CALCULATION OF MAJOR IGBT OPERATING PARAMETERS

This application note covers how to calculate major IGBT operating parameters
- power dissipation;
- continuous collector current;
- total power losses;
- junction temperature & heatsink;
- pulsed collector current

in a user specified environment using the datasheet as a source for device characteristics.

CONTENTS

1 CALCULATION OF POWER DISSIPATION

This section explains how to calculate the maximum allowable power dissipation in the IGBT for a specific case temperature using the datasheet parameters.

Input data from the datasheet:
R_{thJC} - thermal resistance junction-case;
$T_{j(max)}$ - maximum junction temperature.

Additional input information:
T_C - case temperature.

Solution:
The junction temperature rises due to power losses in the device

$$\Delta T = P_{tot} \cdot R_{thJC} \tag{1.1}$$

The difference between junction and case temperature is

$$\Delta T = T_j - T_c \tag{1.2}$$

Results:
The expression (1.3) shown below describes how to calculate the allowable power dissipation in an IGBT for desired junction and case temperatures

$$P_{tot} = \frac{\Delta T}{R_{thJC}} = \frac{T_j - T_c}{R_{thJC}} \tag{1.3}$$

where
R_{thJC} - thermal resistance junction to case;
T_c - case temperature;
T_j - junction temperature.

Example:
Assuming that $T_j = T_{j(max)}$ the maximum power dissipation can be calculated for different values of T_C

$$P_{tot(max)} = \frac{T_{j(max)} - T_c}{R_{thJC}} \tag{1.4}$$

Figure 1.1 shows the maximum power dissipation for an IGBT as a function of case temperature.

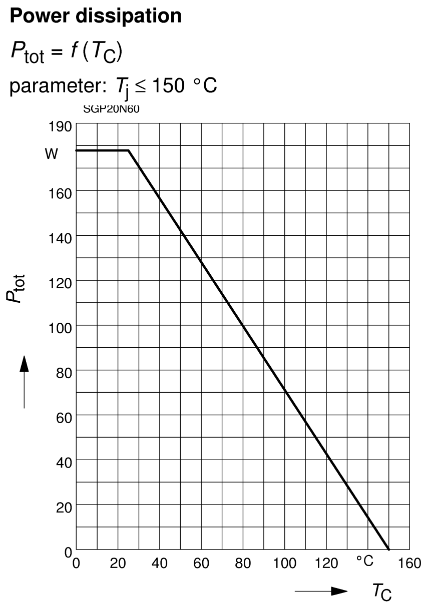


Figure 1.1: Power dissipation of SGP20N60.

Parameters in this example:

R_{thJC} = 0.7 K/W;
$T_{j(max)}$ = 150 °C.

2 CALCULATION OF MAXIMUM CONTINUOUS COLLECTOR CURRENT

This section illustrates how to calculate the maximum continuous collector current of IGBT for a specific case temperature using the datasheet parameters.

Input data from the datasheet:
R_{thJC} - thermal resistance junction-case;
$T_{j(max)}$ - maximum junction temperature;
output characteristic at $T_{j(max)}$.

Additional input information:
T_C - case temperature.

Solution:
The conduction power losses during the on-state of IGBT is the product of the collector current and the collector-emitter voltage drop at this desired current level.

$$P_{cond} = I_c \cdot V_{ce} \quad (2.1)$$

Collector-emitter saturation voltage depends on the collector current flowing through the IGBT. The output characteristic of IGBT at maximum junction temperature (Figure 2.1) can be used to calculate the conduction losses for different current levels. In order to simplify the analysis the output characteristic for a given gate-emitter voltage will be linearly interpolated (Figure 2.2).

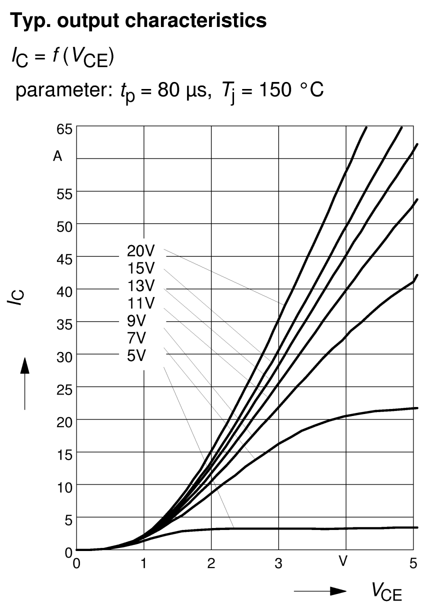


Figure 2.1: Typical output characteristic of SGP20N60 at $T_j = 150°C$.

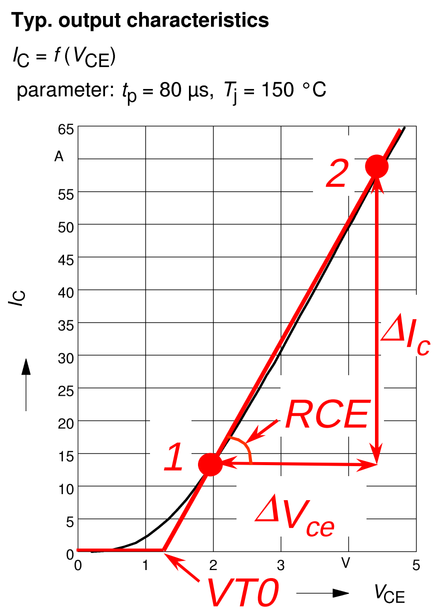


Figure 2.2: Linear interpolation of typ. output characteristic of SGP20N60 at $T_j = 150°C$.

The next equation (2.2) describes the interpolated curve of typical output characteristic.

$$V_{ce} = VT0 + RCE \cdot I_c \tag{2.2}$$

The $VT0$ parameter of the interpolated curve can be defined directly from the figure 2.2. The following equation (2.3) describes how to determinate the RCE parameter.

$$RCE = \frac{\Delta V_{ce}}{\Delta I_c} = \frac{V_{ce(2)} - V_{ce(1)}}{I_{c(2)} - I_{c(1)}} \tag{2.3}$$

Using the equation (1.1) for junction temperature increase due to power losses and equations (2.1) and (2.2) we will become the following equation (2.4).

$$\Delta T = P_{cond} \cdot R_{thJC} = I_c \cdot V_{ce} \cdot R_{thJC} = I_c \cdot \left(VT0 + RCE \cdot I_c \right) \cdot R_{thJC} \tag{2.4}$$

This equation (2.4) outlines the junction temperature increase in dependence of collector current. Solving it for I_c and using equation (1.2) we become

$$I_c = \frac{\sqrt{R_{thJC} \cdot VT0^2 + 4 \cdot RCE \cdot \left(T_{j(max)} - T_c \right)}}{2 \cdot \sqrt{R_{thJC} \cdot RCE}} - \frac{VT0}{2 \cdot RCE} \tag{2.5}$$

In order to calculate the maximum collector current we have to use the worst case output characteristic of IGBT. Usually only typical output characteristic can be found in the datasheet. The worst case output characteristic can be determined using the typical output characteristic and the typical and maximum values of collector-emitter saturation voltage in electrical characteristic table of the datasheet. The typical characteristic has to be moved to the right in direction of higher collector-emitter voltages (Figure 2.3).

