datasheet. Use the Graph Wizard and the same procedure to capture the curves.

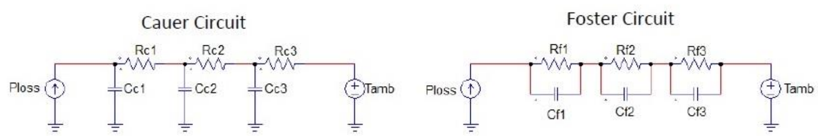
- Enter the diode switching characteristics **trr/Irr/Qrr/Err vs. IF** and **Err vs. RG**:

The diode reverse recovery characteristics trr, Irr, and Qrr vs. the current IF, and Err vs. RG, are not provided in the datasheet. Only the characteristic of the reverse recovery energy Err vs. the current IF is provided in Fig. 3 of the datasheet.

Use the same procedure to capture the curve. The test condition is the same as in Eon vs. Ic.

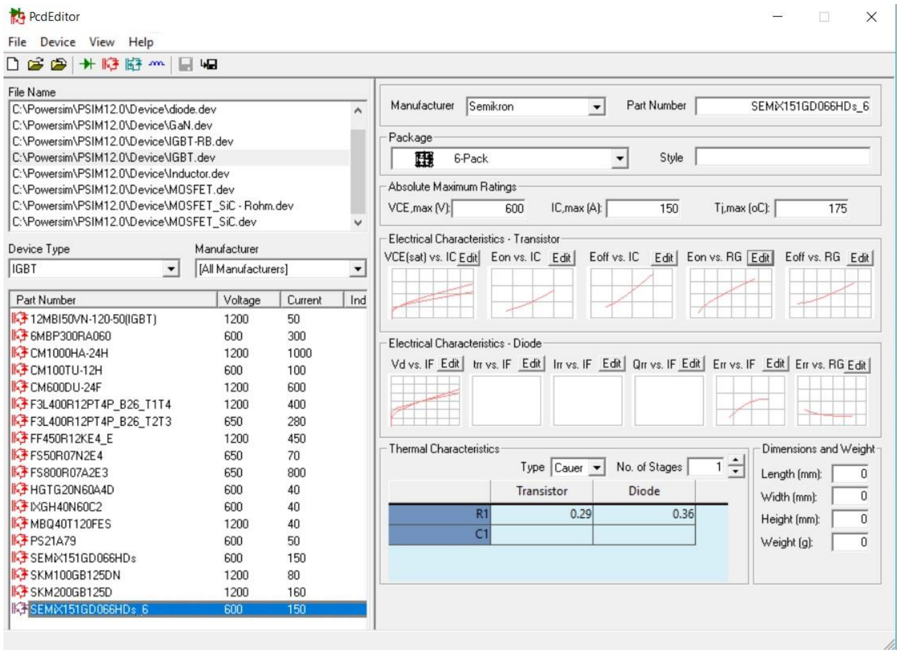
Step 6. Enter the thermal characteristics. Two types of the thermal impedance network are available: Cauer and Froster. For this example, the thermal impedance consists of one resister only, therefore the number of stages is 1 and the values of the capacitor is left empty. The “Tamb” in the circuits below is actually the case temperature. Between case and ambient, there might be a heatsink thermal impedance to be added, as shown in the simulation circuit of the example.





Step 7. Enter the information about dimensions and weight. This information is not used in the calculation, and is for reference only. Entering of the information is optional.

This concludes the entry of the device information into the database SEMiX151GD066HDs_6. The figure below shows the device in the **PcdEditor** after it has been added into the device file “IGBT.dev”.



The newly created database device will be available for next PSIM session. This means, to use the new device in a PSIM schematic, user must exit and re-launch PSIM.

To verify this new device's thermal characteristics, in the example PSIM circuit, replace the IGBT with the newly added SEMiX151GD066HDs_6. The simulation result should be the same with negligible differences.

