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Guideline for determining switching losses associated with switching resistive, capacitive and inductive loads.

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Automotive Power

Never stop thinking.

1. Abstract

This Application Note is intended to provide help in all cases where FET switching losses due to repetitive (such as during PWM mode) or slow switching processes must be taken into account. It focuses on thermal considerations for semiconductor switches in switched DC applications.
A general idea about how switching losses occur and an outline about what amount of power can be dissipated during switching is given. The effect of these power losses for the temperature of the semiconductor switch is covered as well.
The Application Note covers single and/or repetitive switching for ohmic, capacitive and inductive loads.

2. Introduction

If a semiconductor device is used in a DC application as a switch for a load, losses always occur in that device.
Basically these losses can be subdivided into

- steady-state losses (losses during the ON state) and
- dynamic losses (losses during switching).

Calculating the steady-state losses is relatively easy. They generally result from component-specific and load-typical parameters. In the case of semiconductor devices based on a field-effect transistor principle, these parameters are the on-resistance $R_{DS(on)}$ and the load current I_{Load}.
However, calculating the dynamic losses occurring during switching processes is more difficult.

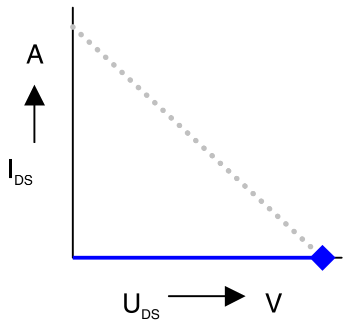
3. General

If a load is switched in a DC application, the switching device passes through various operating states during the switching operation.

During the switch-on process, these are (referred to the load):

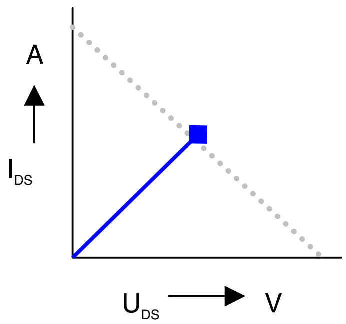
1) No-load:

$V_{DS}=V_{bb}$
$I_{DS}=0$



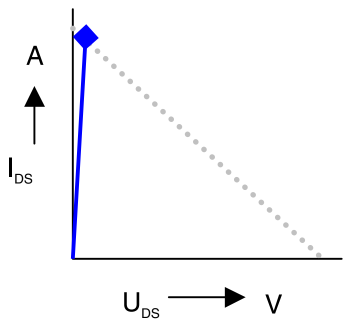
2) Matching

$V_{DS}=V_{bb}/2$
$I_{DS}\neq 0$



3) Rated operation.

$V_{DS}\approx 0$
$I_{DS}=I_{Load}$



During the switch-off process, each switching device passes through these operating states in reverse sequence.
In the case of inductive loads, commutation processes may additionally come into play. These will be discussed in further detail later. Let us just say for now that during commutation processes the energies stored in the load inductance are discharged via the switching device at voltages greater than the operating voltage V_{bb}.

4. Switching resistive loads

The following section deals first with switching losses associated with purely resistive loads. However, the statements made here are also relevant to the subsequent sections.

In the 3 diagrams (no-load, matching and rated operation) it may be observed that all the operating states of the switching device lie on a dotted gray line. This is the load line. This means that the switching losses of each switching operation are influenced by the load.

To examine this further, it is useful to introduce a reference variable which is exclusively a function of the load. A good reference variable is the power dissipation in the device during matching.
This is given by formula (1) as:

$$P_{Matching} = \frac{V_{bb}}{2} \bullet \frac{I_{Load}}{2} = \frac{V_{bb}^{2}}{4 \bullet R_{Load}} \qquad (1)$$

To calculate the switching losses, it is now important to know how the current and voltage vary over time. A distinction may basically be drawn between 2 cases.

