Free-wheeling diode

Turn-off power dissipation: $P_{off/D} = f_s * E_{off/D} (v_d, i_{LL}, T_{j/D})$

Forward power dissipation: $P_{fw/T} = \frac{1}{T}\int_{t_1}^{T} v_F(t) \cdot i_F(t)\, dt$

Neglecting the load current ripple will result in:

$$P_{fw/D} = i_{Lavg} * v_F (i_{Lavg}, T_{j/D}) * (1-D_T)$$
$$= i_{Lavg} * v_F (i_{Lavg}, T_{j/D}) * (D_D)$$

D_D = diode duty cycle

The calculation of IGBT and diode forward power dissipation is based on an ideal duty cycle (neglecting the share the switching time contributes to the total cycle duration).
Selected ratings for energy dissipations during switching as well as for the IGBT and diode forward voltage drop are indicated in the datasheets (see chapter 2).

3.2.1.3 Power losses in pulsed voltage source inverters/rectifiers with sinusoidal currents

Basic circuit: Figure 3.5 shows ideal characteristics of an inverter phase for a sinusoidal modulation according to the sinusoidal pulse-width modulation.

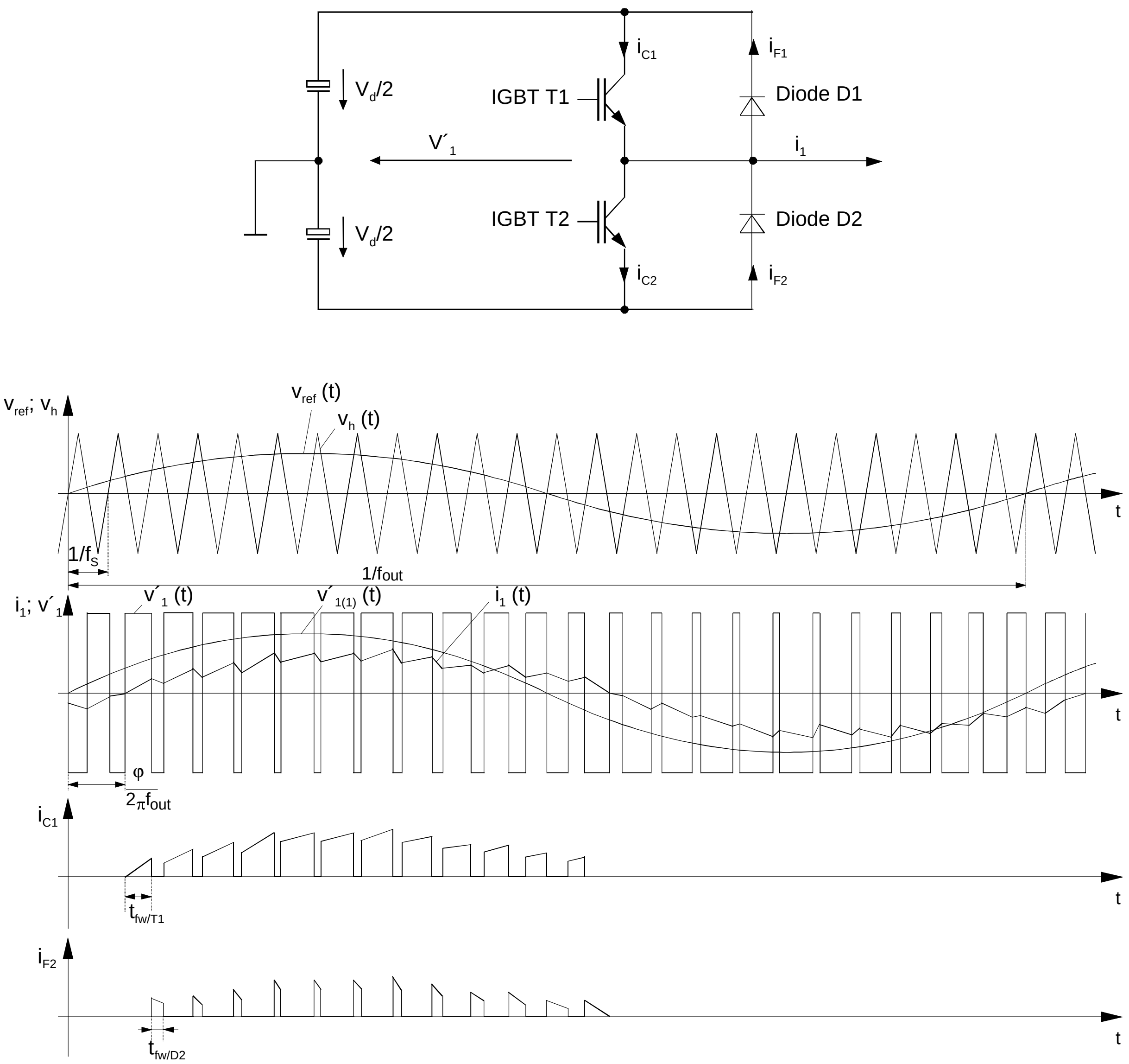

Figure 3.5 Converter phase with sinusoidal modulation according to sinusoidal pulse-width modulation

In the sinusoidal pulse-width modulation the pulse pattern is generated by comparison of a reference voltage v_{ref} to an auxiliary control voltage v_h, whereby the fundamental frequency of the AC-parameters f_{out} is determined by the reference voltage and the switching or pulse frequency of the switches f_s by the auxiliary control voltage.