2. Managing User's Devices in Database

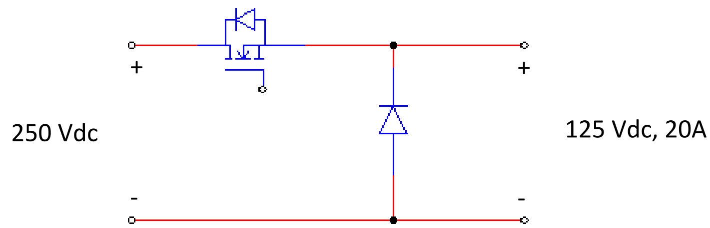
When users add their own devices, they may add these devices into one of the standard device files that come with PSIM. But it is strongly recommended that users save a copy of these devices in their own separate device files. This is because when a PSIM version is updated or upgraded, all the .dev files will be replaced by the files of the newer PSIM version. These user-added devices will be lost. If they are saved to a separate device files, these files can be easily copied to the "device" folder in the newer PSIM version.

To create a user-defined device file "My_Device.dev", and to transfer a device from the "IGBT.dev" file to it:

- In the PcdEditor, click "File >> New Device File". In the correct location (folder), write the file name "My_Device".
- In the PdcEditor, click on the device SEMiX151GD066HDs_6 to highlight it.
- Click on the file "My_Device.dev" in the **File Name** list box to highlight it.
- Select **Device** >> **Save Device As**, and confirm to save the device to "My_Device.dev".

3. MOSFET Loss Calculation

To illustrate how to calculate MOSFET losses with PSIM's Thermal Module, the datasheet of Infineon's MOSFET IRFP460 (500V, 20A) is used in a buck converter example, as shown below:



The buck converter operating conditions are:

DC Input:	250 Vdc
DC Output:	125 Vdc, 20A
Switching Frequency:	20 kHz

3.1 Adding the MOSFET device into the Device Database

Assuming the MOSFET device IRFP460 is not available in PSIM's device database, the first step is to add it into the device database.

Below is the procedure to add this device into the device database file "MOSFET.dev".

Step 1. In PSIM, go to **Utilities** >> **Device Database Editor** to launch the PcdEditor.

Step 2. Highlight the device file "MOSFET.dev" in the **File Name** list box. Select **Device** >> **New MOSFET**, and confirm that you want to save the new device to "MOSFET.dev".

Step 3. Enter the required basic information from the datasheet, such as the part number, package, and maximum ratings.

Step 4. Enter the information for the Electrical Characteristics for the transistor.

Below is a screenshot of the datasheet, with required parameters highlighted in red.

Electrical Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	500	—	—	V	V_{GS}=0V, I_D= 250μA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.63	—	V/°C	Reference to 25°C, I_D= 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	0.27	Ω	V_{GS}=10V, I_D=12A ④
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	V_{DS}=V_{GS}, I_D= 250μA
g_{fs}	Forward Transconductance	13	—	—	S	V_{DS}=50V, I_D=12A ④
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	μA	V_{DS}=500V, V_{GS}=0V
		—	—	250		V_{DS}=400V, V_{GS}=0V, T_J=125°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS}=20V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS}=-20V
Q_g	Total Gate Charge	—	—	210	nC	I_D=20A
Q_{gs}	Gate-to-Source Charge	—	—	29		V_{DS}=400V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	110		V_{GS}=10V See Fig. 6 and 13 ④
$t_{d(on)}$	Turn-On Delay Time	—	18	—	ns	V_{DD}=250V
t_r	Rise Time	—	59	—		I_D=20A
$t_{d(off)}$	Turn-Off Delay Time	—	110	—		R_G=4.3Ω
t_f	Fall Time	—	58	—		R_D=13Ω See Figure 10 ④
L_D	Internal Drain Inductance	—	5.0	—	nH	Between lead, 6 mm (0.25in.) from package and center of die contact
L_S	Internal Source Inductance	—	13	—		
C_{iss}	Input Capacitance	—	4200	—	pF	V_{GS}=0V
C_{oss}	Output Capacitance	—	870	—		V_{DS}= 25V
C_{rss}	Reverse Transfer Capacitance	—	350	—		f=1.0MHz See Figure 5