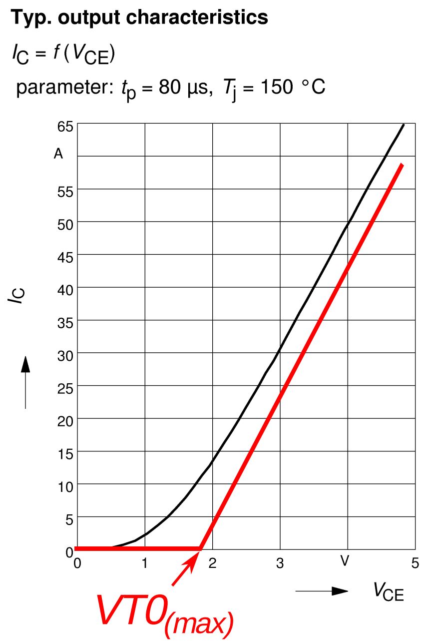


Figure 2.3: Typical output and worst case interpolated output characteristics of SGP20N60.

Parameters in this example:

RCE = 0.056 Ω;
VT0 = 1.28 V;
$VT0_{(max)}$ = 1.78 V.

The *RCE* parameter remains the same. But the *VTO* parameter has to be increased by the value of tolerance between typical and maximum values of collector-emitter saturation voltage at maximum junction temperature

$$VTO_{(max)} = VTO + \left[V_{ce(sat),(max)} - V_{ce(sat),(typ)} \right] \tag{2.6}$$

Results:
Using this equation (2.6) and (2.5) the maximum continuous collector current can be determined for different case temperatures

$$I_{c(max)} = \frac{\sqrt{R_{thJC} \cdot \left[VT0_{(max)} \right]^2 + 4 \cdot RCE \cdot \left(T_{j(max)} - T_c \right)}}{2 \cdot \sqrt{R_{thJC}} \cdot RCE} - \frac{VT0_{(max)}}{2 \cdot RCE} \tag{2.7}$$

where

R_{thJC}	- thermal resistance junction to case;
T_C	- case temperature;
$T_{j(max)}$	- maximum junction temperature;
$VT0_{(max)}$, *RCE*	- parameters of interpolated output characteristic.

Example:
Figure 2.4 shows the maximum continuous collector current for different values of case temperature.

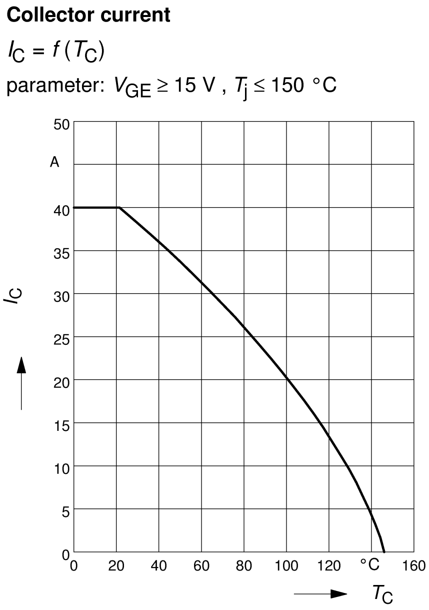


Figure 2.4: Continuous collector current of SGP20N60.

Parameters in this example:

RCE = 0.056 Ω;
$R_{thJC} = 0.7$ K/W;
$T_{j(max)} = 150$ °C;
$VT0_{(max)} = 1.78$ V.

3 CALCULATION OF POWER LOSSES

This section explains how to calculate the conduction and switching power losses in the IGBT from the actual circuit, including the current waveform, voltage and operating frequency using the datasheet parameters.

Input data from the datasheet:

output characteristic at $T_{j(max)}$;
collector-emitter saturation voltage vs. junction temperature;
switching losses vs. collector current at $T_{j(max)}$;
switching losses vs. gate resistor at $T_{j(max)}$;
switching losses vs. junction temperature.

Additional input information:

D	- duty cycle;
$\frac{di_c}{dt}$	- collector current turn on transient rate;
f	- switching frequency;
Q_{rr}, t_{rr}	- parameters of the user specific diode at these operation conditions;
T_C	- case temperature;
T_j	- junction temperature;
t_p	- pulse length;
R_G	- gate resistor;
$V_{DC(on)}$	- DC voltage at IGBT during the off state before the beginning of the turn-on transition;
$V_{DC(off)}$	- DC voltage at IGBT after the end of the turn-off transition.

Solution:
The energy dissipated in the IGBT can be obtained with the following expression

$$E_{tot} = \int_0^{t_p} v_{ce} \cdot i_c \, dt \qquad (3.1)$$

where t_p is the pulse length. Power is obtained by multiplying by frequency, for repetitive switching waveforms

$$P_{tot} = E_{tot} \cdot f \qquad (3.2)$$

In order to simplify the analysis the total power losses can be divided into conduction and switching losses

$$P_{tot} = P_{cond} + P_{switch} \qquad (3.3)$$

The losses during the off state of transistor are negligible and will be not discussed.

3.1 Conduction losses

Conduction losses occur between the end of the turn-on transition and the beginning of the turn-off transition. Using the equation 3.1 and interpolated output characteristic at $T_{j(max)}$ (equation 2.2) the conduction losses can be calculated for different waveforms of collector current.
Usually the junction temperature in the actual operation environment is lower as the $T_{j(max)}$. With the help of datasheet (figure 3.1) the output characteristic of the IGBT can be scaled to a given junction temperature.

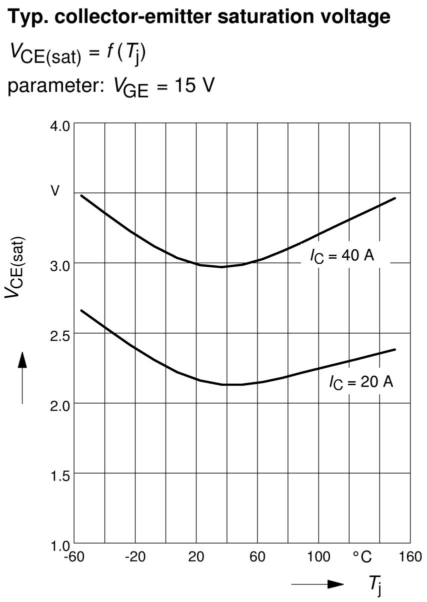


Figure 3.1: Collector-emitter saturation voltage vs. junction temperature for SGP20N60.

