THERMAL DESIGN

Estimate die-junction temp in power ICs

By David Divins
Senior Applications Engineer
International Rectifier
E-mail: ddivins1@irf.com

Among the greatest challenges in designing today's power-consuming products is managing the system's thermal budget. Since most electronic equipment include some form of power conversion, it is necessary to understand the design's thermal constraints, which form the context for many design decisions.

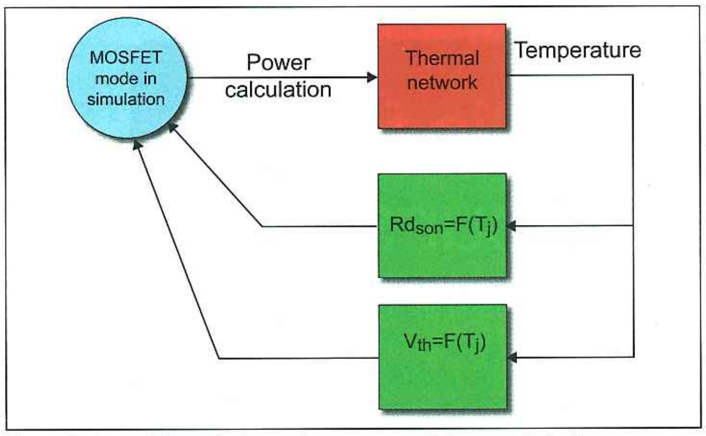

Figure 1: A quasidynamic thermal wrapper model accounts for the power device's parametric dependence on temperature.

Design engineers make a number of trade-offs to mitigate thermal problems: power-conversion topology, switching frequency, semiconductor packaging, IC type, heat sinking, the conversion circuit's location, circuit-board material and cost. There are also questions regarding the need for forced-air convection or, for high power-density applications, liquid cooling. From this list of options and constraints, temperature estimates are necessary to determine the impact of the various choices in finalizing the design.

In most power-conversion circuits, the hottest elements are the power ICs—diodes, MOSFETs and IGBTs. For a given circuit topology, these components heat up as functions of applied voltage, load current, switching frequency, gate-drive circuit, package type and mounting. Of these, the first four dissipate power and model as thermal sources, while the last two models as thermal sinks because they remove heat from the system.

A good first-order estimate of power dissipation in switch-mode circuits is P = DVI, where I is the average conduction-cycle current through the power IC, V is the average conduction-cycle voltage across the device, and D is the duty cycle.

In physical circuits, current is a function of circuit operation. Voltage is a function of current, the device type, junction temperature and IC control method. For example, the forward voltage across a diode is simply a function of current and temperature. The voltage across a MOSFET in the on state is $I_D R_{DS(on)}$—the product of drain current and channel resistance. $R_{DS(on)}$, in turn, is a function of I_D, gate drive and temperature. The voltage across an IGBT in the on state, V=VCE(sat), is a function of current, gate drive and temperature.

To determine the IC's temperature rise, multiply the power dissipation by the thermal impedance. The limitation with this analysis is that it oversimplifies the power calculation and does not account for transient conditions. The power device's data sheet provides thermal response curves, however, with which you can overcome that limitation.

The curves assume a rectangular power pulse of amplitude P for duration *t* with duty cycle D. Follow the curve appropriate to your circuit's duty cycle to the point along the horizontal axis corresponding to the pulse duration. Read the corresponding thermal response from the vertical axis and multiply that value by the power dissipation to arrive at the temperature rise from case to junction.

The thermal response curves only address the case-to-junction temperature rise. They cannot account for the case's mounting method, which contributes to its rise above ambient as a complete thermal-stack model indicates.

Circuit simulation

Rather than approach the problem piece-by-piece, using different tools and data sources to solve each part of the problem, a circuit simulator can calculate the total thermal response. The simulator also allows you to observe the effect of the thermal system on the circuit's parametric performance, which is difficult to deduce from pen-and-paper or spreadsheet analyses.

Circuit simulation uses component models and network analysis, which closely approximates the operating conditions for each device in the circuit. The simulator automatically calculates the power dissipation of power devices, taking into account a full range of circuit and device behaviors that include gate drive, switching transitions and diode reverse-recovery.

However, traditional circuit simulators calculate power based on a static thermal model. In other words, they fix device behavior with respect to temperature. This is adequate for low-power IC simulation because devices in such circuits exhibit little self-heating. Power ICs do self-heat, however, and an accurate simulation must account for the device behavior's temperature dependence. Adding a quasidynamic thermal wrapper model to the static 25°C device model overcomes this limitation (**Figure 1**).

