

Using PSpice Simulator to Model Thermal Behavior in TI's Smart High-Side Switches



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ABSTRACT

Thermal shutdown is a protection feature in TI's *Smart High-Side Switches* that turns off the switch when the main MOSFET reaches a set temperature. This feature protects the switch by limiting the temperature the junction can reach and clamping current or turning off current to the load before any damage to the switch can occur. While useful for protection, thermal shutdown may prevent the turn on of more demanding loads, such as large capacitors or automotive bulbs. This application note covers how junction temperature can be modeled for TI's *Smart High-Side Switches* using the PSpice electrical simulation tool and how to leverage this information to see what loads each high-side switch can drive without interruption from thermal shutdown.

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1 Background

Before examining how to simulate various loading conditions using the thermal PSpice models provided by Texas Instruments, it is important to know the capabilities and limitations of the model. Models with thermal modeling capabilities can provide a power insight on how the device will behave under various ambient and loading conditions; however, in real world applications various factors such as layout and solder coverage will affect the thermal performance of a high-side switch. All high-side switches are designed to perform optimally when using the JEDEC 51-7 board layout standard and the supported thermal models have been made to most closely match the JEDEC standard. When designing a schematic and engineering the board layout, it is important to follow data sheet recommendations to ensure that the thermal performance of the real world device on the PCB will closely match that of the board itself. It is also important to note that currently only a subset of PSpice models published on ti.com currently have thermal modeling capabilities. Refer to [Section 2.3](#) for determining if a published model has the appropriate ambient temperature parameters for modeling thermal behavior.

1.1 High-Side Switch

TI's *Smart High-Side Switches* [HSS] provide reliable off-board load protection by utilizing three main protective features: current sensing, current limiting, and thermal shutdown. As a result of these features, the HSS monitors output current and limits it to a specified value to allow for optimal design for specific capacitive, inductive, or LED loads. This output current can be clamped at either an internal current limit inherent to the device, or a lower current limit, controlled by an external resistor. If the device approaches a certain thermal threshold, the device will shut off, cool down, and auto restart once the temperature has decreased significantly.

With the selection of a HSS, the thermal behavior of the HSS is a factor that should be taken into account. At the core of the thermal protection is the thermal shutdown limit, a specified temperature within the data sheet of the device. When the internal junction temperature of the device reaches the thermal shutdown limit, the device will enter thermal shutdown to protection off-board loads. Devices with a thermal pin [THER] allow for control over the thermal shutdown behavior while devices without the THER pin will either shutdown or reduce the output current limit. The configuration and behavior of the devices with THER pins to enable latching, shutdown, or are found in [Fault and Normal Diagnostic Considerations for Smart High Side Switches](#).

TI's high-side switches that have thermal modeling implemented will model the behavior of the device when it enters thermal shutdown and provide a look into how the internal junction temperature changes with operation. This takes out all the math calculations needed and puts it in a convenient package to use and model device behavior.

1.2 Thermal Modeling Using Electrical Analysis

To determine whether a *High-Side Switch* will hit thermal shutdown, two methods are currently used. A user can experimentally test a use case in the lab or worst-case junction temperature, T_J , can be calculated using [Equation 1](#). The previous method requires the customer to already have the device on hand. In addition, this method does not tell the customer what the temperature of the device is at any time, only whether or not the device will hit thermal shutdown. The downside of calculating worst-case temperature is that this method could generate an overly pessimistic junction temperature, resulting in overdesigning the system.

The steps that lead to calculating the junction temperature, T_J , begins with the worst-case power dissipation of the device. This requires the operating output current of the device, I_{OUT} , and maximum on-resistance, $R_{DS(on)}$ (found in the *Electrical Characteristics* section of the data sheet of the device and denoted by the $T = 150^\circ\text{C}$ test condition). Once the power dissipated, P_{DISS} , in the switch is calculated, junction temperature, T_J is calculated as a function of the power dissipation, P_{DISS} , the ambient temperature, T_A , of the surrounding environment, and the junction-to-ambient thermal resistance, $R_{\theta JA}$, located in the thermal information section of the data sheet.

$$P_{DISS} = I_{OUT}^2 R_{DS(on)_MAX}$$

$$T_J = T_A + R_{\theta JA} P_{DISS} \quad (1)$$

As an alternate, more accurate method, this document uses the electrical simulation software, PSpice, to model the thermal behavior of the high-side switch.

Ohm's law defines the relationship where voltage, V , is equal to the product of current, I , and resistance, R . The power law explains that power, P , is equal to the product of voltage, V , and current, I .

$$\begin{aligned} V &= IR \\ P &= VI \end{aligned} \tag{2}$$

These laws can be used as an analogy for the transient thermal behavior in high-side switches. Equation 2 can be equivalently evaluated as resistance, R , is equal to the division of voltage, V , and current, I . Since thermal resistance, R_{TH} , is measured in units of degrees Celsius, $^{\circ}\text{C}$, per watt, W , this relationship can be equivalently evaluated as temperature in Celsius equals the product of thermal resistance and power in watts as shown in Equation 3.

$$^{\circ}\text{C} = W \times R_{TH} \tag{3}$$

Seeing that voltage and temperature are both similarly proportional to a variable representing impedance or resistance, these two equations help in incorporating heat circuits' theory and a model can be created. The model utilizes the analogy between thermal and electrical units in a one-to-one relationship, as described in Table 1-1.