The intersections of reference and auxiliary control voltage are the basis for commutation times in the converter phase.

If $\hat{v}_{ref} \leq \hat{v}_h$, this is called linear modulation mode of the inverter.

The following explanations refer to the linear modulation mode. Furthermore, it is presupposed that the fundamental frequency of the AC-parameters is exceeded by the pulse frequency by far.

Voltage utilization of the converter may be expressed by the degree of modulation m. It indicates the ratio between fundamental harmonics amplitude of the AC-voltage and 50 % of the DC-link voltage. In case of a pure sinusoidal reference voltage, the degree of linear modulation will be $0 \leq m \leq 1$.

The phase shift between the fundamental harmonics of AC current and voltage is described by the angle φ.
The current and voltage characteristics for IGBTs and diodes, which are time-shifted, will turn out to be identical due to the symmetrical structure of the inverter circuit. Therefore, it is enough to consider just one IGBT (here T1) and one diode (here D2) with reference to the calculation of power dissipation (the result is then multiplied by the corresponding number of IGBTs/ diodes integrated in the inverter).
In contrast to the calculations under chapter 3.2.1.2 duty cycle, load current and junction temperature are not constant under static operation, but vary depending on the fundamental frequency of the AC side (e.g. 50/60 Hz). This means that switching and forward power dissipations of IGBTs and diodes are subject to temporal variability and require a extensive calculation of system power losses.
Consequently, exact results cannot be produced with greatly simplified calculation procedures.

Two calculation possibilities are to be introduced in the following.

1. Approximation of component characteristics by polynominal equations (detailed in [194])

In this calculation procedure, the dependencies of transistor and diode forward on-state voltages on load current and junction temperature as well as of transistor and diode switching energy dissipations on load current, DC-link voltage and junction temperature are approximated by polynominal equations of the type $y = f(x) = A + Bx + Cx^2$. For this, the available component parameters have to be taken from the datasheets or determined by simple pulse converter test circuits, which, however, requires considerable effort.
The following set-up of the polynominal equations may be done by using conventional curve-fitting software.
The coefficients A-C of a following equations comprise the determined dependencies of the parameters.

Accordingly, equations 3.1-3.4 may be set up to calculate the average energy dissipation.
The following simplifications have been presupposed:
- transistor and diode switching times are neglected,
- temporally constant junction temperatures (permissible if f_{out} = ..50 Hz),
- linear modulation of the converter,
- neglecting the switching frequency ripple of the AC-current.

Forward power dissipation

Including forward characteristic approximation of IGBT and diode according to $y = A + Bx$ and considering the temperature coefficients of the forward on-state voltages, results in the following equations:

IGBT T1:

$$P_{fw/T1} = \left(\frac{1}{2} - \frac{t_{dead}}{T_S}\right) \cdot \left(\frac{A_{fw/T}}{\pi} \cdot \hat{i}_1 + \frac{B_{fw/T}}{4} \cdot \hat{i}_1^{\,2}\right) + m \cdot \cos\varphi \cdot \left(\frac{A_{fw/T}}{8} \cdot \hat{i}_1 + \frac{B_{fw/T}}{3\pi} \cdot \hat{i}_1^{\,2}\right) \qquad (3.1)$$

Diode D2:

$$P_{fw/D2} = \left(\frac{1}{2} + \frac{t_{dead}}{T_S}\right) \cdot \left(\frac{A_{fw/D}}{\pi} \cdot \hat{i}_1 + \frac{B_{fw/D}}{4} \cdot \hat{i}_1^{\,2}\right) - m \cdot \cos\varphi \cdot \left(\frac{A_{fw/D}}{8} \cdot \hat{i}_1 + \frac{B_{fw/D}}{3\pi} \cdot \hat{i}_1^{\,2}\right) \tag{3.2}$$

Figure 3.6 explains the influence of switching deadtime t_{dead} on forward energy dissipations (t_{dead} determines the effective duty cycles) with the example of a 1200 V/50 A-IGBT-module. Especially if high pulse frequencies are involved, the arm-interlock-deadtime t_{dead} has to be considered in the calculation of the average power forward dissipation.

