Simulation Assists Thermal Management in Power Semiconductors

As electronic designers seek to cram ever more functions into ever smaller physical spaces, managing the thermal budget becomes increasingly important, particularly for engineers working on power conversion circuitry. In the majority of applications it is the power semiconductors - diodes, MOSFETs, and IGBTs - that dissipate the most power, and hence make the most significant contribution as thermal sources. **David Divins, Senior Staff Field Applications Engineer, International Rectifier, USA**

This trend is exacerbated by the move away from electro-mechanical techniques towards solid state circuits – and not only because the latter are smaller and therefore harder to cool. An electromechanical component such as a relay, for instance, effectively operates as a perfect switch with an on-resistance in the order of 1mΩ or less. The equivalent solid state device – a MOSFET – has many advantages, such as eliminating contact wear, lowering drive current requirements and simplifying current limiting circuitry. But its contact resistance will typically be ten to one hundred times that of the relay, and its on-state power dissipation correspondingly higher. Applications for electro-thermal simulation are i.e. solenoid drivers, motor drives, lighting ballast, DC/DC converters, switch model power supplies, or audio class D amplifiers (see Figure 1).

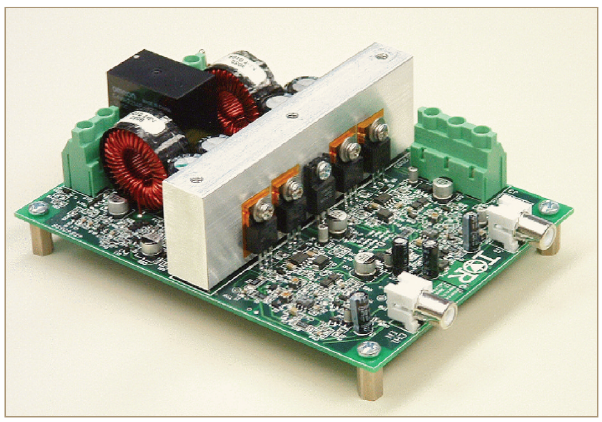

Figure 1: Applications for electro-thermal simulation are i.e. solenoid drivers, motor drives, lighting ballast, DC/DC converters, switch model power supplies, or audio class D amplifiers

Trade-offs in thermal constraints

Increasingly, therefore, thermal constraints are key determinants for many design decisions, which leads to a complex set of trade-offs. Choice of circuit topology is obviously key, but so are details such as precise selection of power converter switching frequency. In terms of physical design, semiconductor type and packaging, and circuit board material, are part of the equation. Then there is required location and environment of operation, available heatsinking alternatives and the practicality of forced-air convection – or, for high power-density applications, liquid cooling. And, as with all designs, cost is an ever-present constraint (see Figure 2).

With all this complexity, it is little surprise that engineers are relying on increasingly powerful simulation software to inform thermal design decisions. Simulators use mathematical models of component behaviour in conjunction with network analysis techniques, to closely approximate operating conditions for each device. For power devices, power dissipation can be investigated, taking into account factors such as gate drive, switching transitions, and diode reverse-recovery.

Although traditional circuit simulators reliably calculate the performance of low-power ICs based on a static thermal model, this approach is inadequate for power circuits, which exhibit substantial self-heating. In this case, accurate simulation must account for the temperature dependence of the device's behaviour. The designer needs to add some elements to the simulation that will model such behaviour – a so-called 'thermal wrapper'. From there, temperature estimates can be obtained to determine the impact of the various design choices in advance of finalising the design.

Power circuit thermal analysis

To understand the use of simulation in such situations, it is informative to take a step back and consider the fundamentals of power circuit thermal analysis – starting with the calculations one might perform if working with spreadsheet-type models.

Heating effects in power semiconductors such as diodes, MOSFETs, and IGBTs can be modelled as functions of a number of parameters, primarily applied voltage, load current, switching frequency and gate-drive circuit. These thermal sources stand in

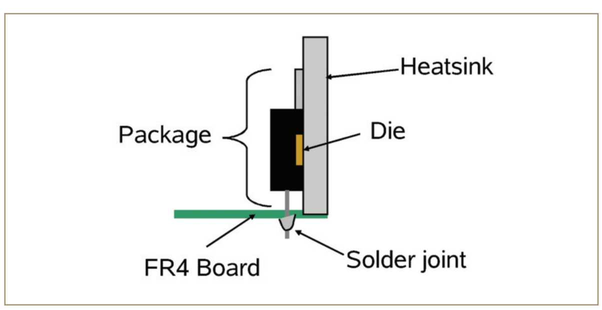

Figure 2: The purpose of Electro-Thermal Simulation is to predict MOSFET junction for a given application