Parameters in this example:

$I_c = 20\ A$;
$T_{j(max)} = 150\ °C$ (from datasheet);
$T_j = 100\ °C$ (user specific);
$V_{ce(sat)}(T_{j(max)}) = 2.4\ V$;
$V_{ce(sat)}(T_j) = 2.25\ V$.

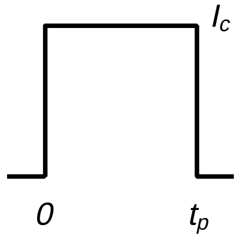
Scale factor for output characteristic for $T_j = 100\ °C$ is

$$\frac{2.25 \cdot V}{2.4 \cdot V} = 0.938$$

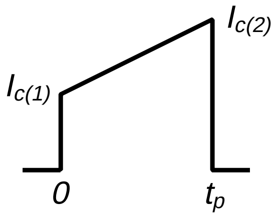
The next expression describes how to obtain the output characteristic at a given junction temperature:

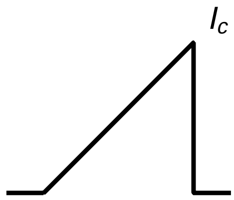
$$V_{ce} = \left(VT0 + RCE \cdot I_c\right) \cdot \frac{V_{ce(sat)}(T_j)}{V_{ce(sat)}(T_{j(max)})} \qquad (3.4)$$

Results:

<table>
<tr><td>Collector current waveform:

</td><td>Mathematical expression:
$i_c = I_c$</td></tr>
<tr><td colspan="2">Conduction energy losses for given pulse length:
$E_{cond} = I_c \cdot V_{ce} \cdot t_p = I_c \cdot \left(A \cdot I_c + B\right) \cdot t_p$ (3.5)

Conduction power losses for periodical signal with given duty cycle:
$P_{cond} = I_c \cdot V_{ce} \cdot D = I_c \cdot \left(A \cdot I_c + B\right) \cdot D$ (3.6)</td></tr>
</table>

<table>
<tr><td>Collector current waveform:

</td><td>Mathematical expression:
$i_c = I_{c(1)} + \left(I_{c(2)} - I_{c(1)}\right) \cdot \frac{t}{t_p}$</td></tr>
<tr><td colspan="2">Conduction energy losses for given pulse length:
$E_{cond} = \left[\frac{1}{2} \cdot A \cdot \left(I_{c(1)} + I_{c(2)}\right) + \frac{1}{3} \cdot B \cdot \left[\left(I_{c(1)}\right)^2 + I_{c(1)} \cdot I_{c(2)} + \left(I_{c(2)}\right)^2\right]\right] \cdot t_p$
(3.7)
Conduction power losses for periodical signal with given duty cycle:
$P_{cond} = \left[\frac{1}{2} \cdot A \cdot \left(I_{c(1)} + I_{c(2)}\right) + \frac{1}{3} \cdot B \cdot \left[\left(I_{c(1)}\right)^2 + I_{c(1)} \cdot I_{c(2)} + \left(I_{c(2)}\right)^2\right]\right] \cdot D$
(3.8)</td></tr>
</table>

<table>
<tr><td>Collector current waveform:

</td><td>Mathematical expression:
$i_c = I_c \cdot \frac{t}{t_p}$</td></tr>
<tr><td colspan="2">Conduction energy losses for given pulse length:
$E_{cond} = \frac{1}{6} \cdot I_c \cdot t_p \cdot \left(2 \cdot A \cdot I_c + 3 \cdot B\right)$ (3.9)

Conduction power losses for periodical signal with given duty cycle:
$P_{cond} = \frac{1}{6} \cdot I_c \cdot D \cdot \left(2 \cdot A \cdot I_c + 3 \cdot B\right)$ (3.10)</td></tr>
</table>

where

$A = RCE \cdot \frac{V_{ce(sat)}(T_j)}{V_{ce(sat)}(T_{j(max)})}$ $\qquad$ $B = VT0 \cdot \frac{V_{ce(sat)}(T_j)}{V_{ce(sat)}(T_{j(max)})}$

$D = t_p / T$ - duty cycle;
t_p - pulse length;
$VT0$, RCE - parameters of interpolated output characteristic.

These expressions (3.5-3.10) describe the conduction losses of the IGBT with typical output characteristic. Sometimes it is necessary to calculate the worst case conduction losses with worst case output characteristic. The same method as described in section 2 (equation 2.6) can be used to obtain the worst case conduction losses. The $VT0$ parameter has to be changed to $VT0_{(max)}$.

3.2 Switching losses

No simple expression can be found for the voltage and current during a switching transient. The datasheet parameters concerning the switching losses have to be used in this case. These parameters are referenced to a specific test circuit that simulates a clamped inductive load operated with a specific diode. In actual power circuit the diode used might be different than the diode specified in the datasheet. In this case the calculation of turn-on losses (equation 3.1) has to be made using the parameters of this particular diode.

Solution:
The switching losses in IGBT during one period of a periodical signal include the turn-on and turn-off losses

$$P_{switch} = \left(E_{on} + E_{off}\right) \cdot f \qquad (3.11)$$

In order to calculate the switching losses the dependence from the collector current has to taken into account. This information can be found in the datasheet (Figure 3.2).

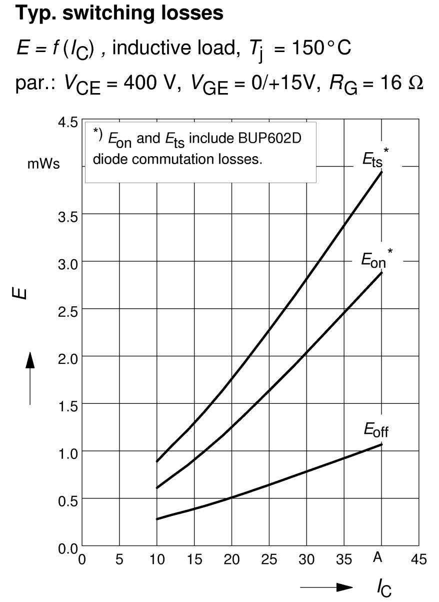


Figure 3.2: Typical switching losses at $T_{j(max)}$ of SGP20N60.