Table 1-1. Electrical to Thermal Analogy

Thermal	Electrical
Power (W)	Current (A)
Ambient Temperature ($^{\circ}\text{C}$)	DC Voltage (V)
Junction Temperature ($^{\circ}\text{C}$)	AC Voltage (V)
Thermal Resistance ($^{\circ}\text{C}/W$)	Resistance ($V/A = \Omega$)
Thermal Capacitance	Capacitance (F)

In a thermal environment two inputs are apparent: power, P_{DISS} , and ambient temperature, T_A , creating one output: junction temperature, T_J . To translate this equation to electrical tools, the ambient temperature would be represented as a DC voltage source on the switch, and the power as an input current waveform to the switch, with temperature variation in the junction be represented by an RC ladder or network.

In an electrical environment, the thermal behavior is represented as an RC ladder as shown in Figure 1-1.

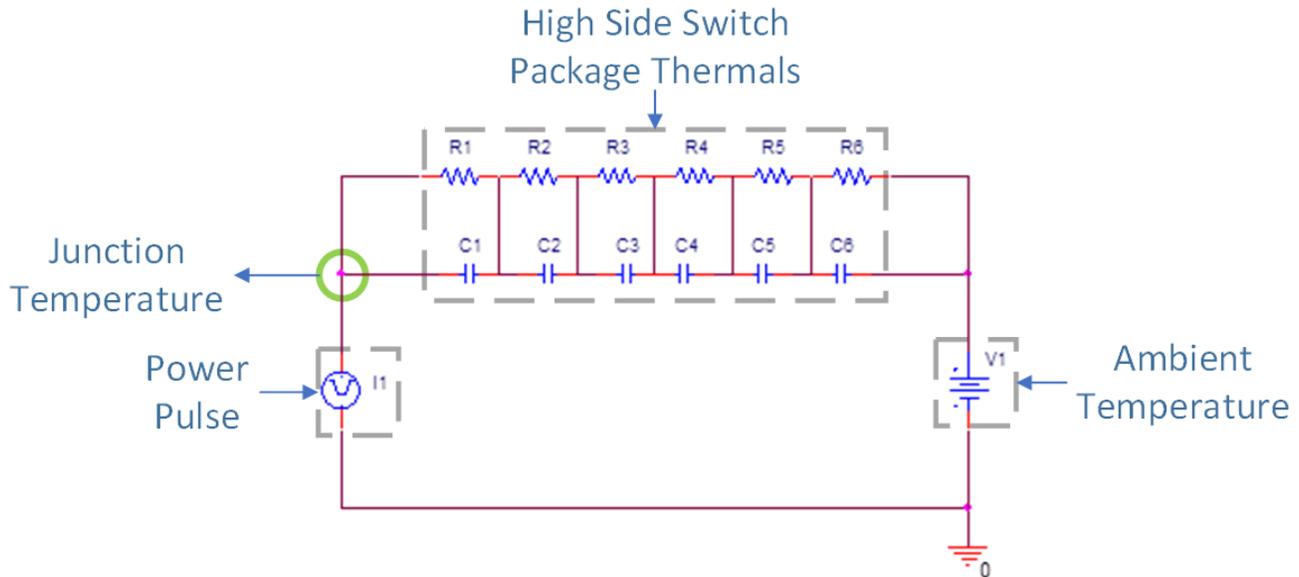


Figure 1-1. Electrical Representation of Thermal Environment

In this setup, thermal units are converted to electrical units as described in Table 1-1. The input power pulse is converted to a current source, the input ambient temperature is converted to a voltage source, and the high-side switch is converted to an RC representation of the thermals characteristics of the switch. These RC values are selected so that the resistances add up to $R_{\theta JA}$ and the capacitances represent the different paths heat will travel within the package.

1.3 Varying $R_{DS(on)}$

The on-resistance, $R_{DS(on)}$, is the inherent resistance of the High-Side Switch device. This value depends on the temperature of the device, as well as whether the switch is in the saturation or linear region. Since $R_{DS(on)}$ is a factor in calculating an accurate power pulse and calculating the junction temperature relies heavily on inputting an accurate power pulse, varying $R_{DS(on)}$ as it varies due to temperature is an important factor to consider. The power dissipated by the switch, P_{DISS} , can be calculated as the product of the current through the switch, I_{DS} , and the voltage across the switch, V_{DS} .

$$P_{DISS} = I_{DS} \times V_{DS} \quad (4)$$

However, in the linear region it is easier to calculate the power dissipated by the switch, P_{DISS} , as the product of the squared current through the switch, I_{DS} , and the on-resistance of the switch, $R_{DS(on)}$.

$$P_{DISS} = I_{DS}^2 \times R_{DS(on)} \quad (5)$$

R_{DSON} varies as a function of temperature, as Figure 1-2 from the TPS1H100 data sheet shows in the *Typical Characteristics* plot of R_{DSON} .

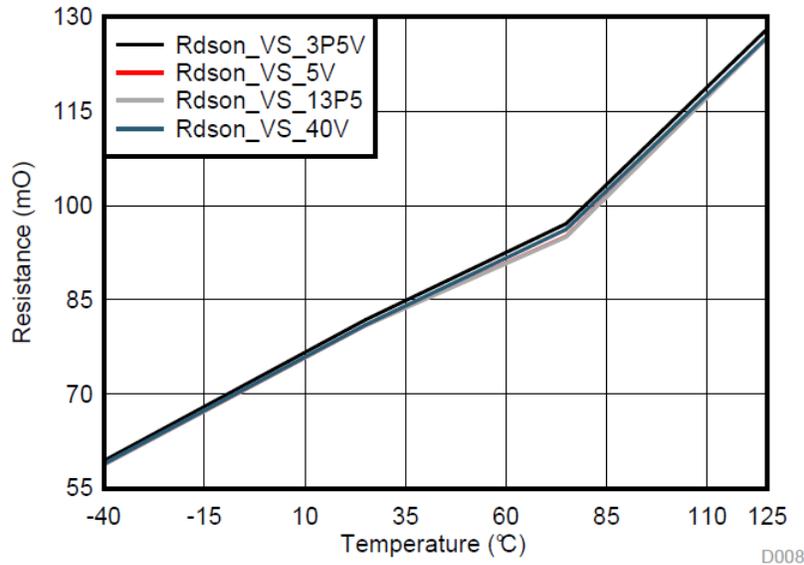


Figure 1-2. Characteristic Plot of R_{DSON} of TPS1H100

To account for this change in temperature, the PSpice model must recursively take into account the maximum temperature, and then recalculate using the corresponding R_{DSON} for that temperature. Since the R_{DSON} decreases for decreasing temperature, the R_{DSON} will eventually converge onto a realistic R_{DSON} value instead of the worst-case R_{DSON} in the data sheet. The equation of the plot can be approximated as a line as Equation 6 shows.

