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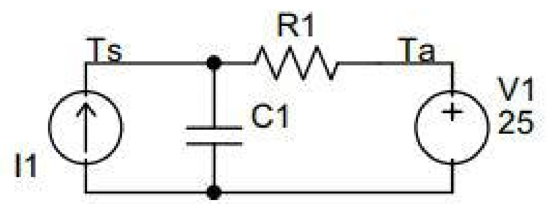
Thermal Modeling of Power Devices in Pulse Mode Operation

INTRODUCTION

In addition to Apex's Power Design software tool, a potent alternative for analyzing temperature rise in Apex's power devices under pulse mode operation is thermoelectric modeling and SPICE simulation.

If a power device heats up due to internal power dissipation during the 'on' time of pulse mode operation, it can cool down again during the, much longer, 'off' time, until the next 'on' time, and so forth. The heating up and cooling down processes are non-linear, as there is an e-based logarithmic relationship between the temperature, time, and thermal parameters of the object that's being thermally cycled, very much like that of voltage, time, and resistance & capacitance of an RC network. This leads to a simple thermoelectric model that looks like this:

Figure 1: Simple Thermoelectric Model



With I1 in amperes corresponding to the power dissipation in watts in a 'source' (the power device), node voltage Ts in volts corresponding to the source's temperature in degrees Celsius. C1 [F] and R1 [Ω] represent the thermal capacitance (θ_C) and thermal resistance (θ_R) of what's between source and ambient (the 'object'), and Ta [V] representing the ambient temperature [°C].

DETERMINING THE THERMAL CAPACITANCE AND RESISTANCE

Now the question becomes: how to determine C1 and R1?

C1 depends on the volume (V) of the object, as well as on its density (ρ) and specific heat (c_p):

$$\theta_C = V \cdot \rho \cdot c_p \left[W \cdot \frac{s}{K} \right]$$

By the way, V·ρ= weight.

Suppose you are cooling down your power device with Apex heatsink HS18; it will be quite hard to calculate its volume, but luckily, we know its weight (=V·ρ) from its dimensional drawing, the weight of this black-anodized, aluminum heatsink is 422g. Since the specific heat of aluminum is 904 J/kg·K, the thermal capacitance becomes 381.5 W·s/K.

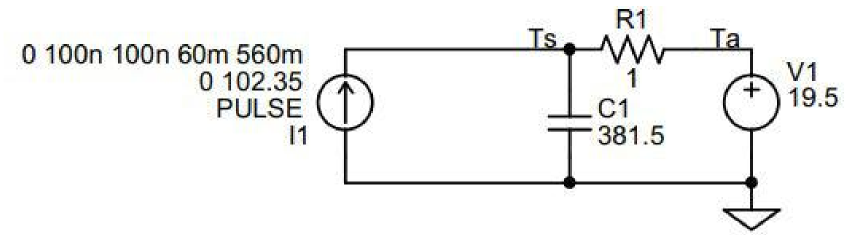
R1 depends on the thickness (L) of the body, its surface area (A), and its thermal conductivity (k):

$$\theta_R = \frac{L}{k \cdot A}\left[\frac{K}{W}\right]$$

It's not easy to determine thickness and surface area of HS18, as the thickness differs, and it's ribbed, it's not a sheet of aluminum. Again luckily, we can just use the thermal resistance mentioned in the dimensional drawing of HS18: 1K/W.