Parameters in this example:

$A_{on} = 0.0755$ mJ/A;
$B_{on} = -0.149$ mJ;
$A_{off} = 0.026$ mJ/A;
$B_{off} = 0.02$ mJ.

The values at the desired current level can be easily found from these curves or the linear interpolation of these curves can be made to simplify the analysis for different current levels. The same methodic as by interpolation of output characteristic (equation 2.2) can be used in this case.
Next equation (3.12) describes the interpolated curve of turn-on losses

$$E_{on} = A_{on} \cdot I_c + B_{on} \tag{3.12}$$

with

$$A_{on} = \frac{\Delta E_{on}}{\Delta I_c} = \frac{E_{on(2)} - E_{on(1)}}{I_{c(2)} - I_{c(2)}} \qquad B_{on} = E_{on(2)} - A_{on} \cdot I_{c(2)}$$

The turn-off losses curve can be interpolated in the similar way

$$E_{off} = A_{off} \cdot I_c + B_{off} \tag{3.13}$$

with

$$A_{off} = \frac{\Delta E_{off}}{\Delta I_c} = \frac{E_{off(2)} - E_{off(1)}}{I_{c(2)} - I_{c(2)}} \qquad B_{off} = E_{off(2)} - A_{off} \cdot I_{c(2)}$$

If the gate resistor of a users' gate drive does not have the same value as the gate resistor in the test circuit specified in the datasheet some correction may be necessary. This can be done with the help of datasheet (figure 3.3).

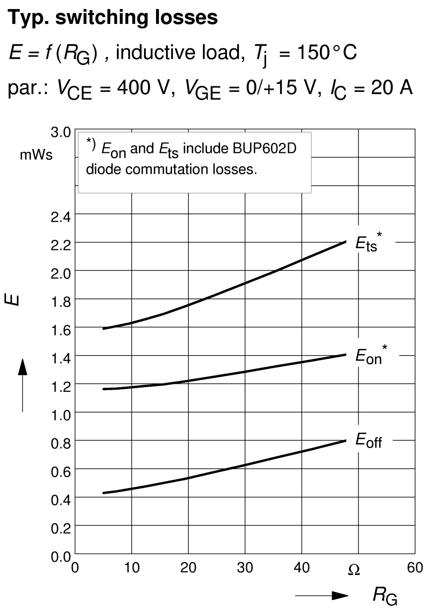


Figure 3.3: Typical switching losses as a function of gate resistor for SGP20N60.

Parameters in this example:

$R_G = 16\ \Omega$ (from datasheet);
$R_G = 30\ \Omega$ (user specific);
$E_{on}(R_{G,datasheet}) = 1.2$ mJ;
$E_{on}(R_{G,user\ specific}) = 1.3$ mJ;
$E_{off}(R_{G,datasheet}) = 0.5$ mJ;
$E_{off}(R_{G,user\ specific}) = 0.65$ mJ.

Scale factor for E_{on} is

$$\frac{1.3 \cdot mJ}{1.2 \cdot mJ} = 1.083$$

Scale factor for E_{off} is

$$\frac{0.65 \cdot mJ}{0.5 \cdot mJ} = 1.3$$

In order to obtain the switching losses at desired gate resistor the switching losses from the equations 3.12 and 3.13 have to be scaled using the information from figure 3.3 for the user specific R_G and the R_G used in datasheets' test circuit (figure 3.2):

$$E_{on} = \left(A_{on} \cdot I_c + B_{on}\right) \cdot \frac{E_{on}(R_{G,\ user\ specific})}{E_{on}(R_{G,\ datasheet})} \tag{3.14}$$

$$E_{off} = \left(A_{off} \cdot I_c + B_{off}\right) \cdot \frac{E_{off}(R_{G,\ user\ specific})}{E_{off}(R_{G,\ datasheet})} \tag{3.15}$$

Since the switching energy is proportional to voltage, the result is scaled by ratio of the actual circuit voltage to the test voltage in the datasheet:

$$E_{on} = \left(A_{on} \cdot I_c + B_{on}\right) \cdot \frac{E_{on}(R_{G,\ user\ specific})}{E_{on}(R_{G,\ datasheet})} \cdot \frac{V_{DC(on),\ user\ specific}}{V_{DC,\ datasheet}} \tag{3.16}$$

$$E_{off} = \left(A_{off} \cdot I_c + B_{off}\right) \cdot \frac{E_{off}(R_{G,\ user\ specific})}{E_{off}(R_{G,\ datasheet})} \cdot \frac{V_{DC(off),\ user\ specific}}{V_{DC,\ datasheet}} \tag{3.17}$$

Finally, the actual junction temperature has to be taken into account. Figure 3.4 shows the dependence of switching losses on the junction temperature.

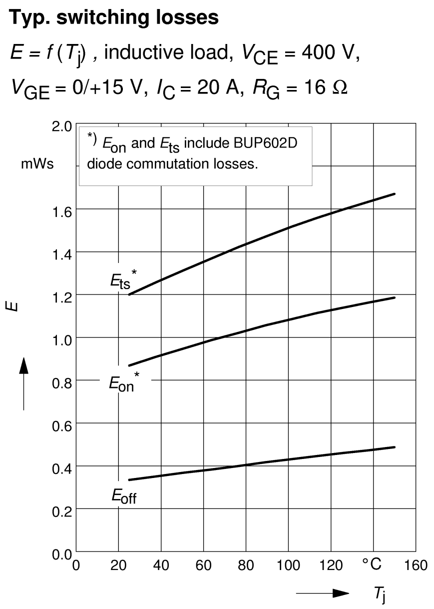


Figure 3.4: Switching losses as a function of junction temperature for SGP20N60.

