3 Hints for application

3.1 Dimensioning and selection of MOSFET, IGBT and SKiiPPACK modules

The selection of power modules for any static or short-term (overload) operating conditions of a concrete application is subject to the consideration of

- voltage capacitance,
- current carrying capacity under realizeable cooling conditions and with reference to the switching frequency and
- safe operating areas (SOA).

Under no circumstances that might occur during any static or dynamic operation must the maximum ratings for blocking voltage (except for avalanche-proof MOSFETs), peak current, junction temperature and safe operating area (see chapter 2.7) indicated in the datasheets be exceeded. The same goes for the limit values of module case parameters (e.g. isolation voltage, vibration strength, climate persistence, assembly instructions).

For the sake of high reliability and long life, modules have to be designed for managing a specified number of switching cycles, which usually go along with considerable temperatures cycling. (Chapters 1.4.2.4 and 3.2.3).

Furthermore, „serious“ dimensioning will not presuppose total thermal utilization of the semiconductors to their maximum ratings $T_{j(max)}$ (e.g. 150°C) in order to keep a margin for theoretically unforeseeable cases and to be able to fall back upon the static and dynamic characteristics taken at a maximum of 125°C and guaranteed by the manufacturers.

As already explained in chapter 2.6, the most important characteristics of power modules will deteriorate when the temperature rises. For this and other reasons, the determination of the maximum operating temperature has to be paid special attention to.

3.1.1 Forward blocking voltage

Since most power modules are applied in DC-voltage links, which are AC-voltage supplied via single-phase or three-phase rectifier bridges, the blocking voltages of universally applied IGBTs (600 V, 1200 V, 1700 V) are adjusted to common line voltage levels; the same goes for highly blocking MOSFET-modules.

Therefore, firstly a rough selection is made from line voltage (control angle 0° for controlled rectifiers) V_N or no-load direct voltage V_{di} as follows:

V_N/V	**rectification**	**V_{di}/V**	**V_{DSS}, V_{CES}/V**
24	B2	22	50
48	B2	44	100
125	B2	110	200
200...246	B2	180...221	500, 600
400...460	B6	540...621	1200
575...690	B6	777...932	1700
...1000...	B6	1500	3300

Afterwards, it has to be checked whether on condition of utmost voltage capacitance, i.e.

- maximum stationary input voltage (nominal voltage + line voltage tolerance, e.g. 15 %),
- transient line overvoltage, as far as it has not yet been reduced by line filters, DC-link capacitors and circuits on the DC-side (suppressor diodes, snubbers, varistors),
- turn-off overvoltage $V_d + \Delta V$

the maximum module voltage will be exceeded with

$$\Delta V = L_\sigma * I_{max}/t_f$$

with parameters as follows:

L_σ:	parasitic commutation inductance, see chapters 1.4.2.5 and 3.4.2,
I_{max}:	maximum turn-off collector or drain current (mostly with active short-circuit turn-off, see chapter 3.6),
t_f:	fall time of collector or drain current.

Here, special attention has to be paid to the fact that the maximum rating for V_{DSS}/V_{CES} indicated in the datasheets is related to the characteristics of the transistor chips and not to the „dynamic“ terminal behaviour of the module. The internal module inductance L_{CE} also indicated in the datasheets (e.g. 20...30 nH) therefore corresponds to a share of L_σ; the voltage applied to the chips will exceed the voltage to be taken at the terminals by $L_{CE} * I/t_f$ during turn-off. This is expressed by a diagram in the SEMITRANS MOSFET datasheets, which explains the derating of the permissible drain-source voltage at the terminals versus the rate of fall of the drain current $di_D/dt \approx I_D/t_f$ (Figure 3.1).

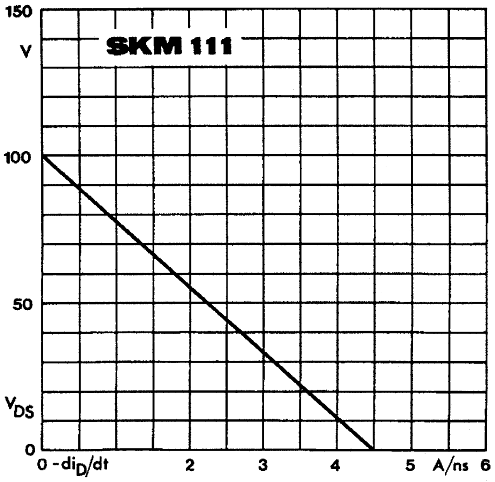

Figure 3.1 Drain-source voltage V_{DS} derating of a SEMITRANS MOSFET-module SKM 111 A versus drain current rate of fall di_D/dt