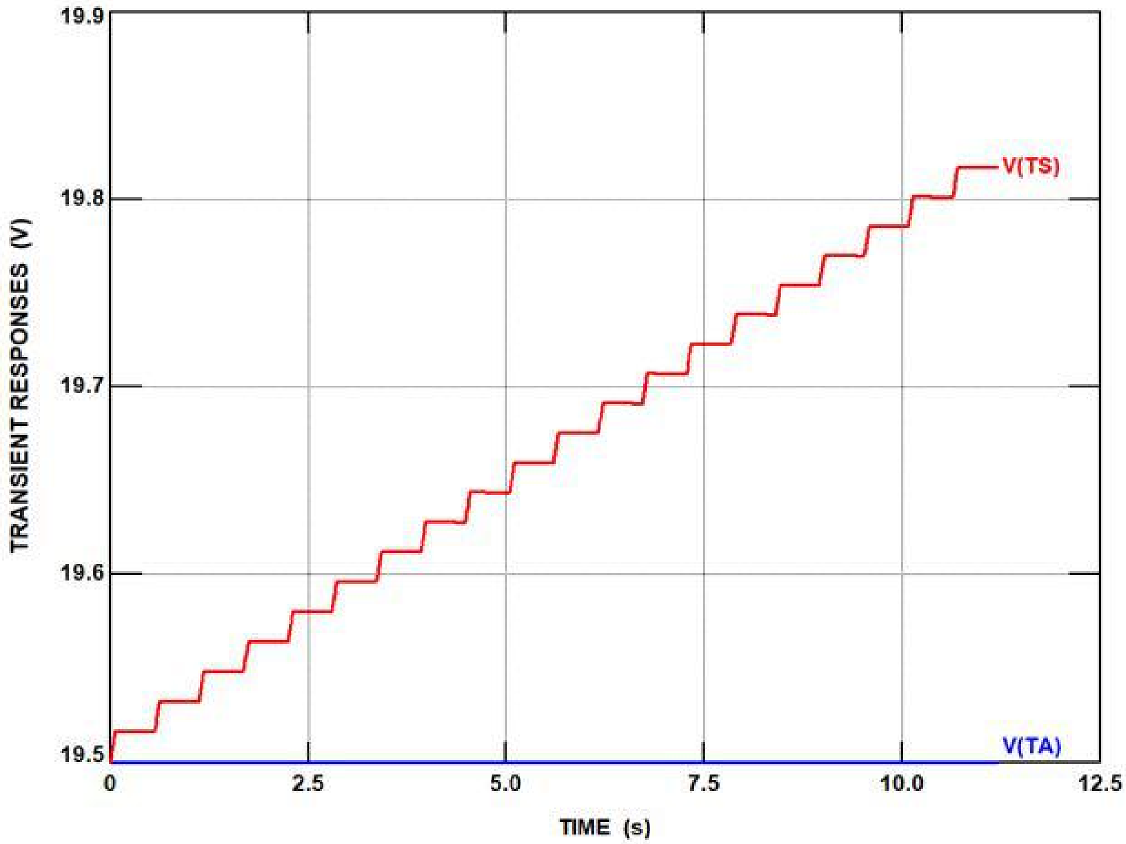
Assuming a pulsed power dissipation of 102.35W for 60ms in every 560ms (duty cycle is 10.7%), an ambient temperature of 19.5°C, and the numbers derived above, the thermoelectric model becomes like this:

Figure 2: Simple Thermoelectric Model with Example-Applied Values



With this SPICE-simulated result (the y-axis represents the temperature):

Figure 3: SPICE Simulation Result of the Thermoelectric Model in Figure 2, the First 20 Cycles



DETERMINING JUNCTION AND CASE TEMPERATURES

This doesn't tell much yet about the eventual temperature of the power device's output transistor junctions (Tj) and case (Tc), as that's what we're interested in.

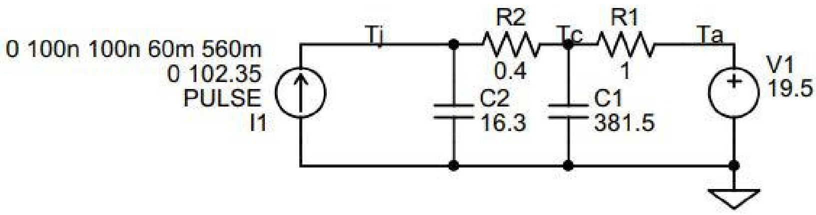
To add some more detail to the thermoelectric model, θ_R and θ_C of the power device itself could be inserted between the heat source and the heatsink. Let's assume that this power device is Apex's PA05 Power Operational Amplifier.

The AC thermal resistance, junction-to-case of PA05 can be found in its datasheet: 0.4K/W.

The thermal capacitance is something else. There's a stack-up of materials, but the dominant weight is in the steel backplate of the PA05. PA05's Material Declaration Report calls out that the header itself contains 36.2g of iron, which has a specific heat of 449 J·kg/K. So, the thermal capacitance of PA05 (actually, of its header, but that's the main pass-through for the heat transfer to the heatsink) becomes 16.3 W·s/K.