$$R_{DSON} = mT_J + b \tag{6}$$

Where m is the slope of the line and b is the value of R_{DSON} at 0°C . To account for this change in R_{DSON} , the PSpice thermal model recursively measures the simulated junction temperature. First, the model inputs the worst-case R_{DSON} , located in the electrical characteristics section of the high-side switch data sheet. After this initial junction temperature value is calculated, the model iterates until the temperature and R_{DSON} converges. Figure 1-3 illustrates this behavior.

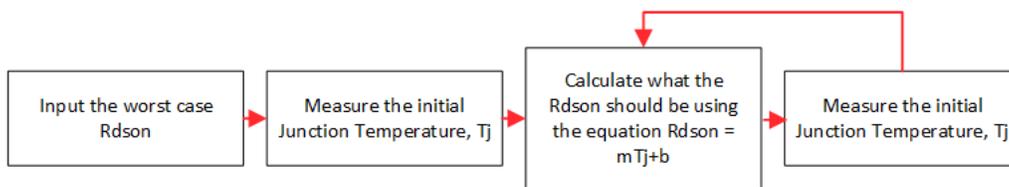


Figure 1-3. Block Diagram of Model

With the implementation of the thermal behavior implemented within the PSpice model, the recursive calculation is automatically taken care of in the software.

2 Using TI's SPICE Models With Incorporated Thermal Behavior

Some models may already have the thermal behavior incorporated and can be found as the transient model under the *Design and Development* section of a product folder. When opening the file in PSpice, a schematic such as the one in Figure 2-1 is available. The junction temperature of the device has been added as a pin on the device and labeled as “TJ”. It is important to remember that this pin is not physically on the device and is used for ease and simulation purposes. Figure 2-1 shows this implementation.

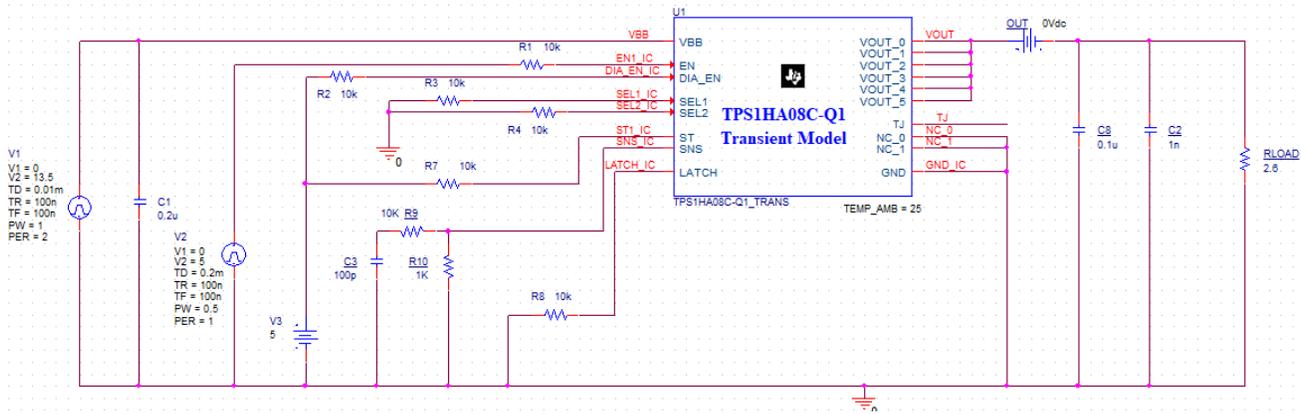


Figure 2-1. TPS1HA08C-Q1 Transient Model With Thermal Behavior

Within the schematic, it is possible to modify schematic in ways such as modifying the supply power, V1, controlling the enable time using V2 power supply, and add the characteristics to the load that the device will be powering.

To accurately model operating conditions, the ambient temperature can be modified by editing the “TEMP_AMB” property that has been added. This property refers to the ambient temperature or surrounding temperature that the device will be operating in.

2.1 Basics of PSpice - Modifying Components

Within the schematic, is it possible to modify schematic in ways such as modifying the supply power, V1, controlling the enable time using V2 power supply, and add the characteristics to the load that the device will be powering.

To accurately model operating conditions, the ambient temperature can be modified by editing the “TEMP_AMB” property that has been added. This property refers to the ambient temperature or surrounding temperature that the device will be operating in.

To modify parts already on the schematic, double clicking the part and modifying the property or double clicking on the parameter to be changed and modify the value as shown in [Figure 2-2](#).