3.1.2 Forward current

The maximum continuous drain or collector currents I_D or I_C, respectively, indicated in the datasheets as typical currents for module designation and as maximum ratings may be calculated for a stationary fully controlled transistor at a case temperature T_{case} of, for example, 25°C or 80°C according to the following formula

$$I_D = \sqrt{\left(T_{j(max)} - T_{case}\right) / \left(R_{DS(on)} \cdot R_{thjc}\right)} \qquad \text{(MOSFET-module)}$$

or $$I_C = (T_{j(max)} - T_{case})/(V_{CEsat} * R_{thjc}) \qquad \text{(IGBT-module)}$$

For modules without base plate T_h will replace T_{case} and R_{thjh} will replace R_{thjc}. The ratings for $R_{DS(on)}$ and V_{CEsat} have been taken at a maximum chip temperature $T_{j(max)}$.
These indications are only intended to give an orientation aid, since under real operating conditions switching and (low) blocking losses will occur additionally to the forward on-state losses, the case temperature will differ and the static maximum ratings of $R_{DS(on)}$ or V_{CEsat} will not be reached during the whole turn-on procedure.
At a given case temperature (25°C, 80°C), the peak current values for I_{DM} or I_{CM} are specified for single pulses with a pulse duration of 1 ms and, at the same time, are designating the maximum current ratings for periodic turn-on and turn-off (SOAR).

Therefore, the utilizeable forward current is determined
- mainly by the total power dissipation of the transistors and free-wheeling diodes of a power module and the chip temperatures within the transistors and free-wheeling diodes arising under specific cooling conditions (R_{thca}), which must not exceed $T_{j(max)}$ (chapter 3.2.2),
- by the limits of the maximum safe operating area, see chapters 2.2 and 2.3. To avoid exceeding the limit values during hard turn-on under ohmic-inductive load, the amount of load current and reverse recovery current of the free-wheeling diode must not exceed I_{DM} or I_{CM}, see Figure 3.2. Due to the reasons mentioned in chapter 1.3.1.3 a compromise has to be found between turn-on speed of the transistor (increase of turn-on losses!) and conductable load current in most cases.

Further restrictions in practice have possibly to be accepted resulting from the characteristics of active overcurrent protection in the driver (see chapter 3.5).

3.1.3 Switching frequency

Figure 3.2 shows the measured turn-on and turn-off behaviour of a power MOSFET and an IGBT module for one specific operating point.

Apart from the characteristics for v_{DS} or v_{CE} and i_D or i_C also the instantaneous power dissipation p(t) had been determined by multiplication of instantaneous current and voltage values; the integral of p(t) reflects the total MOSFET and IGBT losses over the whole period.

To determine total power dissipation of the power module, the losses of the free-wheeling diode(s) within the module have to be added to the losses in the transistor, see chapter 3.2.1.