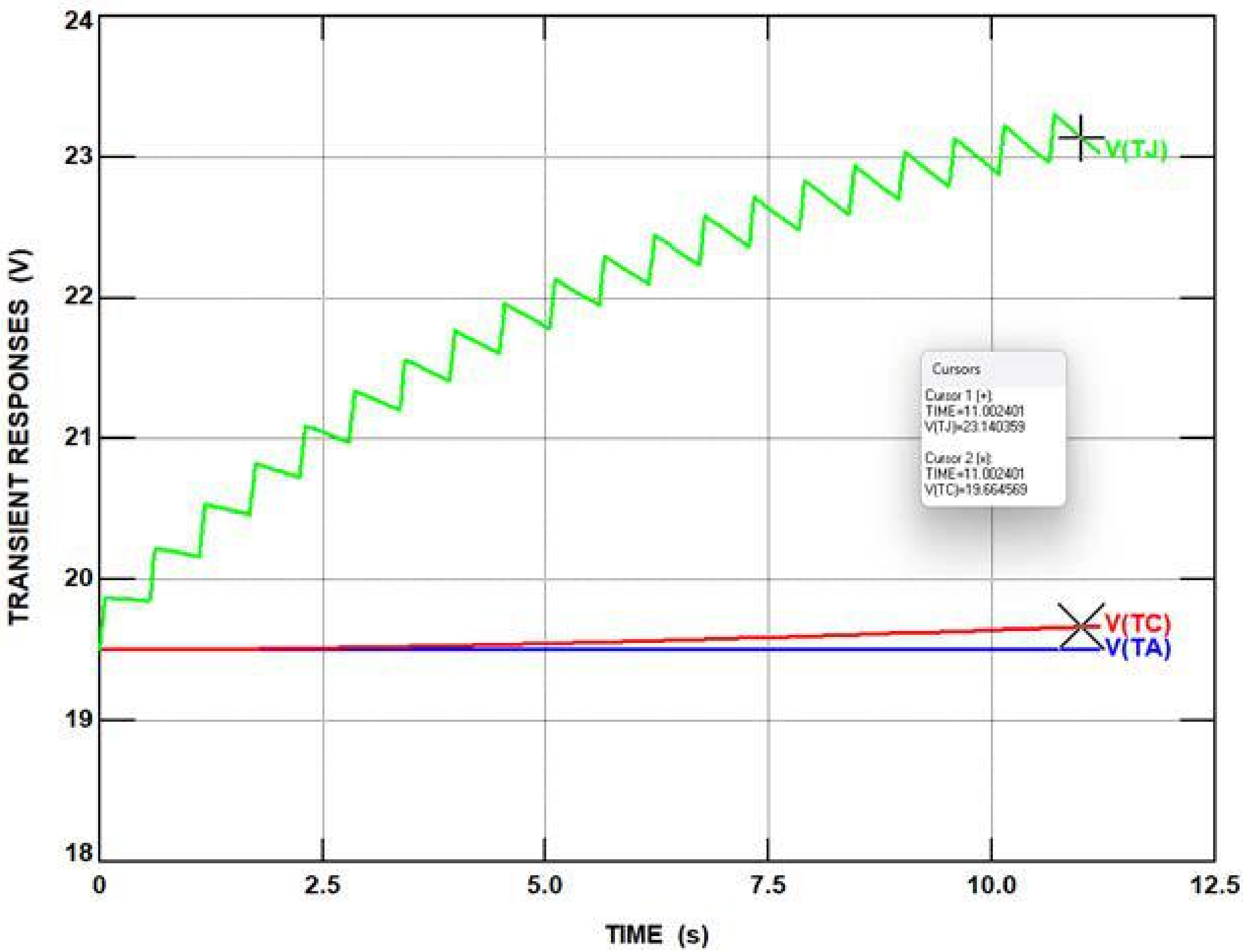
The thermal model now becomes:

Figure 4: Thermoelectric Model of HS18 and PA05 in Pulsed Mode Operation



With SPICE simulation result:

Figure 5: SPICE Simulation Result of the Thermoelectric Model in Figure 4, the First 20 Cycles



This now shows that after 20 cycles or so (~11s), the case temperature has gone up only 0.16°C, whereas the junction temperature went up 3.5°C to roughly 23°C.

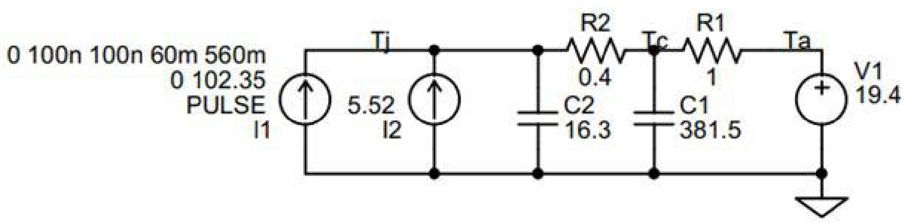
DO NOT FORGET QUIESCENT POWER CONSUMPTION