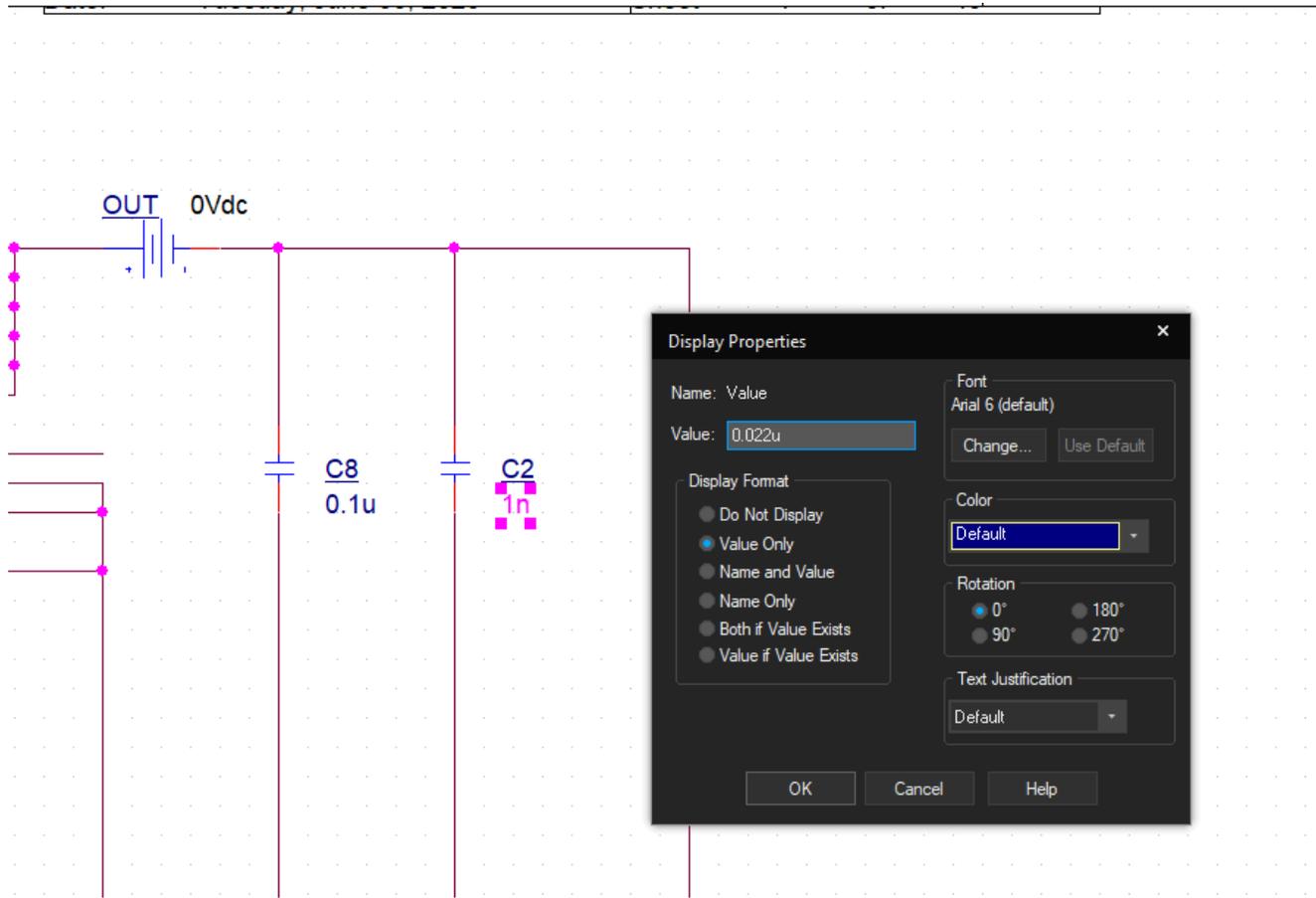


Figure 2-2. Changing Value of Capacitor in PSpice

2.2 Basics of PSpice - Adding Libraries and Components

Libraries in PSpice will make different components available to add them in the schematic. These libraries need to be added to gain access to components such as resistors, comparators, or power sources. [Figure 2-3](#) shows how libraries are found in the 'Place Part' window.

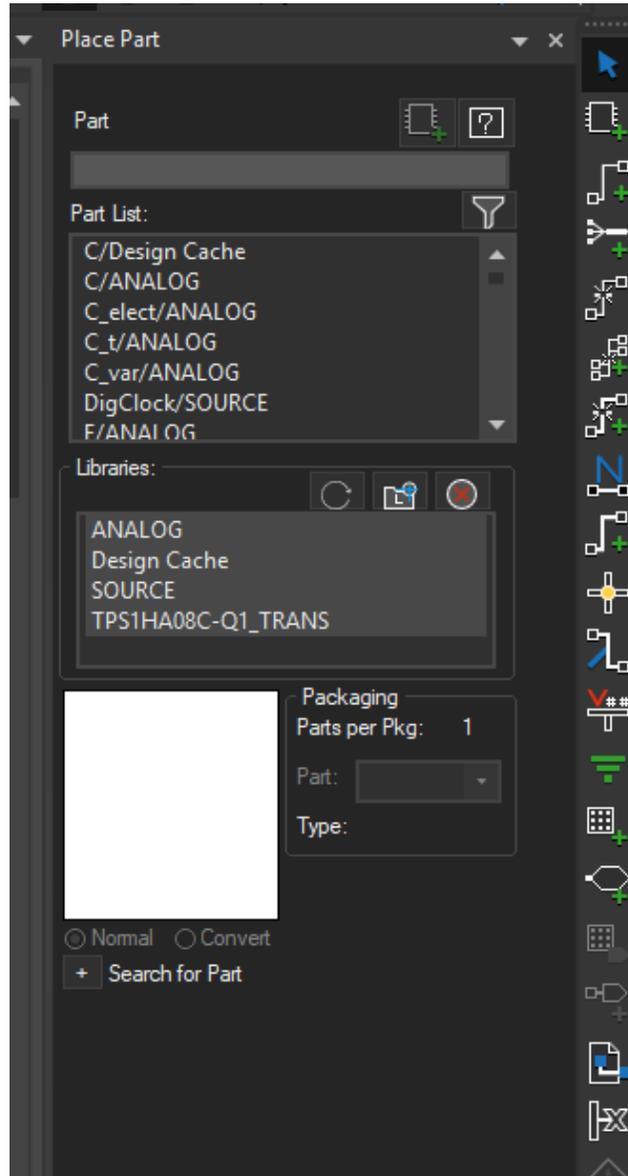


Figure 2-3. 'Place Part' Icon in PSpice

To add a component from the library, selecting the part list will expand to show the components within the library. From there, a component can be added. [Figure 2-4](#) shows an example of selecting a resistor from the ANALOG library.