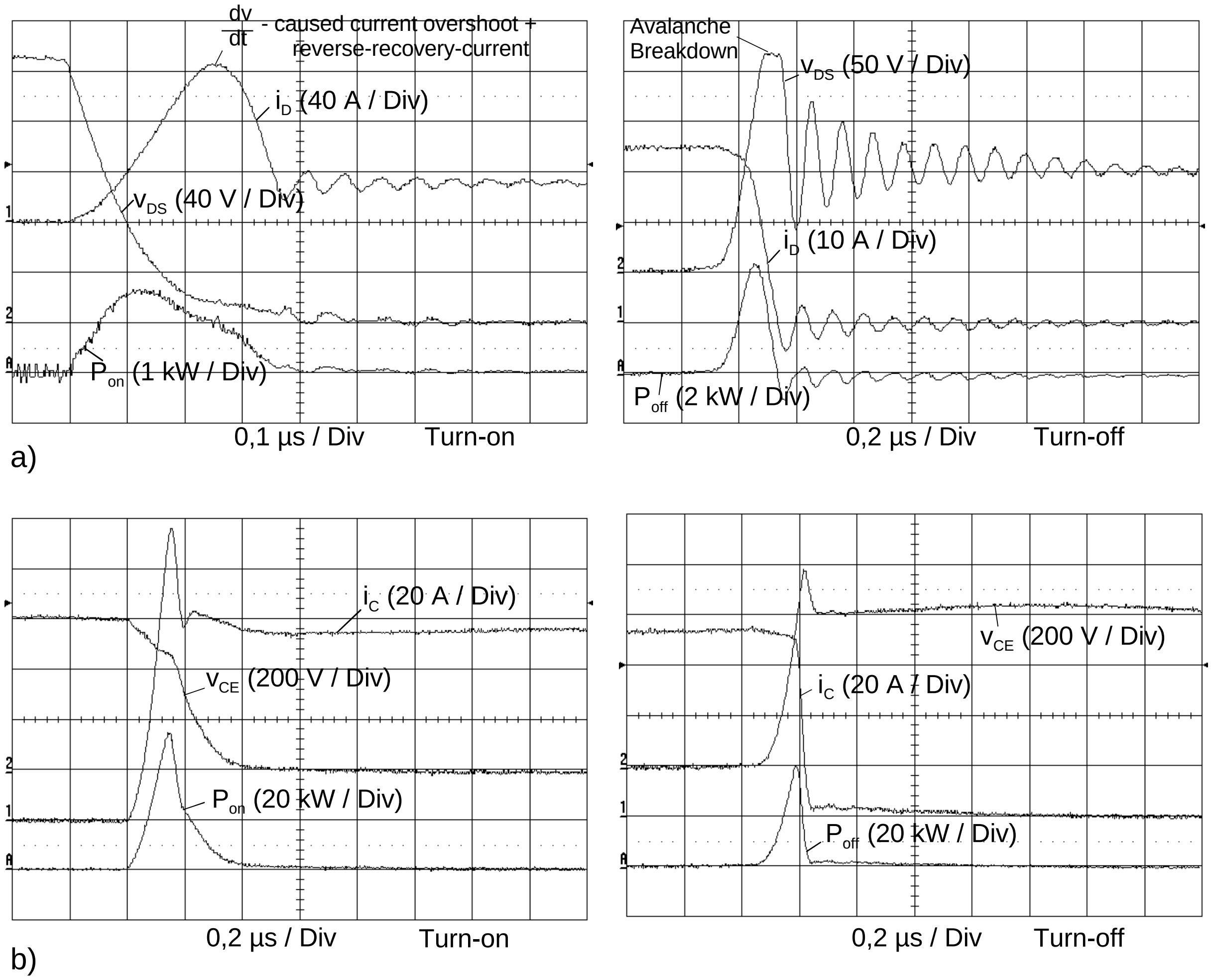

Figure 3.2 Measured switching processes (hard turn-on and turn-off under ohmic-inductive load)
a) Power-MOSFET module b) IGBT module

For explanations on quality features of current and voltage characteristics please refer to the remarks on Figure 1.11 in chapter 1.2.3.

The actual limits to the switching frequency are set by the switching losses, because they are increasing proportionally to the frequency.
Other terminations may be set by the transistor turn-on and turn-off delay times $t_{d(on)}$, $t_{d(off)}$, the reverse recovery times of the free-wheeling diodes, the driver output power which increases proportionally to the frequency and the minimum turn-on, turn-off or dead times necessary for driver, interlocking, measuring, protection and monitoring functions, see chapter 3.5.1...3.5.4.
If switching losses are to be shifted to passive networks (snubbers) or overvoltages are to be limited by snubbers, the recharge time of such networks required after low-loss switching has to be considered as deadtime, see chapters 3.6 and 3.8.

Switching times of MOSFET and IGBT power modules are within the range of some 10 ns to some 100 ns. Especially when high operating voltages and hard switching processes are involved, the theoretically reachable maximum switching frequency cannot be utilized in most cases, since the maximum switching speed is often determined by

- the turn-off speed, limited by the permissible switching overvoltage and

- the turn-on speed, limited by the permissible peak current (load current + reverse recovery current of the free-wheeling diode depending on di/dt).

Moreover, transistor dv/dt and di/dt values, which are prone to be very steep within the high power range, might cause electromagnetic interferences and problems due to dv/dt in certain loads (machines).
Therefore, an optimized compromise between the requirements resulting from the application (e.g. frequency out of range of audibility), switching times/ losses, power dissipation and EMC-features has to be looked for when determining switching frequency and switching times.