Parameters in this example:

$I_c = 20\ A$;
$T_{j(max)} = 150\ °C$ (from datasheet);
$T_j = 100\ °C$ (user specific);
$E_{on}\ (T_{j(max)}) = 1.2\ mJ$;
$E_{on}\ (T_j) = 1.09\ mJ$;
$E_{off}\ (T_{j(max)}) = 0.5\ mJ$;
$E_{off}\ (T_j) = 0.42\ mJ$.
Scale factor for E_{on} at $T_j = 100\ °C$ is

$$\frac{1.09 \cdot mJ}{1.2 \cdot mJ} = 0.908$$

Scale factor for E_{off} at $T_j = 100\ °C$ is

$$\frac{0.42 \cdot mJ}{0.5 \cdot mJ} = 0.84$$

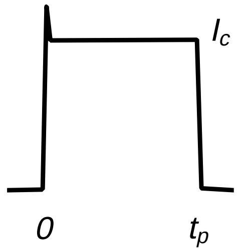
The next expressions outline how to obtain the switching losses for desired operating conditions (collector current, gate resistor, DC voltage and junction temperature) from the datasheet:

$$E_{on} = \left(A_{on} \cdot I_c + B_{on}\right) \cdot \frac{E_{on}\ (R_{G,\ user\ specific})}{E_{on}\ (R_{G,\ datasheet})} \cdot \frac{V_{DC(on),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{on}\ (T_j)}{E_{on}\ (T_{j(max)})} \quad (3.18)$$

$$E_{off} = \left(A_{off} \cdot I_c + B_{off}\right) \cdot \frac{E_{off}\ (R_{G,\ user\ specific})}{E_{off}\ (R_{G,\ datasheet})} \cdot \frac{V_{DC(off),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{off}\ (T_j)}{E_{off}\ (T_{j(max)})} \quad (3.19)$$

Results:

Using equations 3.12-3.19 some modifications can be done in order to get readable results.

Collector current waveform:	Mathematical expression:
	$i_c = I_c$

Turn-on energy losses with the diode specified in the datasheet:

$$E_{on} = A1 \cdot I_c + B1 \qquad (3.20)$$

Turn-on energy losses with the user specific diode:

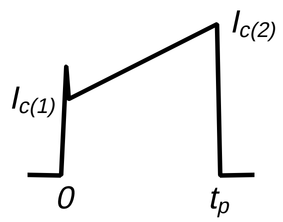
$$E_{on} = \frac{1}{2} \cdot \frac{\left(I_c + \frac{2 \cdot Q_{rr}}{t_{rr}} \right)^2}{\frac{di_c}{dt}} \cdot V_{DC(on),\ user\ specific} + \qquad (3.21)$$

$$+ \frac{1}{6} \cdot \left[t_{rr} - \frac{2 \cdot Q_{rr}}{t_{rr} \cdot \frac{di_c}{dt}} \right] \cdot \left(\frac{4 \cdot Q_{rr}}{t_{rr}} + 3 \cdot I_c \right) \cdot V_{DC(on),\ user\ specific}$$

Turn-off energy losses:

$$E_{off} = A2 \cdot I_c + B2 \qquad (3.22)$$

Collector current waveform:



Mathematical expression:

$$i_c = I_{c(1)} + \left(I_{c(2)} - I_{c(1)}\right)\cdot\frac{t}{t_p}$$

Turn-on energy losses with the diode specified in the datasheet:

$$E_{on} = A1\cdot I_{c(1)} + B1 \qquad (3.23)$$

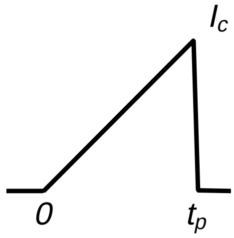
Turn-on energy losses with the user specific diode:

$$E_{on} = \frac{1}{2}\cdot\frac{\left(I_{c(1)} + \frac{2\cdot Q_{rr}}{t_{rr}}\right)^2}{\frac{di_c}{dt}}\cdot V_{DC(on),\ user\ specific} + \frac{1}{6}\cdot\left[t_{rr} - \frac{2\cdot Q_{rr}}{t_{rr}\cdot\frac{di_c}{dt}}\right]\cdot\left(\frac{4\cdot Q_{rr}}{t_{rr}} + 3\cdot I_{c(1)}\right)\cdot V_{DC(on),\ user\ specific} \qquad (3.24)$$

Turn-off energy losses:

$$E_{off} = A2\cdot I_{c(2)} + B2 \qquad (3.25)$$

Collector current waveform:



Mathematical expression:

$$i_c = I_c\cdot\frac{t}{t_p}$$

Turn-on energy losses is negligible:

$$E_{on} = 0 \qquad (3.26)$$

Turn-off energy losses:

$$E_{off} = A2\cdot I_c + B2 \qquad (3.27)$$

where

$$A1 = A_{on} \cdot \frac{E_{on}(R_{G,\ user\ specific})}{E_{on}(R_{G,\ datasheet})} \cdot \frac{V_{DC(on),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{on}(T_j)}{E_{on}(T_{j(max)})}$$

$$B1 = B_{on} \cdot \frac{E_{on}(R_{G,\ user\ specific})}{E_{on}(R_{G,\ datasheet})} \cdot \frac{V_{DC(on),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{on}(T_j)}{E_{on}(T_{j(max)})}$$

$$A2 = A_{off} \cdot \frac{E_{off}(R_{G,\ user\ specific})}{E_{off}(R_{G,\ datasheet})} \cdot \frac{V_{DC(off),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{off}(T_j)}{E_{off}(T_{j(max)})}$$

$$B2 = B_{off} \cdot \frac{E_{off}(R_{G,\ user\ specific})}{E_{off}(R_{G,\ datasheet})} \cdot \frac{V_{DC(off),\ user\ specific}}{V_{DC,\ datasheet}} \cdot \frac{E_{off}(T_j)}{E_{off}(T_{j(max)})}$$

A_{on}, B_{on}, A_{off}, B_{off} - parameters of interpolated curve for switching losses;

$\frac{di_c}{dt}$ - collector current turn-on transient rate;

Q_{rr}, t_{rr} - parameters of the diode at these operation conditions;

T_j - actual junction temperature;

$V_{DC(on)}$ - DC voltage at IGBT during the off state before the beginning of the turn-on transition;

$V_{DC(off)}$ - DC voltage at IGBT after the end of the turn-off transition.

3.3 Total power losses

Total power losses for periodical signal can be calculated as the sum of conduction (section 3.1) and switching (section 3.2) losses:

Results:

$$P_{tot} = P_{cond} + \left(E_{on} + E_{off}\right) \cdot f \tag{3.28}$$

Due to the trade off between conduction and switching losses inherent in IGBT technology it is unlikely that the one and the same IGBT will have the performance of both worst case conduction and worst case switching losses. In order to calculate the worst case power losses in the IGBT it is useful to use the worst case conduction losses and the typical switching losses.

$$P_{tot(max)} = P_{cond(max)} + \left(E_{on} + E_{off}\right) \cdot f \tag{3.29}$$

where

$P_{cond\,(max)}$ - worst case conduction losses (calculated in section 3.1);
E_{on}, E_{off} - typical turn-on and turn-off switching losses (calculated in section 3.2);
f - switching frequency.

Example:

Figures 3.5 and 3.6 show the total power losses in the IGBT in dependence on switching frequency for the following operating conditions:

$I_c = 20\ A$	- peak of collector current;
$V_{DC(on)} = 300\ V$	- DC voltage at IGBT during the off state before the beginning of the turn-on transition;
$V_{DC(off)} = 300\ V$	- DC voltage at IGBT after the end of the turn-off transition;
$R_G = 30\ \Omega$;	- gate resistor;
$T_j = 100\ °C$.	- junction temperature.