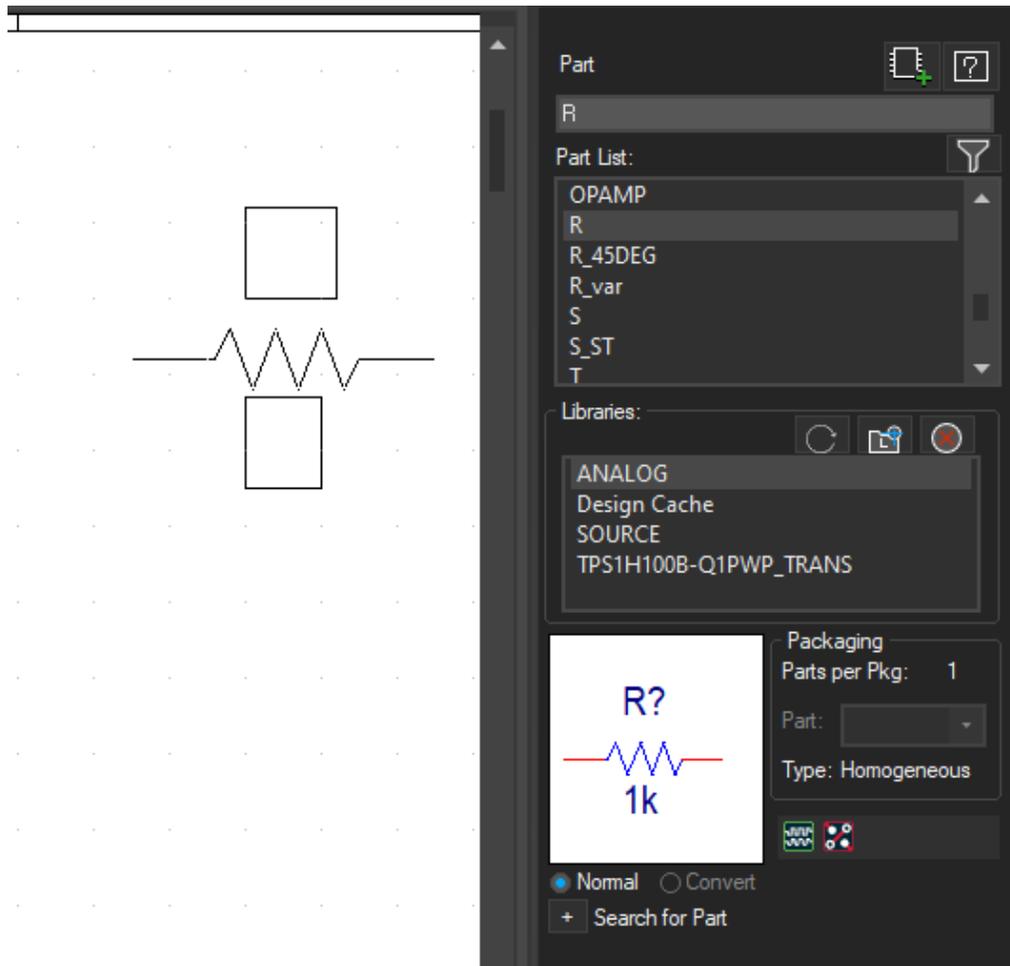


Figure 2-4. Selecting Resistor Within ANALOG Library in PSpice Simulator

2.3 Basics of PSpice - Running Simulations

Once the schematic and operation of the device is correct based on desired behavior and load, the simulation can be run. Before running the default simulation profile, ensure that the simulation profile is configured correctly.

The simulation profile can be edited by selecting *Edit Simulation Profile* in the drop-down menu that appears when selecting *PSPICE* on the main toolbar. A window such as the one shown in [Figure 2-5](#) appears.