Spice can implement the thermal wrapper in macro models. Popular non-Spice simulators can also implement the thermal wrapper with macro models. Alternatively, they can implement the thermal wrapper in a hardware description language such as VHDL-AMS for Ansoft's Simplorer, MAST for Synopsys's Saber or Verilog for Cadence's Spector simulators. Because all of these simulators can use macro models, this article focuses on that approach and models a power MOSFET as an example.

The thermal wrapper must implement two temperature-dependent MOSFET parameters: the threshold voltage, V_{th}, and the fully enhanced channel resistance, $R_{DS(on)}$. The temperature coefficient of V_{th} is approximately -7mV/°C. $R_{DS(on)}$'s temperature-dependence models reasonably well with a quadratic. Implementing the mathematical relationships is easy—deriving the operating temperature that drives these functions is the challenge.

The thermal system usually models as a ladder network comprising Rs and Cs with a step response resembling the single-pulse curve. Most new MOSFET datasheets include the ladder network, but older datasheets only provide the curves. In this ladder model, power is analogous to current and temperature is analogous to voltage.

The first item to obtain for the thermal-wrapper model is channel resistance as a function of temperature, $R_{DS(on)}(T_j)$, which all MOSFET datasheets provide in the form of a characteristic curve. A simple quadratic curve-fitting routine can provide the three coefficients in the form the model requires: $R_{DS(on)}(T_j) = R_{DS(on)}(25°C)(aT_j^2 + bT_j + c)$.

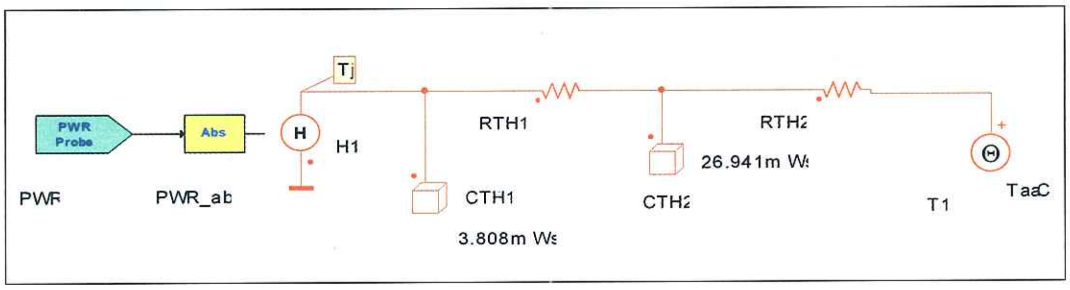

Figure 2: The simulator's calculation of instantaneous power appears as a current source to the thermal network.

The simulator computes the value of $R_{DS(on)}(25°C)$ from the device's Spice model. Taking the derivative of the channel resistance with respect to temperature yields an expression for the self-heating effect on $R_{DS(on)}$: $dR_{DS(on)}(T_j) = R_{DS(on)}(25°C)(2aT_j + b)dT_j$. Add $dR_{DS(on)}$ as a resistor in series with the MOSFET's drain.

The next step calculates T_j from the MOSFET's instantaneous power. Neglecting switching losses in R_G, the gate-interconnect resistance, this is simply: $p = i_D v_{DS}$. This power term serves as the source to the thermal ladder network (**Figure 2**). Note that the absolute-value block in Figure 2 is necessary because power dissipation always adds heat to the system, no matter what the sign of the voltage or current. The output of this model is a voltage that corresponds to T_j.

Finally, the shift in V_{th} compared with the nominal 25°C threshold is simply:

$$dV_{TH}(T_j) = 7\,\frac{mV}{°C}\,(T_J - 25°C)$$

This term appears as a floating voltage source in series with the MOSFET's gate terminal.

With the characterizing equations in hand, creating the model is straightforward. Obtain from its manufacturer the MOSFET's datasheet, Spice model and thermal network. Newer MOSFET datasheets include the thermal networks. Obtain or calculate the quadratic coefficients that describe $R_{DS(on)}$'s temperature coefficient. Finally, implement the macro model, including the equations for $dR_{DS(on)}(T_j)$, the absolute value of the instantaneous power and $dV_{th}(T_j)$.

The if-else statements account for the MOSFET's state during simulation. If V_{DS} is greater than 100mV, a 1µΩ resistance adds to the channel. The model assumes that the MOSFET is fully on if V_{DS} is less than 100mV and it adds the temperature dependent $dR_{DS(on)}$. In this simple model, T_a is the case temperature. It's easy to expand the thermal network, however, to include a heat sink's performance and its effect on the system.

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