4.1. Linear voltage and current characteristic

4.1.1. Assumption

Assuming that the current and voltage vary linearly over time, the switching losses occurring at each instant of the switching process are as follows:

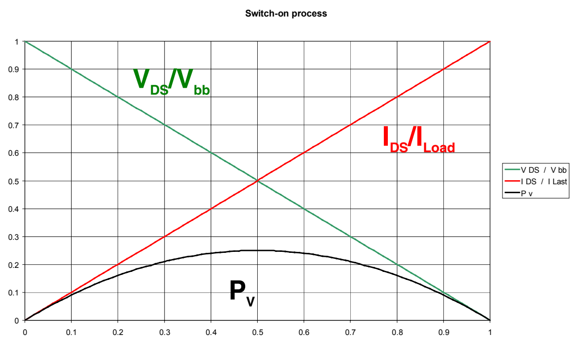


Figure 1 – Normalized switching losses for linear current and voltage characteristics

It can be seen that the maximum losses occur at half the nominal voltage and half the nominal current. This corresponds to the matching case.

The losses occurring at this point are:

$$\hat{P}_{Switching\_max} = P_{Matching} = \frac{V_{bb}^{2}}{4 \bullet R_{Load}} \qquad (2)$$

4.1.2. Calculation

If the averaged losses for linear current and voltage responses are now normalised to the reference value, these losses will be as follows:

$$\overline{P}_{Switching} = \frac{1}{T_{Switching}} \int_{0}^{T_{Switching}} \left(\frac{u}{V_{bb}} \bullet \frac{i}{I_{nom}} \right) dt$$

$$\overline{P}_{Switching} = \frac{1}{1} \int_{0}^{1} x(1-x)dx$$

$$\overline{P}_{Switching} = \int_{0}^{1} \left(x - x^{2}\right)dx = \left.\frac{x^{2}}{2} - \frac{x^{3}}{3}\right|_{0}^{1} = \frac{1}{6} \qquad (3)$$

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \frac{1}{6} \bullet \frac{4}{1} = \frac{2}{3} = \underline{\underline{67\%}}$$

The averaged switching losses for a resistive load and linear current and voltage characteristics are therefore approx. 70% of the losses occurring in the matching case, irrespective of the switching time.
In reality, the 67% calculated may still increase slightly as a result of the R_{on} losses additionally produced close to rated operation, so that 70% is a wholly realistic figure.

4.1.3. Validity and typical applications

This applies to switch-on and switch-off processes, provided no parasitic inductances must be taken into account.
Linear current and voltage characteristics may be observed during slow switching processes. This may occur, for example, if a slowly rising input signal is applied to the device by an external triangular wave generator. This is possible e.g. with discrete FETs, TEMPFET® and HITFET® devices.
As will be shown later, the linear current and voltage response constitutes the less favourable case in thermal terms, since the highest losses occur here. If the true current and voltage

response is not known, this response should be taken as the basis for safety reasons.

4.1.4. Example

By way of example, let us now consider the turn-on process of a BTS149. The BTS149 has been turned on by an external triangular signal. With a supply voltage of V_{bb}=10 volts, it drives a load of 2.18 ohms.
For current (Ch2: 1A/div), voltage (Ch3) and losses (Math1), the following waveforms were observed:

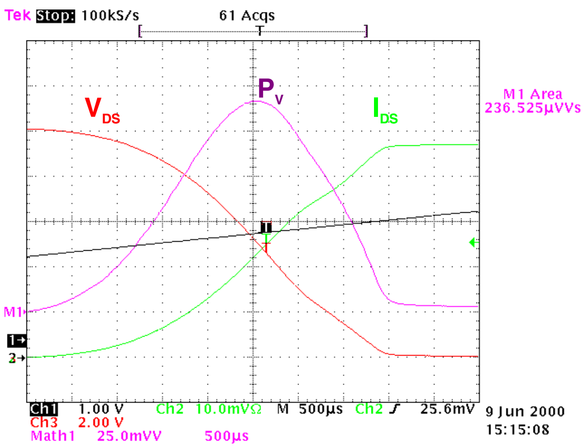


Figure 2 – Slow switch-on process of a BTS149

For a switching time of approx. 3.5 ms, this produces average switching losses of:

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \frac{\frac{1}{T_{Switching}} \; {}_{Tswitching} \; u \bullet i \bullet dt}{V_{bb} \bullet I_{nom}/4}$$

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \frac{\frac{1}{3500\mu 5} \bullet \frac{236\mu 36\mu}{0.01VVs} * W}{11.5W}$$

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \underline{\underline{59\%}} \qquad (4)$$