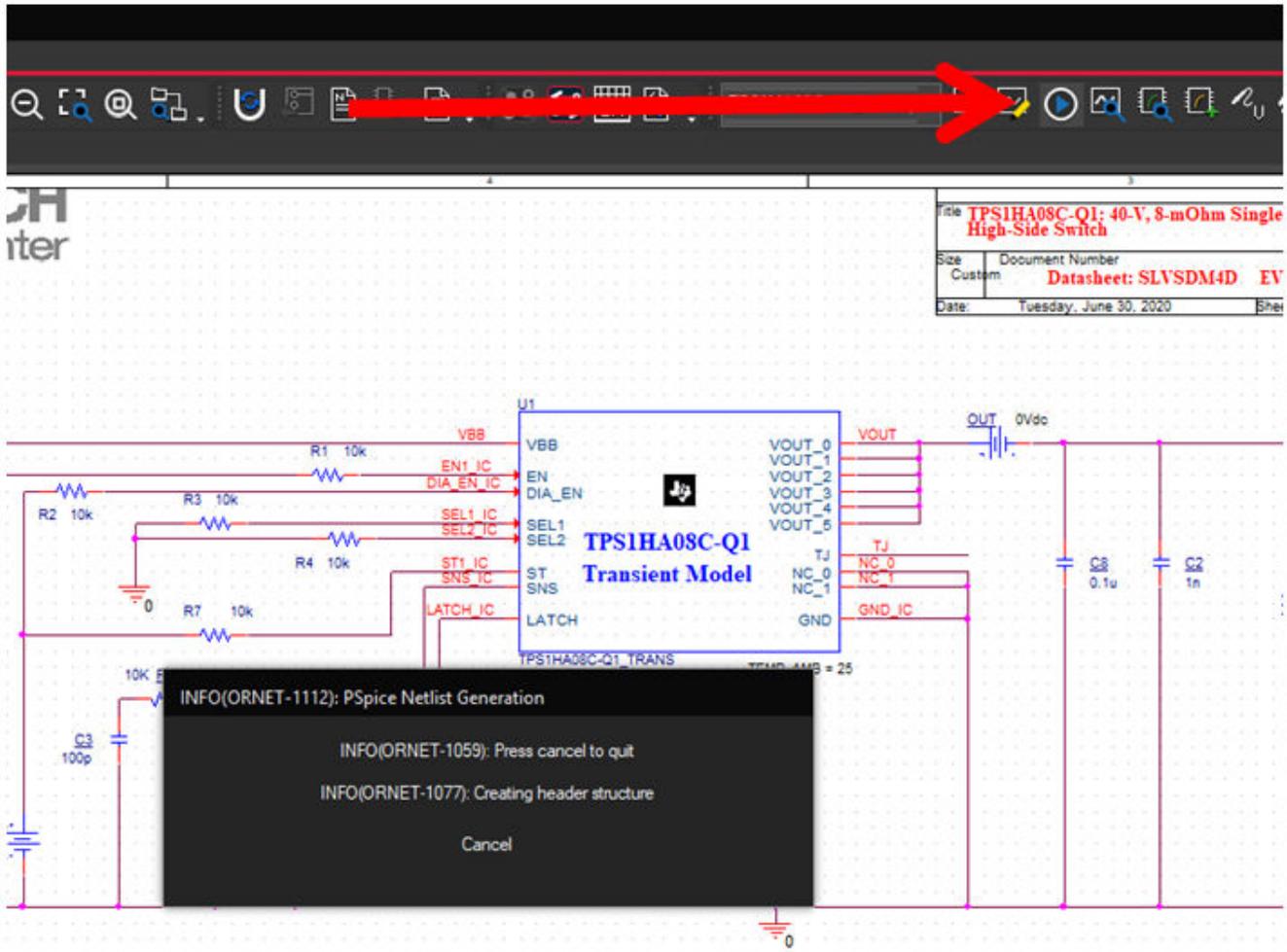


Figure 2-5. Running a Simulation in PSpice

Once the appropriate settings have been configured, select the *OK* button. Running the simulation is done by selecting the *RUN* button on the main bar or clicking the *F5* key.

3 Simulating the Junction Temperature in PSpice

With PSpice and TI's HSS models, devices that have the thermal behavior implemented will follow the calculations in the [Background](#) section. Once the schematic and operation of the device is ready to be simulated, the simulation profile should be configured with at least the settings shown in [Table 3-1](#):

Table 3-1. Settings Recommended for Thermal Behavior Simulations

Analysis Type	Time Domain (Transient)
Start Saving Data After	0 (if not a long scale) 1E-9 (if a log scale is desired)

The simulation, if successful, will export its results and open in PSpice simulator.

The junction temperature will need to be added as a plot to get a full picture of the thermal behavior over time. To do this, add a plot which can be found in **Trace > Add Trace > V(J)**. An example is shown in [Figure 3-1](#):

