Linear Regulator Series

Calculating Junction Temperature from Inrush Current

An inrush current flows to electrically charge the output capacitor of the LDO during startup. Even if the current value exceeds the maximum value of the recommended operating range, the over current protection (OCP) circuit limits the amount of current, so there are no problems in operation. Note that it is necessary to make sure that the junction temperature does not exceed 150°C due to over current. This application note explains how to calculate the power consumption from the measured waveforms and calculate the junction temperature from the transient thermal resistance graph.

Calculating the power consumption from the measured waveforms

Since the inrush current is a short-term over current, the junction temperature T_J can be estimated by the following equation using the transient thermal resistance Z_{TH}.

$$T_J = T_A + Z_{TH} \times P \quad [℃] \tag{1}$$

T_A: Ambient temperature [℃]
Z_{TH} : Transient thermal resistance between junction and ambient environment [℃/W]
P : ICpower consumption [W]

P is the IC power consumption. It can be calculated from the measured waveforms with the approximation equation shown in Equation (2).

$$P \approx \frac{1}{3}(V_{DS1} - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2} I_{D1}(V_{DS1} - V_{DS2}) - \frac{1}{2} V_{DS1}(I_{D1} - I_{D2}) + V_{DS1} I_{D1} \quad [W] \tag{2}$$

“S” in V_{DS} refers to the source, which represents the input voltage V_{IN} if the output MOSFET is the P-channel type. “D” refers to the drain of MOSFET, which represents the output voltage V_{OUT}. Therefore, V_{DS} is the input-output voltage. V_{DS1} and V_{DS2} represent the start and end voltages, respectively.

I_D is the current flowing through the output MOSFET, which is the output current I_{OUT} (≈ input current I_{IN}). I_{D1} and I_{D2} represent the start and end currents, respectively.

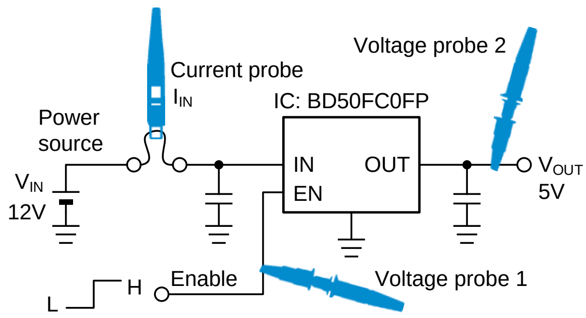

Figure 1. Measurement circuit

As an example to describe the procedure, we use the waveforms in Figure 2 that are measured with the circuit shown in Figure 1.

1. Draw linear trendlines for the V_{OUT} and I_{IN} (≈ I_{OUT}) waveforms and read the minimum and maximum values.

2. Organize the values.

$$V_{DS1} = V_{IN} - V_{OUT1} = 12\ V - 0\ V = 12\ [V] \tag{3}$$
$$V_{DS2} = V_{IN} - V_{OUT2} = 12\ V - 4.6\ V = 7.4\ [V] \tag{4}$$
$$I_{D1} = 0\ [A] \tag{5}$$
$$I_{D2} = 1.85\ [A] \tag{6}$$

3. If I_{D1} = 0, Equation (2) can be simplified to Equation (7).

$$P \approx \frac{1}{6}(V_{DS1} + 2\, V_{DS2})\, I_{D2} \quad [W] \tag{7}$$

4. Substitute the read values in Equation (7).

$$P \approx \frac{1}{6}(12V + 2 \times 7.4V) \times 1.85A = 8.26\ [W] \tag{8}$$

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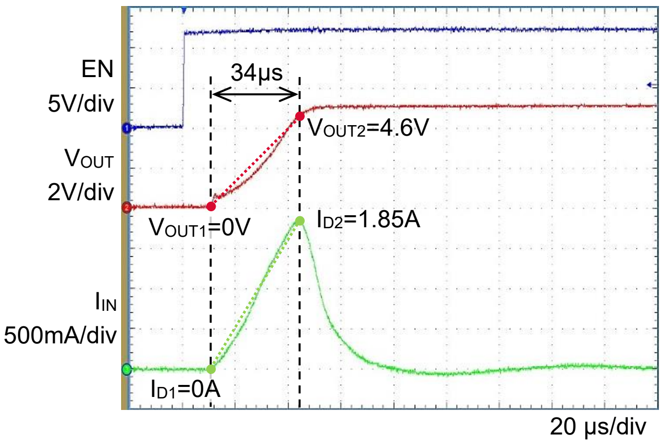

Figure 2. Measured waveforms, C_{OUT} = 10 µF

Calculating T_J from the transient thermal resistance

Next, calculate the transient thermal resistance from the graph in Figure 3. The waveforms in Figure 2 show that the period of the over current is 34 µs. In Figure 3, read the transient thermal resistance at 34 µs. However, use the value at 100 µs because this is the minimum time on the graph. The transient thermal resistance at 34 µs is lower than the value at 100 µs, providing a margin to the design.

