Diode D2:
Provided that the energy dissipation during turn-off is linearly dependent on the diode current, the total power dissipation of a diode may be calculated with:

$$P_{off/D2} = \frac{1}{\pi} \cdot f_s \cdot E_{off/D}\left(\hat{i}_1\right) \quad (3.8)$$

This equation is also based on the assumption that the diode switching losses generated during one sine half-wave are about identical to the switching losses generated, if an equivalent direct current is applied, which would correspond to the average value of the sine half-wave.

Diode switching losses are approximately convertible linearly to other DC-link voltages.

The results rendered by the explained simplified calculation process are sufficient for estimating the expected power dissipation during converter operation mode in practice.
The decisive advantage that is offered to the user is that all necessary parameters can be taken directly from the corresponding module datasheets.

3.2.2 Calculation of the junction temperature

3.2.2.1 General hints

The calculation of junction temperatures is based on the simplified thermal equivalent block diagram of Figure 3.8.
The designations used for transistor and diode are related to those in Figure 3.5.
The equivalent block diagram is restricted to one transistor and its commutating diode in a power module, i.e. to those two components through which the load current is conducted during one sine half-wave (here T1 and D2). The equivalent block diagram for T2 and D1 can be drawn up in analogy.

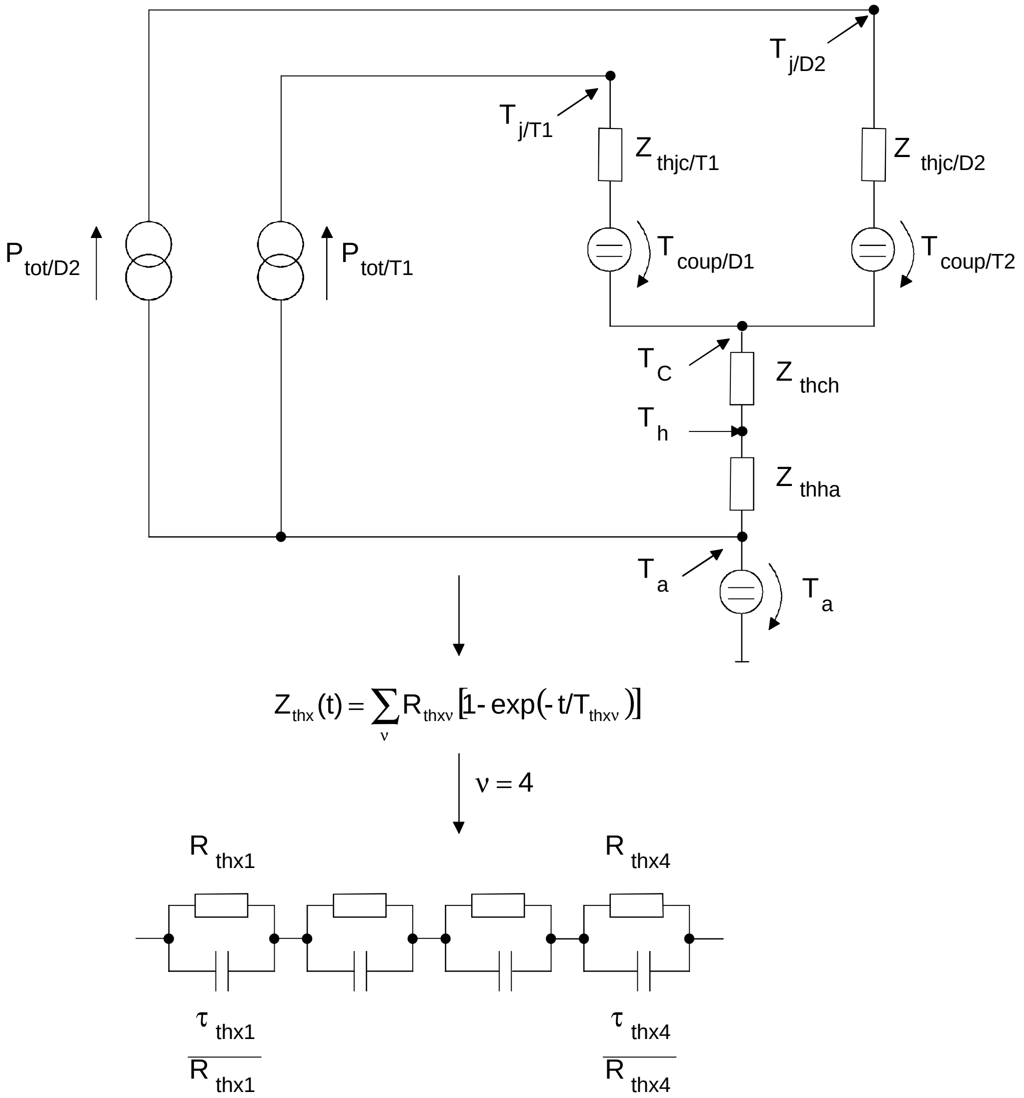

Figure 3.8 Simplified thermal equivalent block diagram of IGBT and free-wheeling diode in a power module