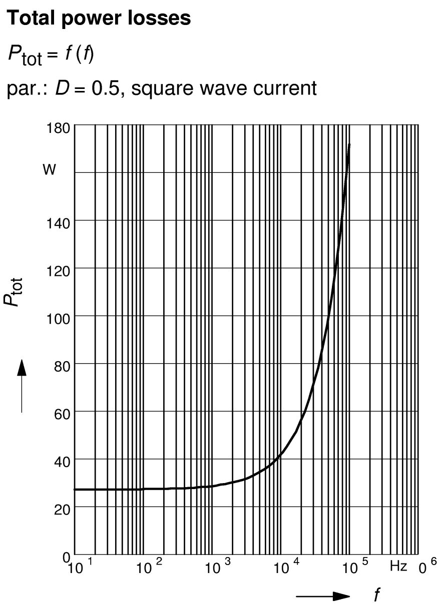


Figure 3.5: Total power losses in case of a square wave collector current of SGP20N60.

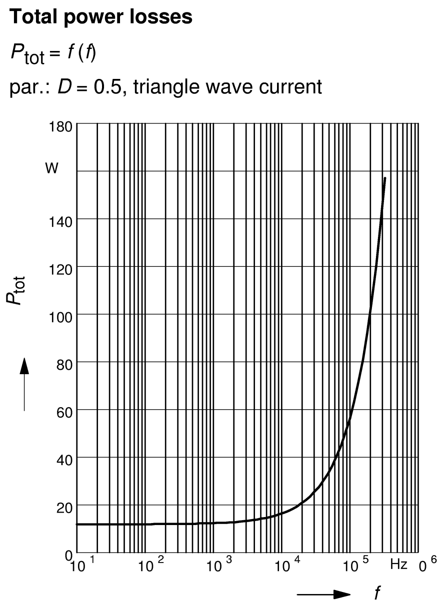


Figure 3.6: Total power losses in case of a triangle wave collector current of SGP20N60.

4 CALCULATION OF JUNCTION TEMPERATURE AND HEATSINK

This section describes how to calculate the junction temperature of IGBT and how to select the heatsink for a given operating condition using the datasheet parameters.

Input data from the datasheet:

R_{thJC} – thermal resistance junction to case;
Z_{thJC} – transient thermal impedance junction to case.

Additional input information:

$P_{tot(max)}$ - worst case total power losses (calculated in section 3);
R_{thCS} - thermal resistance case to heatsink;
R_{thJC} - thermal resistance junction to case;
R_{thSA} - thermal resistance heatsink to ambient;
T_A - ambient temperature.

Solution:

The junction temperature can be calculated using the thermal resistance R_{thJC}. This is suitable for the DC collector current. But in case of pulsed collector current the more accurate results can be obtained if the transient thermal impedance junction-case Z_{thJC} is used. The transient thermal impedance is a function of duty cycle and pulse length or switching frequency:

$$Z_{thJC} = \sum_{j=0}^{n} R_j \cdot \frac{1 - e^{-\frac{t_p}{\tau_j}}}{1 - e^{-\frac{t_p}{\tau_j \cdot D}}} = \sum_{j=0}^{n} R_j \cdot \frac{1 - e^{-\frac{D}{\tau_j \cdot f}}}{1 - e^{-\frac{1}{\tau_j \cdot f}}} \qquad (4.1)$$

Figure 4.1 demonstrates the transient thermal impedance of SGP20N60 for different values of duty cycle and pulse duration.

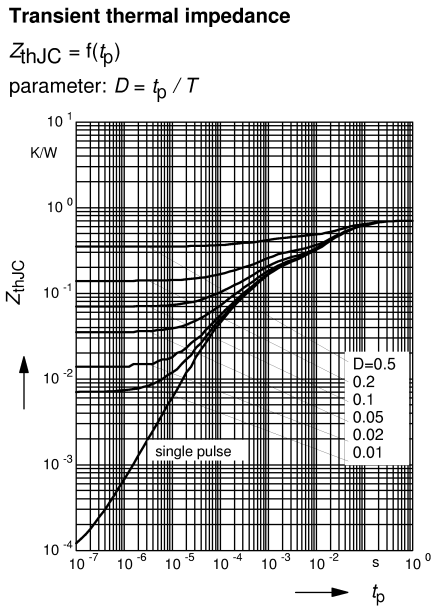
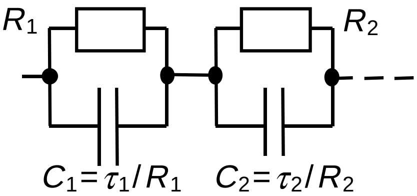


Figure 4.1: Transient thermal impedance of SGP20N60.

Parameters in this example:

R_j, K/W	τ_j, s
0.1882	0.1137
0.3214	2.24e-2
0.1512	7.86e-4
0.0392	9.41e-5



The difference between junction and case temperatures can be obtained using the information of worst case total power losses (section 3.3) and transient thermal impedance for desired values of duty cycle and switching frequency

$$T_j - T_c = P_{tot(max)} \cdot Z_{thJC} \qquad (4.2)$$

Results:
The junction temperature for the defined case temperature, duty cycle and switching frequency is

$$T_j = P_{tot(max)} \cdot Z_{thJC} + T_c \qquad (4.3)$$

The following expression describes how to select the heatsink that keeps the junction at, or below, a given temperature

$$R_{thSA} = \frac{T_j - T_A}{P_{tot(max)}} - Z_{thJC} - R_{thCS} \qquad (4.4)$$

where

$P_{tot(max)}$	- worst case total power losses;
R_{thCS}	- thermal resistance case to heatsink;
R_{thSA}	- thermal resistance heatsink to ambient;
T_A	- ambient temperature;
T_j	- junction temperature;
Z_{thJC}	- transient thermal impedance junction to case for given duty cycle and switching frequency.

Example:
Calculation of the junction temperature for a given operating condition:

$D = 0.5$ - duty cycle;
$f = 75\ kHz$ - switching frequency;
$T_C = 80\ °C$ - case temperature;
$P_{tot(max)} = 45\ W$ - total power losses.