These are the standard values for switching frequencies with standard modules, optimal technical utilization provided:

for hard switching:	MOSFET-modules	low-voltage	up to 250 kHz
		high-voltage	up to 100 kHz
	IGBT-modules	600 V	up to 30 kHz
		1200 V	up to 20 kHz
		1700 V	up to 10 kHz
		3300 V	up to 3 kHz
for soft switching:	MOSFET-modules	low-voltage	up to 500 kHz
		high-voltage	up to 250 kHz
	IGBT-modules		up to 150 kHz

Higher switching frequencies can be realized with modules specially designed for fast switching.

3.2 Thermal behaviour

3.2.1 Balance of power losses

3.2.1.1 Single and total power losses

Introductory remarks

All explanations in chapter 3.2 refer to IGBT modules. All considerations and calculations are applicable to MOSFET modules in analogy, provided all designation indices corresponding to MOSFETs are exchanged.
The following explanations are focused on hard switching converters connected to a DC-voltage-link.

In power electronics, IGBTs as well as diodes are operated mainly as switches, taking on various static and dynamic states in cycles. In any of these states, one power dissipation or energy dissipation component is generated, which heats the semiconductor and adds to the total power dissipation of the switch. Therefore, the maximum junction temperature T_j= 150°C (for silicon components) given by the manufacturer has to be obeyed at any time of operation of the converter when using power semiconductors.

Figure 3.3 shows a survey of the possible single power dissipations during switch operation.

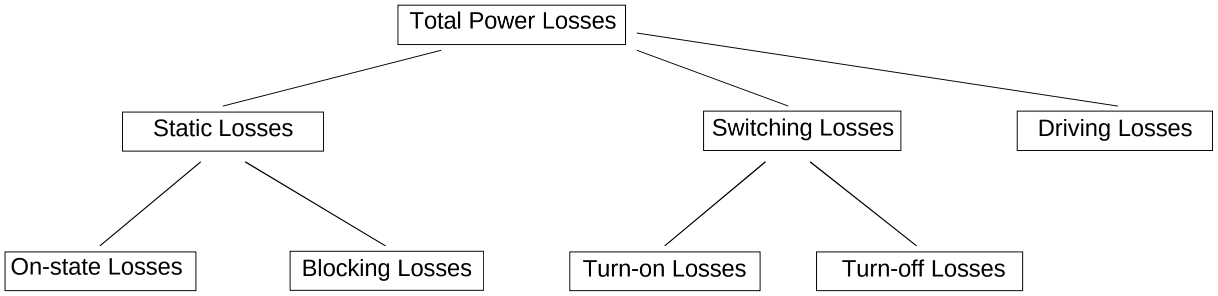

Figure 3.3 Single power losses of power module switches

IGBT

Because they are only contributing to a minor share of the total power dissipation, forward blocking losses and driver losses may usually be neglected.

On-state power dissipations ($P_{fw/T}$) are dependent on:

- load current (over output characteristic $v_{CEsat} = f(i_C, v_{GE})$),
- junction temperature,
- duty cycles.

For given driver parameters, the turn-on and turn-off power dissipations ($P_{on/T}$, $P_{off/T}$) are dependent on:

- load current,
- DC-link voltage,
- junction temperature,
- switching frequency.

IGBT total power losses: $\mathbf{P_{tot/T} = P_{fw/T} + P_{on/T} + P_{off/T}}$

Free-wheeling diode:

Because they are only contributing to a minor share of the total power dissipation, reverse blocking power dissipations may usually be neglected. Schottky diodes might be an exception due to their high-temperature blocking currents.
Turn-on power dissipations are caused by the forward recovery process. As for fast diodes, this share of the losses may mostly be neglected as well.

On-state power dissipations ($P_{fw/D}$) are dependent on:

- load current (over forward characteristic $v_F = f(i_F)$),
- junction temperature,
- duty cycles.

For given driver parameters of the IGBT commutating with the diode, turn-off power dissipations ($P_{off/D}$) are dependent on:

- load current,
- DC-link voltage,
- junction temperature,
- switching frequency.

Total diode power losses: $\mathbf{P_{tot/D} = P_{fw/D} + P_{off/D}}$

Hybrid power module with n IGBTs and m diodes

Total module power losses: $\mathbf{P_{tot/M} = (n \ast P_{tot/T}) + (m \ast P_{tot/D})}$

3.2.1.2 Power losses of a step-down converter

Figure 3.4 shows the circuit diagram of a step-down converter with characteristics generated under ohmic inductive load.