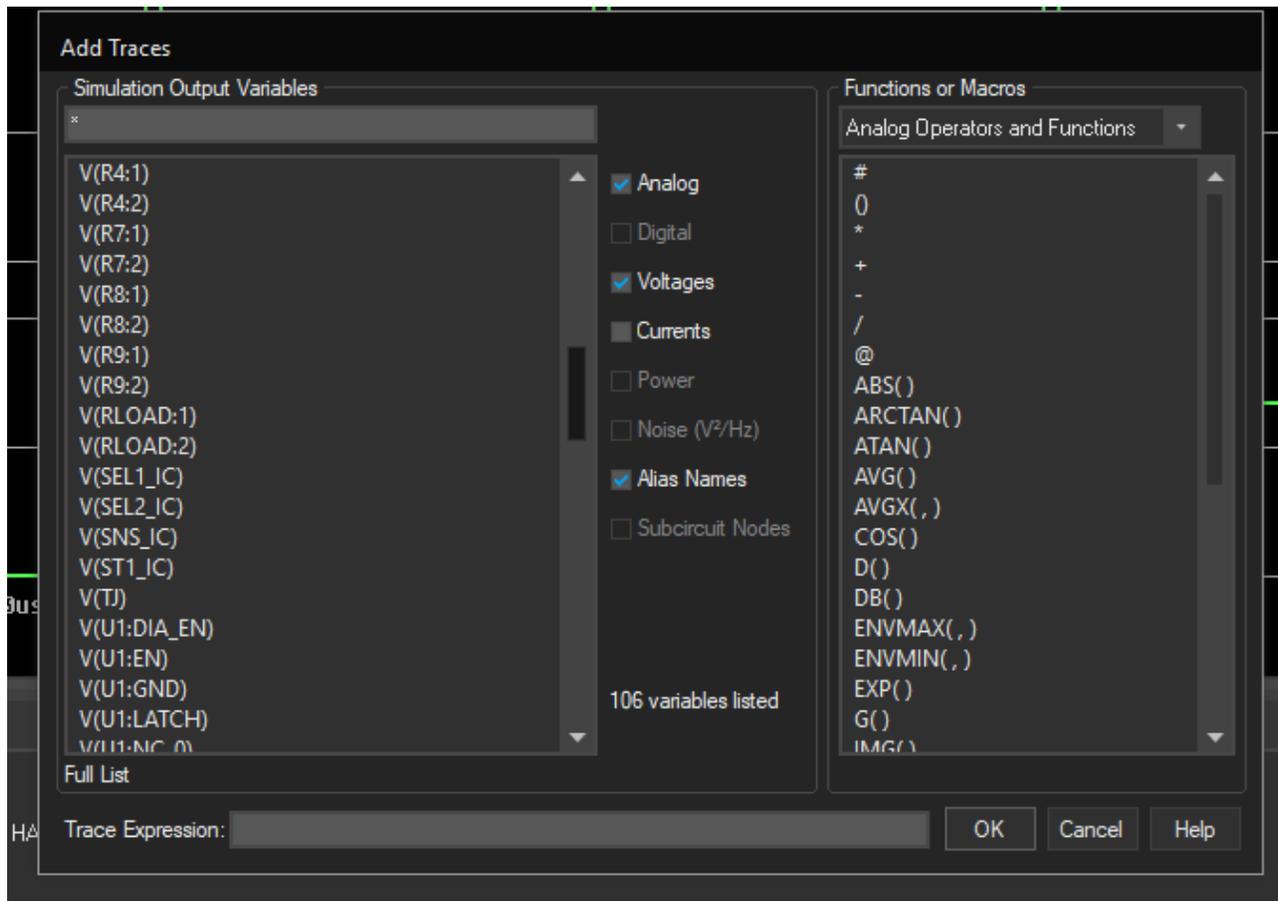


Figure 3-1. Adding Junction Temperature Plot in PSpice Simulator

This will plot the junction temperature of the device as a plot trace in units of V having a 1:1 conversion to C (25 V is equal to 25°C). [Figure 3-2](#) shows an example of the plot.

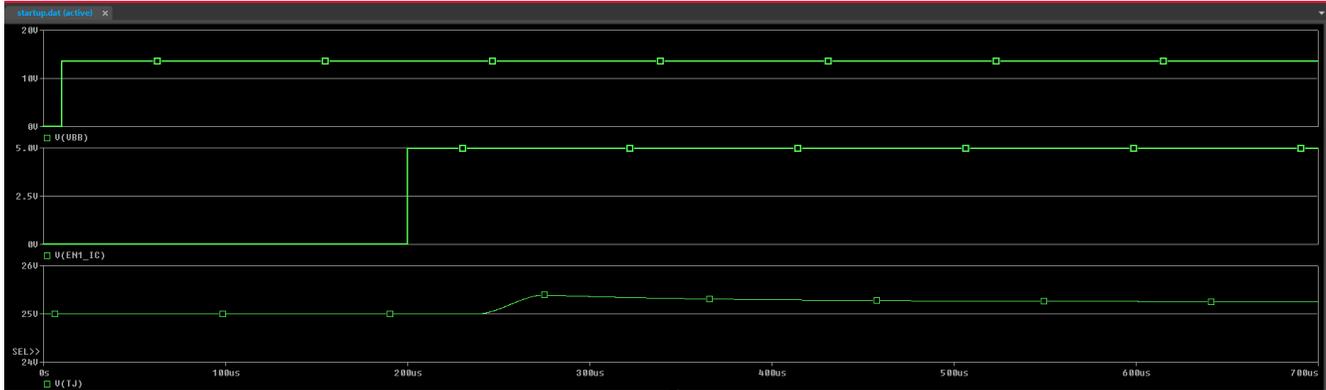


Figure 3-2. Showing Junction Temperature Plot in PSpice Simulation Results

4 How to Leverage Thermal Simulations

The main benefit of having the simulation is to identify whether or not the HSS will enter thermal shutdown where it can shutoff or reduce the current that is being provided to off-board loads. Typically this is done when designing for an application where there is a significant amount of capacitance on the load.

Figure 4-1 shows an example where the TPS1H100B-Q1 enters thermal shutdown as it is modeled in PSpice.

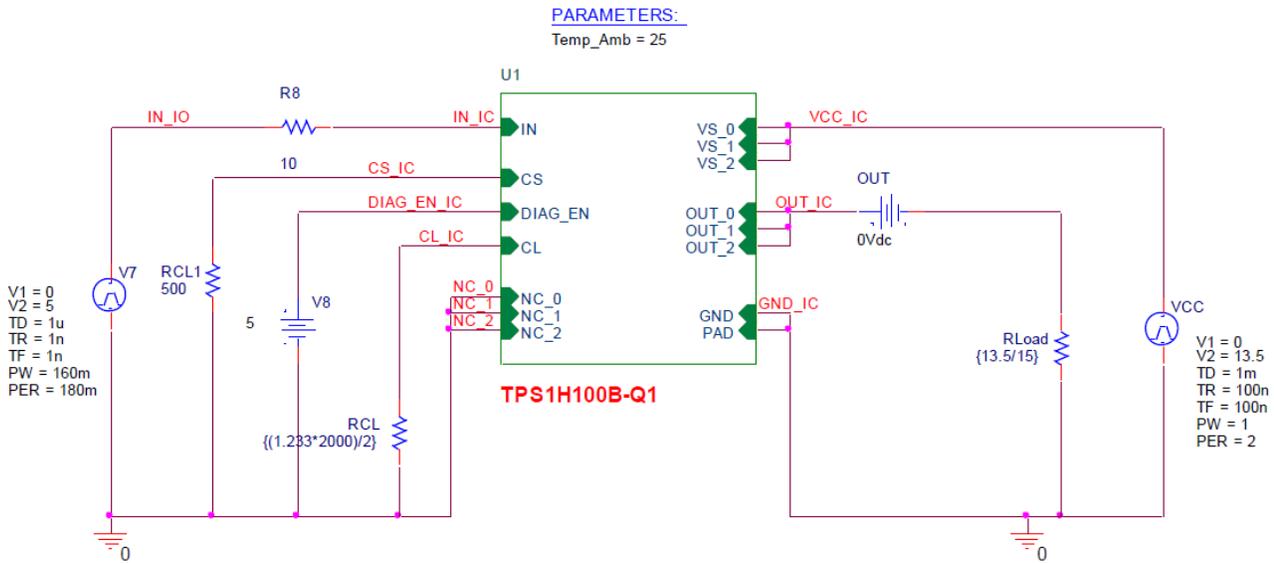


Figure 4-1. Schematic Setup for TPS1H100B-Q1 Simulation With 15- A Load

Figure 4-2 illustrates the simulation results that show the thermal fault:

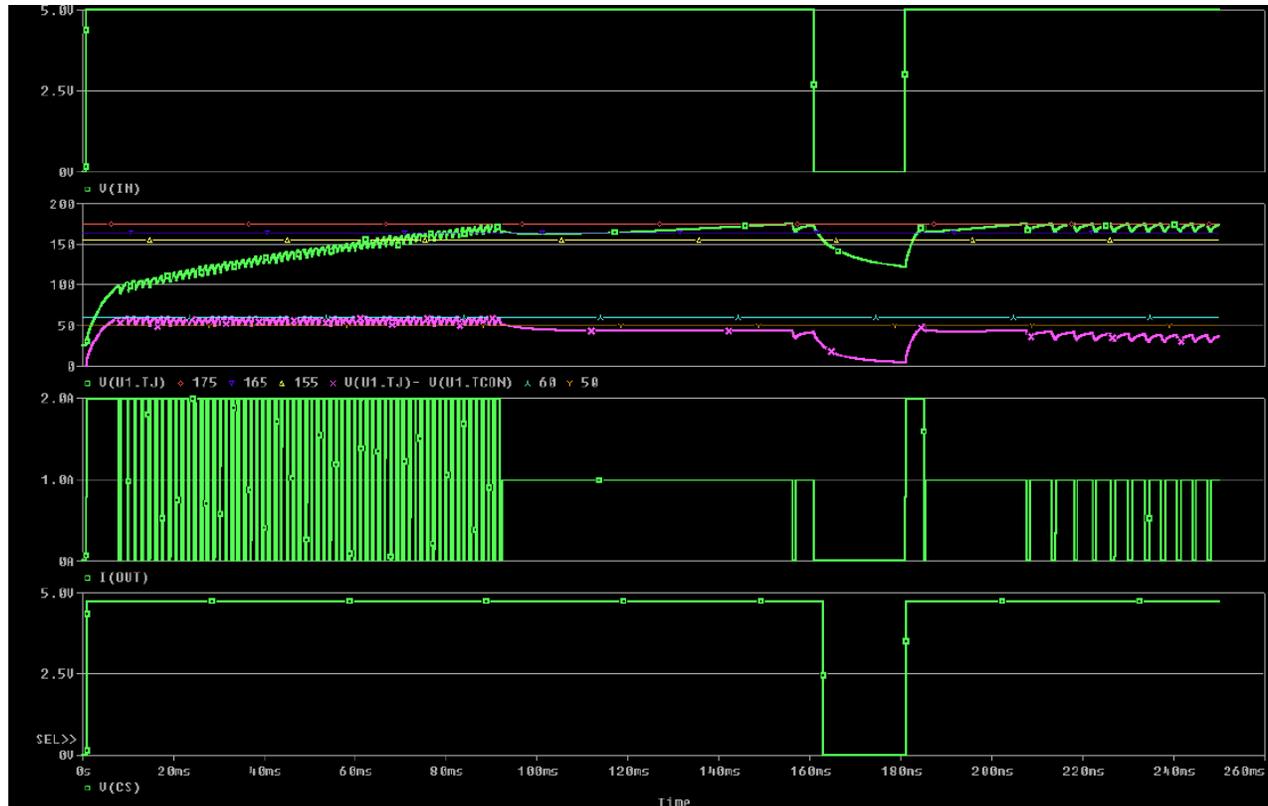


Figure 4-2. Results for TPS1H100B-Q1 Simulation With 15-A Load

This shows that even though the device will limit the current to 2 A, the device will enter thermal shutdown as the load attempts to continuously pull the current to 15 A. The simulation also shows approximately how long it takes for the TPS1H100B to enter thermal swing shutdown in the purple waveform. Thermal swing shutdown occurs when the junction temperature and controller temperature within the device exceeds a temperature difference of 50°C, causing the device to shut down until the difference is below the threshold. The similar green waveform shows the junction temperature and when this waveform exceeds 175°C, the device reduces the output current limit to 1 A, a feature known as current limit fold-back that is used to cool the device. Once both of these temperature thresholds are no longer exceeded, the device outputs a current of 2 A temporarily before going back into thermal shutdown.

With the thermal modeling simulation from PSpice, the TPS1H100B device is shown to not handle the 15-A load even with a current limit and a different device should be used for this application.

5 Model Limitations

The RC values representing the thermals of the package are based off calculations assuming JEDEC board, which refers to nominal silicon with a JEDEC standard board. For better adherence to the thermals of your package, new RC networks must be made to reflect your package thermals. For information on PCB layout and when to expect thermal shutdown for each device, reference the *Layout Guidelines* section of the data sheet for the desired high-side switch. These models are intended as a reference and should be interpreted with these limitations in mind.

6 Conclusion

It is important to know how your device will act thermally so that efforts can be made to select the right device for your application. High-side switch devices offer many load protection features, among them, thermal shutdown. Although, thermal shutdown can affect whether or not a load can be driven using a high side switch device, this protection feature can be better understood and accounted for using the available PSpice models located on TI.com.

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