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Test Conditions
I_S	Continuous Source Current (Body Diode)	—	—	20	A	MOSFET symbol showing the integral reverse p-n junction diode.
I_{SM}	Pulsed Source Current (Body Diode) ①	—	—	80		
V_{SD}	Diode Forward Voltage	—	—	1.8	V	T_J=25°C, I_S=20A, V_{GS}=0V ④
t_{rr}	Reverse Recovery Time	—	570	860	ns	T_J=25°C, I_F=20A
Q_{rr}	Reverse Recovery Charge	—	5.7	8.6	μC	di/dt=100A/μs ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is neglegible (turn-on is dominated by L_S+L_D)				

For the parameter VGS(th), an average value of 3V is selected out of the minimum and maximum values.

Note that the parameter "Temperature Coefficient" of RDS(on) is typically not provided in a datasheet, such as in this case. It needs to be calculated from the graph "Normalized on-resistance vs. temperature" (Fig. 4 for this device), as shown below:

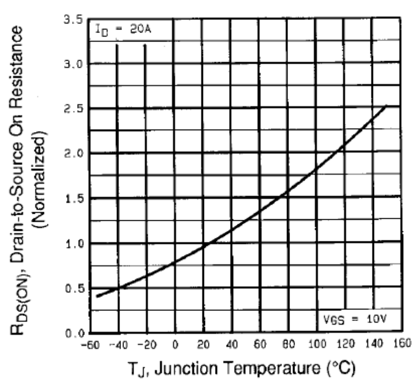


Fig 4. Normalized On-Resistance Vs. Temperature

The temperature coefficient K_T can be calculated using the expression below:

$$K_T = \frac{R_{DS(on)\_normalized} - 1}{T_j - 25}$$

From Fig. 4 of the datasheet, at Tj = 100, we obtain $R_{DS(on)\_normalized}$ = 1.8. We can then calculate K_T as: K_T = 0.01.

The on-resistance RDS(on) is calculated from K_T in the following way:

$$R_{DS(on)} = R_{DS(on)\_25\deg} \cdot (1 + K_T \cdot (T_j - 25))$$

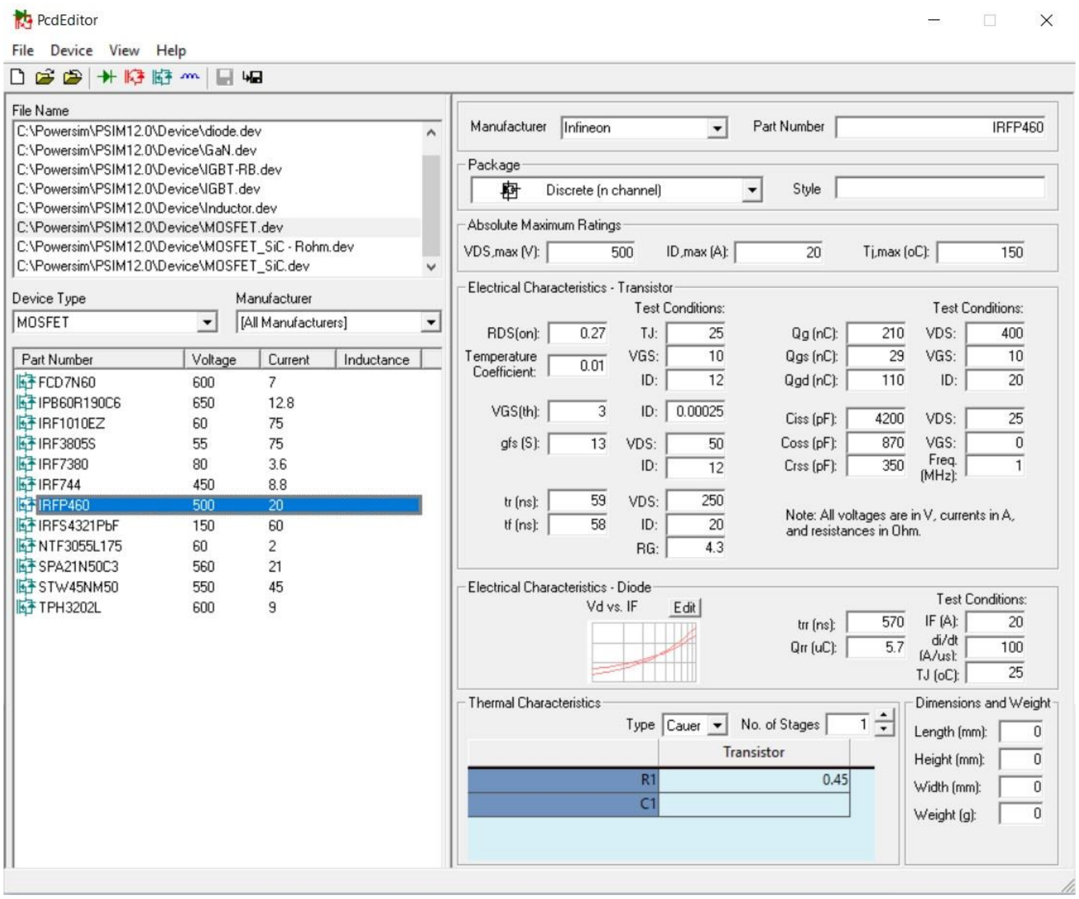
where $R_{DS(on)\_25deg}$ is the on-resistance at 25 °C. In this example, $R_{DS(on)\_25deg}$ = 0.27 Ohm.