The transient thermal impedance for this duty cycle and this switching frequency from figure 4.1 ($t_p = 6.67\ us$) is $Z_{thJC} = 0.35\ K/W$. Using the equation 4.3 the junction temperature can be calculated:

$$T_j = 45 \cdot W \cdot 0.35 \cdot \frac{K}{W} + 80 \cdot °C = 95.75 \cdot °C$$

In order to keep the junction below a given temperature the right heatsink has to be chosen. The required thermal resistance of a heatsink can be obtained from the equation 4.4 using input data from above plus some additional information:

$R_{thCS} = 0.45\ K/W$ - thermal resistance case to heatsink;
$T_A = 40\ °C$ - ambient temperature;
$T_j = 100\ °C$ - junction temperature.

$$R_{thSA} = \frac{100 \cdot °C - 40 \cdot °C}{45 \cdot W} - 0.35 \cdot \frac{K}{W} - 0.45 \cdot \frac{K}{W} = 0.53 \cdot \frac{K}{W}$$

5 CALCULATION OF JUNCTION TEMPERATURE AND POWER LOSSES

In the previous two sections we have explained how to calculate the power losses and the junction temperature. In this section we present an algorithm how calculate both these parameters in a specific application environment.

Solution:
Since the junction temperature affects conduction and switching losses, which, in turn, affect the junction temperature, a direct mathematical solution is not possible. However, if we apply the calculations introduced in sections 3 and 4 iteratively, we will get the results for a given operating condition in very few iterations.

Results:

Step:	Action:	Input:	Output:	Described in section:
1	Assume that $T_{j(n-1)} = T_{j(max)}$	$T_{j(max)}$	$T_{j\,(n-1)}$	-
2 (n-1)	Calculate the total power losses $P_{tot(n-1)}$ at this junction temperature $T_{j(n-1)}$	$T_{j(n-1)}$	$P_{tot(n-1)}$	3
3 (n)	Calculate the junction temperature $T_{j(n)}$ at these total power losses $P_{tot(n-1)}$	$P_{tot(n-1)}$	$T_{j(n)}$	4
4 (n)	Compare difference between the junction temperature from current iteration $T_{j(n)}$ and junction temperature from the previous iteration $T_{j(n-1)}$ with a given precision ΔT_j (usually 5-10°C) *if* $T_{j(n-1)} - T_{j(n)} < \Delta T_j$ *then stop the iterations;* *otherwise - next iteration* *(n=n+1 & go to step 2).*	ΔT_j, $T_{j(n-1)}$, $T_{j(n)}$	Decision to continue or to finish the iterations	-

6 CALCULATION OF PULSED COLLECTOR CURRENT

This section describes how to calculate periodically pulsed collector current for given operation conditions: duty cycle, switching frequency and case temperature.

Input data from the datasheet:

Z_{thJC} - transient thermal impedance junction-case;
$T_{j(max)}$ - maximum junction temperature;
output characteristic at $T_{j(max)}$;
switching losses vs. collector current at $T_{j(max)}$.

Additional input information:

D	- duty cycle;
$\frac{di_c}{dt}$	- collector current turn on transient rate;
f	- switching frequency;
Q_{rr}, t_{rr}	- parameters of the diode at these operation conditions;
T_C	- case temperature;
$V_{DC(on)}$	- DC voltage at IGBT during the off state before the beginning of the turn-on transition.

Solution:

The maximum power dissipation for a given operating condition can be calculated using the transient thermal impedance at this particular duty cycle and switching frequency.

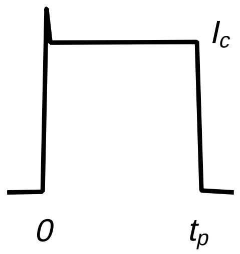
$$P_{tot(max)} = \frac{T_{j(max)} - T_c}{Z_{thJC}} \tag{6.1}$$

The total power losses in the IGBT are described by expressions (3.1) and (3.2) combining these we will get the following equation

$$P_{tot} = f \cdot \int_0^{t_p} v_{ce} \cdot i_c \, dt \tag{6.2}$$

Combining the equations (6.1) and (6.2) the information about the maximum pulsed collector current can be obtained.

Results:

Collector current waveform:	Mathematical expression:
	$i_c = I_c$

Maximum pulsed collector current of IGBT with the diode specified in the datasheet:

$$I_{c(max)} = \frac{\sqrt{B^2 + 4 \cdot A \cdot \left[\left(T_{j(max)} - T_c \right) - C \right]} - B}{2 \cdot A} \qquad (6.3)$$

where:

$$A = D \cdot RCE \cdot Z_{thJC}$$

$$B = \left[D \cdot VT0_{(max)} + \left(A_{on} + A_{off} \right) \cdot f \right] \cdot Z_{thJC}$$

$$C = \left(B_{on} + B_{off} \right) \cdot f \cdot Z_{thJC}$$

Maximum pulsed collector current of with the user specific diode:

$$I_{c(max)} = \frac{\sqrt{B^2 + 4 \cdot A \cdot \left[\left(T_{j(max)} - T_c \right) - C \right]} - B}{2 \cdot A} \qquad (6.4)$$

where:

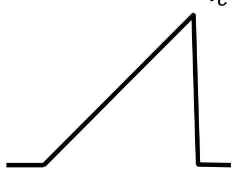
$$A = \left(RCE \cdot D + \frac{1}{2} \cdot V_{DC(on),\ user\ specific} \cdot \frac{f}{\frac{di_c}{dt}} \right) \cdot Z_{thJC}$$

$$B = \left[\frac{1}{2} \cdot V_{DC(on),\ user\ specific} \cdot t_{rr} + A_{off} + Q_{rr} \cdot \frac{V_{DC(on),\ user\ specific}}{\left(\frac{di_c}{dt} \cdot t_{rr} \right)} \right] \text{x}$$

$$\text{x} \; Z_{thJC} \cdot f + VT0_{(max)} \cdot D \cdot Z_{thJC}$$

$$C = \left[\frac{2}{3} \cdot Q_{rr} \cdot V_{DC(on),\ user\ specific} + \right.$$

$$\left. + B_{off} + \frac{2}{3} \cdot \left(Q_{rr} \right)^2 \cdot \frac{V_{DC(on),\ user\ specific}}{\left[\frac{di_c}{dt} \cdot \left(t_{rr} \right)^2 \right]} \right] \cdot Z_{thJC} \cdot f$$

<table>
<tr><td>Collector current waveform:

</td><td>Mathematical expression:
$i_c = I_c \cdot \frac{t}{t_p}$</td></tr>
<tr><td colspan="2">Maximum pulsed collector current of IGBT with the diode specified in the datasheet:
$$I_{c(max)} = \frac{\sqrt{B^2 + 4 \cdot A \cdot \left[\left(T_{j(max)} - T_c \right) - C \right]} - B}{2 \cdot A} \qquad (6.5)$$
where:
$A = \frac{1}{3} \cdot D \cdot RCE \cdot Z_{thJC}$
$B = \left[\frac{1}{2} \cdot VT0_{(max)} \cdot D + f \cdot A_{off} \right] \cdot Z_{thJC}$
$C = f \cdot B_{off} \cdot Z_{thJC}$</td></tr>
</table>

where

A_{on}, B_{on}, A_{off}, B_{off}	- parameters of interpolated curve for switching losses;
D	- duty cycle;
$\frac{di_c}{dt}$	- collector current turn-on transient rate;
f	- switching frequency;
Q_{rr}, t_{rr}	- parameters of the diode at these operation conditions;
T_C	- case temperature;
$V_{DC(on)}$	- DC voltage at IGBT during the off state before the beginning of the turn-on transition;
$VT0$, RCE	- parameters of interpolated output characteristic;
Z_{thJC}	- transient thermal impedance junction to case for given duty cycle and switching frequency.