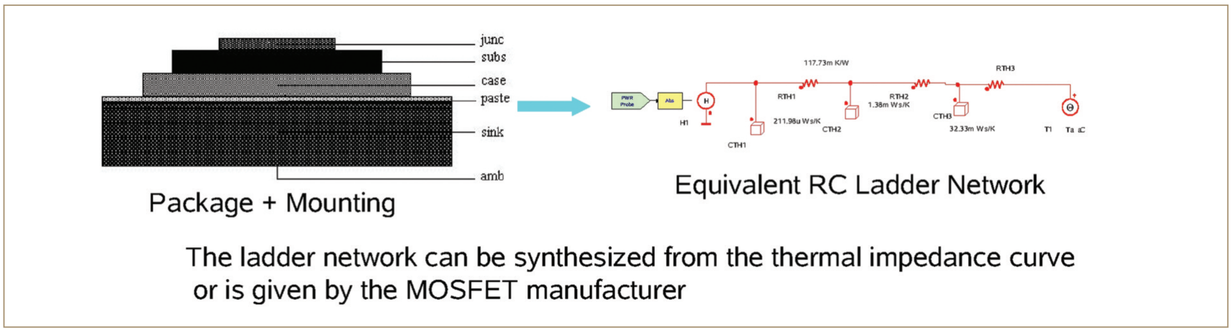

Figure 3: To model the dynamic thermal behaviour of the package and mounting system a thermal RC network is used

balance with the thermal sinks in the system: the package and mounting.

In a time-varying circuit such as a switch-mode power supply, a first-order estimate of power-semiconductor power dissipation is given by the product of three quantities: the average conduction-cycle voltage (V); the corresponding average conduction-cycle current (I); and the duty cycle (D) of the waveform (P=DVI).

When analysing a physical circuit, the current is modelled as a function of circuit operation. In turn, voltage is regarded as a function of current, device type, junction temperature, and semiconductor-control method. For example, voltage across a MOSFET in the on-state is given by the product of the drain current (I_D) and on-state drain-source resistance ($R_{DS(on)}$). $R_{DS(on)}$ itself is regarded as a function of gate drive (I_D), and temperature.

In this first order analysis, the semiconductor's temperature rise can be determined by multiplying power dissipation by thermal impedance. However, this is an over-simplification, because it does not account for transient conditions, which cannot be considered as trivial. Power circuits frequently need to endure high levels of inrush current, particularly when they are switching into predominantly capacitive loads. In such a situation transient currents can easily reach a value ten times more than would be indicated by steady-state analysis.

These limitations can be overcome by the use of the thermal response curves. Commonly provided in the power device's datasheet, these allow the designer to graphically determine the component's thermal response to a pulse of a given duration, amplitude and duty cycle. This information can be used in conjunction with the power dissipation to arrive at the temperature rise from case to junction.

However, this approach is itself limited – while addressing the case-to-junction temperature rise, it cannot account for the case's mounting method, which contributes to rise above ambient. This is illustrated by the complete thermal-stack model of Figure 3.

From this point, further refinements necessarily rely on simulation techniques, which can be used to calculate the total thermal response and to observe the effect of the thermal system on the circuit's parametric performance (Figure 4).

As already observed, traditional circuit simulators make power calculations on the basis of a static thermal model, requiring the designer to add a quasi-dynamic thermal wrapper model to the static (25°C) device model. This can be achieved in a number of ways. Sophisticated models can be implemented using high-level description languages (HDLs). For instance, Ansoft Simplorer users can write the wrapper in VHDL-AMS; Cadence's Spector simulator can be extended via Verilog; and MAST can be used with Synopsys's Saber.

The most common technique, however – and one available in most simulators, including Spice, the de-facto standard analogue simulator in electronics engineering – is to implement the thermal wrapper in macro models. Although more limited than the use of an HDL approach, macros are far easier to implement, and, depending on the simulator, can be quite powerful.

As an example, consider the task of creating the thermal wrapper for a MOSFET. This needs to take account of two temperature-dependent parameters: the threshold voltage (V_{TH}), and the fully-enhanced channel resistance ($R_{DS(on)}$). Both parameters vary relatively simply with temperature. V_{TH} increases approximately linearly, at a rate of around -7mV/K. Changes in $R_{DS(on)}$ can be modelled reasonably accurately with a quadratic equation. The relationships are easily expressed (and implemented)

$$R_{DS(on)}(T_j) = R_{DS(on)}(25°C) *[a*T_j^2+ b*T_j + c]$$

$$V_{TH}(T_j) = -0.007 * (T_j-25)$$

mathematically according to equation 1a/b:

(1a)

(1b)

Although the equations are simple, deriving the operating temperature that drives the functions is the challenge.