Step 5. Enter the Electrical Characteristics for the diode. The **Vd vs IF** curve can be captured as explained in the IGBT section. The test conditions must be entered, too.

Step 6. Enter the Thermal Characteristics, the same way as in the IGBT section.

Step 7. Enter the dimensions and weight, optional.

This concludes the entry of the device information into the database IRFP460. The figure below shows the device in the PcdEditor after it has been added into the device file “MOSFET.dev”.



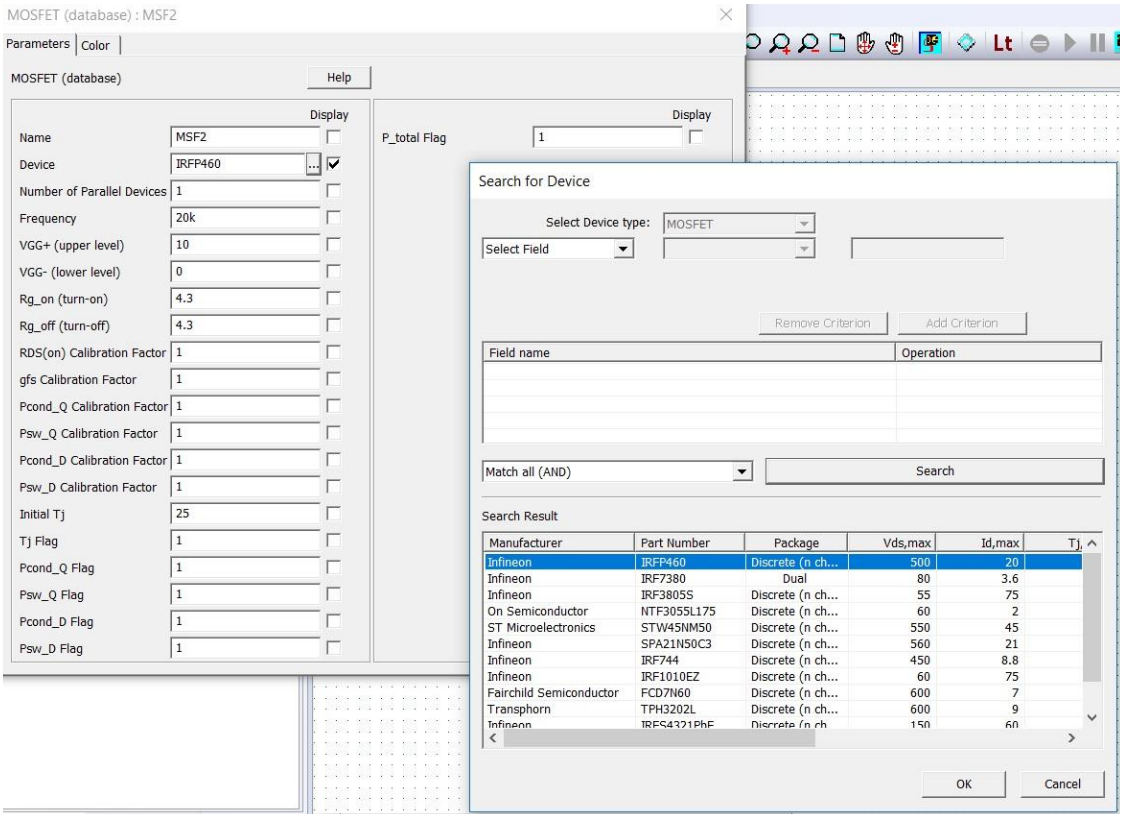
The newly created database device will be available for next PSIM session. This means, to use the new device in a PSIM schematic, user must exit and re-launch PSIM.