There is one more refinement to make and that pertains to the op-amp's continuous quiescent power dissipation. Although it's often way less than the pulsed output stage power dissipation, it should be factored in. The quiescent power dissipation of Apex's power op-amps is:

$$P_Q = (V_{SS} \cdot I_Q)[W]$$

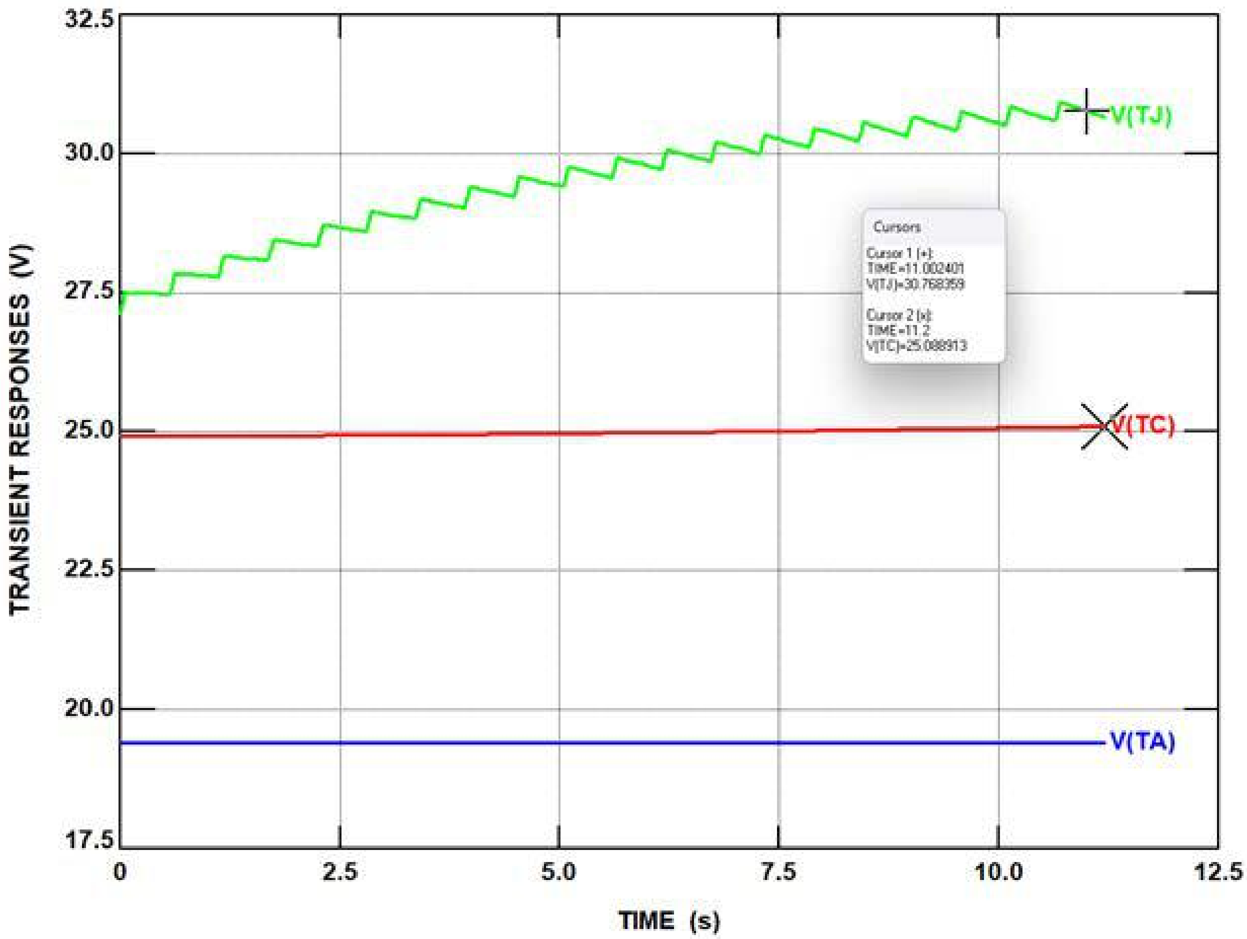
With Vss being the total supply voltage across the device and Iq being the maximum (idle) consumption current specified in its datasheet. PA05's max total Iq is 120mA and, as an example, let's assume Vss to be 46V (±23V). This yields a Pd of 5.52W(!) This can be added to the thermoelectric model as another current source.