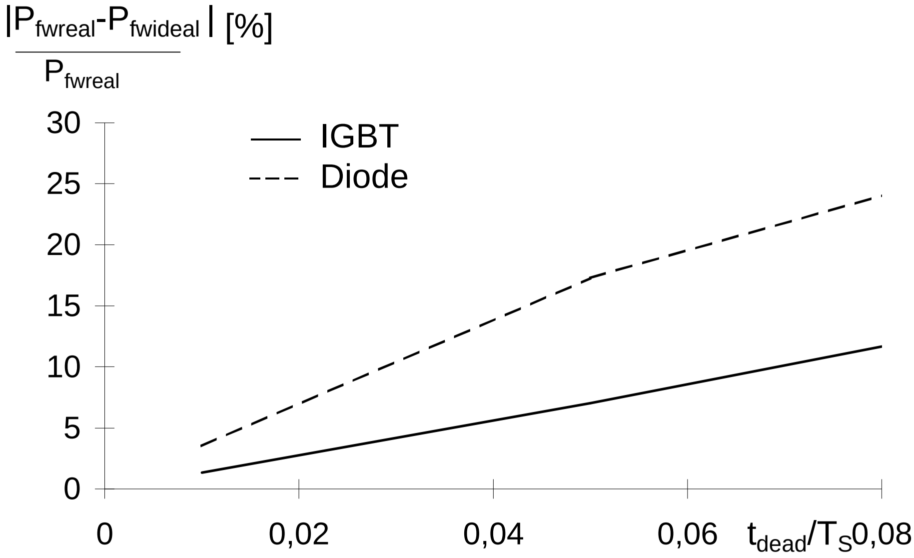

Figure 3.6 Forward power dissipations versus switching deadtimes (i_{1eff} = 25 A; m = 0.8; cos φ = 0.8)

Switching losses

The following equations result from the approximation of the dependency of switching losses on the current according to y = Bx + Cx² in consideration of temperature and voltage coefficients of the switching losses:

IGBT T1:

$$P_{on+off/T1} = f_s \cdot \hat{i}_1 \left(\frac{B_{on+off/T}}{\pi} + \frac{C_{on+off/T}}{4} \cdot \hat{i}_1\right) \tag{3.3}$$

Diode D2:

$$P_{off/D1} = f_s \cdot \hat{i}_1 \left(\frac{B_{off/D}}{\pi} + \frac{C_{off/D}}{4} \cdot \hat{i}_1\right) \tag{3.4}$$

Figure 3.7 shows one result of this calculation method with the example of a 1200 V/50 A-IGBT-dual module in an inverter.