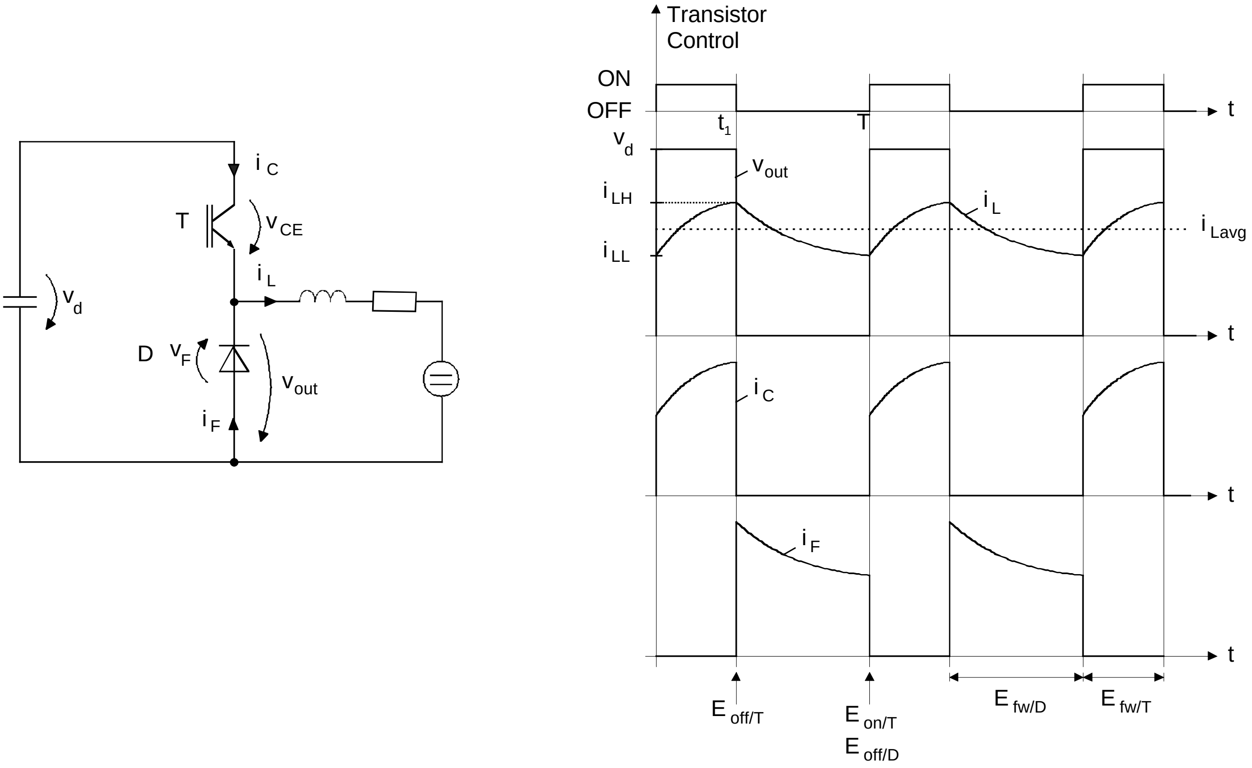

Figure 3.4 Step-down converter under ohmic-inductive load

During the steady state of the circuit, power dissipations at a certain operation point may be calculated as follows:

IGBT

Turn-on power dissipation: $P_{on/T} = f_s \ast E_{on/T}\,(v_d, i_{LL}, T_{j/T})$
Turn-off power dissipation: $P_{off/T} = f_s \ast E_{off/T}\,(v_d, i_{LH}, T_{j/T})$

Foward power dissipation: $$P_{fw/T} = \frac{1}{T}\int_0^{t_1} i_C(t) \cdot v_{CE}(t)\,dt$$

Neglecting the load current ripple will result in:

$$\begin{aligned} P_{fw/T} &= i_{Lavg} \ast v_{CEsat}\,(i_{Lavg}, T_{j/T}) \ast (t_1/T) \\ &= i_{Lavg} \ast v_{CEsat}\,(i_{Lavg}, T_{j/T}) \ast D_T \end{aligned}$$

D_T = transistor duty cycle
i_{Lavg} = average load current