Figure 6: Additional Quiescent Power Dissipation Added to the Thermoelectric Model (I2)



With SPICE simulation results as shown below:

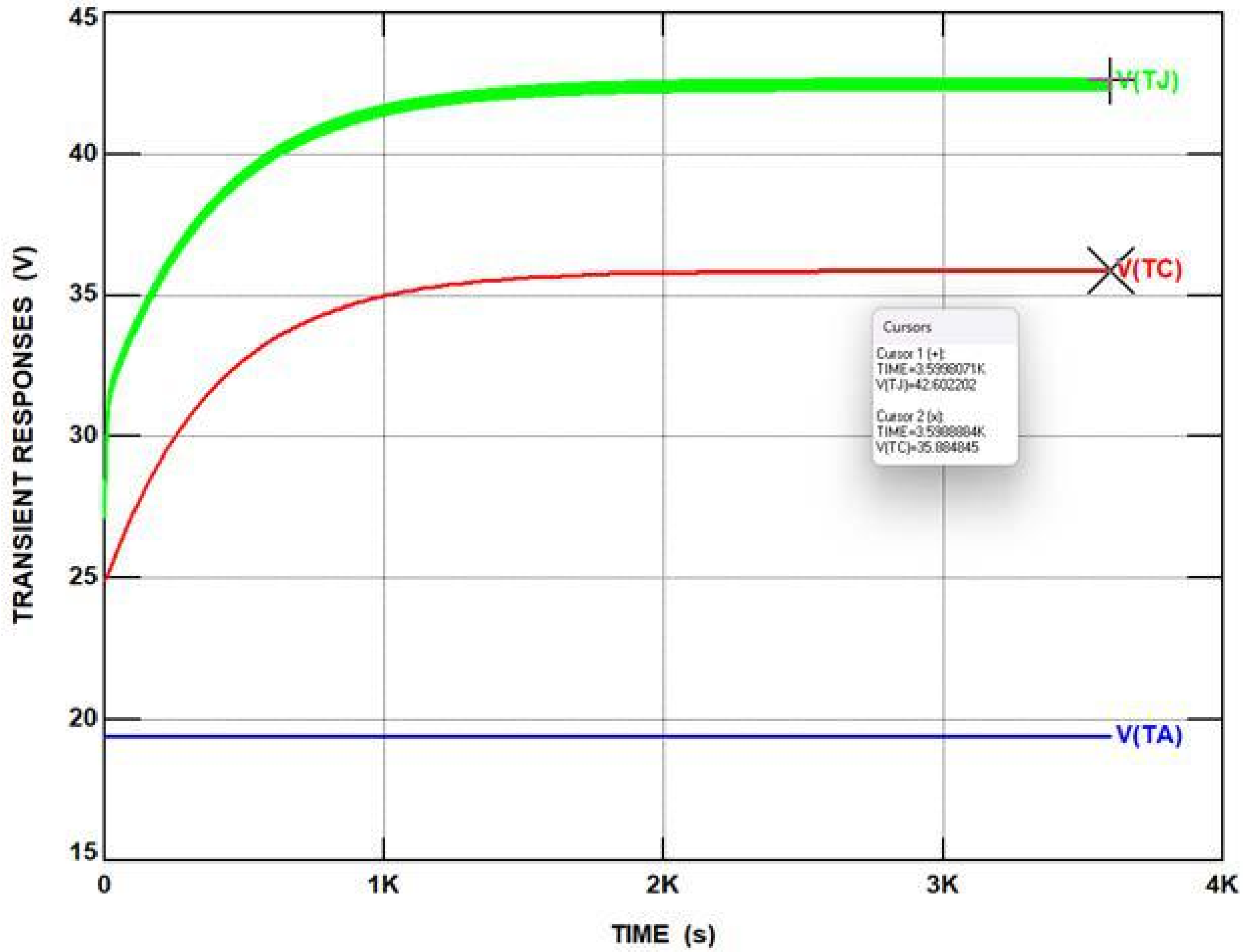
Figure 7: SPICE Simulation Result of the Thermoelectric Model in Figure 6, the First 20 Cycles



Note that in Figure 7, due to the quiescent power dissipation, the case and junction temperatures have gone up with 5.4°C and 7.6°C respectively when compared with Figure 5 (without Pq).