4.2. Piecewise linear current and voltage characteristic

4.2.1. Assumption

If the current and voltage are assumed to exhibit a piecewise linear response, whereby after approx. 30% of the total switching time the voltage across the device has fallen to approx. 20% of the nominal voltage at switch-on, and the current has increased to approx. 80% of the nominal current, the switching losses at each moment of the switching process are as follows:

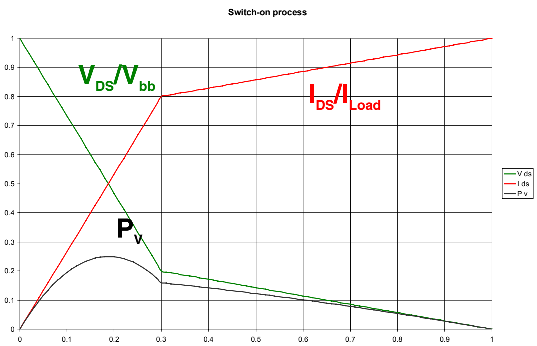


Figure 3 – Normalized switching losses for piecewise linear current and voltage characteristics

4.2.2. Calculation

The switching losses are now:

$$\overline{P}_{Switching} = \frac{1}{T_{Switching}} \; {}_{0}^{T_{Switching}} \left(\frac{u}{V_{bb}} \bullet \frac{i}{I_{nom}} \right) dt$$

$$= \frac{1}{1}\left[\int_{0}^{0,3} \left((1-\frac{8x}{3}) \bullet (\frac{8x}{3}) \right) dx + \int_{0}^{0,7} \left((\frac{1}{5}-\frac{2x}{7}) \bullet (\frac{4}{5}+\frac{2x}{7}) \right) dx \right]$$

$$\overline{P}_{Switching} = {}_{0}^{0,3} \left(\frac{8x}{3} - \frac{64x^2}{9} \right) dx + {}_{0}^{0,7} \left(\frac{4}{25} - \frac{6x}{35} - \frac{4x^2}{49} \right) dx \qquad (5)$$

$$\overline{P}_{Switching} = \frac{4x^2}{3} - \frac{64x^3}{27} \Bigg|_{0}^{0,3} + \frac{4x}{25} - \frac{3x^2}{35} - \frac{4x^3}{147} \Bigg|_{0}^{0,7}$$

$$\overline{P}_{Schalt} = \frac{3}{25} - \frac{8}{125} + \frac{14}{125} - \frac{147}{3500} - \frac{7}{750} = \frac{49}{420} \approx 0,116$$

$$\frac{\overline{P}_{Schalt}}{P_{Anpassung}} = \frac{49}{420} \bullet \frac{4}{1} = \underline{\underline{46,\overline{6}\%}}$$

In the case of a piecewise linear current and voltage response, the averaged switching losses for a resistive load irrespective of the switching time are approx. 50% of the losses which can occur in the matching case.
In reality, the 47% calculated may increase slightly as a result of the R_{on} losses additionally

produced close to rated operation, so that 50% is a wholly realistic figure.

4.2.3. Validity and typical applications

To a first approximation, a piecewise linear current and voltage characteristic may be observed primarily with fast switching processes. It is attributable mainly to the two-stage gate charging process. This is due to the change in the input capacitance during the switching operation. With highside switches such as the PROFET® devices, the effect of the charge pump is additionally present.
This applies to switch-on and switch-off processes provided no stray inductances must be taken into account.
Fast switching processes exist if the device is driven via a low impedance directly by the driver. This is possible in the case of discrete FETs, TEMPFET®, HITFET® and PROFET® devices.

4.2.4. Example

By way of example, let us now consider the turn-on process of a BTS149. The BTS149 has been driven low impedance by a square wave signal. With a supply voltage of V_{bb}=10 volts, it drives a load of 1 ohm.
For current (Ch2: 2A/div), voltage (Ch3) and losses (Math1), the following waveforms were observed:

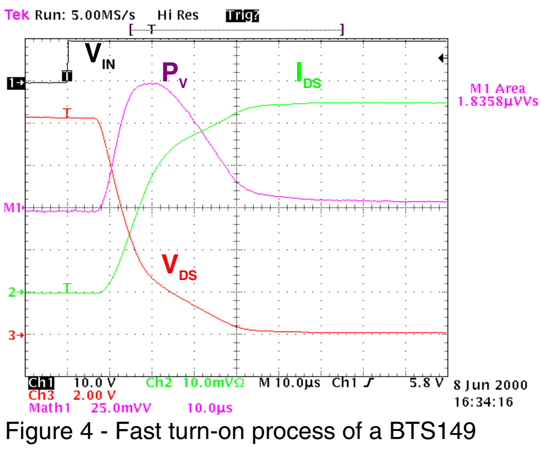


Figure 4 - Fast turn-on process of a BTS149

For a switching time of approx. 35 µs, this results in average switching losses of:

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \frac{\frac{1}{T_{Switching}} {}_{Tswitching} u \bullet i \bullet dt}{V_{bb} \bullet I_{nom}/4}$$

$$\frac{\overline{P}_{Switching}}{P_{Matching}} = \frac{\frac{1}{34\mu 4} \bullet \frac{1.83\mu.83}{0.005VVs} * W}{25W} = \underline{\underline{43\%}} \quad (6)$$

5. Switching capacitive loads

The following section deals with the switching losses associated with capacitive loads. These include for example RC networks or lamps whose time constants are much greater than the switching time of the device itself.
With capacitive loads, the losses produced in the device during each switching operation are again influenced exclusively by the load.
However, in the case of switch-on processes the power dissipation in the device during matching under rated conditions is less critical than the power dissipation during matching under inrush conditions.
This is given by formula (7) as

$$P'_{Matching} = \frac{V_{bb}}{2} \bullet \frac{I_{inrush}}{2} = \frac{V_{bb}{}^2}{4 \bullet R_{inrush}} \quad (7)$$

This will be designated “transient matching power” $P'_{Matching}$ in the following.

I_{inrush} is the maximum inrush current flowing and R_{inrush} the respective total resistance at the moment of switch-on.

In the case of lamps, I_{inrush} may well be 6 to 10 times I_{nom}. Consequently, for lamps the formula is usually:

$$P'_{Matching} = 6..10 \bullet P_{Matching} \quad (8)$$

In the case of RC networks, R_{inrush} results to a first approximation from all the resistances not “short circuited” by parallel capacitances. The following simple example illustrates this. From the resistances shown in Figure 5,

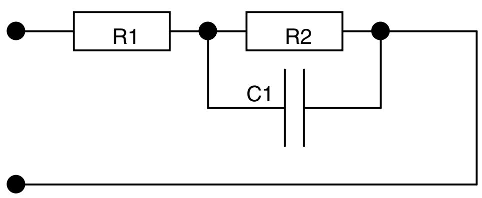


Figure 5 – Simple RC circuit

R1 results as the effective inrush resistance R_{inrush}.

5.1. Linear current and voltage characteristic

Linear current and voltage characteristics may be observed during slow switching processes where the switching time is, however, still well below the smallest time constant of the load. This may occur if a slowly rising input signal is applied to the device by an external triangular wave generator. This is possible, for example, in the case of FETs, TEMPFET® and HITFET® devices.
Analogously to Figure 1 and formula 3, the averaged switching losses are given by:

$$\frac{\bar{P}_{Switching}}{P'_{Matching}} = \frac{1}{6} \bullet \frac{4}{1} = \frac{2}{3} = \underline{\underline{67\%}}$$

$$\frac{\bar{P}_{Switching}}{P'_{Matching}} \approx 6..10 \bullet \left. \frac{\bar{P}_{Switching}}{P_{Matching}} \right|_{load-dependent} \qquad (9)$$

For slow switch-on processes the averaged power dissipations are therefore approx.70% of the “transient matching power”.
For slow switch-off processes a distinction must be drawn between how quickly the device is turned off again after switch-on.
If switch-off takes place immediately after switch-on, the averaged switching losses according to formula 9 are approx. 70% of the “transient matching power”.
If switch-off occurs after rated operation has been attained, the averaged switching losses according to formula 3 are approx. 70% of the matching power.