3.2 Simulation of MOSFET Losses in PSIM

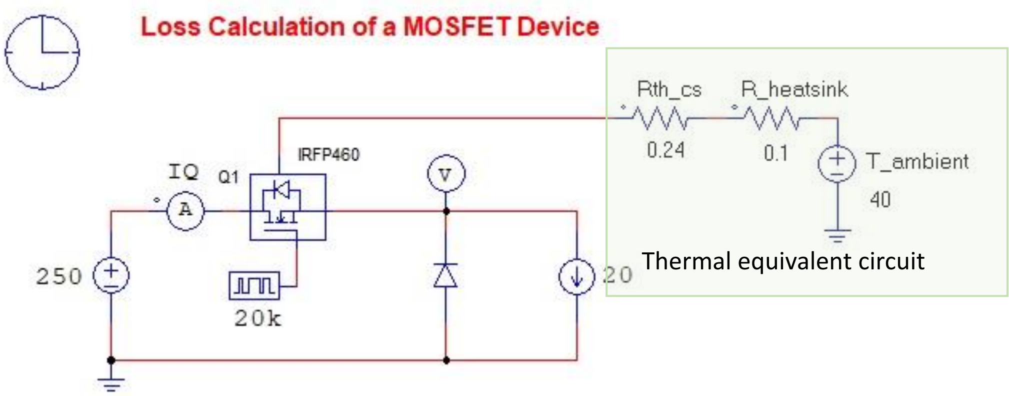
Once the device is added to the device database, it can be used in PSIM for the loss calculation. The newly added device in database should be verified with a simple example circuit before applied to a complex power system.

In PSIM, select **Elements** >> **Power** >> **Thermal Module** >> **MOSFET (database)**.

Place the discrete MOSFET element on the schematic. Double click on the MOSFET element to open the property dialog window. Click on the Browser button next to the "Device" input field, and choose the device "IRFP460". Continue to build the rest of the circuit.



The circuit below shows the completed buck converter circuit using the MOSFET IRFP460.



The MOSFET device (database has an one extra nodes on the top. This node is for the monitoring of the device's thermal effects:

- The voltage at this node is the module's case temperature, can be monitored with a Voltmeter.
- The current flowing out of this node is the total power losses of the whole module (all 6 devices), can be monitored with an Ammeter.

This node should be connected to a voltage source representing the ambient temperature or grounded via a network representing the dynamic thermal impedance between the case of the module and the ambient. In this example, the resistor Rth_cs is the thermal resistances between the case and heat sink, and R_heatsing is the thermal resistance of the heatsink.

The parameters of the MOSFET (database) are defined as below:

The parameter **Frequency** defines the interval under which the losses are calculated. In this example, it is set to be the same as the switching frequency, and the losses in each switching cycle are obtained.