What happens with these temperatures after 1 hour or even longer? Well, a thermal equilibrium will have been reached at that time, which is shown by the SPICE simulation result below:

Figure 8: SPICE Simulation Result of the Thermoelectric Model in Figure 6, Temperatures After 1 Hour

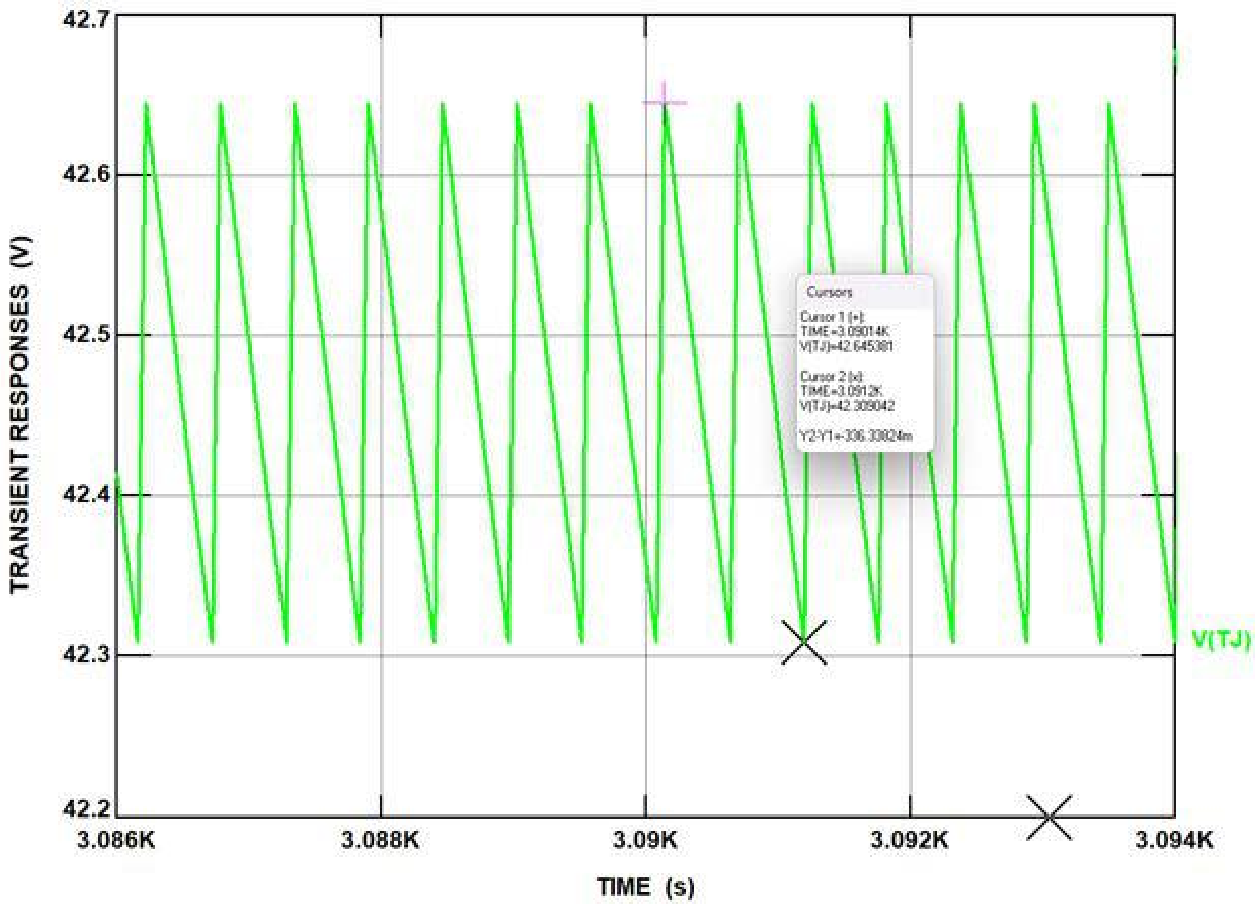


As can be seen, in thermal equilibrium, Tc and Tj become 35.9°C and 42.6°C, respectively. Nothing to worry about. Just like with an electric RC combination, the thermal equilibrium is reached after ~5τ, with the τ of the heatsink being the main contributor. Since that is ~381s, thermal equilibrium is reached around 1907 seconds, or about 32 minutes.