Substitute the values collected so far in Equation (1) to calculate the junction temperature. In this example, 60°C is used as the ambient temperature T_A for the calculation.

$$T_A = 60\ [℃] \quad (9)$$

$$Z_{TH} = 0.92\ [℃/W] \quad (10)$$

$$P = 8.26\ [W] \quad (11)$$

$$T_J = T_A + Z_{TH} \times P = 60 + 0.92 \times 8.26 = 67.6\ [℃] \quad (12)$$

The junction temperature is 150°C or less, so there is no problem.

In this way, since the rise in chip temperature is slight when the inrush current flows for a time less than 1 ms, problems with rising temperatures are minimal.

In the measured waveform in Figure 2, the power is consumed in the section where I_{IN} falls from the peak. However, since the power consumption is smaller and the period is shorter compared with the section where the current rises, the calculation is omitted.

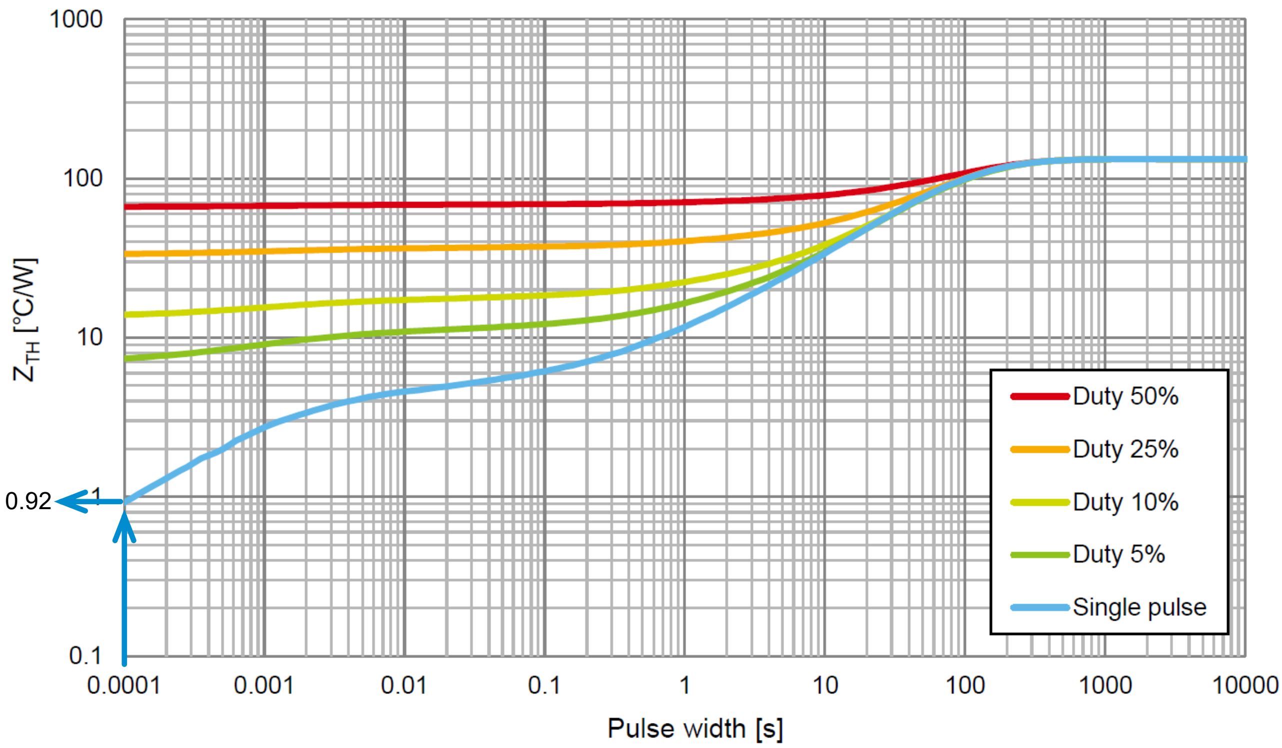

Figure 3. Transient thermal resistance of the TO252 package
JEDEC 1-layer board, copper foil area 49 mm² (footprint)

Another calculation example

Perform the calculation using the output capacitor of 1,000 µF and a large inrush current as an example.

Figure 4 shows the measured waveforms. Due to a large amount of electric charge in the output capacitor, the output voltage is increased with the over current protection circuit of the IC constantly operated since immediately after the startup.

Follow the procedure described above to perform the calculation.