The thermal system is usually modelled as a ladder network consisting of resistors and capacitors, and with a step response resembling the standard single-pulse curves provided as thermal response specifications on component data sheets. Most new MOSFET datasheets include a diagram of the ladder network itself; users of older components may find that only the curves are provided. In the ladder model, power is

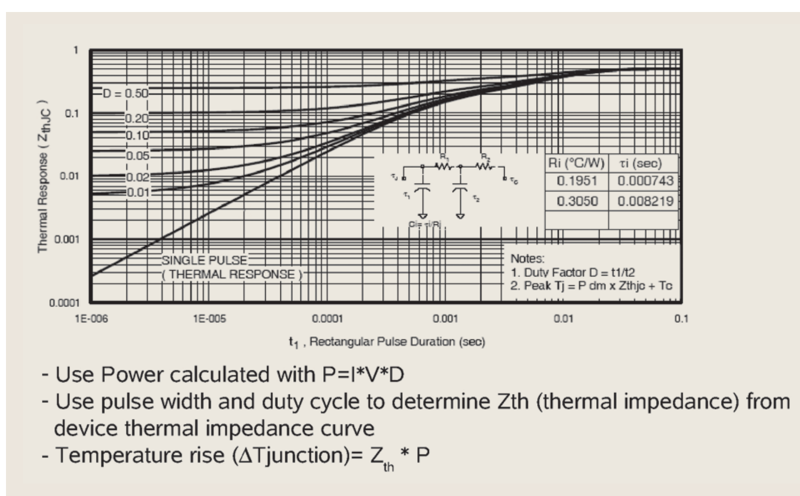

Figure 4: Methods of estimating die temperature

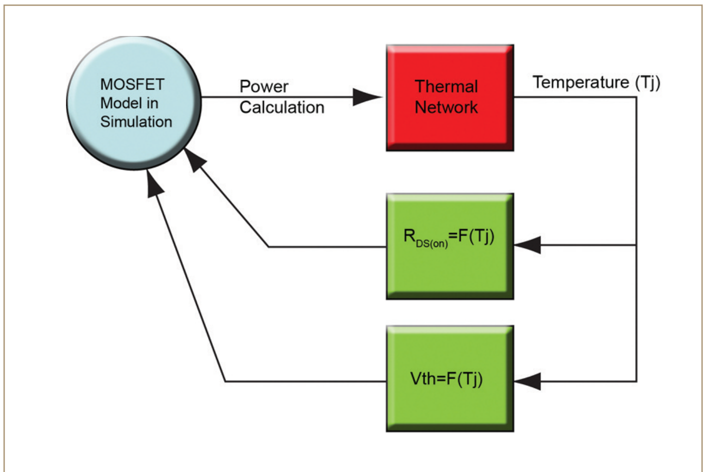

Figure 5: Creating a quasi-dynamic thermal MOSFET model

analogous to current and temperature is analogous to voltage.

The first information required when implementing a thermal-wrapper model is to quantify the relationship between channel resistance and temperature, $R_{DS(on)}(T_J)$. This can be done using a simple quadratic curve-fitting routine, that will take three points on the characteristic curves commonly provided in MOSFET data sheets, and return the two quadratic coefficients a and b and the constant c required by the model.

The final element in the calculation of $R_{DS(on)}(T_J)$ is the value of $R_{DS(on)}(25°C)$. This is computed by the simulator from the device's Spice (or other) model. From this equation, the self-heating effect on $R_{DS(on)}$ is established by taking the

$$V_{TH}(T_j) = -0.007 * (T_j-25)$$

derivative of the channel resistance with respect to temperature according to equation 2:

(2)

Within the model this equates to a resistor, $d_{RDS(on)}$, in series with the MOSFET's drain.

Calculating the junction temperature

Having derived these equations, the junction temperature (T_J) must be calculated from the MOSFET's instantaneous power. Neglecting switching losses, the power dissipation remains the product of the drain current and drain-source voltage. This power term translates to a source in the thermal ladder network (Figure 5). It is important to note that the model must work on

$$dV_{TH}(T_j) = -0.007 * (T_j-25)$$

absolute values of current and voltage, because power dissipation always increases T_J, no matter the direction of the current or polarity of the voltage. The output of this model is a voltage that corresponds to T_J.

Finally, the shift in threshold voltage from the nominal 25°C value is according to equation 3:

(3)

In terms of the circuit model, this represents a floating voltage source in series with the gate terminal of the MOSFET.

Having determined these relationships, the macro model can be built, including the equations for $dR_{DS(on)}(T_J)$, the absolute value of the instantaneous power, and $dV_{TH}(T_J)$. It must also include statements to account for the MOSFET's state during simulation. These would commonly specify that the MOSFET is assumed to be fully on only if V_{DS} is less than (say) 100mV, leading the simulator to adds the temperature dependent $dR_{DS(on)}$.

The next stage of precision in building the model is to take account of