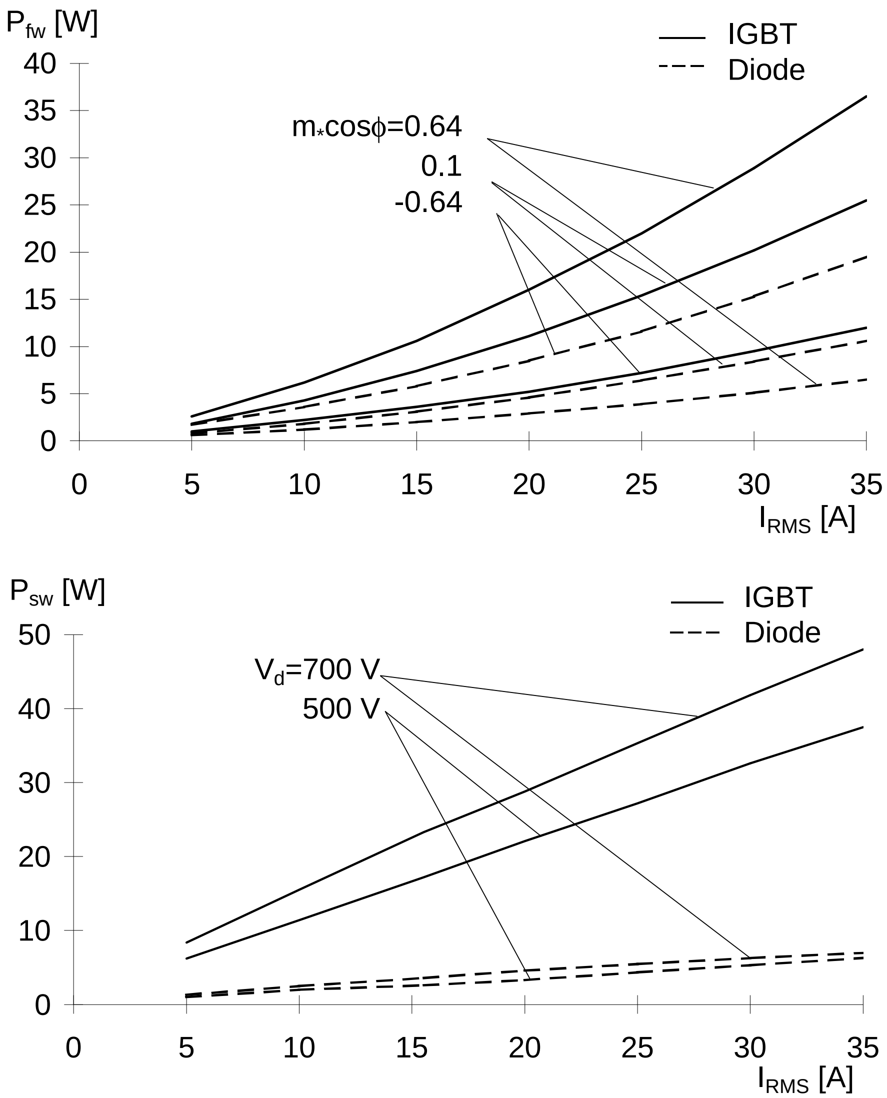

Figure 3.7 a) Forward power dissipations (t_{dead} = 5 µs, T_j = 125°C)
b) Switching losses (f_s = 10 kHz, T_j = 125°C)

The product of m*cos φ determines how the total power dissipation is divided up on IGBT and diode (see also chapter 1.3.1.4).

m*cos φ = 0.64	represents an operating point in inverter mode (motor load)
m*cos φ = 0.1	represents an operating point in motor starting mode
m*cos φ = -0.64	represents an operating point in rectifier mode

The procedure for calculation of IGBT and diode power dissipation described above shows very exact results, however the determination of parameters requires great efforts.
Therefore, the following greatly simplified calculation mode to produce a rough calculation can be recommended.

2. Simplified, linear approach [274]

Assumptions:
- transistor and diode switching times as well as switching interlocking times are neglected,
- temporally constant junction temperatures (permissible if f_{out} = ..50 Hz.),

- linear modulation of the converter,
- neglecting switching frequency ripple of the AC current (sinusoidal current),
- $f_s >> f_{out}$.

Forward on-state power dissipation:

IGBT T1:
If the output characteristics are linearized with y = A + Bx, the temporal dependency of the saturation voltage v_{CEsat} may be expressed as follows:

$$v_{CEsat}(t) = V_{CE0} + r_{CE} \cdot i_C(t) = V_{CE0} + r_{CE} \cdot \hat{i}_1 \sin \omega t$$

with: V_{CE0} = threshold voltage of the output characteristic with $i_C = 0$
r_{CE} = on-state resistance of the IGBT (rate of rise of the output characteristic)

Considering the sinusoidal dependency of duty cycles versus time, the forward power dissipation of IGBT T1 may be calculated according to

$$P_{fw/T1} = \frac{1}{2}\left(\frac{V_{CE0}}{\pi} \cdot \hat{i}_1 + \frac{r_{CE}}{4} \cdot \hat{i}_1^{\,2}\right) + m \cdot \cos\varphi \cdot \left(\frac{V_{CE0}}{8} \cdot \hat{i}_1 + \frac{r_{CE}}{3\pi} \hat{i}_1^{\,2}\right) \qquad (3.5)$$

Diode D2:
If the output characteristics are linearized with y = A + Bx, the temporal dependency of the foward on-state voltage v_F may be expressed as follows:

$$v_F(t) = V_{F0} + r_F \cdot i_F(t) = V_{F0} + r_F \cdot \hat{i}_1 \sin \omega t$$

with: V_{F0} = threshold voltage of the forward characteristic with $i_F = 0$
r_F = on-state resistance of the diode (rate of rise of the output characteristic)

Considering the sinusoidal dependency of duty cycles versus time, the forward power dissipation of diode D2 may be calculated according to

$$P_{fw/D2} = \frac{1}{2}\left(\frac{V_{F0}}{\pi} \cdot \hat{i}_1 + \frac{r_F}{4} \cdot \hat{i}_1^{\,2}\right) - m \cdot \cos\varphi \cdot \left(\frac{V_{F0}}{8} \cdot \hat{i}_1 + \frac{r_F}{3\pi} \hat{i}_1^{\,2}\right) \qquad (3.6)$$

Switching losses

IGBT T1:
Provided that the energy dissipation during switching is linearly dependent on the collector current, the total power dissipation of an IGBT may be calculated with

$$P_{on+off/T1} = \frac{1}{\pi} \cdot f_s \cdot \left[E_{on/T}\left(\hat{i}_1\right) + E_{off/T}\left(\hat{i}_1\right)\right] \qquad (3.7)$$

Equation 3.7 is actually based on the assumption that the IGBT 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.

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