ENHANCED VS STANDARD THERMOELECTRIC MODEL

Working with the described thermoelectric model or using the average power dissipation in the standard thermoelectric model without θ_C (see Application Note 1, Section 7.5), will yield almost the same results with respect to the temperatures in eventual static situation. The simulations with the described model, however, will provide a bit more insight into dynamic thermal behavior, like the temperature increase at start-up and how long it takes before the thermal equilibrium is reached. Also, when the simulated junction temperature is zoomed into, the ΔTj can be assessed, which is a parameter for reliability:

Figure 9: Zoomed in on Tj From Figure 8



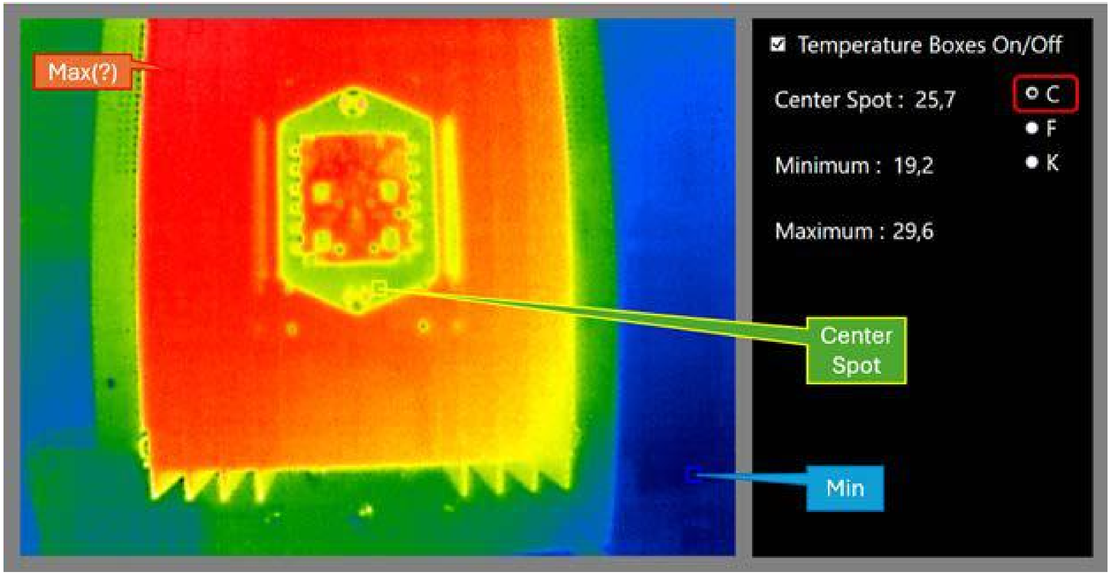
Here, we are looking at a ΔTj of ~0.3°C, which virtually does not affect long-term reliability at all. The ΔTc is even much smaller.

As all previously shown calculations and simulations are based on relatively simple modeling, if it ever comes to that, ALWAYS test power op-amp (or any other Apex power device) performance on the bench. FEA (Finite Element Analysis) would give you more accurate information, but still, you'd be modeling the real world. Bench testing is inevitable!

LAB TESTING

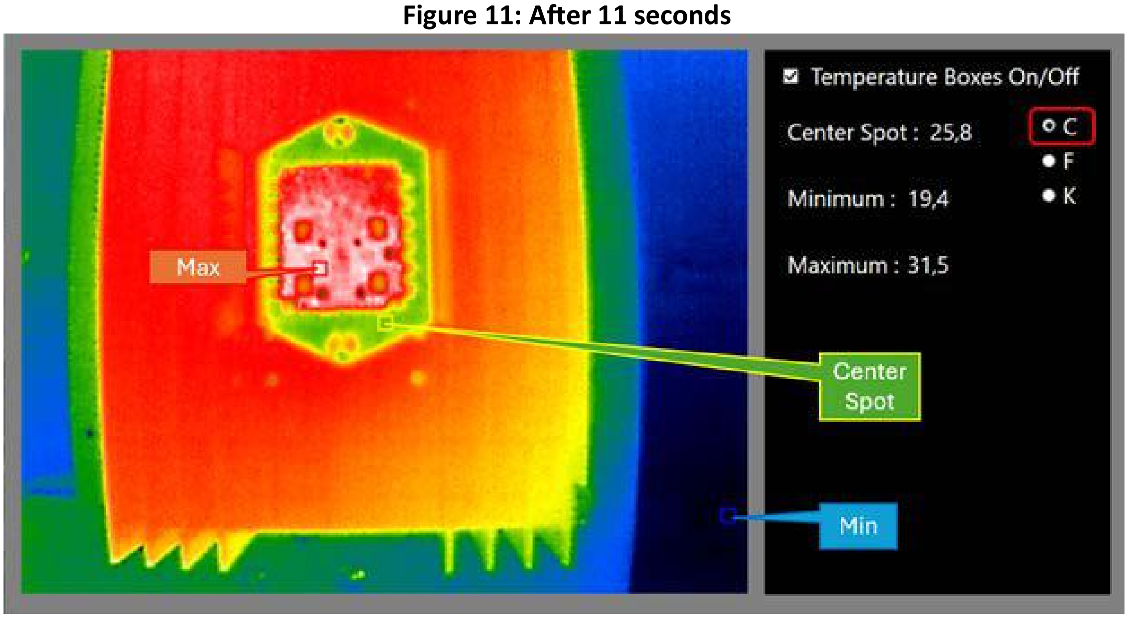
As the proof of the pudding is in the tasting, the lid of a PA05 was carefully taken off (to keep the device functional), after which the device was mounted on an HS18 heatsink and inserted in a circuit to mimic the earlier described operational circumstances: internally dissipating 5.52W continuously and an additional 102.35W for 60ms in every 560ms, etc. Thermal pictures were taken of the inside (Tj) and case (Tc) at the start, after 11s, and after 40 minutes of pulsed mode operation.