Explanation of designations:

P_{tot}	Total power dissipation within transistor and free-wheeling diode
T_j	Junction temperatures
Z_{thjc}	Thermal impedance from junction to module case
T_c	Case temperature
Z_{thch}	Thermal impedance from module case to heatsink
T_h	Heatsink temperature
Z_{thha}	Thermal impedance from heatsink to ambient temperature (see chapter 3.3)
T_a	Ambient temperature

Transistors and inverse diodes are soldered on a common copper plate in a power module. Therefore, the elements $T_{coup/D1}$ and $T_{coup/T2}$ stand for the thermal coupling of T1 and D2 with their corresponding antiparalleled elements D1 and T2, which becomes effective especially at low fundamental frequencies.

Exact determination of this coupling effect is subject to extensive thermal simulation of the module structure [194]. Therefore, this is usually neglected in simplified calculation processes.

If transistor and free-wheeling diode are integrated in the same module, a common heatsink and case temperature may be presumed for simplification.
If this simplifaction is no more permissible for high-power single switches, the values for Z_{thch} have to be entered separately for transistor and diode.

Efficient thermal parameters between case and heatsink are also dependent on the following factors: quality of the module base plate, contact pressure between module and heatsink, thermal paste, surface quality of the heatsink. Please pay attention to the data and recommendations given by the manufacturers (see chapter 1.4.2.2).

For computer-aided simulation of the temporal behaviour of the junction temperature thermal impedances may be divided up into a chain circuit of R-C components (see Figure 3.8).
As a special service to the customer, SEMIKRON offers parameters of 4-6 R-C components for determining the Z_{thjc} of power modules in the databook. Parameters of the cooling systems are also available on request (see chapter 3.3.6).

Following the equivalent block diagram of Figure 3.8, the characteristics of the junction temperatures of transistor and diode versus time can be calculated according to the following equations based on the case temperature:

$$T_{j/T1}(t) = T_C + T_{coup/D1} + P_{T1}(t) \cdot \sum_{\nu=1}^{n} R_{th\nu/T1} \left[1 - \exp\left(- t/\tau_{th\nu/T1}\right)\right] \qquad (3.9)$$

$$T_{j/D2}(t) = T_C + T_{coup/T2} + P_{D2}(t) \cdot \sum_{\nu=1}^{n} R_{th\nu/D2} \left[1 - \exp\left(- t/\tau_{th\nu/D2}\right)\right] \qquad (3.10)$$

Often only the average junction temperatures and their ripples are decisive for the thermal layout of converters. Exemplary calculations for typical loads are explained in the following chapters.

3.2.2.2 Junction temperature during short-time operation

Short-time operation allows for higher currents to be conducted in the power semiconductors than indicated in the datasheets for permanent operation. However, the highest junction temperature generated under the given conditions should not exceed the maximum rating of T_j = 150°C.
The junction temperature can be calculated using formulas 3.9 and 3.10 in chapter 3.2.2.1.

Examples:

Single power dissipation pulse

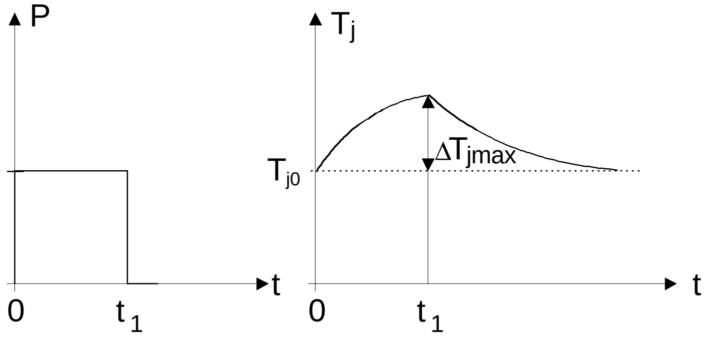

Figure 3.9 Power dissipation and junction temperature of single power dissipation pulse versus time

Maximum value of the junction temperature alteration at t_1:

$$\Delta T_{jmax} = \Delta T_j(t_1) = P \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(- t_1/\tau_{th\nu}\right)\right] \qquad (3.11)$$

Junction temperature during cooling periode:

$$\Delta T\left(t > t_1\right) = P \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(- t/\tau_{th\nu}\right)\right] - P \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(- \left(t - t_1\right)/\tau_{th\nu}\right)\right] \qquad (3.12)$$

These formulas are based on a fixed case reference temperature.