The values **VGG+** and **VGG-** are the upper level and lower level of the gate voltage source.

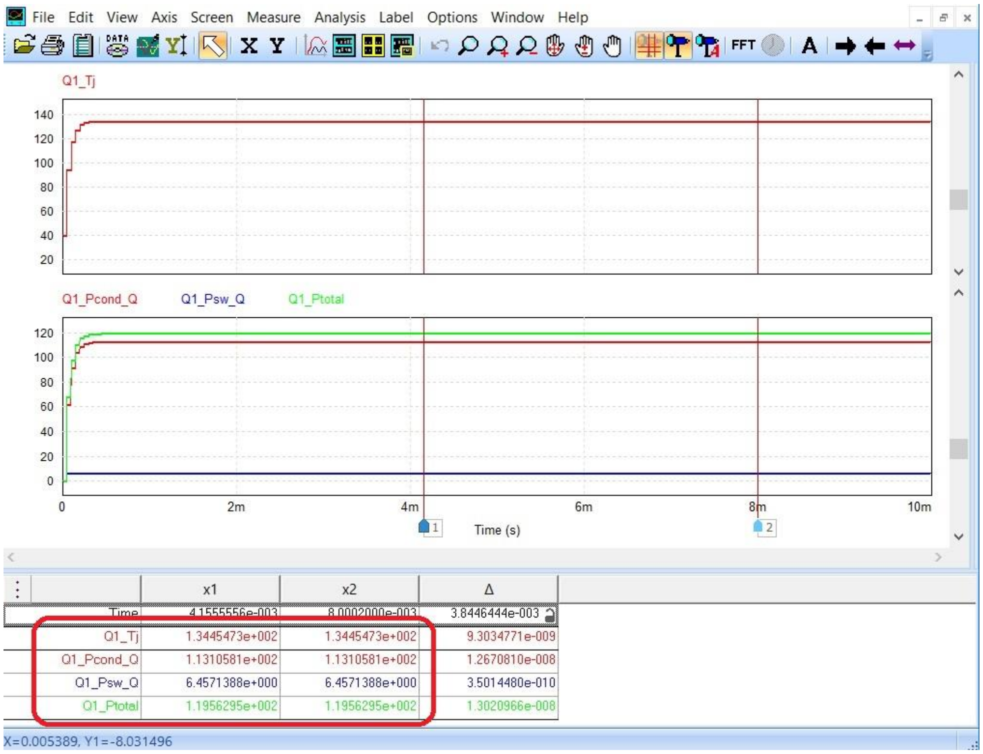
The values **Rg_on** and **Rg_off** are the gate resistances at turn-on and turn-off. They must be defined correctly to reflect the actual operating conditions. If they are not defined correctly (for example, if the gate voltage source is too low, or the load current or the gate resistance is too high), the MOSFET device may not work correctly.

The **Calibration Factors** are used to scale the calculation results against experimental results.

If the ***Flags*** are for the monitoring of the device's thermal behaviour. When the flags are set, the following thermal related characteristics can be monitored:

- transistor junction temperature Tj, in ^{o}C.
- transistor conduction loss Pcond_Q,
- transistor switching loss Psw_Q,
- diode conduction loss Pcond_D, and
- diode switching loss Psw_D.

The simulation result displayed in SimView is as below:



The following losses results are obtained from the PSIM simulation:

MOSFET Junction Temperature (^{o}C):	134.5
Transistor Conduction Loss (W):	113.1
Transistor Switching Loss (W):	6.5
Transistor Total Loss (W):	119.6

The losses of the diode is zero because there is no reverse conduction in this example circuit.

4. Conclusion

PSIM’s Thermal Module provides a quick and convenient way of estimating device conduction and switching losses. One can use the Thermal Module to study device losses under different operating conditions, and compare devices from different manufacturers.

In addition, the Device Database Editor (PcdEditor) provides an easy way to add new devices and manage devices. It also provides an easy-to-use curve capture tool that allow multiple datasheet curves to be entered into the database in minutes.