1. Draw linear trendlines for the V_{OUT} and I_{IN} (≈ I_{OUT}) waveforms and read the minimum and maximum values.

2. Organize the values.

$$V_{DS1} = V_{IN} - V_{OUT1} = 12\ V - 0\ V = 12\ [V] \quad (13)$$

$$V_{DS2} = V_{IN} - V_{OUT2} = 12\ V - 5\ V = 7\ [V] \quad (14)$$

$$I_{D1} = 0.76\ [A] \quad (15)$$

$$I_{D2} = 1.92\ [A] \quad (16)$$

3. Substitute the read values in Equation (2).

$$P \approx \frac{1}{3}(V_{DS1} - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2} I_{D1}(V_{DS1} - V_{DS2}) - \frac{1}{2} V_{DS1}(I_{D1} - I_{D2}) + V_{DS1} I_{D1}$$

$$\approx \frac{1}{3}(12-7)(0.76-1.92) - \frac{1}{2} \times 0.76(12-7) - \frac{1}{2} \times 12(0.76-1.92) + 12 \times 0.76$$

$$\approx 12.25\ [W] \quad (17)$$

4. Read the transient thermal resistance at 3.25 ms from the graph in Figure 5.

$$Z_{TH} = 3.9\ [°C/W] \quad (18)$$

5. Substitute the values collected so far in Equation (1) to calculate the junction temperature. In this example, 60°C is used as the ambient temperature T_A for the calculation.

$$T_A = 60\ [°C] \quad (19)$$

$$P = 12.25\ [W] \quad (20)$$

$$T_J = T_A + Z_{TH} \times P = 60 + 3.9 \times 12.25 = 107.8\ [°C] \quad (21)$$

The junction temperature is 150°C or less, so there is no problem.

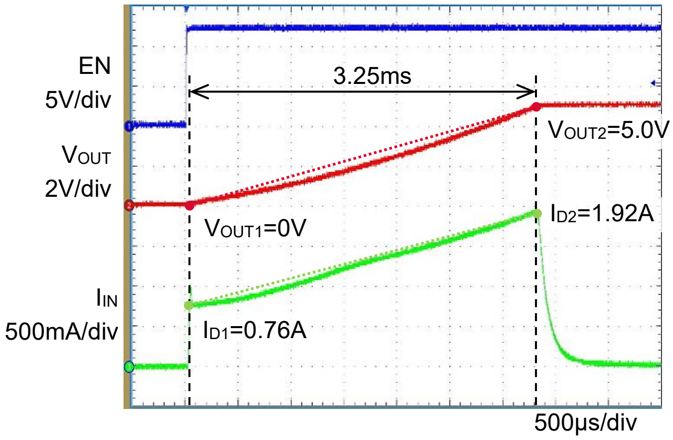

Figure 4. Measured waveforms, C_{OUT} = 1,000 µF

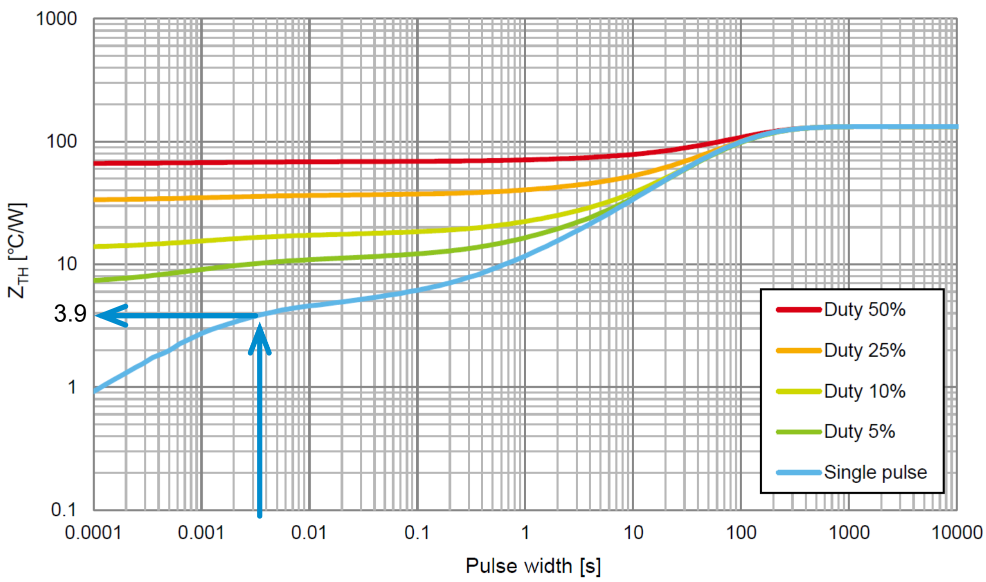

Figure 5. Transient thermal resistance of the TO252 package

JEDEC 1-layer board, copper foil area 49 mm² (footprint)

Application Note

- Calculating Power Loss from Measured Waveforms

The approximate equations shown in Equations (2) and (7) are taken from the equations described in case 3 of Table 1 in this application note. Since the waveform of the inrush current is a single pulse, the term "$\Delta t \cdot f$" in the equations is "1".

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