Single sequence of m power dissipation pulses

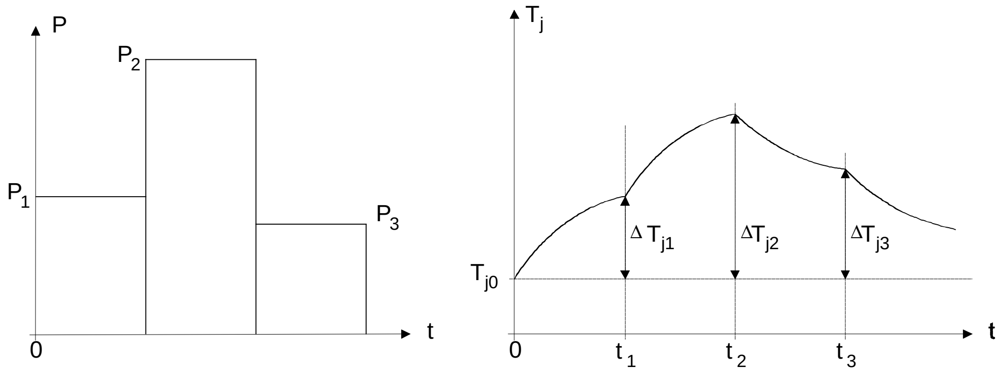

Figure 3.10 Power dissipation and junction temperature at single sequence of m power dissipation pulses versus time

Junction temperature alteration at t_1:

$$\Delta T_{j1} = P_1 \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(- t_1/\tau_{th\nu}\right)\right] \qquad (3.13)$$

Junction temperature alteration at t_2:

$$\Delta T_{j2} = P_1 \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(- t_2/\tau_{th\nu}\right)\right] + \left(P_2 - P_1\right) \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(-\left(t_2 - t_1\right)/\tau_{th\nu}\right)\right] \qquad (3.14)$$

Junction temperature alteration at t_m:

$$\Delta T_j(t_m) = \sum_{\mu=1}^{m}\left(P_\mu - P_{\mu-1}\right) \cdot \sum_{\nu=1}^{n} R_{th\nu}\left[1 - \exp\left(-\left(t_m - t_{\mu-1}\right)/\tau_{th\nu}\right)\right] \qquad (3.15)$$

These formulas are based on a fixed case reference temperature.

3.2.2.3 Junction temperature under pulse operation

The transistor and diode Z_{thjc}-characteristics under periodic pulse conditions indicated in the datasheets may be used for calculation of the average and maximum junction temperature under power dissipation load periodically repeated along with the pulse frequency.
Figure 3.11 shows such a set of curves for the IGBT and the diode of a SKM100GB123D module and a typical current and junction temperature characteristic in the transistor under pulse operation.