5.2. Piecewise linear current and voltage characteristic

Piecewise linear current and voltage characteristics may be observed with fast switching processes. This is the case when the device is driven via a low impedance directly by a driver. This is possible with discrete FETs, TEMPFET®, HITFET® and PROFET® devices.
Analogously to Figure 3 and formula 5, the averaged switching losses are given by:

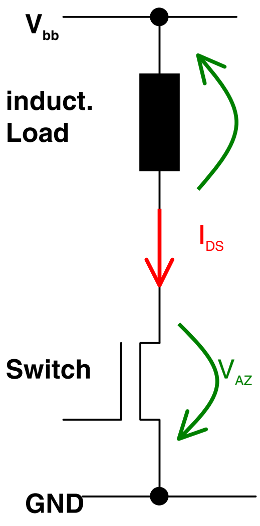
$$\frac{\bar{P}_{Switching}}{P'_{Matching}} = 0.116 \bullet \frac{4}{1} = \underline{\underline{46.\bar{6}\%}}$$

$$\frac{\bar{P}_{Switching}}{P'_{Matching}} \approx 6..10 \bullet \left. \frac{\bar{P}_{Switching}}{P_{Matching}} \right|_{load-dependent} \qquad (10)$$

For fast switch-on processes the effective power dissipations are therefore approx. 50% of the “transient matching power”.
For fast switch-off processes a distinction must be drawn between how quickly the device is turned off again after switch-on.
If switch-off takes place immediately after switch-on, the effective switching losses according to formula 9 are approx. 50% of the “transient matching power”.
If switch-off occurs after rated operation has been attained, the effective switching losses according to formula 3 are approx. 50% of the matching power.

6. Switching inductive loads

The following section deals with the switching losses associated with inductive loads. These include such loads as coils and valves which have no additional active freewheel circuitry (such as a freewheeling diode).
In the case of inductive loads, the losses produced in the device during each switching operation are influenced by the load and by the active Zener or avalanche voltage of the device.
If the switch-on time is much shorter than the time constant of the load, no switch-on losses must be taken into account. This is mostly the case. However, if the device switches off the inductive load from rated operation, the energy stored in the load inductance will be dissipated via the switching device. This process is known as commutation.



To a first approximation the switch-off losses are given by:

$$W_{tot} = W_L + W_{Vbb}$$

$$W_{tot} = \frac{1}{2} \bullet L \bullet I^2 + \int_0^{t_{Switching}} \left(V_{bb} \bullet i(t)\right) \bullet dt \qquad (11)$$

$$W_{tot} = \frac{1}{2} \bullet L \bullet I^2 + \frac{1}{2} \bullet V_{bb} \bullet I \bullet t_{switching}$$

With

$$V_L = V_{AZ} - V_{bb} = L \bullet \frac{di}{dt} = L \bullet \frac{I}{t_{Switching}} \qquad (12)$$

we get

$$W_{tot} = \frac{1}{2} \bullet L \bullet I^2 + \frac{1}{2} \bullet V_{bb} \bullet I^2 \bullet \frac{L}{V_{AZ} - V_{bb}}$$

$$W_{tot} = \frac{1}{2} \bullet L \bullet I^2 \left(1 + \frac{V_{bb}}{V_{AZ} - V_{bb}}\right) \qquad (13)$$

$$W_{tot} = \frac{1}{2} \bullet L \bullet I^2 \left(\frac{V_{AZ}}{V_{AZ} - V_{bb}}\right)$$

For each switch-off process the switching losses are therefore given by

$$P_{Switching} = \frac{W_{tot}}{t_{Switching}} \qquad (14)$$

7. Thermal considerations

The previous sections explained in greater detail how to determine the equivalent switching losses for various loads to a first approximation. This section will now attempt to clarify precisely what this means in terms of thermal loading of the device. In practice there are 2 cases which will be examined in detail below.

7.1. Non-repetitive switching

If a load is switched on or off on single occasions, a distinction can be drawn between the average switching losses produced as shown in the following table:

Load	Switching process	Switching time	Formula
resistive	ON	$T_{Switching}$ <<	5
		$t_{Switching}$ >>	3
	OFF	$t_{Switching}$ <<	5
		$t_{Switching}$ >>	3
capacitive	ON	$t_{Switching}$ <<	10
		$t_{Switching}$ >>	9
	OFF (immediately after switch-on)	$t_{Switching}$ <<	10
		$T_{Switching}$ >>	9
	OFF (during rated operation)	$t_{Switching}$ <<	5
		$t_{Switching}$ >>	3
inductive	OFF	/	14

Table 1 – Overview for determining the switching losses

Further examination of the thermal implications now requires precise knowledge of the thermal conditions of the application as a whole.
For short-duration switching operations up to a few milliseconds, the Z_{thjc} values specified in the data sheets can be used to a first approximation.
However, for longer switching operations, precise knowledge of the overall thermal conditions is necessary. For some products, the data sheet may also indicate how the thermal linkage behaves on a 6cm² copper PCB. If this coincides with the application, this can be taken as the basis.