Example:
The examples of pulsed collector current for SGP20N60 are shown in Figures 6.1 and 6.2.

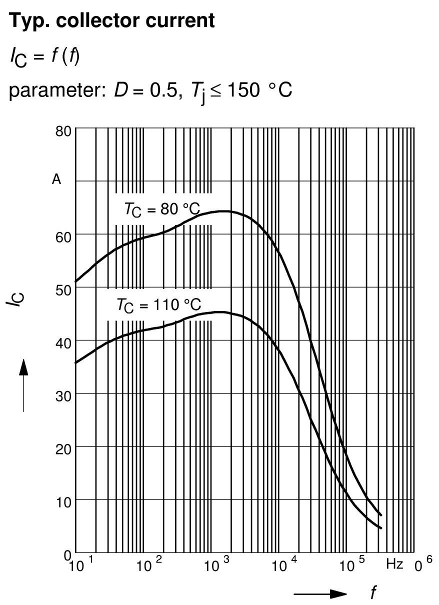


Figure 6.1: Amplitude of a square wave collector current of SGP20N60

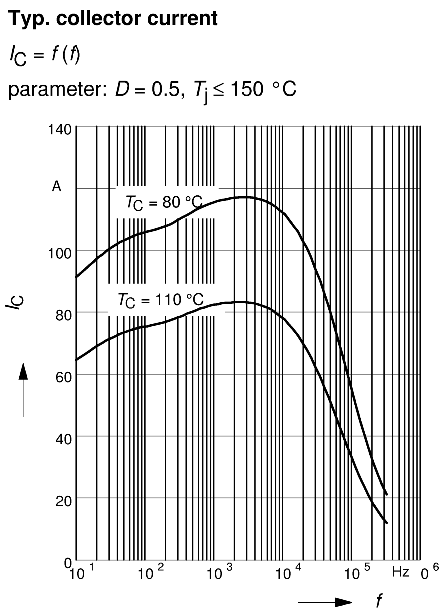


Figure 6.2: Peak of a triangle wave collector current of SGP20N60

7 SAFE OPERATING AREA

This section describes how to evaluate the thermal calculation of the pulsed collector current described above using the datasheet.

Input data from the datasheet:
Safe operating area.

Additional input information:
Pulsed collector current (calculated in section 6).

Results:
The calculations of pulsed collector current described in section 6 are based only on the thermal behavior of IGBT. The peak collector current must not exceed the safe operating area limits.

Example:
Figure 7.1 shows the safe operating area of SGP20N60.

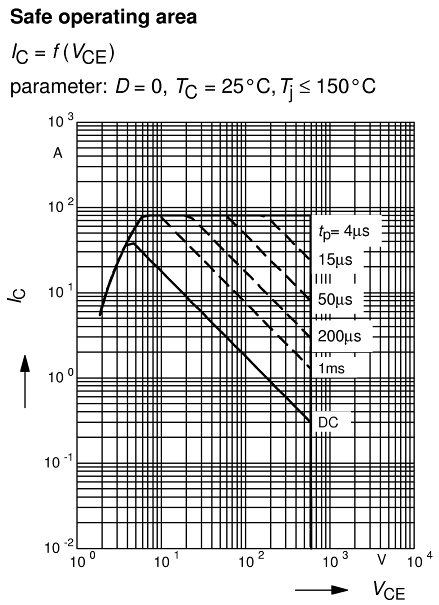


Figure 7.1: safe operating area of SGP20N60.

The maximum peak collector current is 80 A for SGP20N60. The calculated curves do not exceed this limit of 80 A in case of square wave collector current (Figure 7.2). If the collector current has a triangle waveform (Figure 7.3) the calculated curves for both case temperatures exceed the limit of SOA at some frequencies. In this case the peak collector current has to be limited to 80 A for these frequencies.

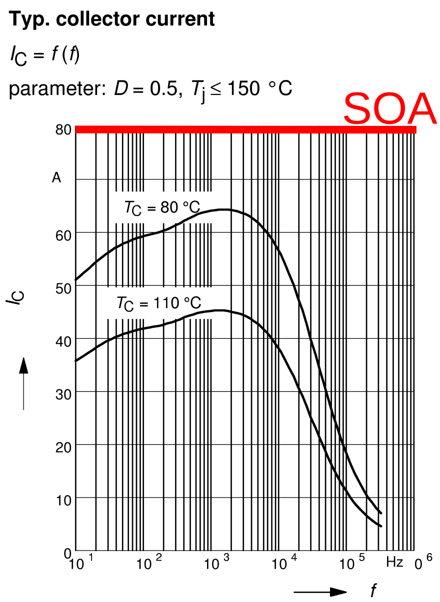


Figure 7.2: peak of a square wave collector current of SGP20N60 and SOA limit

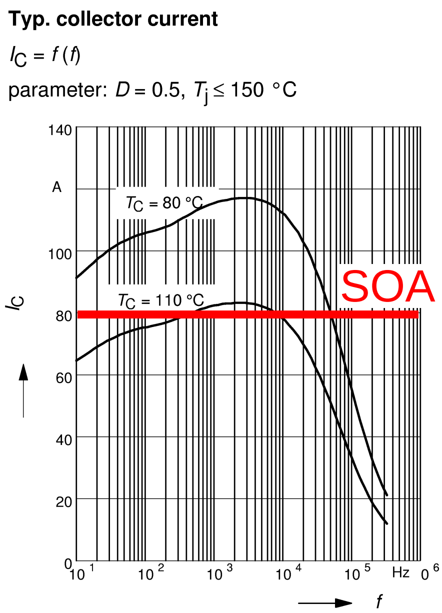


Figure 7.3: peak of a triangle wave collector current of SGP20N60 and SOA limit