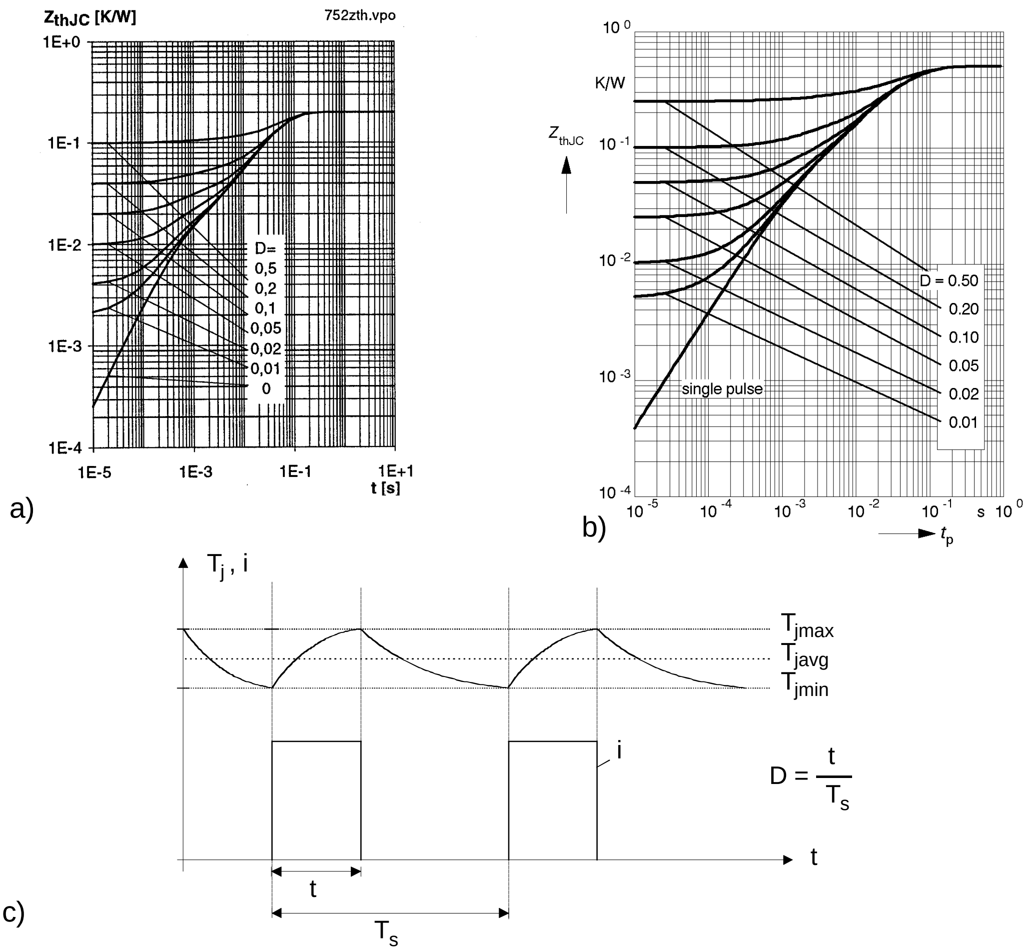

Figure 3.11 Transient thermal impedance Z_{thjc} of IGBT (a) and diode (b) of a SKM100GB123D module c) Current and temperature characteristic

The <u>average junction temperature T_{javg}</u> results from multiplication of the thermal resistance R_{thjc} with the average power dissipation P_{totavg}. The latter is calculated by averaging the energy dissipation per pulse over the whole pulse or switching duration T_s.

$$P_{totavg} = f_s * (E_{on} + E_{off} + E_{fw})$$

$$T_{javg} = T_c + P_{totavg} * R_{thjc}$$

The <u>maximum junction temperature T_{jmax}</u> results from multiplication of Z_{thjc} under pulse operation with the maximum power dissipation P_{totmax}. The latter is calculated by averaging the energy dissipation per pulse over the on-state time t of transistor or diode, respectively, within the pulse duration T_s.

$$P_{totmax} = (E_{on} + E_{off} + E_{fw})/t$$

$$T_{jmax} = T_c + P_{totmax} * Z_{thjc}$$

Examples with a SKM100GB123D IGBT:

<u>Example 1:</u> f_s = 10 kHz; T_s = 100 µs; D_T = 0.2; t = 20 µs
T_c = 80°C; $E_{on} + E_{off} + E_{fw}$ = 25 mJ
R_{thjc} = 0.2°C/W, Z_{thjc} = 0.04°C/W (see Figure 3.11a)

Consequently: P_{totavg} = 250 W; P_{totmax} = 1250 W
T_{javg} = 80°C + 250 W * 0.2°C/W = **130°C**
T_{jmax} = 80°C + 1250 W * 0.04°C/W = **130°C**

<u>Example 2:</u> f_s = 2 kHz; T_s = 500 µs; D_T = 0.2; t = 100 µs
T_c = 80°C; $E_{on} + E_{off} + E_{fw}$ = 25 mJ
R_{thjc} = 0.2°C/W, Z_{thjc} = 0.042°C/W (see Figure 3.11a)

Consequently: P_{totavg} = 50 W; P_{totmax} = 250 W
T_{javg} = 80°C + 50 W * 0.2°C/W = **90°C**
T_{jmax} = 80°C + 250 W * 0.042 °C/W = **90.5°C**

<u>Example 3:</u> f_s = 2 kHz; T_s = 500 µs; D_T = 0.2; t = 100 µs
T_c = 80°C; $E_{on} + E_{off} + E_{fw}$ = 125 mJ
R_{thjc} = 0.2°C/W, Z_{thjc} = 0.042°C/W (see Figure 3.11a)

Consequently: P_{totavg} = 250 W; P_{totmax} = 1250 W
T_{javg} = 80°C + 250 W * 0.2°C/W = **130°C**
T_{jmax} = 80°C + 1250 W * 0.042°C/W = **132.5°C**

<u>Example 4:</u> f_s = 50 Hz; T_s = 20 ms; D_T = 0.5; t = 10 ms
T_c = 80°C; $E_{on} + E_{off} + E_{fw}$ = 5 J
R_{thjc} = 0.2°C/W, Z_{thjc} = 0.12°C/W (see Figure 3.11a)

Consequently: P_{totavg} = 250 W; P_{totmax} = 500 W
T_{javg} = 80°C + 250 W * 0.2°C/W = **130°C**
T_{jmax} = 80°C + 500 W * 0.12°C/W = **140°C**