To determine the temperature swing of a switching operation, the following steps must be followed:

measure the switching time $t_{switching}$
determine the thermal impedance $Z_{th}(t_{switching})$ from the data sheet
calculate the junction temperature of the device using formula 15:

$$\vartheta_j = P_{Switching} \bullet Z_{th}\left(t_{Switching}\right) + \vartheta_{amb} \qquad (15)$$

7.2. Repetitive switching (PWM operation)

If a load is repeatedly switched on or off, in most cases it must be ensured that the junction temperature is not exceeded during quasi-steady-state operation.
However, the on-state losses (P_v(on)) and the switching losses must be taken into account here.

For a device operated in PWM mode at a frequency $f_{Switching}$, we get:

$$P_v = P_{Switching(application)} + P_{R(ON)}\left(t_{ON}\right) \qquad (16)$$

The total switching losses $P_{switching\ (application)}$ are given by:

$$P_{Schalt(Applikation)} = \left(W_{Schalt(ON)} + W_{Schalt(OFF)}\right) \bullet f_{Schalt}$$
$$= \left(P_{Schalt(ON)} \bullet t_{(ON)} + P_{Schalt(OFF)} \bullet t_{(OFF)}\right) \bullet f_{Schalt} \qquad (17)$$

$P_{switching(ON)}$ being the switching losses for each switch-on process and $P_{switching(OFF)}$ being the losses for each switch-off process. These may differ depending on the application and are therefore detailed separately here.

The on-state losses, $P_{R(ON)}$ (t_{ON}), are given by:

$$P_{R(ON)}\left(t_{ON}\right) = P_{(ON)} \bullet duty\ \ cycle$$
$$= I_{load}^2 \bullet R_{ON}(150°C) \bullet t_{ON} \bullet f_{Switching} \qquad (18)$$

The average junction temperature of the device is therefore expressed by formula 19

$$\vartheta_j = P_{Switching} \bullet \left(R_{thjc} + R_{thca}\right) + \vartheta_{amb} \qquad (19)$$

7.3. Typical application

To illustrate the approximating calculation methods described before, one examples is given below.

Temperature swing of a BTS142D for a non-repetitive switch-on process
Given:
A BTS142D mounted on a 6cm² copper PCB is controlled externally by a triangular wave generator. The switching time is extended from the original typical switching time of 60µs to $t_{Switching}$=1ms.
The BTS142D drives a 1 ohm resistance as a load. The supply voltage V_{bb}=14 volts.

7.3.1. Required:

Of interest is the final temperature which the device attains after the switching process for an ambient temperature of 50°C.

7.3.2. Solution:

Using formula 2 we have

$$\hat{P}_{Switching\_max} = P_{Matching} = \frac{V_{bb}^{\ 2}}{4 \bullet R_{Load}} = \frac{(14V)^2}{4 \bullet 1\Omega} = 49W \qquad (20)$$

Assuming a linear current and voltage characteristic here, the averaged power dissipation according to formula 3 is given by:

$$\overline{P}_{Switching} = 0.67 \bullet P_{Matching} \approx 33W \qquad (21)$$

For a single pulse, the BTS142D data sheet gives an approximate $Z_{thJA(@6cm^2)}$=0.2K/W.

In accordance with formula 15, the final temperature is now therefore:

$$\vartheta_j = P_{Switching} \bullet Z_{th}\left(t_{Switching}\right) + \vartheta_{amb}$$

$$\vartheta_j = 33W \bullet 0.2K/W + 50°C = 56.6°C \qquad (22)$$

The device thus undergoes a temperature swing of approximately 6.6K and therefore attains a junction temperature of 56.6°C after the switch-on process.

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