Figure 10: Start



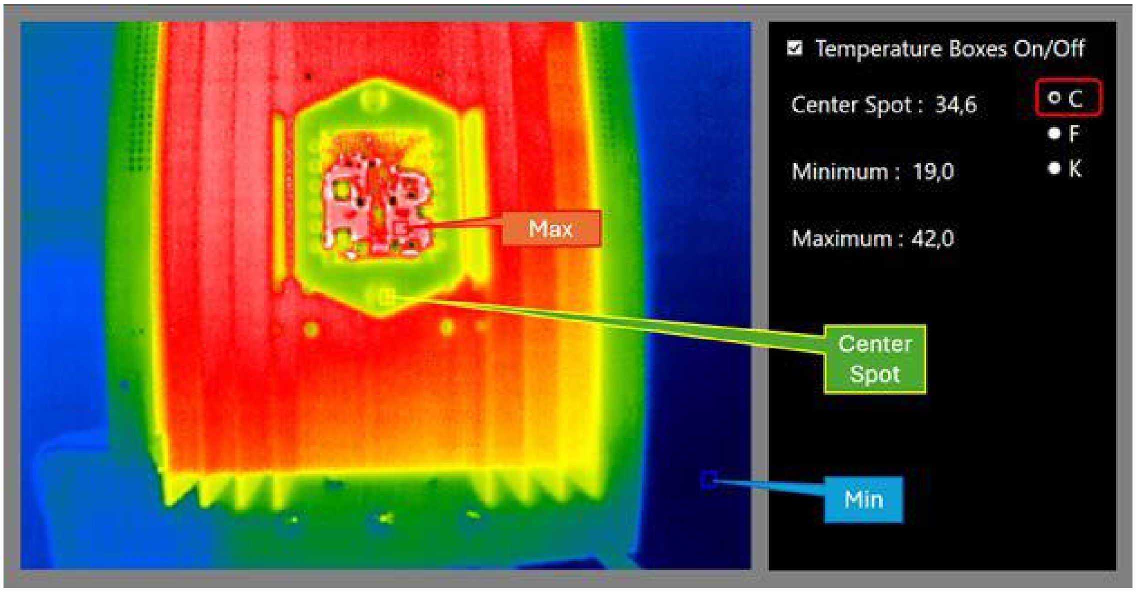
This is with PA05 having been on for a while, without pulsing, but with Pq causing the heatsink to heat up to 29.6°C. Since the thermal camera looks for the hottest spot, it is on the heatsink, not in the amplifier. The Center Spot is indicative for Tc, which is 25.7°C, concurring with the starting case temperature in Fig. 8 (24.9°C). The Minimum is the measured room temperature, 19.2°C (that's why Ta was chosen to be 19.5°C in the thermoelectric models)

Figure 11: After 11 seconds



After 11 seconds, the Maximum temperature is now on the substrate close to the output MOSFETs and thus indicative for Tj: 31.5°C. Again, the Center Spot is indicative for the case temperature Tc: 25.8°. Both values concur with the SPICE simulation result in Fig. 7; Tj = 30.8°C. Tc = 25.1°C

Figure 12: After 40 Minutes



After 40 minutes, Tj = 42.0°C and Tc = 34.6°C. This concurs with the simulation result in Figure 8; Tj = 42.6°C and Tc = 35.9°C

CONCLUSION

This application note describes a thermal modeling method, with which the dynamic temperature behavior of Apex power devices in pulse mode operation can be simulated fairly accurately. Thus, the method can be used to simulate the ΔTc and ΔTj, which are important measures for reliability assessment. The method is accessible to everyone through data freely available on the Internet and Apex's website, along with the use of free SPICE simulation tools. For more advanced analysis or application-specific guidance, we encourage you to explore Apex's Power Design software or contact our technical team for support.

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